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Transportation Research Record 1361

Contents

Part 2—Planning and Finance

Foreword

North American light rail transit (LRT) systems continue to expand at an ever-increasing rate. Since the last national LRT conference in 1988, two all-new LRT systems have begun operation in Los Angeles and Baltimore, and three are in final design and construction in Dallas, Denver, and St. Louis. Seven LRT systems have been extended: Calgary, Edmonton, New Orleans, San Diego, San Francisco, San Jose, and Toronto. Four more LRT systems have additional lines and extensions under final design and construction: Baltimore, Los Angeles, Portland, and San Diego. New systems have also been opened with planned extensions in Guadalajara, Mexico City, and Monterrey. Twenty-one additional LRT projects are in the planning and preliminary engineering stages, including all-new LRT systems for Chicago, Milwaukee, Minneapolis–St. Paul, Salt Lake City, and Seattle. New LRT projects continue to illustrate the flexibility and effectiveness of these systems in providing quality transportation at affordable prices. Efforts to expand virtually all of the new North American LRT systems demonstrate their acceptance by the riding public, the communities through which they pass, and the taxpayers who must fund their construction and continued operation. During the 1990s more all-new LRT systems will be implemented and existing systems extended or upgraded.

This Record contains the technical papers presented at the Sixth National Conference on Light Rail Transit, held in Calgary, Alberta, Canada, May 24–27, 1992, and two papers presented at a TRB Annual Meeting. Together they provide a comprehensive overview of current LRT developments, covering the description of major LRT systems, planning and finance, management and staffing, design and engineering, operations and maintenance, and vintage trolley operations.

The conference theme for this sixth national conference was the performance experience of the new North American LRT systems—that is, how well have the new systems, those opened since 1978, met their goals and objectives in terms of ridership, costs, and cost-effectiveness? The conference featured 11 technical sessions in which 70 speakers presented lessons learned in financing, planning, designing, building, operating, and maintaining LRT systems in the United States, Canada, and abroad. For the first time in the series of LRT conferences, one session was devoted entirely to vintage trolleys, which are gaining in popularity in North American cities.

More than 400 participants attended the 1992 conference in Calgary. Fifth registrants came from 15 countries in Europe, Africa, and Asia—the largest international attendance since inception of the LRT conferences in 1975. Sponsored by the Transportation Research Board, the conference was cosponsored by the International Union of Public Transport, the Canadian Urban Transit Association, and the city of Calgary Transportation Department. Calgary was chosen as the conference site because it has what is considered to be North America's most successful all-new LRT system—a three-line network totaling 18.2 mi and carrying more than 115,000 daily riders. Professionals in the LRT field and elected officials alike came to Calgary to discover the secrets of that LRT system's remarkable success and to try to emulate those elements directly transferable to their own LRT projects. Each of the three LRT lines in the Calgary system is distinctly different, operating on different kinds of right-of-way and presenting an evolving design treatment for blending the line and stations in with the community.

The conference opened with two key presentations, one on the planning, design, and operation of the Calgary LRT system presented by John Hubbel and a second on the current status of North American LRT systems presented by John Schumann. The latter paper includes a narrative description of the latest status of each LRT system in the United States, Canada, and Mexico, and up-to-date tables containing a wealth of vital statistics.

Al Duerr, mayor of Calgary and an urban planner by profession, delivered the keynote luncheon address. He spoke about how LRT was an important tool that Calgary was using to help shape the desired land use pattern for the city and to achieve important environmental goals. The city of Calgary grew from a population of about 400,000 in 1970 to more than 600,000 in 1980, an increase of 50 percent in only 10 years. During this period of unprecedented growth, the city was faced with major decisions on how and where the city should grow and what kind of transportation system would best handle this new growth. Out of this came the decision to implement an LRT system in three major corridors serving the downtown, which contains a major share of the city's jobs and retail trade. Calgary has plans to extend all three existing LRT lines plus add new lines to the west, north, and southeast, all eventually linked through a downtown subway under Eighth Avenue. The LRT system will be gradually expanded as urban growth demands require it and as financial resources permit.

The sixth national LRT conference presented strong evidence that the new North American LRT systems are performing up to community expectations and that, in virtually every city with a new LRT system, additional lines and extensions have been approved and are now proceeding. A wave of new-start LRT systems is sweeping the Midwest, including Chicago, Dallas, Denver, St. Louis, and other cities. The conference also showed that international interest in LRT is very strong, with new LRT systems springing up in many fast-growing cities in Europe, Africa, Asia, and Central and South America. Conference attendees learned that new LRT systems are being developed in Mexico, Hong Kong, the Philippines, England, France, and Sweden. The great diversity in the way light rail is being implemented is striking as is the wide variety of rights-of-way being used, which range from lightly used or abandoned railroads to freeway medians, from surface streets to underground tunnels. Fast-emerging LRT technological developments to watch include both low-floor light rail vehicles and the use of alternating current propulsion systems. Many new LRT systems are beginning to attract high-quality joint development projects around their stations, as shown by the Portland and San Diego systems.

Part 1 of this Record presents nine papers that provide general information on LRT developments in North America and abroad. In addition to the 1992 update and status report on North American LRT systems (three Canadian and two U.S. systems), the light rail operation in Linz, Austria, and the new suburban system in Hong Kong are described in more detail. This first part also contains a comprehensive report on developments of low-floor vehicles in Europe.

Part 2 contains 11 papers on many LRT-related planning and finance issues. Five of those papers describe the plans and development of foreign systems, and two present the planning process used in Portland and Honolulu to integrate LRT with the adjoining neighborhoods. The last four papers in this part describe planning principles of LRT stations and intermodal facilities.

Management, staffing, training, and effective use of manpower are the topics of the four papers in Part 3. Design and engineering for the systems in San Diego, Portland, Baltimore, Dallas, Calgary, and St. Louis are described in Part 4. Part 4 also treats more general engineering issues for control of at-grade LRT crossings, blending light rail into arterial streets, and bridge design.

Part 5 contains nine papers on operations and maintenance. They deal with issues relating to the start-up of new operations, improvements to service of existing systems through better operating control, single-track operations, security of riders, and performance trends of maturing systems.

Part 6, the final part of this Record, presents six papers on vintage trolley projects that are quickly emerging as both downtown circulators and tourist attractions. A national overview of the currently operating systems is given, and the operating experience from five cities is outlined.

This Record and the proceedings of the five previous conferences serve as the single best set of reference texts for technical questions and the state of the art for light rail transit.

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Part 1
Overview

Status of North American LRT Systems: 1992 Update

JOHN W. SCHUMANN

Previous summaries of light rail transit (LRT) systems have covered reconstruction of systems surviving from the first generation of electric railway development and initiation of service on seven completely new lines. This update provides tables that include the eighth all-new project (the Long Beach–Los Angeles Blue Line), as well as extensions and improvements elsewhere. Significant events of the past 3 years include the opening of new lines and line extensions in San Diego, Calgary, Edmonton, San Francisco, and Toronto, and completion in Santa Clara County (San Jose) of the full 32.8-km (20.4-mi) Guadalupe Corridor LRT project. Other cities have purchased additional light rail vehicles (LRVs) and added stations. Sacramento is increasing its double track from 40 percent to 60 percent of total line length. Progress continues in other U.S., Canadian, and Mexican cities that are building, designing, and planning LRT systems. Several North American transit agencies are seriously considering low-floor LRVs, and cities planning LRT also are being introduced to the concept. However, a design is needed that provides low-level entries but that also builds on proven technology to meet North American criteria for crashworthiness and fire safety. New projects continue to illustrate the flexibility and effectiveness of LRT in providing quality service at affordable prices. Efforts to expand all the new LRT systems demonstrate LRT's acceptance by the riding public. The next decade should see more new projects implemented and existing systems extended or upgraded.

Twenty years ago the transit industry was talking about a signal event: the first order in many years for electric surface rail cars, newly dubbed "light rail vehicles" (LRVs), placed jointly by authorities in Boston and San Francisco. This was the first real indication that the few trolley systems still running probably would be saved and renewed for many more decades of service.

Looking back it is surprising how much progress has been made since 1972 by what is now called the light rail transit (LRT) mode. Previous summaries (*1*,*2*) have included the reconstruction of systems surviving from the first generation of electric railway development in nine cities and the initiation of service on completely new LRT lines in seven cities.

At the last national LRT conference sponsored by the Transportation Research Board, it was reported that the previous decade had seen a 47 percent increase in miles of LRT line in service, including new-start systems in Edmonton, Calgary, San Diego, Buffalo, Portland, Sacramento, and San Jose. Progress has continued in the last 4 years. Patronage on most new-start projects has been growing. More new systems have opened and existing systems have grown or been improved.

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This update supplements the previous summaries. It adds data on the eighth all-new project to open (Long Beach–Los Angeles) as well as on extensions and other improvements elsewhere. Baltimore has just initiated revenue service, but only part of the total project is operating and is too new for meaningful statistics. In addition progress on systems being built, designed, and planned in other U.S. and Canadian cities is noted. LRT developments in Mexico are summarized in a separate section.

EVOLVING LRT CONCEPT

Starting with the first national LRT conference in 1975, TRB has played a leading role in dissemination of balanced, unbiased information on planning, design, and operation of LRT systems. An early contribution was a succinct definition of the mode:

> Light rail transit is a mode of urban transportation that uses predominantly reserved, but not necessarily grade-separated, rights-of-way. Electrically propelled vehicles operate singly or in trains. Light rail transit provides a wide range of passenger capacities and performance characteristics at moderate costs. (*3*, p. 1)

Reviewing progress during the intervening years, TRB's LRT subcommittee decided that a revised definition was needed. This was prepared and approved at the end of 1988:

> Light rail transit is a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights-of-way at ground level, on aerial structures, in subways or, occasionally, in streets, and to board and discharge passengers at track or car-floor level.

The goal was a definition that would be more descriptive of the technology that had emerged during those years and would not categorically exclude streetcars but would separate LRT from automated and manually operated guideway transit systems for which full grade separation is mandatory. This is a somewhat different approach from that of the American Public Transit Association and the Federal Transit Administration, both of which simply combine streetcars with the LRT category in their statistics.

CHANGES IN TABLE FORMATS

In previous summaries, tabular data on LRT and streetcar systems were aggregated into three categories:

- LRT—Group I: system average operating speeds of 24 km/hr (15 mph) or higher;
- LRT—Group II: system average operating speeds of at least 16 km/hr (10 mph), but less than 24 km/hr (15 mph); and
- Streetcars: system average operating speeds less than 16 km/hr (10-mph).

The tables in this paper have been recast to combine the Streetcars category with LRT—Group II. Thus 24 km/hr (15 mph) is the single break point in assigning systems to a category. In fact the three systems previously listed as Streetcars do have varying degrees of LRT characteristics:

- New Orleans' St. Charles line operates mostly in reserved median alignments; frequent passenger stops and unprotected grade crossings are the primary reasons for its low commercial speed.
- North Philadelphia car lines still in service are gaining some separation from other traffic by designation of medians as semiexclusive transit lanes, as described below.
- Toronto's new Harbourfront line, operating in a reserved median and a short subway, is clearly LRT.

As indicated in Tables 1–7, the cities in Group I are primarily those using LRT for line-haul express services on relatively long main trunk routes. Systems in Group II tend to have shorter lines serving the heavier routes of the inner urban area. Group I LRV fleets are spread more thinly over their route networks than is typically the case for Group II. There are, of course, exceptions in each category.

The remainder of this paper discusses specific progress made since 1988 by North American LRT systems, new starts, and cities actively planning LRT.

UPGRADING AND EXPANSION OF EXISTING SYSTEMS

Work to renew older systems and expand second generation LRT projects continues. Progress since 1988 is summarized below by city.

Boston (Green Line)

- Specifications have been drafted for the next procurement of LRVs, which are to be low-floor cars. Funding must be identified to proceed with this first step to make the Green Line comply with requirements of the Americans with Disabilities Act. Station modifications will follow in a program staged over time.
- Design work is proceeding on relocation of the North Station area from an elevated structure to a new subway alignment.
- Planning continues for rebuilding the Lechmere terminus.
- The Fort Point Channel Underground Transitway is being conceptually designed for electric trolley or dual-mode buses with the potential for conversion to LRT.

TABLE 1 Line Lengths, Car Fleets, and Productivity

City/System	Parameters			Statistics		
	One-Way Line km(mi)	No. of Cars	Rides/ Weekday	Cars/ km(mi)	Rides/ km(mi)	Rides/ Car
LRT-Group I:						
Calgary, C-Train(a)	29.3(18.2)	85	114000	2.9(4.7)	3891(6264)	1341
Cleveland, Shaker Rapid(b)	21.1(13.1)	48	17500	2.3(3.7)	829(1336)	365
Edmonton, Northeast LRT(a)	11.1(6.9)	37	23000	3.3(5.4)	2072(3333)	622
Los Angeles, Long Beach (a)	35.4(22.0)	54	35000	1.5(2.5)	989(1591)	648
Newark, City Subway(b)	6.9(4.3)	24	14100	3.5(5.6)	2043(3279)	588
Phila, Media-Sharon Hill(b)	19.2(11.9)	29	9200	1.5(2.4)	479(773)	317
Portland, MAX(a)	24.3(15.1)	26	24000	1.1(1.7)	988(1589)	923
Sacramento, RT Metro(a)	29.5(18.3)	36	23000	1.2(2.0)	782(1257)	639
San Diego Trolley(a)	54.7(33.9)	71	53000	1.3(2.1)	969(1563)	746
San Jose, Guadalupe(a)	32.2(20.0)	50	19000	1.6(2.5)	590(950)	380
Subtotals/Averages	263.7(163.7)	460	331800	1.7(2.8)	1258(2027)	721
LRT-Group II:						
Boston, Green Line(b)	40.1(24.9)	225	215000	5.6(9.0)	5362(8635)	956
Boston, Mattapan-Ashmont(b)	4.3(2.7)	12	6800	2.8(4.4)	1581(2519)	567
Buffalo, MetroRail(a)	10.3(6.4)	27	28000	2.6(4.2)	2718(4375)	1037
Ft. Worth, Tandy	1.6(1.0)	8	5900	5.0(8.0)	3688(5900)	738
New Orleans, St. Charles(b)	10.5(6.5)	35	21000	3.3(5.4)	2000(3231)	600
Philadelphia, Streetcars	46.0(28.6)	99	56800	2.2(3.5)	1235(1986)	574
Phila, Subway-Surface(b)	35.9(22.3)	112	48200	3.1(5.0)	1343(2161)	430
Pittsburgh, South Hills(b)	43.5(27.0)	71	36000	2.0(3.2)	828(1333)	507
San Francisco, Muni Metro(c)	35.4(22.1)	128	134300	3.6(5.8)	3794(6077)	1049
Toronto, Streetcars	75.5(46.9)	290	307100	3.8(6.2)	4068(6548)	1059
Subtotals/Averages	303.1(188.4)	1007	859100	3.4(5.4)	2834(4560)	853
Totals/Averages	566.8(352.1)	1467	1190900	2.6(4.2)	2101(3382)	812

(a) New start opened since 1977; (b) Major reconstruction/rehabilitation since 1977; (c) Upgraded from streetcar to LRT standards since 1977

TABLE 2 Key Descriptive Statistics

City/System	R/W Reserved	Avg Sta Spacing	Double Track	Through Routes	No. of Cars: 4-Axle(a)	No. of Cars: 6-Axle(b)	System Average Speed
	(%)	km(mi)	(%)	(No.)	(No.)	(No.)	km(mi)/hr
LRT-Group I:							
Calgary, C-Train	100%	0.9(0.6)	100%	3	0	85	29(18)
Cleveland, Shaker Rapid	100%	0.8(0.5)	100%	2	0	48	30(18)
Edmonton, Northeast LRT	100%	1.3(0.8)	100%	1	0	37	30(19)
Los Angeles, Long Beach	100%	1.6(1.0)	100%	1	0	54	34(21)
Newark, City Subway	100%	0.6(0.4)	100%	1	24	0	28(18)
Phila, Media-Sharon Hill	87%	0.4(0.2)	71%	2	29	0	26(16)
Portland, MAX	99%	0.9(0.6)	89%	1	4(c)	26	30(19)
Sacramento, RT Metro	84%	1.0(0.7)	60%	1	0	36	34(21)
San Diego Trolley	100%	1.6(1.0)	98%	2	0	71	29(18)
San Jose, Guadalupe	100%	1.1(0.7)	95%	2	6(c)	50	32(20)
Subtotals/Averages	98%	1.0(0.6)	91%	15	53	407	---
LRT-Group II:							
Boston, Green Line	89%	0.5(0.3)	100%	4	0	225	22(13)
Boston, Mattapan-Ashmont	100%	0.5(0.3)	100%	1	12	0	20(12)
Buffalo, MetroRail	100%	0.7(0.5)	100%	1	27	0	20(12)
Fort Worth, Tandy	100%	0.3(0.2)	100%	1	8	0	17(11)
New Orleans, St. Charles	88%	0.2(0.1)	100%	1	35	0	15(9)
Philadelphia, Streetcars	5%	0.2(0.1)	100%	3	99	0	14(9)
Phila, Subway-Surface	16%	0.2(0.1)	100%	5	112	0	18(11)
Pittsburgh, South Hills	97%	0.5(0.3)	91%	5	16	55	22(14)
San Francisco, Muni Metro	40%	0.2(0.1)	100%	5	0	128	18(11)
Toronto, Streetcars	10%	0.1(0.1)	100%	10	238	52	15(9)
Subtotals/Averages	43%	0.2(0.1)	99%	36	547	460	---
Totals	68%	0.3(0.2)	95%	51	600	867	---

(a) Non-articulated, rigid body; (b) Articulated; (c) Vintage trolley cars for downtown loop, not included in totals

TABLE 3 Right-of-Way Locations

City/System	km(mi) of Line: Subway/ Tunnel	Exclusive	Pvt R/W	St/Hwy Median	Street Lanes/ Malls	Mixed Traffic	Total
		(a)	(b)	(c)	(d)	(e)	
LRT-Group I:							
Calgary, C-Train	1.9(1.2)	1.3(0.8)	13.2(8.2)	10.5(6.5)	2.4(1.5)	---	29.3(18.2)
Cleveland, Shaker Rapid	---	11.3(7.0)	---	9.8(6.1)	---	---	21.1(13.1)
Edmonton, Northeast LRT	2.9(1.8)	---	8.2(5.1)	---	---	---	11.1(6.9)
Los Angeles, Long Beach	0.8(0.5)	---	29.8(18.5)	3.2(2.0)	1.6(1.0)	---	35.4(22.0)
Newark, City Subway	2.1(1.3)	4.8(3.0)	---	---	---	---	6.9(4.3)
Phila, Media-Sharon Hill	---	---	16.3(10.1)	---	0.3(0.2)	2.6(1.6)	19.2(11.9)
Portland, MAX	---	8.7(5.4)	3.7(2.3)	8.4(5.2)	3.4(2.1)	0.1(0.1)	24.3(15.1)
Sacramento, RT Metro	---	9.5(5.9)	12.4(7.7)	1.0(0.6)	1.8(1.1)	4.8(3.0)	29.5(18.3)
San Diego Trolley	---	---	51.1(31.7)	1.6(1.0)	2.0(1.2)	---	54.7(33.9)
San Jose, Guadalupe	---	15.8(9.8)	1.8(1.1)	13.5(8.4)	1.1(0.7)	---	32.2(20.0)
Subtotals	7.7(4.8)	51.4(31.9)	136.5(84.7)	48.0(29.8)	12.6(7.8)	7.5(4.7)	263.7(163.7)
LRT-Group II:							
Boston, Green Line	7.2(4.5)	17.1(10.6)	---	11.4(7.1)	---	4.4(2.7)	40.1(24.9)
Boston, Mattapan-Ashmont	---	4.3(2.7)	---	---	---	---	4.3(2.7)
Buffalo, MetroRail	8.4(5.2)	---	---	---	1.9(1.2)	---	10.3(6.4)
Fort Worth, Tandy	0.6(0.4)	---	1.0(0.6)	---	---	---	1.6(1.0)
New Orleans, St. Charles	---	---	---	9.0(5.6)	0.2(0.1)	1.3(0.8)	10.5(6.5)
Philadelphia, Streetcars	---	---	---	---	2.1(1.3)	43.9(27.3)	46.0(28.6)
Phila, Subway-Surface	4.0(2.5)	---	---	1.6(1.0)	---	30.3(18.8)	35.9(22.3)
Pittsburgh, South Hills	4.0(2.5)	---	35.6(22.1)	---	---	3.9(2.4)	43.5(27.0)
San Francisco, Muni Metro	10.2(6.4)	---	1.2(0.8)	2.6(1.6)	---	21.4(13.3)	35.4(22.1)
Toronto, Streetcars	1.0(0.6)	---	2.6(1.6)	4.0(2.5)	---	67.9(42.2)	75.5(46.9)
Subtotals	35.4(22.1)	21.4(13.3)	40.4(25.1)	28.6(17.8)	4.2(2.6)	173.1(107.5)	303.1(188.4)
Totals: km(mi)	43.1(26.9)	72.8(45.2)	176.9(109.8)	76.6(47.6)	16.8(10.4)	180.6(112.2)	566.8(352.1)
% Total	8%	13%	31%	13%	3%	32%	100%

(a) Aerial or surface with no grade crossings; (b) Surface, LRT private R/W with grade crossings; (c) Surface, reserved medians of highways and streets with grade crossings; (d) Surface, reserved lanes (other than medians) and LRT/pedestrian malls; (e) Street lanes shared by LRT and other traffic; "streetcar" operations

TABLE 4 Stations, Double Tracking, Electrification, and Signaling

City System	Psgr Stations & Car Stops	Double Track	Traction Power	Substations		Type of Overhead	Signals	
		km(mi)		No.	Rating		Blk	Tfc
	No.	(a)	(VDC)		(mW)	(b)	(c)	(c)
LRT-Group I:								
Calgary, C-Train	31	29.3(18.2)	600	17	≤2	Both	92%	8%
Cleveland, Shaker Rapid	28	21.1(13.1)	600	6	(d)	Catenary	85%	47%
Edmonton, Northeast LRT	9	10.5(6.5)	600	6	(d)	Catenary	100%	---
Los Angeles, Long Beach	22	34.5(22.0)	750	21	(i)	Both	(h)	(h)
Newark, City Subway	11	6.9(4.3)	600	4	0.75	Trolley	100%	<1%
Phila, Media-Sharon Hill	50	13.7(8.5)	635	4	(h)	Trolley	50%	25%
Portland, MAX	26	21.6(13.4)	750	14	0.75	Both	52%	48%
Sacramento, RT Metro	27	17.7(11.0)	750	14	1	Both	77%	23%
San Diego Trolley	33	52.6(32.7)	600	20	1	Both	91%	9%
San Jose, Guadalupe	30	30.9(19.2)	750	15	1.5	Both	58%	42%
Subtotals	267	238.8(148.9)	---	---	---	---	---	---
LRT-Group II:								
Boston, Green Line(f)	84	40.1(24.9)	600	11	3-6	Trolley	61%	39%
Boston, Mattapan-Ashmont(g)	8	4.3(2.7)	600	1	6	Trolley	100%	---
Buffalo, MetroRail	14	10.3(6.4)	650	5	2	Catenary	81%	19%
Forth Worth, Tandy	5	1.6(1.0)	600	1	(h)	Trolley	---	---
New Orleans, St. Charles	50	10.5(6.5)	600	(h)	(h)	Trolley	---	100%
Philadelphia, Streetcars	573	46.0(28.6)	600	(e)	---	Trolley	---	100%
Phila, Subway-Surface	167	35.9(22.3)	600	(e)	---	Trolley	11%	89%
Pittsburgh, South Hills	81	39.7(24.7)	640	6	6	Both	90%	10%
San Francisco, Muni Metro	204	35.4(22.1)	600	12	2-8	Trolley	19%	81%
Toronto, Streetcars	616	76.5(46.9)	600	(h)	(h)	Trolley	---	100%
Subtotals	1802	300.3(186.1)	---	---	---	---	---	---
Totals	2069	539.1(335.0)	---	---	---	---	---	---

(a) Includes paired 1-way street single tracks functioning as double track; (b) Type of Construction: Catenary, Trolley, or Both; (c) % of line km(mi) equipped: Blk-Block Signals; Tfc-Traffic Lights; May not add to 100% as some segments have no signals, others both Blk & Tfc; (d) 1.5 and 3.0 mW; (e) 28 major substations serve all electric transit in City of Philadelphia; (f) 4 of 11 substations also serve other lines; (g) Substation also provides power to Red Line rapid transit; (h) Data not available at time of publication; (i) 19 @ 1.5 mW plus 2 @ 3.0 mW

Newark (City Subway)

- The City Subway celebrated its 55th anniversary in 1990.
- Replacements for the venerable President's Conference Committee (PCC) fleet are scheduled to be purchased during the current decade.
- LRT, as an extension of the City Subway, is one option being considered in the ongoing Newark-Elizabeth transit alternatives study.
- Elsewhere in northern New Jersey, LRT is one option for the Waterfront Transitway along the Hudson River included in an alternatives analysis/draft environmental impact statement (AA/DEIS) to be completed this year.

Philadelphia (Three Subsystems)

- Media–Sharon Hill—No significant change has occurred.
- Subway-surface—Possibly 80 or more articulated cars may be ordered to improve both carrying capacity and labor productivity. If new subway-surface cars are acquired, some Kawasaki cars will become available for North Philadelphia routes.
- North Philadelphia—Lines remaining are 15–Girard (occasionally served by some Kawasaki LRVs), 23–Germantown Avenue (the subject of periodic reevaluation for continued operation, truncation, or elimination), and 56–Erie-Torresdale (augmented with two new trolley median reservations totaling 1 km [0.6 mi]).

Pittsburgh (South Hills)

- Reconstruction of the Allentown route over Mount Washington is nearing completion.
- Design work has begun for revised track layouts at Castle Shannon and Beechview with power-operated switches to improve operating flexibility.
- Studies for future improvements are under way:

—Alternatives analysis nearing completion for Stage II reconstruction of South Hills lines (Overbrook, Library, and Drake);

—Feasibility study nearing completion for Spine Line, 6-mi line to link downtown with North Side and eastern neighborhoods of Hill/Midtown, Oakland, and Squirrel Hill; and

—Planning work initiated for additional downtown subway station near First Avenue to serve new development and redevelopment, including a new criminal justice center.

TABLE 5 Revenue Service Vehicles: Part 1

City/System	Car Types (a)	Endedness	Train (b)	Seats	Capacity (c)	AC? (d)	ATS/ATO
		Characteristics of Car Equipment					
LRT-Group I:							
Calgary, C-Train	LRV-6-A	Double	3	64	162	No	ATS
Cleveland, Shaker Rapid	LRV-6-A	Double	2	84(h)	144	Yes	ATS(g)
Edmonton, Northeast LRT	LRV-6-A	Double	3	64	162	No	ATS
Los Angeles, Long Beach	LRV-6-A	Double	3	76	160	Yes	ATS(f)
Newark, City Subway	PCC-4-R	Single	1	54	83	No	No
Phila, Media-Sharon Hill	LRV-4-R	Double	2	50	95	Yes	No
Portland, MAX	LRV-6-A	Double	2	76	160	No	ATS
Sacramento, RT Metro	LRV-6-A	Double	4	60	144	Yes	No
San Diego Trolley	LRV-6-A	Double	4	64	144	Yes	No
San Jose, Guadalupe	LRV-6-A	Double	2	75	160	Yes	No
LRT-Group II:							
Boston, Green Line	LRV-6-A	Double	3	50	130	Yes	No
(Also in Service	LRV-6-A	Double	3	50	130	Yes	No
Boston, Mattapan-Ashmont	PCC-4-R	Single	1	52	83	No	No
Buffalo, MetroRail	LRV-4-R	Double	3(e)	51	121	Yes	ATS
Fort Worth, Tandy	PCC-4-R	Double	1	60	83	Yes	No
New Orleans, St. Charles	VTL-4-R	Double	1	52	68	No	No
Philadelphia, Streetcars	PCC-4-R	Single	1	50	83	No	No
Phila, Subway-Surface	LRV-4-R	Single	1	51	90	Yes	No
Pittsburgh, South Hills	LRV-6-A	Double	2	62	151	Yes	ATS
(Also in Service)	PCC-4-R	Single	1	50	83	No	No
San Francisco, Muni Metro	LRV-6-A	Double	3	62	130	No	ATS(f)
Toronto, Streetcars	LRV-4-R	Single	1	46	95	No	No
(Also in Service)	LRV-6-A	Single	1	61	159	No	No
(Also in Service)	PCC-4-R	Single	1	50	83	No	No

(a) LRV-Light Rail Vehicle, PCC-Presidents' Conference Committee, VTL-Pre-PCC Vintage Trolley; # Axles, 4 or 6; R-Rigid, Non-Articulated, A-Articulated; (b) Maximum Cars/Train in Regular Operation; (c) Comfortable load, seats + standees at $\pm 4/m^2$; (d) Air Conditioning; (e) 4-car trains for special events; (f) Cab signals; (g) Cab signals, Tower City Center to East 79th Street on segment shared by LRT and heavy rail trains; (h) Seats being reduced from 84 to 80 to make room for chopper ventilation ducts from roof.

Buffalo (Metro Rail)

• A major accomplishment for all Niagara Frontier transit was Erie County's establishment of a secure and dedicated local funding base for operations.

• High costs of mostly subway construction and lack of capital funding prevent early extension of Metro Rail to Amherst as originally planned.

• A plan has been developed, but funds are lacking, for a 10-km (6.2-mi) Tonawanda extension using 12 former Twin Cities PCC cars purchased from Cleveland and modest facilities in existing railroad right-of-way owned by the authority. The line would feed Metro Rail at the LaSalle station.

Cleveland (Blue and Green Lines to Shaker Heights)

• LRT and heavy rail operations are now consolidated in the rebuilt Tower City Center Station, part of Tower City, a major redevelopment of former Cleveland Union Terminal railroad passenger station complex.

• The "dual hub" alternatives analysis is nearing completion and is expected to lead to preliminary engineering on a 2.4-km (1.5-mi) LRT branch from about East 116th to University Circle as part of a plan to provide better central area distribution. This project is likely to include a three-station downtown subway for joint LRT and rapid rail operation.

• Planning has begun to extend the Van Aken line by 4 km (2.5 mi) from the Van Aken Center to a major real estate development west of Interstate 271.

• Long-range planning is evaluating a new LRT line south to suburban Parma, restoration of LRT service to Cleveland Heights via Cedar Boulevard, and extension of the Shaker Boulevard line to I-271.

New Orleans

• St. Charles streetcar—Renewal of wayside facilities was completed in 1990. Work continues on rehabilitating the 35 vintage cars, restoring them to their authentic 1920s appearance.

• Riverfront trolley—This popular tourist trolley, opened in 1988, has been extended and double-tracked with further extensions a future possibility.

• Future LRT lines—Planning is under way for an eventual network of LRT lines serving New Orleans and adjacent communities. Principal among these is a restoration of service along Canal Street for 6.3 km (3.9 mi) and a 21-km (13-mi)

TABLE 6 Revenue Service Vehicles: Part 2

City/System	Car Types (a)	Characteristics of Car Equipment Builder	Fleet	Accelrtn (b)	Max Spd (c)	Length (d)	Weight (e)
LRT-Group I:							
Calgary, C-Train (f)	LRV-6-A	Siemens	85	1.0(2.2)	80(50)	24(80)	32(35)
Cleveland, Shaker Rapid	LRV-6-A	Breda	48	1.3(3.0)	88(55)	24(80)	40(45)
Edmonton, Northeast LRT	LRV-6-A	Siemens	37	1.0(2.2)	80(50)	24(80)	40(45)
Los Angeles, Long Beach	LRV-6-A	Nippon-Sharyo	54	1.3(3.0)	88(55)	27(89)	43(47)
Newark, City Subway	PCC-4-R	St. Louis	24	1.8(4.0)	72(45)	14(46)	17(19)
Phila, Media-Sharon Hill	LRV-4-R	Kawasaki	29	1.3(3.0)	100(62)	16(53)	27(30)
Portland, MAX	LRV-6-A	Bombardier	26	1.3(3.0)	88(55)	27(89)	42(46)
Sacramento, RT Metro	LRV-6-A	Siemens	36	1.1(2.5)	80(50)	24(80)	36(40)
San Diego Trolley	LRV-6-A	Siemens	71	1.0(2.2)	80(50)	24(80)	33(36)
San Jose, Guadalupe	LRV-6-A	UTDC	50	1.3(3.0)	88(55)	27(89)	45(49)
Subtotals			460				
LRT-Group II:							
Boston, Green Line	LRV-6-A	Kinki	100	1.3(2.8)	80(50)	22(72)	38(42)
(Also In Service)	LRV-6-A	Boeing	125	1.3(3.0)	84(52)	22(72)	30(33)
Boston, Mattapan-Ashmont	PCC-4-R	Various	12	1.8(4.0)	72(45)	14(46)	17(19)
Buffalo, MetroRail	LRV-4-R	Tokyu	27	1.3(3.0)	80(50)	20(67)	30(33)
Fort Worth, Tandy	PCC-4-R	St. Louis	8	1.8(4.0)	72(45)	14(46)	17(19)
New Orleans, St. Charles	VTL-4-R	Perley-Thomas	35	0.8(1.7)	43(27)	14(48)	19(21)
Philadelphia, Streetcars	PCC-4-R	St. Louis	99	1.8(4.0)	72(45)	14(46)	17(19)
Phila, Subway-Surface	LRV-4-R	Kawasaki	112	1.3(3.0)	80(50)	15(50)	26(29)
Pittsburgh, South Hills	LRV-6-A	Siemens	55	1.3(3.0)	80(50)	26(84)	36(40)
(Also in Service)	PCC-4-R	St. Louis	16	1.8(4.0)	72(45)	14(46)	17(19)
San Francisco, Muni Metro	LRV-6-A	Boeing	128	1.3(3.0)	84(52)	22(72)	30(33)
Toronto, Streetcars	LRV-4-R	UTDC	196	1.5(3.2)	85(53)	16(53)	23(26)
(Also in Service)	LRV-6-A	UTDC	52	1.3(3.0)	80(50)	23(75)	37(40)
(Also in Service)	PCC-4-R	Various	42	1.8(4.0)	72(45)	14(46)	17(19)
Subtotals			1007				
Total			1467				

(a) See Note (a) on Table 5; (b) Initial acceleration: meters/sec/sec (mi/h/sec); (c) km/h (mi/h); (d) Meters (feet overall, to nearest full unit; (e) Metric tons (short tons); (f) Fleet includes 83 cars with DC propulsion plus 2 with AC drives.

TABLE 7 Changes in North American LRT and Streetcar Systems, 1988–1991

City/Systems	Code(a)	Changes since 1988
LRT-Group I:		
Calgary, C-Train	X	Northwest Line extension to Brentwood, 1.0 km (0.6 mi), 1990
Cleveland, Shaker Rapid	R	Revised Tower City terminal, 1991; cab signals on western 5.6 km (3.5 mi)
Edmonton, Northeast LRT	X	Extended to Grandin, 0.8 km (0.5 mi), 1989; extension to U. of Alberta due in 1992
Los Angeles, Long Beach	N	Opened 1990, 35.4 km (22.0 mi)
Newark, City Subway	-	---
Phila, Media-Sharon Hill	-	---
Portland, MAX	-	New stations: Pioneer Place, Convention Center
Sacramento, RT Metro	VR	Double tracking: 3 projects, 1989-1992; 10 more LRVs delivered, 1990-91
		East Line extended to El Cajon, 18.2 km (11.3 mi), 1989 & Bayside, 2.4 km (1.5 mi), 1990;
San Diego Trolley	VX	41 additional LRVs delivered
San Jose, Guadalupe	N	Fully open, 32.2 km (20.0 mi), 1991
LRT-Group II:		
Boston, Green Line	R	E/Arborway facilities renewal in progress
Boston, Mattapan-Ashmont	-	---
Buffalo, MetroRail	-	Purchased 12 PCC cars from Cleveland, for planned Tonawanda extension
Fort Worth, Tandy	-	---
New Orleans, St. Charles	R	Facilities reconstruction complete, 1990; streetcar rehabilitation under way
Philadelphia, Streetcars	R	56/Erie Avenue transitway(s), 1991; some continuing track reconstruction
Phila, Subway-Surface	-	---
Pittsburgh, South Hills	R	Continue reconstruction of Allentown line
San Francisco, Muni Metro	X	J/Church extension to Balboa Park opened, 3.7 km (2.3 mi), 1991
Toronto, Streetcars	VX	52 new ALRVs delivered, Harbourfront LRT line opened, 2.1 km (1.3 mi), 1990

(a) N-New Start, R-Rebuild/Rehab/Expand Facilities, V-New Vehicles, X-Extension regional LRT line connecting downtown to Moissant International Airport.

Fort Worth (Tandy Subway)

• The privately owned Tandy Subway in Fort Worth celebrated its 30th anniversary in 1992. Service from peripheral parking lots to the Tandy Center Subway Station continues to be operated with the system's twice-rebuilt PCC cars.

San Diego (San Diego Trolley)

• Two extensions have been completed since the 1988 LRT conference. The 18.2-km (11.3-mi) Euclid Avenue–El Cajon addition to the East Line was dedicated in spring 1989. The Bayside extension of the East Line, a 2.4-km (1.5-mi) link from the Santa Fe Depot to Trolley Towers by way of the city's new convention center, opened in mid-1990.

• Since its initial opening in 1981, the San Diego trolley has grown from 25.6 km (15.9 mi) to 54.7 km (33.9 mi). As system length doubled, both the LRV fleet and patronage grew by a factor of five, from 14 to 71 cars, and from 11,000 to 53,000 weekday boardings.

• Construction has begun on the first segment of the North Line from Centre City to Old Town with an eventual destination of North University City, a distance of 22.6 km (14.2 mi).

• Construction continues on more extensions with 5.8 km (3.6 mi) from El Cajon to Santee scheduled for completion in late 1994. The system has ordered another 75 LRVs similar to Sacramento's U2-A cars but equipped with chopper control and other performance features needed to improve running times on the East Line and for other, future, more steeply graded routes.

• A second joint development project—American Plaza, near Santa Fe Depot in Centre City San Diego—has opened with offices rising 34 floors over an LRT station.

Santa Clara County (San Jose)

• After opening a portion of its system in 1987, San Jose extended service in stages. Since 1991 the entire 32.7-km (20.3-mi) project has been operating, including the LRT main line from Old Ironsides to Santa Teresa, and the Almaden Branch.

• Preliminary engineering has begun for the Tasman Corridor, which will extend west from Old Ironsides to a Mountainview connection with CalTrain commuter rail, and east from First Avenue at Tasman Drive to Milpitas, a total of 19.3 km (12 mi). A 1996 opening is envisioned.

• Planning for future lines continues. An environmental study was completed in 1991 for the 11.3-km (7-mi) Vasona corridor to Los Gatos. Santa Clara County's Transportation 2010 plan identifies 15 second- and third-tier corridors for future development.

San Francisco (Municipal Railway)

• Extension of the J-Church Line south for 3.7 km (2.3 mi) to the Green Light Rail Center has been completed and is in limited operation—used by in-service pull-ins and pull-outs. This brings LRT service to neighborhoods not served by rail for many years and also significantly reduces deadhead hours and miles expended to place J-Church and N-Judah cars in and out of service.

• An order was placed with Breda in 1991 for 35 new articulated LRVs with an option for 20 more. The LRVs will have unique design features to fit Muni's system, including movable high-low steps for tunnel and surface operation. The procurement wisely includes four prototype cars for testing. Follow-up orders are expected to begin replacing the Boeing LRV fleet.

• Final design is nearing completion for the Embarcadero turnback. This project will provide an improved terminal at the foot of Market Street with connections to the future Mission Bay extension to the current CalTrain Station site and beyond to the vicinity of 16th and Owens streets, where a second rail maintenance facility is to be constructed. The turnback and first portion of the extension are scheduled for operation in 1996.

• Construction begins this year on the F Line, an extension of Market Street surface trackage west to Castro and Market, east to the Ferry Building, and north along the Embarcadero to Fisherman's Wharf. Rehabilitated PCC cars will be used.

• Systems planning for possible projects in the Bayshore and Geary corridors is poised to begin.

Sacramento (RT Metro)

• Since opening in 1987 Sacramento has extended two sections of double track. As a result, the 29.4-km (18.3-mi) line has been increased from approximately 40 percent to 50 percent double track. A third segment, recently completed, raises the total to 60 percent.

• To increase capacity 10 more LRVs were ordered in 1989. Virtually identical to the initial fleet of 26 cars, all now are in service.

• A major realignment of service in April 1989 improved LRT/bus coordination and sparked a significant increase in both LRT and bus ridership. LRT patronage is between 23,000 and 24,000 per weekday.

• After a local funding measure was passed in 1990, a systems study led to recommendations to extend the Northeast and Folsom lines, and to complete a federal AA/DEIS in the South Corridor to further evaluate transit modes and alignments.

Portland (MAX)

• After 5 years of service the initial Eastside Line is carrying about 24,000 weekday rides.

• Portland's 18-km (11.2-mi) Westside Line to Northwest 185th Avenue has entered final design. This extension includes a 5-km (3-mi) tunnel beneath the 300–360 m (1,000–1,500 ft) hills separating downtown Portland and its western suburbs. Work is progressing toward a 1997 opening.

• Funding also has been secured to purchase 10 more Eastside LRVs, which will be combined with Westside vehicles in a single order for 39 cars. Low-floor cars are of significant local interest.

- An AA/DEIS is in progress to extend the Westside Line to Hillsboro, a distance of about 10 km (6 mi) beyond 185th Avenue.
- Future lines and critical areas have been the subject of recent planning studies sponsored by the city of Portland: North Line to Vancouver, Washington; Southwest Line to Tigard; Sellwood Bridge area; Coliseum area; and downtown Portland tunnel.
- Metro, the region's long-range planning agency, is conducting several studies—preliminary alternatives analysis on two corridors: I-205/Milwaukie and I-5/I-205, Portland Airport/Vancouver, Washington; and a high-capacity transit (HCT) study to prepare a regional HCT plan for the Portland-Vancouver metropolitan region.

Calgary (C-Train)

- From the 12.7-km (7.9-mi) South Line carrying 28,000 weekday boardings in 1981, C-Train has grown to a 29.3-km (18.2-mi), three-line network accommodating more than 114,000 daily rides.
- The most recent extension of the Northwest Line, to Brentwood in 1990, is likely to be the last for a few years because of funding constraints.
- Ultimate system development envisions further extensions to all three lines, plus new lines to the west, north, and southeast, all eventually linked through a downtown subway.

Edmonton

- In 1989 Edmonton extended its single line further through the downtown area to a new station, Grandin. This is the first link of the line across the North Saskatchewan River to the University of Alberta, service to which was expected to start in late summer 1992.
- Surface projects progressed more slowly because construction included a large new river bridge, then a tunnel to and beneath the university campus. However, this difficult and costly work sets the stage for a surface extension to southern residential areas.

Toronto

- In June 1990 Toronto opened its 2.1-km (1.3-mi) Harbourfront LRT route. Beginning in a new subway under Union Station, the line runs west to Spadina Avenue in the median of Queens Quay. Service is provided with rebuilt PCC cars.
- Under the recently adopted "Let's Move" program, planning is under way to extend the Harbourfront Line east and west along Lake Ontario for 8 km (5 mi) and north on Spadina Avenue for 3.5 km (2.2 mi) to Bloor Street.
- Feasibility studies of low-floor car alternatives are being conducted.

NEW-START SYSTEM—LOS ANGELES

Since 1988 Los Angeles has joined the list of places initiating LRT service on a completely new line. The 22-mi Long Beach–Los Angeles Blue Line, opened in July 1990, reuses almost all of the route of the last Pacific Electric Red Car line, which was abandoned in the early 1960s. Level boarding of the 54 articulated LRVs is provided by full-length high platforms at each of 22 passenger stations. By its first anniversary in 1991, the line was carrying nearly 30,000 passengers on an average weekday, nearly 35,000 by the end of 1991.

A significant element of Blue Line operating costs is security. The Los Angeles County Sheriff Department's 132-member transit unit provides a high-profile presence at stations and on trains. Since service began, no major crimes have occurred on the line.

The alignment includes a variety of environments, demonstrating again the flexibility of LRT: railroad right-of-way [LRVs and freight trains on separate tracks over a 26.6-km (16.5-mi) segment], reserved street lanes (median, mall, and side-running) in both Long Beach and Los Angeles, and a half-mile subway to the Los Angeles terminal station, which is to be a transfer point with the heavy rail Red Line when it opens by 1993.

The final cost, in the range of $40 million per mile, reflects the complexities of building a rail transit line through a mature urban area, mitigating the impact to traffic and adjacent land uses, and accommodating the needs of both LRT and freight train operations over much of the line's length. Like San Diego's initial line, the Blue Line was built without federal funding. Instead the project used receipts from Proposition A, the half-cent sales tax approved by voters in 1980.

As the nation's second largest urbanized area, with solid local funding support available and expanding through several voter-approved propositions, metropolitan Los Angeles is in the process of a massive fixed guideway transit program that will use not only LRT, but also rail rapid transit and commuter trains. The second LRT line is the 20-mi Green Line, serving the Norwalk–Airport Area corridor. It will open in 1994 using manually operated vehicles capable of eventual conversion to driverless running. A high priority is designing the region's third LRT line, from downtown Los Angeles to Pasadena. Later LRT lines may serve Glendale and the Exposition Corridor.

NEW STARTS UNDER CONSTRUCTION

Since 1988 four more cities have begun actual implementation of their initial LRT lines: Baltimore, St. Louis, Dallas, and Denver. All projects take advantage of LRT's locational flexibility, and use (or will use) a variety of alignments, including recycling of substantial segments of old railroad lines. A major feature of the St. Louis line is its reuse of an existing unused rail tunnel beneath the heart of the central business district (CBD) and a historic bridge over the Mississippi River. Baltimore's line operates through the CBD on the Howard Street transit mall. Dallas and Denver also will have reserved surface tracks in downtown streets.

Baltimore

Revenue operation has begun on the initial segment of the 43.5-km (27-mi) Central Corridor LRT system extending north from downtown Baltimore. It is anticipated that the full 24-station, 36.2-km (22.5-mi) Phase I line from Timonium (Fair Grounds) through downtown and into Anne Arundel County will be opened by mid-1993. Delivery of 35 articulated LRVs with alternating current-inverter drives is about 60 percent complete.

The line is located mostly on former rail rights-of-way, portions of which will continue to carry local freight trains as well as LRVs on the same tracks. These lines are linked through downtown Baltimore using tracks installed in the Howard Street transit mall. Some significant new construction was required to connect viaducts, particularly across Baltimore Harbor south of downtown and Camden Station, where the LRT line connects with Maryland's state-sponsored commuter trains and a new major league baseball stadium.

Phase I is being funded by the state of Maryland. Work continues to complete designs and obtain funding to finish the north end of the line beyond Timonium to Hunt Valley, to build branches to Baltimore-Washington International Airport from the south line and to Penn Station on Amtrak's Northeast Corridor.

St. Louis

Construction work is evident all along the 29-km (18-mi) Metro Link route from East St. Louis to Lambert Field. This line, scheduled to open in 1993, will serve 20 stations using a fleet of 31 articulated LRVs.

The alignment is of exceptionally high quality, mostly on former railroad lines, and includes reuse of a tunnel under downtown St. Louis and the historical Eads Bridge over the Mississippi River. The University of Missouri at St. Louis provided new right-of-way through its campus. The line then continues along the side of I-70 to Lambert Airport.

By trading properties with area railroads, local public authorities assembled a package of rights-of-way and fixed facilities. Their appraised value was used as the local match for federal funding to build LRT facilities and purchase equipment.

Even as construction proceeds on the initial line, planners are conducting a corridor study to evaluate transit mode and alignment alternatives to extend the system from East St. Louis to Belleville in the Illinois suburbs.

Dallas

Dallas has begun utility relocation work in preparation for the start of actual construction on its 29.8-km (18.5-mi) starter system. From Park Lane, LRT will use an abandoned rail line, then a new tunnel to be constructed beneath a rebuilt Central Expressway to enter downtown from the north. Trains will operate through the CBD on exclusive lanes in Bryan and Pacific Avenues, then on former railroad rights-of-way to the southwest along the leg to West Oak Cliff. The second leg of the Y-shaped system, to South Oak Cliff, will be located in a power line right-of-way once used by Texas Electric interurbans. System design is progressing with an order for 40 articulated LRVs and the start of line construction scheduled during 1992. Funding is from the region's 1 percent transit sales tax supplemented by federal grants.

Denver

Final approval was obtained in summer 1991 to construct Denver's first LRT line. The Metro Area Connection (MAC) will be built using all local funding from the Regional Transit District (RTD) sales and use tax. The 5.1-km (3.2-mi) MAC will link downtown with the Auraria Higher Education Center, convention center, and Five Points business district. The line runs at right angles across Denver's 16th Street Mall. MAC will operate initially as a stand-alone central area circulator but is planned as the core route for a regional LRT system.

MAC construction began with a ground-breaking ceremony in September 1991. Eight articulated cars have been ordered as an add-on to San Diego's large procurement to obtain an affordable unit price. Six LRVs will be used for the initial revenue service beginning in 1994 with two cars kept as spares.

An AA/DEIS scheduled to be under way by the third quarter of 1992 will consider LRT and busway options in the 21-km (13-mi) Southwest Corridor to Englewood and Littleton. Conceptual engineering has been started to extend the MAC south and east from the LRT maintenance facility to the junction of I-25, Broadway, and Mississippi Avenue. This will provide a revenue service line of 8.5 km (5.3 mi) with RTD bus and LRT operations integrated at the outer terminus.

DESIGN AND PLANNING

Numerous urban areas continue to be interested in LRT. Two projects have moved into preliminary engineering. Several others are at various stages in the planning process:

- Salt Lake City has completed a corridor alternatives analysis and is now conducting preliminary engineering on a 24-km (15-mi) line south from its downtown to the suburban town of Sandy. A railroad branch line to be acquired forms the basis for the system, supplemented by reserved lanes in downtown Salt Lake City streets.
- Chicago is just starting preliminary engineering for a central area circulator to connect commuter rail terminals, the Loop District, and emerging growth areas north of the Chicago River and east of Michigan Avenue. Most of the system will be at grade using reserved lanes in city streets with some private right-of-way along the river using a former freight switching line. With short station spacings and high passenger volumes expected, there is strong interest in low-floor cars.
- Planning at various levels of detail is in progress in these five cities:

    —Austin—A feasibility study has been completed for a 24.8-km (15.4-mi) line from East Austin through downtown to northern suburbs.

—Milwaukee—Follow-on planning by Wisconsin DOT is in progress to refine the LRT system plan developed in 1990–91 by the city of Milwaukee.

—Minneapolis/St. Paul—Local and state entities are engaged in consensus building for staged development of LRT in two corridors: Central (downtown St. Paul to downtown Minneapolis), followed by Interstate 35 south from Minneapolis; other corridors may be developed later.

—Norfolk—Improved bus services are the short-term focus with LRT development postponed.

—Seattle—A three-corridor AA/DEIS process is under way; consensus on alignments north and south from downtown Seattle is emerging; a three-county regional policy committee will recommend system technology and more specific alignments later in 1992. The new 2.1-km (1.3-mi) downtown tunnel, presently used by dual-mode buses, was built with tracks (including crossovers) for LRT.

Other urban areas known to be considering LRT include New York City, Hartford, Harrisburg, metropolitan Washington, D.C. (Dulles Airport line), Charlotte, Kansas City, and Tucson.

PROGRESS IN MEXICO

Major Mexican cities have made commitments to LRT and have moved projects rapidly through the development process. As a result, three all-new systems have opened since the last LRT conference, and construction of extensions and additional routes continues at an aggressive pace. Because of high ridership demand, all systems have opted for full-level boarding using high-platform stations.

Guadalajara

Mexico's second largest city opened its first LRT line in 1989. The 15.3-km (9.5-mi) project included conversion of a downtown subway, first opened in 1977 as a tunnel for electric trolley buses, and planned for eventual conversion to rail. Surface segments extend north and south from the tunnel portals to complete the initial line, which has 19 high-platform stations (7 in the subway) and is served by 16 six-axle LRVs.

Extension of the initial line and construction of an east-west line are expected to be completed by the mid-1990s. Two additional routes are in the planning stage, both branching from Line 1: one to the northwest, the other to the southeast.

Monterrey

Revenue service on Line 1 began in mid-1991. The 18.5-km (11.5-mi) route is entirely elevated and connects downtown with eastern and northwestern communities. Construction of a second line has begun, and a third route is planned. When completed, the three routes will comprise a system totaling 74 km (46 mi).

Mexico City

The Federal District is in the midst of a renaissance for surface electric rail technology. However, new services are in the form of modern LRT, not just returning to streetcars.

Spiraling costs of subway construction have led the operator of the city's rubber-tired Metro system to adopt surface alignments for suburban extensions. The first of these lines, a 17.1-km (10.6-mi) line in southeast Mexico City, demonstrates the creative blending of Metro and LRT technologies: steel wheel on steel rail, 750 volts of direct current power from overhead wires, and some grade crossings, but car shells similar to Metro cars and high-level station platforms. One of the world's largest and fastest growing conurbations, Mexico City is planning other "pre-metro" LRT routes to help cope with its serious traffic congestion and air quality problems.

The reconstruction of the single surviving line from Mexico City's old streetcar system was completed in 1988. Since then new cars similar to the Guadalajara and Monterrey vehicles have been ordered from the same manufacturer, Concarril.

LOW-FLOOR LRVs—A NEW TREND

Most of the new U.S. LRT projects built in the 1980s were developed with low capital cost as a major goal. As a result traditional high-floor LRVs with steps and low station platforms were selected (instead of full-length high platforms). Access for people unable to use steps is provided to all trains by lifts, either on the cars or on station platforms, or by mini high platforms accessed by ramps. The Americans with Disabilities Act of 1990 requires that all new cars (not just trains) be accessible, and this has heightened interest in full-level boarding. At the same time, cities seeking low-impact transit systems look negatively at full-length high platforms on city streets.

A potential solution to this dilemma has emerged in western Europe: the low-floor LRV. Several North American systems are seriously interested in procuring low-floor LRVs: Boston, Toronto, Portland, and Chicago. Cities in the planning stage also are being introduced to the low-floor concept.

Numerous design variations have been developed, as recently summarized in *Railway Gazette International* (*4*) and other trade journals. However, virtually all are city-type cars, capable of speeds of 60 to 70 km/hr (37 to 43 mph), and incorporating ride quality and other passenger amenities suitable for the relatively short trips characteristic of all the systems mentioned except Portland's and the longest line in Boston, the 19-km (12-mi) Riverside Line. An additional consideration is that European cars are built to less stringent requirements than are applied in North America for factors such as crashworthiness and fire safety.

As a result, no suitable low-floor design is available more or less off the shelf for LRT systems providing high-quality, 90 km/hr (55 mph) service on relatively long trunk routes linking cities and suburbs. Such vehicles are needed and could solve a variety of LRT service and design issues. Planners in Austin, for example, have found that suitable low-floor cars

- Offer access to all cars for riders with disabilities and simultaneously speed boarding for all passengers as compared to step loading;

- Provide the high levels of speed and comfort needed to attract riders;
- Operate on the variety of alignment types envisioned;
- Use station platforms that would not conflict with local freight trains using the LRT tracks (as would be the case with full or mini high platforms); and
- Help control overall project capital costs.

To achieve these goals, designs are needed that provide low-level entries but also build on technology used successfully on previous designs. This will require a conservative design approach that avoids—insofar as possible—the radical car body structure, articulation joint, truck, suspension, propulsion, and braking technologies being developed for modest-performance, low-floor streetcars but which are not appropriate for the higher performance suburban cars needed by most new North American projects. The author hopes that LRV suppliers will be receptive to developing such designs that could be applied in most of the cities now considering LRT for regional trunk express service.

CONCLUSION

New LRT projects continue to illustrate the flexibility and effectiveness of this public transit mode in providing quality service at affordable prices. Ongoing work to expand all the new LRT systems demonstrates their acceptance by the cities that have built them.

With increasing concern about congestion, air pollution, and the quality of urban life, and with new federal, state, and local funding mechanisms being put in place, the next decade should see more new LRT projects implemented and existing systems expanded.

ACKNOWLEDGMENT

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A Success Story That Was Not Supposed To Happen

CAMERON BEACH

The idea of a light rail transit (LRT) line in Sacramento started with a grass roots citizens group looking at alternatives to automobiles, freeways, and air pollution in the mid-1970s. Transportation "experts" predicted nothing but problems for construction and operation of light rail transit in a low-density area like Sacramento. "It isn't going to the right places," "Nobody will ride it," and "We got rid of the streetcar once, do we have to do it again?" were commonly heard statements during the early stages of the LRT development. RT Metro service was started in March 1987 despite the serious lack of operating funds that plagued the system initially. The service has expanded to provide a viable alternative to the automobile that is cost-effective and operating within the confines of long-standing collective bargaining agreements that have been in place for almost 90 years. Sacramento's light rail success story continues toward the 21st century with serious plans for system expansion, extensions, and a higher level of service.

Sacramento, the capital of California, is in the great valley between the Coast Range and Sierra Nevada mountains. Located at the confluence of the American and Sacramento Rivers some 85 mi northeast of San Francisco, Sacramento, until 1849, was a sleepy little valley community from which agricultural goods were shipped to San Francisco. With the discovery of gold by John Sutter near Coloma in 1849, Sacramento made an almost instant transition to boom town. People from all over the world and all walks of life rushed to northern California in their quest for gold. Many settled in and around Sacramento, including four merchants named Huntington, Crocker, Stanford, and Hopkins. The "Big Four" formed a partnership to construct a transcontinental railroad with Sacramento as its western terminal. The railroad was completed in 1869, making Sacramento a major gateway for commerce in the West.

Public transportation in Sacramento began with horse-drawn omnibuses in the late 1850s. These gave way to horse cars in the 1880s. In 1889 a new technology was introduced: the battery-powered streetcar. Electric streetcars replaced the battery cars in 1890 when overhead wire was strung in Sacramento. In 1895 the first hydroelectric plant opened in Folsom, 22 mi east of Sacramento. This power was used to run the streetcars and to power buildings and street lights as well. In 1906 the merger of several utility companies resulted in the formation of the Pacific Gas and Electric Company (PG&E), which operated streetcar service to all parts of the urbanized area, providing fast, frequent transportation between downtown and the outlying neighborhoods. The streetcar system reached its peak at the end of World War I, when PG&E carried about 16 million passengers annually on the 10 routes within the city. The fare was only 5 cents, and most of the local cars ran every 10 minutes.

The 1930s brought the first declines in ridership. In 1932 PG&E began substituting buses for streetcars on some routes. By the end of World War II, Sacramento had five streetcar routes left and about a dozen bus lines.

National City Lines, a transportation holding company owned by Firestone, Goodyear, Standard Oil, Phillips Petroleum, General Motors, and Mack Truck, purchased the PG&E streetcar and bus system in 1943. It was renamed Sacramento City Lines and began a modernization program that did not include Sacramento's streetcars. On January 4, 1947, the last streetcar made its final run in Sacramento.

Operation of the transit system was passed to the city of Sacramento in 1955 with the formation of the Sacramento Transit Authority (STA). During the 1950s and 1960s STA acquired other private operators and the bus system grew moderately in both fleet size and ridership. By 1970 STA was operating buses on 16 routes with an annual passenger ridership of 7.7 million. The STA provided service primarily to the city. During the late 1960s and 1970s the metropolitan area grew tremendously, primarily in the unincorporated county areas north and east of downtown. In recognition of this growth and the ensuing transportation needs, the Sacramento Regional Transit District was legislatively created to provide public transit service in the greater Sacramento metropolitan area, which had grown to more than 350 mi^2. Regional Transit took over STA's service on April 1, 1973. Additional buses were purchased and employees hired to provide a comprehensive network of bus routes throughout the area. By 1978 the fleet consisted of 223 buses operated and maintained by employees. Annual ridership had grown to 12.8 million, a 66 percent increase over the 1970 figure.

Population growth in California continued at a rapid rate in the 1970s with some less desirable side effects: runaway real estate prices, air pollution, and massive traffic congestion. Growth was primarily centered in the Los Angeles basin and the San Francisco Bay Area where inflation, pollution, and congestion reached all-time highs.

During that same period, a loosely formed citizens advocacy group of environmentalists and public transit supporters was put together in Sacramento. Calling themselves the Modern Transit Society (MTS), they enlisted the aid of more established organizations such as the Sierra Club and the American Lung Association and proposed an alternative form of public transportation in Sacramento.

Sacramento Regional Transit District, P.O. Box 2110, Sacramento, Calif. 95812-2110.

A 10-block area adjacent to the Sacramento River had become the city's "skid row" following World War II. Many of the historical buildings dating from the gold rush era had fallen into disrepair. In the mid-1970s, efforts were being made to clean up "Old Sacramento," restore the buildings, and begin construction of the California State Railroad Museum that would house a priceless collection of steam and diesel locomotives and passenger cars from the gold rush era through the 1950s. The consulting firm of Wilbur Smith and Associates was commissioned to do a study of a historical streetcar operation to connect the railroad museum, Old Sacramento, and the downtown area. This report, published in 1975, became the basis for MTS to look at light rail transit as a problem solving transportation mode for the entire metropolitan area. MTS began meeting with city council members, county supervisors, state assemblymen, and senators, as well as congressional representatives to present their ideas on light rail transit's role in Sacramento's future.

MTS focused on available, underutilized railroad rights-of-way and a 4.5-mi section of freeway right-of-way purchased and cleared in the early 1970s as a bypass route for Interstate 80 into downtown Sacramento. MTS pushed the idea that light rail transit could be a low-cost alternative to additional freeway construction. Arguing that the citizenry did not want to have Sacramento become another Los Angeles or San Jose, they were successfully able to stall the additional freeway construction. MTS pointed out that light rail transit could be built on a "no frills" basis, using service-proven technology and a combination of single and double track to minimize capital expenses.

In 1976 the City Council halted further construction on the I-80 bypass and requested that federal funds programmed for additional freeway construction be allocated toward building a light rail transit line. Additional federal and state monies were sought, and work started on the alternatives analysis process in the late 1970s. In mid-1981 the environmental impact report (EIR) was completed. The EIR envisioned an 18.3-mi (29.2-km) light rail line using the former I-80 bypass right-of-way, an abandoned Sacramento northern interurban right-of-way, a seldom used Western Pacific corridor, and a portion of the Southern Pacific's Placerville Branch right-of-way. The Southern Pacific right-of-way was the location of the first railroad built in California. It had been designed by Theodore Judah and constructed in 1854 as the Sacramento and Folsom Railway. (Judah later gained fame as the chief engineer of the Transcontinental Railroad built by the Central Pacific over the Sierra Nevada through Donner Summit.) In addition to the railroad and freeway rights-of-way, a substantial amount of the light rail operation downtown would be in city streets, giving Sacramento's line more mixed traffic operation than most new light rail starts in recent years.

Construction of the light rail system was delegated to a new joint powers agency called the Sacramento Transit Development Agency (STDA). STDA consisted of the city of Sacramento, the county of Sacramento, the California Department of Transportation (Caltrans), and Regional Transit. STDA's goal was to design and build the light rail line that on completion would be operated by Regional Transit. Historically Caltrans' focus had been the construction of highways and freeways in California. But its director at the time, Adriana Gianturco, wanted to focus on other solutions to transportation problems besides additional road construction. Caltrans was designated as the general engineering contractor for the light rail project, and a selected group of Caltrans engineers assembled to complete final design, procure equipment, award civil contracts, and manage the construction of the system.

In theory the joint powers agency was a good one. It focused political attention on the system at several levels of local government. In practice, however, the agency suffered from a lack of accountability to any one entity. Further complicating the agency's activity was the fact that Regional Transit was the designated federal grantee and as such was responsible for any cost overruns the project might suffer.

In late 1983 Regional Transit, concerned about cost overruns, hired its own consultant to review the project. This evaluation showed that the project budget would be inadequate to complete the system and pointed out the organizational problems created by the joint powers agency.

After a great deal of political handwringing, it was decided that Regional Transit should take over the project in its entirety. A new, more realistic project budget was adopted that projected the final cost at approximately \$176 million. The city of Sacramento, in cooperation with the Sacramento Housing and Redevelopment Agency, issued certificates of participation to make up the \$45 million difference between the original project budget of \$131 million and the revised number. During these difficult times, numerous comments were made about the project. Several parties, including elected officials, voiced such opinions as "Why are we doing this?" "Can we stop the project now and cut our losses?" and "We all knew light rail would not work in Sacramento anyway." Nevertheless the project proceeded. Twenty-six light rail vehicles, ordered from Siemens/Duewag in 1983, were in various stages of construction. Rail, ties, and special trackwork were arriving in the North Sacramento storage yard. Utility relocation was well under way and approximately 3 mi (5 km) of track had been put down by August 1985. On August 16, 1985, Regional Transit formally took responsibility for the project and announced that completion and opening would occur in spring 1987.

The construction of light rail transit in Sacramento was the largest public works program ever undertaken in the area. Even after the budget and organizational problems had been resolved, it seemed that a new hurdle was thrown in the path of the project every week. UMTA raised concerns about the American content of the vehicles. Two of the trackwork contractors went bankrupt during construction. Utility relocation in a downtown area more than 125 years old was always full of surprises. Nevertheless construction continued. The first vehicle was delivered to the shop and yard facility in November 1985. The vehicle was placed on display in North Sacramento on the day after Thanksgiving of that year and received great accolades.

Unlike San Diego's light rail project (to which the Sacramento project was frequently compared), Regional Transit would be starting up a new light rail system within the confines of existing collective bargaining agreements. The Amalgamated Transit Union (ATU) had represented operators on this property since the early 1900s. The International Brotherhood of Electrical Workers (IBEW) had represented maintenance employees for almost as long. San Diego's new start was not obligated to honor any existing collective bargaining agreements. In Sacramento the precedence of union/management relations established over years became the floor for negotiating a separate agreement for light rail operations. In early 1985 Regional Transit management began extensive discussions with both unions concerning wages, promotions, transfers, and training programs. Arrangements were made for union officials to visit other light rail properties, including San Francisco and Calgary. Both Regional Transit and the unions were acutely aware of the political implications of a delayed light rail start-up. To this end both parties worked diligently on agreements to deal with the transition from an all-bus operation to one that was multimodal. These agreements, signed in late 1985, provided a mechanism for both labor and management to work through this transition period.

As a result of the agreements, bus operators represented by the ATU were allowed to bid according to their seniority on light rail operator positions. Any operator wanting to bid a position in the light rail department was required to pass an Ishihara color blindness test that requires picking out numbers from a dot matrix. The Ishihara test is generally regarded as more comprehensive than the standard color identification required by the Department of Motor Vehicles. Given the differences between traffic signals and railroad signaling equipment, Regional Transit decided this test would be critical in the evaluation of employees involved in train operation. The labor agreement also contained provisions that allowed operators to bid back and forth between the bus and rail divisions at an annual "system" sign-up. In addition by mutual agreement operators could be asked to return to the bus division prior to the expiration of the 1-year sign-up. This system has worked reasonably well. It does create a training burden at sign-up time if large numbers of operators are moving between the bus and rail divisions. So far the largest group has been seven people out of 33 budgeted positions.

The agreement with the IBEW specified requirements for filling positions in maintenance classifications. It also required that individuals wanting to move into rail maintenance pass a test of basic electrical, mechanical, and electronic skills. This test was administered to in-house employees as well as new applicants from outside the agency. The maintenance work force consists of approximately one-third in-house transfers and two-thirds new hires. Most of the wayside maintenance staff (linemen and rail maintenance workers) came from main-line railroads in the area that were undergoing major layoffs at the time light rail was starting up.

Regional Transit was fully aware of the need to create a management staff responsible for the day-to-day operation of the system, now called RT Metro. An operations manager was hired in January 1983. By fall 1985 transportation and maintenance superintendents were in place, a small group of supervisors was in training, and the first two operators scheduled to run the test cars were sent to Calgary for training.

By spring 1986 several cars were on the property. A limited amount of test track was available for vehicle testing and evaluation. At the same time construction was proceeding through the downtown area of Sacramento. Building a new street railway in an existing downtown retail and business area was not without its problems. Retailers blamed construction for lost revenue, dirt, flooding, and anything else that could go wrong. Regional Transit had the foresight to bring on board a community relations consultant who had a good working relationship with the downtown merchants. The consultant was able to ease the downtown merchants' concerns through frequent contact and sincere efforts to mitigate the problems. Despite these efforts it was still common to hear disparaging remarks about light rail as the system proceeded to opening day.

During the last few months before opening, Regional Transit's operations and engineering/construction divisions worked closely together to accomplish a long list of integrated tests. These tests determined if the various components of the system would work together. Vehicle clearances were checked, signals were tested, and all the components were evaluated on their ability to work as part of a total system. The last few weeks before opening were spent simulating the actual service to be operated for the public. Drills were held with the police and fire departments to ensure that RT Metro could deal with any emergency.

Friday, March 9, 1987, dawned cloudy and cool in Sacramento. The inaugural train was to depart from the Watt/I-80 Station at 10 a.m. Following speeches by local, state, and national dignitaries, the first train proceeded toward downtown Sacramento. Large crowds were on hand at every station to applaud the return of the electric railway to Sacramento after an absence of 40 years, 2 months, and 5 days. The northeast segment of the line was the first portion opened. Fourteen cars were in service that Friday, Saturday, and Sunday. During that weekend the public was invited to take a free ride on the system. The clouds of Friday turned into the rain storm of Saturday and Sunday. Despite numerous minor delays, more than 200,000 Sacramentans turned out to ride their light rail system on the first weekend of operation.

The following Monday was the first day of revenue operation. Approximately 6,500 people rode the system each weekday during its first month. This number jumped to about 9,000 when connecting bus service was rerouted to the light rail stations on April 5. From the start the system was immensely popular with riders. On Saturday, September 5, 1987, the entire 18.3-mi (29.2-km) Folsom Corridor was opened. Again free rides were offered on the system and again hundreds of thousands of Sacramentans turned out to ride.

With the entire line open, ridership grew to about 12,000 passengers per day. Service was operated from 6 a.m. to 10 p.m. weekdays, 8 a.m. to 6 p.m. on Saturday, and approximately 9 a.m. to 5:30 p.m. on Sundays. Trains operated every 15 min during the week with a half-hour headway evenings, Saturdays, and Sundays. This was substantially less service than had been envisioned, but was all the district could afford given a lack of local financial support for transit service.

The starter line, as originally designed, was more than 60 percent single-track operation. Passing sidings were located at strategic "meet points" that allowed operation of a 15-min headway. Despite numerous negative remarks by transit professionals, the single-track operation worked very well. On-time performance exceeded 98 percent during the first year of operation. It was always RT Metro's intent to double-track as much of the system as possible once the initial starter line had been completed. Additional double-track territory would allow for more forgiveness in the tight schedule and, more importantly, an ability to run trains more frequently than every 15 min.

The first double-track project was put in service in late 1988. This project consisted of approximately 1 mi of main-line track in exclusive right-of-way. The project was relatively simple as no station modifications or grade crossing improvements were involved. Before this project, tail tracks had been constructed at each end of the line to allow bad order cars to be removed from service. At this same time a scissors crossover was installed midpoint on the line. This was located on the K Street Mall. Neither the tail tracks nor the crossover are used extensively. However in cases of emergency, they become a vital part of the system.

The second double-tracking project involved approximately 1.25-mi of track, virtually all of it located in mixed traffic territory. This construction project was substantially more difficult as it involved traffic mitigation and extensive modifications to an existing station. Nevertheless the project was completed on time and under budget. The most recent double-tracking project consisted of approximately 1.5 mi of double track, three modified stations, an additional park-n-ride facility, and enhanced grade crossing protection. This was by far the most extensive project attempted since the line opened. This additional track opened for service in early 1991.

Double-tracking projects, once service has commenced, are at best difficult to complete when trains are in regular service. It requires that extensive work be done on nights and weekends. It also requires using buses to offset occasional disruptions of rail service. Replacement bus service is not as fast or efficient as the trains it replaces. When bus substitutions are necessary, schedules must be rewritten and a substantial amount of operator overtime incurred to accomplish the task. More importantly passenger travel is disrupted, resulting in many unhappy customers. Even though the ultimate result (faster and more efficient rail service) justifies these interruptions, the average rider does not appreciate being 15 min late for work.

Today, the system is approximately 40 percent single track. Additional projects are under way to complete double tracking of most, but not all, of the system in the next few years. In some cases the cost to double track structures would be prohibitively expensive. Therefore the decision has been made to defer such "high-cost" projects until they are required.

In November 1988 voters in Sacramento passed Measure A, which imposed a 1/2-cent sales tax within the county. Two-thirds of these funds were for road construction and maintenance and one-third went to Regional Transit for capital improvements and operational expenses. With the passage of Measure A, Regional Transit quickly ordered 10 additional light rail vehicles to enable the system to operate all four-car trains in rush hour. In addition service was increased on the rail line to the level envisioned during design in the early 1980s. Trains operated every 15 min on weekdays from 5 a.m. until 6 p.m. with half-hour headways continuing until 1 a.m. the following morning. Fifteen-minute service was also introduced on Saturdays and Sundays between 7:30 a.m. and 6:30 p.m. Half-hour headways were also added on weekend mornings between 5 a.m. and 7:30 a.m. and between 6:30 p.m. and 1 a.m. Bus feeder service was increased to provide additional connecting service.

With these service improvements, ridership that had been hovering around the 14,000 to 15,000 weekday average jumped to more than 19,000. Once the citizens of Sacramento realized that increased bus and rail transportation was available, ridership quickly built to more than 21,000 a day. This was an important benchmark for the system, because ridership forecasts in the early 1980s had assumed that 20,500 passengers a day would use the system. Ridership continued to grow to the 22,000 passengers per weekday level.

With the additional rail service operating nights and weekends, bus connections to the rail system became even more critical. The original concept of light rail in Sacramento envisioned timed transfer connections between neighborhood or feeder-type buses and the rail line. This was a new concept for Regional Transit, especially in terms of writing schedules tied to specific time points (light rail stations). The rail system operates on a clock headway with trains running every 15 or 30 min throughout the operating day. Because the trains are not materially affected by traffic, running time remains constant. This is not true for the connecting bus systems, for which running time varies substantially depending on the time of day and day of week. Long motor coach lines scheduled to meet trains at intermediate points have a great deal of difficulty making these connections, especially when heavy traffic or passenger loads impair on-time performance. Although some of these problems have been worked through, a high level of focus still needs to be maintained on transfer connections within the system. Long lines may need to be broken into shorter segments and interlining of different routes may not always prove practical when constructing meets at transit centers geared to the time transfer concept.

Citizens who made comments in the early 1980s like "Why are we doing this?" changed their tune. The new battle cry became "Who gets the next extension?" The sales tax passed in November 1988 was for light rail extensions to the original 18.3-mi (29-km) starter line.

In November 1990 Californians, tired of freeway congestion, air pollution, and a lack of urban mobility, passed $2 billion worth of state bonds for rail transportation improvements in the state. These bonds, along with Measure A revenues and scarce federal funds are being programmed to build two 6.6-mi (11-km) extensions to the RT Metro system. The first of these will use surplus Southern Pacific right-of-way to continue northeast toward the city of Roseville in Placer County. The Folsom Line extension will continue along the Southern Pacific's Placerville Branch toward the city of Folsom.

The recent Surface Transportation Act signed by President Bush identifies $26 million in Federal Transit Agency (FTA) discretionary funds for corridor selection, alternatives analysis, and preliminary engineering of a 13-mi (20-km) south line between downtown Sacramento and Cosumnes River College. The south area has the heaviest concentration of transit ridership in the entire metropolitan area. Two corridors are being evaluated in this process. The first would share the Union Pacific (formerly the Western Pacific) right-of-way between downtown Sacramento and Elk Grove. This corridor would provide service to Sacramento City College and a heavily built-up urban area. The other corridor would use the former Southern Pacific Walnut Grove Branch. This property, purchased by the Sacramento Regional Transit District in the early 1980s to preserve it, wanders through several residential neighborhoods. The land would be shared with the California State Parks Department, which would use some of the right-of-way for historical train operation using vintage steam and diesel locomotives from the State Railroad Museum in Old Sacramento.

Regional Transit is justifiably proud of the system in Sacramento. It has proven that it is possible to build a low-cost, no frills, off-the-shelf light rail transit system for less than $10 million per mile (in 1987 dollars). The system represents the least-expensive federally funded rail transit project in the United States. It is most gratifying that visitors from cities from around the world consult Regional Transit in efforts to duplicate the Sacramento success story that was not supposed to happen.

Five Years of Successful Light Rail Operation

PHILIP A. COLOMBO, JR.

The 5-year (1986–1991) operating experience of the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) with Portland's Metropolitan Area Express (MAX) light rail service can provide transit agencies with models for high-capacity service over varying applications on the 15.1-mi MAX environment on railroad right-of-way (2 mi), through residential and commercial streets (5 mi), alongside two major interstate freeways (6 mi), and on downtown streets (2 mi). MAX performance in the areas of safety, access, ridership, average speed, mechanical reliability, maintenance requirements, and so forth indicate how different line sections and applications matured chronologically with the rail system.

The Metropolitan Area Express (MAX) light rail service operated by the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) is Portland's first publicly owned rail transit and the region's first rail transit service since private companies dismantled the last of a once-extensive network in 1958 (*1*).

Focusing on varying characteristics of MAX's 15.1-mi operating environment and comparing the 5-year operation (September 1986 to June 1991) of four distinct design applications (designated by line section numbers) might assist other transit agencies with planning, construction, or operation of light rail.

Material herein, except as referenced, is the product of interviews with Tri-Met employees, who have daily responsibility for making something new to the Portland metropolitan region operate as if it had been operating for decades.

INFRASTRUCTURE

General Description and Geography

In Line Section I (LS-I), MAX operates as an Oregon Public Utility Commissioner-governed railroad on mostly single-track right-of-way, crossing streets and through a wooded cut at a top speed of 55 mph and protected along the two-direction, single-track segment by an automatic train stop (ATS) system. Vehicular and pedestrian traffic are regulated by standard railroad crossing signals and barriers from the eastern terminus, Cleveland Avenue station (milepost 15.1, elevation 345 ft), past the Ruby Junction Rail Operations Facility to Line Section II (LS-II).

In LS-II, MAX travels east-west at 35 mph in the median of a two-way street (East Burnside Street) along 5 mi of residential neighborhood past 500 properties with commercial centers concentrated at major intersections approximately 1 mi apart. MAX controls traffic signals to platforms located on the far side of these intersections, and vehicular traffic may only cross at these and a few other designated intersections. There is no median fence, and pedestrians cross between intersections at unsignaled, protected crosswalks along the 110-ft right-of-way. One-way automobile lanes border the track with left-turn/U-turn lanes at many intersections, and sidewalks and landscaping. Between Ruby Junction (milepost 12.8, elevation 258 ft) and 102nd Avenue (milepost 7.9, elevation 283 ft) are eight stations.

In Line Section III (LS-III), MAX parallels 6 mi of two interstate freeways (I-205 and I-84) on completely separated right-of-way accessible by stairs and elevators from pedestrian and automobile overpasses at three of four stations. The remaining station, a major transit center, is served by a dozen bus lines and is accessible to automobiles and pedestrians. MAX operations in this high-speed (55 mph) section are protected by an automatic block signal (ABS) system between 99th Avenue Station–Gateway Transit Center (milepost 7.0, elevation 291 ft) and 42nd Avenue–Hollywood Transit Center (milepost 3.9, elevation 158 ft) and east of Hollywood where LS-III continues for another 1.7 mi to Line Section IV (LS-IV).

In LS-IV, MAX traverses 32 blocks of downtown Portland on four streets at 15 to 25 mph, crossing the Willamette River on the Steel Bridge (owned by Union Pacific Railroad). Except on bridge lanes, MAX tracks are reserved for trains but mix with cross traffic, allowing vehicles and pedestrians to cross at almost every intersection. MAX stops at 15 stations between Lloyd Center–Northeast 11th Avenue (milepost 2.2, elevation 136 ft) and Galleria (milepost 0.1, elevation 78 ft). A maintenance facility, the Southwest 11th Avenue Terminus (milepost 0.0, elevation 89 ft), provides a turnaround in Portland's central business district (CBD) (*1*).

Track/Rail

Tri-Met's MAX rolls on two types of track rail: girder rail and T-rail. Standard T-rail is located in the yard and on the main line in LS-I, LS-II, and LS-III. In LS-IV, girder rail is imbedded in the street, flush with the surface and surrounded by a hard, rubberized substance to absorb train vibrations and prevent stray currents from deteriorating utilities (*2*).

The line is essentially double-tracked, except for the easternmost 2.2-mi section (LS-I). That section is single track with a second track provided at Gresham City Hall (midway) and at the outer terminal, Cleveland Avenue. In the heart of

Tri-Met, 4012 S.E. 17th Avenue, Portland, Oreg. 97202.

downtown Portland, westbound and eastbound tracks are a short block apart.

Three tracks are available at Southwest 11th Avenue loop (milepost 0.0) for vehicle staging and infrequent maintenance inspections. A third track at Coliseum Transit Center (milepost 1.6) is used to load passengers from special events and at Gateway Transit Center (milepost 7.0) for staging and for stubbing eastbound trains, increasing line capacity on LS-III and LS-IV between Gateway and downtown Portland. Frequent track crossovers compensate for main-line obstruction problems requiring temporary single-track operation. En route equipment failures have been rare, but at six spots along the line a car can be dropped to await maintenance assistance.

Power Supply

Portland General Electric (PGE) and Pacific Power (PP) supply alternating current (AC) to 14 substations located at or near passenger stations. PGE & PP deliver power to the substations at 12,500 volts of alternating current (VAC). Passing through AC circuit breakers into transformers, 12,500 VAC is reduced to 640 VAC, which is converted from AC in a solid state rectifier to a nominal 750 volts direct current (VDC) and transmitted through circuit breakers to the overhead wires.

Trolley wire, a more rigid overhead power system suspended from cross span wires and requiring precise alignment, is located on the west portion of LS-IV in downtown Portland, across the Steel Bridge to Coliseum Transit Center, and in the Ruby Junction Yard.

Catenary wire, a less rigid system of messenger wire hung from span to span in a naturally curving sag, supports contact wire hanging from the messenger wire by stringer wires and is located over all LS-I, LS-II, and LS-III main-line and auxiliary tracks. Stringer wires vary in length as messenger wires sag, holding contact wires level above the track. Catenary wires stagger laterally from pole to pole, maintaining uniform contact and wear on light rail vehicle (LRV) pantographs.

Isolators section the overhead power system, allowing one section to shut down without affecting the entire system. Power failures at individual substations (radio signaled to rail control and indicated visually by flashing lights) do not shut down the line.

Power is grounded through the track, which carries approximately 50 volts of DC (not a hazard to personnel or the general public) back to substations and signal paths for signal track circuits. Track is also sectioned, preventing electrical current flow from one rail to another and primarily used in ABS to separate signal track circuits. Yard track is sectioned from the main line and from the shop (*2*).

Signals

Train operators and train presence control the varying line signal configurations. MAX combines the use of two types of signals: railroad (vertical bar: proceed; horizontal bar: stop) and color (green: proceed; amber: caution; red: stop).

ABS and an ATS component protect trains from human or signal failure in LS-I and LS-III, tripping relays in any violating vehicles, stopping them, and preventing two trains from entering LS-I single track from opposite directions or two high-speed trains from being on the same block of LS-III track at an unsafe distance. Similar shutdown protection is built into each vehicle's speed governor, preventing speeds higher than 57 mph.

A preemption signal system governs train movement in LS-II and the eastern portion of LS-IV (Lloyd Center to Coliseum). As trains proceed over them, output from call loops embedded under tracks approximately 1,400 to 1,600 ft ahead of intersections preempt and phase traffic lights to give trains priority to proceed and directing automobile and pedestrian traffic to stop and wait.

Trains proceed on white vertical signals and stop on yellow horizontal signals that flash for approximately 5 sec before changing. Traffic signals in LS-IV are augmented by large, red signals that flash Train as trains approach or proceed through intersections.

Trains exceeding LS-II's 35 mph maximum speed beat the preempt to the signal. Trains slower than 20 mph miss the signal. After passing signals, trains pass over checkout loops returning signal priority to regular traffic.

In LS-IV trains do not have preempt power over traffic signals, but operators exercise control through a wayside signal control system (Vetag). At stations, operators stop trains over loops embedded in streets, illuminating Vetag buttons on LRV control consoles. Operators depress the call button, beginning a cycle that enters trains into normal traffic signal sequences rather than favoring trains over regular traffic (*2*).

Automatic Block Signal System

The ABS system, a series of consecutive blocks (sections of track with defined limits for train movement) equipped with train-actuated, wayside signals that govern train passage, is located in LS-I and LS-III. ABS governs electric switches, crossing gates, and traffic signals in its territory, guaranteeing that only one train occupies each block at a time.

Track circuits in each block detect trains. At the ends of each block, signals define the occupancy of the next block and, in some cases, the next two blocks. A device located between the rails trips an irreversible maximum service brake application in trains failing to stop at a red signal. ATS sounds an audible alert, lights up the ATS trip annunciator on the LRV control console, and registers on the ATS trip counter in the LRV operating cab (*2*).

Train detection activates main-line signals. Operators clear signals that govern train movement between main-line and auxiliary tracks by route selection at key-by boxes.

Switches

Normally electric switches govern main-line train movement. When trains occupy the track, track circuits request a normal route for main-line operation. If the requested block is not occupied by another train, ABS properly aligns and locks the switch point for the route, displaying appropriate signals.

Five slap (spring stay) switches located only in the yard throat at Ruby Junction allow trains in a trailing move through a switch to use wheel flanges to throw the switch and proceed on the normal route without manually throwing the switch. All other yard switches are manual (*2*).

Yard and Facility

Entering the yard from the main line, trains first pass through the yard throat that connects the yard to the main line tracks and either maintenance or storage track ladders: maintenance tracks on the west side of the yard; storage tracks to the east of Ruby Junction Rail Operations Facility.

Wash and blow-down tracks complement storage and maintenance tracks, and a run-around track enables vehicles to circle the facility and enter either end of the three-story building that houses administrative offices and rail control on the third floor, maintenance training and special shops on the second floor, a machine and vehicle shop on the main floor, and parts storage in the basement.

Its design is simple, accommodating no more than two vehicles on each track, preventing the "hemming in" of a vehicle, which invariably necessitates moving a vehicle still under maintenance. The overall building layout, conducive to productivity and enhancing working conditions, is open, bright, and airy. Hand washing facilities on the shop floor minimize employee time away from vehicles or other tasks. A foreman's office halfway down the floor allows full view of all work areas.

Stations

The 30 MAX stations differ slightly as dictated by function. All stations are just over 200 ft long to accommodate two-car trains. Gateway station is slightly longer.

LS-I and LS-III station platforms either surround or border tracks. LS-II station platforms are situated on the far side of intersections, offset, essential to the traffic signal preemption, because trains can be timed through intersections without allowing for station stops of varying length, and accommodating left-turn/U-turn traffic lanes. LS-IV station platforms are widened city sidewalks on one or both sides of the street.

Train customers use stairways from arterial and pedestrian overpasses to access three LS-III stations on the north side of I-84 at highway grade. Passengers unable to use stairs use an elevator.

Transit centers have more than one Autelca ticket vending machine (TVM). All stations have at least one TVM, except west- or southbound LS-IV stations west of the Willamette River. The TVMs are on platforms except at 82nd and 60th avenues where the TVMs are installed at the head of the stairs on overpasses. A July 31, 1991, ordinance makes these two platforms open only to passengers with proof of payment (valid passes, tickets, or transfers).

Most stations have passenger shelters with upright supports ringed with leaning rails designed for waiting passengers to lean on and benches of wrought iron and wood slats.

Accessibility for Handicapped Passengers

Wayside lifts located on each platform at the front of each train enable riders in wheelchairs and those who cannot climb stairs to board trains. Each MAX train carries two customers in wheelchairs. FY 87 daily lift use ranged from 10 to 20; FY 91, near 50.

Transit Centers

Five transit centers (TCs), Gresham (LS-I), Rockwood (LS-II), Gateway and Hollywood (LS-III), and Coliseum (LS-IV), afford passengers off-street transfers from bus to bus or bus to train or train to bus (Figures 1 and 2). Transfers are timed at Gresham TC and Gateway TC.

Gateway TC, a unique design, allows 12 bus lines to encircle three tracks. Passengers wait on two westbound platforms and one eastbound platform. The main-line westbound track is served by two platforms enabling all 16 doors on a two-car train to be opened and the typical 50 or more passengers waiting for each morning train to board quickly.

East of westbound trains (headed north at Gateway) are stalls for six Tri-Met feeder bus lines serving areas east of Gateway and for one bus line serving Vancouver, Washington, to the north. Buses and trains are scheduled for timed transfers primarily outside peak hours, but some peak buses arrive at the same time as trains, allowing westbound passengers to transfer from feeder buses to trains in a few steps. West of eastbound trains (headed south at Gateway) are stalls for five city bus lines. The center track is used to reverse trains between Gateway and downtown.

Bus passengers wait in small shelters located near each bus bay; MAX passengers use open metal and glass shelters reinforced with windscreens.

Park and Ride Lots

Five lots provide Tri-Met passengers free parking in just under 1,800 spaces at Cleveland Avenue (377 spaces) and Gresham City Hall (285 spaces) (LS-I); at 181st Avenue (252 spaces) and 122nd Avenue (405 spaces) (LS-II); and Gateway Transit Center (480 spaces) (LS-III) (*1*).

Vehicles

Tri-Met's LRVs, manufactured and assembled in 1981 by the French-Canadian Bombardier Corporation in Barre, Vermont, cost $800,000 per vehicle. The current replacement cost is approximately $2 million each. The car body is made of low alloy steel, fluorescent lights illuminate the interior, and a roof-mounted, forced-air system ventilates the 87,090-lb (approximately 44-ton) LRV. It seats 76 and comfortably stands an additional 90 for a total of 166 passengers. Under crush conditions, each LRV can carry 256 customers; each two-car train, more than 500.

Through train pantograph contact with overhead wires, 750 VDC is delivered to the static converter and transformed to 37.5 VDC for doors, wipers, exterior lights, radios, and other low-voltage systems. The converter supplies 37.5 VDC to the inverter turning 37.5 VDC into 120 VAC for interior lights, destination signs, heating systems, fans, and blowers. In a power failure, each LRV has an on-board battery system to provide backup 37.5 VDC for approximately 1 hr.

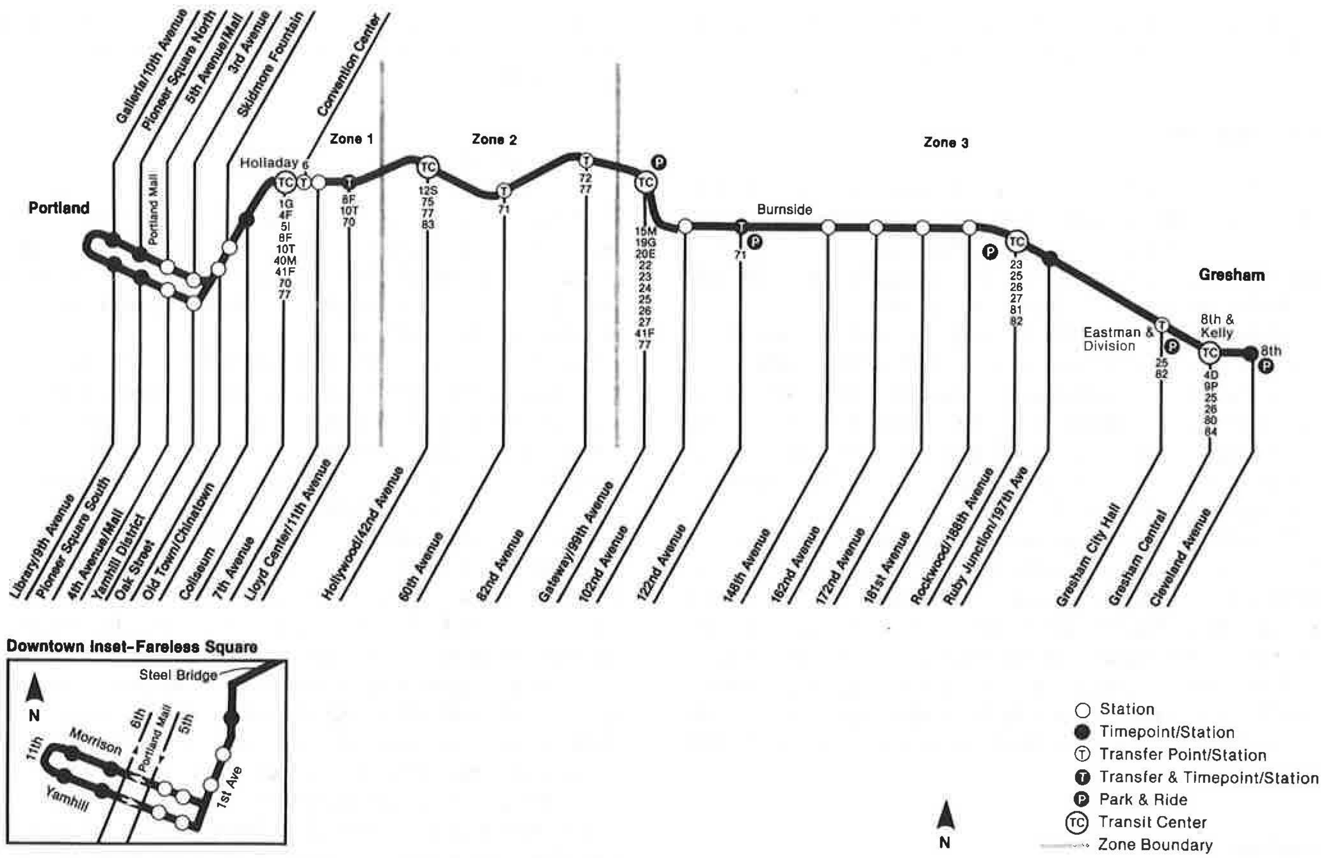

FIGURE 1 Tri-Met's MAX light rail service connecting downtown Portland with suburban Gresham.

A computerized electronic control unit on each LRV governs on-board train systems to blend braking and acceleration, to train-line systems in two-car consists, and to control safety features. The maximum 55 mph operating speed is governed by an overspeed restrict that brings the train to a maximum service brake stop if 58 mph is reached.

Operators control acceleration and braking by moving a motoring drum handle through 16 positions: six acceleration, six braking, three speed maintains, and one coast position. Traction motors located on the two extreme trucks of each LRV draw 550 to 600 amps in propulsion modes, providing 192 to 250 horsepower and accelerating at a rate of 3 mi/hr/sec.

Braking, provided by a blended dynamic/spring-applied disc hydraulic system that includes three brake types (dynamic, friction, and track), uses dynamic brakes as the primary system, reversing traction motors and dissipating heat generated through resistors on the car roof until car speed is reduced to 3 mph.

Disc brakes that bring trains to a complete stop (operating at 3 mph or less) are friction brakes, applying brake pads to train wheels on all three trucks. Disc brakes on end trucks are used in normal braking. The larger pads of the disc brakes on the center trucks are used only in emergency situations.

Track brakes, spring-suspended electromagnetic units on each truck, become attracted to and contact the rails for maximum braking power. Operators can apply track brakes manually for low-speed, precision stops. Track brakes also deploy automatically in emergency situations. Disc and track brakes with sanders are applied with maximum force.

Maximum service brake (blended braking of all braking systems) decelerates at 3 mi/hr/sec. In an emergency, however, the maximum braking (MB) rate is 4.7 mi/hr/sec—disc and track brakes not blended—in which traction motors draw 415 amps. Even with MB, trains need 750 to 800 ft to stop completely from a speed of 55 mph (*2*).

Communications

A console radio in each LRV cab, the primary means of communicating with the controller, is supplemented by a portable radio for use should operators leave the cab or primary console radios fail. Transportation and maintenance each have two reserved channels for their primary use. Before using the radio, employees verify that the channel is clear and direct all transmissions to controllers unless controllers authorize direct communications with other employees (*2*).

Rail Control

Located on the third floor of the rail operations facility, rail control serves as the main-line command center and sign-in

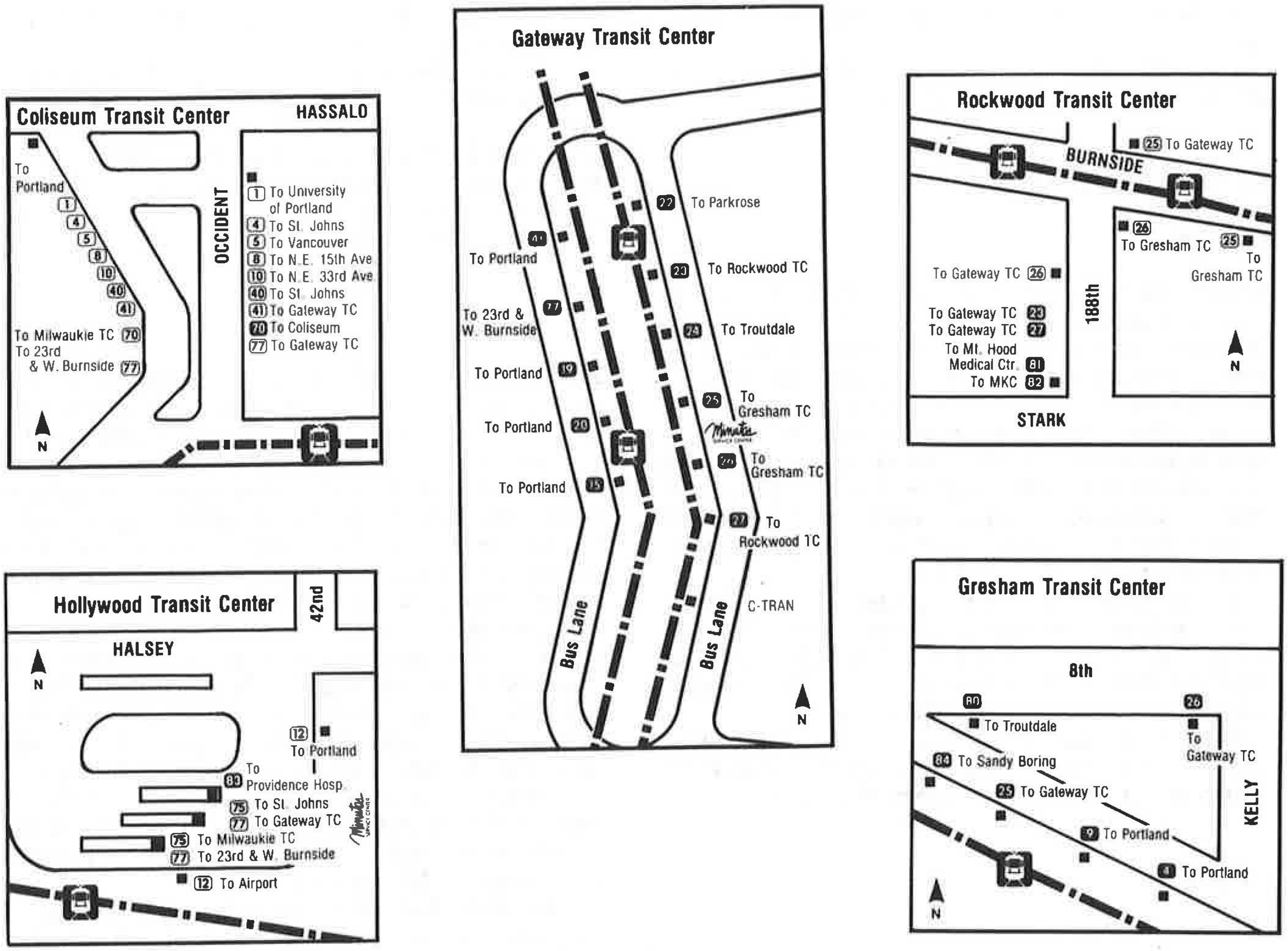

FIGURE 2 Transit centers.

station for operators where they report to work, pick up pouches, and review special orders.

Designed to low-tech specifications, rail control includes an open channel two-way radio with several channels, a magnetic yard/alignment board, and computer equipment to monitor ticket vending machine and substation security alarms. (Substation alarms were originally only flashing lights on site.) Controllers use a word processor to log major events and provide 24-hr coverage, combining duties of bus station agents and dispatchers. Controllers are responsible for ensuring safe operation of the entire light rail system, including the following:

- Covering all runs;
- Assigning trains and extra-board work;
- Issuing train orders, special instructions, pouches, portable radios, flashlights;
- Ensuring that equipment works properly;
- Assisting operators to troubleshoot train defects; and
- Coordinating light rail activities with police, fire, emergency, and county and municipal services.

Assisting the controller, rail supervisors work along the right-of-way to do the following:

- Conduct on-time performance checks;
- Assist in troubleshooting defects;
- Maintain system safety;
- Serve as primary investigators of rail accidents (taking pictures, inspecting damage, interviewing witnesses, conducting drug testing, and completing all necessary reports);
- Perform evaluations of and make suggestions to improve operator performance;
- Assist in customer relations (investigating complaints, providing timetable; and ticket vending information);
- Assist in cutting or adding cars to trains; and
- Operate trains in revenue service if necessary.

Following directions and working under supervision of the rail controller or supervisors, operators do the following:

- Follow all rules, procedures, and other special instructions;

- Take charge and operate trains on established schedules; and
- Use best judgment to provide safe and reliable service to the public and protection of property (*2*).

OPERATING EXPERIENCE

Financial

With a 1990–91 budget of $7,812,380, about 142 percent of the first year's projected budget ($5,511,796), MAX has experienced 5 years of steadily increasing expenses brought about by increasing service levels, phased-in maintenance staff, and beginning major maintenance on used equipment no longer under warranty. Transportation and maintenance employees have increased from 78 to 124; of the increase, transportation accounted for 12 additional employees; rail maintenance, 34. Maintenance staffing was phased over a 5-year plan because of manufacturers warranties and the relatively low maintenance in the first years for new LRVs.

Transportation's FY 87 operating budget of $1,792,531 covered 1 director, 1 manager, 8 controller/supervisors, 1 secretary, and 26 operators; its FY 91 budget of $2,309,302 supported 1 director, 1 training supervisor, 10 controller/supervisors, 1 secretary, and 36 operators.

Maintenance began revenue operation in FY 87 with a budget of $3,719,265 to support 51 employees, compared to a FY 91 budget of $5,103,018 to support 85 employees (*3*).

Maintenance

Vehicles

Routinely, car interiors are cleaned nightly; exteriors, every other day. Two of the 26 cars have been evaluated for overhaul needs, and a program is under way to incorporate some overhaul steps into the preventive maintenance program.

Tri-Met's maintenance team has, in 5 years of operation, found very few major difficulties with MAX LRVs. Any vehicle has problems that usually occur on most used parts. The major problems encountered on Tri-Met's 26 LRVs involved motors, doors, and brakes.

During FY 87 motors developed flashover problems because of improper interpole location. The contractor made necessary modifications on all motors; service was affected before modifications were complete only by lesser acceleration rates—noticed at first by customers, but something to which they acclimated quickly.

The weight and size of the swing plug-type doors on the LRV considerably flexed the framework supporting cam switches controlling door operations. A modification relocated these cam switches to an area ensuring rigidity and proper, consistent door operation. Operators' ability to activate the doors, enabling passengers to open them only when needed (not every door has to open at every station), keeps door problems to a minimum.

Extreme wearing of the friction brake actuator cylinder brought on by the force required to stop the vehicle caused brake fluid leaks. Modification of the actuator curbed wearing and, subsequently, leaks.

Rail maintenance personnel discovered that more frequent wheel truing (shaving minute amounts of material from the outer circumference of the metal tires) resulted in less material being shaved and tires lasting longer. Over time, a program was developed to schedule each car for wheel truing every 20,000 to 25,000 mi, the frequency being determined by reviewing the worn wheel profile.

Right-of-Way

Routine maintenance of way includes walking inspection of all 15.1 mi each week and monthly adjustment and lubrication of switches. A crucial design problem causing additional labor costs for LS-III between Gateway and Lloyd Center is the inaccessibility of the track except from stations or by highway/rail (hi/rail) vehicle. In emergencies parking along the freeway may become necessary. Additional labor costs result from the extra time crews take to arrive at the point of maintenance. A service road in the right-of-way would be a solution.

Tri-Met already has had to replace a right-of-way infrastructure component: grade crossings not designed to cope with traffic volume and weight. A decision to detour a truck route may have played a part in the breakdown of hard rubber modules and their replacement within 6 years of installation, along with shortcuts, low bids, and little aggressive cooperation with traffic and design engineers to determine eventual road use. Failed material is being replaced with precast, prestressed concrete panels expected to last for at least 10 years and to withstand bus and truck traffic.

Other extraordinary costs include vandalism cleanup and replacement especially at stations designed with large glass windows which were targets for ballast rocks made handy by trackway design. Material costs ranged between $20,000 and $25,000 annually added to cleanup labor costs.

Designing stations with as little glass as possible and paving LS-I, LS-II, and LS-III right-of-way for several hundred feet on either side of stations may have reduced vandalism costs substantially. Staffing the design team with experienced operations personnel to work with architects would help incorporate operating possibilities in the final design.

Frequent urination in elevators providing access between overpasses and LS-III stations along I-84 deteriorated support materials under tile floors, forcing renovation that included replacing underflooring material and installing shallow stainless steel "bath tub" floors. Renovation did not stop the urinating but did prevent structural materials from deteriorating.

Ticket vending machines (TVMs) have been extremely reliable and easy to maintain. Locating TVMs to protect machines and customers from the elements would improve future operation and maintenance. One major TVM improvement was installation of a radio alarm system, signaling any intrusion or attempted intrusion directly to rail control. Original audible alarms were only on site.

Wayside lifts, simple elevators with a drawbridge facing the vehicle, have also been easy to maintain but are subject to the elevator urination problem. A design flaw that allowed rainwater to fall on passengers and operators was corrected by adding to the rain gutter.

Graffiti on vehicles and right-of-way is a moderate problem, happening in spurts and handled as it occurs. To keep the problem under control, never place an LRV in service with graffiti or damaged upholstery; immediately remove all graffiti and repair damage on the right-of-way.

Stations are pressure-washed at least four times annually, and most heavily used stations are pressure-washed upwards of eight times annually, a very labor-intensive, expensive process. All stations are cleaned daily; some, twice daily. Special problems are handled as they arise.

Heavy maintenance of way is usually conducted when MAX is not running (between 1 and 5 a.m.). Routine maintenance of way sometimes spurs attendant labor problems e.g., catenary line counterweight settings must be performed at mean temperatures—not always achievable during early morning hours when crew are assigned.

Time and material costs to service any large portion of LS-IV track (where girder is embedded in an insulating substance to contain stray currents and dampen vibration and noise) are unknown. Grinding or welding any LS-IV track would require chipping away the surrounding substance and replacing it under temperature-accurate conditions.

Using a privately owned river span (the Steel Bridge in LS-IV) has posed both operational and maintenance problems, making operations unreliable. The bridge frequently has been inoperative, and Tri-Met's bus division has deployed buses to transport passengers via another bridge (standard operating procedure for accidents or equipment problems that interrupt service on both tracks of any section).

Maintenance time windows needed to perform specific tasks have been restricted when MAX handles special events such as the Rose Festival, marathons, and other races.

Service and Schedules

In peak hours 22 vehicles in 10 two-car and 2 single-vehicle morning trains and 11 two-car afternoon trains carry heavy loads. In midday, evening, and weekend operation, eight two-car trains are the rule; eight single-car trains, the exception. The FY 91 service configuration, however, was not always so.

Running times and quantity of service required to transport passengers effectively, essential factors in producing transit schedules, made it obvious to Tri-Met's rail operations team before start-up that initial running time estimates were low. Initial scheduled times, however, have held up with relatively minor adjustments.

Since FY 87, several factors have affected running times. Adverse effects are as follows:

- Fifty daily wheelchair uses for 84 train trips in each direction daily place chances of a wheelchair being loaded on each round trip at 60 percent. Providing accessible service has made Tri-Met an asset to the handicapped community, but necessary schedule recovery time is included in terminal layovers.
- Four additional round-trip LS-IV stops have been added, two at the Pioneer Place office and retail development to the west side of the river and two at the Oregon Convention Center to the east.

Beneficial effects are as follows:

- Installation of the train-to-wayside (Vetag) signal preemption system allows smoother and more efficient schedules downtown.
- Right-of-way on all but 500 ft of track over the Steel Bridge (LS-IV) is exclusive or reserved.
- Signal preemption is used throughout LS-II and LS-IV.
- Sufficiently wide station spacing in LS-I, LS-II, and LS-III permits reasonably fast operation.
- Self-service fare collection permits all doors to be used freely at each station and minimizes dwell time.

Balancing these factors permitted MAX to hold its own on running time. Increased vehicular traffic, ridership, and additional stops has not had any seriously detrimental effect on MAX operation.

Since FY 87 Tri-Met has made incremental changes to MAX service. Public interest in a highly publicized start-up resulted in heavy loads, especially during weekends and off-peak weekday hours. "Curiosity" patronage eventually leveled off as peak business ridership increased in the first 2 years (FY 87 and FY 88) of operation. Beginning in mid-1989 MAX total ridership began to increase with subsequent fiscal years showing patronage gains of about 13 percent (*4*).

Planned peak weekday schedules of 20 of the 26 LRVs with 12-min headways and day base headways of 20 min proved too little, as popularity forced immediate improvement of day base headways to 15 min. Peak headways have been further adjusted and improved to accommodate growing ridership, particularly in the heart of the morning peak.

FY 91 schedules employed 22 cars with trains operating at 6.2 min in the "peak of the peak" half-hour period. Creative scheduling techniques to derive maximum effective use of the available equipment and reduce overcrowding have included weekday splitting of a two-car outbound train at Gateway into two one-car trains to increase capacity between the two most heavily loaded inbound trains from 7:25 a.m. to 7:35 a.m.

Frequent schedule adjustment keeps pace with load increases and has balanced loads and minimized loss of customers from peak period overcrowding. Tri-Met service standards for MAX call for the number of riders not to exceed 76 passengers per car (a full, seated load) east of 122nd Avenue in LS-II in either direction (*5*). Counts during summer 1991 indicated that 8 of the first 13 weekday westbound trains exceeded that standard as far east as 197th Avenue.

Special Events

To emphasize the regional nature of MAX service, the Friday, September 5, 1986, service start-up followed three public ceremonies (9 a.m. at Gresham City Hall, 10:30 a.m. at Gateway and noon at Pioneer Courthouse Square). More than 1,000 attended the Gresham ceremony, more at Gateway, and about 11,000 downtown.

Beginning at about 1 p.m. and continuing all weekend (5 a.m.–1 a.m.), Tri-Met operated 12 trains at 10-min headways carrying more than 200,000 celebrants free on the innovative transit mode. Businesses and private citizens contributed more than $200,000 to fund entertainment and refreshments at five stops along the way. Tri-Met returned 200,000 tickets to those contributors, priming the ridership pump for the next several months.

With no major accidents, no major injuries, and few lost children, MAX demonstrated to operators and controller/supervisors how light rail can meet special needs with special service.

In regular service, the need of Portland's Memorial Coliseum was obvious. A third (special events) track at the Coliseum Transit Center allowed rail supervisors to hold back one or more cars, normally cut from a two-car train after the evening commute, for crowds leaving the Coliseum from Trailblazers basketball games, concerts, and other events (circus, conventions, etc.). Extra service accommodated the first wave; trailing riders take regular service.

Christmas holidays and spring break have been marketing opportunities to showcase MAX for new customers. The surge in holiday ridership calls for two-car trains most of the day and night and sometimes volunteers on platforms to help newcomers.

The 1987 Rose Festival was MAX's first "crush" test since opening weekend crowds. Since 1987 MAX has not let a Rose Festival crowd down, carrying more than 10 percent (*4*) of the close to 500,000 parade watchers downtown and shuttling them afterwards between waterfront Festival Center (First Avenue Station), the Lloyd Center, Hollywood, Gateway, Rockwood, and Gresham. In 1987 a Gresham business owner reported having seen a sailor near his shop for the first time ever during the Rose Festival. The festival draws more than 5,000 sailors and marines to the Rose City seawall each year; MAX lets them see more.

Bus Connections

Tri-Met's service standards call for bus routes to maximize connections with rail stations when riders would benefit (*5*), a goal accomplished in 1986 by restructuring service that crosses and parallels MAX.

For LS-I, LS-II, and Gateway, bus routes were changed to provide convenient MAX access from as far south as Southeast Division Street (2 mi south of and parallel to East Burnside). Timed bus connections were given priority to facilitate local travel with bus-to-bus connections as well as train-to-bus connections.

Feeder lines replaced all radial lines extending from the east side into Portland's CBD east of Gateway and north of Division Street, and converged on Gateway Transit Center for timed connections with MAX trains, between feeder lines, and five Portland city bus lines (on streets parallel to MAX), with one line serving Vancouver, Washington (operated by C-Tran), and with each other. Some feeder lines converged on Gresham Transit Center for timed connections with each other and MAX, and some also met MAX at Rockwood but without timed connections.

Tri-Met opted for this service over a grid of north-south crosstown lines to preserve east-west movement patterns Tri-Met traditionally provided to the area and provide access to MAX. A full set of crosstown routes was not within the agency's financial means in FY 87, so limited resources were allocated only to crosstown service on 122nd Avenue and 181st/182nd avenues where housing density and commercial development suggested maximum ridership potential.

Timed transfer meets at Gateway were scheduled for 24 and 54 min after each hour, a pattern retained during peak hours when additional meets were inserted as needed at 9 and 39 min past the hour.

Major route restructuring was not needed in the rest of LS-III and LS-IV, because Tri-Met restructured city and eastside service in September 1982, putting in place a basic pattern of crosstown lines needed to support light rail service. Two major objectives of LS-III and LS-IV changes called for nondowntown bus-rail connections for nondowntown trips whenever possible and for MAX to replace a heavily used bus line (on Northeast Sandy Boulevard) as the urban trunk line for northeast Portland. The resulting radial line on Sandy Boulevard was re-routed to Portland International Airport, initiating the first direct bus service between Portland's CBD and the airport.

A single 15-min crosstown line replaced three radial and one crosstown overlapping lines on portions of two east-west streets, connecting MAX at Gateway, Hollywood, and Coliseum Transit Centers, continuing west over the Steel Bridge to Northwest Lovejoy Street and breaking up a long circular line that ran from northeast Portland to Lake Oswego via Beaverton.

To simplify and coordinate passengers' orientation to MAX service from the downtown reference point, the Blue Snowflake stops (one of seven designations used to identify geographical sections of Tri-Met's service area) were removed from the Portland Mall on Southwest Sixth Avenue. MAX was designated the only Blue Snowflake service from downtown Portland; its feeder buses serve the rest of that geographical area (*6*).

The FY 87 bus service has continued for the last 5 years with minor adjustments as patronage and requests for service warranted. Average weekday bus ridership in the Blue Snowflake service area (LS-I and LS-II) has grown 6.4 percent from 3,550 in FY 87 to 3,777 in FY 90. Ridership for crosstown city bus lines feeding MAX (LS-III and LS-IV) has increased 14.2 percent from 23,485 in FY 87 to 26,828 in FY 90. FY 91 line performance figures are not available (*4*).

Ridership

MAX weekday ridership has grown 20.0 percent from a FY 87 average of 19,500 boardings to an FY 91 average of 23,200 (Table 1). During FY 87, because of budget considerations, Saturday, Sunday, and, consequently, weekly and monthly ridership were not measured consistently enough to produce reliable figures, so FY 88 statistics are used as the benchmark for those numbers.

Since FY 88 MAX Saturday boardings have dropped 4.5 percent from 19,800 to 18,900 in FY 91. Sunday ridership increased 5 percent from a FY 88 figure of 10,000 to 10,500 in FY 91. Weekly ridership increased 13.3 percent from 128,000 FY 88 boardings to 145,000 in FY 91. Monthly total boardings averaged 550,000 in FY 88 compared to 620,000 in FY 91, a 12.7 percent increase, and boarding rides per service hour

TABLE 1 MAX Weekday Boardings and Percentage of Total Boardings by Line Section (*4*)

Line Sections	FY87	% Total	FY89	% Total	FY91	% Total
I. Railroad	2,600	12.5	1,808	9.9	2,376	10.5
II. Residential	3,848	18.5	3,266	17.9	4,352	19.2
III. Freeway	3,972	19.1	3,845	21.1	4,246	18.7
IV. Downtown	10,378	49.9	9,375	51.4	11,749	51.7
TOTALS	20,800	100.0	18,244	100.3	22,713	100.1

increased by 14.0 percent from 151.34 in FY 88 to 172.57 in FY 91 (*4*).

Station Use

A Tri-Met on-board ridership survey published in June 1987 identified Pioneer Square stations as the most used stops (with 14 percent of all boardings), with Library, Lloyd Center, and Gateway a close second (with 8 percent each). Weekends, however, saw most boarding activity shift to Lloyd Center (12 percent) and Library (10 percent); Pioneer Square (9 percent), Gateway (7 percent), and Skidmore Fountain (7 percent) followed close behind.

In FY 89 Pioneer Square stations continued to be the most used (14.8 percent) followed by Gateway (9.3 percent), Library/Galleria (7.9 percent), and Lloyd Center (7.8 percent). In FY 90 the Fifth and Fourth Avenue stations opened just two blocks east of the Pioneer Square stations, and the Convention Center station came on line early in FY 91. Although the addition of these four round-trip stops caused a shift in station use, LS-IV increased its share of ridership to over 50 percent (*7*).

PROGRAMS

Safety

An extensive FY 86 outreach effort aimed at schools and community groups along the MAX line resulted in hundreds of individuals viewing videotape productions pointing out potential safety problems. The objective was to make the community aware that it had a new "neighbor" that is larger and quieter than any motor vehicle—a new aspect of everyday life with which they would have to cope in a safe manner.

Despite efforts to educate motorists about the "new kid on the block," accidents, primarily at intersections, typically involved drivers who ignored signalized or signed intersections (Table 2). Accidents have been dramatically reduced in the last 2 fiscal years. It was at that time that signage (the flashing Train lights) and computerized signals (Vetag) were introduced.

The vast majority of MAX accidents have occurred in LS-IV, in the CBD. No accidents have ever occurred at LS-I gated crossings over the entire 5-year operation.

Three fatalities have been recorded. Two occurred at night in LS-III along I-84. Pedestrians got on the right-of-way, in one case on foot from the Lloyd Center station, walking east on the eastbound track, and in the other case after parking a car on I-84 and climbing concrete barriers to walk west on the westbound track. The third fatality occurred at an intersection in LS-IV during daylight hours after a motorist turned in front of an LRV, which partially crushed the vehicle.

The LS-III incidents are being studied with an eye to possibly installing intrusion alarms and improved lighting along high-speed sections of track.

Revenue Collection

MAX revenue collection includes two distinct programs: first, the daily collection of revenue from 68 ticket vending machines (maintained by rail maintenance) and currency processing at agency facilities; and second, the checking for proof of payment by fare inspectors. Both functions are administered by the revenue section of Tri-Met's finance and administration division.

Tri-Met contracts daily revenue collection and transporting services to a private, armed guard security firm and to an armored truck firm. Revenue is collected each morning; bank deposits are made each evening. Revenue section supervisors coordinate daily schedules for both services and perform checks and balances for these activities.

Eight full-time fare inspectors carry out inspection activities, working 10-hr shifts 7 days a week during all MAX operating hours under the direction of a chief fare inspector and a dispatcher. Five inspectors work three different shifts: 6 a.m. to 3 p.m. (two inspectors); 11 a.m. to 9 p.m. (one inspector); and 3 p.m. to 1 a.m. (two inspectors). Nine extra fare inspectors supplement the full-time staff. The extras are full-time bus operators.

Two changes made over the past 5 years have contributed to enhancing both employee job satisfaction and inspection productivity. One was the change to a 10-hr/day, 4-day work week from the previous 8-hr/day, 5-day week. This change resulted in a rotation of 3 days off for fare inspectors, enabling

TABLE 2 Accidents Involving MAX by Fiscal Year

TYPE	FY87	FY88	FY89	FY90	FY91	Totals	% of all
Intersection	29	26	31	11	11	107	42.8
Turns in front of LRV	13	10	25	6	**	**	**
Right Angle Collision	16	16	6	5	**	**	**
Head-on	0	0	0	0	1	1	0.4
Sideswipe	1	1	0	0	1	3	1.2
Rear-ends	0	0	1	0	0	1	0.8
LRV/other	0	0	0	0	0	0	0.0
Other/LRV	0	0	1	0	0	1	0.8
Pedestrian	5	4	1	2	4	16	6.4
In crosswalk	0	1	0	1	**	**	**
On platform	2	1	0	1	**	**	**
In Right-of-way	3	2	1	0	**	**	**
LRV hits object in r-o-w	33	5	11	17	19	85	34.0
Derailments	0	0	0	0	0	0	0.0
Others	2	3	13	15	4	37	14.8
Total by FY	70	38	57	45	40	250	100.0
% of all accidents/all FYs	28.0	15.2	22.8	18.0	19.2	100.0	

** figures not available

them to focus more attention on performing inspection-related assignments with the additional 2 hours of work daily.

The second change was the relocation of the fare inspectors' office to Coliseum Transit Center (LS-IV) on the MAX line, eliminating approximately 1-1/2 hr daily travel time for each inspector between the former report area at Tri-Met's administration building and the MAX line, approximately 3 mi away.

A fare inspection plan is being developed that will assess fare inspection needs over the next 5 years, looking at staffing needs and deployment options for both buses and MAX leading up to the 1997 estimated start-up time for westside MAX. A staff of 25 full-time fare inspectors is envisioned (more than double the current number) with a gradual staff increase each year to reach full strength by 1997, eliminating a sudden increase in inexperienced fare inspectors and providing an opportunity for expanded bus inspection and staff training in the interim.

A 1990 fare evasion review of the Tri-Met system estimated that MAX riders contributed $3 million annually in fares. Monthly levels of inspection varied from approximately 50,000 to 70,000 passengers, and the fare evasion rate varied from approximately 4.3 to 6.9 percent. The average evasion rate was 4.81 percent, which translates into an estimated revenue loss of $122,580. Total fare evasion for both MAX and buses was estimated at $350,000 annually. Fare inspection operating costs are $410,000 annually.

Fare inspectors also provide invaluable customer information services on board MAX and at platforms, telling customers (including tourists and visitors) how to use bus and rail service, how to purchase fares, and so forth. Fare inspectors also act as a crime deterrent and are credited with lowering vandalism and graffiti incidents, giving the public a sense of security because inspectors can summon help by two-way radio in emergencies.

Training

Since April 1986 when the first Tri-Met bus operators were selected to be light rail operators, the training regimen has been the same. More than 100 operators have gone through the course; about 10 percent washed out in the first 3 weeks—several have been asked to return to bus operation for failure to comply with regulations; some have gone back as a matter of choice. Annual refresher training updates operators' knowledge and skills.

To operate a Tri-Met rail vehicle, employees must be certified by the light rail transportation department after passing the light rail operator's training course—an intensive 3-week program designed to familiarize trainees with various aspects of light rail operation.

Operator trainees complete 1 week of intensive classroom and field instruction, 1 week of main-line training by a qualified instructor, and 1 week of main-line burn-in accompanied by another qualified operator. After this training, operators are expected to have the knowledge and experience to operate a train safely in revenue service and maintain service in varying conditions.

During the first week of training, operator trainees take five written tests, each consisting of 20 questions on the previous day's lecture material. At the end of the second week, trainees take a 100-question final exam, covering daily lectures, standard operating procedures, the *Light Rail Operations Rulebook*, handouts, and practical skills demonstrated by the trainers.

A passing grade is 85 percent; any lower is a failure. Any trainee failing two or more daily exams, a daily and the practical, or the final exam is terminated from the training program and returned to the last position held at Tri-Met (*2*).

TABLE 3 Tri-Met's Five-Year Light Rail Experience

Characteristic	1986-87	1987-88	1988-89	1989-90	1990-91
Line miles	15.1	15.1	15.1	15.1	15.1
Stations	27	27	27	29	30
Transit Centers	5	5	5	5	5
P & R Spaces	1,799	1,799	1,799	1,799	1,799
Actual Expenses	$4,293	$5,439	$5,893	$6,898	$7,412
Transportation	$1,664	$2,020	$2,069	$2,256	$2.309
Maintenance	$2,629	$3,419	$3,824	$4,642	$5.103
Employees	78	101	108	113	124
Transportation	37	47	47	49	49
Maintenance	41	54	61	64	75
Vehicle Miles	70,000	70,000	70,230	71,050	71,000
Ops Cost/Veh Mile	$5.81	$6.49	$6.88	$8.06	$8.91
Revenue Hours	41,232	43,692	43,596	43,584	43,428
Ops Cost/Rev Hr	$90.24	$98.44	$103.80	$120.71	$133.10
Miles/Veh Accident	14,725	19,552	15,606	22,437	20,779
Miles/Pas Accident	6,560	****	21,069	25,837	21,845
Miles/Rail Call	16,999	24,023	52,857	64,115	62,334
Annual Boardings	****	6.6M	6.36M	6.72M	7.44M
Weekday	19,500	19,600	19,700	20,500	23,200
Saturday	****	19,800	16,600	17,400	18,900
Sunday	****	10,000	7,800	9,400	10,500
Weekly	****	128,000	123,000	129,000	145,000
Monthly	****	550,000	530,000	560,000	620,000
Boardings/Serv Hr	****	151.34	145.28	152.88	172.57
Ops Cost/Boarding	****	$0.82	$0.92	$1.04	$1.01
KW hr/Car Miles	8.14	6.49	6.87	6.66	6.97
Avg. Speed (MPH)	15.54	15.17	15.09	14.92	14.94
Pullouts Made	99.95%	100.00%	99.95%	100.00%	99.79
Connect Bus Boardings	27,035	****	****	30,605	****
East Feeder	3,550	****	****	3,777	****
West City	23,485	****	****	26,828	****

**** figures not available

RELATED AREAS

Operational aspects of Tri-Met's 5-year experience with light rail transit treat just a few facets of the effect MAX had on Tri-Met and the region. Much material for other studies lies in the exploration of future expansion of infrastructure and service, economic development, property values, architecture, customer service, marketing, security, and so forth.

Taken as a body, these studies would prove useful to agencies embarking on light rail planning, construction, or service start-up in the near future. Although specific applications of experience must be adjusted for each agency, some generalizations and rules of thumb can be developed that would prove beneficial.

CONCLUSION

In 5 years, Tri-Met's MAX light rail service has gone far beyond what agency officials, political and community leaders, and the general public expected (Table 3):

- Operating experience has been positive, making an increasing contribution to Portland's livability and economic development, and enhancing the transit agency's public image.
- A vote taken in November 1990 was 74 percent affirmative to use property taxes to finance a $125 million bond issue as part of the local match (12.5 percent) to finance a 12-mi extension of MAX service (to the west side of Portland

to Hillsboro) and to fund preliminary engineering of a north-south rail corridor (connecting Clackamas County with the MAX system).

- Nearly $1 billion in public and private development has occurred on or near the MAX line over the last decade.

Hindsight, however, indicates areas in which different decisions would have made the operating experience decidedly more positive:

- An option on 10 cars at 1981 prices was passed up by the agency because it had been negatively affected by an economic recession that caused service cutbacks. Not having the extra cars has constrained improvement of peak-hour schedules to meet passenger demand.
- Vehicle air conditioning was not chosen; some of Portland's hottest days occurred during the summers of 1987 and 1988.
- Single-tracking of LS-I was selected as more economical but schedule frequency is constrained to a maximum of 7-1/2 min.
- A video security system for platforms and facilities was passed up in favor of concession licensing; concessions did not prove profitable at all stations and the necessary presence to deter vandals was not provided.
- A vehicle communication system was retrofitted to allow passengers to communicate with operators in case of emergencies.

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Light Rail Transit in San Diego: The Past as Prelude to the Future

THOMAS F. LARWIN AND LANGLEY C. POWELL

In San Diego a bare-bones and simple light rail transit (LRT) system has grown into a maturing, expanding rail system. Key decisions made in the development of a growing LRT network in San Diego have guided the operating performance of the system over the past 10 years and are shaping its future. The maturation of the system, together with ridership growth, has influenced a change in design criteria and operating features.

The San Diego metropolitan area, with a population of about 1.8 million people, includes 10 cities of which the largest is the city of San Diego. The area has grown considerably since World War II, and population forecasts for the year 2010 project a metropolitan area population in excess of 2.2 million residents.

The San Diego Metropolitan Transit Development Board (MTDB) is responsible for setting transit policy and developing public transit facilities within this metropolitan area. MTDB was created in 1975 by state legislation authored by Senator James R. Mills, chairman of MTDB since 1985. Legislated provisions provided MTDB with broad-based and important powers with regard to public transit coordination, planning, and capital project programming for the metropolitan area (*1*,*2*). These transit responsibilities provided MTDB with the powers of implementation and financing that "put teeth" into the guideway development functions. A retrospective look shows that, along with the successful growth of light rail transit (LRT) in the San Diego metropolitan area, a parallel, positive, and gradual expansion of MTDB's role outside the individual project development area has occurred.

DEVELOPMENT OF THE SAN DIEGO LRT SYSTEM

Overall LRT project development had roots in studies carried out by the San Diego Comprehensive Planning Organization (MTDB's long-range planning partner, now called the San Diego Association of Governments, or SANDAG) in the early 1970s. Substantive MTDB technical guideway planning work began in late 1976 and culminated in opening the first increment of service in July 1981 (*3*–*5*). Generally based on UMTA's decision not to provide financial assistance for a proposed rail system in the Denver metropolitan area, MTDB early on decided to build a system using only local and state financial resources (*6*). In retrospect this funding decision became a significant advantage in that, to a very large degree, it placed decision making almost totally at the local level. In turn responsibility and accountability were centralized with MTDB members and management. This centralized control not only aided efficient decision making but, with an MTDB policy that linked individual pay raises with adherence to project budget and schedule objectives, also created a significant incentive for management to produce.

MTDB has become the planner and developer of public transit services and facilities in the San Diego metropolitan area and functions as an umbrella agency. It owns the assets of San Diego Transit Corporation (SDTC) and San Diego Trolley, Inc. (SDTI), both of which were formed under California law as nonprofit public corporations. In addition, MTDB owns the San Diego & Arizona Eastern Railway Company (SD&AE), a Nevada railroad corporation that covers 108 mi and 2,000 acres of property. The operations and maintenance of the two transit services and of the freight railroad are all handled through specific agreements with each of the three separate operating organizations. All day-to-day functions, labor matters, and maintenance are managed by the individual operating corporations.

The MTS (Metropolitan Transit System) is also under policy control of MTDB and not only includes SDTC and SDTI, but also several other municipal operators. Under MTDB, unified policies exist to foster high-quality transit services in the areas of fares and passes (*7*), telephone information, regional marketing, and route numbering.

Design Criteria

In late 1976 MTDB adopted principles for low-cost implementation of guideway transit in San Diego. These principles formed the basis for the eventual initial LRT starter line and primarily called for the following:

1. A corridor that extends a relatively long distance and provides opportunity for high-speed operation;
2. A line with low capital cost;
3. A line primarily at grade and primarily in exclusive right-of-way; and
4. A system with low operating costs and high probability of meeting operating costs with farebox revenues.

These principles eventually led to Board Policy No. 1, which provided the foundation for the system-design criteria applied to the initial South Line LRT Project. The next step in the process was the evolution of site-specific design criteria after

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the planning work was completed. In preparation for engineering activities these criteria, adopted by MTDB in three workshop meetings in late 1978 and early 1979, provided the basis for design of the South Line LRT Project (*8–10*). These early criteria were general and performance-oriented, but proved workable at the time. They were effective in the sense that they provided the necessary direction for management to carry out the project. They have, however, proved to be too general as the system has matured and new extensions have come on line (*11–17*).

The original criteria have been brought up to date, made more comprehensive, and made more explicit. Examples of several significant changes in the design criteria over the past 12 years, and adopted by MTDB in 1991 (*18,19*), include

- Use of concrete ties instead of wood ties;
- Use of standardized rail size (115 lb);
- Widened passenger station platforms;
- Use of rubber crossing material instead of cast-in-place concrete;
- Installation of additional track crossover switches, providing more flexibility for train operations;
- Predominant use of single-pole (center), steel traction power supports;
- Strategic placement of pocket (turn-back) and passing tracks;
- Higher performance vehicles and addition of total climate control (heat, ventilation, and air-conditioning system);
- Gradual introduction of train-to-wayside signaling; and
- Smaller but more powerful traction power substations.

Light Rail Transit Selection

Using MTDB's principles and comparing them with the modal options available led to selection of LRT technology as the most practical guideway alternative in 1977. After a tour of North American and European systems and an evaluation of options, LRT was judged to be suitable to the environmental, density, and transportation demands of the San Diego region (*20*). Further LRT's flexibility in allowing construction to fit within existing transportation rights-of-way, built-up communities, and undeveloped areas seemed to make it a logical choice. On the other hand MTDB was faced with numerous skeptics. Some pointed to the problems that Bay Area Rapid Transit (BART) was having in achieving its objectives (this project, too, was initiating service in California during the 1970s). Others brought up such things as the past problems with streetcars, the flexible and low-capital cost advantages of buses, and the public being enamored with people movers and monorails. But, in the end, MTDB made a unanimous decision to go with LRT (*21*).

Fare Collection System

MTDB's examination of successful European transit systems revealed the need for simple station facilities and a fare collection system with minimal personnel requirements. In another key decision, risky at the time, MTDB opted for the barrier-free proof-of-payment (POP) or self-service fare collection approach becoming prevalent in Europe (*21–23*). At the time, skepticism seemed to be widespread concerning the practicality of the POP system. The perception seemed to be that people in the United States were less honest than people overseas. As it turned out, POP fare collection has worked well and has not resulted in unacceptable fare evasion rates. Results with San Diego trolley continue to show evasion rates hovering around 1 percent with inspection rates of roughly 25 percent. Further, initial capital and longer-term operating cost savings are significant (*24–29*).

Coordination

Perhaps because of MTDB's broad role in public transportation development and planning, the organization recognized that to ensure success any rail transit line had to be an integral part of the overall regional transit network. In parallel with design and construction efforts, MTDB decided a coordinated bus feeder plan for the South Line LRT Project rail would be implemented when rail service began (*30*). In addition fare and transfer policies were established that would permit passenger transfers among all MTS rail and bus operators (of which there are now seven) and implementation of an MTS regional pass system (*7*). This coordination has not only made the regional system healthier but also has been instrumental in helping ridership and fare revenues grow for each of the MTS operators. In 1978 total MTS operating revenues (i.e., fares) were 30 percent of operating costs, whereas projections for 1992 indicate that the figure may exceed 52 percent. This positive economic trend would seem to demonstrate the mutual dependence of bus and rail services and how their coordination ends up making the entire system operate more productively.

Incremental Expansion

In accordance with the functional spirit of LRT and legislative directives, the San Diego trolley system has continued to expand. The first, basically single-tracked South Line opened in July 1981. Double-tracking was completed in early 1983. In 1986 the first increment to the east opened service; it was 4.5 mi (7.2 km) long and added four new stations through southeast San Diego. Two more extensions were added: one in 1989, further extending the East Line to the city of El Cajon; and another in 1990, along the Bayside corridor in Centre City San Diego.

The current San Diego trolley system, shown in Figure 1, consists of two routes:

- *South Line*—15.9 mi (25.6 km) from the Santa Fe Depot in Centre City to San Ysidro at the international border with Mexico. About 1.7 mi (2.7 km) are on city streets and the remainder on the existing, rebuilt railroad right-of-way. Eighteen stations are on the line.
- *East Line*—19 mi (30.4 km) with some of the Centre City portion shared with the South Line. This line heads east to a terminal at the El Cajon Transit Center. The line has 6 common stations with the South Line (all in Centre City) and 15 additional stations (including 3 in the Centre City Bayside corridor).

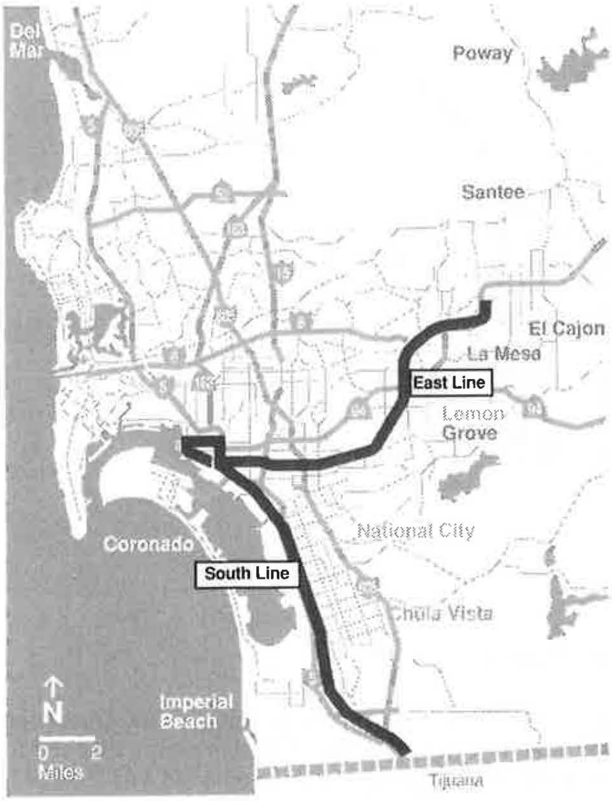

FIGURE 1 San Diego rail plan: existing service.

The initial 14-car fleet has grown to 71 (with 75 on order), all manufactured by Siemens-Duewag. The cars are double-ended, articulated, and have six axles. They are furnished with 64 seats and are 80 ft (24.3 m) long. Maximum speed is 50 mph (80 km/hr) with an average running speed, including stops, of 30 mph (48 km/hr) outside Centre City and 9 mph (14.4 km/hr) in Centre City. Each of the 71 cars has a single on-board wheelchair lift in one of the doorways next to the operator cab. This door is not available for regular passenger use.

In response to the need to enhance the system, several improvements to plant facilities and the rail fleet have been accomplished. The light rail vehicle is currently manufactured with heat, ventilation, and air-conditioning (HVAC) and a handicap lift as standard equipment. The HVAC units are modular and if they fail they can be replaced within approximately 2 hrs.

In all, including the various enhancements, the capital investment for San Diego's LRT network now stands at about $320 million or roughly four times the initial investment in the South Line that opened in 1981.

SAN DIEGO TROLLEY, INC.

Consistent with the desire to concentrate on transit development and policy setting, MTDB created San Diego Trolley, Inc. (SDTI) in August 1980 as a wholly owned subsidiary to operate and maintain the light rail transit system then under construction. SDTI is a nonprofit, public-benefit corporation, governed by a seven-member board of directors appointed by MTDB. The SDTI board includes an ex-officio, nonvoting member of MTDB.

Prerevenue Operations

Public rail transit services were terminated in San Diego during the late 1940s. Thus, no local reservoir of electric rail transit experience existed, and little was available nationally. MTDB and SDTI used consultant services to assist in the development of rail start-up procedures and standard operating procedures for operations and maintenance (*31*). A staffing plan for prerevenue service was developed in late 1980 and recruitment initiated. In September 1980 the general manager of SDTI was hired and took over the final development of an initial LRT staffing plan for the organization and eventual management of the system.

Service Expansion

As a result of continuous ridership growth and improvements to the system, the operating plan for the trolley has been modified several times. In February 1983 STDI adopted a 15-min headway interval between 5 a.m. and 8 p.m., and service hours were extended with 30-min headways to 10 p.m. In July 1983 train service hours were further extended to 1 a.m. with 60-min frequencies initially during these late hours, going to 30 min in 1988. In March 1991 7.5-min morning and evening peak period headways were inaugurated on the South Line.

The first segment of the East Line, ending at Euclid Avenue, opened in March 1986, with the second and third segments to the cities of La Mesa and El Cajon opening in May and June 1989, respectively. The East Line added approximately 16 mi (25.6 km) to system route mileage. Service frequencies began with 30 min in 1986 and in 1989 went to 15 min. In 1990 another extension was added to the East Line, this one in the Bayside corridor of Centre City.

As indicated in Table 1, annual train miles and train hours have more than tripled since the first year of operation. First-year miles were 517,503 whereas in the 10th year, FY 1991, train miles increased to nearly 1.8 million. Likewise, train hours went from 29,653 in FY 1982 to 93,520 in FY 1991.

Staffing and Training

As service levels have increased, the SDTI staff has grown slowly but steadily. SDTI initiated revenue service operations in 1981 with 57 full- and part-time employees. As indicated in Table 1, by late 1991 SDTI employed a total of 280 full-time equivalent employees. To maintain efficiency and economy in operations from "day one," SDTI has required flexibility in job assignments and, therefore, routinely cross-trains both full-time and part-time employees to perform several tasks within their respective departments. In the early years, whenever an emergency occurred, all management personnel, regardless of discipline, participated in resolving the incident. In fact this practice has continued and, without their help

TABLE 1 San Diego Trolley Performance Trends

Fiscal Year	Total Train Miles*	Total Train Hours*	Full-Time Equivalent Employee	Operating Cost*	Boarding Passengers*	Fare Revenue*	Accidents
82	518	30	62	$ 3,531	3,886	$ 2,747	91
83	522	31	79	4,258	4,138	3,037	31
84	774	36	82	4,955	5,437	3,976	40
85	772	36	85	5,530	5,943	4,760	19
86	842	42	94	6,271	7,003	5,561	16
87	994	56	118	7,309	7,974	6,337	19
88	1,054	58	126	7,927	9,281	7,317	27
89	1,143	63	148	9,159	11,217	8,729	32
90	1,713	86	232	13,550	16,005	12,411	38
91	1,794	94	280	16,840	18,030	13,453	25

*These numbers are in 1,000's.

being requested, a majority of personnel volunteer to resolve emergency situations.

Operating Budget

SDTI's operating budget has some unique characteristics. Consistent with the commitment to control costs, SDTI does not perform all associated operating tasks with in-house personnel. Around 12 percent of the FY 1992 budget represents private- and public-sector contracts for services such as fare inspection, security, office janitorial, light rail vehicle interior cleaning, maintenance of communication equipment, legal and consulting services, and claims administration services. The purpose and philosophy for contracting out certain tasks is to reduce operating and overhead expenses, reduce liabilities, and encourage local business community participation.

Table 1 gives a comparison of the total operating budgets for FY 1982 and FY 1991. In FY 1982 the total operating budget was $3.5 million, which included approximately 45 percent designated for personnel. For FY 1991, about 51 percent of the total $16.84 million operating budget was dedicated to personnel.

A common question is how the relationship between MTDB and SDTI is handled in regards to MTDB services. Included in SDTI's operating budget are all direct costs associated with printing timetables, for example. However, items such as regional public information and fare media are handled by MTDB for bus and trolley services as a regional MTS obligation. Also, all planning and engineering related to LRT projects are an MTDB cost and do not show up in SDTI's budget. Fare inspection (MTDB employees) and any MTDB service related to SDTI operations (certain marketing activities) are billed accordingly, along with an appropriate overhead rate that covers legal services provided to SDTI. The composition of this rate is based upon work completed in 1982 (*32*) and is subject to verification by the annual audits. MTDB's services are provided for SDTI, SDTC, and MTDB contract bus services in a similar manner.

Fare Structure

Initially the South Line began operations charging most patrons a flat fare of $1.00; the fare within Centre City and for senior and disabled patrons was 15 cents. In July 1984 MTS fares were changed to reflect the distance traveled. This zone fare system increased revenues and ridership increased appreciably. The new fares ranged from 50 cents to $1.50. In 1989, upon completion of the East Line, the range was extended to $2.00. A July 1991 fare increase modified the zone system slightly and pushed up the highest fare to $2.25.

Single-trip tickets may be purchased from self-service fare vendomats at each station. Multitrip tickets (2- and 10-ride) and monthly passes, generally offering discounts, may be purchased at outlets throughout the community.

Consistent with the POP fare collection system, patrons must have a valid ticket, transfer, or pass before boarding. Fares are inspected on a random basis, and patrons are required to show proof of fare payment on the request of the code compliance officer. The barrier-free collection system has been successful and is generally liked and respected by patrons.

Ridership and Fare Revenues

With regard to ridership, planning projections for the first year were for approximately 9,500 riders per weekday. At the onset of revenue service, weekday ridership exceeded projections by approximately 2,000 riders per day and was in the range of 11,000 to 12,000. By early 1992 average weekday ridership has stabilized between 48,000 and 53,000 (summer being the peak period of the year). On Saturdays ridership has been between 43,000 to 48,000 and on Sundays, between 35,000 and 40,000. In addition SDTI currently handles approximately 700 wheelchair trips per month. Roughly 60 to 65 percent of SDTI's ridership is on the South Line; but both lines seem to be increasing at generally consistent growth rates. As shown in Table 1, on an annual basis, rides have increased from 3.9 million in FY 1982 to slightly over 18 million in FY 1991—an increase of 4.6 times.

Farebox revenues have tracked well with operating cost increases, rising from $2.7 million in FY 1982 to $13.5 million in FY 1991 (see Table 1). As a result, the farebox recovery rate over the years has remained impressive, ranging from a low of 71 percent in FY 1983, the second year of operation, to a high of 95 percent in FY 1989. Since then the rate has decreased to slightly under 80 percent, reflecting the impact of additional service and some extraordinary cost increases.

Performance Trends

Wahl and Humiston, in a paper in this Record, note that common with an expanding LRT network are ridership and operating cost increases. In general SDTI has managed to have farebox revenues keep pace with operating costs.

Some key performance indicators listed in Table 2 for the 10-year period show the following:

- *Effectiveness*—Operating cost per passenger was about the same in FY 1991 as in FY 1982, 93 and 91 cents, respectively. Given inflation over this 10-year period, the actual cost per passenger in constant dollars has decreased.
- *Efficiency*—Operating cost per train mile has increased 38 percent, from $6.82 to $9.38 in the 10 years.
- *Productivity*—Train hours per full-time equivalent employee have fluctuated over the 10 years; the figure was down 30 percent in FY 1991 from FY 1982. On the other hand average system speed has increased from a low of 16.7 mph (26.7 km/hr) in FY 1983 to 19.2 mph (30.7 km/hr) in FY 1991.
- *Service utilization*—Passengers per train hour have increased about 47 percent (193 in FY 1991 versus 131 in FY 1982), with a general upward trend, whereas the figure for passengers per full-time equivalent employee has tended to hover around the FY 1982 level (63,000 then and 64,000 in FY 1991).
- *Accidents*—After a rough start, seemingly typical of new LRT systems, accidents involving light rail vehicles have not exhibited any significant trend. However, train miles per accident have increased in recent years, with the FY 1991 figure (71,779) being significantly improved over the early years of operation.

SDTI as Part of MTS

A significant aspect of the San Diego trolley operation relates to its function as part of the MTS network of services. If LRT works well, and as the productive foundation of the transit network, then it should make MTS work better and vice versa.

Since its inauguration in 1981, SDTI train miles have increased to represent about 10 percent of total annual MTS service miles (bus miles plus train miles) in FY 1991. To compare this with service delivered, ridership trends are shown in Figure 2. In FY 1991 LRT ridership made up 30 percent of total annual MTS ridership. Even more significantly, SDTI's farebox revenue was 35 percent of the MTS total, as shown in Figure 3. And the SDTI share of MTS operating assistance has been relatively minimal—only 9 percent in FY 1991.

WHAT LIES AHEAD?

The aim of MTDB's short-range transit plan is to lay out a program of improvements to the MTS network to combat the congestion and air quality problems that result from the San Diego region's high growth (*33,34*). Therefore the primary goal emphasizes service and facility improvements that increase ridership by attracting more "choice" riders.

The 10-year history of SDTI has demonstrated that travelers who have a choice of transportation modes can be attracted to mass transit—even in automobile-dependent Southern California. Thus the short-range transit plan focuses on improvements that not only continue development of the LRT network as a foundation of ridership growth, but also target corridors that have high potential demand for high-quality bus service improvements.

TABLE 2 San Diego Trolley Performance Indicators

Fiscal Year	Operating Cost/ Passenger	Operating Cost/ Train-Mile	Train Hours/ F-T Eq. Employee	Train Miles/ Train-Hour	Passengers/ Train-Hour	Passengers/ F-T Eq. Employee*	Train Miles/ Accident*
82	$0.91	$6.82	478	17.5	131	62.7	5.7
83	1.03	8.16	395	16.7	133	52.4	16.8
84	0.91	6.40	437	21.6	152	66.3	19.3
85	0.93	7.16	426	21.3	164	69.9	40.6
86	0.90	7.45	443	20.2	168	74.5	52.6
87	0.92	7.35	477	17.7	142	67.6	52.3
88	0.85	7.52	460	18.2	160	73.7	39.0
89	0.82	8.01	423	18.3	179	75.8	35.7
90	0.85	7.91	372	19.8	185	69.0	45.1
91	0.93	9.38	334	19.2	193	64.4	71.8

*These numbers are in 1,000's.

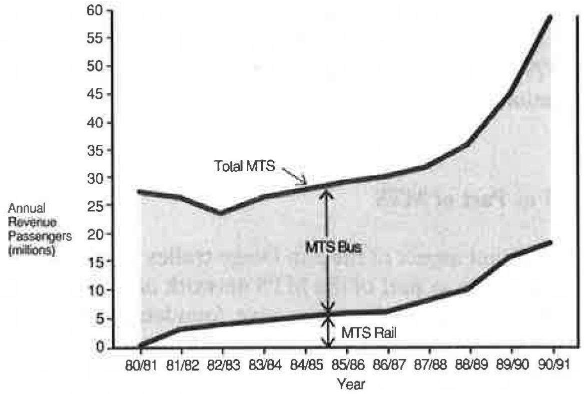

FIGURE 2 MTS ridership.

In July 1992 MTDB opened a short, two-station increment to the north and is into the early stages of construction on two short extensions of the system (see Figure 4). One extension is a continuation of the East Line from El Cajon to the neighboring community of Santee. The other is the second segment of the northerly extension of the LRT system from downtown San Diego to the historic district of San Diego called Old Town. Each of these extensions is approximately 3 mi long; they are scheduled to be in revenue service in 1995.

By the year 2005 MTDB should have three more segments of the San Diego trolley system in operation (see Figure 4). MTDB is in the initial stages of final engineering for a line segment that would extend east from Old Town through Mission Valley, terminating just east of San Diego Jack Murphy Stadium (Mission Valley West Segment). Other segments are also displayed on Figure 4 that reflect projects in various stages of planning that would bring about a post-2005 rail plan for San Diego.

Joint Development Beginnings

To show the way to local developers, MTDB and SDTI provided the first significant display of joint transit-land use development in San Diego by locating their offices above the Imperial and 12th Transfer Station (*35,36*). This project was a joint effort with the county of San Diego and includes ground floor retail uses and an adjacent multilevel parking garage.

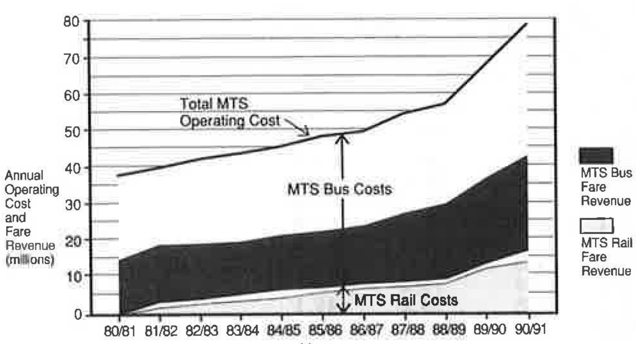

FIGURE 3 MTS operating cost and fare revenue.

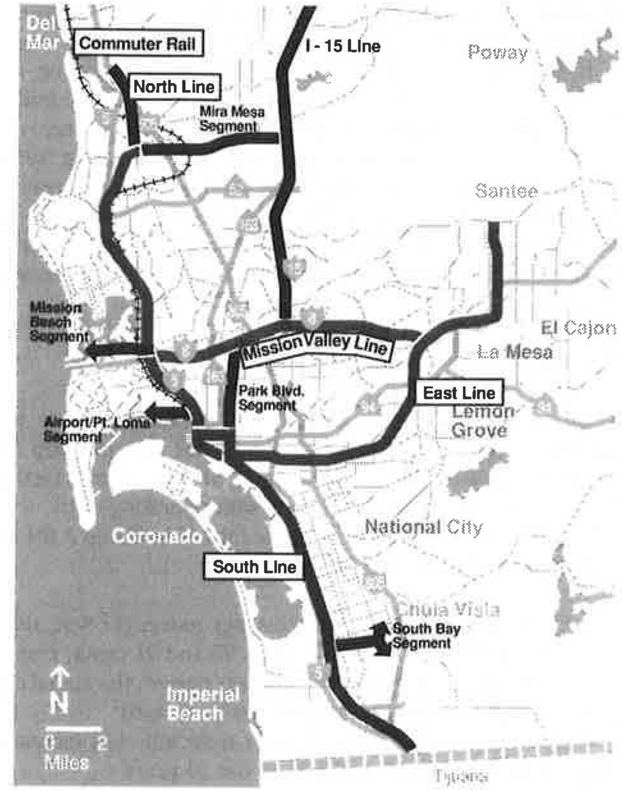

FIGURE 4 San Diego rail plan: service beyond 2005.

Now even larger joint development projects are under way at other stations, including the area's tallest office building. Smaller, yet compatible, joint projects have been implemented and more are being planned, including child care facilities (*37*). One such facility has been in operation for nearly 2 years at the 47th Street Station.

Varied and Creative Financing

Ways of financing transportation projects are changing, and in San Diego the situation is no different. The initial South Line was financed primarily through state gas tax (87 percent) and state sales tax (Transportation Development Act) revenues. No federal monies or local dedicated funds were available. However, since then a wide variety of sources have been tapped:

- Federal discretionary (Section 3) and formula grant (Section 9) monies for the East Line extension and some enhancement projects;
- A local half-cent transportation sales tax (passed in November 1987 by San Diego voters), one-third of which is dedicated for transit purposes;
- City of San Diego hotel room tax revenues for the Bayside extension and other extensions in the city;
- Revenues from sale or lease-back of light rail vehicles (under terms of now-defunct provisions of the 1982 Economic Recovery Act) provided local funds toward matching state

and federal grants for the East Line (*38*); "offshore" sale and lease-back of another group of light rail vehicles is providing funds for enhancement projects;

- State grade separation improvement funds permitted three at-grade crossings to be separated;
- Financial contribution from the Port of San Diego for the Bayside extension and a grade separation project on the Old Town Line; and
- Revenue from California's transportation bonds passed in June 1990.

Another important financing decision by MTDB in 1981, coincident with South Line implementation, was to fund a capital depreciation account (*39*). This account has already proven useful for annual SDTI capital replacement needs and will become increasingly valuable as the system and its equipment age.

CONCLUSIONS

In looking back at the San Diego program, certainly the benefits of using light rail technology in a large, metropolitan, medium-density area are evident. However, another clear realization is that the incremental approach to system development further produces tangible benefits:

- It forces management (development and operations) to keep up with the state of the art, establishing a local "think tank" atmosphere.
- It produces enthusiasm among the operating personnel by giving them new challenges to look forward to and in-house promotional opportunities.
- It provides ongoing "free" publicity to the transit system through routine news coverage and, in so doing, stimulates the public's enthusiasm, too.
- It allows for the system to grow intelligently with personnel and other operating budget needs justified by intimate knowledge and requirements of the existing operation and the capabilities of the existing labor force.
- It provides a learning atmosphere in which mistakes and failures are relatively small as a result of the system being rather short and services simple, and so corrective actions can be taken based on the lessons learned in actual operating experience.

On the other hand, incremental development has drawbacks:

- A 1979 design "mind set" had to be converted to 1992 standards and requirements that go beyond minimal designs and related longer-term capacity and system requirements.
- An initial low-cost project is difficult (if not impossible) to duplicate as the system expands—the system becomes necessarily a more complex operation. (The low-cost beginning led to a continued expectation that future extensions could be developed for under $10 million a mile, for example—clearly no longer possible in San Diego.)
- Higher levels of service drive requirements for more grade separations, larger stations, pocket tracks, and more complex systems.
- At times, relatively new projects or enhancements must be torn up and replaced, creating public perceptions of waste. In such instances, however, the early improvements were useful on an interim basis.

All in all, San Diego residents can look forward to a greatly improved public transit network with LRT at its foundation. The tradition founded in the mid-1970s—that of a no-frills, functional approach to public transit—has worked well in San Diego and will continue to be the cornerstone of future LRT extensions. However, now that the San Diego LRT is a "mature" rail system, the standards for incremental LRT development are necessarily being upgraded. Yet, there is the need—if not a local political mandate—to keep the farebox recovery rate at its historical high level, an indication that the past can be nothing more than the foundation for the future.

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LRT Lessons That Can Be Learned from Edmonton and Calgary

J. J. Bakker

Although Edmonton established the first light rail transit (LRT) system on the North American continent, it did not sustain momentum. Edmonton learned from cities such as Cleveland, Frankfurt am Main, and Philadelphia. In turn Calgary learned from Edmonton. Now, 14 years since the first line in Edmonton opened, it is useful to sum up the lessons. First, continue at a steady rate of development so that there is continuity in the planning and design experience. This also allows local contractors to develop expertise. Second, keep the stations simple. With a proof-of-payment fare system, stations can be simple. Avoid changes in levels for passengers, and make the stations user friendly. Third, surface lines should be introduced early. Once tunneling has started, a constituency develops that wants to build a metro system rather than the light construction really needed. Fourth, ridership should be developed by first introducing express buses, which can later be transformed into feeder bus lines to the LRT. The transfer to a higher-class mode of transportation is not a deterrent to patronage. Catering to the car with plenty of parking near the outlying stations will also help in reducing peak hour traffic congestion. In an economic downturn LRT appears to hold its passengers better than a bus system. Fifth, land development around LRT stations is not a given. It requires sound planning policies. A strong central business district and a commitment to keeping it strong will help the viability of LRT. Both Calgary and Edmonton have placed major sports facilities near their LRT lines, which helps attract off-peak passengers and reduce the parking requirements near these venues.

Edmonton and Calgary have been rival cities since the start the century. This rivalry has manifested itself in the light rail transit (LRT) developments in both cities. It is worthwhile to compare what happened in both cities and also to see whether lessons can be learned from the experience of them both. Are there better ways to achieve good LRT results? In fact, could or should LRT lines have been planned or developed differently?

EDMONTON'S LRT IN RETROSPECT

Edmonton started some rail transit planning in 1961, but real planning came about from 1973 to 1974. In 1962–1963 a study was made by Bechtel (*1*) of the feasibility of a rail rapid transit system. A downtown tunnel under 102nd Avenue was suggested with three branches at each end. All junctions were grade separated in true Bay Area Rapid Transit (BART) style. The report was received as information.

In 1968 a balanced transportation plan (*2*) was proposed that had three railway branches, one to the northeast, one to the southwest via the University of Alberta, and one to the northwest. The downtown distribution was in the form of a loop with one-way operation, in tunnel under Jasper Avenue with a single track and above ground along the Canadian National (CN) right-of-way. In the early 1970s it was finally realized that Edmonton could not afford to build freeways towards the central business district (CBD). The planning evolved from heavy rail to light rail and, some would say, back again.

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Influence of Other Cities

Edmonton's rail transit planning was influenced by several other cities, most notably Cleveland, Frankfurt am Main, and Philadelphia.

Cleveland

A visit by the author and planners of Edmonton Transit to Cleveland in the 1960s showed that a rail transit system could be developed along a rail right-of-way and that it should serve the CBD directly and not at the perimeter.

In Edmonton the use of the northeast and northwest CN rail rights-of-way was considered as well as the use of the High Level bridge to the south along the Canadian Pacific (CP) railroad without taking the line through the CBD. The conclusion after the visit to Cleveland was that rail rights-of-way could be used but serving Edmonton's CBD from those rights-of-way was eliminated from consideration.

Frankfurt am Main

A visit to Frankfurt am Main in 1969 showed that great improvements can be made to a streetcar system if, in the CBD, the tracks are taken underground and, in the outskirts, are longitudinally separated from other traffic. Although Frankfurt was upgrading streetcar lines, the task in Edmonton was to downgrade a full rail rapid system to something similar to what was being built in Frankfurt am Main. In fact, both Frankfurt and Edmonton were converging toward the new concept of an LRT system.

Philadelphia

In the Philadelphia area, the Port Authority Transit Corporation (PATCO) system demonstrated several ways in which a new rail system should be operated. First, stations should be monitored with closed circuit television for security; second, when the system is opened passengers should be actively assisted through the new system; and third, the system operator should assist in developing a good rule book and later provide training for supervisors and trainers of drivers.

First Line to the Northeast

Edmonton's first line to the northeast (*3*) was mainly a 3.5-mi (5.6-km) surface line within a rail right-of-way with a 1-mi (1.6-km) downtown tunnel. The original Bechtel report suggested 102nd Avenue would be a good location. Later the alignment was shifted one block south to Jasper Avenue (see Figure 1) because this location made the design of curves easier. Tunneling was chosen because Edmonton had good tunneling experience with its trunk sewer system, ideal soil conditions, and relatively low tunneling costs. The examples of Frankfurt am Main, Cologne, and other German cities also were influential. The alternative of taking a surface line though the CBD was never really considered. It was believed that the traffic capacity, which was already limited to four roads in the east-west direction, should not be reduced. This concept was developed in the late 1960s and early 1970s when Edmonton experienced economic boom conditions.

Stations in Edmonton range from elaborate to simple. The underground stations in downtown Edmonton have a mezzanine level. With a proof-of-payment fare system such a separate floor is no longer really necessary. The first two surface stations, Stadium and Coliseum, have grade-separated pedestrian entrances, with pedestrians walking under the track. The next two stations are simpler. Belvedere passengers cross the track at grade, and at Clareview passengers walk from the end of platform to either bus or car park. The busiest stations are Belvedere (15 percent of total boardings), Clareview (16 percent) and Central (18 percent) (see Figure 2). Clearly a simple layout is not an obstacle to handling high volumes of passengers.

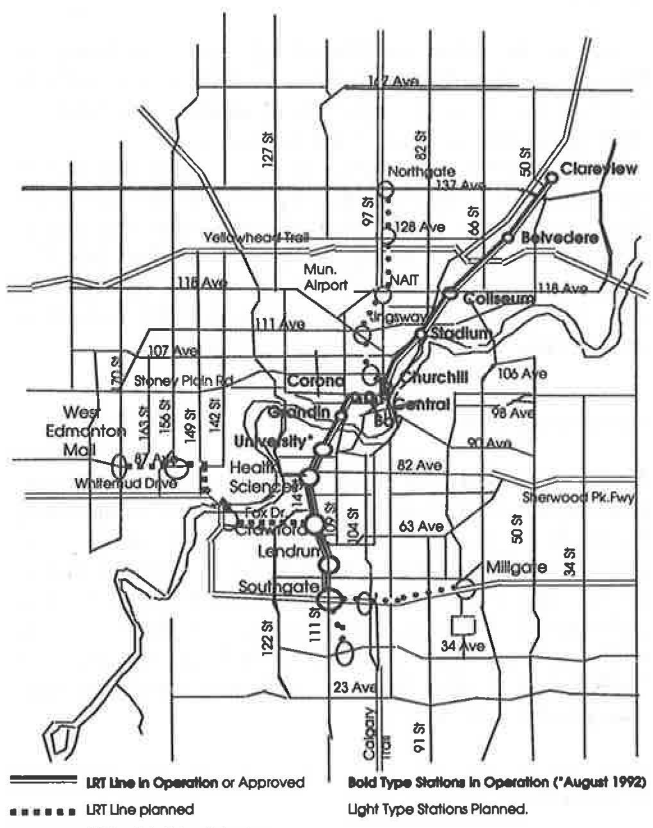
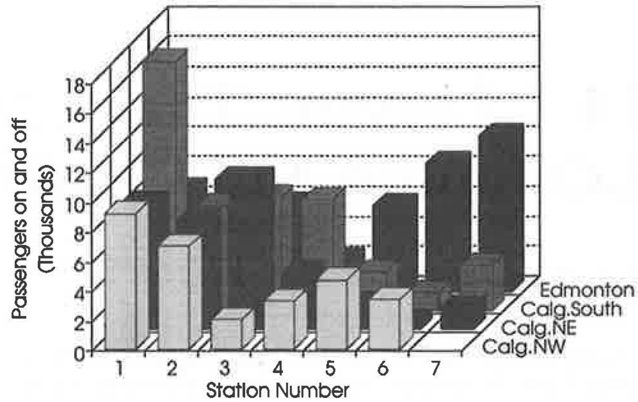


FIGURE 1 Edmonton L.R.T. Line.



Station #	1	2	3	4	5	6	7
Edmonton	Clareview	Belvedere	Coliseum	Stadium	Churchill	Central	West of Central
Calgary							
South	Anderson	Southland	Heritage	Chinook	39th Ave	Erlton	Stampede
Northeast	Whitehorn	Rundle	Marlbor.	Franklin	Barlow	Zoo	Bridgel
Northwest		Brentwood	University	Banff Tr	Lion Pk	SAIT	Sunnyside

FIGURE 2 Edmonton and Calgary station use.

The first portion of the line was built within budget and opened ahead of schedule. It was considered a success and stimulated many other cities of medium size to consider LRT as an alternative transportation option.

Lessons from the Period After Stage 1

Edmonton lost its momentum in LRT construction almost before the opening of the northeast line in April 1978. The small project team dispersed. The project manager went to Portland, Oregon, where his expertise was used and where LRT momentum continued. Meanwhile in Edmonton changes in management and planners resulted in a series of delays. Extensions were built underground downtown (to Corona by 1983 and to Grandin Station by 1989) and a surface extension was built northeast to Clareview (1980). Before taking LRT construction south, Edmonton built a major maintenance facility and bought additional cars to fill the facility even though the actual extension to the south was delayed.

The South LRT

Controversy developed over where to locate the south LRT line (*4*). LRT in Edmonton remained underground and tended to be too much like a heavy rail system. To speed up service implementation, it was proposed that the line from Grandin Station to the new LRT bridge and from the bridge to the university be single-tracked. These proposed cost savings were never implemented. The LRT bridge, with a pedestrian bridge underneath it, is a very attractive-looking structure.

The University Station is 75 ft (23 m) below the surface, one of the deepest excavated stations. Normally it would be expected that such a deep station would be mined using the sequential excavation method (SEM) with sloping access from the surface. But local experience has been to use cover-and-cut with tangent piles. Three other factors played a role in the choice of excavation method: politics, the Kings Cross Underground Station fire in London, and the 1985 Alberta building code. Because of the slowdown in the economy it was politically desirable to have more but smaller contracts. SEM would have required one contractor. After the Kings Cross fire, the 1985 Alberta building code was applied to the University Station, particularly in regard to the stair width needed in case of fire. The station was designed for an occupancy of 1,000. This translates into a required exit width of 16.6 units based on 60 persons per exit width of 1 ft 7 in. (550 mm).

After the cover-and-cut-type of construction was chosen, tangent piles were driven, forming a wall around the station. This box was then covered with precast-prestressed concrete highway bridge beams, giving a clear span of 60 ft (18.2 m). The first concourse level is 13 ft (4 m) down. From there escalators carry passengers to another intermediate level 21 ft (6.5 m) below the concourse. Passengers then have to walk to a second set of escalators to get to the platform level another 18 ft (5.5 m) down. The layout of the staggered escalators is like that in a department store. An elevator and two sets of emergency stairs provide alternatives to the escalators. No allowance was made for the emergency exit of people through the rail tunnels.

Although the author is not aware of any other station with so much opportunity to exit in case of emergency, the layout of the escalators is such that it raises the suspicion that the designers hated passengers and wanted to make it as difficult to enter and leave the station as possible. Yet the University Station is likely to be the busiest station in the system.

During construction of the station, the bus terminal on 89th Avenue was temporarily moved about four blocks to southwest of 87th Avenue and 114th Street. The university administration then proposed that the bus station remain there. Such a move would have made transfers from bus to LRT even more difficult. Faculty, staff, and students blocked this proposal, which seemed to show a certain lack of concern by the university administration for transportation to and from their institution.

Neighborhoods south of the university want to keep the LRT underground. The city insists that the system be above ground because of costs. In fact the financing is not available to continue construction of an underground metro system. From the University Station the plan was to go south and up at a 4.5 percent grade with an intermediate underground station at the University Hospital. Then the line was to go under University Avenue and surface on 114th Street. This plan is now under review. The provincial government has cut funding to the cities by 40 percent, and any further extensions of LRT are in doubt unless other sources of funds are found or the provincial government changes. Along 114th Street, the proposal is to locate LRT on the west side with an at-grade crossing at 72nd Avenue.

Edmonton is now trying to reorient to a true LRT system with the extensions from the University to Southgate and West Edmonton. The reorientation is one that is needed politically, in planning, in management, and in operations.

Financing, Costs, and Ridership

The overall financing philosophy of the city of Edmonton has limited the pace of the extensions. Edmonton wants to maximize the use of provincial contributions and minimize its municipal debt. One result was hardly any parking lots were provided along the northeast line. Another result was when the LRT extension south was delayed; a major maintenance facility was built and filled instead. The fleet of Edmonton's light rail vehicles (LRVs) is now 37, although only 21 are needed before service is extended to the university.

The provincial funding for Edmonton and Calgary initially was a capital grant of $7.5 million (Canadian) per year for 6 years. The grant was to be spent on transit, although money could have been placed in a bank to accumulate interest. Interest earnings also were to be spent on transit. The province exercised no planning or design control. Financial accountability was at the end of the year.

Later the capital grant formula was changed to 75 percent/ 25 percent split between the province and the city with an annual limit. Provincial project approval was also required. Edmonton spent $350.5 million for 12.7 km of LRT line (see Table 1). The provincial government paid $274.9 million or 78 percent. The cost per kilometer was $27.6 million.

Edmonton has discovered that underground stations are not necessarily cheap to maintain. The downtown underground stations all used the same construction with tangent piles on the side, covered with precast concrete beams, which in turn were covered with a membrane, insulation, and a concrete roadway cover. In March 1992 it became clear that this construction causes excessive leaking during and after rainstorms. Making the roofs of four stations waterproof with proper drainage will cost an additional $12 million over the next few years.

Ridership in Edmonton is shown in Figure 3. Ridership was affected by the recession of 1982. Edmonton developed its ridership prior to LRT with express buses running near future LRT stations were to be. These routes then were converted to feeder bus routes to the operational LRT. The transfer to a higher quality transit mode proved not to be a deterrent to ridership. LRT in Edmonton is primarily bus fed. Table 2 shows the number of buses feeding LRT. The LRT northeast line resulted in a faster trip to the CBD even though Edmonton Transit kept its operating speed fairly low (initially 60 km/hr maximum, now 72 km/hr, although the equipment is designed for 80 km/hr).

Land Development

Rail transit is often considered a tool for promoting land development. In Edmonton the results have been disappoint-

TABLE 1 Cost Comparison: Edmonton and Calgary

Line Segment	Length (km)	Construction Period	Cost[a] ($ Millions) Total	Provincial	Comments
Edmonton					
Central-Belvedere	7.2	1974–1978	65	45	Incl. 14 LRVs
Belvedere-Clareview	2.2	1978–1980	9	6.8	Incl. 3 LRVs
Central-Corona	0.9	1981–1983	96	82.0	Incl. 20 LRVs
Storage and Maintenance		1981–1983	30	27.9	
Corona-Grandin	0.8	1987–1989	61	45.8	Single track
Grandin-University	1.6	1989–1992	89.5[b]	67.4[b]	Incl. second track
Total	12.7		350.5	274.9	78 percent provincial
Calgary					
South LRT					
Mall & South Line	12.5	1977–1981	174.4	61.9	Incl. 27 LRVs
Track rehabilitation		1985–[c]	5.3	3.9	
Southland Crossover		1985–1988	0.8	0.6	
South LRT ext. study		1982–1984	0.9	0.9	
Southeast ext. study		1985–1986	0.1	0.07	
Northeast LRT	10.0	1982–1985	157.7	72.7	
Northwest LRT to University	5.6	1985–1987	101.1	76.1	
Northwest LRT University Brentwood	0.7	1988–1990	29.2	24.0	
56 LRVs		1984–1985	64.1	61.5	
LRV maint. & rebuilt		1986–[c]	3.3	2.5	
Total	28.8		536.9	304	57 percent provincial

[a]Average cost per km is Edmonton, $27.6 million; Calgary, $18.6 million.
[b]Budget.
[c]Ongoing.

ing. At Clareview the station is surrounded by pasture land because the New Town development did not occur, primarily because of a surplus of retail space in Edmonton as a result of the construction of West Edmonton Mall and the 1982 recession. Clareview Station has, however, excellent park-and-ride facilities.

At Belvedere, land southeast of the station that was owned by the city, which decided to locate an equipment maintenance facility for the engineering department on this site. Because the soil conditions were poor, a park-and-ride lot would have been a better and more economic alternative.

Near the Coliseum and Stadium stations some possibilities for redevelopment still exist, but nothing major has occurred. However, the Coliseum, the Northlands Exhibition Grounds, and the Commonwealth Stadium attract off-peak passengers to the LRT.

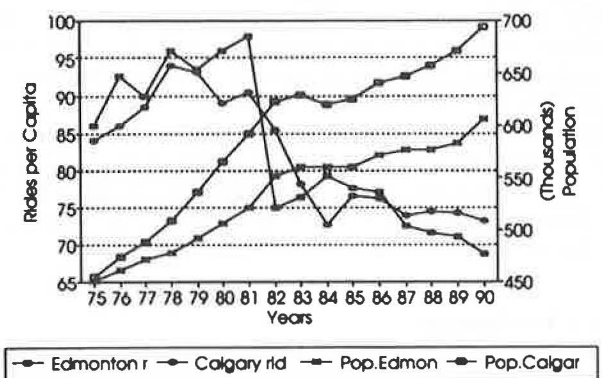


FIGURE 3 Comparison of rides per capita and population in Edmonton and Calgary.

In the CBD many redevelopments have taken place. At first sight, a map showing developments since the decision was made to proceed with LRT looks impressive. Yet very few of these developments are directly because of LRT. One major redevelopment that was because of LRT was Canada Place, an office complex for federal government offices just east of Churchill Station. In the CBD an extensive pedway system has evolved linking such major developments as the Convention Centre, Canada Place, and the Citadel Theater with Churchill Station. Edmonton Centre was also connected with a pedway to Churchill Station in 1991. Unfortunately the signing in these interconnecting pedways is almost nonexistent.

The Central and Bay stations are connected to adjacent developments. The Grandin Station is connected via tunnels to the Legislature Building and other provincial government buildings. The walks, however, are long.

The University Station is connected to the university by an overhead pedestrian system at the east end of the station. At the west end the station initially will not interconnect with the university buildings. However, the design allows for future connections.

In general it can be said that Edmonton should have had stronger policies promoting development next to the LRT stations. In several cases proposals were so poorly dealt with at the bureaucratic level that nothing happened.

Future Extensions in Edmonton

Edmonton has committed itself to an LRT extension from the university as far as Southgate. The holdup is funding and a difference of philosophy between the provincial govern-

TABLE 2 Bus-LRT Connections

Edmonton			Calgary		
	Buses/Hour			Buses/Hour	
Station	Midday	Peak	Station	Midday	Peak
			South		
Clareview	12	44	Anderson	25.5	45
Belvedere	18	46	Southland	13.22	26
Coliseum	24	50	Heritage	19.5	43
Stadium	10	20	Chinook	13.1	29
University	35	74	39 Avenue	1.5	3.9
Total Edmonton			Erlton	2	2
Before University opening	64	160	Total	74.8	148.9
After University opening	99	234	Northeast		
			Whitehorn	14.6	35.5
			Rundle	8	18
			Marlborough	17.3	32.6
			Franklin	2.4	4
			Barlow	5.9	14
			Zoo	0	0
			Bridgeland	0	0
			Total	45.8	100.1
			Northwest		
			Brentwood	31	57
			University	0	
			Banff Trail	0	0
			Lions Park	19.5	25.5
			SAIT/Jubilee	0	0
			Sunnyside	3	3
			Total	53.5	85.5

NOTES: Edmonton uses clock-headways on all routes, giving integer numbers in buses per hour.
Calgary uses nonclock-headways on some bus routes, giving non-integer numbers in buses per hour.
Both Edmonton and Calgary use an LRT headway of 10 min midday and 5 min in the peak hour.
SOURCES: Edmonton Transit and Calgary Transit maps

ment, which wants to see road construction, and the city, which wants to extend the LRT. An extension to Southgate would save 18 buses per hour north of Crawford Station and a further 36 buses per hour north of Southgate Station. The extension to Southgate would be built in two stages. The staging would limit the size of contracts and the rate of funding.

Stage 1 would extend LRT service from the university to the Crawford Centre (113th Street and about 68th Avenue), a distance of about 2.3 km. Two intermediate stations would be built at the University Hospital and at 76th Avenue and 114th Street. No additional LRVs would be required. Stage 2 would extend LRT service from Crawford Centre to Southgate, a distance of about 2 km, with probably one intermediate station at Lendrum (111th Street and 57th Avenue).

Edmonton is also doing preliminary planning on an extension to West Edmonton Mall. From Southgate LRT would go further south to Kaskitayo, intercepting 22 buses per hour, or east to Millgate Transit Centre, where it would intercept 40 buses per hour in the peak period, or both. To the north a line is being considered from Churchill Station via NAIT to Northgate. These extensions are not being planned in detail.

CALGARY'S LRT IN RETROSPECT

Calgary followed the lead of Edmonton, then deviated briefly, and finally improved on Edmonton's LRT. Calgary also started with a grade-separated rapid rail transit proposal (*5*). The 1966 proposal recommended a south and north line converging on a CBD distributor and splitting again in northwest and southwest lines. In addition, a northeast-CBD-west express bus system was proposed. The plan was viewed as something to consider in the future.

A "balanced transportation concept" for Calgary was proposed in 1973 that called for the planning of a rapid transit system to commence. Although no particular system was recommended, the concept implied that the system should be computer operated and respond to travel demand. The concept had similarities to a Denver proposal. The idea of an on-demand computer-controlled system was dropped because technology was not that advanced yet. In the meantime, Calgary implemented an expanded express bus system supplemented with some dial-a-ride services in addition to the regular bus system.

In 1977 Calgary chose an LRT alternative (3 years after Edmonton) rather than an exclusive busway system for South Calgary (*6*). The reasons given were that LRT is reliable, uses a proven technology, has a high level of service, has low labor use, has a low environmental impact, and would be effective in guiding land use. It was also stated that LRT would improve the mobility of the handicapped and the elderly; however, when constructed the south line was not made accessible. Notwithstanding the reasons given, the real reason LRT was chosen was that Edmonton had started building an LRT and Calgary could not stay behind its rival city to the north. In addition the capital grants from the province as formulated for Edmonton were also available to Calgary. Because Calgary was not ready for LRT when this provincial financing program began, the city invested first in a new bus storage and maintenance facility (along 32rd Avenue N.E.).

However, once Calgary began its LRT program, it learned from the experiences of Edmonton. Calgary was also helped by nature in that its soil conditions do not permit easy tunneling. Hence, Calgary stayed above ground, wherever possible, particularly downtown.

Stage 1 to the South

Calgary started its LRT program by building a maintenance facility (near Anderson Station) and buying LRVs.

Like Edmonton, Calgary built its first line along a rail right-of-way. With the exception of one station, the south line has costly, elaborate stations that are awkward for passengers. The line is located in a tunnel under a cemetery mainly because the transportation department wanted to widen McLeod Trail (which cuts through the cemetery) at the same time (see Figure 4). Calgary also used concrete ties that give better gauge control and track stability. There were, however, some cracking problems with the grouting pads used with track on concrete base. Also, because of a design error, a bridge toppled. Fortunately all parties were insured with the same insurance company so litigation was avoided. In operations Calgary's LRT has from the beginning operated at a higher speed than Edmonton's, saving passengers significant travel time. One of the distinct features of the Calgary south line, completed in 1981, is the extensive availability of parking lots.

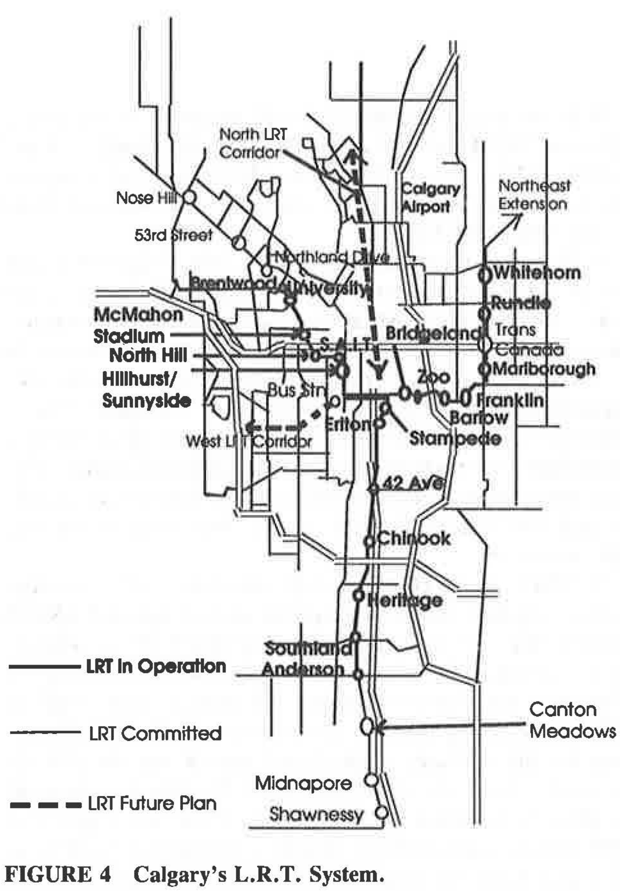


FIGURE 4 Calgary's L.R.T. System.

Downtown Transit Mall

Although Calgary has more east-west avenues, each avenue is narrower than Edmonton's four east-west routes. Calgary could therefore dedicate one avenue as a surface transit mall. Both elevated and subway alternatives were also examined. The at-grade route along Seventh Avenue was finally chosen because of its low cost, minimum disruption during construction, and low impact on pedestrians. The possibility of later constructing a subway under Eighth Avenue remains an option.

The transit mall was completed in 1981. The only problem seems to be the high-level platforms do not have enough capacity in the peak hours. Otherwise the system has been working satisfactorily.

Stage 2 Became Stage 3

Calgary wanted to extend the LRT to the northwest, an extension made more important by the winter Olympics that were awarded to Calgary in 1981 for 1988. Some of the communities adjacent to the city's center objected, however, so Calgary continued construction first to the northeast instead.

Northeast Line

The northeast line is a real LRT line, except for its stations. Along 36th Street N.E. residential development is east of the road and commercial/wholesale development is on the west. Some valuable location lessons could be learned from the northeast line regarding median versus side location; station complexity versus simplicity, and land use and LRT. The LRT line was placed in the median although an eastside location could have kept the station access at grade and would have greatly simplified the design. Stations have to be reached by overhead walkways, which present an obstacle to passengers.

Northwest Line

What is noticeable about the northwest line is the sensitivity in construction, the efforts at landscaping and the simplification in stations. The neighborhoods adjacent to Calgary's downtown did not like the Ninth Street N.W. route proposed for the LRT line. Either 10th Street N.W. or 14th Street N.W. was considered to be less intrusive. Although the city insisted on the Ninth Street N.W. location, more landscaping was used to minimize the intrusion. As in Edmonton, the university was not a willing transit partner. The line is at the perimeter, which is good for further extensions, but not for university patronage. But at least the university is being served—5 years ahead of Edmonton's.

Financing, Costs, and Ridership

Calgary was prepared to go into debt to speed up and continue LRT construction. The city spent $536.9 million for 28.8 km of LRT line, of which the provincial government paid $303.97 million or 57 percent. The cost per kilometer in Calgary was $18.6 million.

LRT was completed to the northwest in time for the Winter Olympics. Calgary has a far more extensive and true LRT system than Edmonton, and this shows in the ridership figures—Calgary's ridership is more than four times that of Edmonton's (see Figure 3). Like Edmonton, Calgary developed its initial ridership by operating express buses from future LRT station locations and converting these lines to feeder routes (see Table 2). Calgary does not always use clock-headways, which is not a problem when connecting to a frequent LRT service, but it does not allow for good bus-to-bus connections. Clock-headways are also easier to remember, particularly if the service is infrequent.

Land Development

The city of Calgary has had stronger land use policies than Edmonton. Calgary did not permit a development like West Edmonton Mall and was able to strengthen its CBD. Calgary also developed a "15+" pedestrian concept that provides a grade-separated pedestrian level connecting various buildings at a height of 15 ft (4.6 m).

Like Edmonton, Calgary has not attracted much development near its outlying LRT stations. One reason could be that the land close to the stations is occupied by park-and-ride lots.

Future Extensions in Calgary

Calgary has plans for several extensions.

Two extensions are proposed for the northwest line:

- Brentwood (31st Street N.W.) to Dalhousie (53rd Street N.W.)—This extension would be 1.9 mi (3.0 km) long and would require seven LRVs.
- Dalhousie to Nose Hill Drive (85th Street N.W.)—This extension would be 2.5 mi (4.0 km) long and would also require seven LRVs. Major park-and-ride facilities are planned.

Two extensions are also proposed for the south line:

- Anderson to Midnapore Station (146th Avenue S.)—This extension would be 2.2 mi (3.6 km) long with one intermediate station at Canyon Meadows. Again seven additional LRVs would be required as well as an extension to the LRV storage facilities.
- From Midnapore the options are to go southwest and southeast—These extensions are in a preliminary stage only.

The proposed northeast extension would leave 36th Street N.E. and go more directly through the residential area. There is no proposal to link this line to the Calgary airport (about 4.5 km or 3 mi).

The proposed west extension may only go as far as the bus station, which is just west of the CBD.

RIDERSHIP IN EDMONTON AND CALGARY

The populations of Edmonton and Calgary are, roughly speaking, the same size. Edmonton's city population is slightly less, but its metropolitan population is greater because the metro area includes the populations of the two independent municipalities of St. Albert and Sherwood Park. Revenue passengers are also similar in volume. In rides per capita, that is revenue passengers per capita in 1 year, Calgary's figure is slightly less than Edmonton's. Both cities suffered from the 1982 economic recession. The change from almost full employment to 15 percent unemployment meant also about a 15 percent reduction in transit use. In addition, Edmonton had a transit strike for 6 weeks, which further prompted passengers to find alternative transportation. Both systems added to the reduction in passengers by drastically reducing bus services and increasing fares.

The most noticeable aspect of transit use is that LRT patronage either remained stable or continued to increase, whereas bus patronage continued to decline. Because Calgary has more LRT lines it also has more revenue passengers. In both systems LRT relies on feeder buses, and so the number of boardings (and transfers) has also increased. In Edmonton the feeder buses have kept their riders, although the rest of the system suffered a greater decline. Calgary, however, has more park-and-ride facilities, which reduces the need for more feeder services.

It should also be noted that all lines in Edmonton and Calgary attract most passengers at the outlying stations (see Figure 2). The inner stations attract fewer passengers, which may be because of the flat fare system as well as a resistance to transferring from bus to LRT close to the destination. Also note that the free fare zone in downtown Calgary attracts 20,000 passengers per day. Edmonton allows free travel downtown midday between 9 a.m. and 3 p.m.

THE LESSONS

What are the real lessons to be learned from the Edmonton and Calgary LRT experiences?

Continue momentum even if it means going into debt. It is very hard to start up again after a time lapse.

Continuity means that the project team and the local contractors keep developing their expertise.

Keep stations simple and user friendly. Both Edmonton and Calgary have user-unfriendly stations that could have been designed to be less elaborate at lower cost, and without up or down stairs.

Introduce surface lines early. Once tunneling begins a constituency of politicians (prestige), consultants, and contractors develops that will push for a real metro system. A surface LRT, however, has better two-way visibility between potential customers and businesses. The average cost per kilometer in Calgary is two-thirds that of Edmonton (see Table 1) because Edmonton chose to tunnel.

Calgary is therefore a good example of LRT. Once Edmonton has developed its surface lines to Southgate and West Edmonton Mall, it also will have a real LRT system.

Land development is not automatic when rail transit is introduced. Land development or redevelopment will only occur if strong planning policies are in place and if these policies are adhered to. Both Edmonton and Calgary have located major sports facilities close to their LRT lines, fueling off-peak ridership and reducing parking requirements near the sporting facilities. However, a strong CBD will make an LRT line more successful. A mega-mall detracts from a CBD.

Ridership should first be developed by introducing express buses, which can later be transformed into feeder bus lines to the LRT. The transfer to a higher class mode is not a deterrent. Catering to the car with plenty of parking near the outlying stations will also help reduce peak hour traffic congestion.

In an economic downturn LRT appears to hold its passengers better than a bus system.

ACKNOWLEDGMENTS

The author acknowledges the excellent assistance provided by both the Edmonton and Calgary transportation departments. Officials provided data generously and made useful comments. The views expressed in this paper are, however, those of the author.

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Rail Transit Performance

TOM PARKINSON

Rail transit can deliver higher performance, offer lower operating costs, and have less environmental impact than other transport modes. Comparing heavy rail, light rail, and an automated, driverless rail system demonstrates how well new rail systems meet these goals.

Rail transit has been advocated as a cost-effective solution to urban mobility problems. It can deliver high performance combined with low operating costs and low environmental impact. Rail transit has a proven record of attracting both greater ridership and focusing development around stations. This focused development is the goal of land use planners in many cities and in turn encourages transit use, increasing ridership and reducing the use of and dependence on the automobile.

These benefits come at considerable capital cost. Conventional rail transit—subway or heavy rail—is fully grade separated and has become too expensive for many of the lower density urban corridors in North America. Filling the breech are two intermediate capacity rail transit modes, light rail and automated guideway transit.

Light rail is a particularly flexible mode that, at one extreme, can be built inexpensively on-street or, at the other extreme, can be fully grade separated—approaching the performance and capacity of heavy rail. The meld of these extremes produces a wide range of systems. Since the early pioneering days of TRB's Light Rail Committee in 1973, light rail has become the dominant rail transit mode in North America. In the last decade three-quarters of all new rail transit systems have been of the light genre.

Automated guideway transit may be considered as an alternate to rail transit, but it has been noted more for its promotion than its performance. Other than airport, institutional, or amusement park applications, six urban systems have been built: Morgantown's primarily institutional line, the downtown people movers in Miami and Detroit, a small operation in Jacksonville, the Toronto Transit Commission's Scarborough subway feeder line, and BC Transit's SkyTrain system in Vancouver, British Columbia. Only the latter is a full-fledged, rail-based, urban transit system that merits inclusion in this report. Although the Vancouver system is classified by the American Public Transit Association (APTA) as automated guideway it is more often considered as a rapid transit system sharing heavy rail's fully grade-separated characteristic with the geometric flexibility of light rail and with the unique attribute of unmanned operation.

The benefits and efficiencies of rail transit are not without their doubters. Although undeniably some rail transit planning has overestimated ridership and economic benefits while underestimating costs, such biases or errors pale in comparison with several one-sided attacks against rail transit—usually in favor of bus operation.

The proof of the pudding is in the eating. Enough new rail transit systems are in operation for their actual results, costs, and efficiencies to be examined to determine how well the best designed and operated rail transit systems meet the goals of high-quality, cost-effective service.

THE DATA

Most information in this paper is abstracted from the APTA's *1991 Transit Operating and Financial Statistics*. This data summary includes the results of fiscal years ending in calendar 1990, collected in accordance with the Section 15 rules of the Federal Transit Administration (formerly UMTA). Canadian properties included in the APTA summary do not report according to Section 15 rules. Only Calgary Transit and BC Transit sufficiently disaggregate their data to allow rail transit to be broken out, the important index of passenger miles to be estimated with information from the properties concerned, and overhead assigned as closely as possible to FTA Section 15 rules. Other data sources or adjustments are specifically noted.

The data tabulation was carried out for all rail transit systems built or substantially modernized in the last 20 years. Light rail systems with large streetcar components are not typical of modern operation and San Francisco's Muni, Boston's MBTA, and Philadelphia's SEPTA have been excluded. The older heavy rail systems are not included—their infrastructure and labor practices preclude a fair comparison.

Also omitted are the Santa Clara and Los Angeles light rail systems. Neither was in full operation for the whole of 1990. It is intended that this statistical analysis will be repeated annually and that these systems will be included next year followed by the St. Louis and Baltimore light rail systems—both of which have the potential to be among the more efficient operations.

FTA Section 15 reporting has become more consistent over the past decade. Nevertheless discrepancies remain and adjustments have had to be made where there is confusion over car versus multiple-unit train miles or hours. In many systems services that are contracted out are inadequately reported. These services are usually so small a proportion of overall costs that the results are not skewed.

The principal rail transit product used in this paper is the passenger mile, as reported in the modal service data section of APTA's statistics. On systems with automatic barrier fare collection and variable fares this data can be determined with

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reasonable accuracy. On the majority of systems an open fare system requires passenger miles to be determined by sampling. Checkers ride cars and count passengers getting on and off at each station. Fare profiles are similarly sampled. These samples are then correlated with load counts and revenue collected to estimate total annual passengers and passenger miles. The results can be accurate to plus or minus 10 percent but may be less reliable.

Although it is not the intent of this survey to compare one rail transit system specifically with another, the results inevitably show a pecking order. Rail transit systems are not necessarily built to be the most efficient or cost-effective. They may be built to reinforce beneficial land uses, to substitute for alternate transport projects that could have both higher costs and greater environmental impact. For example, a 30-ft-wide light rail line can provide the capacity of a 200-ft-wide, 12-lane freeway—and does not need the interchanges and will not generate the pollution, the noise, or the blight. Rail transit construction can reduce or defer highway infrastructure costs and offer other tangible and intangible benefits to a community. These benefits include reduced highway deaths, reduced noise and pollution, focused development, high-quality handicapped accessibility, and lower bus costs.

Each city, each system, and each rail corridor is a unique entity. Population density, transit riding habits, highway networks, ease of pedestrian access, bus feeder routes, fare and schedule integration, park-and-ride facilities, transit labor practices, funding limitations, and data collection accuracy can influence the ridership on which these comparisons are primarily based. Consequently it is inappropriate to compare two systems directly.

Despite these caveats this comparison does show those systems with outstanding performance. It is hoped the data will encourage the management of the less efficient systems to improve and new systems to emulate the designs and operating and maintenance practices that contribute to the performance of the best systems.

RIDERSHIP

Total 1990 annual ridership ranges from 182 million unlinked trips or revenue boarding passengers for Washington, D.C.'s

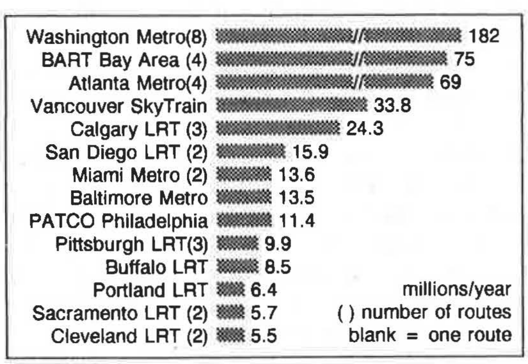

FIGURE 1 Rail transit ridership, 1990. (Bar chart lengths are approximate; the numbers are correct.)

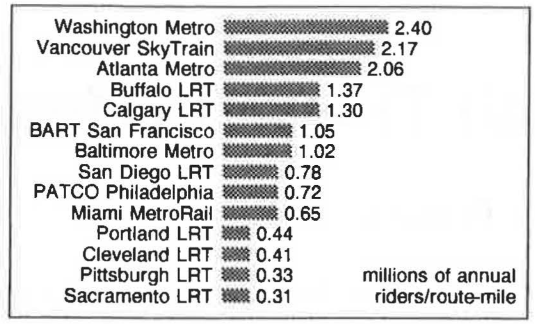

FIGURE 2 Annual riders per route mile, 1990.

Metro to 5.5 million for Cleveland's light rail (Figure 1). Calgary ridership excludes the 17.3 percent of daily riders who make short trips in the "free" central area. Pittsburgh's light rail system includes two old routes to Library and Drake, primarily operated with PCC cars, and one new route equipped with modern articulated cars. Consequently the system is not fully representative of modern light rail. This comparison does not take into account the number of routes on each system—a route is defined as a separate line into the center of the city—or the miles of route. This is shown in Figure 2. Washington Metro has the highest ridership per mile of route at 2.4 million annual passengers per route mile followed closely by Vancouver's SkyTrain at 2.2 million passengers per route mile. The most intensely used light rail systems are Buffalo and Calgary.

OPERATING COSTS

The direct operating cost per passenger mile is calculated by dividing the annual passenger miles into the total annual modal operating and maintenance expenses. Costs include all direct operating and maintenance costs, including management, supervision, security, fare collection, electricity, insurance, fringe benefits, and overhead. All capital costs and any costs of interest during construction are excluded. Under FTA Section 15 rules, management and other overhead and contracted services are required to be equitably allocated between modes.

In the evaluation of Figure 3, consideration should be given to those eastern properties whose labor restrictions force them to use an operator on each car of a multiple-unit train. Among the tabulated systems, Cleveland and Pittsburgh are afflicted with this inefficiency—which can also extend to maintenance practices.

The only driverless rail system, Vancouver's Skytrain, shows the lowest direct operating cost per passenger mile. SkyTrain has roving attendants who play multiple roles—security, supervision, ticket checking, public information, and correcting sticking doors and other minor technical problems. Normally there are about as many attendants as trains. In the peak periods this ratio is reduced to about two attendants for every three trains.

One sample of an unmanned system cannot be representative. One of the claims of automated, driverless operation is that unit operating costs will decline as ridership increases. This economy of scale can apply to all one-operator multiple-

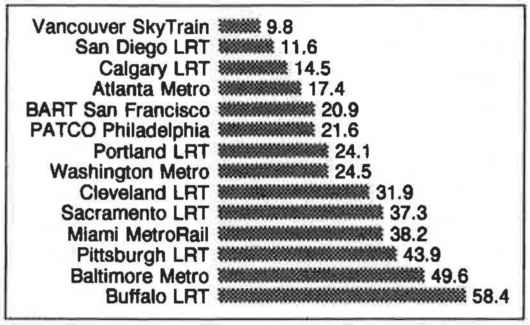

FIGURE 3 Direct operating costs, 1990, in U.S. dollars. (Cleveland RTA is an older streetcar system that has been rehabilitated; it is not fully representative of modern light rail.)

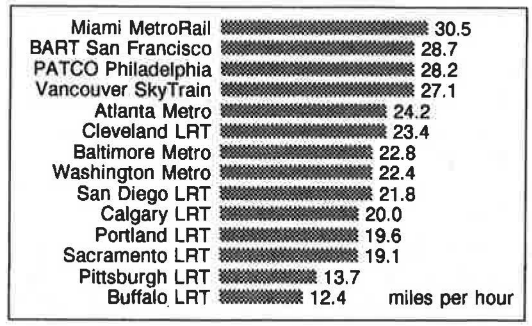

FIGURE 5 Average operating speed. (Miami's average speed should be lower than BART's or PATCO's and may represent a data inconsistency.)

unit rail transit. The cost trend for SkyTrain, shown in Figure 4, supports the claim for automated driverless systems. The costs are in the dollars of each respective year with no adjustment for inflation.

Cost recovery cannot be directly calculated from the APTA statistics. Three rail transit properties have outstanding recoveries and are believed to top their respective categories. For heavy rail Philadelphia's PATCO has a recovery in the mid-70 percent range. For light rail San Diego has a recovery in the high 80 percent range, and Vancouver's driverless system has a recovery of 90 percent to 110 percent, depending on how fares are allocated to feeder buses.

SPEED AND VEHICLE PRODUCTIVITY

The average speed shown in Figure 5 is derived by dividing revenue vehicle miles by revenue vehicle hours. This commercial speed includes any terminal layover time and will understate the schedule speed slightly. (Schedule speed is the average speed from leaving the first station to arriving at the last station. It excludes terminal station dwells and layovers.) All modern rail transit vehicles have comparable performance except for BART's cars, which have higher maximum speeds. Speed is principally a function of station spacing and the extent of grade separation. As may be expected, the grade-separated heavy rail systems and Vancouver have the higher average operating speeds.

Cleveland has the highest light rail speed followed by the closely matched San Diego, Calgary, and Portland systems. But travel time is a more important criterion to passengers than speed. Here the slightly lower speed of light rail can be more than fully offset by the faster, more pleasant access to surface light rail stations and the often faster, more convenient, interchange with feeder buses.

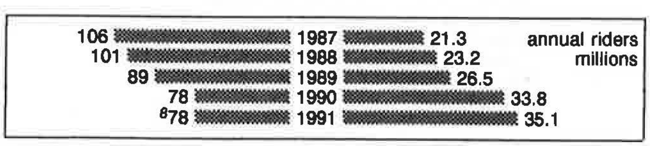

FIGURE 4 SkyTrain operating cost per trip, in U.S. dollars for each year converted at the rate of 0.87, versus annual riders. (1991 costs were influenced by major service increase.)

Vehicle productivity is an important criterion. Vehicles are expensive to buy, operate, and maintain. Figure 6 shows the annual passenger miles per revenue vehicle-hour, after adjusting to a common size—approximately 160 passengers per car at the height of the rush hour. This criterion shows the scheduling efficiency of the property in matching supply to demand.

Policy headways can severely affect this criterion. Policy headways can be set by management or politicians. They involve higher levels of service than demand would otherwise dictate—usually at off-peak times. They are often based on clock headways, that is, every 10, 15, 20, or 30 min. For this reason Vancouver's showing is unexpected, as policy requires a minimum headway of a train at least every 5 min from 5:15 a.m. to 1:15 a.m. daily—slightly shorter hours on weekends. This frequent service has attracted high off-peak ridership with the daily ridership of 110,000 being 15 times the maximum peak hour direction ridership of 7,300. Vehicle productivity for Vancouver is for a married pair, as the two 41-ft cars have equivalent capacity to single 80- to 90-ft six-axle articulated light rail cars or rapid transit cars in other cities. Buffalo's light rail vehicle data are adjusted for their smaller four-axle cars by a factor of 1.6.

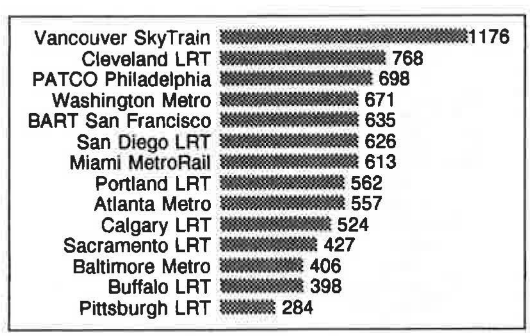

FIGURE 6 Vehicle productivity in revenue passenger miles per revenue vehicle hour.

STAFF PRODUCTIVITY

Labor is typically the largest single component of rail transit costs with a unionized staff year now costing in excess of $50,000 inclusive of overhead and fringe benefits. Dividing annual passenger miles by the total number of staff assigned to the rail operation produces a simple measure of staff productivity.

Vancouver's driverless system tops this criterion by a larger measure than would be expected given the roving attendants and higher maintenance associated with the advanced technology vehicles and train control (Figure 7). The Vancouver figure is probably overstated by about 10 percent as the APTA statistics do not include 12 contracted police officers and 25 contracted cleaners.

San Diego and Calgary lead the light rail systems by a significant margin, whereas BART is outstanding in the heavy rail sector. The extent of contracting out on these properties is unspecified but is not believed to be high.

ENERGY EFFICIENCY

Energy consumption typically costs 10 to 15 percent of a rail transit system's annual budget. Station spacing and the extent of heating and air-conditioning loads are major factors together with the amount of station power consumption—favoring western properties with less extreme weather conditions. Chopper and alternating current (AC) propulsion equipments are significantly more efficient than the now obsolete resistor-switched motor controls—particularly where full-featured regenerative braking is used.

Most rail transit cars use their motors—acting as generators—to serve as part of the braking system. The resulting energy is burned in on-board resistors and the electric braking is termed *dynamic*. Where the energy is returned to the line—third rail or overhead—the electric braking is called *regenerative* or in Europe, recuperative. Regenerative braking has become more common in the last 10 years and is particularly effective on AC propulsion cars where energy can be recovered to quite low speeds. Full-featured regeneration senses the line voltage several times a second and continually tries to return the power to the line. The line will only be *receptive* to returned power if other cars are within a reasonable range (about 1 mile) requiring power. This favors systems with a denser service. However, on well-designed cars some or all of the regenerated power will serve the car's total load, including heating and air-conditioning.

The outstanding energy efficiency of San Diego and Vancouver is surprising (Figure 8). San Diego has recently retrofitted air-conditioning—most of the fleet was so equipped for these 1990 statistics—and has resistor-switched motor controls without regenerative braking. Vancouver's linear motors are inherently 30 percent less efficient than rotating motors, obviously fully offset by the light vehicle weight—with aluminum trucks, underframe, and body—and the high levels of regenerative braking from the AC propulsion equipment and intensive service. Vancouver's cars do not carry the usual resistor banks but rather rely on resistors in each traction substation. These automatically connect when any regenerative braking causes an over-voltage and for a duration of 22 sec consume not only the braking energy but the full output of the associated substation. This considerable inefficiency is obviously offset by power efficiencies elsewhere.

The average rail transit energy consumption of the 14 rail systems tabulated is 0.26 kilowatt hour (kwh) per passenger mile—one-sixth the average energy consumption of a passenger mile by automobile and approximately half the average consumption per passenger mile by diesel bus. The best systems are 10 times as efficient as the average car.

ON-TIME PERFORMANCE AND DELAYS

Attempts to compare on-time performance and delays failed. Only a minority of the properties contacted either collected or were willing to share this information. There appeared to be no common reporting standards. For example, Portland reported that a small 1991 sample showed that 6 percent of trips were delayed by 2 min or more. With the advantages of data summarized from its computerized operation, Vancouver reported that, in a typical single month in 1991, 15,900 one-way trips were operated, of which 29 were canceled and 21 terminated short of their destination. Of all trips 2.4 percent were delayed by 2 min or more resulting in an accumulated monthly delay of 13.6 hr from the 9,200 train hours operated (0.015 percent). However, any delays to trains behind the affected train were not counted. Similarly Portland averaged an excellent 102,600 car miles per in-service failure, whereas

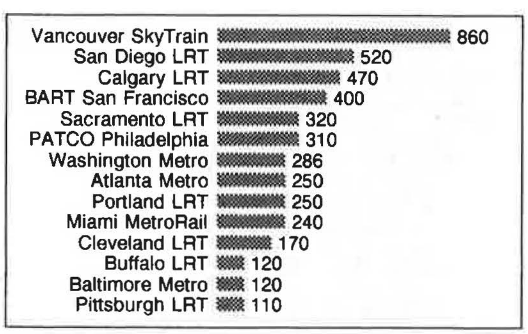

FIGURE 7 Staff productivity in thousands of passenger miles per employee per year.

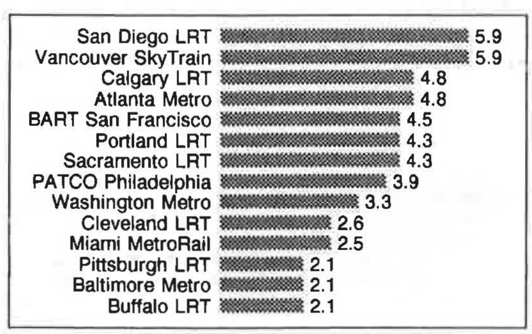

FIGURE 8 Energy efficiency in passenger miles per kilowatt hour of electricity.

Vancouver stated an average of 86,800 car miles per "unscheduled train removal from service." In Sacramento delays caused by grade-crossing incidents average 4 min, according to the chief operating officer of the transit district.

This limited information is not statistically significant but does suggest that well-run light rail systems do not suffer significant delays because of surface operation. Conversely automated systems tend to have longer delays caused by automatic train control problems. Vancouver experiences three to four major delays annually from computer outages that shut down half the system for up to 2 hr.

APTA, FTA, and the Canadian Urban Transit Association do not collect this type of information. They should develop standard reporting criteria and compile suitable operating performance and delay statistics. Similarly no consistent or coherent accident statistics are available for rail transit. These would be useful to confirm the excellent record of new rail transit systems and dispel erroneous views based on rare, but well-reported, accidents—in particular that grade-crossing accidents are significant on at-grade light rail systems. For example, in 1989 the Washington (D.C.) Metropolitan Area Transit Authority calculated that a ride on its Metro was 1,000 times safer than a similar journey by automobile.

NOISE

Nonpolluting rail transit also is noted for its low environmental impact. But one potential problem is noise. Measurements are not available from most systems, but data obtained for elevated rail transit (*1*) and Vancouver SkyTrain and light rail (*2*) allow a comparison of multiple-unit trains (at speeds of 50 mph) with other transportation modes (Figure 9). Some rapid transit and light rail systems do not reach 50 mph, requiring noise readings to be adjusted using an industry-accepted formula. Road traffic noise data were obtained from work by Beaton and Bourget (*3*) and Thiessen and Olson (*4*).

The Calgary single-event noise level (SEL) is a good surrogate for other light rail properties that operate similar vehicles. Noise is higher on curves and at switches but is less when on ballasted track and much lower when operating at reduced speeds typical of station approaches and downtown street running. Effective mitigation measures are available for light rail. The most pleasant is grass between the tracks and landscaped berms. Calgary developed an active noise attenuator for a difficult location on its northwest line. This highly effective, low-profile design was then adapted for residential areas on Vancouver's SkyTrain where noise was severe until a wheel and track grinding program was completed in 1990. Miami's elevated MetroRail had significant noise problems and installed several miles of concrete barriers.

Community noise standards are not based on SELs but on averages over a 24-hr period and expressed in dBA Leq_{24}. Canadian standards for residential areas are 55 dBA Leq_{24}, whereas those in the United States are 62 dBA Leq_{24}. Train frequency is taken into account in such measures (Figure 10).

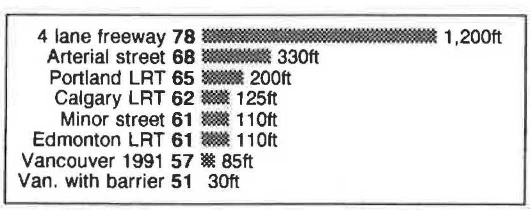

FIGURE 9 Transportation noise ranges [single-event noise levels (SELs)] at 50 ft and 50 mph in decibels on the A scale. (Noise is measured on logarithmic scale in which 3 dBA represents a doubling in noise energy; however because human hearing is nonlinear, an increase of 6 dBA is required to produce a perceived doubling in noise.)

CAPITAL COSTS

The high capital cost of many rail transit systems is often deemed a problem. However, when translated into the equivalent annual cost per passenger the amount can be put into perspective.

An equitable way to look at capital costs is to calculate the amortized capital cost equivalent per annual passenger. This is shown in Figure 11, which shows capital costs as published by each transit authority, inclusive of any local, state, or FTA (UMTA) grants. These are indexed to 1990 dollars, amortized over 40 years at 8 percent, then divided by the 1990 annual

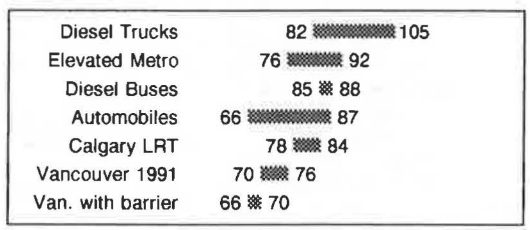

FIGURE 10 Average noise levels over 24-hr period in dBA Leq_{24} at 50 ft and 50 mph (*5*) at various distances from transportation facility to meet the 55-dBA Leq_{24} residential standard. (Four-lane freeway is Highway 1, Burnaby, British Columbia; minor street is West Boulevard in Vancouver, a trolleybus route.)

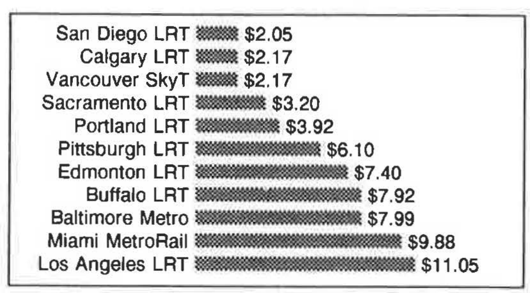

FIGURE 11 Rail capital cost comparison (amortized capital cost equivalent per annual passenger): 1990 data in U.S. dollars.

ridership from APTA's 1991 *Transit Operating and Financial Statistics*. Canadian dollars were converted at the rate in effect when the system was built—usually 2 years before opening. Two light rail systems, San Diego's and Calgary's, and the Vancouver system are the most capital cost-efficient. The full capital cost has been used irrespective of local or FTA capital funding. Some discrepancies may occur if projects use or share rights-of-way acquired or built as part of a highway scheme. Data are not available for other rail systems. This figure will be expanded in future revisions of this paper.

Alternative analysis can be used to compare rail transit and highway schemes. In a Vancouver study the annual amortized cost of a highway project would have exceeded $40 per passenger trip. Although not directly comparable, this is an interesting contrast with the SkyTrain capital cost of $2.17 per passenger trip.

OPERATING SAVINGS

One of the many rationales for building rapid transit is that the operating cost is lower than that for carrying the same passenger by bus. The ratio of direct operating cost per passenger mile on rail transit is compared with the average cost per passenger mile by bus in Figure 12.

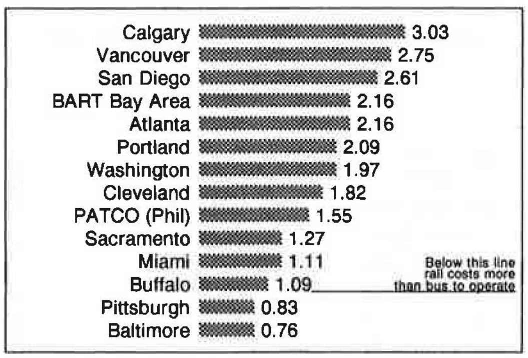

FIGURE 12 Ratio of bus to rail operating costs per passenger mile [BART rail compared with AC Transit (Oakland) buses; PATCO rail compared with NJ Transit buses.]

In this ratio Calgary, Vancouver, and San Diego show outstanding performance with rail costs per passenger trip 33 to 38 percent of the equivalent bus cost. In Vancouver this corresponds to an annual saving of $48 million from carrying people by rail rather than by bus. This saving does not yet cover the system's debt charges but is expected to grow to cover them in the future.

CONCLUSION

Critics of rail transit can find poorly performing systems. However, when all new rail transit systems are analyzed, the poorly performing systems are in the minority, In general, rail transit systems, and particularly the better light rail systems and Vancouver's SkyTrain, meet the expectations of high-quality, high-performance, cost-effective, environmentally sound transportation that attracts riders—with operating costs well below the bus alternative.

ACKNOWLEDGMENTS

The assistance of the American Public Transit Association, the British Columbia Rapid Transit Company (SkyTrain), and Calgary Transit is gratefully acknowledged.

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LRT Placement in a Medium-Sized City: Linz, Austria

HERBERT BRANDT

Linz, the third largest city in Austria, has succeeded in revamping and then extending its public transportation network to include light rail transit (LRT), which carried 31.6 million passengers on its 15.32 km in 1990. High running speeds, short peak-hour headways, noise-reduction measures, few pedestrian crossings, and a fare system that eliminates collecting or checking fares on board while allowing passengers to transfer freely from other modes have all contributed to LRT's popularity in the region. That LRT is helping to hold down traffic congestion and pollution in Linz's historic city center has added to its appeal. Two additional extensions are planned: one above ground south of the city to serve new housing developments and one underground to link an LRT line directly to the city's central rail station.

In 1960 the city of Linz, Austria, had returned to its commercial and economic importance within the north and western region of the nation. Household income was still modest but it was regular, and unemployment was below 2 percent. Review of social, education, and population statistics and records indicated that the city had experienced an urban phenomenon—increased private automobile ownership.

At the time, the city had a public agency for urban transit. This agency was using streetcar, trolley bus, and regular diesel bus for services. A specialty of Linz is the mountain tram to the top of Pöstlingberg, which is one of the steepest trams in the world with a gradient up to 10.5 percent and therefore a prime tourist attraction.

The city had two tram lines (which are still in service on a route network in the 2.3 mi^2 central business district (CBD) in the north-south direction). A low-frequency tram line crossed the other two lines in the city center (it was the first street crossing with traffic lights in Linz). Each line had a 5-min headway per direction in a base day. On the two main lines motorcars with one or two trailers were running; on the third line, only single cars.

The municipal owners of the public utility agency were informed by their transit management that the streetcar equipment—track, power, and rolling stock—would require a near-term commitment to replacement because of age and obsolescence. Given the world trend of shifting corridor transit from rail to road options, the city studied the merits of continued streetcar operations.

REVAMPING THE SYSTEM

First it was found that the third tram line, named M, could not be developed into a modern light rail transit (LRT). The trams were running on small streets with many curves, and the line was only 2.6 km long with a low number of passengers. So it was decided to replace the old tram cars with modern single buses, and rail operation was abandoned in 1968.

The second decision in these studies was to keep the trams on the two main lines and to keep the existing 900-mm gauge. What was found was that the core routes of the city were very well patronized; the projected residential density within the corridor would ease, but would remain high. During the shift in residential demands, the older units would be converted or replaced by new structures and commercial or professional business units. As found with public transit in Zurich, Switzerland, the way in which high-frequency trip use could be retained was by keeping the high-frequency service. The valley configuration of the city and the concentrated early public interest in environmental issues also shaped transit decisions. The CBD was identified as a key area in which the government and the citizens did not want additional particulate and gas pollution in the air.

The infrastructure of the existing streetcar system had been rehabilitated after 1945 in a manner that permitted gradual phased replacement of components. In effect all the vehicles and all the track did not require immediate change because of safety conditions and worn condition. Therefore the city concluded that streetcar technology could benefit the city. Power—hydroelectric and coal-fueled—was available within the region, but the region was not self-sufficient in petroleum fuel. Therefore strategically it was a benefit to maintain the most important portions of the public transit with hardware not powered by petroleum.

The city and its public utility agency designed a program for a multiyear replacement and renewal. It started with the construction of two turning loops on the main line for the new single-ended cars. In 1970–71 the Linz agency purchased seven units of six-axle, single-articulated and eight units of eight-axle, double-articulated vehicles to replace the 1943 and 1947 single-truck and double-truck streetcars. In 1973–74 it was decided to enlarge the six-axle cars by using midsections, making them into eight-axle cars instead of using trailers.

As mentioned the trams on the two main lines historically represented the basic system of transportation in Linz. (Line 1 went from Kleinmünchen to Sonnensteinstrasse on 7.4 km of double track; Line 3 went from Hauptbahnhof to Bergbahnhof on 3.3 km of double track.) Within the CBD both lines were running for 2.0 km (seven stops) on the same track and providing high-frequency services with 2 to 3 min headway per direction. These lines in the north-south direction through the main shopping area influenced the entire growth pattern of the city.

Linzer Elekrizitats, Fernwarmer und Verkehrsbetriebe Ag-EGS, Museumstrasse 6-8, Linz, A 4010, Austria.

But in 1970 new developments and communities on the outskirts of Linz began, especially in the north; the university was situated there. At this time only bus lines were serving the area north of the Danube River. To reach the city center all passengers had to change from bus to tram—no solution for the future. It was evident that it was not enough to renew the trams and keep the lines as they had been for the last 50 years. The lines had to be adapted to the new housing developments. So the Linz agency started planning the extension of the tram Line 1 in the north; the period of modern LRT began.

Some consulting groups and academic interests started to suggest that the city should emphasize rail technology by adopting metro-type parameters for the remodeled lines. Some consideration was given to the proposal, but it was quickly determined that the traffic required to support and justify underground placement did not exist and would not within the next half century. Secondly, the capital cost for such underground methods would require funding that would exceed the borrowing capacity of the region. Therefore rather than mortgage the whole city for a status solution, municipal engineers, officials, and transit management embarked on a phased upgrading of the streetcar lines toward the German-demonstrated technology of LRT. There was no projected shortage of electricity—new power dams and regional transmission grids were being built.

In the planning period it was found that the extension of the new line could serve about 40,000 inhabitants, 80 percent of the inhabitants in the northern part of Linz. And about two-thirds of these 40,000 would have less than a 400-m walk to the stops. Construction of the track started in 1974 and, at the end of 1977, the new line to the university opened. The extension of the new line is 5.5 km; the median distance between the 12 stops is about 476 m. The total length of Line 1 is now 12.9 km.

The tramline expansions featured the following:

- Reserved tracks for 4.5 km; separated surface sections with markings on the street emphasizing the higher priority for rail vehicles (1.0 km);
- Rail track embedded in sods to achieve a noise reduction of 5 dB compared with tracks lying in pavement;
- Rail track fenced in, embellished with a hedge;
- Minimized number of pedestrian crossings outside of the stops because of the high running speeds. (Only one such crossing was necessary; all others are at the stops or in connection with street crossings, which also were minimized);
- Appropriate signals and warning lights at crossings (Most of these street intersections have full priority for public transport);
- Fare collection as per a Swiss model; passengers buy tickets at machines at each stop (No tickets are sold, collected, or canceled in the cars, which represents a considerable advantage in operational speed).

The result of these features is a commercial speed of 21 km/hr on the new track. The maximum speed of LRT is 60 km/hr.

The success of the new line was shown by 20 percent increases in passenger volume in the catchment areas of the new line. For the passengers service improved in terms of waiting periods because intervals were reduced from 15 min to 4 min for buses and 7.5 min for trams. Travel time was also reduced by the higher speed of the trams and passengers did not have to change transit modes.

Given the high level of usage in Linz, this increase of 20 percent represents more or less the best possible result from feasible investments in the field of public transport.

Until 1977 the eight-axle cars on Line 1 ran as mentioned before. For the extension of Line 1 the Linz agency purchased 12 eight-axle cars with chopper control. The design, body, and dimensions were equal to the first articulated cars, but the construction was adapted to extend the cars with a mid-section to get a 10-axle car (which already had been done in 1979–80).

In spite of LRT, private vehicle ownership and demand for the use of private vehicles were slightly increasing. However, the public was convinced that such private vehicles would not fit well within the CBD if its historic and amicable condition were to be maintained.

So at the same time as Line 1 to university was opened, a 700-m pedestrian light rail vehicle (LRV) street opened within the CBD. The two stops with the highest frequency in the CBD are situated in this pedestrian zone. It is remarkable that the platforms of the stops in this zone are about 120 mm above the top of the rails. The pedestrian zone has a track construction in pavement so that pedestrians prefer walking beside the track, which is a good safety measure. As a result, there have been no problems between pedestrians and the trams. The maximum speed of the trams in the pedestrian/LRV street is 30 km/hr.

In subsequent years new developments began to the south. The success of the Line 1 extension inspired the extension of Line 1 south of Linz. This second extension of about 1.5 km with four stops opened in 1985, making the total length of Line 1 14 km. The 15,000 inhabitants in the new catchment area again added 20 percent increases to passenger volume. The extension features a big interchange station for the tram and connecting bus service with a roof covering the whole station, passengers, trams, and buses.

Finally it was necessary to renew the last of the old two-axle trams. In 1985 the Linz agency purchased 16 new 10-axle, articulated trams, three of them for the new line. These trams, again produced in Austria, rank among the most advanced in Europe. And in Linz in particular, the reduction of noise from 88 to 70 dB at a speed of 60 km/hr represents an outstanding accomplishment. To provide proper and professional maintenance of this new and fairly sophisticated equipment, a new workshop opened in 1982 after a construction period of approximately 3 years.

FINANCING THE SYSTEM

The capital costs for the main investments mentioned were as shown in Table 1. The funds for these investments were raised partly by the central government (240 million shillings from automobile taxation), partly by the city of Linz (250 million shillings) and partly by the province of Upper Austria (60 million shillings). The largest share, however, came from the municipal utility corporation itself, which is providing not

TABLE 1 Capital Costs

Year	Cost	Austrian Shillings (millions)
1970–1974	15 8-axle cars	90
1977	Extension of Line 1 to university 15.5 km double track including bridges, signals, two power stations, overhead, two turning loops)	200
1977	Pedestrian zone	15
1973–1977	New track on Wiener Strasse	40
1977–1980	12 8-axle cars including extension to 10 axle	132
1982	New workshop for trams	200
1983	Turning loops for Line 3	10
1985	Extension of Line 1 to Auwiesen (1.5 km double track)	40
1985–1986	16 10-axle cars	264
Total		991

only public transport services but also electric power and district heating for the city of Linz.

This quite remarkable expansion of mass transit was received by the public very favorably. Between 1975 and 1985 passenger journeys rose from 47.4 million to 65.8 million, equivalent to an increase of 40 percent. This percentage also represents the highest improvement rate among all cities in Austria. In an opinion poll 80 percent of all those questioned about public transport at that time were satisfied or very satisfied. These results are particularly significant because criticism in this area of community life generally tends to be rather at the harsh end of the scale. It could thus be inferred that the expansion and increased attractiveness of the system were the right approach.

RIDERSHIP AND COST-EFFECTIVENESS

The number of passengers using the trams, buses, and trolleys grew steadily over the years with only the mountain tram to the top of Pöstingberg recording a decline (Table 2).

The success of the tram extensions is shown by the growth in ridership.

In 1990 the 68.1 million passengers carried was equivalent to 289 trips per person that year. The importance of the tramway is underlined by the fact that, with a length of only 15.3 km, equivalent to 12 percent of the total length of the network of 132 km, no less than 46 percent of all passengers use the tramway. An interval of only 2 min between trams during the morning rush hour shows the high rate of use. It is remarkable that the two LRT lines are serving a catchment area of about 120,000 inhabitants. Compared with this, the catchment of the total network is about 235,000 inhabitants.

Nevertheless the number of passengers using buses also increased between 1980 and 1990. Although LRT is appropriate to high-frequency service, buses are used for low-frequency services. Hence a new bus line may serve low-density housing developments that could not be served by LRT. Therefore it is necessary to coordinate rail and bus services efficiently. In Linz about 40 percent of all passengers have to change between bus and LRT. All tickets allow this interchange.

A comparison of the running costs of the different modes of public transport in Linz shows the cost-effectiveness of LRT (Table 3), which is based mainly on the high capacity of the LRVs.

CURRENT OPERATIONS

Linz, the third largest city in Austria after Vienna and Graz, has about 202,000 inhabitants. The route network however

TABLE 2 Increase in Passengers, 1975–1990

	Passengers (millions per year)							
	1975		1980		1985		1990	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Tram	18.5	39.0	27.9	47.5	30.5	46.4	31.6	46.4
Bus	16.6	35.0	16.4	27.9	19.1	29.0	19.9	29.2
Trolley	11.7	24.7	13.9	23.6	15.7	23.9	16.1	23.7
Pöstlingbergbahn	0.6	1.3	0.6	1.0	0.5	0.7	0.5	0.7
	47.4	100.0	58.8	100.0	65.8	100.0	68.1	100.0

TABLE 3 Running Costs for Transport Modes in Linz

	Running Costs (Austrian shillings)		Running Costs Including Vehicle Depreciation (Austrian shillings)	
	Per Kilometer	Per Seat-Kilometer	Per Kilometer	Per Seat-Kilometer
Ten-axle tram (190 seats)	40.	0.21	80.	0.42
Single bus (70 seats)	30.	0.43	35.	0.50
Articulated bus (110 seats)	35.	0.32	45.	0.41

reaches beyond the city limits and includes parts of four bordering communities. The area covered is approximately 100 km^2 with a population of about 235,000.

With 160,000 jobs within the city limits, approximately 80,000 commute every day between the city and surrounding communities, a comparatively high percentage. The modal split for Linz is (for all days and all trips): 17 percent, public transport; 51 percent, private cars; 28 percent, pedestrian; and 4 percent, bicycle.

As a point of interest, the degree of motorization in Linz is presently around 370 cars per 1,000 inhabitants and is still slightly increasing as in other cities.

As of 1990 the Linz network of public transport consisted of the elements shown in Table 4. The rolling stock in 1990 included the following:

Vehicle	*No.*	*Description*
Tram	15	8-axle articulated trams
	28	10-axle articulated trams
Bus	30	Articulated buses
	55	Single buses
Trolley-bus	20	Articulated trolley-buses
	4	Single trolley-buses
Pöstlingbergbahn	15	2-axle trams

The Linz region has had a coordinated fare system since 1989 that includes the railways and regional buses. Hence the number of passengers using the railway and changing from railway to LRT is increasing. As a result 39 (instead of 37 previously) of the 43 trams are used during the morning rush hour.

The expansion of LRT combined with parking restrictions has reduced the use of private cars, especially in the city center. But on some streets the increasing traffic congestion obstructs the bus lines more and more, and the buses have great difficulty keeping to the timetables. LRT has fewer problems. Nevertheless LRT needs improvement, too. So Linz intends to separate all parts of the track from private cars and to minimize the waiting time at traffic lights where LRT does not have full priority. By the end of 1992, the travel time of trams is expected to be reduced, thus allowing the system to reduce the number of trams running in the peak hour on Line 1 from 30 to 28 without extending the headways. These two trams will be used on Line 3 to serve the railway stations better.

TABLE 4 Linz Network of Public Transport, 1990

	No. of Lines	Route Length (km)	Passengers	
			Millions	Percent
Tram	2	15.32	31.6	46.4
Bus	17	98.38	19.9	29.2
Trolley-bus	3	14.96	16.1	23.7
Pöstlingbergbahn	1	2.90	0.5	0.7
Total	23	131.56	68.1	100.0

FUTURE DEVELOPMENTS

Because LRT offers high-efficiency, cost-effective public transport in Linz, the city is considering two new expansion schemes. One is a branch off Line 1 in the south to new communities. For this project to succeed, it is vital that the houses be near the tram stops. Scattered housing is very difficult to serve with LRT.

Our vision for improving public transport in Linz is to connect Line 1 with the central rail station. At the present Line 1 runs about 700 m away from the central station, and the only connection between LRT and railway is via Line 3. To connect Line 1 with the main station, the only way (which has been avoided wherever possible) is to build a tunnel 1.6 km long, with two or three underground stations. The LRT cannot cross the railway by surface sections.

It is evident that the funds for these investments (300 million shillings and 900 million shillings, respectively) have to be provided by the federal government and the province of Upper Austria. The public utility can only cover the running costs.

LRT in Hong Kong's New Suburbs

JONATHAN YU

The first phase of Hong Kong's light rail transit (LRT) system opened in September 1988, providing a fully integrated transport service for the fast growing northwestern region of the New Territories. Designed as a high-capacity carrier yet providing a comprehensive network of services, the system features a large number of stopping points located in commercial, industrial, and residential areas. Many of the stops are directly linked by footbridges to transport interchanges and into the housing developments. The system opened on time and within budget, with very few technical start-up problems. Yet its early days of operation were clouded by controversy, and at one time it was branded as dangerous and trouble-prone by the local media. The LRT system is the only public transport service in Hong Kong that features an open fare system, giving maximum customer convenience without turnstiles on the platforms or in the vehicles. Passengers pay for the number of fare zones they travel through rather than the route they take. The system now regularly operates with 98 percent punctuality and 99.9 percent reliability despite having 18 major and 51 minor road crossings, all at grade and without barriers. Average journey speeds achieved are 20 km/hr including stops. Despite the low fares, the system already covers about 100 percent of its direct operating costs. Three new links have been added and 30 more cars will be delivered starting in late 1992. The operating regime is described, with the line-of-sight driving that achieves this daily performance, the priority request system to obtain signals to proceed over the road junctions, experience to date, as well as plans for the future.

The first phase of Hong Kong's light rail transit (LRT) system commenced operation in September 1988, providing a fully integrated transport service for the fast-growing northwestern region of the New Territories with a target population of 800,000 by the late 1990s. Clouded by a series of controversies initially, including concerns about monopoly and safety, the system has gradually started to gain passenger and public recognition and has become an integral part of Hong Kong's multimodal public transport scene.

Patronage on the 23-km Phase 1 system has increased about 50 percent to average 262,000 daily (including some 37,000 who traveled on bus services feeding the network) in 1991, making it one of the most heavily used LRT systems in the world.

Operated largely on its own right-of-way but entirely at grade with 56 road junctions (73 on the expanded network) where the system meets other road vehicles, the system has consistently been attaining excellent safety, punctuality, and reliability records.

On an average day over 99 percent of the 1,600 light rail vehicle (LRV) trips on the timetable are operated and 98.5 percent arrive at their destinations within 3 min of their scheduled time. The accident rate is the lowest of all road-based modes of public transport, and no major incident has occurred that caused widespread interruption of service for an extended period of time.

Despite the very low fares charged (which, at the end of 1991, averaged HK$2.10, more or less the same charged by ordinary Hong Kong buses), fare revenues almost cover 100 percent of the system's direct operating costs (excluding provisions for depreciation) thanks to continued rapid patronage growth and productivity enhancements.

BACKGROUND ON THE SYSTEM'S CONSTRUCTION

The northwest part of the New Territories of Hong Kong, which includes the new town of Tuen Mun, a developing market town, Yuen Long, and the Castle Peak Road corridor between the two towns, has been developing rapidly since the mid-1970s under the Hong Kong government's new towns development program to cope with rapid population growth.

The idea of introducing an LRT system into the region dated back as far as 1972, when a commercial firm proposed building a circular tram route in Tuen Mun. This triggered a series of studies to determine the most appropriate transport system for the new town. A wide range of modes was initially screened, ranging from minibuses, buses, street trams, a light rail system, a automated guideway system, a conventional metro, and elevated monorail. Finally the government decided to provide an advanced light rail system to the new towns. Apart from such advantages as independence from fuel oil, better quality of service, and greater environmental compatibility, it was thought that a light rail system would help to promote the image of the new towns.

In November 1983 the government invited the Kowloon-Canton Railway Corporation (KCRC), a public corporation running a passenger and freight heavy rail service, to build and operate the LRT, which by that time had developed conceptually from a Tuen Mun town system into a regional system for the whole northwestern New Territories, including a loop for another new town called Tin Shui Wai.

In July 1984 the KCRC accepted the offer to build the LRT system. KCRC was granted an exclusive right to provide the major public transport services (i.e., LRT and its feeder bus services) in the designated transit service area.

In August 1985 the KCRC awarded a turnkey contract of HK$1.1 billion to an Australian consortium of Leighton Contractors Asia Ltd. and MTA (Metropolitan Transit Authority of Victoria, Melbourne) to build and equip the first phase of the LRT project. Following an intense 3-year construction period, the 23-km Phase 1 system commenced commercial service on September 18, 1988 (see Figure 1), managed and

KCRC Light Rail Division, Depot 55-65, Tuen Mun Road, Hong Kong.

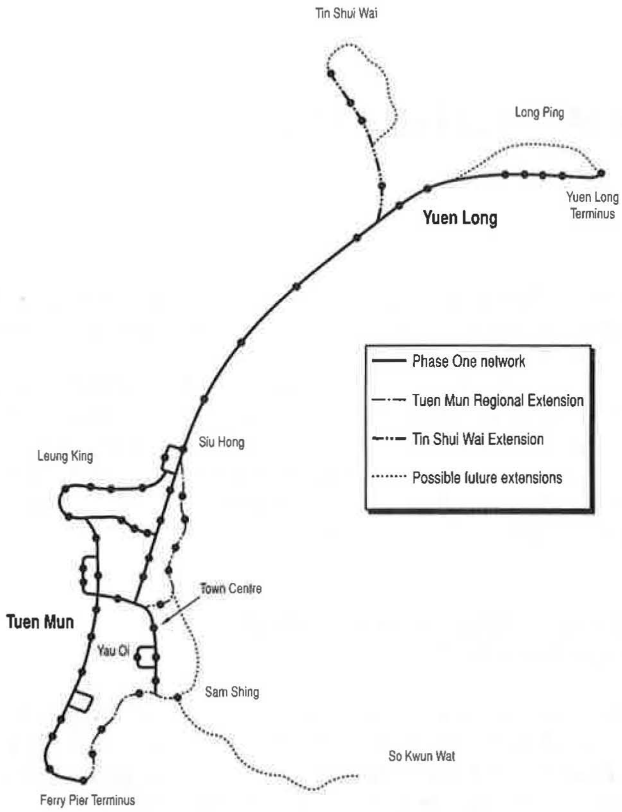


FIGURE 1 LRT network in Hong Kong's New Territories.

operated by the light rail division, one of KCRC's business divisions.

SYSTEM FEATURES

Network

The Phase 1 system is 23 km of double track and 41 stops. Three extensions to the system in Tuen Mun, totaling 5 km of track with 10 stops, opened for service between November 1991 and February 1992 (see Table 1).

TABLE 1 Technical Information, Tuen Mun LRT: Network

	Phase 1	Expanded Network[a]
Route length (km)	23.35	33.05
Roadside reservation (km)	20.00	29.30
Paved, segregated median (km)	2.25	2.25
Paved, street track (km)	1.10	1.50
Length of single track, excluding depot (km)	46.00	71.43
No. of signalized road crossings	56	75
No. of unsignalized road crossings	13	13
No. of stopping places	41	55
Platform height (mm)	910	910
Platform width, usual (m)	3	3/4
Platform width, min/max (m)	2/5	2/5
Minimum design headway (sec)	60	60
Passenger capacity/dirn/hour[b]	22,800	22,800

[a]Early 1993.
[b]Based on two-car trains and standees at 6/m².

The Phase 1 system is entirely at grade but the extensions feature three LRT bridges. Over 90 percent of the system runs on its own right-of-way, which in Tuen Mun was formed as part of the development of the new town. As a result construction work caused the minimum disturbance to the community.

The bulk of the system is fenced off to prevent pedestrian access other than at specified crossing points (largely located adjacent to the stops) and at road junctions.

Track

Standard gauge (1,435-mm) steel rails are used (see Table 2). The tracks are generally laid on ballast, with the exception of road junctions, the section through Yuen Long town, and three small sections in Tuen Mun, two of which are the only

TABLE 2 Technical Information, Tuen Mun LRT: Trackwork

	Phase 1	Expanded Network[a]
Contractor	Henry Boot (Far East)	Balfour Beatty Ltd./Henryvicy Consortium
Flat-bottomed rail		
Type[b]	UIC 54	UIC 54
Supplier	British Steel	Sydney Steel
Grooved rail		
Type	Ri 60	(not used)
Supplier	Thyssen	(not used)
Track gauge (mm)	1435	1435
Precast concrete sleepers[c]	F27S	F27S
No. of points	128	168 (Total)
Supplier of points (motors/controllers)	Hanning & Kahl	Hanning & Kahl
No. of diamond crossings	29	38 (Total)
Minimum curve radius (m)	23	23
Maximum gradient (%)	6.1	6.1

[a]Early 1993.
[b]With plating for some street track.
[c]Timber used for special work.

parts of the system where LRVs share the same road space with other road vehicles.

The maximum possible gradient on operational track is 8 percent, though for short distances only. In actual fact the steepest gradient is 6.1 percent. The maximum within the depot and the yard is 0.2 percent.

The grade of the track generally follows that of the adjacent street. So far as reasonably practicable, the track alongside platforms is straight and level.

The tracks are aligned to provide a 150-mm clearance between the kinematic envelope of the vehicle and any fixed object, such as a building or overhead structure, adjacent to the line. Because of geographical constraints, the minimum curve radius was only 20 m.

Stops

The stops are conveniently located in commercial, industrial, and residential areas, generally 300 m apart in the urban areas and 500 m in the more sparsely populated areas.

All stops are high-level platforms 910 mm above rail level to match the height of the vehicle floorline to facilitate boarding and alighting. One platform is provided for each direction of travel and access is normally by adjacent footpaths or footbridges. Each platform is 40 m long to accommodate two vehicles simultaneously. The width varies but generally is 3 m wide on the Phase 1 system and 4 m on the new stops.

All stops have stairs and ramps, and the system can be used by the disabled, including the wheelchair-bound.

Stop canopies are provided, and each platform is equipped with automatic ticket vending machines, a public address system, and passenger and fare information.

Vehicles

Of German-Australian design, the light rail vehicles (LRVs) are constructed to provide a high quality of passenger convenience and comfort consistent with operational requirements and proven technology.

The LRVs are rigid frame, stainless steel vehicles, single-decked, 20 m long and 2.65 m wide, with 52 seats and a carrying capacity of 205 passengers (see Table 3). The LRVs are four-axle with a single pantograph and single-ended with a driving cab at one end only, though an auxiliary driving position is at the rear for emergency and shunting purposes.

The LRVs can be operated singly or in pairs, and each has three sets of double doors on one side. They are fully air-conditioned and, with the latest electronic power control system and regenerative braking, are very energy efficient, with up to 40 percent of the traction current recycled within the system. The resilient, cushioned wheel rim and the use of a split-type air-conditioning unit help to reduce vehicle noise.

Power Supply

The LRVs are electrically powered from a 750-volt (V) direct current (dc) lightweight overhead power supply system provided initially at 11 kV via two primary substations and then distributed through the LRT's own 12 rectifier stations and workshop substation (see Table 4).

The overhead line system has been designed to withstand typhoon conditions and the whole system can be supplied by either one of the two primary substations in case one fails.

The majority of the rectifier stations are provided with two 11-kV feeders forming a series of ring mains. Cables installed in cable troughs along the track provide the connections between rectifier stations. The capacity of the rectifier transformers and the overhead line equipment is so designed that, if one rectifier station fails, operation can be maintained on the affected section by feeding from neighboring rectifier stations.

The rectifier stations are unmanned and equipped with a supervisory control and data acquisition (SCADA) system for remote control of the power supply network from the operational control center (OCC) at the LRT depot.

A low voltage system, connected to the auxiliary transformer at each rectifier station, provides power supply to each LRT stop.

Communications and Control

Regulation and supervision of vehicle operations and supervisory control of associated electrical, mechanical, and communication systems are carried out at the OCC to ensure safe and efficient service, whereas the actual operation of the vehicles is under the manual control of the LRV driver.

The LRT system has 73 at-grade junctions where LRVs interface with road traffic. The LRT signals at the junctions are synchronized with road traffic signals to give a degree of priority to LRVs. For minor junctions (largely serving isolated developments) where road traffic rarely interferes with the LRT, 100 percent priority is accorded to LRVs. But at the most complex junctions, for example, where the LRT T-junction is superimposed on a major road T-junction, little priority could be given because of heavy road traffic. The LRT traffic signals are controlled from the adjacent electronic road traffic controller. The LRT point signals are controlled by the presence of the vehicle, although this control may be overridden by driver command. An LRV will cross a road junction by making an automatic request to the road traffic controller and LRT track equipment.

The track is equipped with separate vehicle identification loops between rails to initiate traffic signal and point signal request and cancel commands. There is no interlocking between the track point switching controller and the road traffic signal controller.

Each LRV is equipped with a transponder. When it passes over the traffic request loop and point request loop, the LRV sends its identification to the trackside computer at the nearest stop. The computer then makes the request for LRV right-of-way to the road traffic controller, switching the point switch to the right position and sending the LRV identification back to the central computer at the OCC for location identification and further processing.

After a safety period the road traffic controller will give the right-of-way to the LRT vehicle.

When the LRV passes, the cancel loop resets the previous request. The traffic controller will then restore the service and the request loop will wait for the next LRV instruction.

TABLE 3 Technical Information, Tuen Mun LRT: LRVs (Phase 1)

Specification	70 cars delivered between October 1987 and August 1988
Drive and braking systems	Monomotor bogies with quill shaft axle drive; regenerative/pneumatic service braking, with emergency battery-fed magnetic track brakes, sand assisted; bogie centers offset 24 mm to compensate for externally hung doors
Lighting systems	Exterior: dual front, rear, brake and direction indicators Interior; fluorescent
Control systems	GTO thyristor chopper controls capable of m u operation up to three cars; rear-end backup shunting control
Suppliers	
Main contractor	Comeng, Australia
Body	Comeng
Bogies	Duewag
Propulsion equipment	AEG
Control equipment	Siemens
Brakes	Knorr
Interior fittings	Comeng
Seats (fiberglass)	Duewag
Doors	Stone Peters
Air-conditioning (split type)	Sigma
Pantograph (type DR-23LA)	SMC
Couplers	Scharfenberg
Body specification	
Frame	Steel
Exterior walls	Stainless-steel ribbed panels
Interior walls	Aluminum alloy
Insulation	"Tuff-skin" fiberglass
Floor	Stainless steel
Floor overlay	Plywood and "Treadmaster"
Doors (externally hung)	Sliding
Windows	Beclawat Design 14, with hopper vents
Heating	None
Flange lubricators	Fitted to 14 cars
Vehicle performance	
Maximum velocity (km/hr)	80
Steepest gradient capability (%)	8
Service acceleration (m/sec^2)	1.3
Service braking (m/sec^2)	1.3
Emergency braking (m/sec^2)	>2.6
Emergency brake reaction time (sec)	1.0
Max. jerk rate (m/sec^3)	3.0
Min. curve radius capability (m)	
Horizontal	20
Vertical (crest/sag)	300
Passenger capacity:	
Seats	52
Standees ($6/m^2$)	153
Noise (inside), on level, clean ballasted track	Li 70 dB(A) at 60 km/hr
Noise (outside), tare load on level, clean ballasted track, 7.5 m from car	La 75 dB(A) at 60 km/hr
Dimensions	
Length over fenders (m)	19.400
Length over couplers (m)	20.200
Height of floor over rail (m)	0.948
Height of roof over rail (m)	3.415
Height of lowered pantograph over rail (m)	3.785
Inside width (m)	2.588
Headroom in center aisle (m)	2.187
Width of center aisle (m)	1.078
Doorway width, minimum (m)	1.500
Doorway height (m)	1.900
Weight, empty (t)	27.032
Weight, fully loaded (t)	37.862
Propulsion and braking	
Track gauge (mm)	1435
Bogie centers (m)	11.0
Bogie wheelbase (m)	1.9
Motors (monomotor drive), type	ABS 3322.2
Motor rating, per car (kW)	2 × 195 (cont)
Motor voltage (V dc)	750
Gear ratio	5.556:1

TABLE 4 Technical Information, Tuen Mun LRT: Electrification

	Phase 1	Expanded Network[a]
Contractors		
Overhead	Balfour Beatty	Balfour Beatty
Power	Hawker-Siddeley	Balfour Beatty
No. of infeed substations	2	2
No. of rectifier substations	11	13
Voltage (V dc)	750	750
Contact wire height (m)		
Normal	5.6	5.6
Max/min	6.0/5.4	6.0/5.4
Wire type		
Catenary and trolley (at triangle junctions and termini)	Hard-drawn copper	Hard-drawn copper Silver copper
Span wires	Synthetic rope	Synthetic rope

[a]Early 1993.

TABLE 5 Technical Information, Tuen Mun LRT: Fare Collection

	Phase 1	Expanded Network[a]
Ticket vending machine		
Autelca	215	
Cubic Western Data		148
Total		363
Zonal fares issued		Yes
Monthly seasons issued		Yes
Stored value tickets accepted		Not yet
Free transfers		to LRT buses
Fares (adult/child)		
1–2 zones		HKD2.40/1.20[b]
3 zones		HKD3.00/1.50[b]
4–5 zones		HKD3.50/1.80[b]
Monthly		
3 zones (Adult)		HKD117[b]
All zones (Adult/Child)		HKD172/60[b]
Student season (quarterly)		
3 zones		HKD268[b]
All zones		HKD390[b]
Surcharge/no ticket		HKD175[b]

[a]Early 1993.
[b]Fares as of early 1992.

If a number of LRVs are following closely, or approaching the junction in opposite directions, the situation could arise in which LRV demands continue for long periods. To prevent the LRV phase staying green for too long, with unacceptable delay to road traffic, it has a "maximum green" timer similar to a normal vehicle actuation phase. This timer is set so that two fairly closely following LRVs could pass through the junction before the stage change.

The computerized vehicle information system enables the traffic controllers at the OCC to see all LRV positions and deviations from scheduled running times so that corrective action can be taken whenever required. Required changes in service can be communicated to LRV drivers through a radio link. The OCC can also make public address announcements to passengers on vehicles or stops, singly, by route, or systemwide.

Fare Collection

The LRT adopts an open fare system, which is the first of its kind in Hong Kong. It has a zonal fare structure with full integration between LRV and feeder bus fares, allowing free transfer within the same fare zone. Passengers pay for the number of fare zones they travel through rather than the route they take. Currently five fare zones are employed with three fare steps (see Table 5).

Without turnstiles or gates at stops, the open fare system, which is also an honor fare system, enables passengers to travel conveniently by holding a valid ticket. Infrequent travelers can purchase a single-ride ticket from the automatic ticket machine at LRT stops and travel within a 2-hr limit in one direction within the fare zone(s). The ticket vending machines provide change and issue tickets stamped with the origin and destination zone numbers, machine number, time, and date. All ticket machines are linked to a computer terminal in the OCC, and malfunctioning and vandalism trigger alarms.

Various multiride passes are offered for frequent travelers and are sold at substantial discounts. Both monthly passes and student season passes allow unlimited rides and free transfers within the zone or zones specified on the ticket. Adult and student multiride passes are divided into four zonal types: Tuen Mun pass, Central pass, Yuen Long pass, and all-zone pass. The first three zone passes can be used as all-zone passes on Sundays and public holidays. Passengers can purchase multiride passes at LRT passenger services counters at major stops and termini, as well as local convenience stores.

To protect the interest of honest passengers and LRT revenue, teams of passenger services assistants conduct random ticket inspections at LRT stops and on LRVs in addition to their regular duties of providing assistance to passengers. A heavy penalty equal to 50 times the maximum single journey fare is imposed on passengers found without a valid ticket.

Depot and Workshops

The depot and workshops together with the LRT administration building (which houses the OCC) occupy a site of about 5 hectares. The depot, when developed to its full capacity, can be used for the stabling, cleaning, and maintenance of a fleet of 143 LRVs and a number of auxiliary vehicles used for maintenance purposes.

There will be 17 tracks for stabling purposes and three more with 1.5-m-deep pits for LRV servicing and inspection.

Vehicles due for major inspection and overhaul will be brought into the workshops by a traverser. Facilities include a bogie repair shop, wheelset repair shop, motor repair shop, shop for couplers, brakes and compressed air system, battery shop, machine shop, air-conditioning equipment shop, and electronic workshop where electronic equipment on LRVs, the signaling system, and automatic ticket vending machines are tested and repaired. A body workshop has an underfloor wheel lathe, door repair shop, and area for scheduled and unscheduled repair of car bodies. The workshops are also equipped with two sets of overhead traveling cranes, two sets of vehicle-lifting screw jacks, and all necessary jigs, tools, and testing instruments. The permanent way and overhead line equipment are repaired in a separate workshop accessible from a special siding.

EARLY PROBLEMS AND SOLUTIONS

Safety

A series of road accidents at road/LRT junctions involving LRVs during the trial running and early stages of passenger service in mid- to late-1988 resulted in a lot of adverse publicity for the system. People questioned whether something was wrong with system design in terms of safety.

Part of the problem was associated with the fact that many new traffic signals were not installed prior to commencement of trial operations, leaving very little time for motorists and pedestrians to become familiar with new traffic conditions after installation was completed and the LRT started full-scale commercial operation. Both the government (which has overall responsibility for road safety in Hong Kong) and the KCRC were unaware of the extent of the perception problems about what an LRT system is. Many road users might have equated LRT with the slow-moving trams on Hong Kong Island, while the general public might, on the other hand, equate the LRT with other fully segregated heavy railways in Hong Kong that do not conflict in any way with road traffic.

Through large-scale safety public education campaigns, improvements in signage, road markings, and modifications to traffic signal positioning as well as junction layouts, the early concern on safety has largely died down. Even in 1988, the LRT had the lowest accident record among all road-based public transport and recent statistics have indicated that LRT traffic junctions are safer than non-LRT junctions.

Political Problems

A White Elephant?

The decision to go ahead with building an LRT system to serve the internal public transport needs of the northwestern New Territories was most controversial. Hong Kong's other rail-based transport systems all serve the built-up urban area or link the urban area with the new towns of the New Territories. Government's housing and new town development policy successfully brought more and more people to live in the New Territories. However, most of the people still work in the urban areas where the major employment activities, especially for the commercial services sectors, are concentrated. Hence many of the residents believed that the priority for a rail system in the northwestern New Territories was for a rail link to the urban heavy rail networks instead of an internal system, which, it was thought, could adequately be provided for by a bus service. It was extremely difficult for people to look at the requirement for an LRT to cope with long-term growth and development of the region with additional benefits such as environmental advantages.

Though this has changed somewhat as internal travel has built up with the new towns maturing and as more educational, community, and other infrastructure projects are completed in the region, the demand for a rail link to the urban areas remains.

The Monopoly Issue

It had been established since the days when the LRT was first conceived for the region that transport demands there could not support both a bus system and the LRT, hence the government decided that the LRT would replace the internal bus network that was operating (and this was one of the conditions for KCRC to undertake the project). However, it was perceived that KCRC acted in a high-handed manner in forcing people in the area to use LRT service by ending bus service. This requirement for the creation of a transit service area (TSA) is, of course, a new concept as far as new transport facilities in free enterprise Hong Kong is concerned, and it has remained an issue of contention to this day. Although in terms of actual choice, residents in the TSA have no less choice now with the LRT than with the previous partial monopoly enjoyed by the buses.

It has to be pointed out that though the TSA franchise confers a degree of monopoly for the KCRC, on the other hand, the LRT has the responsibility to provide an adequate level of service for the entire region, including the money-losing feeder bus services.

Political Battlefield

Tuen Mun is a special new town in Hong Kong because it is farther away from the urban area with relatively few community facilities (including no rail service) and a younger and generally less affluent population. About 70 percent of the residents live in subsidized government housing. All these factors have caused a mushrooming of quasipolitical pressure groups that vie for influence and support at a time when Hong Kong is developing a more representative form of government, including district-based consultative District Boards and elected representatives to Hong Kong's law making Legislative Council. Added to this is the clash of ideas and, at times, interests between these new, public housing-based young groups with a more radical outlook and the traditional rural elements who had previously enjoyed tremendous influence in affairs in the New Territories. Hence Tuen Mun is the most politically active area in Hong Kong and, as could be expected, public transport (including the LRT) is always an issue and an easy target for political debate.

Community Relations Initiatives

To address the many political and communications issues, the LRT has carried out a very comprehensive community relations program to ensure effective communication channels are maintained with passengers, community organizations, political forces, and the media. The program includes a telephone enquiry and complaint hotline service, passenger services counters at the major stops, the publication of a monthly newsletter, participation in the District Board traffic and transport committees, school talks and visits, exhibitions and briefing sessions, courtesy and safety campaigns, as well as the establishment in 1991 of passenger liaison groups through which regular two-way dialogue is maintained with users of the system.

A "Get to Know the LRT" project was launched in 1989 and is still popular. This program is targeted at students, community organizations, and the general public outside the region (who would have little opportunity or need to use the LRT), inviting them to visit and experience the system firsthand.

Teething Problems

Like other new transport systems, the LRT in 1988 also suffered from teething problems such as passengers' lack of knowledge about the new ticketing system, the learning curve of operators resulting in slower journey times as well as slower handling in incidents. These problems have all now been overcome.

A problem that has yet to be fully rectified is the air-conditioning system on the LRVs. The 42 kw of cooling capacity proved to be inadequate in the hot summer with temperatures rising to as high as 35°C, the frequent opening and closing of doors given the short distance between stops, and the problem of dust and dirt that affects air flow and performance of the condenser units underframe. A HK$21 million scheme to upgrade the system to provide more than 60 kw of cooling capacity is now being implemented to be completed by spring 1993.

Patronage Estimates and Marketing Information

A passenger transport system like the LRT relies on patronage for financial viability. Patronage derives in turn from population and its distribution, trip rate factors, and trip distribution. As opposed to the urban metro system, which serves densely populated corridors with very high travel demand, the LRT's service area is developing new towns with rapidly changing infrastructure, population, and very different demographic characteristics, traveling requirements and patterns.

In Hong Kong demographic prediction is hazardous, and forecasting population distribution is even more difficult. Population in the TSA has grown at a slower pace than original estimates predicted, its distribution has changed, and patronage estimates have to be constantly revised. With 3 years of operating experience on board, patronage projections have, in the last 2 years, become quite reliable.

The open fare system and the unique competitive environment present special challenges to the LRT's marketing team. Unlike the "closed" ticketing systems of the heavy rail system that have very accurate computer records of how a single ticket is used and hence very accurate passenger movement statistics, the LRT's machines selling single-journey tickets can record only the origin stop but not the destination stop of the passengers. And with the growing popularity of the monthly and season tickets, now accounting for 50 percent of total journeys, the traveling characteristics of these passengers holding tickets cannot be captured at all and have to be ascertained by extensive market surveys.

The LRT's major competitors are taxis, public light buses and special purpose buses (factory and school coaches), and the private car. Information on the use of these modes is at best sketchy and sometimes nonexistent.

Hence extensive use of market surveys has been developed and fine-tuned in the past few years to obtain the necessary market information for planning services and future development plans. These include regular telephone surveys of multiride ticket holders to quantify monthly and season ticket usage; boarding and alighting surveys to gather statistics by time period, platform, and route from which peak-hour factors and vehicle occupancy ratios are ascertained; customer travel profile surveys designed to obtain passengers' traveling pattern, demographic profile, and use of tickets; trip rate and market share surveys; and usage and attitude surveys to obtain passengers' views on such issues as waiting times, cleanliness, safety, staff attitude, comfort levels, fares, and overall image of LRT services.

SERVICE PROVIDED

The LRT system now operates 19 hours every day from 5:30 a.m. to 12:30 a.m.

The fleet of 70 LRVs operates more than 1,600 trips daily on six routes, three within Tuen Mun and three between Tuen Mun and Yuen Long. The peak-hour headways range from 5 to 8 min on individual routes and from 8 to 10 min in between peaks. The combined headway in the peak periods on busy sections is between 1½ to 2 min against a theoretical design minimum headway of 1 min. Five coupled-sets are timetabled.

An average operating speed, including stops, of about 22 km/hr is achieved in the peak hours, and the longest route from end to end takes about 38 min to complete a 14-km journey.

Forty-two feeder buses, operated by the Bus Division of KCRC, feed the LRT on nine routes, covering more remote areas or areas where LRT extensions are not yet built.

OPERATING AND MAINTENANCE PHILOSOPHY AND PRACTICES

General Principles

The heavy reliance of the traveling public on Hong Kong's public transport system and growing customer expectations mean that the LRT is always expected to provide a highly reliable standard of service that can meet growing demands of the new towns. Hence very high operating standards are set and all equipment maintained to very high standards of availability and reliability.

A policy of preventive servicing and modular replacement of components is adopted in maintenance, whereby failures or faults are anticipated by servicing or replacement sufficiently in advance of possible breakdown or damage, both in system design as well as in the preparation of maintenance and service manuals. This ensures that availability of the system is as high as possible.

Great emphasis has been placed on operator training, not only on rules and regulations and the basic techniques for carrying out the normal duties expected of the job, but also in dealing with incidents and emergencies. Refresher courses are conducted incorporating experience learned from actual recent incidents.

Productivity Improvements

Productivity improvements are achieved firstly by carefully controlling headcount increases with better staff deployment and multiskilling to cope with expansion in network. Secondly, productivity improvements are achieved through cost savings in the maintenance areas. This includes constant review of maintenance schedules, design modifications, building up internal repair capability to minimize requirements for external repair, using cheaper contractual labor for low-skill and nonroutine jobs, closely monitoring and extending maintenance limits for wear and tear components, and sourcing of alternative and local material supplies.

Driver Training and Performance

LRV driver performance is closely monitored to ensure safety and efficiency. New recruits undergo a 6-week training program to be fully qualified as an LRV driver.

Drivers are trained to use defensive driving techniques that emphasize alertness during driving and quick response to anticipated irregularities. During driving practice, a commentary driving technique is also adopted that requires drivers to speak out what they are observing en route. Refresher courses are organized for each driver every 6 months.

Service Standards

High quality of service relies on the setting of high and measurable standards. Half-yearly as well as annual targets are set to guide and direct operational and maintenance activities. Those targets define the required achievements for the period in punctuality and reliability of service, the peak-hour availability of LRVs, the reliability of LRVs (interpreted as the number of kilometres operated per failure), the reliability of signaling system and fixed infrastructure, and the availability of ticket vending machines. Detailed passenger and operation safety standards are devised requiring continuous improvement efforts to meet these standards. Railway operational safety is monitored by the Railway Inspectorate appointed by the government.

PATRONAGE PROMOTION

With low fares charged and political constraints on fare increases, apart from productivity enhancements, the LRT has to rely on patronage growth to improve its financial performance. A variety of patronage promotion programs are regularly carried out to build up a core group of LRT users and stimulate off-peak optional travel.

Increased usage of multiride passes not only has the advantage of cementing customer habit and loyalty, but also can reduce platform congestion and relieve the pressure on the automatic ticket machines. The LRT has been organizing various promotional activities to encourage the use of multiride tickets, which, together with the fare strategies of offering more discount to the multiride pass users, have successfully increased the usage of monthly and season passes from some 30 percent in 1988 to 43 percent in 1991. These promotional activities include giveaway souvenirs, a joint promotion coupon book with local retail shops, cash redemption for domestic appliances, lucky draw, and bonus pack promotions.

SYSTEM PERFORMANCE AT A GLANCE

Table 6 gives an overall view of how the LRT system has performed and progressed in the past 3 years.

FINANCING AND PROPERTY DEVELOPMENT

The LRT has been built and operated without any government subsidy, apart from the fact that the KCRC does not have to pay for the formation and structures necessary for the wayleaves that have been provided from the government's public works program. The costs of forming the reserves amounted to about HK$570 million for the Phase 1 system and HK$700 million for the extensions. The rationale for this is that the formation constituted part of the region's transport infrastructure without which greater investment in roads would have been necessary.

KCRC financed the construction of the LRT and the operating deficit from its own resources—profits generated from its other businesses as well as commercial loans. The Light Rail Division is a business division of the corporation and a profit center. The LRT is expected in the longer term to be self-supporting financially and to generate a return on investment.

As with other rail companies in Hong Kong, KCRC has been allowed to develop property over its rail stations and depots. Residential and commercial development projects have been completed above the stabling yard in the depot and Tuen Mun terminus. One development above the Yuen Long terminus and one above the Sam Shing interchange are in progress. The two completed developments have generated a cash profit of about HK$700 million for KCRC and a recurrent commercial income of HK$11 million per annum. These profits have not been incorporated into the LRT's operating account and are used to finance KCRC'c capital expenditure program (including the LRT) and reduce total borrowing required.

TABLE 6 Overview of LRT Service in Hong Kong's New Territories

	1988[a]	1989	1990	1991
TSA population	507,000	526,000	568,000	600,000
Average daily patronage				
LRV	151,000	171,000	201,000	225,000
Bus feeders	30,000	37,000	34,000	37,000
Total	181,000	208,000	235,000	262,000
Total passengers carried (millions)	19.2	76.0	85.8	95.7
LRT routes (no.)	5	6	6	6
LRV trips per day (year end)	1,227	1,617	1,599	1,626
LRV-km operated (millions)	1.32	4.96	5.84	5.83
LRVs in morning peak-hour service (no.)	53	59	61	64
LRV peak-hour availability (%)	78	87	91	90
LRV reliability (km run per casualty causing delay to service of more than 3 min)	22,600	23,000	35,400	29,400
Service reliability (LRV trips run to trips timetabled) (%)	99	99	99	99
Service punctuality (LRV trips running within 3 min of timetable) (%)	99	99	99	99
Ticketing vending machine availability (%)	—	99.1	99.7	99.7
Peak-hour factor (%)	13.6	10.8	11.9	12.1
Single-ride ticket passengers as percentage of total LRV passengers	66	71	64	57
Average fare per boarding ($)	1.43	1.43	1.83	2.00
Detectable fare evasion rate (%)	—	0.32	0.33	0.20
Passenger complaints per million passengers (no.)	44.0	14.5	8.8	6.6
Fatal accidents (no.)	1	4	2	2
Total no. of passengers and public injured per million km-run	28.2	16.7	10.8	15.0
Incidents causing delay to service of over 20 min	6	13	7	7
System revenue (HK$ millions)	30	111	161	195
Direct operating costs (excluding corporate overhead) (HK$ millions)	64	129	166	193
Deficit after depreciation (HK$ millions)	82	111	104	104

[a]1988 statistics are from 18 September.

The KCRC adopts a risk-free approach in its property business, entering into joint ventures with reputable property development companies that provide the cash required for the government land premium as well as construction cost for the development in return for a share of the profits.

THE FUTURE

As described earlier, the extensions in Tuen Mun totaling 5 km and 10 stops and costing more than HK$300 million were completed in February 1992 (hence the operating system now totals 28 route km with 51 stops).

A HK$150 million 2-km extension with four stops is being built to serve another new town called Tin Shui Wai, which will house 135,000 people by 1996, to be commissioned by early 1993. To cope with patronage growth and to serve the Tin Shui Wai extension, 30 new LRVs costing almost HK$400 million are on order and they will be delivered between October 1992 and early 1993.

With continued population growth in the TSA and system expansion, it is projected that the LRT daily patronage will reach 420,000 by 1996.

Other potential extensions to the regional LRT system are on the drawing board, including a 2.1-km line in north Yuen Long—which will provide relief to the section running through Yuen Long town—further extensions in Tin Shui Wai, and a line in southeast Tuen Mun.

The government is now studying a rail link between the LRT and the urban rail system(s). The LRT could also possibly be extended northwards to the Chinese border at Lok Ma Chau to link with a proposed LRT system in the Shenzhen special economic zone that will connect to its Huang Tien Airport.

LRT systems have also been proposed for other areas in Hong Kong and these are being examined in detail by a rail development study commissioned by the Hong Kong government to be completed in early 1993. There is little doubt that the LRT has established its place in Hong Kong's public transport scene and will further grow and develop in the coming decade.

Low-Floor Light Rail Vehicle Development in Europe

JOACHIM VON ROHR

Growing pressure by handicapped groups in recent years has induced European public transport systems to improve accessibility not only on buses but also on the numerous and important (as compared with the case on the American continent) light rail vehicles and streetcars. The installation of wheelchair lifts has been generally avoided in providing greater accessibility for wheelchairs and for some elderly and handicapped persons because of the high cost of their installation and maintenance. Instead, European cities have tried to lower the car floor, at least partially, so that boarding and alighting becomes easier for the handicapped with and without wheelchairs. Various basic low-floor car designs developed by the active European car builders are described and compared. It is evident that no standardization has yet been achieved and that there are still more designs on the drawing board. Some projects are likely not to go beyond the prototype stage. Another problem is the comparatively high prices of these cars; a reduction in such costs appears possible only when fewer designs are being built in greater series. The problems arising from the joint operation of routes upgraded to light rail transit operation with high and low platforms and of classic surface streetcar routes equipped with low-floor cars throughout are reviewed.

On the North American continent, especially in the United States, handicapped groups have been applying pressure on legislators, government, and the public transport systems for the last 20 to 25 years to make the facilities accessible to handicapped people in general and to wheelchairs in particular. As a consequence, public money for construction of new facilities and new rolling stock is only being provided if these facilities and vehicles are easily accessible for the handicapped and for wheelchairs. Although in subways the remedies have been concentrated on fixed facilities, accessibility for the handicapped and wheelchairs for buses could only be achieved by remedies within the vehicles themselves. Light rail transit (LRT) and streetcar systems have not been the object of this pressure because there were only a few systems in a few cities and they had small fleets.

In Europe the pressure by the handicapped associations gained importance only during the last few years. This led to the need for the public transport systems to deal directly with the problem. For the subways in Europe, the same need is valid as for those on the American continent, that is, the measures required are limited to fixed facilities. The surface transportation systems in Europe, however (i.e., the buses and the existing and new LRT and streetcars), have responded differently than those on the American continent. They wanted to avoid lifts for wheelchairs, which are expensive to install and to maintain. Such lifts, when installed in conventional vehicles, provide accessibility for wheelchairs but do not help older or handicapped passengers, because they would still have to negotiate the usual steps at the doors to board and to leave the vehicles. The only other possibility to provide full accessibility was to lower the floor of the vehicles to a minimum value allowed by their structural design and thus avoid all steps at the vehicles' doors. First, buses were fitted with the kneeling system in which the front end was lowered at stops and a depressed floor was provided at the rear entrance with small retractable plates to bridge the gap between the bus floor and the platform.

Strassenbahn-Werkstatten, Rheinische Bahngesellschaft AG, Ekrather Strasse 30, D-4000 Düsseldorf, Germany.

Because of the longer working life of rail vehicles, existing rail systems have had a limited chance to build new vehicles accessible to handicapped and wheelchairs. Thus the first European low-floor rail vehicles were built for two smaller systems, one of which was built entirely new (Grenoble, France); the other, which already existed, replaced all of its car fleet at once (Geneva, Switzerland).

Although this paper deals with light rail vehicle (LRV) development, it is necessary to distinguish among

- Light rail systems built entirely new,
- Light rail systems or lines upgraded from existing surface streetcar systems, and
- Classic surface streetcar systems.

The systems built entirely new can be designed and built to be completely accessible to the handicapped and wheelchairs, either by providing high platforms throughout (e.g., Calgary, Edmonton) or by using low platforms or by loading from the street level and providing low-floor cars (e.g., Grenoble), or both.

The upgraded streetcar systems are usually not accessible to the handicapped and wheelchairs, or only partly so. They frequently have tunnel stations with high platforms of about 900 mm (35 in.) above the top of the rail (TOR) in the city center, but low platforms in the connecting surface stations. The high platforms in the tunnel stations can be made accessible by lifts (and any high platforms on the surface by ramps), but the cars, which must then have movable steps, remain inaccessible from low platforms.

The development of low-floor cars began on classic streetcar systems (*1–3*) in which cars are boarded or exited by means of three to four steps either from street level or from platforms about 150 mm (6 in.) above TOR. Installation of wheelchair lifts was excluded from the outset because of issues of reliability, high costs, and excessive time loss connected with their use.

In the introduction of low-floor cars on those systems, operation on the same routes of the existing high-floor cars with fixed steps or even of new light rail cars with movable steps with the new low-floor cars can produce problems such as the following:

1. Low-floor cars with a greater width (after the track centerline distance had been widened during maintenance);
2. Differences in the kinematic envelopes for whatever reason, for example, the unpowered running gear is not under the articulation;
3. The understandable wish to further increase the height of the platforms from the 150 mm mentioned earlier to about 200 to 250 mm (8 to 10 in.) above TOR in order to lessen the difference between platform height and car floor height, making access still easier; and
4. Use of outside-swing or swing-slide doors instead of folding doors.

Thus, before new low-floor cars are introduced into an existing system, a careful assessment must be made to avoid later problems with the operation of both old and new cars on the same route or routes. Factors to be considered here are wear of the tires, compression of the springs (primary and secondary suspension) under the load, wear of the rails (both vertically and horizontally), and construction tolerances for platforms with regard to TOR and track centerline; also important are differences within the kinematic envelopes of the existing older cars, which may have tapered ends, and the new low-floor cars. The assessment may result in major rebuilding of some stops situated on or near curves and also used by buses (*1,4*).

Therefore, entirely new-built systems are better because only one car type is used and an optimal layout can be achieved between position and height of the platforms and the car floor height.

LOW-FLOOR CAR DESIGNS

The three basic types of low-floor cars (*5*) are vehicles with

1. Low-floor area of less than about 15 percent of the total floor surface,
2. Low-floor area of about 60 to 70 percent of the total floor surface, and
3. Low-floor area of 100 percent.

All these designs are built as articulated cars. For streetcar and LRT systems, a four-axle low-floor car design appears to be technically unsuitable and uneconomic because of problems with the installation of the electric or pneumatic equipment, or both, and because of the reduced car length. Thus, these cars have been built only rarely during the last two decades.

Low-Floor Area Less Than 15 Percent

Designs with less than 15 percent low-floor area are usually an outgrowth of standard streetcars, which have a floor height of about 850 to 900 mm (33 to 35 in.) over TOR. All vehicles are three-section, eight-axle articulated cars in which a small part of the floor in the center section has been lowered to a height of about 300 to 350 mm over TOR. The low-floor area is thus only sufficient for two wheelchairs. Fixed seats are almost impossible; only tip-up seats can be used. Between the low- and high-floor sections, usually two to three steps (rarely four) have to be provided.

Because of all these limitations, such low-floor cars as those running in Freiburg (*6*), Würzburg (*4,7*), and Mannheim and Nürnberg in Germany; in Basel, Switzerland; in Nantes, France; and in Amsterdam, Netherlands (*8*), can only be considered a bad compromise. Because they could be built quickly, and especially because existing powered and unpowered trucks could be used without any problems, they were used mostly to offer handicapped passengers some relief. In some of these cases (Mannheim, Nürnberg, Basel, and Nantes) existing two-section, six-axle cars have been converted into three-section, eight-axle cars by adding a center section with a low-floor area.

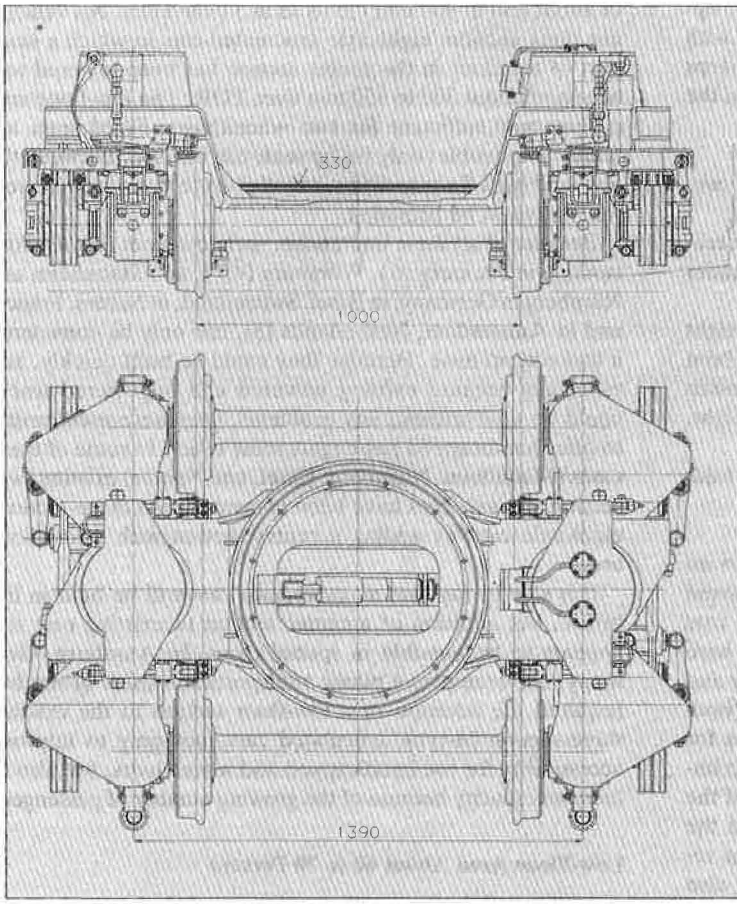
It is safe to say that no more such cars will be built in the future, but addition of a center section to existing cars still appears to be possible in special cases. In Augsburg, Germany, for example, a public transportation users group has required the addition of a low-floor section to the existing three-section M-type articulated cars, not only to improve accessibility for the handicapped and wheelchairs, but also to increase capacity because of the growing number of passengers.

Low-Floor Area About 60 to 70 Percent

The car type that is most common at present has about 60 to 70 percent low-floor area. Because the floor area above the powered trucks at both ends of the car is not lowered, standard powered trucks can be used. Between these and across the articulations, the entire width of the floor is lowered to about 350 mm (14 in.) above TOR. Provision of ramps at the doors permits the entrance height of the latter to be lowered still more to about 250 to 280 mm (10 to 11 in.).

However, the design of these cars requires special measures for the unpowered running gear to achieve a continuous lowering of the floor between the powered trucks. At this time the following possibilities are available:

1. Trucks with very small wheels [diameter of about 350 mm (14 in.)] designed by Ateliers de Constructions Mécaniques de Vevey (*1, 9*) and used on the cars running in Geneva (*10,11*) and Bern in Switzerland and in St. Etienne, France.
2. Trucks with normal-diameter wheels supported on short axle stubs, which eliminates a through-axle shaft, used on Italian cars in Rome and Torino (*12,13*) as well as on cars in Grenoble (*14*).
3. Single (steered) axles under the center section, used by Bombardier-Rotax on cars in Wien, Austria, that are to be used exclusively on the U 6 *Gürtel* (Belt) route, which runs on viaducts, in tunnel, and on reserved surface track. Platform heights locally are generally 350 mm, allowing reduction of the low-floor height to only 440 mm (17 in.) over TOR and permitting normal wheelsets and providing a slope between the low-floor area and that over the powered trucks, which is 525 mm (21 in.) over TOR.



Technical characteristics
"Berne"-type bogies

		Bogie motor	Bogie carry-ing
Wheelbase	(mm)	1,800	1,000
Overall length	(mm)	2,600	1,450
Width	(mm)	2,150	2,060
for floor height at	(mm)	710	350
Wheel diameter (new/used)	(mm)	560/500	410/370
Transmission ratio	(i)	1:5.85	—
Hourly output	(kW)	155	—
Primary suspension	(mm)	25	25
Secondary suspension	(mm)	50	45
Transverse suspension:			
— primary	(mm)	± 8	± 8
— secondary	(mm)	± 25	± 30
Disk brake number		2	4
Magnetic pad	(kN)	2 × 52	2 × 34
Mass	(kg)	4,100	1,950
Maximum speed	(km/h)	70	75

FIGURE 1 Unpowered truck on Bern low-floor car.

4. Single wheels, also supported on axle stubs. Apart from the three prototypes built by Verband Offentlicher Verkehrsbetriebe [VÖV, now Verband Deutscher Verkehrsbetriebe (VDV)], to be described later, this design has so far been used only for the cars in Kassel, Germany (*1*).

Because these designs lower the entire floor between the areas above the powered trucks, most of the seats are located directly on the low floor. Only the designs using normal wheels with diameters between 550 and 670 mm (22 to 26 in.) require so-called podia along the inside walls of the cars because the wheels protrude into the vehicle. Seats have to be mounted on these podia, which can cause a problem if such cars have to be built for meter gauge, because the space between the podia (i.e., the aisle) will then be very narrow. As with the car designs mentioned in the previous section, two to three steps are necessary to connect the low-floor area with the high floor over the powered trucks.

Another problem with this car design concerns the purchase of tickets. On many European public transport systems, single-ride tickets are still sold by drivers. A passenger requiring a ticket has to board the car at the front door, using the two or three steps necessary because of the high floor. The passenger can then stay in the high-floor section or walk down two to three more steps inside the car to reach the low-floor area and later leave the car there. (Leaving the car from the front door is not desirable because it hampers the boarding passengers.) Newly built systems usually provide ticket-vending machines (TVMs) at every stop and thus avoid this problem. With existing systems, especially larger ones, use of TVMs would be very expensive because of the larger number of stops to be so equipped. Sometimes TVMs are installed on the cars themselves. This solution, however, creates other problems, which cannot be discussed in detail here.

Low-Floor Area of 100 Percent

As discussed in the previous section, a car cannot be built with a low floor over its total length because of the use of more or less conventional powered trucks. Changes in the design of the powered trucks are inevitable if a vehicle with truly 100 percent low-floor area is to be achieved. However, there are physical restrictions that cannot be overcome.

The overall dimensions of traction motors, gears, and wheels cannot be reduced to values that allow the low floor to be extended over the powered running gear within the total car width, even if every effort is made to reduce as much as possible the total car weight and thus the power requirements. It must therefore be admitted that cars that are termed 100 percent low floor are really not. The low-floor area is limited here to all door areas and the aisles. Passengers having to buy a ticket from the driver no longer face a problem, since the front entrance area of these cars is at the same level as the other areas. All (or most) seats are mounted on podia, which are necessary to cover those parts of the running gear that cannot be kept under the car floor, the bottom surface of which is only about 200 to 250 mm over TOR. Even when seats could be mounted directly on the low floor, this is not normally done in order to have all seats at approximately the same level. The arrangement is very similar to that in buses; passengers have to board the podia, which are usually about 150 to 180 mm high, before reaching the seats. The podia above the running gear are elevated with boxes on which the seats are mounted directly without any seat brackets.

As with the designs mentioned in the previous section, cars for meter gauge encounter the problem of a rather narrow aisle between the wheels of the powered running gear.

The following car designs (all prototypes) to which these criteria apply have been built:

- The Maschinenfabrik Augsburb-Nürnberg (MAN) three-section type for Bremen (*1,15*) and München (*16*), Germany. About 200 cars of this design have been ordered for Bremen, München, Braunschweig, and Zwickau.
- The VÖV types for Düsseldorf, Bonn, and Mannheim/Ludwigshafen, Germany (*17–19*).
- The Brugeoise et Nivelles (BN) LRV 2000 type running in Bruxelles, Belgium.
- The Società Costruzioni Industriali Milano (SOCIMI) S-350 LRV running in Milan, Italy.

MAN Low-Floor Car

The general design for this type (Figure 2) is based on the cars that have been running for about 30 years in Bremen and for 20 years in München, developed by the now-defunct Hansa-Waggon. The construction rights were taken over by MAN.

The design is characterized by trucks at the center of each section rather than at the ends and under the articulations of the car. Thus there are only as many trucks as there are sections, and no additional trucks as with standard articulated cars. In the new low-floor cars, in addition to a completely new car body, the standard powered trucks have been replaced by specially designed new ones. (The old cars all have two-sections with powered trucks only, but there are some trailers of the same design in Bremen.)

FIGURE 2 München-Bremen low-floor car.

The new trucks (*20*) have four independent wheels running on axle stubs mounted on an inside truck frame, which by its design allows a floor height of 350 mm (14 in.) between the wheels. Two of the wheels are unpowered. The other two wheels are driven by an AC motor via a longitudinal cardan shaft and two outside spur gear boxes connected by a transverse shaft under the floor and one gear box with additional bevel gears in order to transfer the rotation between these two shafts. The motor is located in the car floor on the side of the car without doors (the cars are single ended with doors only on one side).

The older cars had normal pivots and bolsters between the trucks and the car bodies and thus needed a rather complicated mechanical (later hydraulic) steering system to keep the articulation within the kinematic envelope of the car. The low-floor car dispenses with bolsters and pivots. Thus the trucks are connected to the car bodies only by simple rubber springs (or air springs, as in München) that provide the steering force and movement for the articulations and the secondary suspension.

Inside the car, podia 180 mm (7 in.) high cover the wheels, gear boxes, and motors. The modular design applied here allows cars with two sections and more to be built [the Bremen series order is for four-section cars, which will be 35 m (115 in.) long]. There is, however, a disadvantage with this design: the car cannot easily be built with 100 percent adhesion or as a double-ended car, or both. In both cases, the placing of the (additional, if applicable) traction motors is likely to present problems, because these would have to be located partly below the entrance areas, in which podia would be impossible.

VÖV Low-Floor Car

The most radical change from any conventional streetcar or LRV design has been achieved with the VÖV low-floor car in Germany, which was a joint development by four German car builders [Düsseldorf-Uerdinger Waggonfabrik AG (Due-

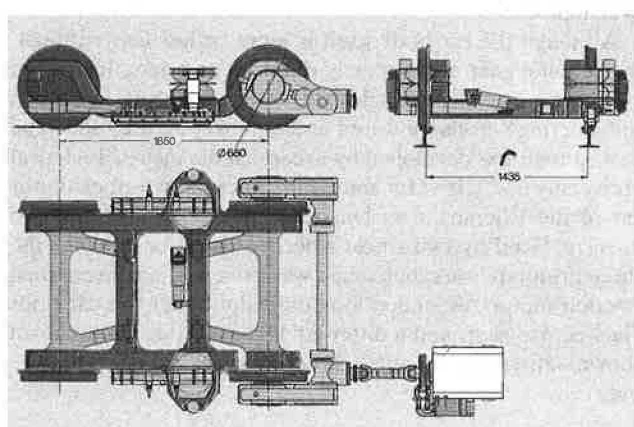


FIGURE 3 Powered truck arrangement of München-Bremen low-floor car.

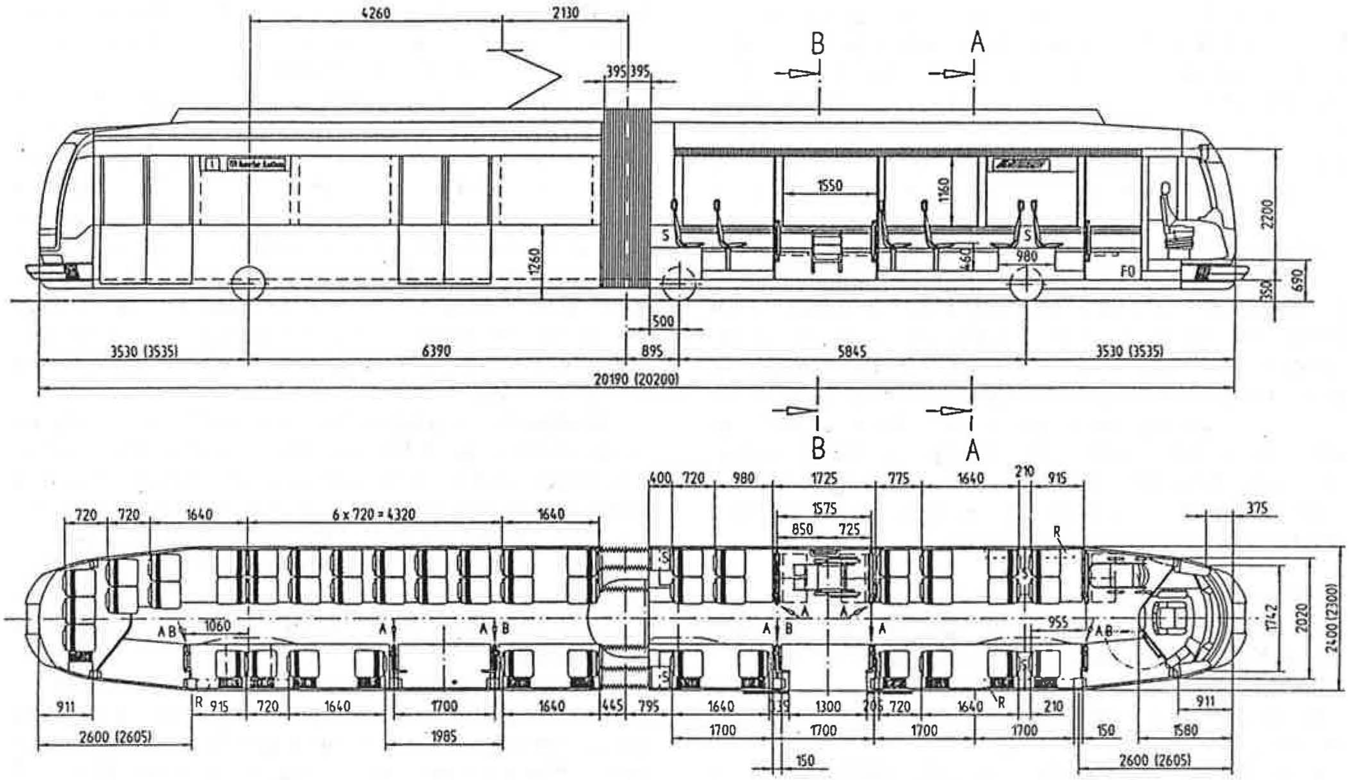


FIGURE 4 Principal dimensions of VÖV two-section low-floor car.

wag), Linke-Hofmann-Busch GmbH, MAN, and Waggon-Union], four German electric equipment builders (ASEA Brown Boveri AG, Allgemeine Elektrizitäts-Gesellschaft, Siemens AG, and Kiepe Elektrik GmbH), and four German public transportation authorities [Rheinische Bahngesellschaft AG, Düsseldorf (project leader); Stadtwerke Bonn, Verkehrsbetriebe; Mannheimer Verkehrs-AG; and Verkehrsbetriebe Ludwigshafen GmbH].

The development was promoted financially by the German Federal Ministry of Research and Development and the states of Nordrhein-Westfalen, Rheinland-Pfalz, and Baden-Württemberg.

Although the car body itself is more or less conventional, the running gear is completely different and new. Instead of conventional trucks or single axles with two wheels, individual self-steering wheels, powered and unpowered, are used. The basic design was developed by Frederich of Aachen Technical University and tested for some time under a two-truck motor car of the Rheinbahn in Düsseldorf whose front truck had been replaced by two single wheels as used later under the three prototype cars, but which was driven by a conventional traction motor suspended longitudinally under the car floor via a cardan shaft and a differential gear. After the tests had shown satisfactory results, three different prototypes were built:

1. A single-ended, two-section, six-wheel car 2.4 m (8 ft) wide with a steel body and four powered wheels under the front (A) section, of standard gauge, for Düsseldorf;
2. A double-ended, two-section, six-wheel car 2.4 m wide with a screwed aluminum body (ALUSUISSE patents) and four powered wheels under the A-section, of standard gauge, for Bonn; and
3. A single-ended, three section, eight-wheel car 2.3 m (7 ft 7 in.) wide with a steel body and six powered wheels under the front (A) and center (C) sections, of meter gauge, for Mannheim/Ludwigshafen.

The running gear (*21*), which is the speciality of these cars and was designed by Duewag and Bergische Stahl-Industrie (BSI), cannot be described here in detail. It consists of a frame the transverse members of which are depressed to permit a low floor. The wheels are supported on axle stubs, but these can rotate in a horizontal plane around a vertical shaft slightly outside the wheels for about 15 degrees to both sides of the transverse centerline through the two wheels. Both wheels are connected by a gauge rod (as with the front wheels of an automobile). Each of the powered wheels is driven by a 60-kW AC motor via two intermediate spur wheels and a system of planetary gearing and three bevel gear wheels that allow the rotation of the stub axles around the vertical shafts. The unpowered wheels are provided with the same gear boxes (which are part of the running gear frame) but do not have motors or gear wheels. In order to provide smooth running and to avoid shocks when the wheel flanges touch the railhead, the wheel profile has been modified as compared with the standard ones used for streetcars and LRVs running on grooved rail track.

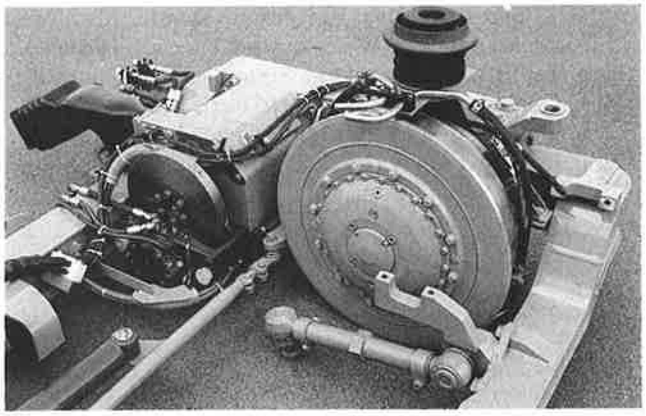


FIGURE 5 Powered single-wheel running gear of VÖV low-floor car.

All three prototypes are still being tested, and it is not possible to predict when they will go into revenue service nor when they will be ordered in series. However, the unpowered single-wheel running gear has already been used in a slightly different design under the central section of the Kassel cars mentioned earlier, and they will also be used in the Bochum-Gelsenkirchen, Rostock, Halle, and Bonn cars now under construction.

BN LRV 2000

The BN LRV 2000 runs on trucks with four single wheels, two of which have a small diameter [375 mm (15 in.)] and two of which have a large diameter [640 mm (25 in.)]. Each of the large-diameter wheels is powered by a 40-kW AC hub motor via planetary gearing. The truck looks very much like the maximum traction type used frequently for streetcars before the advent of the President's Conference Committee (PCC) car. The individual parts of the truck frame are connected by various link rods, so that it fits easily into even narrow curves.

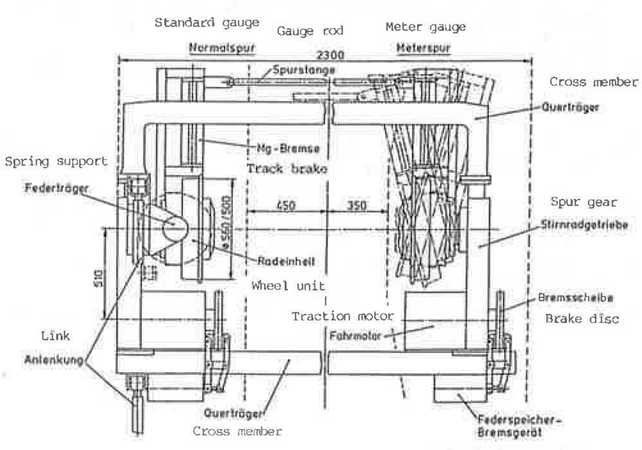


FIGURE 6 Diagram of single-wheel running gear of VÖV low-floor car.

The body of the prototype car was developed from that of a guided bus and has a floor height of 350 mm above TOR. Seats above the trucks are mounted on podia as with the other cars of this group. Cars of this design have been ordered for Bruxelles with a short center section as in the Grenoble cars and a four-motor, equal-wheel truck beneath.

SOCIMI S-350 LRV

The SOCIMI S-350 LRV is, so far, the only double-truck car (without articulation) built as a low-floor car. The four wheels (550 mm in diameter) of each truck are again supported on stub axles. Each wheel is driven by a 20-kW AC motor mounted directly on the outside of the truck frame via a double-reduction spur gear. The low transverse members of the truck frame permit the car floor to be lowered to 350 mm. All seats above the trucks are on podia, and the electric equipment is located in boxes under the other seats.

The first series of cars built with this design will be for Strasbourg, France. It will be a rather unique car with seven sections, the four small ones (two at the ends with the driver's cabs and two in the middle) having trucks under them (three powered, one unpowered).

FURTHER LOW-FLOOR CAR DEVELOPMENTS

Although the cars described in the preceding sections (except those for Bruxelles and Strasbourg) have reached the prototype stage or have already gone into series production, there are further developments in low-floor cars that have not yet left the drawing board.

Among the car designs with 60 to 70 percent low-floor area, two three-section types should be mentioned that are equipped with four conventional trucks (in both cases with powered ones only) and where the low-floor area is about 40 to 50 percent. These are new cars for Freiburg and Sheffield, England, to be built by Duewag that have to negotiate heavy gradients up to 9 percent. For this reason, all axles must be powered.

A car for Frankfurt/Main (*22*), also to be built by Duewag, is still in the design stage. It will be similar to those for Bremen and München mentioned earlier in that the trucks are below the center of each section, but it will be a double-ended car. Each of the four wheels of the truck will be driven by a water-cooled, 50-kW hub motor via planetary gear. The Frankfurt car will have three sections and powered trucks under the end sections only. The unpowered truck under the center section will have wheels with a slightly smaller diameter, thus allowing the podia here to be somewhat lower.

A further interesting development is being pursued by Simmering-Graz-Pauker (*23*) and tested in Wien with a prototype center section between two trailers modified accordingly. The single wheels are arranged in the transverse centerline of the articulation. When powered, they are driven by vertical AC motors in the articulation portal. This design allows the floor height to be further reduced to 200 mm (8 in.) in the center of the car and to 150 mm (6 in.) at the doors. Clearance below the floor would be only about 130 mm (5 in.), which could present a problem at the peaks of vertical curves.

Schindler Waggon and Schweizerische Industrie-Gesellschaft are working on still another concept known as Cobra 370. This car will use a truck design with steerable wheel sets having independent wheels, the two on either side driven by a longitudinally mounted motor via cardan shafts and bevel gears. The wheels sets are steered by the articulations via a system of rods.

CONCLUSION

This review has shown that the development of low-floor cars has not yet finished. The prospective customers can select from more than a dozen designs, all of which have their advantages and disadvantages. The choice among them is made easier if prototypes have been built and tested. For an existing LRT or streetcar system, careful assessments will have to be made before low-floor cars are introduced, and these evaluations may result in excluding one or another design. The maintenance costs should be kept in mind. Another problem is the suitability of any existing shop for the maintenance work. In most low-floor car designs, it is necessary to move much of the equipment to the car roof. This requires elevated service platforms in addition to those existing for pantograph, lightning arrestor, main circuit breaker, and resistance maintenance. The maintenance shops, in which roof equipment components weighing up to 500 kg (1,100 lb) have to be removed and reinstalled, must have sufficient roof height to accommodate the necessary cranes.

In spite of all these problems, it is quite safe to state that almost all new LRV or streetcar procurements will have to be some type of low-floor car. However, low-floor cars cannot be used on those systems, especially in the western part of Germany (e.g., Hannover, the Ruhr area cities, Düsseldorf, Köln, and Frankfurt), where streetcar routes have been upgraded to light rail operation and have high platforms in the tunnel sections and at some surface stations and low platforms elsewhere. This may lead to a situation in which, after all the old streetcar-type vehicles for the remaining surface routes of these systems have been replaced by new low-floor cars, total accessibility is available, whereas on the light rail routes it is not. How this situation could be improved or changed is a consideration for the future.

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Part 2
Planning and Finance

Light Rail Transit and Effective Land Use Planning: Portland, Sacramento, and San Diego

FRED GLICK

The economic benefits of integrating effective land use planning with light rail transit (LRT) corridors are becoming increasingly obvious. Coupled with land use planning, opportunities for successful economic development greatly increase through careful corridor selection. Land use planning is more than just incidental to the transit corridor development process. Economic development can be a central goal of regional LRT corridor selection. Effective land use and LRT project coordination is beginning to change the shape of some North American metropolitan environments. Portland's leadership in regional transportation policy and land use planning philosophy is viewed as highly innovative, but other communities also are making creative efforts at effective land use and LRT coordination. Generally such efforts focus on two distinct types of development approaches: economic revitalization coupled with infill development along already developed corridors and newly developing areas within a region where LRT currently does not exist. North American cities that have undertaken land use programs in conjunction with contemporary light rail transit corridor development include San Diego, Sacramento, and Portland. In Portland, land use is the focal point and keystone of the region's planning strategy. Successful LRT corridor development and successful ridership levels ultimately can be optimized through regional coordination of land use planning by cities undertaking regional rail system development.

On the basis of a brief survey of three North American cities (through September 1991)—San Diego, Sacramento, and Portland—it appears that coordination of land use planning and light rail transit (LRT) varies greatly from region to region, even in locales with existing and expanding LRT systems. True LRT and land use integration appears most likely within a metropolitan area when regional-scale coordination efforts are undertaken.

SAN DIEGO

The San Diego area has recently undertaken a regional effort to increase development densities in transit corridors. Driven by air quality issues and traffic congestion, as well as urban sprawl, a problem solving regional approach has been taken to improve the transportation systems, air and water quality, and the overall quality of life in this southernmost region of the California sun belt. These desired improvements have led to numerous overlapping programs within San Diego, all designed to achieve the same goal—better quality of life. To date these programs have not been coordinated on a regional level. The desire is to develop land and communities in a more compact fashion—urban design and planning that establishes an urban pattern and form—integrated with light rail transit facilities toward LRT corridors.

The California Air Resources Board directs all local air pollution control districts to gain compliance with the state's Clean Air Act. The regional Council of Governments is developing a transportation demand management program, focusing on reducing traffic congestion and reducing use of single occupancy vehicles during peak hours. The San Diego area currently has no parking management plan, but within two blocks of LRT stations, some degree of parking controls is necessary to achieve a coordinated response to the consolidation need brought about by the inclusion of LRT in the land development fabric. To reduce vehicle trips and length of trips, land use is increasingly seen as playing a major role.

To date efforts to promote transit-oriented development in the San Diego area have consisted of medium- to large-scale, mixed-use projects to encourage more transit trips and fewer auto trips. Examples of this approach include two significant projects developed integrally along and around the LRT system: the MTS/James R. Mills Building, a public-private partnership development (*1*) and One America Plaza, a wholly owned private development project (*2*).

MTS/James R. Mills Building

The MTS/James R. Mills Building is located at the Imperial and 12th Transfer Station and serves as a regional transportation center for downtown San Diego. It is located where three trolley lines and several major transit bus lines converge and includes a unique 10-story facility featuring a creative design spanning the trolley tracks. In this regard, it serves as a model development project for integrating LRT and commercial or office development. An impressive 15-story (233-foot) free-standing clock tower adds to the architectural presence of the building, combining to serve as a landmark and as a testament to the vision of the development team. A public-private partnership between the Starboard Development Corporation and the San Diego Regional Building Authority served as the development team. The Regional Building Authority was a joint powers agency that involved the county of San Diego and the Metropolitan Transit Development Board (MTDB).

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As MTDB's Limber notes:

> The use of fast-track, private sector design/build techniques to construct and fully furnish this turnkey project allowed occupancy just 14 months after ground breaking. The entire timeline from project conception to completion took less than 3-½ years. The $35 million project was financed through the sale of $43.6 million in tax exempt lease revenue bonds. (*1*)

Created by the state Legislature in 1975 and empowered to plan, construct, and operate mass transit guideways, MTDB was best known as a guideway development organization during its first 10 years. Because MTDB served as the policy setting and overall coordination agency for public transportation in San Diego's metropolitan area to perform near-term planning, Joint Development became an obvious evolutionary opportunity for the agency with the expansion of its light rail system. San Diego trolley started operating in 1981. In 1983 MTDB's Board of Directors acquired a 2.65-acre parcel for future use as a transfer station between the agency's south and east LRT lines. MTDB's goals for development of this site were (1) to develop a project that would be cost-effective for its own needs, and (2) to serve as a model for future private-sector participation in mixed-use projects at transit facilities. (MTDB acquired the Metropolitan Transit System in 1985.)

A team of expert consultants was called in to assist in the developer solicitation process, evaluate the proposals, and make recommendations on developer selection. In late 1985 a request for qualifications was issued, calling for developers to submit their qualifications to build an administrative office building of 40,000 ft^2 while maximizing additional office space for private occupancy and ground floor retail space to serve the building's occupants. On-site parking was also a design parameter. Through extensive local discussion, political negotiations, and development team input, the project scope had increased by spring 1987 to a 10-story, 180,000-ft^2 building with an adjacent parking garage and 15-story clock tower.

The architectural team was given explicit instructions by the MTDB directors "to design an edifice which did not look like just another office building." Civic pride and revitalization for the downtown skyline was their primary motivation. The project became a complete turnkey effort, with construction costs developed integrally among the architect, interior designer, and contractor. Revenues from the parking garage were dedicated to offset property management costs and projected operating expenses with any surplus offsetting the debt retirement payments of the county and MTDB. The project's successful implementation can be credited to close coordination among the developer, the construction manager, and the clients on all aspects of the design/build program.

A wonderful example of how the project became "a success through self-fulfilling prophecy" was given by Jack Limber, General Counsel, San Diego Metropolitan Transit Development Board, who wrote:

> As construction progressed, a question arose as to where we would obtain a clock for the 15-story clock tower. Swiss Bank Corporation (which had secured the bond holders' interest with a letter of credit) shocked us with the announcement that they had arranged for the donation of a clock from Ebel of Switzerland. Presented as a gift to the citizens of San Diego, the clock has been valued at $700,000 and exemplifies the special attention given to this project by Swiss Bank Corporation. The tower, most appropriately, has now been dedicated the Ebel Clock Tower. (*1*)

Limber concluded that there were some lessons to be learned from this successful joint development project effort by MTDB. These included (*1*)

1. Choose the best team to develop a project concept—do not let the concept drive the selection.
2. Use a qualified local development team because their motivations to ensure a successful project will go far beyond their economic return on the transaction.
3. Set the project budget and schedule fairly, with recognition for changes.
4. Dare to dream and challenge others to implement those dreams as their own.

America Plaza

Located on the Bayside Line, an LRT loop within the Centre City area, America Plaza will likely become an important destination in the fabric of downtown San Diego. Its location can be considered the hub of all public transportation including trolley, bus, rail, and air (it is within a short drive of San Diego's airport). This, combined with its proximity to the waterfront and walking distance to hotels, retail, and services, will ensure the project's long-term success. Located just three blocks from San Diego Bay, the mixed use development is situated on 3 acres and will have three major components:

- A 34-story, 565,000-ft^2 office tower—1 America Plaza; construction cost is $125 million.
- A 15-story, 272-room luxury all-suite hotel—a Guest Quarters Suite Hotel; estimated construction cost is $42 million.
- A Transportation Arcade that will link the office and hotel buildings with its crescent-shaped, fully enclosed trolley station, which will connect the existing downtown trolley service and the Bayside Line, which opened in 1990. Also featured will be 42,000-ft^2 of retail and restaurant space. Estimated construction cost is $4 million.

A four-level subterranean garage beneath the two-block project will provide 1,250 parking spaces.

America Plaza was sited and designed to take advantage of the downtown trolley service, the Bayside Line, and the bayfront. The project area overview prepared by the developer(s) clearly capitalizes on San Diego's marvelous qualities. Its climate, economy, and continued population growth remain attractive when compared nationally. Housing and employment trends will continue to increase more than national and state trends and will boast an average retail per capita income increase over the next 20 years of 40 percent, compared to 29 percent nationwide, according to Starboard Development Corporation (*2*).

SACRAMENTO

The Sacramento metropolitan area has undergone unprecedented growth over the last 20 years, resulting in greater congestion on Sacramento's streets and highways. Innovative alternatives have been sought to improve the flow of both traffic and people. The Sacramento Regional Transit District has become increasingly aware of the potential benefits brought about by integration of land use and LRT system development. The following efforts have been undertaken since 1987 and include several responses by regional agencies to deal more effectively with the challenges arising from the interface between land use and LRT.

Coordination of Land Use and Transit

In 1987 the Sacramento Regional Transit District produced a brochure identifying some practical suggestions for a transit-supportive environment and community (*3*). The brochure was intended for developers, planners, designers, consultants, public officials, and interested citizens to outline the benefits of including public transit in their planning and development activities.

The brochure focused on answering some of the following questions about land use and transit:

1. Why coordinate land use and transit?
2. What are Regional Transit's land use policies?
3. What are the problems?
4. What can be done to alleviate the problems?
5. What are the benefits (to the developer, to local government and the community)?

Continuing with examples of land use/transit coordination, the brochure cites the need to incorporate public transit into land development projects, concluding with a section on development of design guidelines for bus and light rail facilities. These guidelines illustrate what developers and local governments generally need to consider in the project planning process for smooth transit service (*3*).

Transit-Oriented Development

The transit-oriented development (TOD) concept is a growth strategy intended to assist Sacramento County in implementing the guiding principles of the land use element of the 1991 county general plan update. These principles include the following:

- Maximizing the use of existing neighborhood urbanized areas;
- Reducing consumption of non-urban areas;
- Linking land use with transit;
- Reducing the number of auto trips and regional vehicle miles traveled;
- Reducing air pollutant emissions;
- Providing a diversity of housing types; and
- Designing the urban area efficiently.

Linking land use and transit will result in more efficient patterns of development that support a regional transit system and make significant progress in reducing traffic congestion and air pollutants. Transit-oriented development with mixed land uses within a pedestrian-friendly area connected to transit allows for minimum environmental and social costs while providing for growth.

As described in *Transit-Oriented Development Design Guidelines*:

> Transit-Oriented Developments are mixed use neighborhoods, between 20 and 160 acres in size, which are developed around a transit stop and core commercial area. The entire TOD site must be within an average one-fourth mile walking distance of a transit stop. Secondary Areas of lower density housing, schools, parks, and commercial and employment uses surround TODs for up to one mile biking distance. TODs must either be located on a segment of the Trunk Line Network (either a light rail or express bus line) or on a segment of the Feeder Bus Line Network within 10 minutes transit travel time from the Trunk Line Network. (*4*)

The guidelines document has ample illustrations that help communicate design parameters for all aspects of transit-oriented development. These include project siting and design, land uses, densities, streets and circulation, pedestrian and bicycle systems, transit stops, parking requirements, open space and parks, and relationship to surrounding land uses.

Comprehensive Land Use/Light Rail Transit Guidelines

Today the Sacramento Regional Transit District (SRTD) is preparing a more comprehensive perspective on LRT and land use coordination. The agency's position is that the county standards—although a fine effort at formulating design guidelines for developing areas of the community—will not suffice for SRTD's larger goals. These goals include (a) enhancing transit in central development areas to better serve greater numbers of the public; (b) establishing urban form with relevance to the light rail transit/land use relationship; and (c) developing site design standards that are pedestrian-friendly and are components of transit system development that can be as influential to the public's acceptance of the project as the system itself. These critical geographical areas are seen as essential for increasing transit service to serve large numbers of the public more effectively. SRTD believes that LRT has the effect of improving a transit system's creativity.

PORTLAND

The Portland metropolitan area first undertook regional-scale land use planning when Oregon's statewide land use planning goals were developed in 1973–1974. The state's Land Conservation and Development Commission approved the goals at the end of 1974. Every municipal, county, and regional jurisdiction in the state has had to comply with these statewide goals in implementing its own comprehensive land use plan.

The Transit Station Area Planning Program (TSAPP), initiated in 1980 by the Metropolitan Service District (the Portland area's elected regional government) and funded by the Tri-County Metropolitan Transportation District of Oregon (Tri-Met), was the area's first effort at coordinating regional land use planning relative to a specific transportation program—the Banfield light rail project. With the region recognizing the importance of the relationship between land use planning, mass transit, and economic development, TSAPP became the first example in the United States of land use planning measures for a light rail corridor being implemented prior to the initiation of revenue service. Since that time, land use planning has become one of the primary reasons that the city of Portland's regional rail program has taken on a fairly aggressive schedule. The goal is to build five more LRT corridors to complete a seven-corridor regional system by the year 2010. Implemented simultaneously, regional LRT and regional land use planning can help shape the settlement patterns of a half million new residents projected for the region within the next 20 years.

Transit Station Area Planning Program

Between 1981 and 1982 planning for the Banfield light rail project in Portland focused on a 15.1-mi, 25-station light rail corridor to connect downtown Portland, East Multnomah County, and the city of Gresham to the east. In addition to providing the region with mass transit, one of the Banfield project's main objectives was to help shape development. Along the 5 ½-mi East Burnside portion of the corridor, the county's planners had long wanted to use light rail for shaping growth. All three jurisdictions agreed that light rail could also be the tool for restructuring zoning codes and development practices even before the line became operational. To support the regional goal, Tri-Met spent $1.2 million to achieve these planning and development objectives.

The area's regional government, the Metropolitan Service District (METRO) administered the Transit Station Area Planning Program (TSAPP) for all three jurisdictions and put in place a team of planners, architects, and economists. These jurisdictions each intended to create a new zoning framework for all land within each station area.

Ultimately the region has benefited from the TSAPP process in that new zoning ordinances and development policies were implemented prior to the construction of light rail. This action encouraged transit-oriented development during both the planning and construction processes. The region has seen more than $800 million in both private and public development built, designed, or enter planning stages since the line opened in 1986. All this development is either adjacent to the line or within a block or two of the system. Transit-related design with a spirit of pedestrian activity has resulted in the Portland region, fostering higher density residential growth and higher intensity commercial development. Such an approach is seen as necessary for successful implementation of future light rail lines, adding to the initial successes of the Banfield project (called MAX in operation for Metropolitan Area Express) in the areas of both corridor design and transit-oriented land use planning.

Much of the transit-oriented development is "retrofit" development—fitting new, higher density projects into existing neighborhoods, or re-creating neighborhood structures where such an approach is feasible. In Portland the approach has been to place new light rail lines in existing, mostly developed corridors, optimizing development and revenue generation (5).

Central Beaverton Development Program

The Beaverton area began developing in the 1840s and the city of Beaverton was incorporated in 1893. Today Beaverton is a first-tier suburban community poised for additional development and redevelopment. The central Beaverton area is composed of the original Old Town with a regular grid system of streets and blocks. Around the turn of the century, this area had a trolley system that was removed in recent years. Today the Old Town area is surrounded by highway strip commercial, auto-oriented malls, multifamily residential, and industrial uses. The area is vibrant and active with streets and parking lots choked with vehicles. Because of congestion and the low-intensity development pattern, it is difficult to be a pedestrian there.

With the promise of light rail transit in central Beaverton (i.e., the Westside light rail corridor as an extension of the Banfield light rail project), the city has sought to maximize the integration of land use and transportation developments. The downtown development plan seeks to arrange land uses and circulation elements in a manner that takes full advantage of transit. LRT station areas will be surrounded primarily by multifamily residential and office uses with auxiliary retail. Additional retail outside the LRT station influence area is now and will continue to be served by auto. The area's high-tech electronics firms can be served directly by auto, LRT, or a shuttle from LRT. An extensive open space system featuring bike and pedestrian paths is planned on pedestrian streets and along stream corridors. The bike and pedestrian paths will allow people living, working, shopping, and visiting central Beaverton to access various land uses and LRT without private, individual vehicles.

The Beaverton community has worked for over 3 years to develop its downtown development plan to give the community direction for the next century. LRT will be a reality in central Beaverton towards the end of the 1990s. With the downtown development plan as a start, the community will continue to develop the regulatory environment that will take full advantage of LRT. Four major components comprise the draft downtown development plan:

1. A concise statement of design and development principles that can be used to plot and measure future public and private development actions (these objectives are an outgrowth of an initial vision workshop and subsequent meetings with the Central Beaverton Advisory Committee;
2. A downtown framework establishing the type and location of desired land uses; the network of roads, pedestrian ways, and transit facilities to serve these uses; the design concept for integrating these land uses; and transportation facilities to ensure a well-functioning and attractive downtown that will be a source of community pride;
3. More localized guidelines for the design and development of the subareas of central Beaverton to ensure that the intended role and design potential of these areas will be realized; and
4. An implementation program for attaining the goals of this study as well as identifying which actions deserve priority.

The draft plan established for the city of Beaverton is based upon the premise that the city wishes to make a series of important decisions on behalf of a more positive, well-founded development future. These decisions include creating a major park downtown to serve future generations; combining local civic functions with cultural and community facilities into a centrally located civic center complex; allowing the downtown to become *the* major commercial center for the western portion of the Portland metropolitan area; and allowing the downtown to become a constantly functioning 7-day-a-week center for community life.

As of September 1991, the Beaverton City Council adopted the draft downtown development plan as submitted and included it as a significant element in the city's comprehensive land use plan (*6*).

Regional Rail Program

The city of Portland is assisting Tri-Met in developing a transportation planning framework for a regional rail system consisting of seven LRT corridors within the next 20 years. Five new corridors would be built in addition to the existing Banfield and Westside corridors. The city's primary purpose is to capture a large portion of the projected population increase of nearly 500,000 for the Portland metropolitan area over the next 20 years. The city would like to increase residential densities and employment centers within a quarter mile of each LRT station. At this time, the city is evaluating future corridor alignments regarding the need for zoning changes, identification of potential suburban activity centers, and associated public infrastructure improvements needed to support the plan. Future alignment studies and planning decisions include ridership projections and future employment and residential development opportunities along each corridor.

Regional Urban Growth Goals and Objectives

The Metropolitan Service District, the Portland area's metropolitan planning organization, is in the process of establishing regional urban growth goals and objectives. When combined with proposed bylaws for an ongoing regional policy advisory committee and a work plan for the next steps, the goals and objectives make up a package that the Urban Growth Management Plan Policy Advisory Committee will recommend to the Metro Council for adoption.

The goals and objectives, referred to as the RUGGOs, were prepared after an extensive public review process. The document begins with a background statement outlining challenges posed to the livability of the region by growth. A visionary statement about future citizen concerns sets the tone of the new regional goals established by Metro. The following examples represent some of the goals being considered:

Goal I is a procedural statement outlining the regional planning partnership needed to address growth issues. Significantly it calls for the creation of an ongoing citizen involvement program at Metro, the creation of a regional policy advisory committee to recommend to the Metro Council a course for regional planning, and the first written description of the process for functional planning in the metropolitan area. Functional plans each cover a single element of regional significance, such as solid waste, transportation, or water quality, that, when adopted, would become binding on the localities in the metropolitan area.

Goal II concerns the broad area of urban form. It focuses on maintaining the livability of the urban region through the preservation of environmental quality, the coordination of the location of jobs, housing, and infrastructure, and the interrelationship of growth in one part of the region with growth (or the absence of growth) in another. Specific objectives relating to the natural environment, the built environment, and growth management and the urban growth boundary are also included.

The importance of Metro's RUGGOs work relative to LRT is that these goals and objectives are being developed concurrently with expansion of the regional rail program. Consequently regional urban growth goals and objectives will affect regional land use planning along light rail corridors, both in shaping urban form and increasing LRT patronage (*7*).

Region 2040

The purpose of Metro's Region 2040 project is to better understand the alternatives for accommodating the growth expected within the region in the next 50 years and the choices that may be involved. This project originated with a recommendation made as part of the process leading to the adoption of the RUGGOs. The Region 2040 project is intended to guide the testing and implementation of RUGGO concepts. Products from Region 2040 will include an explanation of the likely outcome of relying on existing transportation and land use plans to accommodate growth within the region; up to five additional regional transportation and land use development alternatives; and criteria with which to evaluate the alternatives. The project will strive to include participation from citizens, cities, and counties of the region, special districts, business and trade organizations, environmental organizations, Metro committees, and the Metro Council. The work is expected to be completed by December 1992 (*8*).

CONCLUSION

Based on this brief survey of three cities, it appears that coordination of land use planning and light rail transit varies greatly from region to region, even in locales with existing and expanding LRT systems. The state of the art of LRT and land use integration seems to range from large, high-quality mixed-use and institutional developments (e.g., San Diego) to coordination of state, regional, and local layers of opportunity within the LRT/land use sphere (e.g., Portland). The large-scale development exhibiting LRT and land use integration within a single project in San Diego, for example, must be viewed as building blocks within the larger evolution of regional urban form.

A single, 15-mile LRT line is de facto regional in nature, almost always passing through several communities and cities. The existing environmental characteristics and development character inherent in each community vary as a result of physiographic, geomorphic, and development era differences. Regional-scale thinking combined with application of the educational tools required to raise the public's level of awareness about LRT and mass transit can stimulate the implementation of transit-supportive development.

Opportunity for true LRT and land use integration within a regional community (metropolitan area) appears to be greater when regional-scale coordination efforts are undertaken. Sacramento is turning toward regional scale land use/LRT coordination. Portland has established its RUGGOs and is beginning its Region 2040 planning process intended to establish both a vision and realistic goals for the Portland metropolitan area's evolving urban form into the next century. Regional goals and objectives can help structure a consistent framework for all involved in this process to gain a common understanding of the underlying principles involved in effective land use/ LRT coordination within a developing, regional LRT system. Communities within a region can learn from each of these by participating in establishment and eventual acceptance of the regional program goals as their own. Then with local implementation of these parameters, development of specific, LRT-related community design efforts indigenous to a particular locale can be undertaken while fostering regional consistency and integrity of urban form.

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Manchester LRT System

J. Roger Hall

The light rail transit (LRT) system in greater Manchester, Metrolink, has employed specific design features to lessen environmental impact within the city of Manchester and to facilitate full accessibility for those with mobility impairments. An economic evaluation was undertaken for Metrolink to compare it with other transport options and funding options were weighed to reduce the financial burden on the public sector and to find a way to transfer risk to the private sector. The specific financial options chosen to meet these requirements is known as "the complete concession approach." The unique approach was taken to developing bidding and contract documentation to encompass design, build, operate, and maintain requirements and to bid evaluation and project management.

The conurbation of greater Manchester has a population of some 2.6 million people who generate approximately 350 million passenger journeys per annum on public transport. Approximately 25 million of these passenger journeys are on the 16 rail radial commuter lines.

History was made in Manchester in 1830 when the world's first passenger railway station at Liverpool Road was opened. Manchester achieved another first in early 1992 when a light rail transit (LRT) system, Metrolink, which uses both existing rail and new track within the city center, went into operation.

The LRT project began in 1982. The Greater Manchester County (GMC) Council initiated a rail strategy study with the Passenger Transport Executive (PTE) and British Rail (BR). By 1984 the rail study group had recommended a light rail solution.

The PTE, GMC Council, and BR accepted the recommendation and in November 1984 the PTE deposited a private bill in Parliament seeking powers to construct a light rail system in Manchester. Royal assent for the bill was received in February 1988 by which time the secretary of state for transport had indicated that a government grant would be available subject to private-sector capital involvement.

A two-stage bidding process was embarked upon with the issue of documentation in October 1988 and the award of the contract to the GMA Consortium in October 1989. The first phase of the system, the Bury to Manchester Victoria section, was opened for public use in March 1992. The remaining sections through the city and to Altrincham are programmed to open in April and May 1992.

RAILWAY STRATEGY FOR GREATER MANCHESTER

The full potential of greater Manchester's extensive suburban rail network has never been reached because of the lack of city center penetration and cross conurbation links. Attempts to solve the problem date back to the birth of the railways: the first proposal for a Piccadilly to Victoria rail tunnel came in 1839. A succession of proposals over the past 150 years all failed to materialize.

When the GMC Council initiated a joint study with Greater Manchester Passenger Transport Executive (PTE) and British Rail (BR) in 1982, it was to examine a wide range of options. The options evaluated included BR-gauge central area tunnels, light rail with tunnel or surface links, and busways and guided busways. The preferred option emerged as light rail with surface links across the regional center because this offered a high level of benefits at modest cost and would therefore give the best rate of return.

As well as the technical and financial attractions of this option, public consultation exercises indicated that it would be a popular solution. Final approval was given only after examining similar systems overseas so that highway and traffic engineers, town planners, and politicians could be satisfied that such an approach would be practicable.

It was clear that it would not be feasible to build the entire 100-km LRT network as one project. Therefore a first-phase system was defined, embracing the city center sections and the two most heavily used local lines, those to Bury and Altrincham. Progress was delayed by two major changes, the abolition of GMC Council in March 1986 and deregulation of bus services in October 1986. The impact of abolition was limited. The GMC had effectively completed the strategic development of the light rail and the new Passenger Transport Authority was quick to affirm its unanimous support for LRT. Deregulation was potentially more significant. It meant the end of integrated transport planning and a new, unpredictable operating environment.

However, market research indicated that rail services would be fairly robust in the face of bus competition, and this was supported by actual experience after deregulation. Rail patronage increased as bus patronage fell.

The development of light rail was given a major boost, not just in Manchester but throughout the United Kingdom, in March 1987 by a unique demonstration of the rail industry's faith in British LRT proposals. A group of manufacturers set up a 3-week demonstration of a light rail vehicle (LRV) and associated equipment in Manchester. A Docklands Light Railway car was diverted on its way to London and fitted temporarily with a pantograph for overhead operation. A temporary timber station, part of a new low-cost station in the PTE's ongoing program, was erected, and a variety of static exhibits set out, including a section of typical sleeper and grooved rail track.

More than 10,000 people visited the demonstration, including professionals and politicians from every conurbation in the United Kingdom as well as members of the public.

Greater Manchester Passenger Transport Executive, P.O. Box 429, 9 Portland Street, Picadilly Gardens, Manchester, M60 1HX, United Kingdom.

FINANCIAL FEASIBILITY OF METROLINK

Detailed comparisons and benefits of Metrolink against other transport options were developed from the original 1982 study: Metrolink versus existing rail, full bus option, and a suboption (part only of system to be converted to light rail). The financial and economic appraisals looked first at capital, operating costs, and revenues. From each option total project cost was then subtracted from the economic benefits, using the existing rail figures as a basis. Although the total estimated cost of the network was seen as extremely modest it was evident that central government would have to have an extremely convincing case put to them if they were to entertain a grant application. The financial studies culminated in an application in July 1985 for a grant. There then followed an intensive period of meetings with the Department of Transport to clarify detailed workings and assumptions. Finally in January 1988 the secretary of state for transport announced in the House of Commons that the case for an LRT system for Manchester had satisfied his department, *but* he asked for options to be investigated for private-sector contributions.

Private-Sector Options

To satisfy the secretary of state's requirements, the Department of Transport (DTp) and the Greater Manchester Passenger Transport Executive briefed merchant bankers to investigate the options for private-sector contribution for Metrolink. Some 15 possible options emerged, and after discussion on feasibility five options were developed:

- Rolling stock ownership and operation,
- Complete system ownership and operation,
- Rolling stock ownership and operation *plus* infrastructure maintenance,
- Public-sector construction, system sold on completion, and
- Public-sector construction, system franchised on completion.

Each option was then evaluated against the stated objectives of risk transfer, private-sector contribution, and grants sharing costs. It is noteworthy that cheaper than any of the above options was full public-sector ownership and operation. This fact was accepted by DTp. However, as some form of private-sector funding was being sought then, private-sector ownership and operation of rolling stock was, in the PTE's view, the best of the sub optimum solutions. This option was also akin to bus industry privatization in which the operator buys the buses but does not pay for highway maintenance.

However, this elegant solution was not to be. DTp asked their merchant bankers also to look into the question of privatization and what has come to be known as the complete concession approach was considered. This required the private sector to bid for an amount of one-off grant to design, build, operate, and maintain the system. In this way as much risk as possible was transferred to the private sector even though this was likely to be expensive. Comparing this with PTE's preferred option, the difference was the requirement of the private sector to maintain the infrastructure at its expense. DTp appears to have preferred a larger one-off grant being given to the private sector than leaving the PTA/E with the ongoing public-sector revenue cost of maintenance of the infrastructure.

Complete Concession Approach

The complete concession approach means *one contract* to design, build, operate, and maintain Metrolink was awarded. The private sector will design and construct the system with all assets remaining in the ownership of PTE. The appointed contractor will then operate and maintain the system for a predetermined period of time. The contractor in essence will assess two aspects of the bid for the contract: the cost to design and build the system, and the value the contractor will pay for the right to operate.

By deducting the operating concession value from the cost to build the contractor will ask for an amount for a one-off grant for the contract. The grant will be funded from PTA (50 percent) and from the grant from the central government (50 percent). Because the contract is to design, build, operate, and maintain, this arrangement allows the contractor to be to some extent its own customer and also allows the contractor to make certain trade-offs between revenue and capital expenditure. It also transfers fully the design risk.

As part of evaluation of the bids these aspects played a major part but the physical characteristics and maintenance issues were also reviewed in much detail. What caused more concern, because of the need to safeguard the public sector's position, is the concession agreement itself, the document that transfers the operating rights to the private sector.

Concession Agreement Provisions

The PTE will grant the rights to operate the first phase of the system, comprised of parts of the existing British Rail lines from Bury to Victoria and from Altrincham to Cornbrook together with the city center link. For such rights to be granted, PTE will have vested in it some existing British Rail track, stations and buildings along the route, and will also be granted licences by British Rail in respect to other areas of track. In the future it may be feasible to have more than one operator on the system and therefore provision is made in the concession agreement for multiple operations over common sections of the track.

PTE is to retain ownership of all assets and infrastructure. To protect its assets it will have the right to inspect any part of the system including the rolling stock at all reasonable times.

The agreement is for a 15-year term but the bidders were given the option of submitting bids on alternative periods, either shorter or longer. As the contract is for a predetermined period it is important that the assets (which are owned by the public sector) are maintained to standards that will ensure that, on reversion, the system has not been run down.

Although PTE will require the contractor to participate in the concessionary fare scheme, the contractor will nevertheless be free to determine the level of fares. Failure to meet the levels of service and reliability will result in financial penalties being imposed. It is envisaged that measures of performance reliability will be determined by reference to lost train miles. These measurements will be made on a quarterly basis and can be audited by PTE.

Network expansion is a particularly complex area but the agreement will allow PTE to expand the system at any time during the period of the agreement after obtaining the necessary Parliamentary powers and the approvals of DTp and PTA. If expansion is feasible within the first 3 years then PTE will enter into negotiation with the incumbent contractor to design and build the expansion and then to operate the expanded network.

Summary of Privatization Option

Under the complete concession approach, in return for a public-sector contribution (which will be significant) and with the service frequencies set by the PTA/PTE, the contractor takes on an obligation to operate the system. In this way the public sector can capture the economic benefits. The private sector has promised to design, build, operate, and maintain a system that should be safe and reliable. The contract documents have to ensure the private sector lives up to that contractual promise.

METROLINK OVERVIEW

The requirements for Phase 1 of Metrolink can be summarized as follows:

- The modernization and conversion of the existing Bury and Altrincham suburban railway services to LRT;
- The linking of these two lines and Piccadilly Railway Station by new tracks (through the city center) laid "in street" with appropriate signaling and traffic management measures to ensure an efficient and reliable operation;
- The provision of six-axle, single articulated LRVs approximately 28 m long and 2.65 m wide (Figure 1) (LRVs must be capable of negotiating curves at 25-m radius and maximum gradients of 6.5 percent; maximum service speed should be at least 80 km/hr);
- The satisfaction of PTE's specified minimum level of service and PTE's preferred operating strategy; and
- The system to be fully accessible to those with mobility impairments.

FIGURE 1 A six-axle articulated LRV built for Metrolink by Firema in Italy with electrical equipment by GEC Alsthom.

These summary requirements were expanded into two volumes of detailed reference specifications for the bidding documentation. They were termed "reference specifications" because they provided a possible solution to PTE requirements. The selected bidders were however given the option to present in addition their own alternative solutions. To appreciate fully the extent of the total engineering works resulting from the reference specifications it is useful to outline salient aspects.

Route, Stations, and Civil Engineering Works

The Metrolink route from Bury Interchange through the city center to Altrincham Interchange is double-tracked throughout except for a short length through Navigation Road. The single-line section commences just north of Deansgate Junction, continues through Navigation Road Station, but immediately south of the level crossing becomes double again into Altrincham Station. The routes in line diagram form are as shown in Figure 2, and the Manchester city center proposed route and existing BR lines are shown in Figure 3.

The 19 existing stations on the Bury/Manchester and Altrincham/Manchester lines needed to be refurbished to make them more open and accessible. In addition five new stations needed to be built in the city center. Both the new and existing stations are to be fully accessible for those with mobility impairments.

In addition to the stations, the civil works involved in the project include the following:

- Upgrading and modifying existing track;
- Providing of new in-street track through the city center:
  - —Constructing an underpass at Cornbrook Junction;
  - —Renovating disused viaducts and bridges;
  - —Constructing a new viaduct alongside the G-MEX Exhibition Centre; and
  - —Providing depot and workshop facilities.

Power Supply and Signaling

The electrical power to the LRVs is to be a maximum of 750 volts direct current (dc) for both the on-street sections and the existing rail services. The new power supply equipment was required to be adequate for anticipated train loadings and also capable of extension to provide additional power for subsequent phases.

The defined requirements of the signaling system were automatic reporting of each train unit location via track circuits or transponders; and automatic routing of train units by activation of points using the train detection system. The signaling to be adopted must permit safe operation of trains at the specified headways.

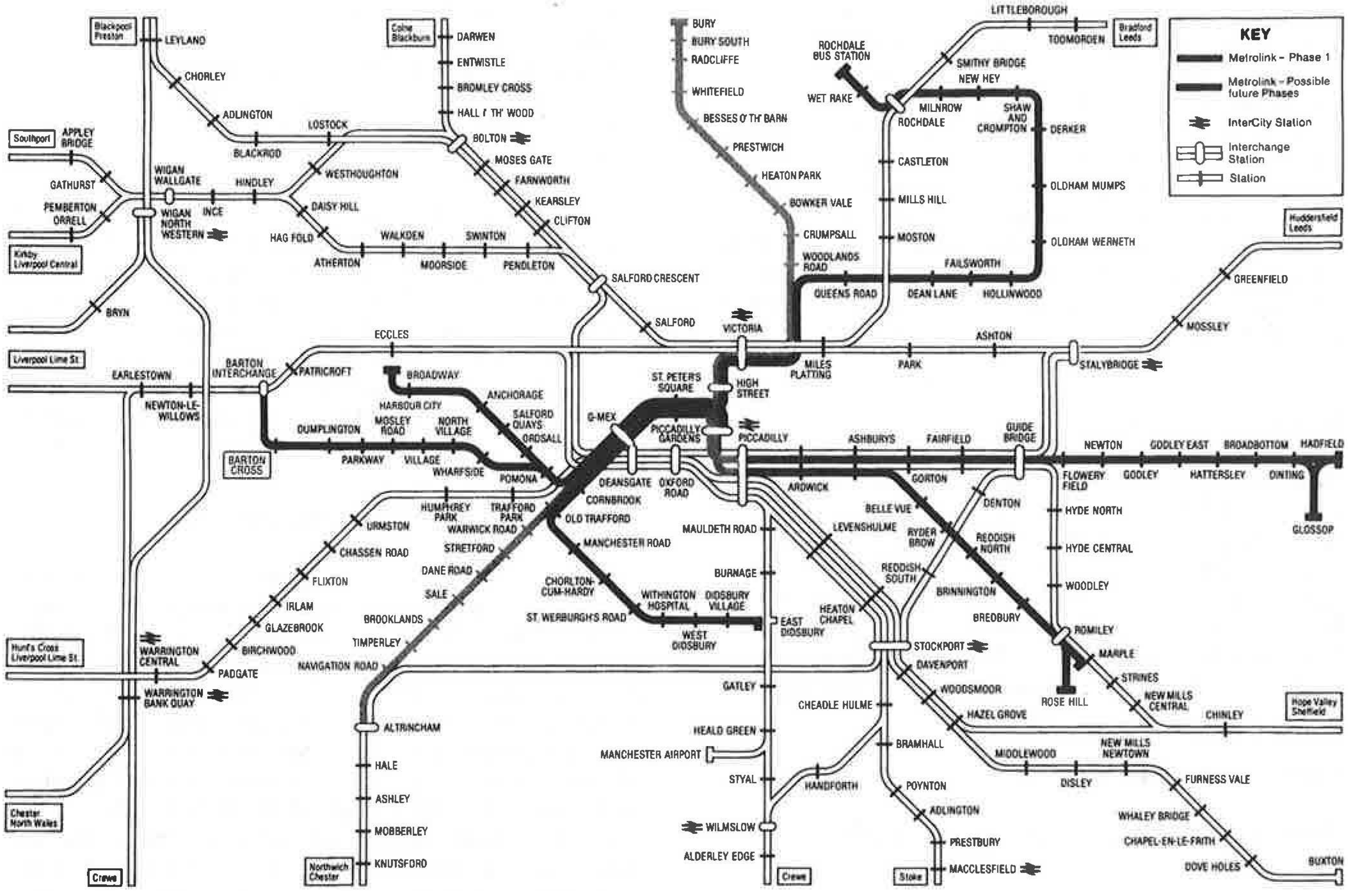

FIGURE 2 Proposed Metrolink routes.

The two rail signaling options available are conventional lineside block signaling fully track-circuited and automatic, or block signaling with cab signals. For on-street running the LRVs are to be driven by sight with drivers required to observe and obey highway signals. Stop/proceed instructions will be conveyed to the LRV drivers by means of a white semaphore indication to avoid confusion with highway red/green/yellow signals.

Train Services

Greater Manchester Passenger Transport Authority stipulated operational headways ranging from 5 to 15 min depending on location and day of the week. GMPTA also require that the Metrolink service be operated from 6 a.m. to midnight on weekdays and 7 a.m. to 11 p.m. on Sundays and holidays.

GMPTA also stipulated that the number of passengers should not exceed 130 percent of nominal load in the peak period and that no passenger should stand for more than 15 min in the peak period except by choice.

Environmental Design Aspects

A significant criterion of the design requirement was that the Metrolink system blend into the city of Manchester. Treatment of the LRT works was therefore required to be sympathetic to surroundings in terms of the surface finishes, station details, overhead line equipment, and power supply. Attention must also be given to minimizing noise levels during construction and when the system became fully operational.

The reference specification required that noise levels should not be greater than 79 dB(A) externally and 66 dB(A) internally with the LRV accelerating through 50 km/hr on ballasted track.

An additional important aspect is avoiding or at least minimizing of stray electrical currents from the operating system. The reference designs and specifications presented to the bidding contractors embraced these environmental aspects. Details of the city center station designs and outline forms of support systems for the overhead electrification system illustrate the attention given to environmental aspects. The design of all the key elements together with the corporate identity color scheme had to satisfy the city's planning committee.

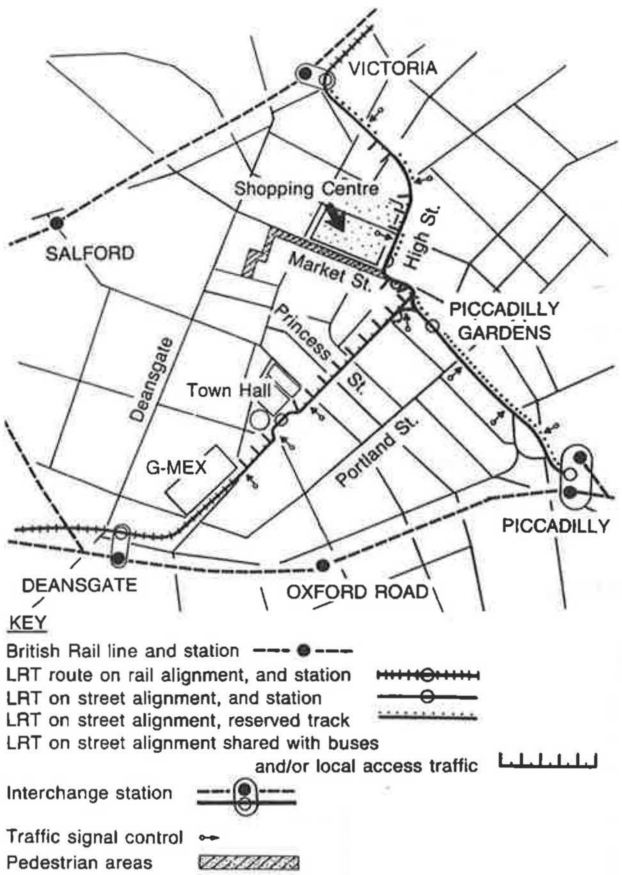

FIGURE 3 Metrolink route and preexisting BR lines in Manchester city center.

ACCESSIBILITY

GMPTA specifically required the whole Metrolink system to be accessible to those whose mobility is impaired. Included within this category are people in wheelchairs (with or without attendants), parents with baby carriages and strollers, people loaded with shopping, and others who, although ambulant, have difficulty in moving, particularly when using steps. It is estimated that in excess of 10 percent of passengers could be in this category.

In seeking a solution, the Metrolink design team studied how light rail systems in other countries had approached the problem. It was found that most LRT systems developed from older tramways did not provide full access for the disabled. High, full-length platforms would be difficult to accommodate in Manchester, particularly from the environmental design aspect. Low-floor vehicles, although an alternative, would present difficulties in modifying the high platforms at existing railway stations. Wheelchair lifts either on the vehicle or platform tend to be slow and unreliable as well as embarrassing to the user.

The reference solution presented in the bidding documentation was based upon a short-length high platform. The solution finally developed for Manchester has been termed a "profiled platform," which provides a level access to the two center doors of the LRVs (Figure 4). The remainder of the platform is at a low height, one step up from pavement level and therefore two steps from road level. A sliding retractable step is provided at these LRV door access points to give two 250-mm (10-in.) steps from the low-platform level into the vehicle.

BIDDING AND CONTRACT DOCUMENTATION

The contract would be to design, build, operate, and maintain the Metrolink with all assets remaining in the ownership of the PTE. The successful contractor or consortium is to operate and maintain the system for a predetermined period (i.e., the concession period).

A two-stage tendering process was adopted by PTE to reduce the cost of bidding by the would-be contractors and to reduce the time and resources needed by PTE to evaluate the bids.

The work undertaken by all the bidding consortia, both at Stage 1 and Stage 2, was most commendable. The quality of all the submissions was excellent. Great care was taken to fulfill the extensive and sometimes onerous bidding conditions.

The evaluation team, with its consultant support, worked long hours to ensure that a fair and constructive evaluation was undertaken. Certainly the response from a number of unsuccessful bidders would indicate that both the bidding procedure and evaluation had achieved just that.

Documentation

The contract between PTE and the contractor, Greater Manchester Metro Limited, was finally signed on June 5, 1990 although the contract commencement date was December 11, 1989. The design, build, operate, and maintain form of contract embraced a 2-year period and a fluctuating price at October 1989 base rates. With this somewhat unique form of contract the determination of each contract document was complex and certainly a time-consuming task. Even the logistics of the contract signing became a formidable task.

Constitution of Operating Company

The consortium established as Greater Manchester Metro Limited (GMML), the contractor appointed to build Metrolink, was a company created specifically for the contract and had therefore to create its own management structure, operating and financial contract procedures—a considerable task in itself.

Contract Program

A 2-year program was submitted as part of the tender documentation and was accepted under the terms of the contract as the contract period. The detailed works program required considerable consultation to ensure minimum disruption to

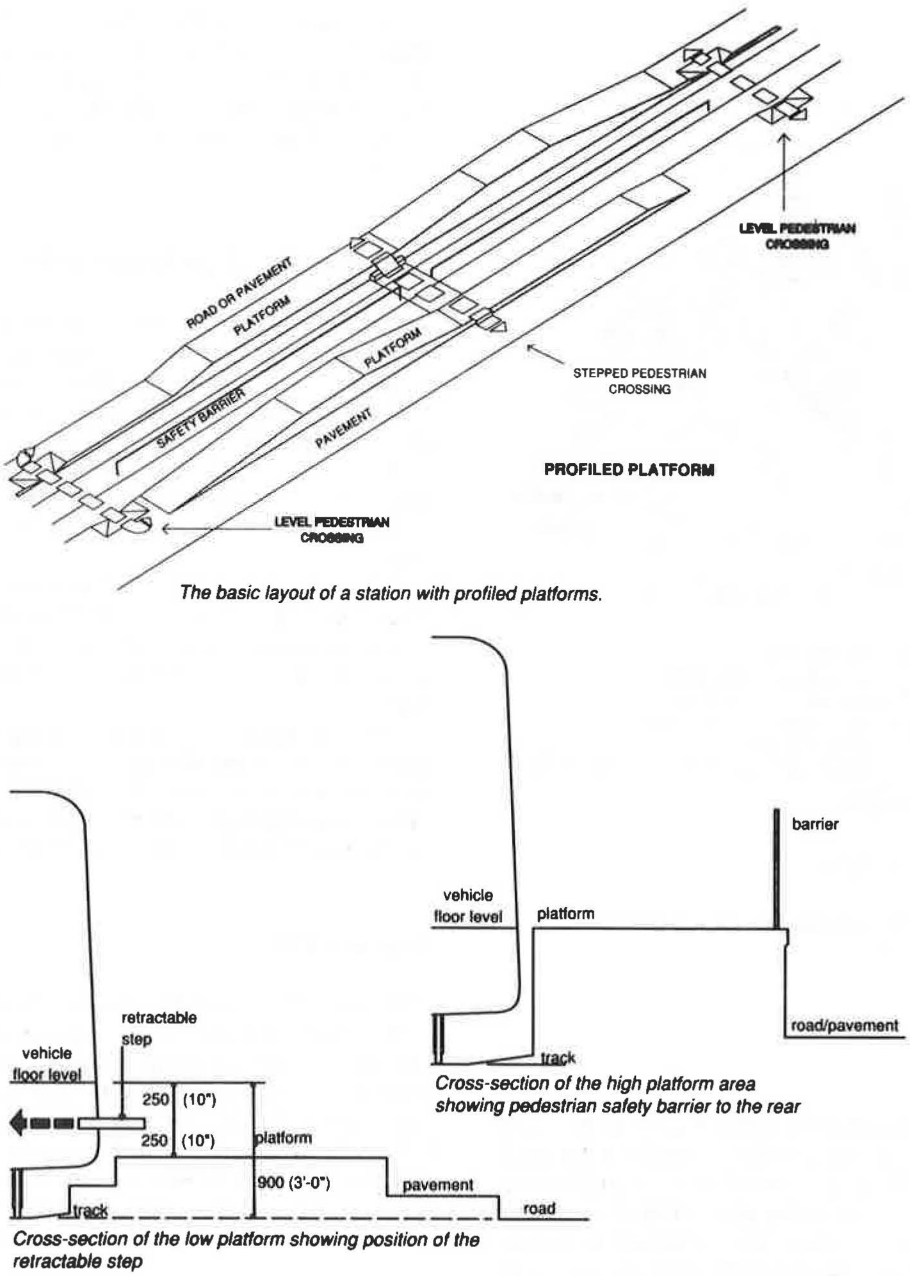

FIGURE 4 Proposed platform profile to make Metrolink accessible to those with mobility impairment.

both existing rail services and city center traffic. Emphasis within the program was given to minimizing disruption at critical periods. For example, the contractor ceased city center works for 2 weeks during the Christmas period. And during closure of the Bury Line and Altrincham Line rail services, alternative bus services were to be provided by PTE in liaison with local bus operators.

CONTRACT IMPLEMENTATION

No matter what format is chosen, each contract brings its own difficulties. With a design, build, operate, and maintain contract format that has so many new elements, the difficulties are more numerous and complex. Difficulties can also result from the organizational arrangements of the parties to the contract. PTE, for instance, has mechanisms that must be followed in addition to consultation and approval procedures and also has to take account of both local and central government policies and procedures. Likewise, the contractor, as a newly formed company with major shareholders that are also the principal subcontractors, had its own difficulties.

The implementation of a contract of the scale and complexity of Metrolink highlights many areas of weakness that, with the benefit of hindsight, could have been reduced or avoided. Many paths were followed, which if starting again certainly would not be trodden.

At present, it is not possible to examine all the elements of difficulty and, in particular, discuss issues of financial delicacy. Nevertheless it is possible to review some salient issues.

Design/Build Contract Format

Even excluding the elements of operate and maintain, the undertaking of a contract of the scale and complexity of Metrolink using a design/build approach has many difficulties. Although a design/build format enables a fast track approach to be taken and, in some cases, to achieve benefits, it does lend itself more to a "green field" site, rather than work in a busy city center and conversion of an existing rail system. With the complex liaison and approvals procedure required on Metrolink and the controlling interests of third parties, delays to the fast track process are inevitable with all the contract financial implications.

Although at the bidding stage considerable attention was given to the development of a reference specification, which proved valuable, experience has shown that the detail and extent of the reference specification should have been greater. Establishing priority and understanding on details with a contractor at the bidding stage is much cheaper than negotiating during the contract period.

The client-body and third-party approvals involved in a design/build contract present potential difficulties created that cannot be overstressed. Within a design/build program sufficient time never is allowed for the approvals procedure, possibly because at the time of bidding the contractor does not know what to allow. In addition to the formal approval procedure, a great deal of liaison is also required with specialist groups, all of which are time consuming and, in many instances, part of the approval process.

Organization

In simple terms, the contract exists between PTE and the contractor, GMML. A supply subcontract exists between GMML and GMA Group (i.e., GEC/Mowlem/AMEC). In strict contractual terms PTE has no part to play with the subcontractors but in fact in this case it is the subcontractors who are undertaking the design/build element of the project.

Throughout the contract it is therefore essential that all instructions and acceptances pass only between the PTE and GMML. Although this is simply said, with the almost daily task of exchanging detail and approvals between all the parties, it is not so readily maintained. With the added difficulties of ancillary contracts and the requirements of third parties, the difficulties multiply rapidly.

Service Diversions

The service diversion contracts were deliberately kept separate from the main contract, the main service diversion contracts being let some 12 months prior to the commencement of the Metrolink contract.

Prior to the letting of the service diversion contracts, considerable liaison took place with the city engineer, police, motoring organizations, and many other interested parties. As a result it was decided to separate the service diversion contracts from the main contract and undertake most of the service work in advance of the main contract. This decision has been criticized because it resulted in specific areas of highway being worked on on numerous and separate occasions by the service contractors only to be repossessed again by the main contractor for track laying.

Taking account of the different and, in some cases, extended lead times required by different statutory undertakers and the almost impossible task of coordinating two service contractors to work in the same trench, PTE continues to believe that the separate letting of the service contracts was correct. The disruption and delay to the main contract, if all service diversion works had been included in the main contract, would have been considerable—no doubt with a financial penalty to pay.

The success of the operation has been very much because of the efforts of the city engineer and police authority together with the support of motoring organizations and, last but not least, the traveling public of Manchester.

Unforeseen Work

Unforeseen work covers specific physical work not known before awarding the contract and also the unknown requirements or detailed understanding of third parties as existing at the time of contract signing.

All the bidders were given volumes of data bank information so that they would have as much information as possible about the current state of the physical work. It was up to each bidder to use the information or further investigate before determining a contract price.

The difficulty for PTE was to ensure or know that all elements of existing conditions had been covered. Of greater difficulty was to determine the degree of change likely in the conditions of work before the hand-over—particularly if some elements of the contract had delayed hand-over dates within the contract period. To agree on both a conditional state and, in some cases, responsibility for correction over and beyond the bid price puts considerable strain on the parties.

Public Relations

Both before and after the contract was awarded, PTE and GMML gave considerable attention to public relations. In particular PTE has endeavored through media coverage to inform the public of greater Manchester precisely what was going to happen and to respond as appropriate to questions raised by the media and the public about specific difficulties.

PTE set up a dedicated team to liaise directly with all who had premises fronting the alignment in the city center. In addition to many specific difficulties dealt with as a result of work in the city center, the team also held liaison group meetings with residents and interested parties on the Bury and Altrincham sections.

During the contract period a joint working party was established between the PTE and GMML to establish a mutual public relations strategy to avoid duplication of effort and ensure a common basis was developed for all press releases.

This was particularly important during the difficult days when the temporary closures of the Bury and Altrincham lines had to be extended and of even greater significance when Metrolink's operation was delayed.

LESSONS LEARNED

With the somewhat unique nature of the design, build, operate, and maintain form of contract, it may be of value to state a few areas that would be reconsidered or improved if PTE were at the fortunate position of being at the commencement rather than at the concluding stages of the contract.

Form of Contract

Although suitable for some types of major contracts the use of a design/build format for a complex LRT project would need careful evaluation before being repeated. Particularly as the benefits, if any, of bringing in the operational elements within the building element have yet to be realized.

Reference Specifications/Data Bank

With a traditional redesigned format, the detail of specification would be reflected within the prebidding design. With design/build the necessary detail of reference specifications and data bank information should not be underestimated. The more that is included in specifications, the less that is open for debate, and this also removes any ambiguity as to what is and is not in the contract.

Third-Party Agreements

Irrespective of contract format (but even more so with design/build) the level of detail required in advance agreements and understanding with third parties should not be underestimated. Third parties in this instance include British Rail, the Highway and Planning Authority, building owners, and utilities. To itemize all the elements for consideration with third parties would be difficult except to say whenever it is considered that all the elements have been covered, the plain fact is, they have not.

Advance Work

Certainly experience has shown that the more advance work that can be isolated from the project, the less opportunity there is for disruption. The target should always be to present to the contractor as an ideal a "green field" site. Whatever sets out as good intent in combining work elements with different contracting groups always seems to conclude with a price to pay.

Contingencies

The level of financial contingency and "float" in respect to time never, in hindsight, appears sufficient. An appropriate formula does not exist to determine such allowances except that whatever is first considered—double it.

Time Scales

In general terms the time taken to develop the design, build, operate, and maintain form of contract (including the reference specifications and data bank information and the bidding and evaluation period) was just under 2 years. With a traditional predesign fully detailed specification and measured or approximate quantities (including the bidding period and evaluation), it may have taken 3 years. The approach therefore has possibly brought forward by a year the operation of Metrolink in Manchester. As yet the full cost has not been evaluated.

FUTURE METROLINK EXTENSIONS

As the Phase 1 Metrolink plan moves toward completion, the planning of new phases has continued. The routes identified in the earlier rail strategy study included conversion of BR lines to Oldham and Rochdale, Glossop and Hadfield, Marple and Rose Hill, and the former BR route to Chorlton and Didsbury. Two new routes have subsequently been added to serve Salford Quays and Trafford Park, and a possible diversion to serve Ashton town center has also being examined. The most recent proposal is a new line to Hulme as part of the Manchester City Council's "City Challenge" project.

Salford Quays is in essence Manchester's former docklands, which are now being developed for a variety of exciting new uses. An alignment has been established to provide a branch from the Phase 1 system at Cornbrook Junction, crossing the Manchester Ship Canal and serving a number of major developments in the Salford Quays area. A Parliamentary bill was deposited in November 1987 and enacted in 1990. The line to Trafford Park has been developed in close consultation with the Trafford Park Urban Development Corporation and Trafford Council, and is intended to encourage new development in this important area.

A fourth Parliamentary bill was deposited in November 1988 seeking powers to construct and operate the proposed line to Trafford Park, works on the Rochdale via Oldham line (excluding the extension to Rochdale town center), part of the Chorlton and Didsbury line, and an amendment to the Salford Quays alignment. The Trafford Park alignment leaves the Salford Quays line shortly after the Cornbrook Junction and follows a route to the south of the Ship Canal that links a number of major development sites. It terminates at Dumplington, the possible location for a major shopping complex adjacent to the M63 Manchester Outer Ring Road. This could also form a useful park-and-ride location for journeys to the regional center.

The Trafford Park route was withdrawn to meet some objections and resubmitted in November 1989 in a further Parliamentary bill, which also included powers to operate over existing BR tracks to Oldham and Rochdale. Royal assent was expected shortly.

In April 1988 PTE commissioned a major study to examine possible light rail extensions, to review their feasibility and costs, and to evaluate each extension in terms of operating costs, estimated passenger traffic and revenues, and the impact of each extension on local economic evaluation against a base situation without the extension. The study also assisted in prioritizing subsequent phases of Metrolink. The initial findings were reported to the PTA in July 1991.

A number of more detailed studies have also been undertaken of, for example, an extension of the Oldham-Rochdale line to serve Rochdale town center, a deviation to serve Oldham town center, and more detailed engineering studies on parts of the Salford Quays and Trafford Park alignments. More detailed studies to assess future options for the eastside lines serving Tameside and the eastern part of Stockport have also been undertaken.

The Rochdale town center extension and the remaining part of the Chorlton to Didsbury route were included in a second bill deposited in November 1989 which has recently obtained royal assent. The most recent bill, deposited in November 1990 (the seventh LRT bill promoted by the PTE), seeks powers for the diversion to serve Oldham town center. It has almost completed its passage through the House of Lords and will then pass to the House of Commons.

Despite this considerable progress in obtaining Parliamentary powers, a number of issues remain to be resolved before a firm program of extensions can be developed. These include, in particular, the method of funding—as it is unlikely that the government will authorize further grants unless private-sector developers make a substantial contribution. This may well be feasible in the Trafford Park and Salford Quays areas where major new developments are in progress that would benefit significantly from light rail access. However, the difficulties in obtaining funding make it unlikely that any of these extensions will be built in the near future, despite strong support from many bodies, including the district councils and development corporations.

CONCLUDING REMARKS

Since the Metrolink concept was developed, many difficulties have been encountered and some have been overcome. The early days of operation will no doubt bring more unforeseen problems both to the contractor and PTE.

At least to date the common aim has been to provide an LRT system for Manchester that both enhances and complements public transport within the conurbation for the benefit of the traveling public.

With the central core of a light rail system now established in Manchester, the possibility of extending the system to Salford Quays, Trafford Park, Dumplington, Oldham, Rochdale, Chorlton, Didsbury, and Hulme may not always be a dream.

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Istanbul: A Successful Turnkey System

PETER ALBEXON

For light rail transit (LRT) systems, turnkey procurement methods can offer cities more rapid construction, less risk, and assistance with financing the project. Turnkey arrangements are particularly useful for cities that lack an existing mass transit system with in-house expertise for developing LRT. Istanbul relied on the turnkey approach to construct a state-of-the-art, 24.2-km LRT system in two stages. The system was in operation within 30 months and a financing package was put together with the assistance of the governments of the countries involved in the project (Turkey, Sweden, and the United Kingdom) through the use of different export credit systems and by an international syndicate of some 16 banks. With the first stage of the system in operation, ridership has already reached 65,000 per day.

Before addressing the benefits of a turnkey system approach to light rail transit (LRT), some definitions are necessary. So-called turnkey deliveries can be on several levels, depending on how much responsibility the operator would like to put on the contractors. Still, turnkey means the supply of a system, or parts of the system, ready for operation.

One approach to turnkey systems is design/built. Design/built means that the operator or purchaser designs the system or parts of the system up to a certain point. After this initial design, contracts are awarded to one or several contractors who are responsible for the detailed design and supply. One of the contractors is also given the responsibility for the coordination of the total system.

Turnkey means that the operator or purchaser gives one contract to one contractor based upon a performance specification for the total system (i.e., more or less all the design work is carried out by the contractor). The contractor hands over the system ready for operation to the purchaser.

The contractor could also be responsible for arranging financing for the total supply. Financing could be made on commercial or more favorable mixed credit terms. This kind of arrangement is sometimes called super turnkey. When financing is not available and when, in particular, commercial credit must be raised for the construction of a system, it can be beneficial for the purchaser to combine the turnkey approach with a complete supplier-arranged finance package. The reason is that private institutions will favor taking a risk when one reputable major company takes on the turnkey responsibility. The credit risk is deemed smaller when the system becomes operational within a short time period.

Two other types of system supply definitions are in use: BOT (build, operate, transfer) and BOO (build, own, operate). In these cases the contractor has to take on both the design and construction of the total system, as well as the financing of the system. Financing in this case means that the contractor will take equity in the operating company and find commercial or mixed credit to support the rest of the construction. The contractor will also operate the system for a certain period of time, normally 10 to 15 years. Then the system will be transferred to the purchaser.

Most mass transit systems do not run at a profit, in particular when the financial costs are included in the calculation. Hence the BOT/BOO approach for this type of operation seems to be impossible unless construction companies can be given rights to exploit real estate. The real estate around stations and lines of a mass transit system normally increases in value. Part of that value increase could then be exploited by the civil contractor involved in the building of the mass transit system. It is however unclear how such a deal can be structured.

BOT and BOO put a heavy burden on the contractor and, as profits will not come from the operation, it is doubtful whether such systems will appear other than in rare cases. The same objectives can more or less be achieved by something one could call BTO (buy, transfer, operate). The total system is built by a contractor according to a performance specification. It is then transferred to the purchaser. The contractor is then awarded a contract for the operation, maintenance, and service of the system, including guarantees for its performance. In this case a contractor has all the responsibility to ensure that the system is designed properly and can be operated within certain cost limits. From the purchaser's point of view, a long-term contract covers the operation, but the purchaser has to pick up the difference between ticket revenue and operational/financial costs. This BTO principle should be feasible in many places where the transit authority lacks the experience to build and operate a system. This is a further development of a super turnkey operation and will further enhance the availability of credit institutions assuming the financial risk.

TRADITIONAL PROCUREMENT METHODS

The traditional method for constructing transit systems has been that the customer or operator spends years preparing detailed specifications for each subsystem. This is done by the customer organization or by hired consultants.

Very often the specifications are very detailed being more or less a design document. With this approach, the customer will take on the total integration responsibility (i.e., the responsibility of fitting all subsystems together). Any gray zones leading to missing equipment or unnecessary overlaps are with the customer.

This is why all specifications are very detailed. To involve several suppliers, the customer tries to open up the docu-

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ments; however, normally too many restrictions still remain. No supplier can fulfill all requirements with its standard products, which lead to redesigns and increased costs. Further new designs will produce problems during the start-up of the system. Once the specifications are ready, the customer calls for bids, selects interested bidders, and negotiates the contract.

As a result the customer is the total project manager and requires a strong customer organization with a lot of good experience. When building a system over a long period with several lines, this can be justified, as the project organization is continuously in operation over considerable time. After completing the project, this organization is redundant.

WHY TURNKEY?

Within the sphere of public transportation, turnkey procurement has not yet evolved as a major feature, although some contracts have been awarded, especially for fully automatic systems. The traditional contract route is to use separate packages for civil works, buildings, vehicles, and different electromechanical supplies, leaving the overall coordination with the customer or the customer's consultant. A typical public transportation turnkey project has two main portions, civil works and electromechanical works. The number of subsystems in the total concept will vary depending on the complexity of the mass transit system.

Systems will, however, become more and more complex. Advanced passenger information systems, both on board trains and at stations, require integrated solutions. Advanced automatic control systems make it possible to shorten the headways between trains safely. Trains can also be operated automatically without drivers. These new technologies call for a change in responsibilities. Automatic guided transit (AGT) systems call for a turnkey package as reliability, availability, and total safety must be integrated in the total system design.

Turnkey system engineering, employing one contractor with overall responsibility, results in effective coordination of the design process and produces synergies of implementation. Initial traffic studies, consultancy reports, and procurement procedures traditionally employed can all be streamlined.

Complete systems responsibility also ensures direct channels of communication, integrated systems planning, and a better scope for parallel activities in production and materials handling. Lead times are considerably shortened and the transit system will be put into revenue service earlier. The short implementation times of system design engineering reduce capital costs and allow the public to enjoy the benefits of an efficient city transport system much sooner. System design engineering is based on a common set of objectives agreed to by both customer and contractor. Systems responsibility is assumed for both the design and implementation phases of the project, which ensures that realistic and effective designs, products, and procedures are employed.

System design engineering gives a single contractor full responsibility for the delivery of a complete rail transit system. Deliveries of various hardware elements are coordinated and optimized through proven methods applied by an experienced contractor.

Turnkey supply means

- One contract with the technical performance defined, one single time schedule, and one price;
- No multiparty discussions; and
- The client's risk held at a minimum.

The performance requirements should state

- Plant and system objectives, such as availability and reliability;
- General descriptions, such as conceptual layouts, general design principles, and anticipated traffic flow; and
- Design requirements, such as quality and maintainability.

For the client to have the full control, appropriate milestones should be set in the contract, such as

- Submittal and approval of technical specifications (preliminary and final);
- Inspections and tests according to plan regarding essential equipment, subsystems, and the complete system; and
- Provisional training and final documentation relating to operation, overhaul, and maintenance.

The turnkey concept is most favorable when the following general conditions apply:

- The customer lacks the knowledge to perform the total project coordination, and the customer does not consider it cost-effective to develop this knowledge. This implies that the customer is most likely a new transit organization with no system in operation.
- Financing arrangements are more advantageous if a turnkey approach is used.
- The customer has an interest in minimizing the risks to the customer organization.

PROJECT ISTANBUL

The Istanbul LRT system is a successful example of a turnkey project. The customer, the greater city of Istanbul, awarded the total responsibility for the construction as well as for the finance package to one contractor.

Istanbul—A Living History Book

Istanbul is on the shores of the Bosphorus, a narrow strait between the Asian and the European continents. By controlling the Black Sea–Mediterranean and the east-west trade routes, the city has always flourished and because of its strategic position, the threat of being conquered has always been real.

According to tradition, the history of Istanbul started with Byzas, a wanderer from west of Athens. He founded the city as Byzantium around 650 B.C. In 330 A.D., the Roman emperor Constantine moved the seat of his empire from Rome and founded East Rome on the seven hills of this city as the new Christian capital—Constantinople.

In 1453 the Turkish sultan Mehmet II Fatih conquered the city, and it became the capital of the Turkish Ottoman Empire, which extended over a large part of southeast Europe and a major part of the Arab world for some 450 years. The last sultan abdicated in 1915.

The nation of Turkey has a very short history of democracy. A democratic constitution was formed for the first time under the presidency of Kemal Atatürk when he formed the Turkish republic in 1920. To defend the constitution, the military has an obligation to run the government if a major crisis is occurring.

The last takeover was in 1980 when total anarchy was ruling. General Kenen Evren took over the presidency and stayed in power until 1983, when national and local elections took place. ANAP, the Motherland party, won a majority in Parliament and most of the mayoralties. A government under Prime Minister Turgut Özal was formed. The Turkish economy then entered a period of very rapid growth and a large number of investment projects were begun.

Traffic Planning

The ancient city of Istanbul has the fastest population growth in Europe, increasing by some 1,000 per day, because of migration to the city and a rather high birth rate. The number of inhabitants is officially some 7 million, but unofficially figures of around 10 million are mentioned. The public transportation network, however, can barely cope with present demands, let alone those of the future. Sooner or later the situation would have become so severe in terms of both traffic and population that traffic would have come to a complete standstill.

In common with many other cities of the world, those in Istanbul responsible for traffic planning can hardly foresee the needs that such rapid growth brings. City authorities today are confronted with insuperable problems in finding day-to-day solutions for travelers of every kind. And time is continually against them.

The mayor of Istanbul, Mr. Dalan, who took office in the early 1980s, made a policy decision that within 5 years Istanbul's water supply and sewage systems would be improved, the sea would be free of pollution, traffic would be running smoothly, and the new infrastructure of the city would be complete.

Istanbul had a streetcar tramway system in operation until 1964, but like in many other cities the system was closed down, so that the only modes of traffic were buses, dolmuses (shared taxis) and minibuses, taxis and private cars, and commuter trains to the central stations of Haydarpasa (Asia) and Sirkeci (Europe).

Since the opening of the first Bosphorus Bridge in 1973, car traffic between the Asian and European sides has increased tremendously. The number of cars in Turkey for a long time doubled every 4 years, and most of these cars are located in Istanbul. Since the 1960s a discussion regarding an underground rail system, a metro for Istanbul, had been going on. A number of feasibility studies had been performed, but even though Istanbul has one of the oldest existing funiculars, the 500-m Golden Horn "Tunnel," no decision was made to start the construction of any further underground rail systems.

The city authorities had two alternatives. One was to develop road systems to cope with a dramatic increase in road traffic capacity and then to make extensive use of buses. For the current volume of traffic in Istanbul this would have meant several major motorways each 100 m wide, sweeping through this beautiful 2,500-year-old city. This solution was quite unacceptable.

The other alternative was a rail system.

In 1984, as in other cities around the world in a similar situation, proposals for the construction of an LRT system started to appear in Istanbul. It was soon realized that LRT had much to commend it, being cheaper and faster to construct than conventional metro or heavy rail, yet providing a permanent alternative to road transport.

Design/Build Turnkey Contract

By the end of 1984 the greater city of Istanbul had put together a performance specification based on a design/build turnkey contract scheme. Bids were invited, and best and final bids were received in mid-1985. Negotiations with the successful consortium were held during the autumn, and a contract was concluded, including final prices for civil works, which led to the signing of a letter of intent in December 1985.

In February and May 1986, contracts were completed for the construction of a 24.2-km LRT system in two stages from Yenikapi to Ataköy on the European side of Istanbul, south of the Golden Horn.

The successful ABB-Yapi Merkezi Consortium consisted of ABB Traction AB (formerly ASEA Traction) of Sweden as consortium leader and Yapi Merkezi Insaat ve Sanayii AS of Turkey, as civil works partner. ABB Traction is a member of the ABB, Asea Brown Boveri, Group. In addition to being the consortium leader, the company is responsible for all electrical and mechanical equipment, including the light rail vehicles (LRVs). ABB has been involved in the development and supply of electric railroad technology for the past 100 years and has worldwide experience in the power supply and railroad vehicle sectors.

Yapi Merkezi is one of the leading civil engineering and construction companies in Istanbul. The company is responsible for all building, civil construction, and track work. Yapi Merkezi has completed a number of major construction projects in Turkey, such as roads and bridges and the restoration of several historic buildings.

The contract is on a design/build turnkey basis, which means that in theory, but not in practice, the customer can place the contract, walk away, and come back later to take over the completed railway system. The customer has passed on to the contractor the responsibilities for coordination and the interface between individual contractors and professional consultants. However, the responsibility for operation, utilities diversion, expropriation, and clearance of sites remained with the customer. This type of contract was chosen because of the specific key benefits it offered:

- A reduced time schedule,
- Lower overall cost,
- A clear relationship: one client–one contractor,
- Clear responsibility for quality,
- Close integration of electrical, mechanical, and civil systems, and
- Unambiguous responsibility for performance.

The general conditions of the contract are the internationally well-known conditions of contract for works of civil construction from Fedération Internationale des Ingenieurs-Conseils (FIDIC).

Financing Contract

As a condition of the contract being awarded, the city insisted on an attractive financing package. ABB was able to finance the total sum of approximately $400 million (U.S.). This package was made possible by the support of governments of the countries involved in the project through the use of different export credit systems, and by an international syndicate of some 16 banks.

The financing covered all contractual works, both local and others. However, it had already been anticipated at this stage that additional financing might be necessary before the start of the second stage.

Istanbul LRT System

The initial contract, for 24.2 km of segregated double track, is divided into a first stage of 8.9 km and a second stage of 15.3 km. The civil works portion of the contract includes the design and construction of tunnels and viaducts; track and track bedding; a depot for 165 cars; a maintenance and overhaul building; a traffic control center; 19 passenger stations; power supply substation buildings; and service systems, such as cable, water, drainage, and sewer systems. The electrical and mechanical works include the design, supply, and installation of

- 105 complete LRVs—70 MD-cars with a driver's cab and 35 M-cars without driver's cab;
- Power supply consisting of transformer and rectifier substations, switchgear, and overhead catenary system, remote control (signaling control and data acquisition [SCADA] computer system), and cabling;
- Signaling and communication systems consisting of a microcomputer-based interlocking system, automatic train protection, centralized train control, radio communication, public address, and central clock; and
- Service systems consisting of functional design and equipment of the maintenance and overhaul workshop for 165 cars, lighting and power distribution, and heating and ventilation in the workshop.

In addition, the contract called for a comprehensive training program for the employees of the operation company; commissioning of the subsystems; and a complete system test.

Originally only minor tunnels and a number of viaducts were planned in the routing, but before the effective date of contract, 2.5 km of cut and cover tunnel was added. The tunnel stretches from Aksaray to Ulubatli in the downtown area, to a major extent following the main avenue, Vatan Caddesi. Three underground passenger stations are included. This was the result of a more extensive feasibility study during the last phase before work started.

The stations are designed to handle four-car trains although only three-car trains will be used initially. This will enable the system to be expanded without problem.

The vehicles are operated as three-car train sets with cabs in the outer cars. Each car is made up of two articulated sections and three bogies, with two of the bogies being powered and a trailing center bogie under the articulation. The electric motors are used for acceleration and regenerative braking of the train. The system ensures that the maximum amount of energy is returned to the power system.

The entire electrical system is fully microprocessor-controlled and includes a fault logger and an electronic display in the driver's cab to indicate the faults. The metro system is controlled by a state-of-the-art, microcomputer-based interlocking and safety system. Power is fed to the metro vehicles through a catenary system and is distributed from the main supply station to rectifier stations along the route.

The traffic control center is the heart of the metro operating systems and includes radio communication to the drivers, monitoring of the main line interlocking system, and power supply operation.

The Customer

The greater city of Istanbul was the main customer and the head of the technical department was appointed project manager, the engineer. A separate contract was signed with Istanbul Technical University (ITU) to act as technical consultant to the engineer.

The city's intention was to allow the Istanbul Bus Company to be responsible for the operation of the LRT system, but in 1988 a new company, Istanbul Transportation Company (ITC), was formed for this task.

Subcontracting and Consulting

For parts of the civil works, Yapi Merkezi subcontracted other design and construction companies, both Turkish and from abroad, but the design coordination and planning of these parts was handled by Yapi Merkezi themselves. For the track, the Swedish company GIA Industri was subcontracted. As a main consultant, involved in the civil engineering design of the first stage, the Turkish company United Engineers Group, BMB, was contracted.

ABB Traction handled the deliveries of the LRVs and the power supply system within its own organization. For the other electromechanical subsystems very reputable companies were contracted by ABB Traction, such as

- ABB Signal (former Ericsson Signalling Systems) of Sweden for the signaling and safety systems,
- Balfour Beatty of the United Kingdom for the overhead catenary,
- Brown & Root Vickers (former Vickers Design & Projects) of the United Kingdom for the workshop,
- Simmering Graz Pauker (SGP) of Austria for the car bodies, and
- Ascom Radiocom (former Autophon) of Switzerland for the radio communication.

The principal consultants called in for technical assistance during the execution of the first stage were Scandiaconsult of Sweden, MARConsult of Sweden, and Dogan Haritas of Turkey. Other companies involved in the project were Gothenburg Transit Authority of Sweden, Stockholm Metro of Sweden, London Transport International of the United Kingdom, and Birmingham University, also of the United Kingdom.

Success in Record Time

In March 1989, not more than 30 months after the effective date of contract, the first stage was inaugurated. A trial operation was initiated along with an extensive training period for ITC personnel on driving the cars, dispatching the traffic, and maintenance and overhaul.

Verification tests were performed in July and August of 1989 with the fully trained personnel. The final test included operation with 2.5-min. headways with crush load for 1 hour. The test results were overwhelmingly good and showed that the performance of the different subsystems, when working as one LRT system, was excellent. The results also indicated that ITC personnel were well-qualified to participate in the test, both from a driving and a dispatching point of view.

Because of political implications, a second inauguration was conducted in September the same year. Commercial operation was started from that date with an ever-increasing patronage.

Today

A number of complications with the second stage, even though they had been discussed since early summer 1988, became even more obvious with the start of commercial operation. The feasibility study and the final routing for the second stage had not been concluded. Additional financing, because of additions in the first stage, had become a necessity.

The political change in the mayoralty and the introduction of a new engineer on the city's side eliminated the possibility of a rapid solution and led to a 2-year moratorium.

The feasibility study for the second stage was completed in the beginning of 1991 and alters the routing to absorb many of the existing heavy routes of travel rather than developing routes in new areas of the city. The new routing goes from Otogar to Yeni Bosna, close to the airport. The distance is 9.7 km and includes 1.6 km of viaduct and 750 m of cut and cover tunnel. A financing package covering $100 million (U.S.) has been arranged and the work has now started.

The time frame for the second stage is 26 months. In the meantime, a temporary passenger station has been opened at the Ferhatpasa/Esenler depot and the number of passengers has increased to some 65,000 per day for the portion of the system in operation.

Sustainable Development for Istanbul

The design/build turnkey method of contracting allows traditional design, manufacturing, and construction timescales to be significantly reduced. In the Istanbul case it would also have been impossible to finance the local works if a turnkey contract had not been employed.

The turnkey contract made it possible to move from the original idea in 1984 to the start of the project in 1986 and then to the opening of the first stage as soon as 1989. The reduced timescales also allowed costs to be reduced.

The situation today is that the operational revenue covers operational costs and makes a contribution towards the paying off of the capital investment. If, however, the contribution to the national economy is considered, the LRT system

- Provides lower travel costs compared with cars, buses, etc.,
- Operates at a higher average speed than other modes, and
- Emits no exhaust fumes into heavily polluted areas of Istanbul.

Considering that the second stage will bring more densely populated areas within reach of the LRT, the future looks very bright.

The modern state-of-the-art system, which introduces LRVs with converters based on GTO thyristor techniques and a microcomputer-based interlocking signaling system to Turkey, is today operated and maintained by the Istanbul Transportation Company, without any support from the consortium. It is a success story both for the city of Istanbul and for Turkey as a nation.

To this sustainable development should be added the level of expertise achieved within the Istanbul Technical University and also within the civil works partner in the consortium, Yapi Merkezi. Additionally it can be noted that Yapi Merkezi has been the sole contractor for the construction of a 1.9-km heritage tram service along the Istiklal Caddesi in Istanbul, between Tunnel and Tksim, which opened in December 1990. Yapi Merkezi also has a contract for the laying of 3.7 km of track for a tramway from the Istanbul LRT passenger station Akşaray to the railway station Sirkeci. These two contracts would most probably not have been possible without the experience Yapi Merkezi gained on the LRT system.

CONCLUSION

The result of the turnkey approach is faster implementation, which leads to less cost because the capital is brought into operation earlier. The contractor can also use standard solutions, although the overall system performance specified must be met, which means lower costs in design and less risk with problems during start-up and so forth. By combining the turnkey approach with an operation and maintenance contract, the customer organization can further lower its risk and ensure that the system meets its long-term performance specifications both in terms of transport capacity and operational costs.

The Istanbul project verifies the benefits of the turnkey approach, including the financial part. The system was in operation within 30 months, and the complete financial package, including the extension, was arranged.

Joint Development Strategy for Honolulu's Fixed Guideway

CHERYL D. SOON

Honolulu has been planning a rapid transit project for more than 25 years. This capital city of Hawaii has a resident population of more than 850,000 and a de facto population (residents plus military and visitors) of more than a million each day. The population is primarily contained in a dense corridor on the leeward side of the island of Oahu stretching approximately 40 mi. The business and economic centers are even more condensed within the corridor, consisting primarily of Waikiki, Kakaako, downtown, Iwilei, airport, and Pearl Harbor.

As now proposed, Honolulu's rapid transit line will stretch 15.7 mi from Waiawa, where H-1 and H-2 (Central Oahu) freeways meet, to the University of Hawaii campus in Manoa to serve the popular athletic facilities there. The transit line will be part of an integrated islandwide transportation system with bus routes reconfigured as feeder lines. In November 1990 the city and county of Honolulu issued a request for proposals (RFP) to procure its system. The procurement was unique in several ways:

- Technology was not preselected but the system had to be automatic (driverless);
- Turnkey operation would include design, build, operate, transfer (DBOT);
- Fixed-price bids with a very detailed cost proposal were required; and
- Joint development proposals were strongly encouraged but would be evaluated separately.

After a spirited and competitive process, the team selected was a consortium called Oahu Transit Group (OTG). Its joint venture partners include Morrison-Knudsen (managing partners), AEG Westinghouse Transportation Systems, EE Black, and SCI Contractors & Engineers. OTG bid a 208-passenger articulated vehicle. The vehicle will ride on an innovative elevated concrete guideway designed to have maximum span lengths of 180 ft, walls and an emergency guideway that double as noise barriers, and extensively landscaped exterior planters.

Since Phase 1 of the project was awarded December 3, 1991, OTG and the city have been completing route selection and station locations as well as a supplemental draft environmental impact statement (EIS) and a final EIS for the project. The Honolulu City Council is scheduled to take a crucial vote to raise the current 4-cent general excise tax by an additional half cent to fund Phase 2 construction. Of the total \$1.7 billion costs, one-third (or \$618 million) will come from the federal government. The local share will come from the half-cent excise tax cushioned by a partial state rebate to resident taxpayers.

Oahu Transit Group, 401 Kamakee Street, Honolulu, Hawaii 96814.

JOINT DEVELOPMENT AS FINANCING MECHANISM

In recent years Honolulu has had a very active real estate market, fueled in part by heavy Japanese investment. At the market's peak (1988–1989), some land costs along Kapiolani Boulevard (a major city artery that runs parallel to the transit route) were running \$500 to \$600/ft^2 of frontage. During this time the city was putting together its initial cost estimates and financial plans for the transit line.

The Urban Mass Transit Administration [now Federal Transit Administration (FTA)] enthusiastically committed a 30 percent share in return for promises that the city would attempt to involve the private sector to the greatest extent possible. Next the state legislature, meeting to consider the project financing, permitted two alternative plans:

- Plan A: If 35 percent financing were received from the private sector, the state would contribute \$50 million a year for 17 years; or
- Plan B: If 35 percent private financing were not received, the city was authorized to raise the general excise tax by a half cent for a 10-year period. In this case the state would provide partial rebates to resident taxpayers to offset their burden.

At the time this legislation was approved, it was believed by many that Plan A could be achieved through the provision or sale of development rights along the line or elsewhere. This impression was fueled by an interested party who circulated stories widely in the legislature that the line's expenses could be fully covered by the sale of development rights. Unfortunately, as it turned out, none of the bidders was even able to achieve the 35 percent goal with up-front money (roughly \$600 to \$700 million). What happened?

JOINT DEVELOPMENT'S ROLE IN EVALUATION CRITERIA

To understand what happened, one needs to begin with the RFP evaluation criteria. There were four major criteria, each with a set of subcriteria listed in order of importance. The major criteria were as follows:

- Technical and management expertise,
- Cost proposal,
- Benefits to the city, and
- Joint development options.

Five teams chose to submit draft proposals and all five were eventually invited to submit a best and final offer (BAFO). A considerable amount of variation appeared among the teams' proposals. Each, for example, selected a different technology: magnetic levitation (maglev), rubber tires, monorail, and steel-on-steel (proposed by two bidders).

Although the teams initially formulated their proposals around the technologies, as the process moved along the proposals became more and more dominated by the construction element. This was in part because of the stiff requirements for bid and performance bonds—requirements that could only be met by the deep pockets of a major construction company partner. It is noteworthy that all of the teams were highly qualified in a technical sense and that the three lowest bids were within $100,000 of each other on a $1.17 billion job.

It is also noteworthy that the RFP was extremely well written and the evaluation and selection process were fair and smoothly run. Only a single challenge to the selection was made, and after two rounds had been lost in court, that suit was dropped.

The Group IV privatization and joint development criteria described in the RFP included the following points:

- Whether the city considered the option appropriate;
- Whether the option was likely to be approved by the jurisdictional authority;
- Depth, quality, and financial feasibility of the plan;
- Degree of commitment; and
- Potential value to the city net any costs or disbenefits.

JOINT DEVELOPMENT PROPOSAL BY THE WINNING BIDDER

Very little is known about the joint development proposals of the losing bidders because each chose to classify these volumes as proprietary. It is rumored that they varied considerably, ranging from no submittals to a series of alternate alignments and extensions coupled with a franchise proposal. Competition in the area of joint development was especially fierce between the draft and BAFO submittals as rumors flew around town about the content of competitors' proposals. In retrospect much of this was probably speculation fueled by competitive fears because the city's security was airtight.

OTG's winning joint development proposal was presented to the City Council and the media immediately following selection. OTG offered seven basic proposals, four of which were as follows:

- Prepare a master plan for joint development along the entire line;
- Contribute $100 million for the development rights at eight stations, specific plans to be consistent with an approved master plan;
- Revenue sharing at a major proposed mixed-use development to be called Concert Galleria (Concert Galleria would include a 1.8-million-ft^2 retail mall, 1,440 units of market-priced housing, and 1.25 million ft^2 of office space; the city would share 20 percent of net revenues); and
- Master concessionaire plan with revenue sharing at 60:40.

These four proposer options were offered by a separate joint venture formed by Morrison-Knudsen and The Myers Corporation, a major Honolulu developer with a successful development portfolio in residential, office, and hotel projects. In addition, OTG offered three other options:

- Dillingham Plaza, a mixed-use project at a station site, proposed by Bedford Properties, a respected developer in Honolulu and California;
- Newtown Industrial Park, which offered a financial contribution to the transit project; and
- Pearl Highlands, which offered to build an extra transit station at its power mall then under construction.

This set of proposer options represents a range of opportunities although hardly a comprehensive set of the possibilities inherent along the line. It would have been impossible to do that during the relatively short period of time available and within the resource confines of what was required for the rest of the transit proposal. Meanwhile the city has a 1-year period in which to exercise the above options.

EVALUATION OF THE JOINT DEVELOPMENT PROPOSALS

Although several of the proposers offered privatized financing techniques (for example, benefit assessment and tax increment financing, cross border leasing, or leveraging of federal and state money), none were qualified in the evaluation as a private source within the proposers' authority, and therefore they were not given any points. Franchise proposals from two of the bidders were not awarded points for failure to provide sufficient information, including monetary data.

The seven options offered by OTG, the winning bidder, were initially valued at approximately $487 million, or slightly more than half the amount required to initiate Plan A financing. This amount was heavily discounted. In a state analysis for the legislature the value of the private offer was reduced to $347 million by eliminating some of the proposals as outside city authority or current zoning policy. Furthermore, and perhaps most significantly, the OTG proposal and the city analysis showed that most of the private-source revenue would come by sharing future year revenue streams. Net present value analysis substantially reduced the value of the income stream.

Moreover, even had everything gone according to plan, much of the revenue would have come in the future; only $65 million would have been received from private sources by 1998, the year in which the construction would be completed. This amount represents only 8 percent of the total costs.

City and state officials recognized that, given the overall size and nature of the rapid transit project, some private revenues could be expected. However, these revenues were considered to be too unreliable or unpredictable a source to use in a financial plan. The conclusion therefore was to focus on Plan B, the half-cent excise tax as the major (70 percent) financing source for the capital costs of the project. This fallback position has not been without its political ramifications in that raising taxes in Hawaii is as unpopular as anywhere.

JOINT DEVELOPMENT IN PHASE 1

The role for joint development has taken a dramatically different course than initially anticipated. Instead of financing a major portion of the capital cost, joint development is viewed as a supplemental source for operational and maintenance costs and as a resource for implementing land planning objectives. Joint development has for the moment taken a back seat to the more urgent tasks of completing the final environmental work and mustering the political will for the financial package and the half-cent tax increase.

This is not to imply that nothing is proceeding—quite the contrary. Both the city and OTG are progressing with their plans for development. The city has taken two steps. First, the city has selected an independent consultant to prepare a master plan for land use along the entire alignment. OTG options, city joint development options, and other private development proposals will all be evaluated against the work of the master plan consultant. The city has formed eight citizen advisory committees (CACs) for different segments of the alignment. The CACs, which have already been involved in station location and design, will next work with the master plan consultant to define station area character and land uses.

Second, the city has advanced its own joint development program by identifying selected city-owned sites and in certain instances negotiating to acquire sites. These sites will be awarded through an RFP process to interested developers who are willing to provide city amenities or share the revenue stream with the city. The City Council is deliberating a proposal to dedicate such revenues to operations and maintenance of the transit line.

The state legislature has not lost interest in the concept of using private development revenues for the capital costs. A proposal under consideration would permit this option. The objective of this legislation is to reduce the number of years during which the excise tax would have to be levied.

As for the OTG options, none has been selected at this time, most likely because the city is awaiting the outcome of the master plan process. Meanwhile Myers/Mk Partners has proceeded with landowner, community, and agency negotiations on Concert Galleria, the major mixed-use development. As the development plans progress a significant amount of redesign can be expected before the project takes its final shape.

Myers-Mk is also working on a series of transit-based housing proposals along the route. Affordable housing is a major problem in Hawaii with its high land prices. Shortages have been estimated at 20,000 to 40,000 affordable units and including a portion of affordable housing is a common condition of most rezoning actions. Myers-Mk is looking to provide a major demonstration of how housing and transit can work together by working through a nonprofit development fund.

CONCLUSION

Joint development in the Honolulu rapid transit project has evolved from viewing it as a major financing mechanism for the capital costs to viewing it as a supplemental resource and revenue stream for operations. Most recently the view of joint development is focused on its potential for integrating land use and transit and for building communities. The transit project is still in its infancy. In the next several years it can be expected that real estate and joint development will become recognized contributors to both good land use and sound financial planning.

Stockholm's Plans for LRT in the Suburbs

THOMAS J. POTTER

A new light rail system, referred to as the Snabbspårväg or literally, "fast tramway," is being planned for the city of Stockholm. During preliminary planning the designation for the project was "Hästskon" or horseshoe line because of its appearance when drawn on a map. This name was dropped in favor of Snabbspårväg because officials feared that the name might conjure up images of a return to the old streetcar systems, perhaps even drawn by horses. The project is the responsibility of the transit operating agency for the greater Stockholm region, Storstockholms Lokaltrafik (SL), and is now in the final phases of detail planning. Construction of the first section will begin in 1992 with a planned opening in 1995. Taugbøl & Øverland a.s., a Norwegian consulting firm, was involved in the detailed planning of a 10-km section of the line.

The first rail transit operator in Stockholm, Stockholms Spårvägsbolag, was established in 1876. The following year horse-drawn streetcars began to operate on the streets of Stockholm. Over the ensuing years, the lines were extended and electrified.

By 1930, Stockholm, like many cities throughout Europe and North America, boasted an extensive system of streetcar lines. In that year, the total route length of the streetcar system reach its maximum length of 88 km. As in other cities, the number of automobiles competing for the use of city streets increased dramatically in the 1930s. The decision was made in 1941 to replace most of the streetcar lines with an extensive heavy rail system operating mostly in tunnels, both in the central areas and in the outlying districts as well. The first T-bane (tunnelbane) opened in 1950.

As the tunnel system was extended, streetcar lines were abandoned and tracks were removed from city streets. Today only two lines remain, the Nockebybanan on the west side of the city and the Lidingöbanan on the east. These two lines survived mainly because both operate in areas not served by the heavy rail system and operate entirely along separate rights-of-way. Also, because they operate on separate rights-of-way that are not parallel to existing roads, it was difficult to substitute bus service.

Despite these logistical and practical obstacles, Storstockholms Lokaltrafik (SL) made several efforts to eliminate these two remaining lines in the 1970s and 1980s. Only vigorous public opposition saved the lines. It is also interesting to note that both lines serve neighborhoods considered "exclusive"—areas where bus service would not be expected to enjoy high ridership levels.

By 1967 all light rail operations with street running were gone. But the streetcars returned to Stockholm in 1991, to coincide with the International Union of Public Transportation conference. The new line is relatively short (3 km) and runs from the center of the central business district (CBD) along a seafront promenade to a park and recreation area. It does provide a transit service but is also used to evaluate various types of vehicles for the Snabbspårväg. It will serve the same purpose as the mock-ups used in many cities, but will obviously give the public a better chance to evaluate the various proposed vehicle types.

POSTWAR DEVELOPMENT PATTERNS

During the past 50 years Stockholm has experienced a substantial increase in automobile traffic and congestion. In this regard the region is similar to many other large cities in Europe and North America. Unlike other cities, this congestion can partly be attributed to the officially planned pattern of development proposed and implemented in the 1960s.

The city of Stockholm is an archipelago, with many sections of the city isolated from neighboring areas by the various rivers, channels, and other bodies of water that give Stockholm a special character. The city's central business district is a major source of employment, culture, entertainment, and commerce.

Swedish urban planners in the 1960s, possibly in response to the topographic isolation caused by the water system, proposed satellite CBDs with offices, shopping centers, and housing. Each of these secondary CBDs was to be located on one of the recently completed rapid transit lines. The satellite CBDs would be separated from the central area and other satellite cities by extensive green areas, so called "urban lungs."

The Swedish satellite cities differ in some ways from the so-called "edge cities" of the United States in that a substantial number of people also live in these developments and public and social activities are located there as well. Extensive networks of pedestrian and bicycle paths were built within the developments and between them and the CBD through the reserved green areas.

The plan of course was based on the idea that the new developments would be the center of activity (work, shopping, entertainment, etc.) for their residents. In such a way, a better environment could be provided as it was planned from the ground up with green common areas, the internal pedestrian/bicycle paths, special areas for delivery vehicles, and so forth. Unfortunately although housing and employment were potentially available at the same location, it was difficult to

Taugbøl & Øverland a.s., Conrad Mohsveg 9, N-5032, Minde, Norway.

always find a job in the particular place that one lived. So, transport became a problem. And transport between multiple satellite cities is difficult when the public transportation system, a heavy rail system based on a radial pattern, is oriented for travel toward the CBD.

ROAD BUILDING

Concurrent with the building of the satellite cities, Stockholm also engaged in a massive program of highway construction. Despite gasoline prices, which still stagger most visitors from North America (now approximately $1.20 per liter or $4.50 per U.S. gallon), the use of the private automobile increased dramatically.

Roads and bridges were built connecting not only the suburban areas with the CBD but also connecting the suburban areas with each other.

In recent years many proposals have been made to reduce dependence on the private automobile through incentive schemes (such as improved alternative transportation service) as well as disincentives (proposals for road pricing in the CBD). The Snabbspårväg was proposed to offer public transit service in corridors and areas not served well by existing surface transit services.

LRT PROPOSAL

In the early 1980s it was recognized that the transportation system in Stockholm had developed such that

- Public transport services were oriented primarily toward the CBD;
- Planned development, such as the satellite cities, led to increased demand for transport between suburban areas; and
- Road building provided a better alternative for many travelers not going either to or from the CBD.

This is not to say that public transit in Stockholm suffered the decline in ridership experienced in many American cities in the 1970s. Ridership was relatively stable. But its modal share did decline.

The T-bane system in Stockholm is based on three main lines, each with outlying branches, coming together at one major downtown station, T-centralen. This station serves more than 150,000 to 200,000 passengers per day with center platforms only 4 m wide. It is extremely crowded despite headways of less than 90 sec during the peak periods. Thus any improvements in public transport would have to address this capacity restraint at the center of the rail network.

The Snabbspårväg was a direct response to two needs: better communication between outlying areas and reduced passenger traffic through the bottleneck of the T-centralen station in the CBD. The obvious solution, and the one proposed and accepted, was a circumferential line not directly serving the CBD.

A plan for a rail transit line, originally proposed in the 1960s using available industrial rail trackage south of the CBD, was resurrected. The original plan called for the use of a few kilometers of available rail rights-of-way. The plan in 1985, however, was expanded to a complete light rail ring around Stockholm.

Light rail transit (LRT) was proposed for the new line for the following reasons:

- International development—The success of the new lines in the United States, Canada, and France, together with the continuing success of upgraded systems in Germany, Switzerland, and the Netherlands, showed the potential of the mode.
- Environmental considerations—The growing concern in the 1980s for the environment forced the issue of providing a transportation alternative to the automobile.
- Cost considerations—LRT has many of the same benefits of a heavy rail system but with 30 to 50 percent lower construction costs.
- Effective land use—Stockholm is proud of its extensive green areas in the outer parts of the city: It was thought that LRT would blend in well with these areas.
- Structure for future development—The presence of a light rail line and major terminal stations, with interchange with heavy rail lines and the bus system, would stimulate and focus future development.
- Accessibility and reliability—LRT offered the benefits of better accessibility and reliability mainly because of the level of priority normally given to a light rail line.
- Visibility—LRT operating at grade, or in streets, is an attractive advertisement for public transport.
- Comfort—LRT offers superior comfort for passengers compared to diesel buses.
- Attraction—Because of many of the characteristics just mentioned, LRT can attract automobile users to an extent that diesel buses cannot.

DESCRIPTION OF NEW LINE

The circle line would be 45 km long if ever completed as a ring approximately 5 to 10 km from the CBD. The first phase runs from Gullmarsplan southeast to Alvik, west of the city.

Phase two runs from Alvik over the old airport at Bromma to the end of one of the heavy rail lines at Ropsten. The final phase would be the completion of the ring between Ropsten and Gullmarsplan. This is proposed for reasons of symmetry more than traffic at this point. Details of the LRT project are as follows:

Item	*Amount*
Length (m)	
Alvik-Liljeholmen	5,180
Liljeholmen-Årstafältet	2,800
Årstafältet-Älvsjö	3,150
Årstafältet-Gullmarsplan	2,930
Total	14,060
Length of different right-of-way (ROW)	
Grade-separated (viaduct or tunnel) (m)	2,470–3,220
At-grade, separated (m)	8,640–10,430
Street-running in traffic (m)	1,160–2,200
At-grade crossings (no.)	Approx. 25
Stations	
Total number	15
Distance (m)	
Maximum	1,700
Minimum	600
Average	1,000

The line combines a variety of ROW types including street running, separated ROW at grade, and in tunnel, over bridges, and elevated. It crosses existing heavy rail lines at five major transfer stations and will operate jointly with the Nockebybanan along 1.5 km of that line near its terminal station at Alvik. The Nockebybanan will be extensively renovated concurrent with the construction of the Snabbspårväg to accommodate the new 60-m train-sets and higher operating speeds.

Integration with Existing Transit Network

The Snabbspårväg, being a circumferential line, intersects many of the radial rapid transit lines. At these intersection points, interchange stations are proposed with easy transfer between the two rail systems, as well as feeder bus lines and park-and-ride facilities.

Rolling Stock

The Snabbspårväg will be operated using one- or two-car train sets. Each car will be approximately 30 m long, have a low floor over most or all of its length, and operate at a maximum speed of 80 km/hr. Low-floor vehicles are being specified because the line will operate both on separate right-of-way and on the street.

Right-hand Versus Left-Hand

Another interesting aspect of the project was the question of left or right side operation. Sweden was historically a left-hand drive country. In 1962 the country changed over to right-hand driving on roads, whereas rail operations, including rail transit, to this day continue operating on the left. It was felt that rail facilities were a closed system, and the conversion costs to right-hand operation were unacceptably high.

As the Snabbspårväg interfaces other rail lines at so many stations, the question of left versus right emerged early in the discussions. There was no disagreement that, when operating in streets, even pedestrian areas, right-hand operation was necessary for safety reasons. The difficulty and cost of changing to left-hand operation for several stations led to the decision that operation would be on the right side for the entire line.

Automatic Operation

At one time the planning process considered whether the line could be operated automatically sometime in the future. This would necessitate a completely separate right-of-way. When the change was made to automatic operation, new vehicles would be substituted for the existing vehicles. This appeared very difficult, and the idea was eventually dropped.

Priority for transit does not necessarily mean a separate right-of-way in all circumstances. Rerouting road traffic, pedestrianization of streets, signal priority, and placement of right-of-way away from existing traffic corridors were also incorporated into the system. Of course, it is a truism that most potential passengers live, work, or want to travel to those areas with a lot of traffic. So the possibilities in this regard are limited.

However, because the line is circumferential, it tends to run at a right angle to the established radial travel corridors. As mentioned earlier, the topography of the Stockholm archipelago, with many separate land masses, also has helped to establish rather rigid transport corridors. The Snabbspårväg cuts across the established travel grain. The disadvantage of this strategy is the necessity of building two major river crossings, both of which are important arteries with ocean-going vessels and the accompanying requirements for clearance.

Alignment Decision Based on Time-Motion Analysis

One of the interesting elements of the project was the establishment of the exact route based on a model of running times given different horizontal and vertical alignments. The shortest running time weighed heavily in the decision of where to place the alignment of the route. An overall goal for the Snabbspårväg is an operating speed of 35 km/hr.

Construction Costs

The cost of the first phase from Gullmarsplan to Alvik (length 14 km) is estimated at 1 billion Swedish kroner (approximately $180 million U.S.). This price does not include the cost of rolling stock or additional maintenance facilities.

Cost-Benefit Analysis

A detailed analysis of the benefits of the new line was done. This analysis included the following benefits:

- Savings in operating costs,
- Reduction in waiting time because of improved regularity,
- Time savings for current and new public transit users,
- Improved traffic safety, and
- Environmental benefits (air and noise pollution, health).

The major economic justification for the construction of the line is the reduction in travel times for both current and new passengers. This explains the importance attached to routing decisions based on travel times. The goal of the line is to provide a high standard of public transit services in a corridor and to areas not previously served to such a standard by existing transit services. Travel times compare as follows:

	Snabbspårväg (min)	*Existing Transit Services (min)*
Alvik-Liljeholmen	8	26 (T-bana)
Liljeholmen-Älvsjö	10	18 (Bus 133)
Liljeholmen-Gullmarsplan	10	18 (Bus 130)
Gullmarsplan-Älvsjö	12	19 (Bus 144)

CONCLUSION

The Snabbspårväg represents an attempt to use a rail-based system to serve passengers with travel patterns not conducive to the provision of public transit services. The authorities in Stockholm believe that this is the challenge for public transit in the future; that is, to serve the ever-increasing percentage of trips not oriented toward the CBD.

ACKNOWLEDGMENTS

The information included in this paper is from *Spårväg: I Morgondagens Stockholm*, Idéskiss Stockholms trafikkontoret, 1988; and *Snabbspårväg I Stockholm: Delsträcka Alvik-Gullmarsplan*, AB Storstockholms Lokaltrafik, Regionplane- och trafikkontoret, Oct. 1990.

Control and Phased Development of LRT for Stuttgart

MANFRED BONZ

Stadtbahn Stuttgart is a good example of how to introduce a light rail transit (LRT) system successfully. In Stuttgart political will was the key to launching the LRT system. The success of the Stuttgart LRT system partly depends on central coordination of all public transport modes, which enables every mode to fulfill a useful function. To reach general approval by the political institutions in charge, the Stuttgart experience reveals, an appropriate way to introduce the system by convincing steps is fundamental. To realize this a flexible and upgradable system is essential. In addition, development worked out quite well in Stuttgart because of the high quality of the vehicles and their performance. The influence of good equipment on the public's perception should not be underrated. Finally, a consistent financial program, supported by objective guidelines for grants and the requirements to obtain them, played an important role.

Taking into account that there are different conditions under which LRT systems were introduced, it is necessary to make the following distinctions in general. First, some light rail transit (LRT) systems represent an entirely fresh start for public transport service by rail. That means there has never been such a system before or, more often, a former tramway system has been abandoned previously. Second, some LRT systems originally opened years ago as conventional electric tramways. They represent upgraded versions of traditional systems. Stuttgart's LRT system is in the second grouping. Its origins are a horse tramway opened in 1868 and replaced by electric streetcars in 1895.

The scheme of mixed traffic in city streets worked until the first decade after World War II when a rapid increase of private car ownership began. This led to the problem with which everyone is now familiar: congestion in the city center.

It is interesting to look at the conclusions local politicians drew from this completely new experience. A very remarkable point was that even during the 1950s they did not simply discuss the road system. The Stuttgart City Council saw quite clearly that it was urgent to tackle the problems affecting the tramway system as well. The council reached a majority decision that showed the first signs that it was recognized that quality of public transit had an effect on traffic congestion in the city. This seems even more comprehensive given that it was during this period that residents' tendency to move to the outskirts of greater Stuttgart area while continuing to work in the city center became perceptible. The latter factor indicated that things might get even worse. At this early stage of post-war development, the city council was quite aware that improving public transit could be a promising way of regulating traffic. It seemed a logical thing to employ two local experts from Stuttgart University to prepare a study on an appropriate scheme for urban and suburban rail systems.

Stuttgarter Strassenbahnen AG, Postfach 80 10 06, Shockenriedstrasse 50, 7000 Stuttgart 80, Germany.

In this respect the first lesson from the Stuttgart experience is that, from the very beginning of drafting proposals for improved/public transit, a broad political consensus is needed. It is essential to convert expectations of the political sponsors concerning an increase in passenger demand and, in turn, lessened road congestion in the city into an effective array of measures.

CENTRAL COORDINATION

The study submitted in 1959 emphasized that it was important to design rail service for the greater Stuttgart area in a way that would fulfill urban and suburban functions. The study recommended two compatible systems:

- An advanced commuter railway system (German term: S-Bahn) based on the existing suburban railway system operated by the German Federal Railway (DB), and
- An upgraded tramway system, improving the quality of service by introducing separated, surface sections wherever possible and subsurface sections where the achievements of urban development and private transport conflicted with those of public transit.

The part of the recommendation referring to the existing tramway was the root of the current Stuttgart LRT system. In the context of the study the later LRT system is characterized as an integral part of a multimodal public transit system. It is important to emphasize this fact because the successful introduction of LRT in Stuttgart was, in part, the result of this integrated approach, including a coordinated fare structure. That means LRT has to bridge the gap between commuter railway service and local bus services. Buses, from the point of view of transport efficiency, have to provide more and more of the feeder services for rail systems.

Against this background a second lesson from Stuttgart is that central coordination of all public transit modes within a city or within an area is essential to the success of LRT.

CONVINCING PLAN FOR INTRODUCING LRT

The main result of the 1959 study was the design of an improved tramway network. So the crucial question facing the municipal authorities and the public transit executives 30 years ago was, What is the best way to proceed?

It was quite clear that the only realistic way to get the tunnel measures recommended for the city center was to do it step by step. The decisive reasons were financial and operational. It has to be considered that at that time financing of public transit infrastructure was different from today. It was totally a municipal obligation. In addition every effort had to be made to ensure the opening as soon as possible to improve service. This seemed to be essential because it was a promising way to show visible results to the political sponsors at very early stage. Therefore in the very beginning of LRT construction work in Stuttgart even comparably limited measures, such as the tunneling of crossroads, were separately opened.

In fact this step-by-step approach worked very well, and the financing of further measures always met with general approval from the city council because the visible, positive effects of the proceeding projects proved their benefits for public transit service. So a third lesson from Stuttgart is that an appropriate way to introduce the LRT system is through visible, convincing steps that upgrade public transit.

FIGURE 1 LRT underground station.

FLEXIBILITY AND UPGRADABILITY

Flexibility and upgradability of the new infrastructure was not only a question of step-by-step construction. In this context another question arose: What was the proper size of tunnel cross sections? This was a crucial point, too, because a small dimension set by the existing articulated tramcars would only allow use of the tunnels by vehicles 2.2 m wide. This decision had to be made just at the time when other big German cities came up with plans to introduce new metro systems. In view of this, Stuttgart left its options open to use the new infrastructure by vehicles wider than the traditional tramcars so that even the German metro cars of the standard width—2.9 m—should fit.

From the present point of view this was a very reasonable decision. Already by the end of the decade plans had been submitted to replace the improved tramway system by a real heavy rail metro system using 2.9-m-wide cars. These plans were furthered by forecasts that predicted about 800,000 inhabitants in the city—an increase by more than 30 percent. But these plans were not to last long. Once again a change in the forecasts submitted at the beginning of the 1970s revealed that a metro system would be out of proportion to the current number of inhabitants and their expected public transit patronage. But there was no going back to the initial tramway system. In 1976 the city council approved for a plan with

- Separated guideways were to be used. If required by topography or urban structures this means tunnels (Figure 1); otherwise separated, surface railroads (Figure 2) within or next to regular traffic areas were to be built.
- Priority to trains was to be ensured with fully train actuated signals (Figure 3).
- Vehicles that were 2.65 m wide and that used standard gauge tracks were specified (Figure 4). This feature required technical facilities for mixed operation of the new standard gauge light rail cars and the existing meter gauge tramcars. These facilities included three-rail tracks (Figure 5) and an overhead contact wire system to supply both types of vehicle.
- Implementation of high platforms (Figure 6) and combined high- and low-level platforms where mixed operation was provided.

As for flexibility and upgradability, the fourth lesson from the Stuttgart experience may be summed up by quoting the 1983 International Union of Public Transportation (UITP) definition of light rail system (*1*):

> Light rail systems are a rail-borne form of transport which can be developed in states from a modern tramway to a rapid transport system operating on its own right-of-way, underground, at ground level or elevated. Each stage of development can be the final stage, but it should also permit development to the next higher stage.

FIGURE 2 Separated surface alignment.

FIGURE 3 Level crossing with fully actuated signals.

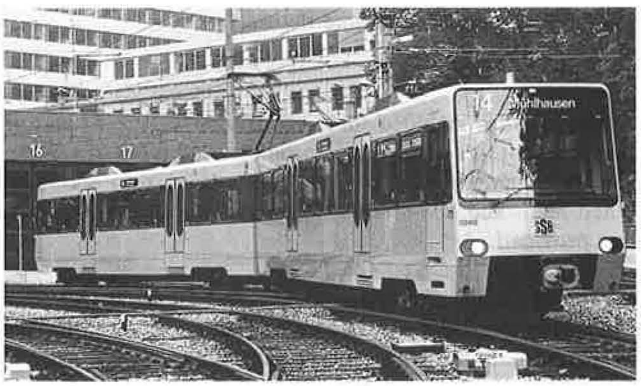

FIGURE 4 A two-unit Stuttgart LRV (Type DT8).

FIGURE 5 Three-rail track for mixed operation.

QUALITY VEHICLES AND PERFORMANCE

Stuttgart's successful introduction of LRT in Germany is ironic in that the city is southern Germany's center of the automobile industry. The metamorphosis of the tramway to LRT has caused a remarkable increase in public transit patronage, between 15 and 100 percent. The fact that passenger loads jumped

FIGURE 6 High platform at a surface LRT station.

15 percent without any reduction in trip time reveals that much of this success can be credited to the new twin car units especially developed for Stuttgart. They had to compare with the quality of the locally made Mercedes automobiles, so it was essential they provide a very high standard of ride, comfort, and seating (Figure 7). On the other hand, high-quality furnishing of light rail vehicles (LRVs) and stations led to decreased vandalism.

As for quality, on-schedule performance and reliability are no less important. The infrastructure measures mentioned, such as tunnels and segregated tracks, are not the only contributions to ensure performance. A computer-aided command and control system (Figure 8) and train-actuated signaling of level crossings are essential as well.

So the fifth lesson from Stuttgart is that it is very important to have quality LRVs that perform to a high standard to improve the public perception of public transit service.

FINANCIAL PROGRAM

Part of the decision made in 1976 is the plan of a fundamental network for the light rail with a local length of 88 line km (53 mi). Based on the 1976 plan, 72 line km (44 mi) of Stadtbahn Stuttgart have been opened so far. Eighty-one new LRVs are

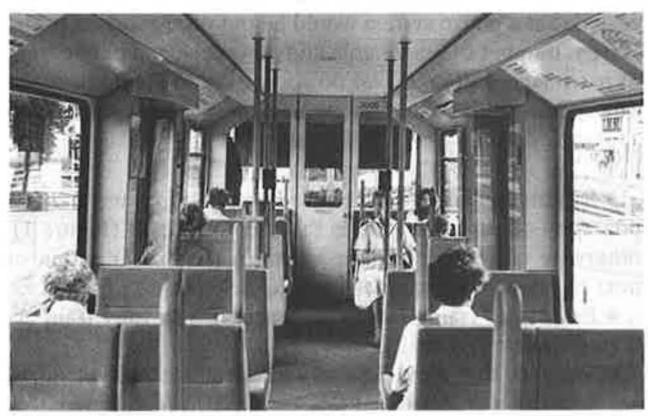

FIGURE 7 Stuttgart LRV interior layout.

FIGURE 8 Stuttgart central control.

serving six routes. Another 19 line km (11.5 mi) are under construction or are prepared to start construction work soon. A further extension of the network up to a total of 130 line km (79 mi) is being discussed.

The essential reason that these plans have every prospect of succeeding is the way public transport infrastructure is financed in Germany. As mentioned before, at the beginning of LRT construction in Stuttgart, finances were totally the municipality's obligation. Were that still true, no infrastructure investment on this scale would be realistic. But the approach of the national and state governments taking a financial stake in public transport infrastructure made it possible to invest more than 2 billion DM (more than $1.2 billion U.S.).

Since the end of the 1960s, the Stadtbahn Stuttgart project was funded by a 60 percent infrastructure grant from the national government. Another 25 percent was funded by the State of Baden-Wurttenberg of which Stuttgart is the capital. This extent of grants to create rail systems is laid down by federal law, so the financial arrangement is the same throughout Germany. The balance has to come from local sources. In contrast to other German cities where this amount is paid by the municipality, in Stuttgart the public transit company, Stuttgarter Strassenbahnen AG (SSB), has to provide this money. Not getting the money from the city has an advantage. It is easier for a stock company to raise money than for the municipal administration to do so, hence this is a more flexible way of providing the balance required.

In addition the financial source for funds from the national and state governments is a dedicated share of the fuel tax. Raising the fuel tax was connected with an extension of the grants to rail vehicles. Therefore, in the state of Baden-Wurttenberg about 40 percent of the investment in LRVs is now covered by government grants.

Good results from a standardized economic evaluation following the approach of cost-benefit analysis is the most important condition for getting infrastructure funds.

So the sixth lesson from the Stuttgart LRT emphasizes the important role of reliable financing. An LRT plan and a consistent financial program have to go together and be supported by objective guidelines for grants and the requirements to get them.

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South Yorkshire Supertram

S. Pont and J. G. Boak

Sheffield, with the surrounding metropolitan area in the county of South Yorkshire, has become the second city in the United Kingdom to reintroduce trams and the first city to plan for extensive street running. To be built in eight phases, the South Yorkshire Supertram system is to have the first phase completed by the end of 1993; the entire project, by 1995. Of its total 20 route-miles, about 10 mi will have on-street running, 8 mi will have segregated track adjacent to roadways, and 2 mi will be on converted British Rail track. The 25 double-articulated, low-floor vehicles, designed to carry 250 passengers, will operate on 5-min headways most of the day. The bulk of the funding for the project, which is estimated to cost $400 million (U.S.), comes from the central government with a limited amount contributed by property developers and other real estate interests.

Situated in the metropolitan county of South Yorkshire, the city of Sheffield was once the heart of the British steel industry. Its name is known worldwide through the production of special steels and fine cutlery. Sheffield entered the first tram age in 1873 when a private company operated horse-drawn carriages. Electric trams were introduced in 1896 when the city took over the system. The system ultimately expanded to some 100 route mi. However, the system was gradually abandoned over the years and finally closed in 1960. Sheffield is now the second city in the United Kingdom to reintroduce the tramcar and the first with extensive street running over the route.

With the rationalization of the steel industry in the United Kingdom, many of the steel mills in the lower Don Valley area of Sheffield were closed down. This area is being redeveloped under a central government initiative by the Sheffield Development Corporation for recreational, leisure, shopping, business, light industry, and residential purposes. Major new sports and athletics stadiums and an olympic-sized swimming pool were constructed in time for the World Student Games held in Sheffield in July 1991. Line 2 of the South Yorkshire Supertram network is being constructed through the lower Don Valley, linking the new Meadowhall retail malls with the stadiums and the city center.

Sheffield reconsidered the benefits of a modern light rail transit (LRT) system in the late 1970s and early 1980s, and finally, when route alignment and other parameters were agreed on, steps were taken to obtain the necessary acts of Parliament and royal assent without which construction cannot take place.

Funding is provided almost wholly by the central government with a limited level of private contribution from property developers and other real estate interests. South Yorkshire Supertram Limited (SYSL) was then formed as a wholly owned subsidiary of the Transport Executive to construct, operate, and maintain the system. Following prequalification processes, a number of international companies and consortia submitted bids for the separate contracts to design and build the infrastructure and the rolling stock. Siemens Plc was awarded the rolling stock contract for 25 double articulated vehicles. Balfour Beatty Power Construction Limited (BBPCL) secured the contract for the construction of the network, including the civil engineering, trackwork, overhead contact system (OCS), power supply, maintenance depot, and tram signaling and control system. Some of the utilities are realigning their services under separate arrangements with SYSL; road traffic signaling and ticket equipment are also separate, direct contracts.

Balfour Beatty Power Construction Limited, 200 Lumley Street, Sheffield 29 3LP, United Kingdom.

SUPERTRAM SYSTEM

Predominantly a double-track system, the 20-route-mi Supertram network will consist of two lines that form three radial routes joining together in the city center (Figure 1). Some 10 mi of the route will have on-street running, 8 mi of segregated track will be sited adjacent to the roads. whereas the remaining 2 mi will run on converted British Rail track. The terrain for much of the Supertram route is hilly; design includes gradients of up to 10 percent.

Supply to the overhead contact system will be at 750 volts (V) direct current (dc), and the present requirements are for 12 substations. Maximum operating speed is 50 mph, with lower limits on-street and at intersections. The 25 light rail vehicles (LRVs) are bidirectional, double articulated units, each about 115 ft long by 8 ft 8 in. wide. An innovative feature of the LRV is its low floor, allowing boarding from very low platforms, eminently suitable for in-street use. They are designed to carry 250 passengers and will have a service frequency of 5 min in each direction throughout the major part of the day. Sufficient flexibility is built into the system to provide special high-frequency services to accommodate major events at, for example, the Don Valley Stadium.

The system will be constructed in eight phases. The northeast radial (Line 2) will be Phase 1, due for completion by the end of 1993, and will provide a 5-mi link between the city center and the large shopping complex at Meadowhall in the northeast of Sheffield (Figure 2). This route takes the line along the Don Valley redevelopment area and links with the Transport Executive's new transport interchange at Meadowhall, which brings together all transit modes within a single facility. The remaining seven phases (Line 1), 15 mi long, will run from Middlewood in the northwest to Halfway in the southeast. Lines 1 and 2 will meet on the delta junction and viaduct structure near the city center. The whole project is due for completion in 1995.

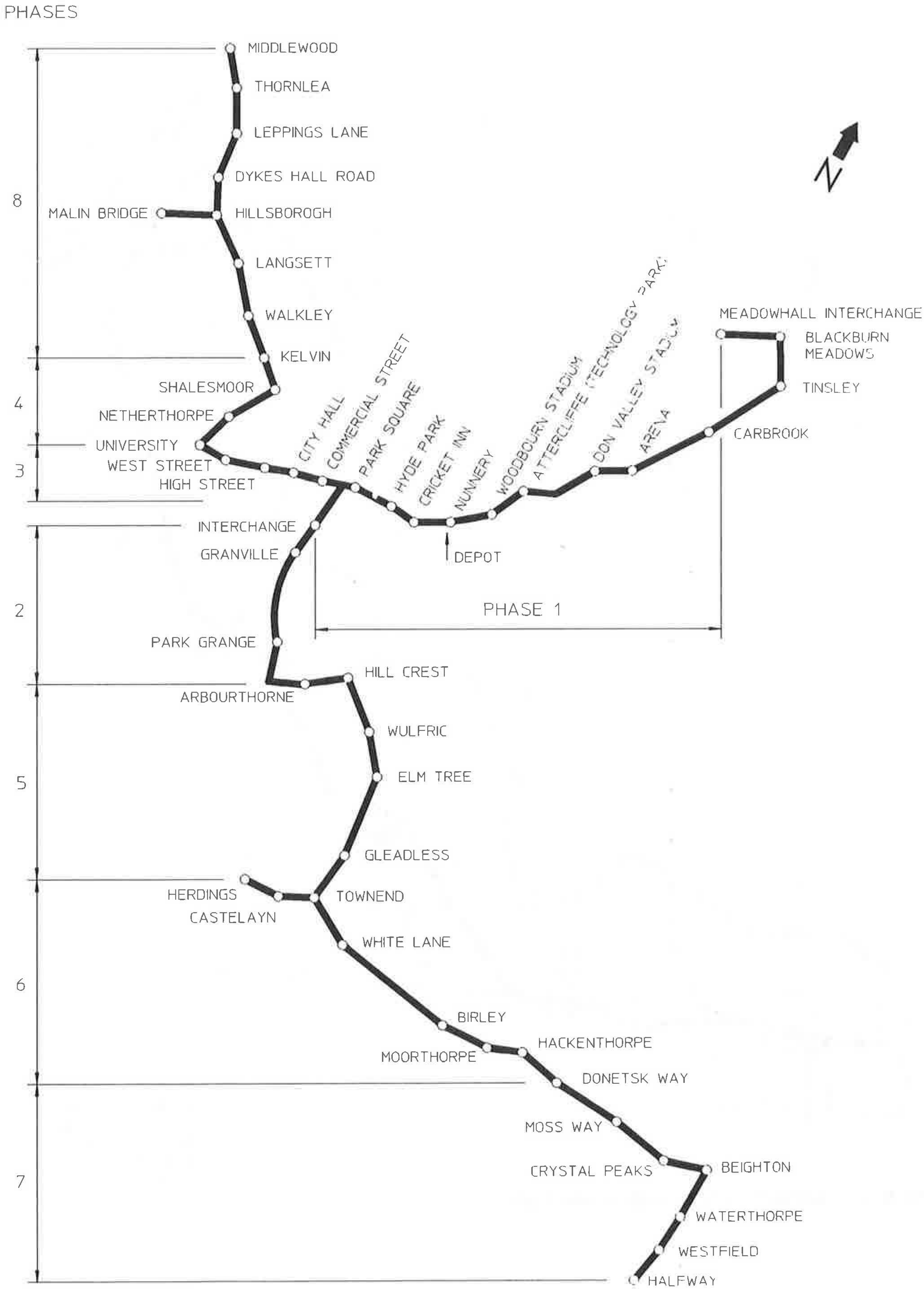

FIGURE 1 South Yorkshire Supertram routes and phases.

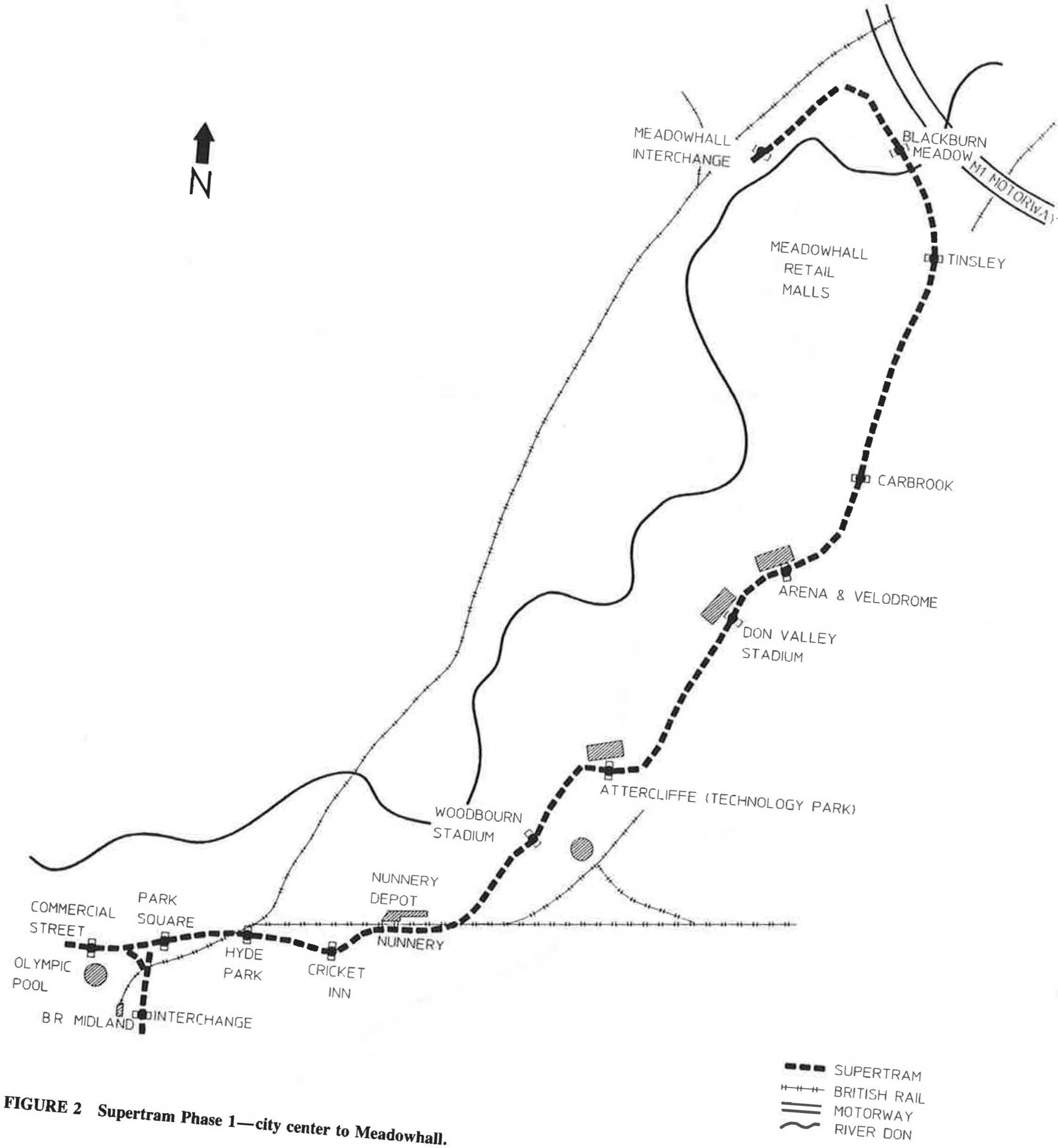

FIGURE 2 Supertram Phase 1—city center to Meadowhall.

Interestingly, the majority of recent new and planned developments in commercial, industrial, retail, and residential facilities are along the light rail route.

Finance

The funding for the project comes mainly from central government. A major portion of the estimated cost of $400 million (U.S.) is to be funded by direct capital grant aid with the bulk of the remainder from authorized borrowing by the Regional Transit Authority. Private investment from local businesses that are likely to benefit from access to Supertram is also captured in the total financing package. Supertram will thereby only need to service its operating costs with no capital debt burden. A condition of central government's agreeing to provide finance is that the LRT system will be privatized in due course and then be operated and maintained without revenue subsidy for a concession period of 30 years. The capital assets will remain in the public ownership of the Transport Executive.

Client's Structure

The task of coordinating the project on behalf of the South Yorkshire Passenger Transport Executive (SYPTE) is SYSL's consultant, Turner and Townsend Project Management Limited (TTPM). TTPM is coordinating the building process using Kennedy Henderson Limited for the tramway electrical and mechanical disciplines and the Design and Building Services (DBS) consultancy for the technical specification design approval, supervision of civil and highway works, together with design of some structures and retaining walls, mainly on Line 2.

Both before and during the construction process, detail consultation with owners of property fronting the system has been undertaken so that the layout can accommodate the needs of the local people. This public consultation process is being handled by an independent consultancy. A fourth agency will provide architectural and landscape services to the project management team. The overall structure of the Supertram project team is shown in Figure 3.

TECHNICAL ASPECTS

Civil Works

Consulting engineers were commissioned by BBPCL to carry out the detailed design work on alignment and structures. Although the client's documents generally identified the locations where structures were envisaged, the nature and extent of such elements were left largely to BBPCL to determine within parameters laid down in the contract. The basic alignment involves a total of 30 structures ranging in scale from modifications to existing subways to a nine-span, 980-ft-long reinforced concrete viaduct.

The three structures forming the Park Square delta area were designed by the DBS consultancy on behalf of the client. The design of the remaining structures was included in BBPCL's scope, although at certain locations the client indicated a preferred form of structure.

Vertical alignment was substantially fixed by the street running nature of the system, and by the position of at-grade street crossings and headroom clearances for new and existing structures.

The geology of the area was such that coal-bearing measures could be expected near the surface with areas of drift found in the Don Valley where Line 2 was to be built. A geological study provided a detailed breakdown of the further requirements for site investigation involving boreholes up to 150 ft deep and test pits with in situ and laboratory testing as necessary. The extent of shallow mine workings and positions of shafts and other voids were identified, such that structure design could incorporate treatment of such features.

BBPCL clearly recognized the potential impact of major construction works within substantially urbanized areas and so maintained a close liaison with their consultant throughout the design. This ensured that the form of the structure and its major components would be suitable to minimize the effects of construction on the day-to-day life of the city.

Viaducts

The system contains two major viaducts, at Sheffield Parkway and Norfolk Park. The former structure was designed by DBS on behalf of the client and consists of a six-span, 970-ft-long viaduct carrying twin tracks. The structure crosses the four lanes of Park Square's traffic circle, a major intersection on the city's road system, and subsequently runs parallel and immediately adjacent to the westbound lanes of the Sheffield Parkway. The structure is of post tensioned reinforced concrete construction using precast segments erected in balanced cantilever methods. The precast solution provides benefits to the overall construction period and minimizes the disruptive effects associated with constructing a major viaduct over a key thoroughfare.

The Norfolk Park viaduct is a BBPCL-designed structure based on a steel composite bridge construction. The 1,000-ft-long viaduct is founded over a substantial portion of its length in the slopes of an existing cut adjacent to British Rail main lines. At its southern end the structure passes over Norfolk Park Road and a private car park before running back onto the embankment. The original design for the viaduct was an in situ constructed reinforced concrete box-type structure with a retaining wall. However, limited access and the constraints imposed when working adjacent to an operational railway led BBPCL to alternative design solutions in the form of reinforced earth embankments and steel composite bridge construction. Ultimately technical and commercial considerations showed the steel composite design coupled with a conventional reinforced concrete retaining wall to be the most suitable solution.

Bridges

The contract requires nine bridges to be constructed. The two bridges in the Park Square area have been designed by DBS and are intended, together with the Sheffield Parkway via-

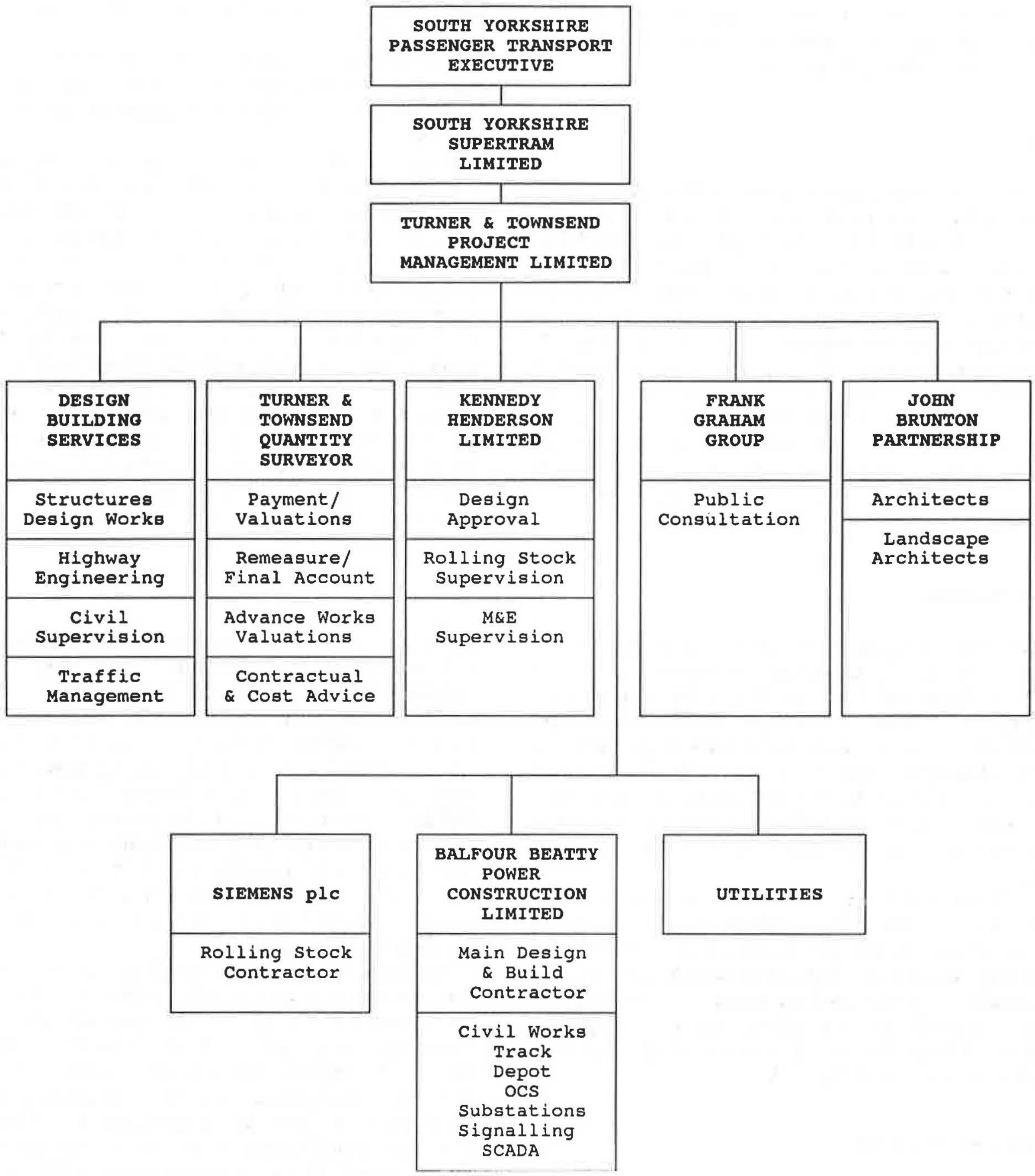

FIGURE 3 Supertram project team.

duct, to present an aesthetically pleasing solution to this highly visible core of the route. The Commercial Street Bridge is a three-span, 360-ft-long structure crossing the four lanes of the Park Square traffic circle with a 240-ft-long center span.

The bridge is of steel composite construction with simply supported side spans and a bow girder center span, all supported on pile foundations through fill to bedrock. BBPCL's major consideration on this structure has been to develop a construction method that provides maximum flexibility of work consistent with the need to maintain traffic flows on the traffic circle. This has resulted in the superstructure being preassembled in sections, adjacent to the bridge site, and lifted into place at night and during weekends. The method has required substantial temporary intermediate supports, the locations of which have been specifically chosen to minimize the reduction in roadway width during construction. The program and methods of working have been developed with the intent of progressing from the ends of the structure, again to reduce disruption to traffic.

The second bridge in Park Square is a 114-ft single-span structure of precast, post tensioned reinforced concrete construction. The geometry and form of the structure dictated that the precast units, weighing 50 tons each, be supported on temporary trestling spanning the live roadway section. Limited headroom was available beneath the box for temporary support.

The eight bridges within the Don Valley section of the route are BBPCL designed. Cricket Inn Road bridge is a single span structure carrying the twin tracks over an existing rock-faced railway cut. At the eastern abutment, the existing ground level and geology permit a conventional reinforced concrete foundation to be formed on the shallow bedrock. However, at the western abutment, the ground level is significantly lower and close to old coal-working areas. The bridge foundations will therefore be extended below the coal-working levels with mass concrete fill placed to form a suitable bedding for a conventional reinforced concrete foundation. The 154-ft-span superstructure is designed as two pairs of braced steel girders with a reinforced concrete deck slab. The girders will be preassembled adjacent to the bridge site and launched into position during railway possession periods. This minimizes the number of railway possessions required and reduces construction time.

The Sheffield Parkway bridge is a 107-ft-long skewed structure carrying twin tracks across a main dual roadway. The client's preferred solution was a reinforced two-span concrete box-type structure with the central pier situated within the median of the road. BBPCL provided an outline design of such a structure but offered an alternative solution based on steel composite construction, which had a number of advantages.

- The depth of the superstructure would be reduced, thus lowering the height of the adjacent embankments with consequent financial and schedule benefits;
- The need for a central pier would be eliminated; and
- The amount and nature of traffic management associated with this form of construction would be significantly lessened.

The alternative solution was subsequently approved.

Woodbourn Road bridge carries twin tracks over British Rail tracks and is adjacent to an existing bridge. The design incorporated reinforced concrete spread footings founded on bedrock with the underlying faulted rock removed and replaced with mass concrete where necessary. The exposed elements of the structure have been designed to match the adjacent bridge. The 92-ft single-span superstructure is designed using precast, prestressed concrete beams launched into position during a limited number of railway possession periods.

The system is carried over the Sheffield and South Yorkshire canal on an arch-type of bridge. The arch form was retained as it complemented a similar structure located nearby. The type of structure chosen imposed considerable technical demands because of the large loads on the thrust blocks. Bedrock was identified as lying close to the surface and no shallow mine workings were evident. However, historical information suggested that mine shafts were present in the area of the southern piers. Provision was made within the design for capping of shafts, and the bridge was to be founded on spread footings based on rock. The structure crosses the canal over a deep cut with rock-faced batters. Access at the bottom of the batters is extremely limited, resulting in construction access at the ends of the bridge. BBPCL opted to use a steel composite superstructure to allow the arch to be preassembled in sections and lifted into position using large cranes. This method obviated the need for the substantial temporary support works required for a similar type of structure in concrete.

The Darnall Road bridge is a single-span, 62-ft-long structure that carries the route over a local side road. Foundation design incorporates the removal of shallow mine workings with mass concrete fill replacement, the reinforced concrete footings then being founded on the rock. The superstructure was designed as two pairs of steel girders supporting a reinforced concrete deck slab to minimize the need for traffic management on the highway below.

The River Don bridge will use the substructure of an existing British Rail bridge, but the superstructure will be replaced in its entirety. The bridge is a three-span, 180-ft structure with intermediate piers in the River Don. The existing substructure was strengthened with capping beams. To minimize the weight imposed on the substructure, a steel composite superstructure was adopted. The continuous steel girders are preassembled in pairs behind the abutment and launched across the river, thus resolving the problem of limited access for the large cranes required for lifting.

Retaining Walls

Retaining walls were required at various locations along the route and total nearly 1 mi in length, ranging in height from 3 to 33 ft. Generally the walls are of reinforced concrete founded on spread footings on the relatively shallow rock. For ease and speed of construction, standard panel lengths of 33 ft have been adopted, thus allowing maximum reuse of formwork systems. The route at Hillsborough Corner takes a sharp turn to extend to Holme Lane. To achieve an acceptable track radius at this point, it was necessary to widen the corner to maintain the roadway width and to carry the realigned road over a weir of the adjacent River Loxley. This will be achieved by constructing a retaining wall and a reinforced concrete slab on piers spanning the weir. The geology of the area showed a 16- to 33-ft layer of sand, cobbles, gravel, and boulders overlying bedrock. It was necessary to provide bearing piled foundations for the structure at this location. All retaining walls are being faced with brickwork or masonry to blend with existing facades.

Underpass

At Brook Hill, the route crosses a large traffic circle that forms a major intersection of the city's road system. Crossing at grade is not possible because the required tram priority could not be achieved and an elevated crossing with headspan clearance could not be provided with an acceptable vertical alignment. An underpass solution was consequently chosen. Various forms of structure were considered, but the limited depth of material above the roof of the underpass ruled out conventional tunneling or corrugated steel structure solutions. A reinforced concrete box design has, therefore, been adopted. The geology of the area shows approximately 8 ft of fill overlying bedrock (mudstone and siltstone), the top 3.6 ft of which is highly weathered. The structure is thus founded within rock on conventional reinforced concrete bases.

Construction of the 450-ft-long tunnel and 300-ft-long approaches will be undertaken using cut and cover methods.

This will be carried out in stages, to maintain traffic flows at the traffic circle, with completed sections backfilled and restored to provide diversionary routes for traffic. A significant part of the excavations will be through rock of varying states of weathering. The exposed rock faces will be rock bolted.

General

The construction of an LRT system clearly is a major logistics exercise in dealing with existing utility equipment, identifying, designing, and implementing traffic management measures necessary to construct the works, and reinstatement or regrading of the existing highway system along the route.

Throughout design and construction, BBPCL has maintained close liaison with the local authorities and utilities. The necessary service diversions have been planned within the overall program such that, wherever possible, areas are clear of utilities prior to the start of construction.

Similarly a close liaison has been maintained with the Local Highway Authority to determine the most suitable form of traffic management for the various phases of construction. These have ranged from long-term diversionary routes to short-term temporary measures for lifting of bridge beams and so forth. These systems were developed early so that the public has been notified well in advance of any disruptive situation. BBPCL has similarly worked closely with the local authority to identify areas where construction activities bring potential conflict with established pedestrian routes and to implement suitable alternative arrangements.

Trackwork

General

The standard gauge track (4 ft 8 1/2 in.) consists of two types:

- Ballasted track for off-street running, and
- paved track for on-street running.

The request for proposals (RFP) called for flat-bottomed rail with a number of alternative specifications for both base plates and ties for the ballasted sections and grooved rail of cross-sectional area between 11.625 and 12.09 $in.^2$ for the paved areas. The paved track support system was to be of concrete construction with embedment of the rails rather than mechanical fastening.

Final Trackforms

The final designs chosen after due consideration of the technical aspects, economic considerations, and the interface with the rolling stock were as follows:

Ballasted Track British Standard flat bottom section 80A wear-resistant grade-A rail mounted on concrete duo-block ties with Pandrol fastenings was chosen. Duo-block ties were chosen for economic reasons and to provide good resistance to lateral track movement. Switches are of a standard design mounted on timber ties. Ballast of at least 10 in. below the ties is provided by a no-fines, well-graded, bed of hard dense angular stone to National Standard Specification.

Paved Track For the on-street paved section plain track, 35G-TF grooved rail to French Standard NF F52 523 was chosen and, for standard switch construction, grooved rail to VOF Standard 785 (RI60) was chosen. The rails are embedded in a groove in the concrete paving using an elastomeric grout that

- Locates and fixes rails without the need for mechanical fastenings;
- Provides the rails with a resilient support for both passenger comfort and absorption of noise and vibration generated by the wheel/rail contact; and
- Provides electrical insulation to limit stray currents.

This type of design and construction was chosen because of its proven service record both in Europe and Hong Kong.

Drainage of the grooved track relies on special drainage boxes fixed to the underside of the groove. Run-off is channeled through ducts to the roadside surface water drains.

Rail Jointing Generally the system is designed as continuously welded rail (CWR) with fishplated joints confined to switches, depot, and tight radii curves. Rails are laid as 59-ft lengths and welded together using the alumino thermic process to form continuous lengths. Scarf-type expansion switches have been introduced at joints between CWR and fishplated tracks and over structural movement joints on bridges and viaducts. Rail lengths are destressed at a neutral temperature at predetermined lengths and welded together to form CWR.

Points Machines The switches on the main routes are designed to be trailing. Where facing points are installed, they have been designed to be switched automatically or manually.

Stray Current Protection The trackwork designs and materials have been chosen to provide the tracks with adequate insulation to meet the performance specification of 100 ohm·km single track between rail and earth and 10 ohm·km between single rails.

Measures adopted on ballasted tracks allowed for the following:

- Insulating rail pads and insulation between rail and clip,
- Leaving the ballast 1 in. below bottom of the rail,
- Use of CWR or bonded out rail, and
- Providing fault current return at substations.

For the paved track, the following measures have been adopted:

- Embedment of a grooved rail in an insulating material,
- Provision of an earth mat in the concrete track base under the rails and bonded out, and
- Jumper bonds across rails.

Where short sections of different trackform are provided, the rails are isolated from the surrounding supports to ensure no electrical continuity.

Depot

A depot facility to stable and maintain the 25 articulated trams is provided near the delta junction. The design allowed flexibility for trams to enter and exit the main lines at both ends of the depot.

Initially the maintenance schedule was to clean the inside of the trams daily, wash them two or three times a week, and inspect bodywork, chassis, wheels, pantograph, and general systems on a routine basis. Minor repair items would be carried out by depot staff, and major repair items would be done off site by contract. Subsequently the philosophy was changed, and the main workshop is now sufficiently flexible and well-equipped to do all but total rebuild. Specialist equipment includes a wheel lathe, water recirculating washer, sand filling equipment, engineers siding, casualty bay, jacking, and bogie jigging. Although space was restricted because of land availability, careful design allowed for a circular track from the end of the stabling lines into the main workshop, the minimum radius being down to 82 ft.

Infrastructure maintenance and warehousing are also based in the area together with the operations and driver control rooms and cafeteria facilities.

Overhead Contact System

General

With a large proportion of the route running on-street through the city center, aesthetic consideration has a major influence on the design of the overhead contact system (OCS) style, the assemblies, and the supporting structures.

OCS Style

Although simple catenary equipment could have been designed for short sections of the route in the outlaying areas, it was decided to use trolley wire equipment throughout as it provided a number of benefits:

- Visually less obtrusive,
- Uniformity of design and a saving in structure and component variety, and
- Absence of hangers simplifies construction and maintenance.

To meet the required current rating, twin 4/0 AWG cadmium copper trolley wires were used. Where 50 mph running is possible, the trolley equipment is auto-tensioned at 2 × 14 kN. Where the speed is restricted to a maximum of 30 mph, fixed terminations are used with tensions of 2 × 12 kN at 50°F. Maximum spans are 197 ft for the auto-tensioned equipment and 164 ft for the fixed equipment. At junctions, minimum radius curves, and other complex areas with speeds limited to 15 mph, the tension of the fixed termination equipment is reduced to 2 × 6 kN at 50°F and has a maximum span of 66 ft. In the depot area the equipment is similar, but has a single 4/0 AWG trolley wire because of the lower current requirements.

The equipment height varies according to the location. For on-street areas and in the depot, the height is governed by road traffic requirements with normal heights at supports of 19 ft 9 in. for auto-tensioned, and 20 ft 8 in. for fixed equipment. For off-street running, the optimum height of 18 ft 5 in. is used with an allowable minimum of 12 ft 6 in. To allow for abnormal loads, certain crossing points have a maximum height at supports of 21 ft 4 in., while the pantograph will have some reserve in its range, being designed for a reach up to 23 ft 0 in.

Equipment Design

Wherever possible, the trolley wires will be supported by back-to-back cantilevers on central poles, hence minimizing the number of foundations and structures. The cantilevers are constructed from 1 5/8-in. diameter steel tube with fiberglass rod insulation of similar diameter and synthetic rope ties. The avoidance of large insulator sheds is more environmentally acceptable.

In situations where center poles are not acceptable, such as on-street running without a median, span wires will be suspended from side poles or adjacent buildings. The span wires are made from synthetic ropes, avoiding the need for cut-in insulation.

All equipment, with the exception of switches, is double insulated from the supporting structures. This avoids the need to earth-bond the structures to rails with the associated risk of corrosion in foundation reinforcement because of stray currents. At switches the structures are bonded to rails but are insulated from the foundations so that there is no current path.

The auto-tensioned equipment will have the balance weights located inside the anchor poles, and most of the switching will be indoors or in cabinets. These considerations help to minimize the visual impact of the equipment, protect it and contribute to safety.

Foundations and Structures

A range of standard side bearing foundations has been designed for the variety of ground conditions encountered in an urban situation. The foundations have a small cross section, typically only 2 ft to 2 ft 8 in. wide, except where unique designs are prepared.

The design of the supporting structures is influenced by aesthetic, engineering, and cost considerations. Stepped tubular poles are used throughout and have bolted base attachments to allow easy installation and replacement in the event of damage. The unsightly bolting will be hidden by a decorative trim. A requirement for a small number of special structures is anticipated, one known example being a large central pole at Park Square delta junction, from which an array of span wires will radiate.

Computer Applications

The use of computer-aided techniques in the OCS design is extensive. The static and dynamic characteristics of the equipment and the pantographs have been investigated and optimized using BBPCL analysis software. Structures and foundations are designed with spreadsheets and proprietary structural analysis programs, and almost all drafting uses computer-assisted drafting and design (CADD). The use of Moss CADD for installation design is increasing the level of integration of the various disciplines involved in the project. Survey data and the track alignments in Moss CADD are used directly by the installation design engineers without the need for extensive redrafting.

Substations

The original RFP specification was based on a power supply arrangement comprising an 11 kV ring main, feeding eight 1 MV substations spaced at regular intervals along the route. Seven of these substations had a single 1 MV transformer rectifier, and the remaining substation, which fed the depot as well as the main line, had two 500 kW equipments for increased security. The nominal voltage specified was 750 V dc with maximum no-load rectifier voltage of 700 V and a minimum pantograph voltage of 525 V in the absolute worst case. The system is generally required to be designed for vehicles operating at a maximum frequency of once every 5 min in each direction, although a reduced service may apply on certain parts of the route. The overhead equipment was originally specified as having a continuous current rating of 500 A root mean square (rms), and a resistance not exceeding 0.08 ohm·km at 20°C with the contact wire worn by 20 percent.

During the design phase, more detailed information became available. In particular

- The car manufacturer was selected, and the vehicle power characteristics were identified.
- Operational requirements were more closely defined.
- The types of equipment used for the power distribution were selected. These include 2,000 A semi-high-speed circuit breakers and transformers with dry-type insulation. The overload rating of the rectifiers is 150 percent for 2 hr and 200 percent for 1 min.
- A review of the power system was carried out. This involved the use of the BBPCL proprietary computer program, RAILPOWER, which simulates the operation of the vehicles running according to the defined schedule and calculates electrical parameters on a second-by-second basis. The wide range of digital and graphical output produced by RAILPOWER enables the system performance to be assessed quickly.

In light of this more detailed information, the design evolved such that the system currently proposed incorporates 12 600 kW substations, which feed twin 4/0 AWG cadmium copper trolley wire equipment. This is adequate to cater for the maximum continuous current requirement of approximately 600 amps per track. The system design is such that when a substation is out of service, continued operation is possible, albeit at a somewhat reduced performance level.

The trolley wires of the up and down tracks are not segregated electrically but are interconnected at regular intervals. This gives improved operational characteristics and a significant saving in energy thanks to regenerative braking. A significant saving in the capital cost is also possible because of the reduction in the amount of switch gear required. A further advantage is that the electrical sectioning of the overhead equipment is greatly simplified, particularly at junction areas.

Maintenance of the overhead equipment is simpler and safer because the problem of working alongside live conductors does not arise. Furthermore wrong-side running in streets full of general road traffic is, in any case, hazardous. The only disadvantage of this arrangement is that if the overhead equipment associated with one track fails, the other track is automatically taken out of service. The advantages of electrically common overhead equipment far outweigh the one apparent disadvantage.

Signaling and Control System

Different sections of the Sheffield Supertram system fall within each of the U.K. National Regulatory Standards for LRT categories:

- LRT 1: Street-running system shared with other users,
- LRT 2: Street-running, but not shared with other users, and
- LRT 3: Wholly segregated from other road traffic split as either—
  - —LRT 3A: Line-of-sight and not fully fenced, and
  - —LRT 3B: Fully fenced and under the control of an interlocked signal system.

On normal street-running the supertram operates on line-of-sight and obeys normal vehicle traffic signals redesigned to give priority to the tramway. Centralized urban traffic control is the only overriding authority. On LRT 3B the fail-safe interlocked signaling system operates on line-of-sight operation or, in the event of a clear track circuit in front of the train, a visual indication is given of a higher permissible speed. Lamp failures or faults revert back to line-of-sight operation, enabling the tramway to continue operation at safe driver-controlled speeds.

Overall control of the system is aided by a simple signaling control and data acquisition (SCADA) computer system, with video display set in the depot control room. The monitoring system currently covers selected areas such as substation traffic control and fault locations with radio control for instruction. Flexibility for control advancement is provided for future addition as the requirements develop.

COMMERCIAL ASPECTS

Planning

A fully integrated schedule, encompassing all the disciplines involved in the project, was produced to manage and control the project.

The network initially used for the project allowed for more detailed programming to be incorporated within it as information became available, and the design progressed. The Metier Management Systems Artemis 7000/386 software product is being used on the project because of its versatility and speed. The 7000/386 language is not particularly user-friendly, so Artemis Project 7000, a menu-managed system, is also being used. It is more user-friendly and, at the same time, the more complex and versatile 7000/386 language can be integrated with it to allow the production of reports tailored to site management. The system is being developed to incorporate design control; drawing register; variation order control; progress curves, overall, and for each discipline; delayed discipline; personnel resource scheduling; and construction labor histograms.

Cost Control

Whatever type of project is being undertaken, the contractor's key objectives must be to ensure that the project:

1. Is completed safely from the viewpoints of both the project personnel and the public,
2. Is built to the specification standards,
3. Is completed on time and to budget,
4. Makes an adequate profit for the contractor.

Only the third objective is dealt with here.

Limit of Authority

The project, because of its size, will have key managers who will answer for the project's financial performance. Thus it is essential for these individuals to have firm control over the expenditure and cash flows on the project with delegation to the appropriate level of their staff. These managers will also have the required delegated authority with respect to commercial contracts with the project's subcontractors and key suppliers, ensuring that the best technical and commercial terms are achieved in all respects.

Contract Reports

The contract requires two contract reports, each providing different types of information to different levels of the project staff. The first report is prepared weekly, enabling the line managers to determine whether or not they are operating efficiently in the field. This report deals with two key resources, labor and equipment. The project will be expected to achieve a level of productivity in the field in terms of completion of specific tasks, and these tasks will have a value of which the labor and equipment will be key elements. Having identified the tasks to be completed by means of a detailed program, they are then valued from within the overall budget for the contract. Each week the tasks are measured, valued, and compared with the costs. The line manager can identify the problem areas of low productivity and determine a course of action to rectify the problem. It is essential that this information is available on the Monday morning following the week of measurement and value. Although it might be considered that this frequency is too low, experience indicates that a weekly period is the most practical and manageable. Material control is not included on a weekly basis for reasons that will become apparent later.

The second report is prepared monthly and brings together all aspects of the project key elements of cost and value (e.g., construction labor, equipment, materials, subcontractors, staff, and site establishment).

This monthly report separately declares the cost and value against each of the above key elements and splits the individual cost and value against specific key elements (e.g., individual subcontractors or materials). It may be argued that, if the key elements have been procured within the values generated by the project, this level of reporting is not required. It is nevertheless essential that the management of the project be aware on a monthly basis of how each element is performing, both against the procurement declarations and the budget. If either one is showing slippage, then managerial decisions regarding the project's future can be made in terms of resource expenditure, reprogramming, and, if necessary, ensuring the client is kept well aware of the more serious effects on the project. Furthermore it is valuable in assisting the manager in deciding whether any systems put in place for material control, material reconciliation, weekly labor, and equipment cost and value reconciliations are having any effect, and if not, why not.

Budgets—Cost and Value to Completion

The project must have a budget in terms of both cost and value so that management can determine how the project is operating in the overall schedule. In some cases the budget assists management in making key decisions about scheduling and the use of personnel.

Once overall costs and value are determined, they are then analyzed against the project's monthly report to determine the financial effects on the project's physical performance (in terms of meeting milestones) and financial targets (in terms of procurement resource performance, such as material handling control, efficient utilization of labor and equipment).

Should the original budget be shown to be inappropriate through either under- or overachievement on the project program, then the budget must be updated. Frequencies greater than quarterly are not recommended.

Material Control

More than half of the project's cost and value is to be found within the material element. It is essential that this element is effectively managed by a control system. The system used was originally developed by BBPCL to control stock from point of sale to goods delivery.

The system has some sophisticated spin-offs in that it can also allocate to location, readjust for "as fitted" changes, and produce a number of used-on facilities. Coupling this with the need to monitor suppliers—inspection and testing, deliveries, and shipment details—the system can be almost a minute-by-minute timetable or location chart of what is happening to the material from advice of order to erection in the line. The fact that certain elements are subject to a wastage and loss factor is also taken into account, so the system provides exceptional control for managing both costs and material movement.

The system itself was developed for use on a mainframe computer, but has since been modified for on-line terminal use. Further ongoing development will make it possible to revamp to UNIX, 386 desktop facilities.

Management of the material control system is possible at site level, but using the centrally based purchasing function within BBPCL's divisional offices secures maximum discount and flexibility of suppliers.

Visual display of the various elements, such as allocated requirements, order requirements, manufacturing dates, inspection details, shipment and dispatch details, received on site, in stock details, allocated to line, issued to line, loss details, and so on, assist the material controllers in maintaining an effective stores control procedure. Variance reports are produced for management control and information. Using this information with the sales analysis and cost reporting schedules, item pricing and material valuation became virtually automatic as part of the total material control system.

THE FUTURE

Unlike its continental neighbors, the United Kingdom has steadily closed down almost all its tram systems. Modern tram networks are now being enthusiastically promoted. No doubt when the South Yorkshire Supertram system has been completed and its quality service has been experienced, it will represent a powerful argument for the introduction of such projects in other cities in the United Kingdom.

Key Issues in Light Rail Transit Station Planning and Design

JEROME M. LUTIN AND GREGORY P. BENZ

Planning for light rail transit (LRT) systems often focuses on the development of alignment alternatives to maximize use of available rights-of-way. The selection of station locations sometimes seems to follow almost as an afterthought. Ideally, station sites should be planned first, and the alignments should be developed to connect the stations. In practice, however, LRT planning involves a balance between locating alignments and locating stations. Some of the major issues planners must address in locating and designing stations include station spacing, station location, mix of land uses served, pedestrian access to stations, station layout and its relation to operations, and implementation. How LRT planners can address each issue to maximize ridership and reduce costs is illustrated by examples from recently constructed LRT systems and systems still in planning.

Transit systems, including light rail transit (LRT) systems, exist to move people safely, conveniently, and efficiently. Along with the transit vehicles, a transit system's primary interface and exposure to the passenger is through its stations. Station location and design have a major effect on the ability of passengers to access and use a transit system.

To gain the support of citizens and elected officials for a new LRT system, planners must demonstrate that the system effectively serves the community. The system must take people where they want to go, be convenient to use, and offer a transportation service that is better than the available alternatives. Ideally in planning and designing stations every decision should be tested against these criteria.

The following principles should guide station planning:

- Station sites should be planned before alignments.
- Travel speeds needed to attract riders should be considered in determining station spacing.
- Alignments in residential areas are preferred over industrial corridors.
- Pedestrian access to stations should be considered early in the planning process.
- Land use plans for new developments, such as suburban office parks, should emphasize the clustering of buildings around station stops to reduce walking distance.

Because the LRT planning process is ultimately exposed to public scrutiny, planning ideals such as these will inevitably be challenged by politics, NIMBY (not-in-my-back-yard) sentiments, and the pragmatic consideration of costs. Trade-offs and compromise will be needed.

The importance of stations, their location, and design are often not fully recognized and reflected in the implementation of rail transit projects. Rail alignment design criteria, right-of-way, and land availability may dictate the locations of stations rather than allowing stations to be where they can best serve the riders. Trade-offs are necessary to make a project affordable and implementable, but too often station planning and design issues that could easily be addressed well in the conceptual planning stages are given low priority as detailed design, construction, land acquisition, and implementation issues are addressed in later phases. LRT technology has several special characteristics that make it possible to locate stations where they can serve the riders.

PLANNING OBJECTIVES, STATION TYPES, AND LRT TECHNOLOGY

Station planning and design should achieve a number of objectives. The primary issues relate to providing a means for passengers to use the transit system safely, conveniently, and comfortably. Safety includes minimization of accidents, falls, and crush load conditions as well as security considerations and provisions for emergencies (including evacuation of the station and train occupants). Convenience is reflected by the ease of use, relatively short and direct travel paths, minimal queuing (delay), and reduction of congestion and crowding. Comfort addresses issues of amenities, architectural and environmental (lighting, air, noise) treatments, and aesthetics.

Many other objectives for station planning and design exist, such as encouragement of land development and community cohesion. The focus here, however, is on objectives related to passenger service and train operations issues.

Depending on the nature, extent, and location of the transit system and methods of fare collection and other operating procedures, stations may accommodate a number of passenger activities, including

- Interchange with the transit system(s) and access to and from the station,
- Transfer between transit services or modes,
- Fare transactions and collection,
- Information regarding use of system, and
- Waiting, including seating and weather protection.

Although these activities are generally common to all transit technologies and even most other transportation modes, LRT

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stations may provide for them in a wide range of ways. For instance, stations may be as simple as stops with on-board exact-change fare collection (like a bus system) or as elaborate as multilevel stations with fare gates defining a "paid" zone similar to most rapid rail transit systems.

Station Functional Types

Stations can be categorized into three functional types reflecting the role they serve for passengers. One, the line-haul collector function, is typical of a suburban station that serves as a focus of passengers coming from residential origins. Provisions should include park-and-ride, kiss-and-ride, feeder and shuttle buses, walk-in, and bicycles. This type of station is primarily subjected to boarding flows in the morning, with the need for ample inbound platforms, and evening alighting flows, with the need to accommodate exit surge volumes of automobiles and buses after passengers leave outbound trains.

Another type, the line-haul distributor function, is typical of stations at a major development concentration such as a central business district (CBD) or a major activity center in a CBD fringe or suburban area. Provisions must be made for pedestrian access as well as distributor bus services, and taxis and shuttle vans. These stations primarily have alighting morning flows, and therefore need ample inbound platform egress capacity, and boarding flows in the evening principally headed for the outbound platform.

The third type is the transfer stations. Although all stations involve some interchange of travel modes, this type of station involves the interface with another line-haul or major distributor transit service. This could be another line of the same mode or a different technology. Stations must contend with the particular transfer volumes and patterns at different periods of the day, accommodate the particular fare control and informational needs of each system, and accommodate the passenger needs in the event of service disruptions on one or more of the intersecting services. Convenient passenger transfers are a primary objective. This type of station may also have one of the other functions as well, particularly in a CBD setting where line-haul services often intersect and the station must play the line-haul distributor role as well.

Terminal stations at the end of the line, stations where lines branch, and those serving special trip generators such as an arena or airport have special needs and considerations peculiar to the situation.

LRT Technology

LRT is characterized by steel-wheeled vehicles running along paired steel rails with power supplied via an overhead wire. The size, configuration, capacity, performance, and other features vary. Trains can be a single vehicle or multicar consists. The characteristics of LRT as a technology that enable LRT stations to be advantageously located are its flexibility, adaptability, and potential range and combinations of system feature choices. In particular an LRT alignment has the ability to have relatively tight turning radii (as low as 100 ft), relatively steep grades (as much as 8 percent), and to operate with single-track sections and in a variety of environments—in street, semiexclusive, exclusive, or a combination. A light rail vehicle's (LRV's) floor height is typically 39 in. (1 m) above the top of the rail. Platforms can be high level—at the same height as the vehicle floor—or low level—passengers use on-vehicle stairs to access the vehicle. A low-floor LRV—approximately 12 in. (0.3 m) above the top of the rail—allows level boarding from "low" platforms.

Similarly, as will be discussed later, LRT stations can have a range of features and be adapted to the specific site conditions, service needs, and system operational requirements. LRT's flexibility, adaptability, and range of choices give this technology an ability to reduce cost or avoid major cost or community and environmental problems. Even when taking advantage of these LRT features, site-specific conditions can sometimes require a compromise with travel speeds (such as in mixed traffic environments or around a tight curve) or schedule reliability (because of grade crossings or single-track segments.) More than most other transit options, LRT provides the opportunity to trade off and optimize operating objectives with station placement, costs, and effects.

STATION PLANNING AND DESIGN PRINCIPLES

These station objectives, activities, and functions can be addressed by LRT station design by exploiting the special characteristics inherent in LRT technology.

Station Spacing

Modern LRT systems function in a competitive environment, and station spacing has a direct bearing on the competitiveness of an LRT line. Almost every household in America has an automobile available and many have more than one. To be successful an LRT line must draw as many automobile users out of their cars as possible. LRT service must therefore be competitive with automobile travel in terms of travel time and convenience.

Patrons want both a short walk to and from the station and high-speed travel between stations. Yet, these two desires, short walking distance to the line and high speed travel, present conflicting goals for the LRT system planner. Trade-offs must be made to achieve a satisfactory balance.

A number of factors are included in the mathematical equation used to determine average speed on an LRT system:

- Station dwell time,
- Vehicle acceleration rate,
- Vehicle deceleration rate,
- Jerk (rate of change of acceleration or deceleration),
- Vehicle top speed, and
- Distance between stations (*1*).

Station dwell time is a function of the number of people boarding and alighting, time needed to collect fares on entering or exiting the vehicle, and the number and width of the doors available. Vehicle acceleration, deceleration, and jerk rates are generally governed by comfort levels. All three parameters must be kept in a range that allows standing passengers to maintain their balance easily when the vehicle starts or stops. Top speed is a function of vehicle motor capacity and gearing but more frequently is governed by horizontal and vertical curvature and superelevation of the tracks.

Distance between stations, as it affects LRT line speeds, differs from the factors just mentioned. Whereas all the other factors are determined largely by the laws of physics, station spacing is almost entirely a judgment call, left to the planners' discretion.

To illustrate the relationship between average line speed and station spacing, an "average" North American LRV was assumed based on published vehicle performance data for nine North American systems (*2*). Figure 1 shows the average speed attained on a typical line segment between two stations as a function of station spacing with an assumed dwell time of 20 sec. The example shown assumes that the vehicle accelerates to its maximum cruise speed (Vmax) and decelerates to a stop. Where the line segment is too short for the vehicle to reach Vmax, the vehicle is assumed to accelerate to the point at which it must begin braking for the next stop. From this example one can see that 0.25-mi (0.4-km) station spacing yields an average speed of 15 mph (24 km/hr), 0.5-mi (0.8-km) spacing yields 23 mph (37 km/hr), 1-mi (1.6 km) spacing yields 32 mph (51.5 km/hr), and 2-mi (3.2-km) spacing yields 40 mph (64.4-km/hr).

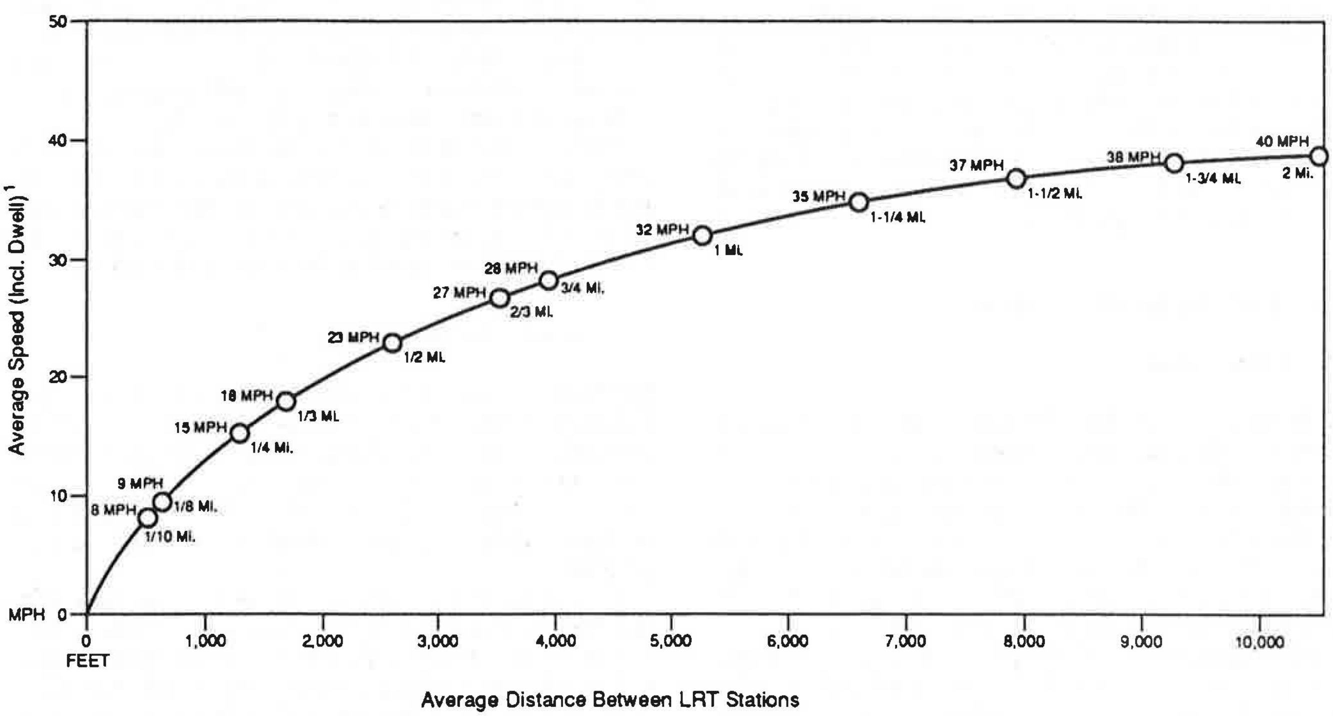
This example clearly indicates that the LRT planner must consider the implications of station spacing on meeting the travel time goals and objectives established for the prospective system. If, for example, a major goal is to improve service for existing transit riders using a local bus system averaging 12 mph (19.3 km/hr) on local streets, then stations spaced as close as 0.25 mi (0.4 km) may be used. If, however, a major goal of the planned system is to attract drivers from a parallel freeway on which they average 25 mph (40.2 km/hr) in the peaks, then average station spacing must be kept to 1 mi (1.6 km) or more to maintain a speed average.

In most corridors it is possible to adjust station spacing to accommodate local access conditions. In CBDs where most riders walk to and from stations, closely spaced stations are most appropriate. In the suburbs where the line is intended to serve either dispersed office concentrations or park-and-ride users drawn from residential areas, more distant station spacings can be used.

In the early sketch planning phases, however, planners should calculate the average station spacing over the entire line and check to see if it will allow the line to achieve the desired travel speed needed to attract the potential riders the line is intended to serve.

Station Location and Trip Purposes

People make trips because they have needs that can be met only at a location other than the one at which they happen to be. This simple fact means that given the way our cities are laid out, the heaviest travel demands lie between areas with differing land uses. If a new LRT line is to be successful,



[1] Assumes V_{MAX} = 53.3 MPH, Jerk = 3.05 MPH/Sec^3, Accel = 1.64 MPH/Sec^2, Decel = 3.06 MPH/Sec^2, Dwell = 20 Sec.

FIGURE 1 LRT station spacing—average speed relationship.

it must provide connections among the land use types and activity centers that correspond with the reasons people make trips. Consequently station locations must be planned with regard to existing trip-making patterns in a corridor or provide opportunities to create new trip patterns among diverse land uses.

Rail transit's traditional role has been to serve work trips linking residences (preferably high-density) with jobs (also preferably concentrated in high-density locations). Historically the home-work-home trip has constituted the majority of all trips made on transit. Today, however, new trip patterns are developing in response to changes in lifestyle and family composition. Examples of changed lifestyles that affect travel are more dual-worker households and more single-parent households.

Dual-worker households often result in home-drop spouse-work-pick up-spouse-home trip patterns in which one spouse drives to work and the other takes transit. This pattern will increase the need for convenient kiss-and-ride access to stations, which lends importance to locating stations with easy access to arterial streets that run between residential areas and employment concentrations. It also requires convenient drop-off points and kiss-and-ride circulation at stations as well as adequate space for cars to queue for evening pickups.

Dual-worker households also have less time available for shopping and personal business. Consequently the evening trip from work to home often becomes a work-shop-home or work-day-care-eat meal-home trip. More riders may be attracted to stations at the residence end if they are located close to shops and restaurants.

Single-parent households often have unique trip needs, requiring home-day care-work-day-care-home or home-school-work-baby sitter-home daily trip patterns. Locating a park-and-ride station close to a school or day care center may provide a way to attract single-parent users who otherwise might find transit too inconvenient given their hectic schedules.

The essence of these examples is that station locations in a proposed LRT corridor should be planned to link sensible destinations that correspond with contemporary travel needs of the expected user population.

Land Use Environment for Stations

Rail Rights-of-Way

In laying out prospective LRT lines, planners often concentrate on finding continuous alignments, because the issue of continuity is critical and most problematic. In many instances planners strive to find an at-grade alignment to avoid the expense of subway tunneling or aerial structures. The search for available corridors often focuses on existing rail freight rights-of-way, either active or abandoned, and leads to LRT alignments that pass through industrial corridors.

Although an old freight line satisfies the need for a continuous corridor, the adjacent land uses typically include industry, warehousing, and often abandoned industrial buildings and vacant land. These land uses are poor trip generators today, and prospects for future development may not be great either. Such properties may be contaminated with hazardous waste, have poor automobile access (as well as security concerns about leaving a car in a lot or using the station late at night), or appear sufficiently unattractive to discourage developers from investing in the area.

The pattern of industrial corridors radiating out along rail rights-of-way is typical of many urban areas, and residential corridors tend to lie between the industrial corridors like alternating spokes of a wheel. In essence the radial pattern of residential corridors is "out-of-phase" with the pattern of existing rail corridors most readily available for rail transit.

Another implication of this pattern for LRT planners is that the residential population may be fairly distant from the rail corridor, and pedestrian access routes to stations may traverse inhospitable tracts of industrial or vacant land. In these instances the LRT planner should examine the relationship between residential areas and station sites at a micro level. Although using an industrial corridor is very appealing, other alignments may be needed that pass closer to the residential areas to be served if the maximum benefit to riders is to be obtained.

Suburban Office Parks

In some urban areas new growth has taken place in suburban office parks and light rail service is often seen as a way of serving reverse commute trips and reducing the highway congestion that accompanies such development. Yet suburban office centers are often planned with buildings in a campus setting, set far back from the main road, with large parking lots and landscape buffers. This layout creates long, exposed, walking distances between places of employment and possible station sites. In such areas the LRT station should be located to minimize walking distances. Where this is not possible shuttle bus service should be planned with full consideration of the likely impact of shuttle operating costs on the annual operating budget and the impact of shuttle frequency, travel time, and transfer penalties on system ridership.

If LRT service is planned to suburban office parks still under development, the planners should strive to have site development master plans revised to cluster future buildings around LRT station sites and create short, direct pedestrian links to the stations, avoiding the need for shuttle buses.

Park-and-Ride Stations

Most new LRT lines expect to draw a significant share of their CBD-bound riders from park-and-ride access, especially in low-density suburban residential areas. To minimize regional automobile vehicle miles of travel and gain maximum transit passenger miles of travel, park-and-ride lots should be located to capture riders as close to suburban residential areas as possible.

In many areas the LRT line will not be competitive with automobile travel time on suburban portions of radial, CBD-bound freeways. Closer to the CBD, however, traffic congestion worsens and LRT can be faster than automobiles for the downtown portion of the trip. Park-and-ride lots should be conveniently located to take advantage of travel time differences that favor transit. Consequently "intercept" lots should be located with access to major commuter roads at points just before traffic congestion begins to build in the morning peak.

In considering the environmental effects of prospective LRT lines, it is usually assumed that LRT will reduce automobile use and improve air quality. At large park-and-ride sites, however, the reverse may be true. Park-and-ride lots may have very sharp peak hour usage, as large numbers of riders take advantage of travel time savings by leaving home closer to the time they must arrive at work. In the evening peak train arrivals bring several hundred passengers at a time, creating surges of vehicles departing the station parking lot.

To reduce the potential environmental consequences of park-and-ride lots, the lots should be planned in locations away from areas with land uses likely to have peak traffic flows that coincide with the transit system peaks. As a practical matter prospective park-and-ride sites should also be planned with ample vacant space for expansion.

Pedestrian Access

Pedestrian access is crucial to the success of any light rail line in terms of patronage. At least one end of a transit trip involves a walk between the station and the point of origin or destination. Over 90 percent of local transit riders walk less than 1,500 ft (457 m) or about 6 min. Fifty percent walk less than 3 min. LRT planners can assume that virtually all origins or destinations served by pedestrian access from the system lie within 0.25 mi (0.4 km) of a station.

The pedestrian access area is defined by the pedestrian network serving the station, usually the street grid. In the typical rectangular street grid network, the pattern of all points lying within 0.25 mi walking distance of a station is described by a square rotated 45 degrees from the axes of the street grid, with sides approximately 1,870 ft long (549 m), covering a total area of 80 acres (32.4 ha). See Figure 2. Using a circle with a radius of 0.25 mi to represent the area served by a station in a street grid can overstate the area served within a 5-min maximum walk by almost 60 percent.

Land use and pedestrian access within the immediate vicinity of the station require close attention if the station is to be located to draw the highest possible ridership. Planners should avoid locating stations in places where they cannot draw riders from all sides, such as along a river bank or other barrier. Placing stations adjacent to a freeway or park, which can act as barriers to pedestrians, adds to the average walking distance for most riders. Placing an LRT station in the median of an expressway with frontage roads is also to be avoided from an access perspective. Such locations can add significantly to the station access walking time. The roadway system itself can consume up to 17 percent of the land available within a 5-min walking time, reducing the area available to generate transit trips.

Because of the critical importance of pedestrian access to LRT line ridership, walk-in safety and security are paramount. Pedestrian routes to stations must be well-lighted, active, and visible. Avoid mixing walk-on's with park-and-ride and kiss-and-ride vehicle flows. To access stations pedestrians should not be routed through parking lots. They should be provided with direct, wide, well-drained sidewalks buffered from adjacent traffic flows.

Because so many issues must be considered in early planning for an LRT line, the micro level issues just discussed are often dismissed with statements such as,"We can deal with that in the final design stage." It is necessary, however, to consider pedestrian access issues early in the planning. In the alternatives analysis/draft environmental impact statement (AA/DEIS) stage, the ridership forecasting methodology should incorporate a realistic estimate of pedestrian access. UMTA's *Procedures and Technical Methods for Transit Project Planning* devotes several pages to a discussion of transit access modeling. In addition the planners should conduct some "reality checks" by spending time walking the areas around each station site and questioning assumptions about future conditions.

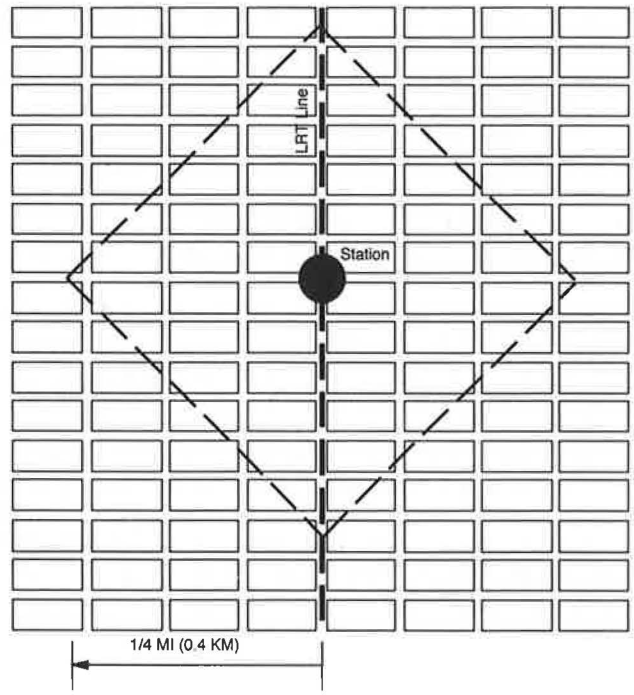


FIGURE 2 Area within a nominal 5-min walk.

In the preliminary engineering (PE) phase, station siting studies should be conducted to a refined level of detail, and pedestrian access conditions should be fully investigated. If station access and ridership forecasts are based on assumptions about future site development or redevelopment, then agreements should be negotiated with local developers, and amendments to zoning and master plan ordinances or regulations should be enacted to ensure that the assumptions are realizable. By the end of the PE phase of the project, all major station siting issues should be resolved, and access assumptions should be verified.

Station Layout and its Relation to Operations

With any public transportation technology, the physical layout of the station must be integrated with the vehicle and its operation to create a "system." For most rail systems, a single set of standards for stations, vehicles, and operations must be established and followed throughout the entire system. LRT, perhaps more than any other mode, provides flexibility and variety to these relationships, allowing many possible combinations that can vary within a specific system or line. Some of the primary issues affecting station configurations and the relationships to vehicle configurations and operation need to be explored.

LRT trains can operate as single cars and multicar consists, which largely determines the necessary platform length. Maximum train lengths are often governed by constraints along at-grade segments, particularly city block length (distance between intersecting streets) in a CBD or other developed area. If the train length exceeds the length of a block, a stopped train can block the cross streets and interfere with crossing vehicular and pedestrian traffic.

A feature of most LRVs is that passengers cannot move between cars because of full-width operator cabs at the ends of the cars. Therefore LRT platforms should be able to handle the maximum length train. (Commuter rail platforms, on the other hand, can be shorter than the maximum train length, if necessary, because passengers can move through the train to access the platform.) Some compromise in platform length can be achieved by making multiple stops at a station, which slows down operations but may be doable for low-volume "flag stops"-type stations.

Platform Configuration

Platforms can have a number of configurations: side, center, side/center, single, or split (see Figure 3).

Side With the side configuration, a platform is located on each side of the tracks. The distance between the track centerlines can remain constant through the station so that the right-of-way requirements expand beyond the track needs only at the station. Usually passengers must cross the tracks to reach a platform (over, under, or at grade) for either the initial or return portion of the trip.

Center With the center arrangement a single platform is placed between the two tracks. The track centerlines must widen to allow for the platform, which requires a track transition zone with a spiral or S-curve several hundred feet long. The right-of-way requirements for the tracks must similarly widen. This can be a design issue where an existing rail right-of-way is being used. However, when center catenary support is used, the amount of widening is reduced. Because it must handle two-directional loading, allow two safety boundaries along the edges, and accommodate possible vertical circulation, a center platform is generally wider than a one-side platform but is narrower than the sum of two side platforms.

Combined Side/Center In certain conditions it may be advantageous to have both a center and two (or one) side platforms. At high-volume stations, especially with heavy simultaneous boarding and alighting movements in the same direction, boarding passengers can use one platform and

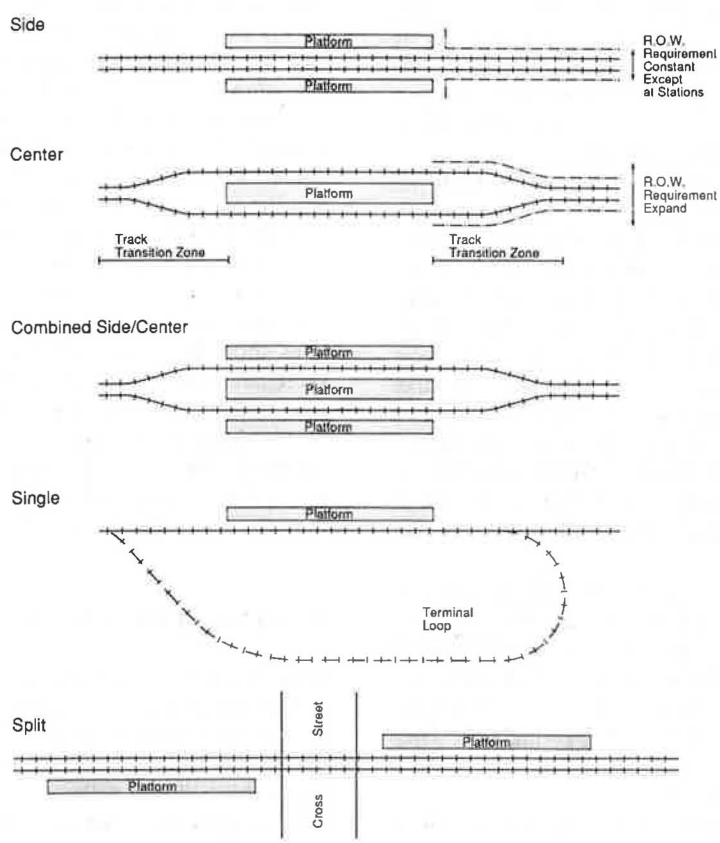


FIGURE 3 LRT platform configurations.

alighting passengers can use the platform on the other side of the car. This reduces dwell time. Also, this arrangement provides extra platform capacity at a station subject to heavy surge loads such as one near a stadium or arena. It can also be used where certain types of system interlining or branching occurs.

Single Where there is a single-track loop or a single-track segment (because of cost reduction or other constraints), a single-sided platform can serve both directions of travel. The end of the line is a potential location for this configuration. Two side platforms could be used as well, but the second platform is usually not needed. The Franklin Avenue terminal loop of the Newark City Subway has a single platform although it often discharges people at the front end and then pulls farther up the platform to pick up passengers. The New Orleans waterfront line has a single side platform station on a two-track segment where passengers in one direction board from the track area of the other direction. The trolley operating environment of this system makes this feature possible. Wheelchair patrons at this station board from the one platform only and can travel the other direction by going to end of the line (the next station) and get on the next return train.

Split In the split configuration, the two platforms are separated longitudinally. This often occurs in restricted right-of-way conditions where insufficient width is available for paired side or a center platform as is often the case in CBD-street environment. The platforms are frequently split on either side of an intersecting street with the platform located on the near side of the intersection so the train dwell time at the station and any intersection signal delay time can overlap.

Access to the platform depends on site-specific conditions. Platforms can be end-loaded (accessed from the ends) or center- or side-loaded. In the vertical dimension, access can be from above or below the platform or at grade across the tracks. With the use of the overhead power pickup for LRT, passengers can cross the tracks with designated crossing areas and other design features and operating policies to ensure safety. Because LRT allows at-grade access to the platform, costly overhead or underground facilities and elevators for wheelchair access required with grade-separated access are reduced.

Selecting the appropriate platform arrangement depends on a number of factors, particularly site constraints. LRT offers a variety of options that can be used to meet the particular needs and conditions.

Fare Collection

Platform height and placement can be strongly influenced by two systemwide features—fare collection and elderly and disabled access. Fare collection and control have a wide range of characteristics that influence station layout.

Self-Service Fare Collection With self-service fare collection the passenger pays a fare and receives a proof-of-payment or purchases and validates a ticket for a given trip. Once in the LRV the passenger must show the validated ticket or proof-of-payment to an inspector on demand. This fare collection system is common on most new LRT systems in North America and lends itself to being highly automated. No in-station fare collectors are generally required. Space is needed for ticket vending, fare payment, or ticket validating equipment, and perhaps change-making machines. Other than instructions and information on fare structure and fare zone maps, no other equipment or station facilities are required.

On-Board Fare Collection With on-board fare collection a passenger pays the fare either when entering or exiting by dropping a token or cash into a fare box usually in view of the driver or attendant, or by validating a ticket using a machine on board the vehicle. This system is common on older trolley systems. Little if any in-station equipment is required, although ticket or token purchasing or change-making equipment or attended booths can be provided along with information and instruction signs.

In-Station or Barrier-Type Fare Collection The in-station or barrier-type fare collection type of system is common in rapid rail transit systems. It involves a barrier separating a "free" or unpaid area from a "paid" area. Turnstiles or fare gates form the barrier and require deposit of cash, token, or fare card to gain entry to the paid area. In more sophisticated applications with zone or trip length-based fare structures, fare cards with a machine-readable magnetic strip passed through a fare card reader allow entry into the paid zone. The card may also be required to allow exit from the paid area to the free area at the destination station. This type of system has the greatest requirements for station layout in that a secured "paid" zone that includes the platform must be defined and the necessary architectural features provided to define the paid zone and allow for the barrier. Access to the platforms is restricted except through fare control barriers. At platforms access from the trackway must be controlled, which in exclusive guideway environments is not particularly difficult. In nonexclusive alignments, especially with at grade sections, preventing unauthorized access to the platform can be challenging. High platforms, where the platform is the same height as the LRV floor, are a solution. Because high platforms require the vehicle to have a different type of door configuration on the vehicles, mixing high- and low-platform stations within the system, although possible with LRT systems, does add to design and operating complexity. Barrier systems also require fare vending equipment and can involve attended booths.

High-level platforms offer the potential for shorter station dwell time than low-platforms. Passengers can board and alight faster because no steps on the vehicle have to be negotiated. As discussed earlier, high-level platforms aid in barrier-type fare collection systems. However, high-level platforms require that the vehicles have a floor that meets the platform within a few inches of the platform edge and that the doors either open clear of the platform or retract within the vehicle walls. Systems can mix high and low platforms such as in San Francisco where retractable floors cover stairwells at the high-platform stations. In Pittsburgh, the new LRVs are essentially designed for the high-level platforms in the new CBD section but also have a second door near the operator with steps to serve the low-level platforms on the rest of the system. Because President's Conference Committee (PCC) cars still operate on the line, the new high-platform stations have a low-level area at the end of the platform.

The nature of the fare collection method, discussed previously, can affect station layout and train operations. Collecting fares in the station or using a self-service method, particularly at high-volume stations, reduces dwell times by allowing all doors of the LRVs at the platform to be used. However, more in-station facilities are needed than for on-board collection. Capital and operating costs of providing in-station facilities must be compared against the cost and operating efficiency, schedule, reliability, travel time, and fare evasion rates under the various options. Fare collection systems, of course, can be mixed in LRT system. The Newark City Subway, for instance, employs barrier-type fare collection in some of its underground downtown stations and on-board collection at its other stations.

Wheelchair Access

Probably the most significant factor influencing platform configuration is the Americans with Disabilities Act (ADA), particularly the provisions for wheelchair access. ADA, like its antecedent, the 504 Regulations, requires wheelchair access between the station and LRV. The most direct method to achieve wheelchair access is high-level platforms such as those used on the Los Angeles–Long Beach line or the low-floor LRVs being used in Grenoble, France, and proposed for Boston's Green Line.

Several methods are possible at low-level platforms including use of wheelchair lifts in the LRV, use of platform lifts as on the Portland MAX, use of mini-high or "high-block" platforms at the end of the low platform as used on the Sacramento and Baltimore lines. The mini-high platform employs a short high-level platform at the front (operator) end of the station platform that is accessible via a ramp or some sort of lift. When a wheelchair passenger needs to board or alight, the operator aligns the front door of the first car with the mini-high-level platform which is next to the operator. The operator manually lowers a plate that covers the stairwell and unfolds a second plate that covers the gap between the platform edge and the vehicle floor. This arrangement requires all wheelchair patrons to use only the first car. This can introduce limitations on split-train operations for branch lines. The use of platform lifts or on-vehicle lifts imposes fewer special design and operational considerations other than defining a designated loading location. Use of a mini-high platform can create constraints on end-load platforms, especially center platforms, by restricting passenger circulation from the low-level portion of the platform.

Providing wheelchair access throughout the rest of the station poses some special design considerations as do other features of the ADA requirements, including those dealing with visual, auditory, and mobility impairments other than those rectified by wheelchairs. However, when incorporated into the design of the station from the outset, many of the accessibility-oriented design features can benefit a large portion of the patron population.

IMPLEMENTATION ISSUES

As discussed in the previous section, LRT can have a number of station layout, vehicle/system, and operational characteristics. Lines can be located in mixed-traffic environments, semiexclusive, or exclusive alignments. Tracks could be single or double (or more). Platforms can be high, low, or mixed and located in a variety of arrangements. Any number of fare collection methods can be used. These features can be mixed and combined within a given system, especially as they affect stations. This flexibility enables the design of an LRT station to adapt to its application and environment, avoid certain types of costs and problems, and better serve the needs at particular sites.

The flexibility in LRT station design is particularly beneficial in implementation phasing, especially when financial or construction schedule constraints exist. Systems can be constructed very "lean" initially with segments of single-track and single-sided platform stations. The San Diego and Sacramento systems are good examples of how this can be done. Stations can be constructed initially with low platforms and upgraded to high platforms later as required. This has been done in many European "pre-metro" systems. At-grade alignment segments can be built initially with very simple, low-cost "stops" and upgraded to grade-separated segments with very little lost capital in the "stations" on the initial alignment. LRT stations along with the rest of the system can be implemented, operated, and later upgraded in phases as conditions allow.

CONCLUSION

Passenger stations (and transit vehicles) are the primary interfaces for passengers with a transit system. Therefore sound station planning and design are essential to successfully maximizing the potential benefits of a transit system. LRT's particular flexibility and adaptability provide station locations and layouts that can serve the riders well while avoiding to some degree cost and problems. Several station planning and design principals exploit the inherent advantages available with LRT systems.

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Planning and Design of On-Street Light Rail Transit Stations

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Planning for contemporary light rail transit (LRT) systems often presents the challenge of integrating modern stations into an on-street setting. In this context the planning and design of the station has consequences not only for the alignment and operation of the light rail line, but also for pedestrian movement, traffic flow, and safety. The planning and design of on-street LRT stations is divided into two general areas. First are the specific features of the stations and intersections, including platform size, high or low platforms, facilities for the disabled, fare collection arrangements, and other station features plus such roadway features as turn lanes and crosswalks. The second aspect is the configuration of the station tracks and platforms on or adjacent to the street.

Unlike commuter and rapid rail stations that are usually located off-street and streetcar stops that provide minimal facilities for the passenger, today's light rail transit (LRT) systems often present the challenge of integrating a station with multiple design features into an on-street setting. In this context the planning and design of the station has consequences not only for the alignment and operation of the light rail line but also for pedestrian access to the station, operation of the roadway or intersection, utilities, and safety. For purposes of this study, "on-street" includes stations that are on the side of a street as well as stations in the center of a street.

Early streetcar lines normally operated on tracks down the middle of a street in mixed traffic (with horses and carriages at first, then automobiles). Frequently no platform was provided—passengers had to contend with other traffic (and horse "exhaust") when boarding and alighting the vehicles. As streetcar and interurban services became more sophisticated, simple platforms were provided, but these often lacked shelters, seats, travel information, or other amenities for the passenger. Platforms were small, particularly in on-street settings. On the new generation of LRT systems, developed since 1980, more elaborate stations are standard, even where LRT is operating within a street right-of-way. New stations are normally at least 10 ft wide, 300 ft long, and often include shelters, seating, fare machines, transit information, facilities for the disabled, and high platforms. As older systems are refurbished, some of their stations are upgraded to contemporary LRT standards, as in Pittsburgh and San Francisco. Modern stations improve the quality of the transit passenger's trip, making LRT more competitive with car travel, but increase costs and problems, particularly in an on-street setting where space is often limited.

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The planning and design of on-street LRT stations can be divided into two general areas. First are the specific features of the stations and intersections. These include platform size, high platforms versus low platforms, facilities for the disabled, fare collection arrangements, safety provisions, and other station features plus such roadway features as turn lanes and crosswalks.

The second aspect is the configuration of the station tracks and platforms on or adjacent to the street. Examples include a center platform station in the center of the roadway, side platforms in the center of the roadway, a station to one side of the street, a "near and far" platform station where light rail vehicles (LRVs) stop on opposite sides of an intersecting street, and many other variations.

PLANNING ON-STREET STATIONS

The station planning and design process has two phases that overlap and interact. In the first phase, specifications and criteria that apply to all stations on a line or section of a line are determined. Such specifications and criteria include design features of the vehicles to be used that, once fixed, are quite inflexible. For example, if LRVs are obtained that allow only low-level or only high-level boarding, then all stations must conform. The third option, high and low platform boarding, gives the most flexibility but may not be justified in many cases. Another example is access for the disabled. Normally a single method of providing for disabled access to vehicles is established for an entire system or line. Other standards such as platform length and width, minimum curvature in stations (if any), and architectural design may be set for an entire line or system but may be flexible where conditions warrant.

The second phase of station planning addresses the requirements of each individual station. Planning and design of each station responds to its particular setting and system standards may be modified where required. For on-street stations, variations may include configuration of the platforms, tracks, roadway, turn lanes, traffic and pedestrian access patterns, platform width, arrangement of walkways and crosswalks, and station amenities such as shelters, benches, vending machines, ramps, and landscaping.

Station Planning Issues

A number of issues may affect the configuration and design features of a particular station or all stations on a line. These include physical and alignment geometry constraints at a particular location, utilities present, anticipated patronage, climate, and the design of LRVs to be used. Other less tangible factors such as personal safety, environmental concerns, political considerations, and community input may also affect station planning and design. Although many issues are common to all stations, including on-street stations, other issues or their effects are unique to on-street stations.

Accessibility for the disabled is an increasing concern as a result of the Americans with Disabilities Act of 1990. The act requires that key stations in existing rail transit systems and all new stations be made accessible to the disabled.

Pedestrian Access

Because all passengers will, for some time, be pedestrians at the beginning and end of their trip by light rail and most will reach their destination on foot at one end of the trip (rather than transfer to car or bus), pedestrian access to stations is an important consideration in the overall quality of the transit trip. Pedestrian access to on-street station platforms is affected both by the layout of platforms, tracks, and roadways and by barriers to pedestrian movement that may be incorporated into the design of the station. At the broad scale, pedestrian access means locating a station as close as possible to passenger destinations, particularly dense concentrations such as office buildings, shopping, or entertainment centers. Likewise a station may be located so that new development can be clustered around it. The distance to destinations, which must be measured in terms of actual walking distance (not necessarily a straight line), becomes increasingly critical as Americans and others become increasingly accustomed to the "park in front of the door" convenience of the automobile. With on-street stations, station location and distance to destinations must be balanced with alignment constraints, roadway design, and other factors. The LRT planner must bear in mind that the ultimate purpose of the LRT system is not to merely operate trains but to deliver passengers most conveniently to their destination.

Layout of the station and its on-street setting is the second aspect of providing convenient pedestrian access to the station platforms. The fact that the station is on or adjacent to a street itself places a constraint on easy pedestrian access, depending on the volume and speed of traffic and the width of the roadway. If crosswalks to the platform are located only at one end of the platform, then passengers approaching the station from the opposite end will have a significantly longer walk to reach the appropriate position on the platform—or they may jaywalk, a safety problem. In cases where traffic on an adjacent roadway is extremely heavy or fast, a pedestrian bridge or tunnel may be used. Other design elements may limit pedestrian access and circulation deliberately or unintentionally. Normally, pedestrians can cross LRT tracks because there is no third rail. At some locations, however, this may be undesirable or impractical. Elements that may restrict pedestrian circulation include barriers to crossing tracks, high platforms, restrictive signage, or other barriers. Naturally a balance must be struck between pedestrian safety and free pedestrian circulation but excessive concern for safety may unnecessarily limit circulation.

Transit Operation

Providing fast, reliable, and safe operation of the LRT line is a central consideration in planning on-street stations. Any location where cars or pedestrians may cross tracks creates a potential constraint on LRV operation. Where vehicles may be "caught" on tracks or pedestrians cross in large numbers, safety may be compromised and operation must be slowed to compensate. This issue also pertains to the placement of platforms at a signaled intersection. Whereas bus stops may be most effectively located on the far side of an intersection when buses are in heavy mixed traffic, LRT platforms are often best located on the near side of the intersection if the LRV is on an exclusive trackway and no signal preemption is provided. Other things being equal, the speed of LRV operation is enhanced if a station is placed near a location where the LRV would have to slow or stop anyway (such as a tight curve or signaled intersection) instead of a location where open running is possible (such as the middle of a long straight run). In all cases, however, the final measure of LRT operation is in service to the passenger, not in the operation of trains.

Traffic Flow

Layout of an on-street LRT station may significantly affect the movement of traffic by the provision or exclusion of left or right turn lanes, conflict with pedestrians approaching the station, and buses or cars stopping in traffic lanes to pick up or drop LRT passengers. Both the volume of traffic on the street and the volume of "conflicting" movements by buses, LRVs, pedestrians, and turning cars are factors in determining what steps should be taken to maintain traffic flow.

Transfers to Bus

Convenient transfer between buses and light rail is an issue at many on-street LRT stations. The transfer itself is an integral and important part of the overall transit trip. Locating bus stops close to station platforms and making the transfer connection as convenient and visible as possible are key. Depending on station layout, a number of bus stop locations may be possible, including along a parallel road, cross street, along the outside of the LRT platform, or with buses sharing the LRV travel lane to stop at the same platform. In each case, space for buses to stop, their effect on local traffic, and space for bus stop elements and queues must be considered. An additional arrangement involves joint operation of LRVs and buses on the same transitway allowing both to use the same platforms. This may occur along a stretch of the LRT line or may occur only at certain stations. In this case, the effect of shared right-of-way on LRT and bus operations must also be considered.

Safety

Safety is a critical issue throughout any transit system. However, nowhere are safety issues more visible than around an on-street LRT station. Four potential safety concerns are found here. First is the conflict between pedestrians and street traffic.

Whether station platforms are located in the median or along the side of a roadway, pedestrians will cross the road to the station. Passengers trying to catch an approaching train may pay little attention to traffic. The second conflict occurs between LRVs and pedestrians who are usually allowed to cross the tracks near stations. Because an LRV may approach relatively rapidly and silently, passengers disembarking an LRV may fail to see a train approaching from the opposite direction, or other pedestrians may fail to look both ways before crossing tracks. The third safety conflict is between LRVs and traffic. Although this issue is not directly related to the station, on-street stations are often located at intersections where roadways cross tracks, so the overall layout of the station and intersection is integral to safe LRT operation. Depending on the frequency of LRVs and the volumes of traffic and pedestrians, these first three conflicts can be mitigated by visible crosswalks, clear roadway markings, physical barriers, signs, and signals for vehicles, trains, and pedestrians. In the most severe cases, grade separations may be used.

Personal security of passengers is the fourth safety issue at on-street stations. The on-street location of these stations provides more visibility and natural surveillance from the community than most off-street locations. However, in some cases, increased visibility, enhanced lighting, or emergency call boxes are suggested. If a station is even *perceived* to be unsafe, patronage will suffer.

Access for the Disabled

Accessibility for the disabled is an increasing concern. In the United States this concern resulted in the Americans with Disabilities Act of 1990. The act requires that key stations in existing rail transit systems and all new stations be made accessible to the disabled. The act requires that at least one vehicle per train be accessible by July 26, 1995. Key stations on existing systems should be accessible by July 26 although extensions may be granted. All stations constructed or remodeled after January 26, 1992, must be accessible. In addition to the accessibility issues at all light rail stations, on-street stations often require that handicapped persons cross the street to reach the station.

The act distinguishes between two types of right-of-way and requirements for accessibility. "Vehicles intended to be operated solely in light rail systems confined to a dedicated right-of-way, and for which all stations or stops are designed and constructed for revenue service after January 26, 1993, shall provide level boarding. Vehicles designed for and operated on pedestrian malls, city streets, or other areas where level boarding is not feasible shall provide wayside or car-borne lifts, mini-high platforms, or other means of access." For level boarding or high blocks, the U.S. Department of Transportation stipulates that the horizontal gap between platform and vehicle floor be no greater than 3 in. and that the height of the vehicle floor be no more than 5/8 in. above or below the platform.

Fare Collection System

The fare collection system in use on a line or at a particular station may have a direct bearing on the design of a station. Two basic methods of fare collection may be used in light rail systems, on-board or in-station. With an on-board fare collection system, tickets are validated or fares collected by an on-board validation machine or the operator. With an in-station fare collection system, tickets, tokens, or fares are collected as the rider enters a controlled area of the station. Where fares are collected on-board, ticket vending machines may be located in stations, if desired, but no barriers, turnstiles, or other fare collection devices need be located in a station and access to the platform can be from any direction. An in-station fare collection system places greater demands on station space and design, but improves system operation at a busy station. In-station fare collection requires space for ticket vending machines, turnstiles, and barriers to segregate the paid fare zone. In addition, access and egress from the station are limited to certain locations, potentially increasing walking distances and congestion. Self-service proof-of-payment (or "honor") systems, in which passengers validate their own tickets or carry passes and inspectors make random inspections, display characteristics of both on-board and in-station fare collection and provide the smoothest operation and fewest demands on station space.

Patronage at Station

The pattern of passenger usage at a particular station may be important in the layout of the station. The volume, primary direction, and frequency of use on each platform may be considered in sizing platforms and walkways, providing amenities, and determining operating practice at the station if these differ from the norm for the system. The direction of travel is particularly important in determining whether passengers will be primarily boarding or alighting at a particular platform, or both. Passengers who are boarding typically wait on the platform, thus requiring such amenities as benches and shelters whereas passengers alighting will depart the platform quickly. Thus two platforms at the same station may be appointed differently. In situations where patronage is very low and intermittent, shorter than standard platforms and on-call or "flag stop" service may be provided. A station where excessive volumes are periodically generated, such as at a sport stadium or fair grounds, may have longer platforms to load more than one train simultaneously or a siding to hold waiting trains.

The patronage at a station may have a direct impact on the size of platforms required. Generally a minimum platform width and length is specified for a system to accommodate the maximum train length and provide a space deemed adequate or comfortable. If patronage at a particular station would exceed the reasonable capacity of the minimum platform size, then a wider platform may be needed. The size requirements of inbound and outbound platforms may differ because passengers may dwell longer on one platform (usually inbound) than on the other. The same platform may also require more features such as shelters, ticket vending machines, and other vending machines.

In-Street Utilities

When an LRT line and stations are incorporated into an established urban setting, extensive utilities are almost always found under streets. To maintain underground utilities, surface access must remain possible, often by relocating utilities away from the LRT trackbed. Where the cost of reconfiguring the utilities or providing alternate access is prohibitive, the layout of tracks and station may be modified.

Design of LRVs Used

In the early stages of planning, the features of the LRVs to be used may interact with planning for stations. However, once the design of LRVs is fixed, station design must conform, whether or not the station is in an on-street location. This is particularly relevant to the placement and loading height of doors, including left- versus right-side boarding, width of cars, and maximum length of trains.

Station Design Elements

To address the issues just discussed, a number of specific features of the station and roadway design are considered. For on-street stations the design of the station is integral to the design of the street or intersection. Thus design elements relevant to on-street stations include elements of the street, such as traffic lanes, turn lanes, crosswalks, and traffic signals, in addition to elements directly related to the light rail line. In determining the design of the station, conflicting issues must be resolved or balanced, and design features must respond to each other and the physical constraints of the site.

Platform Level and Access for the Disabled

Platform level and the provision of access for the disabled to trains are interrelated, so these features can be addressed together. Four basic combinations of features are possible. To some extent, more than one of these combinations can be used at different stations within a system.

High Platform High platforms are approximately 39 in. above rail and street level. A ramp approximately 44 ft in length, including one landing, is required for wheelchairs to reach platform height from street level. Other access may be provided by stairs and additional ramps. Advantages and disadvantages of high platforms include the following:

- Provides fastest easiest loading for all passengers,
- Controls and limits movement of people around the station,
- Provides easiest loading for people who would not use a wheelchair lift but who have difficulty climbing steps, including people with baby carriages and passengers carrying packages,
- Requires no maintenance and does not suffer from potential unreliability (unlike mechanical devices),
- Allows boarding by disabled with no delay to operations (unlike mechanical devices),
- Requires a ramp to reach platform and additional space that may further affect on-street setting,
- Has higher construction cost than low platform, and
- Requires that all stations on a line use high platforms, unless LRVs are equipped to load from both high and low levels.

Low Platform with Mini-High Platform A mini-high platform (or "high block") is a small raised platform at vehicle floor level normally located at the front end of the full platform. The mini-high platform, approximately 39 in. above rail level, is normally reached by a ramp approximately 44 ft in length, although a lift can be used to reach the mini-high platform. Even the smallest mini-high platform may be difficult to accommodate in a tight setting, but larger and more elaborate mini-high platforms can be used where space permits. Trains may stop regularly with the front door by the operator's cab on the mini-high platform so that anyone who wishes can use the level entrance, or LRVs may stop short of the mini-high platform except when a disabled person wishes to board or alight at the mini-high platform. When the vehicle's stairwell creates a gap between the mini-high platform and the vehicle floor, a movable bridge is placed by the operator to cross the gap. Advantages and disadvantages of low platforms with mini-high platforms include the following:

- Depending on operating procedure, the platform may be used by others who have difficulty climbing steps, including the elderly, passengers with baby carriages, and passengers carrying packages.
- Unlike mechanical devices, the platform requires little maintenance and does not suffer from potential unreliability.
- Unlike mechanical devices, the platform allows the disabled to board without causing delay to operations.
- Mini-high platforms require more space than mechanical devices, especially because of ramps. They can be difficult to accommodate in a tight station space, such as in a street median or on a narrow sidewalk. Required placement (usually at the front of the train) may limit circulation onto the platform in some station configurations.
- A lift may be used with a mini-high platform to save space and loading time (the LRV does not have to wait for lift to be operated), but this introduces a maintenance cost and the potential unreliability of a mechanical device.
- Most passengers must climb steps into the vehicle, which makes loading slower than from a high platform.
- Low platform can be approached from any direction and passengers can cross tracks directly if desired (no stair or ramp is required to reach the platform). However, placement of the mini-high platform can limit circulation, particularly in a tight setting.
- Mini-high platforms may introduce operational constraints where the splitting or combining of trains is desired to serve multiple branches of an LRT line.

Low Platform with Mechanical Lift Mechanical lifts come in a variety of designs and may be located at stations or may be built into LRVs. In-station lifts take much less space than a mini-high platform with ramps. However, a mechanical lift that accesses the vehicle directly must be operated while the LRV waits in the station, delaying all of the passengers, whereas a lift to a mini-high platform can be operated by the user before the train arrives. Advantages and disadvantages of low platforms with mechanical lifts include the following:

- They require less space than mini-high platforms.
- They require maintenance and may suffer from potential reliability problems.
- Because lifts must be operated then locked away while the LRV sits in the station, they cause a delay to all passengers.
- Most passengers must climb steps into the vehicle, which makes loading slower than from a high platform.
- Because of the inconvenience of using lifts, only wheelchair passengers will generally use them. Others who may have difficulty climbing into the vehicle will climb nonetheless (or use other transportation).
- Lifts are normally installed at stations (wayside lifts) or on LRVs (on-board lifts).
- A low platform can be approached from any direction and passengers can cross tracks directly, if desired (no stair or ramp is required to reach the platform).
- Fixed position wayside lifts may introduce operational constraints where the splitting or combining of trains is desired to serve multiple branches of an LRT line.

Low Platform with Low-Floor Vehicles A relatively recent development in LRV design, low-floor vehicles have a floor height approximately 12 in. above rail or street level as compared to approximately 39 in. for standard LRVs. Thus a platform raised only slightly above street level (say 6 to 12 in.) and a simple ramp on the vehicle provide easy access for wheelchair passengers. Boarding for all passengers is essentially level. Low-floor LRVs have been introduced in a number of European cities. Advantages and disadvantages of low-floor vehicles include the following:

- They provide fast, easy loading when all doors are at low level.
- They offer easiest loading for the elderly and disabled who would not use a wheelchair lift, people with baby carriages, and passengers carrying packages.
- No mechanical devices require maintenance or suffer from potential unreliability.
- Unlike with mechanical devices, boarding by the disabled causes no delay to operations.
- A low platform can be approached from any direction and passengers can cross tracks directly, if desired (no stair or ramp is required to reach the platform).
- Replacement of existing vehicles may not be practical in some locations.
- Low-floor vehicles increase constraints to vertical curvature of tracks and may cause undervehicle clearance concerns, particularly in snowy conditions.

Left and Right Turn Lanes

For on-street stations located at or near intersections, the provision of left or right turn lanes is integral to the overall design of the station and intersection. Left or right turn lanes may compete with station platforms for limited space. At the same time provision of turn lanes may be made more important by the presence of the LRT line. If the LRVs and parallel traffic are signaled to proceed at the same time, then turning vehicles that would cross the tracks must wait. If no turn lane is provided, waiting vehicles will block one of the through lanes, significantly reducing intersection capacity. Although left turn lanes are most common, right turn lanes may be required where an LRT line parallels one or both sides of a street and may compete with station platforms for limited space. Where there is sufficient space, turn lanes can be located adjacent to a station platform. Where space is more constrained or where better roadway geometry is desired, locating platforms on the far side of the intersection in line with turn lanes reduces right-of-way requirements. When parking is provided along a street with an LRT line, parking can be eliminated at intersections to provide space for a turn lane or station platform. Locating a station in midblock also frees space at intersections for turn lanes but raises other issues such as pedestrian access.

Pedestrian Access to Station Platforms

Access to station platforms is provided by walkways, crosswalks, stairs, or ramps and is limited by pedestrian barriers, signs, and by changes in height as with high platforms. Passengers may be able to reach platforms from any direction, including across tracks, or access may be limited to only one or two points. Provision of more access points shortens walking distances but may adversely affect safety and train operations. At the same time, because many passengers will take the shortest route when possible, omitting a walkway or attempting to restrict movement through signage may simply inconvenience the passenger without really enhancing safety or operations.

LRV Lane Shared with Traffic and Exclusive Right-of-Way

The LRT right-of-way at a station may be independent of all other traffic, may be shared with general traffic, or may be shared only with buses. Use of a shared lane reduces overall space requirements but inhibits LRT operations and vehicular traffic when an LRV is stopped in the station. Where LRVs run in mixed traffic along most of a roadway, an exclusive lane for LRVs may be provided approaching a station at an intersection where traffic queues could block passage of the LRV. This arrangement allows LRVs to stop without blocking any traffic and to pass a line of cars waiting at the signal.

Size of Platforms

Platform size is determined by minimum design standards, patronage, and amenities to be located on platforms, such as benches, shelters, ticket machines, and vending machines. Where vehicular traffic is very light and slow, little or no platform may be provided—passengers can board through traffic lanes as was common with streetcars. Where a platform is required because of traffic conditions or minimum design standards, platforms may be as narrow as 3 ft. However, contemporary standards for new station construction, including ADA provisions, typically call for platforms at least 10 ft in width for side platforms and 15 ft for center platforms. More space may be provided where high boarding volumes warrant or simply where space and budget are available.

Associated Bus Stops

Where transfer between LRT and bus routes occurs, the location of associated bus stops is an integral part of overall station and intersection design. Placement of bus stops affects the distance that transferring passengers must walk and the traffic they must cross (if any). If no bus pull-out is provided, stopped buses also block traffic on the street, suggesting placement of the bus stop on the less traveled road where possible. On-street stations provide opportunities to directly relate bus stops to station platforms without diverting buses from their routes. Depending on station configuration, potential bus stop locations include a cross street, a parallel roadway, directly across from the LRT on the same platform, or buses may share the LRT lane and load at the same platform.

ALTERNATIVE STATION CONFIGURATIONS

Potential configurations of on-street station elements, including platforms, tracks, roadways, and pedestrian facilities, are nearly unlimited. Moreover, each configuration has consequences for transit, traffic, pedestrians, and adjacent land uses. The many possible configurations can be represented by a more limited number of basic configurations. These configurations are presented in this section under three categories: stations at intersections, midblock stations, and stations on transit malls. As indicated in the introduction, on-street stations may be either in the center of a roadway, on both sides, or to one side of the roadway.

For purposes of presenting alternative station configurations in a uniform manner, certain dimensions that vary in practice are held constant on the accompanying figures. Most of the layouts shown include left turn lanes. However, a narrower cross section can be achieved if left turn lanes are omitted.

Stations at Intersections

Center Platform Station in Street Median

Figure 1 shows a center platform station located in the street median with LRT tracks on exclusive right-of-way. Access to platforms in this arrangement, like most median stations, is normally limited to one or both ends of the station. Care must be taken that pedestrians waiting on the median to cross do not block the tracks. If sufficient right-of-way is available, curbside parking can be located along the sides of the street at the station or parking can begin beyond the station as tracks and roadways converge. Operation of LRVs on an exclusive right-of-way at the station limits the impact on traffic and LRT operation, particularly if left turn lanes are provided.

A similar layout with LRVs in mixed traffic at the station is also feasible. Left turn lanes are not practical with this layout. Operation of LRVs in mixed traffic at the station has a significant impact on traffic and LRV operation—LRVs may have to wait for cars waiting at the signal to move before stopping at the station and cars, particularly those turning left, must wait for an LRV to leave. Therefore such a layout is most useful where traffic is light and available right-of-way is minimal.

Side Platform Station in Street Median

Figure 2 shows a side platform station located in the street median with LRT tracks on exclusive right-of-way. Access to platforms may be limited to one or both ends of the station or, if traffic is light and low platforms are used, crosswalks to adjacent sidewalks can be located along the length of the station. If sufficient right-of-way is available, curbside parking can be located along the sides of the street at the station or parking can begin beyond the station as tracks and roadways converge. Operation of LRVs on an exclusive right-of-way at the station limits the impact on traffic and LRT operation, particularly if left turn lanes are provided.

Near and Far Platform Station in Street Median

Figures 3 and 4 show "near and far" platform stations located in the street median with LRT tracks on exclusive right-of-way. Figure 3 shows the layout with a straight track alignment and left turn lanes, whereas Figure 4 shows the layout with an S-curve but without left turn lanes. The primary advantage of these schemes is their minimal right-of-way requirements. "Near and far" platform arrangements offer the narrowest right-of-way requirements. A layout in which the outside track on each side of the intersection is in mixed traffic is also possible. Access to platforms may be limited to one or both ends of the station or, if traffic is light and low platforms are used, crosswalks to adjacent sidewalks can be located along the length of the station. If sufficient right-of-way is available, curbside parking can be located along the sides of the street at the station or parking can begin beyond the station. Operation of LRVs on an exclusive right-of-way at the station limits the impact on traffic and LRT operation, particularly if left turn lanes are provided.

Sidewalk Platform Station with LRT on Both Sides of Street

Figure 5 presents a sidewalk platform station with LRT tracks along both sides of the street. This layout may be applied either with the LRT on an exclusive right-of-way (as shown) or in mixed traffic. Platforms may be fully integrated with sidewalks or may be separate, particularly if high platforms are used. The layout of the street and turn lanes is flexible with this arrangement but curbside parking is not possible with either layout. Operation of LRVs on an exclusive right-

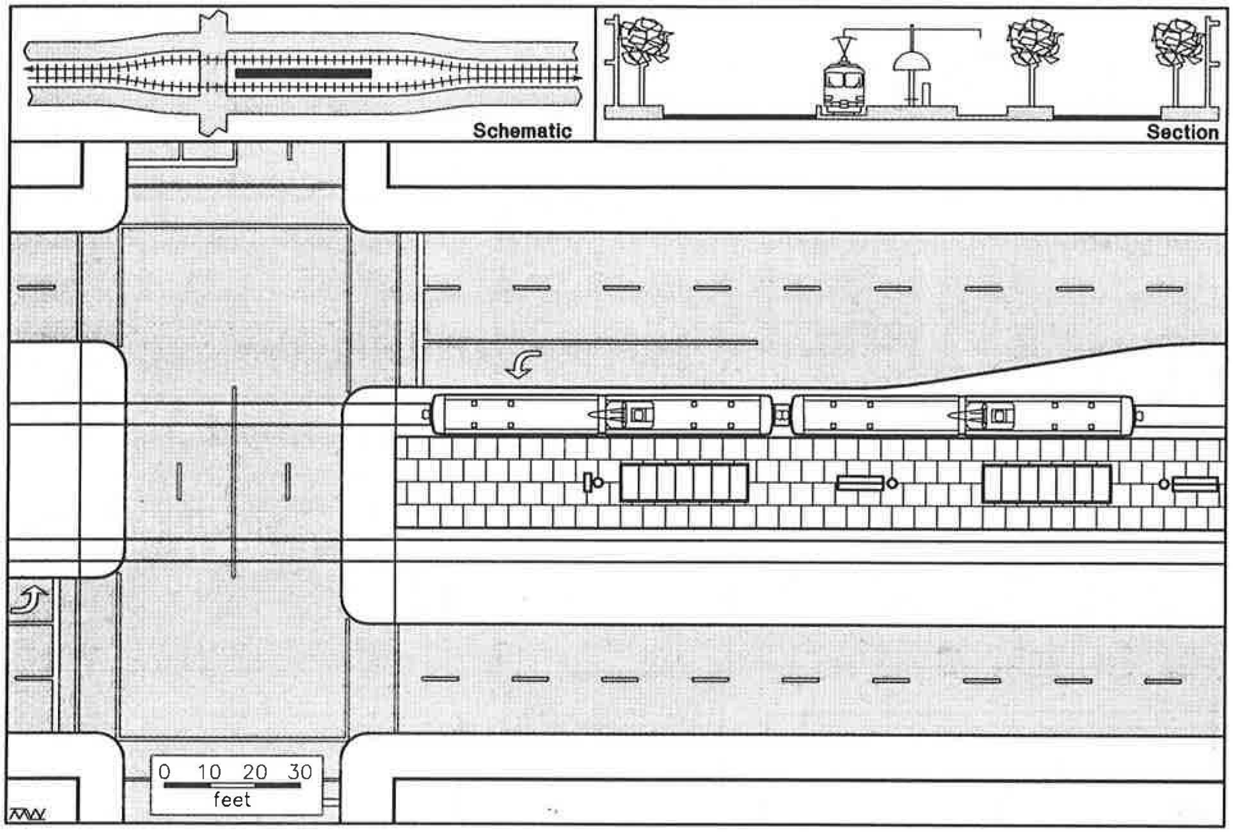

FIGURE 1 Center platform station in street median.

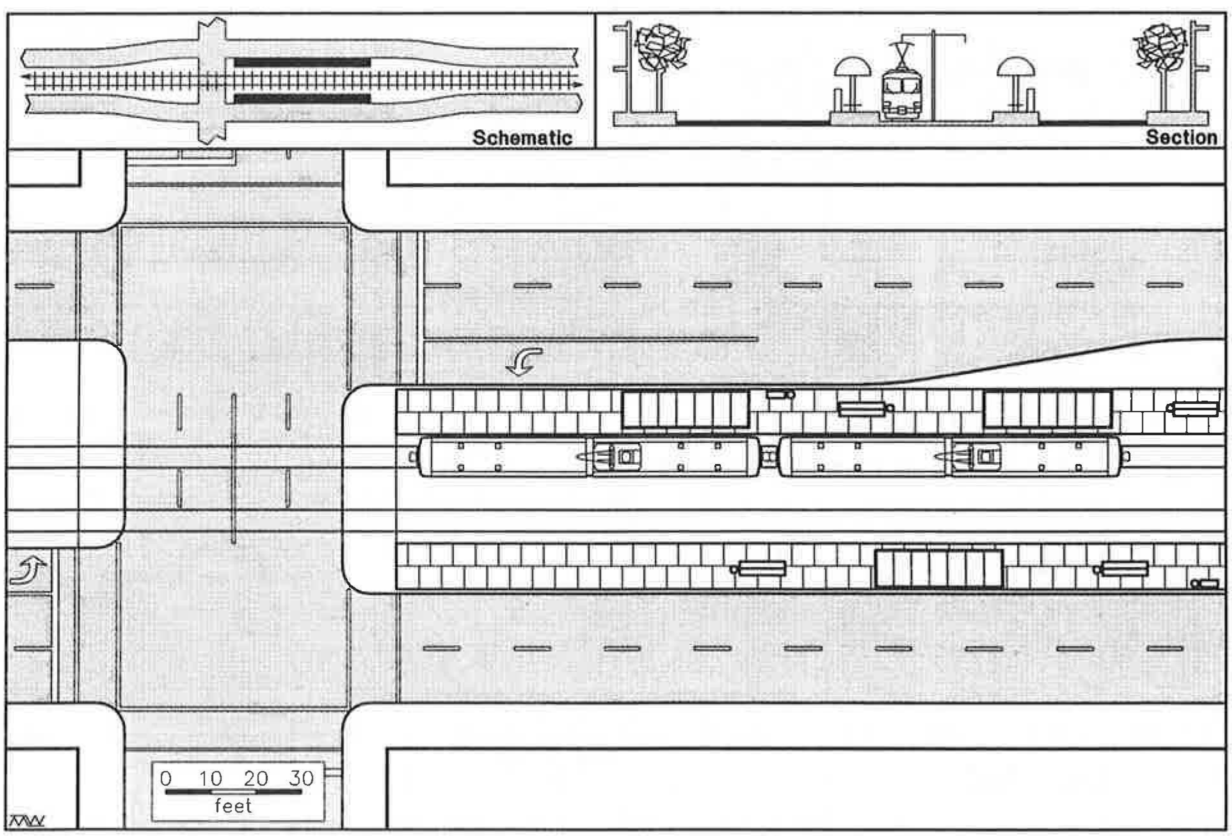

FIGURE 2 Side platform station in street median.

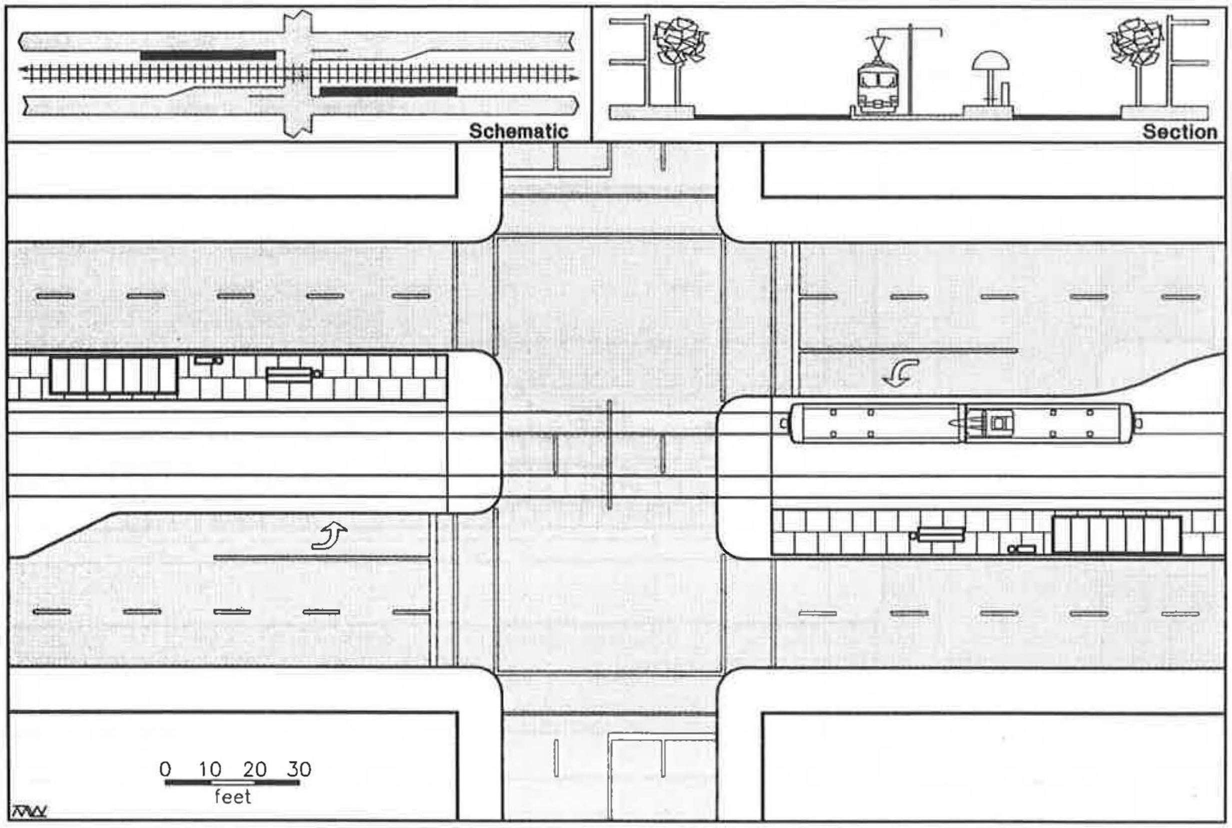

FIGURE 3 Near and far platform station with left turn lanes.

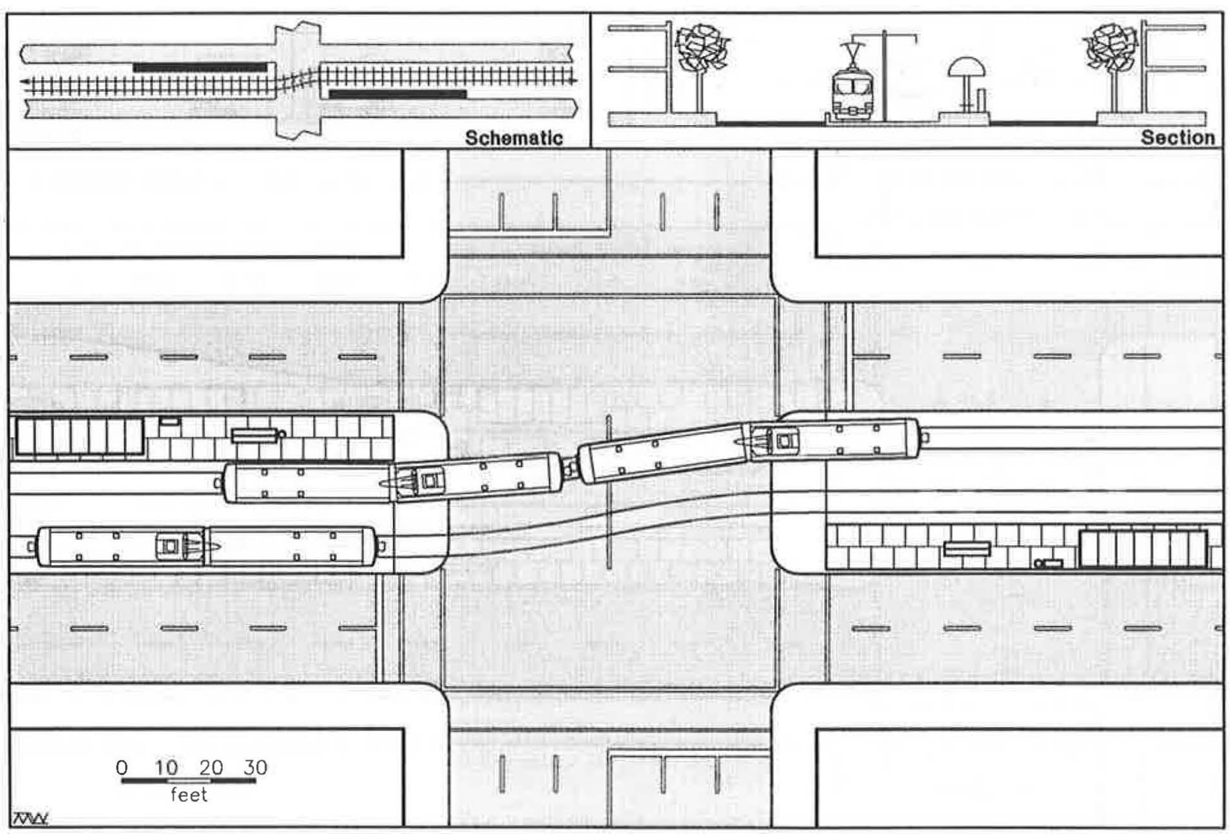

FIGURE 4 Near and far platform station in minimum right-of-way.

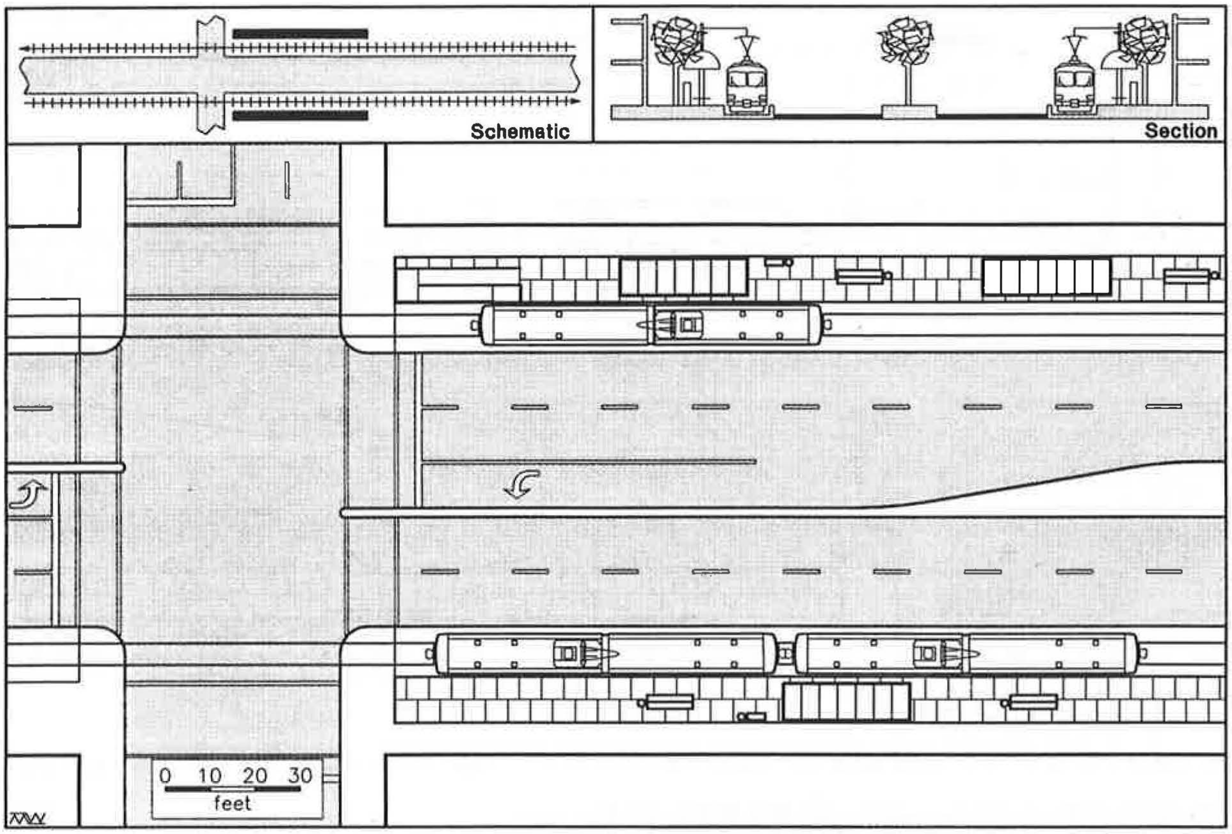

FIGURE 5 Sidewalk platform station with LRT along both sides of the street.

of-way limits the impact on traffic, whereas mixed traffic operation in curbside lanes affects traffic and invites standing or disabled vehicles to block LRVs. In either case buses can stop at the platform, providing a direct LRT-to-bus transfer.

Sidewalk Platform Station with LRT Running "Outboard" on Both Sides of Street

Figure 6 presents a sidewalk platform station with LRT tracks located "outboard" on both sides of the street. In this layout station platforms and sidewalks are between the street and the LRT tracks. The layout of the street and turn lanes is flexible with this arrangement and operation of LRVs on an exclusive right-of-way limits the effect on traffic and LRT operation. Unlike the arrangement presented in Figure 5 the "outboard" configuration does not affect parking in the curb lane and buses can stop adjacent to station platforms, making for a direct transfer between LRT and bus. However, direct access to properties along the right-of-way is limited unless a parallel walkway is provided. Therefore this alignment is most useful where properties do not front directly on the street.

Center Platform Station on One Side of Street

Figure 7 presents a center platform station where both tracks are located in exclusive right-of-way on one side of the street. Access to the platform is limited to one or both ends of the station. Care must be taken that pedestrians waiting at the end of the station to cross the street are aware of trains and do not block tracks. Because one track is adjacent to the street, cars cannot park along the curb, and direct bus loading is not possible. Direct access to properties along the right-of-way is limited, making this arrangement most useful where properties do not front directly on the street. The layout of the street and turn lanes is flexible with this arrangement and operation of LRVs on an exclusive right-of-way limits the impact on traffic and LRT operation.

Side Platform Station on One Side of Street

Figure 8 presents a side platform station where both tracks are located to one side of the street. Care must be taken that pedestrians waiting at the end of the station to cross the street are aware of trains and do not block tracks. With side platforms and a continuous sidewalk between the roadway and adjacent tracks, curb parking can be located along the side of the street at the station or buses can stop adjacent to station platforms, making for a direct transfer between LRT and bus. Access to adjacent properties is not limited by this arrangement, and the layout of the street and turn lanes is flexible.

Midblock Stations

Most of the arrangements presented for stations at intersections may also be applied at midblock locations.

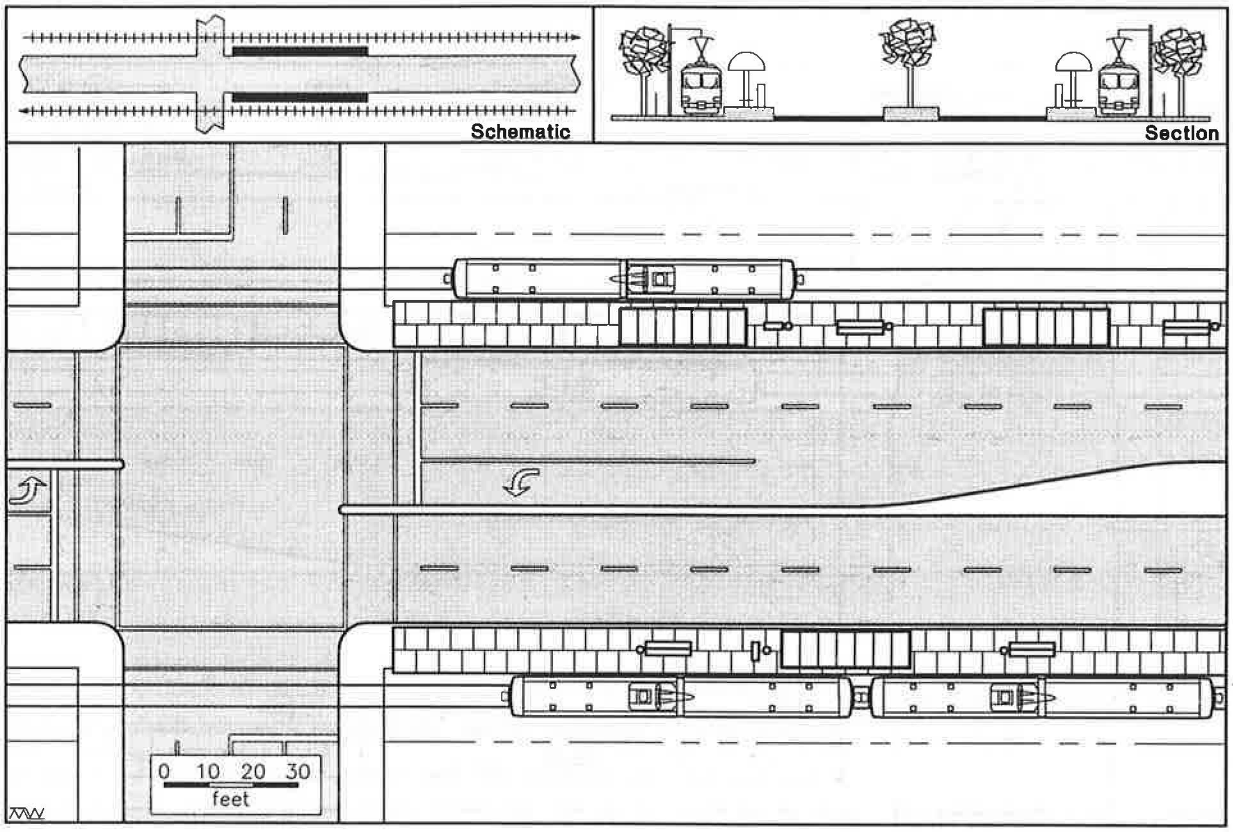

FIGURE 6 Sidewalk platform station with LRT on the outside.

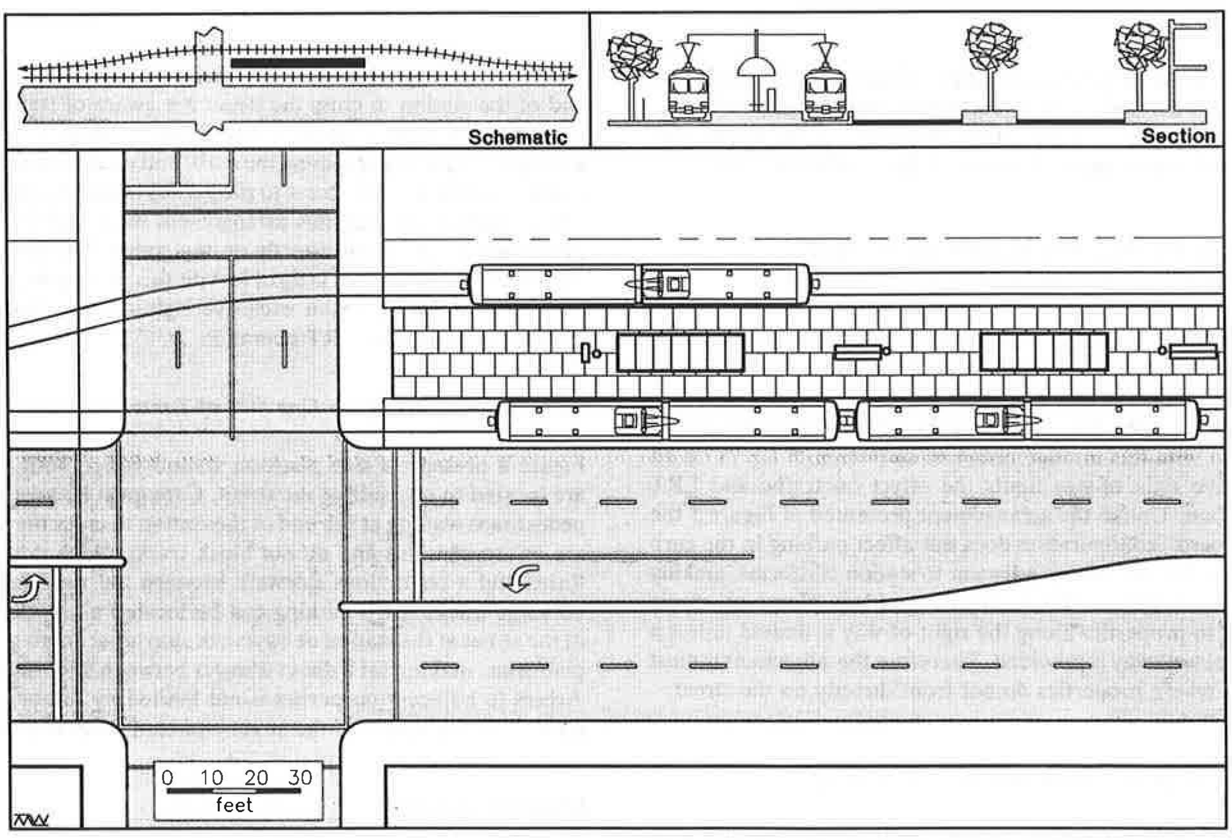

FIGURE 7 Center platform station on one side of the street.

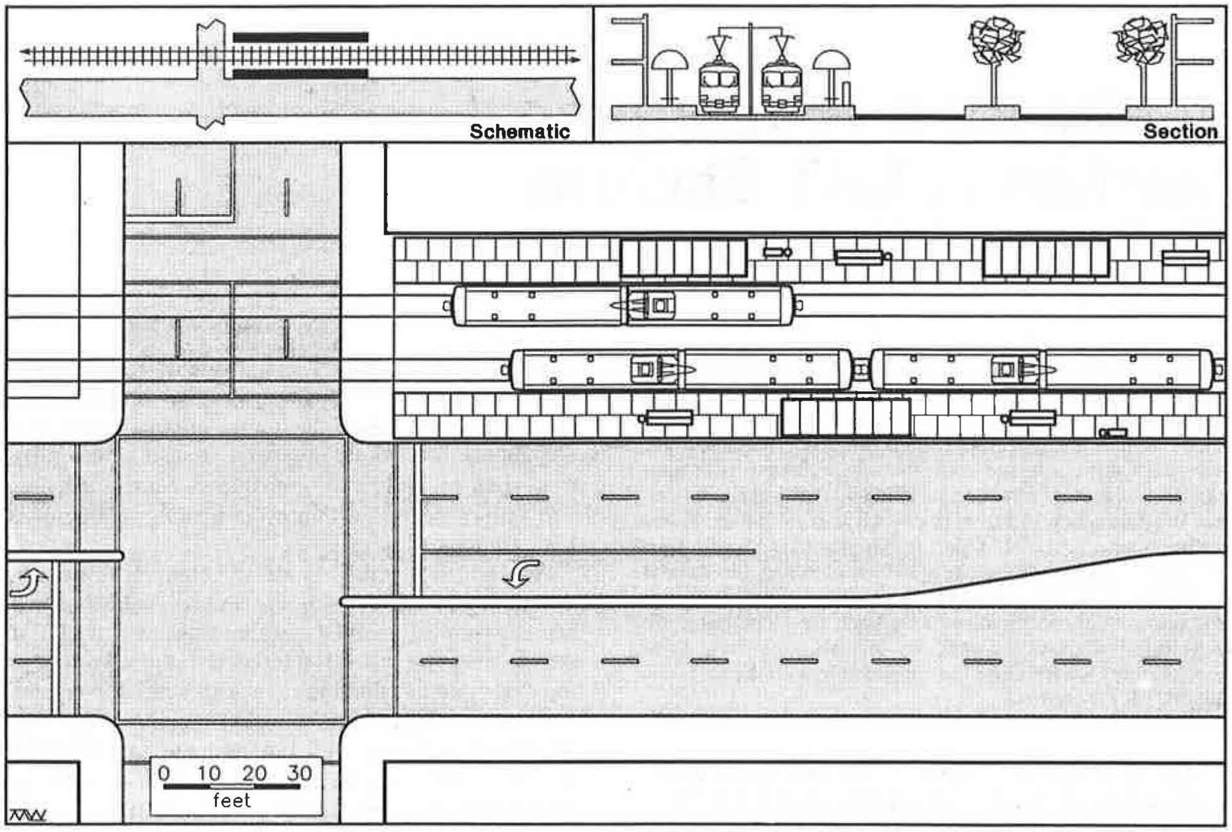

FIGURE 8 Side platform station on one side of the street.

A midblock station may be located where a major trip generator or pedestrian route lies between intersections. A midblock location also avoids the traffic congestion and competition for limited space found at intersections.

Stations on Transit Malls

Closing a street to general traffic and developing a transit/pedestrian mall is the ultimate answer to minimizing pedestrian-automobile and transit-automobile conflicts. This option is useful where traffic can be diverted, where pedestrian volumes are heavy, or where available space is limited. A transit mall may be limited to LRVs, or may allow buses to share the same roadway and station facilities.

ACKNOWLEDGMENT

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Coordination of Intermodal Transfers at LRT Stations

T. R. Hickey

Effective intermodal coordination can significantly enhance the attractiveness and productivity of a combined light rail transit and bus transit operation beyond the potential of either mode operating alone. The coincidence of bus and rail services at a station, however, does not constitute coordination. Effective coordination can also represent a economical means of improving the expanse and frequency of bus services while simultaneously reducing bus operating costs. Operational planners should take certain considerations into account when planning intermodal coordination at light rail transit (LRT) stations. Evaluation criteria for intermodal coordination have been developed and are discussed here in light of a case study involving intermodal operational planning accomplished in conjunction with the St. Louis Metro Link LRT system.

From a passenger's perspective, the ideal transit service would link all potential origins with all potential destinations without ever requiring a transfer. This idealistic level of service was actually provided, more or less, by the electric railway systems operated between the late 1890s and the 1930s. The old streetcar and interurban lines often preceded commercial and residential development in their service areas and for a time represented the only reasonable means of transportation access to the areas that they served. Patterns of urbanization and suburbanization followed the alignments of the early electric railway lines and the resultant communities were developed on a "pedestrian scale," surrounding stations and car stops. The practical limits of development during this era were effectively defined as the distance that a passenger would walk from a rail transit route.

Public transportation services today, in contrast, must contend with a predeveloped environment where land use has been oriented to an "automobile scale" with little regard for transit access or the pedestrian. Decades of development based on the private automobile as the predominant mode of transportation have resulted in low-density residential communities and dispersed employment centers. In the modern urban and suburban environment, meeting automobile competition with a "one-seat transit ride to anywhere" is a fantasy that would be neither practical nor cost-effective for a transit operator to implement.

The concept of the "one-seat ride" is all the more difficult to deliver with the new light rail transit (LRT) systems. A new LRT line is superimposed on a predeveloped landscape and—although LRT is the most flexible of the rail transit modes—it can be physically constrained by its alignment. The perfect right-of-way within walking distance of major concentrations of residential, employment, and commercial activities is seldom standing vacant, idly waiting for tracks to be laid. Economy often dictates the use of abandoned railroad alignments through old industrial areas that may form a barrier—real or perceived—separating nearby neighborhoods and activity centers within a reasonable walking distance of LRT stations.

As a practical reality, however, relatively few of a region's households, worksites, schools, and commercial activities are actually within a reasonable walking distance of LRT stations. Access planning at LRT stations is a major consideration in the design and evaluation of a proposed LRT system. Park-and-ride and kiss-and-ride provisions represent important means of access for modern LRT stations in our automobile-oriented society, particularly on the home end of a transit journey. Automobile-dependent access can be restrictive, however, to potential passengers without an automobile or to families with only one vehicle. Automobile-dependent access is also of little utility at the work end of an LRT commute or when vacant land is not available for parking development. For these reasons, the effective coordination of intermodal transfers at LRT stations is an important consideration of access for modern LRT systems.

TRANSFER MOVEMENTS

The Traveler

Discarding the concept of the "one-seat ride," a greater number of current trips would be compatible with transit if travelers would consider making transfers enroute. But the necessity to transfer can discourage patronage even for a single-mode transit operation. Most transfers introduce walking, waiting, and other activities that can add time, inconvenience, and anxiety to a traveler's journey. A poorly coordinated transfer can require long, irregular waits for infrequent connecting services in unpleasant surroundings, especially at night or during inclement weather.

The normal aversion to transfers can be worse, however, in a multimodal transit environment. The change of mode reinforces the differences between bus and rail operations and fosters the impression—real or not—that each mode is a separate and distinct entity that operates independently. Planning an intermodal journey involves working with at least two service timetables, possibly published in different formats. Information is rarely available at intermodal transfer points regarding schedules and connecting services. Many transfers further inconvenience the traveler by requiring payment of

Delaware Railroad Administration, 100 S. French Street, Wilmington, Del. 19801.

an additional or a new fare. The addition of institutional gaps apparent in the marketing, service planning, scheduling, or operational management of each mode can leave the traveler with the sense of stepping into an undefined void in the transportation planning process, exacerbating the fear of being stranded. As such, travelers' aversions to intermodal transfers can represent a major obstacle to the effectiveness of a multimodal public transportation system.

The Operator

In contrast the introduction of transfers enhances the utility and cost-effectiveness of a fixed-route transit system from the perspective of the transit operator. Transfers permit reasonably direct access to the maximum number of destinations with the minimum number of specific routes and services. Transfers also enhance operational efficiency by segmenting an overall system into a number of smaller intersecting operational components, each of which can operate at a level of service appropriate to the variations in traffic demand and physical characteristics experienced on the specific segment over time.

The flexibility to independently adjust the level of service on each operational component of a multimodal system is an important consideration to the economy of an LRT system. Connecting bus transit services can function more economically as local distributors when properly matched with the line-haul service provided by LRT. Conversely, a high-speed LRT service operating trains on exclusive right-of-way with close headways and long station spacing can function more economically as a regional line-haul service than buses in mixed traffic. But, although LRT operates effectively as a line-haul carrier, it makes a poor local distributor for multiple low-density activity centers (such as a suburban office park). The convoluted nature of such local services retards performance advantages of the mode and makes LRT unattractive for through passengers. The alternative of multiple, single function spur lines would be economically unfeasible to construct and difficult to operate. LRT can effectively function as its own local distributor for a major concentration of activity centers (such as a central business district [CBD]), however, especially when located at or near a terminal.

The point of balance between the traveler's demand for direct service and the transit operator's need for economy often lies with the level of attention given to the details of the transfer movement. Transit operators excel in safely transporting passengers *within* their vehicles in a reliable, timely, and cost-effective manner. Equal attention needs to be given to the planning and operation of that part of the transit journey that take place outside their vehicles. Well-planned, convenient transfers can offset a traveler's apprehensions about making transfers and promote a more effective transit system.

ST. LOUIS EXPERIENCE IN INTERMODAL PLANNING

The effectiveness of intermodal coordination at LRT stations was a particular concern for the Bi-State Development Agency, the predominant transit operator for the metropolitan districts of Missouri and Illinois that surround the city of St. Louis. Bi-State chose to undertake the construction of a 16.9-mi LRT line extending from East St. Louis, Illinois, through downtown St. Louis to Lambert St. Louis International Airport. The ready availability of more than 12 continuous miles of unused railroad facilities—extending from Illinois, across the Mississippi River, beneath the heart of the downtown business district and through the northwestern suburbs—permitted the economical construction of a new line-haul rail transit service that could effectively compete with the automobile to attract new riders to public transportation.

It should be noted at this point that the original 17.5-mi, 20-station Metro Link LRT line was temporarily reduced to 16.9 mi and 18 stations, primarily as the result of FAA concerns regarding the alignment of the Berkeley spur near the airport. The ridership projections and analysis discussed hereinafter are based upon characteristics of the *original* line; the relative proportions quoted remain relevant for the reduced line. Bi-State intends to complete the Berkeley spur when reengineering is complete.

The alignment of the new LRT line—locally referred to as Metro Link—is fortuitously located to attract riders by directly serving the downtown business district and a number of the major employment, commercial, cultural, and recreational centers for the region, including Busch Stadium, Laclede's Landing, the Jefferson National Expansion Memorial (the Gateway Arch), Union Station, Keil Auditorium, Forest Park, St. Louis University, University of Missouri, and the aforementioned airport. Based on the strength of these trip attractors "linked" by a uniquely suitable alignment for fast, frequent LRT service, Metro Link has been projected to carry about 16,800 passenger trips per weekday during its initial year of operation (*1*). Ridership is anticipated to further increase to about 37,100 passenger trips per weekday by the year 2000 (*2*).

Bi-State recognized early in the planning process that an LRT service alone could not realize these potential levels of ridership. Although Metro Link passes through a number of residential communities, a relatively limited number of households are actually within walking distance of a Metro Link station. Furthermore a number of suburban employment centers and other trip generators are also nearby but beyond a reasonable walk. Bi-State realized that the effective integration of LRT and bus operations was key to achieving the level of ridership projected for Metro Link. This opinion was supported by the alternatives analysis, which projected that an independent LRT service in same alignment without effective intermodal support would only attract about 16,300 weekday passenger trips by the year 2000—only 44 percent of the ridership projected for an integrated LRT-bus system (*2*).

The importance of the bus network to the success of Metro Link is borne out by the projections regarding morning peak period station access. The largest portion of Metro Link passengers were projected to arrive by bus (44 percent), compared with those who park-and-ride (33 percent) or walk (24 percent). At the opposite end of the trip, 35 percent of all morning peak period passengers were projected to transfer to buses to complete their journey. The rate of bus egress from stations during the morning peak period was projected to be significantly greater at stations outside of the CBD: an average 56 percent bus egress with a high of 83 percent at one particularly productive site (*3*).

Restructuring existing Bi-State bus routes as feeder and distributor services for the line-haul LRT service was determined to be the most cost-effective way for Bi-State to increase overall transit ridership. These "rubber-tired extentions" of Metro Link will effectively connect the LRT service with residential communities, employment centers, and other significant activity centers outside the CBD that are not within a reasonable walking distance of a station.

ROUTE RESTRUCTURING AND THE LOYAL RIDER

Restructuring existing bus routes as feeder and distributor services subordinent to the line-haul LRT service introduces another aspect of the predeveloped landscape that a new LRT line must contend with: existing constituencies.

The routes and services of the existing transit system have evolved to effectively serve this sprawled, automobile-oriented environment without consideration of LRT. The existing transit system probably includes routes that parallel the LRT alignment and provide roughly similar service oriented around the same trip generators that the proposed LRT is targeted to serve.

Likewise the transit system has an existing clientele with riding habits developed without consideration of LRT. Despite the enthusiasm of the LRT designers, the LRT service and station locations may be inconvenient, irrelevant, or contrary to the specific needs of a significant number of existing transit riders. Service planners must be sensitive to the fact that the introduction of LRT service—although representing a significant improvement from a systemwide perspective—can also represent a significant disruption and deterioration in bus service from the perspective of a particular individual who relies on the existing system.

EVALUATION CRITERIA FOR INTERMODAL COORDINATION

The Bi-State Development Agency took advantage of the availability of special funding to develop a more detailed evaluation of its bus route restructuring plan for Metro Link. The funding was from the Exxon Oil overcharge settlement through the U.S. Department of Energy and the Missouri Department of Natural Resources Division of Energy. Sverdrup Corporation of St. Louis, in association with Manual Padron & Associates of Atlanta, was commissioned to conduct the evaluation under the guidance of the Bi-State's service planning and scheduling department.

Bi-State provided the consultants with the evaluation criteria with the overall goal of making cost-effective changes in Bi-State bus routes and services to enhance regional mobility for the greatest number of passengers. The following objectives, as spelled out in a 1990 internal Bi-State memorandum, governed the development of the plan:

- Provide transit routes and services that are responsive to identified passenger travel patterns.
- Minimize overall travel time for the most passengers.
- Simplify the overall route structure.
- Avoid unnecessary disruptions of present routes and services without clearly demonstrated benefits.
- Maintain consistency with Bi-State transit service standards.
- Improve the overall operating efficiency of the Bi-State transit system.

Overall, LRT is intended to be the predominant line-haul carrier in the corridor it serves. Bus routes would be redesigned to function as complimentary and coordinated local feeders and distributors for the line-haul service provided by LRT. The process of redesigning an existing bus system to coordinate with LRT needed to be carefully undertaken on a station-by-station, route-by-route basis, however, to avoid needless disruption of the existing bus transit system. The planning process attempted to balance concerns for extending travel time for through passengers with the need to minimize the walking distance and wait encountered by intermodal transferees. Broad-brushed generalities were avoided. For example, although the general orientation of the process is to eliminate inefficient duplication of bus and rail services, parallel bus and rail routes may not necessarily be duplicative considering that the high-speed, limited-stop style of service that makes LRT an attractive line-haul carrier is not as effective serving a myriad of minor local destinations located between station stops.

General Considerations

Bus and rail transit routes and services should be designed to maximize system ridership, consistent with the following three guidelines. First, overall travel times and travel opportunities should be maintained or improved for the majority of passengers on any route changed to accommodate the LRT service. Second, overall bus and rail operating costs should be minimized. Third, any route changes proposed should have reasonable expectation of being implementable in light of local public and political considerations.

Note how these guidelines translated into evaluative terms. The degree of coordination between connecting services at a transfer site can significantly influence passengers' perceptions of discomfort. Because an *uncoordinated transfer* enroute can have the most pronounced effect on ridership, it was proposed to weight such transfers in a travel time calculation at a rate equal to half of the headway of the connecting service multiplied by a factor of 2.5. *Passively coordinated transfers*, in contrast, would be weighted at a rate equal to the scheduled waiting time multiplied by a factor of 2.5, whereas *dynamically coordinated transfers* would be penalized at a rate equal to the scheduled waiting time alone.

Scheduling Considerations

Schedules for bus and rail transit routes should be coordinated to minimize the out-of-vehicle time experienced by transferees and for maximum passenger convenience consistent with the following two guidelines. First, extraordinary measures to coordinate schedules should not be considered necessary for transfers between connecting routes operating at headways of 10 min or less. Under these circumstances, service frequencies would be sufficient to ensure timely connections for intermodal transferees.

Second, one of three transfer coordination strategies should be considered when one or more connecting routes are operating at headways greater than 10 min:

- Passive schedule coordination synchronizes the headways of connecting routes with the line-haul route and adjusts the operating schedules so that the connecting route passes through a station prior to or following the scheduled arrival of the line-haul route, depending on the predominant flow of transfer traffic.
- Dynamic schedule coordination provides an enforced delay of connecting transit vehicles (typically the buses) until the line-haul route arrives (typically the train). Headways on connecting routes are also synchronized with the line-haul route.
- Timed-transfer ("pulse") coordination schedules all routes to meet simultaneously and dwell at a station for a period of time sufficient to ensure connections for transferring passengers. Under most circumstances this strategy is not technically applicable to rail transit, except at terminal stations (such as the Southeastern Pennsylvania Transportation Authority's Norristown Transportation Center). Rail transit can effectively participate in timed-transfers at intermediate station, as in the case of the Gateway Transit Center on Portland's Tri-Met LRT system, where the LRT trains are scheduled to pass through the timed-transfer site in both directions while buses dwell.

Routing Considerations

Routing considerations begin with the LRT designers, who should provide an effective path for buses through a station environment that is direct and will not add significant travel time for through bus passengers. Direct access through the station environment and to the station boarding area should be prioritized based on the capacity of each mode and the length of time a vehicle will remain in the station. As such, the most direct access through the station environment to a point as close as possible to the boarding platform should be afforded to bus transit, followed by paratransit, kiss-and-ride, taxicabs, and—last, albeit most popular—park-and-ride.

The design of LRT infrastructure notwithstanding, bus transit routings should be designed to minimize convoluted routings and for maximum passenger convenience consistent with the following five guidelines. First, an existing bus route that parallels the LRT line should be considered for rerouting, truncation or elimination if

- Overall travel time for the majority of passengers currently using the parallel bus route (including transfer time) would be reduced;
- The majority of passengers currently using the parallel bus route have origins or destinations within a quarter mile of an LRT station; or
- The parallel bus route would not function as a local distributor along the LRT alignment, synergistically complementing the express service provided by LRT.

When a parallel bus route is truncated at an LRT station, its headways should be synchronized with the LRT service, and an appropriate degree of schedule coordination should be considered. Parallel routes may be segmented at LRT stations to provide better bus-to-bus connections, to discourage competitive through-riding on the bus, and to improve service reliability.

Second, an existing bus route that crosses an LRT line in the vicinity of a station site and is expected to be carrying a significant number of through bus passengers beyond the LRT station should be considered for rerouting to the LRT station consistent with these points:

- Through bus route/low orientation to rail—If the majority of the passengers on board the route at the LRT station are not anticipated to transfer to LRT service, that bus route should not be rerouted to the LRT station if that action would significantly prolong travel times for through passengers. When a through bus route can be rerouted to the LRT station without prolonging travel times for through passengers, bus headways should be synchronized with LRT and passive schedule coordination should be considered.
- Through route/high orientation to rail—If the majority of the passengers on board the route at the LRT station are anticipated to transfer to LRT service, that bus route should be routed as close as possible to the station platform to accommodate transfers. In such cases bus headways should be synchronized with LRT and passive schedule coordination should be pursued to the maximum extent possible. Some form of dynamic schedule coordination should also be considered to a degree that would not prolong travel times for through passengers aboard the bus and that would not significantly reduce service reliability for passengers elsewhere on the bus route.

Third, an existing bus route that terminates at or near an LRT station site, or an existing bus route that crosses an LRT line in the vicinity of a station site and is not expected to be carrying a significant number of through bus passengers beyond the LRT station, should be considered for rerouting to the LRT station or truncation consistent with these points:

- Terminating route/low orientation to rail—If the majority of all passengers using the route are not anticipated to transfer to LRT service, bus headways should be synchronized with LRT and passive schedule coordination should be considered to the maximum extent possible without disrupting service reliability for passengers elsewhere on the bus route. These buses should also be routed as close as possible to the station platform to accommodate any intermodal transfers that do occur.
- Terminating route/high orientation to rail—If the majority of all passengers using the route are anticipated to transfer to LRT service, such a route should be considered a dedicated feeder route for LRT service. In such cases bus headways should be synchronized with LRT service and dynamic schedule coordination should be provided to enforce connections in a positive way. These buses should also be routed as close as possible to the station platform to accommodate transfers.

Fourth, where an existing bus route terminates in the general vicinity of a LRT station but does not currently cross the rail line and a significant number of passengers are anticipated to use the LRT service, that route should be considered for rerouting to the station if such an extension was determined to be cost-effective. In such cases, the appropriate degree of schedule coordination should be consistent with the preceding guidelines.

Fifth, the potential for concentrating bus routes at key stations should be considered, if possible, to maximize bus-to-bus transfers. The use of timed-transfer ("pulse") coordination for some or all of the bus routes at a particular station should be considered wherever feasible.

Service Expansions

If significant net reductions in operating costs are identified through the integrated operation of a revised, intermodal transit network, a portion of those savings can be reallocated to improve transit service in the LRT corridor as follows:

- Cost savings in bus operations would cover part of the rail operating costs;
- Consideration can be given to adding off-peak service in areas that currently have peak period service only;
- New service could be added to respond to demands from developing suburban areas; or
- Some resources could be used to facilitate timed-transfer coordination at LRT stations, which would require better reliability, improved headways, or additional layover time on some bus routes to be effectively implemented.

The consultants separately evaluated Bi-State bus routes operating in the Missouri and Illinois tributary areas of Metro Link. Although guided by the evaluation criteria developed by Bi-State, the consultants and Bi-State staff agreed that the full set of evaluation criteria just presented was more detailed than necessary to support the preliminary planning activities defined in the study scope of work. An abridged set of guidelines was agreed upon for the consultants to employ for route evaluation. The full set of evaluation criteria was reserved for subsequent use in more detailed service planning, developing actual timetables, and working out operational priorities.

The consultants concluded that Bi-State could improve and expand transit service, plus realize a significant reduction of bus operating costs by rerouting existing bus routes consistent with the evaluation criteria. Bus service duplicated by Metro Link would be scaled back or eliminated, and timed-transfer centers were proposed for five outlying Metro Link stations in Missouri and Illinois. In Missouri some of the savings were redeployed to provide extensions into new service areas and longer service hours on existing routes. Two new dedicated feeder bus routes would link the LRT line with the city of Clayton in suburban St. Louis County. In Illinois the plan proposed to truncate several local routes that currently operate through to downtown St. Louis at the LRT terminal in East St. Louis (*4*).

Under the consultants' route restructuring plan, weekday bus miles in the Metro Link service area would be reduced by about 8 percent (nearly 1 million mi annually), while the number of weekday bus trips would increase almost 11 percent. This apparent contradiction reflects that very long line-haul bus routes would be truncated or eliminated, whereas most of the new feeder routes would be relatively short. The peak bus fleet would decrease by 38 buses in the morning peak period and 51 buses in the evening peak, although the midday service requirement would increase by 9 buses. Weekend service would also increase under this plan. The recommended service plan is projected to reduce annual bus operating costs by $1.7 million (*4*).

CONCLUSION

The coincidence of bus and rail services at a station does not constitute coordination. The benefits and effectiveness of a new LRT line can be significantly improved by restructuring existing bus services on a comprehensive basis. To achieve these benefits, however, operators and designers need to look beyond their vehicle and plans and consider every aspect of a passenger's trip via transit from the customer's perspective. Particular attention is necessary to the details of coordinating any transfer movements en route. In the rush to develop new and more effective services, the impact of service changes and reroutings on the current ridership needs to be carefully considered.

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Planning and Design of Park-and-Ride Facilities for the Calgary Light Rail Transit System

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Park-and-ride facilities are an integral part of the Calgary light rail transit (LRT) system. At the present time, there are approximately 6,800 parking stalls at 11 stations on 29 km of LRT line. On a systemwide basis, utilization is over 90 percent for long-term parking, and stations at two of the three terminals of LRT lines have 100 percent utilization of park-and-ride facilities. To determine the demand for surface park-and-ride facilities on the Calgary LRT system, a method has been developed based on the number of transit users in the station catchment areas using the automobile mode to reach the LRT system. Catchment areas are defined by a commutershed concept and vary in size and shape depending on station spacing and the road network in the immediate vicinity of a station. The primary market for LRT park-and-ride facilities within each catchment area is downtown employees. Planning guidelines for LRT park-and-ride facilities have also been developed. They include location criteria, access and egress considerations, and number and location of parking stalls (including short-term and long-term parking, kiss-and-ride, handicapped parking, and parking facilities for bicycles and motorcycles).

Park-and-ride has been an integral component of the Calgary light rail transit (LRT) system since it opened in 1981. The importance of the approximately 6,800 stalls at 11 stations on the 29 km of LRT line is manifested in an occupancy level of 90 percent on a systemwide basis.

Owing to the importance of park-and-ride as an access mode, the transportation department at the city of Calgary has developed procedures for the planning and design of such facilities and has learned several lessons from a decade of experience.

OVERVIEW OF PUBLIC TRANSIT IN CALGARY

Calgary's economy has been largely based on its favorable location as a service and distribution center for the vast agricultural lands of southern Alberta and for the oil and gas industry that developed in the area. The city has a (1991) population of approximately 708,000 and encompasses an area of 672 km² (see Figure 1). About one-third of the city's employment is in the central area, one-third along the east industrial area, and one-third spread throughout the city.

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Downtown Transportation Strategy

Although the downtown area accounts for less than 20 percent of all travel in Calgary, the intensity of this travel, combined with crosstown traffic, causes congestion and disruption to the inner city. Maintaining a strong, viable downtown area is a goal of the city. Therefore a number of its objectives emanate from a desire to manage traffic in the downtown and inner city areas. The thrust of many of these objectives is to improve the physical environment of the downtown and inner city sectors, and this can be translated into one transportation objective: to reduce unnecessary vehicular traffic in this area.

The primary target for change is the downtown worker who contributes to peak hour congestion and who stores a vehicle downtown during the work day. The strategy to initiate change is based on the gradual reduction in the availability of parking relative to downtown growth while increasing public transit service between the suburbs and downtown. Complementary policies, such as traffic management, road capacity restrictions, improved pedestrian environments, and downtown residential development, complete the strategy.

Historical Development of Downtown Transit Service

The importance of transit steadily declined from a high point in 1945 to a low, in terms of rides per capita, in the mid-1960s. Rapid transit studies also began in the mid-1960s with the first plan recommending two legs of heavy rail transit and a downtown subway (*1*).

In the early 1970s, Calgary instituted a new bus service marketed as the Blue Arrow system. The Blue Arrow system acted as its own feeder in the farthest suburbs and interconnected with crossing feeder routes as it approached downtown. Limited stops between the outer suburbs and the downtown area gave it some of the characteristics of an express service. A series of park-and-ride lots were developed with particular emphasis on proposed future rail corridors. Thus the Blue Arrow and its feeder bus systems combined with park-and-ride facilities to form a prototype for the development of the LRT system in terms of service and corridors. Between 1971 and 1981 the percentage of work trips to down-

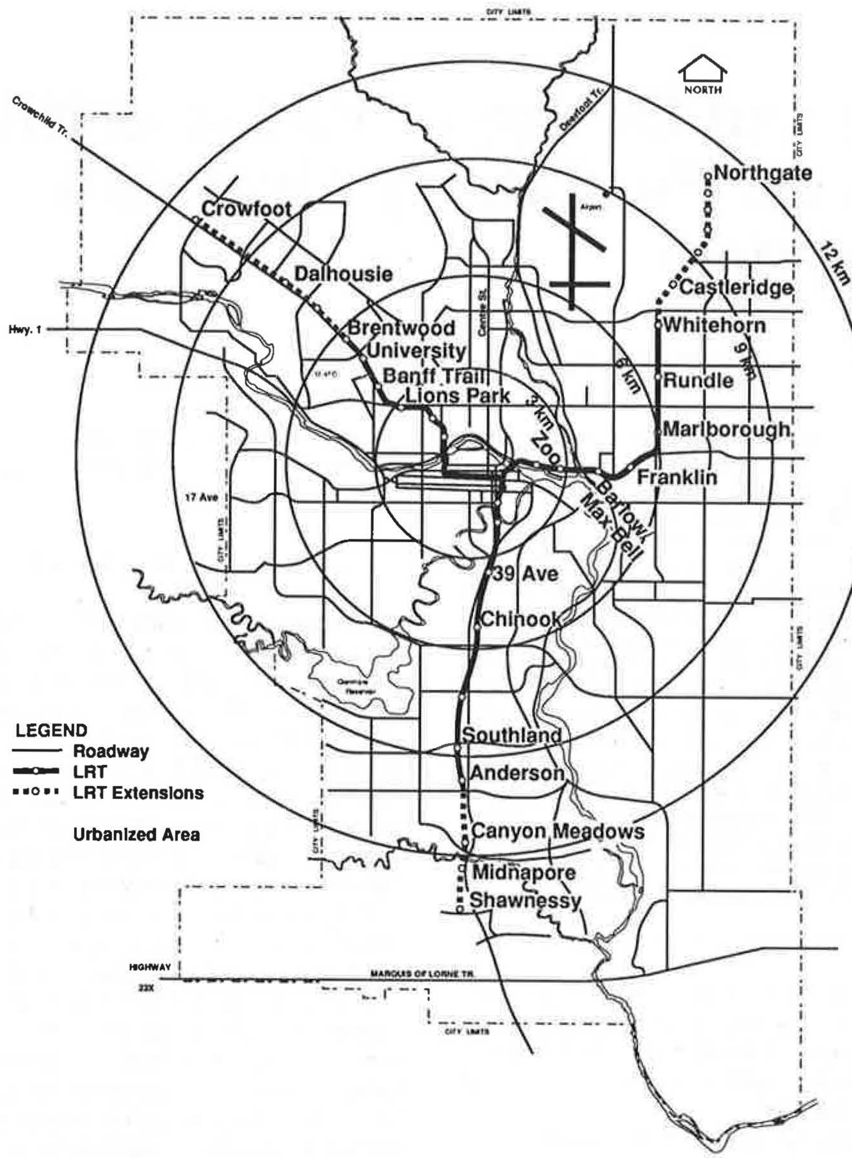

FIGURE 1 Calgary roadway and LRT network.

town by transit increased from 34 to 43 percent, a level that the LRT system has since maintained.

Implementation of Light Rail Transit

Implementation of the LRT system was a major impetus to the development of park-and-ride facilities in Calgary. These facilities have been planned in concert with other access modes (e.g., feeder bus, passenger pick up and drop off, walking, and cycling) to provide a comprehensive, balanced range of travel options for transit customers.

The LRT opened in 1981 with a 12.9-km (south) line served by 2,450 parking stalls. In 1985 another 9.8-km line was added (northeast) served by 2,100 parking stalls. In 1987 the 5.6-km northwest LRT leg opened and incorporated 530 parking stalls. The northwest line was extended by 1 km in 1990 and an additional 905 parking stalls were provided at the new Brentwood Station.

Table 1 shows the current status of park-and-ride facilities provided by Calgary Transit. This information reflects an expansion of parking capacity on the south LRT (650 stalls), which was undertaken to respond to parking pressure at the suburban stations.

In 1991 the Calgary Transit system had 118 routes serving approximately 53.6 million revenue passengers annually (excluding transfers). The fleet is composed of more than 592 buses and 85 LRT vehicles, with 503 buses and 72 LRT vehicles operating in the peak hours. On weekdays the LRT system carries approximately 114,500 passengers (400 boarding passengers per operating hour). Average weekday bus ridership is approximately 156,600 passengers (39 boarding passengers per operating hour).

TABLE 1 Number of Park-and-Ride Stalls by Corridor, 1990

Corridor	Length of Line (km)	Year Opened	No. of Park-and-Ride Stalls
LRT south	12.9	1981	3,102
LRT northeast	9.8	1985	2,250
LRT northwest	6.6	1987[a]	1,435
Bus express	—[b]	—	260
Total	29.3		7,047

[a]Includes 1-km extension in 1990.
[b]Denotes data not applicable.

OVERVIEW OF PARK-AND-RIDE IN CALGARY

Planning Objectives and Location Criteria

The establishment of park-and-ride facilities along major LRT and main-line bus corridors has expanded the transit market in Calgary to include customers who wish to use their private automobiles for a portion of their trips. These facilities are appealing to the automobile commuter because they provide greater flexibility and comparatively faster travel time than accessing the main-line LRT and bus services via the feeder bus system. Free parking and automobile block heater plug-ins (to facilitate cold weather starting) are also provided at park-and-ride lots to encourage use of these facilities. Park-and-ride trips are intercepted upstream of heavier traffic congestion in proximity to the downtown; therefore use of these facilities also assists in peak period transportation demand management.

Park-and-ride facilities have been strategically developed at designated stations along existing and proposed rail transit corridors and at major transit terminals on main-line bus routes. The sites selected for park-and-ride facilities are generally beyond a minimum distance of 5 km from the downtown core to intercept automobile commuters at the earliest opportunity and to discourage continuation of the trip by private automobile. Approximately 97 percent of the existing park-and-ride stalls (approximately 6,800 stalls) provided by Calgary Transit are located at LRT stations (see Figure 2). Three percent of park-and-ride stalls (approximately 260 stalls) are distributed along main-line bus corridors.

LRT Station Access Design Guidelines

The existing design guidelines for suburban LRT stations provide for a range of customer access modes (e.g., bus, private automobile, walking, bicycle); however, feeder buses are intended to be the primary mode of access to the LRT. The existing policy target is to accommodate approximately two-thirds of total patron arrivals in this manner. This strategy recognizes that the trip generating capacity of a park-and-ride stall is quite low when compared to a feeder bus system (each park-and-ride stall in Calgary generates only 2.63 transit trips daily) and also addresses community concerns regarding the traffic and environmental impact of developing large parking facilities adjacent to residential areas.

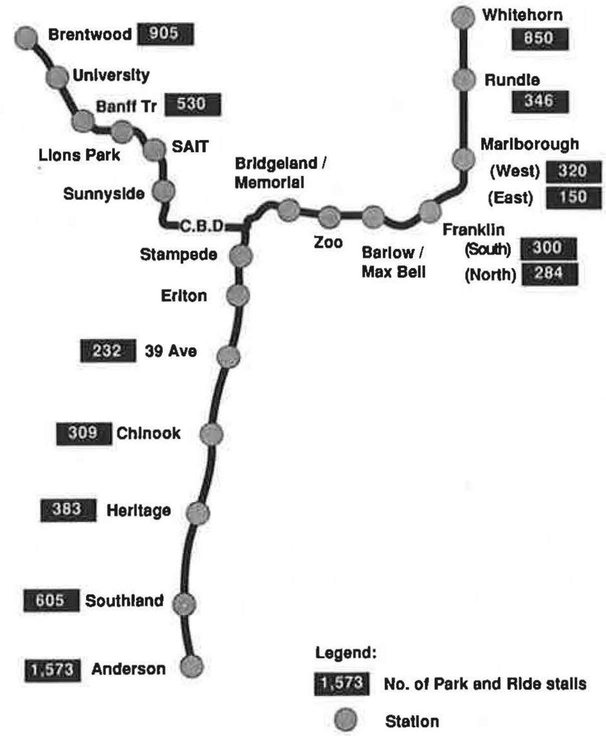

FIGURE 2 Calgary LRT network, stations, and park-and-ride.

To ensure the provision of a high-quality feeder bus service, every effort is made, as part of the route planning and service design process, to integrate feeder bus and LRT service effectively. In Calgary, public transit requirements are reviewed and incorporated at each stage of the development process (i.e., area structure plans/design briefs, concept plans, outline plans, subdivision plans, development and rezoning applications) as a condition of development approval. This iterative process contributes to the successful integration of transit within the community by maximizing area coverage and providing a high standard of access to transit service (i.e., interior walkways, sidewalks, lighting, bus zone aprons).

The frequency of service currently provided on the feeder bus networks in the existing three LRT corridors is generally in the 15- to 20-min range during peak periods. Base service operating during the weekday, midday, and Saturday periods is provided every 30 min on most routes. Evening and Sunday service operates on a 30- to 60-min frequency.

The current access design guidelines for suburban LRT stations allow for approximately one-third of the total patron arrivals by private automobile either through automobile passenger drop off (kiss-and-ride) or park-and-ride activities.

Access Mode	*Modal Share (%)*
Bus	60–65
Park-and-ride	15–20
Kiss-and-ride	15
Walk	5

Suburban park-and-ride lots on the two initial LRT lines in the south and northeast corridors were sized to accommodate 15 percent of all LRT trips based on the estimated maximum development of the transit market within the catchment area for each station. In response to parking pressure experienced at the south LRT stations, the park-and-ride design guidelines were increased in 1986 to a range of 15 to 20 percent of all LRT trips. Subsequent to this decision park-and-ride lots at five LRT stations on the south LRT leg were expanded to increase parking capacity by approximately 650 stalls. A subsequent review of park-and-ride requirements at the proposed northwest LRT stations also concluded that additional parking would be required to accommodate an expanded modal share for park-and-ride travel.

LRT Park-and-Ride Inventory

At present approximately 6,800 park-and-ride stalls have been developed for the initial three-leg LRT system (see Table 2), with the potential for an additional 5,900 stalls when future extensions to the south, northwest, and northeast LRT lines are opened, for a total of approximately 12,700 stalls. Other plans call for more short-term and handicapped parking and special storage for bicycle security.

A proportion of the park-and-ride stalls at each LRT station has been allocated for short-term parking (4 hours maximum), automobile passenger pick up (15 min maximum), and handicapped parking (by permit only). The existing practice is to initially designate approximately 10 to 15 stalls at each LRT park and ride lot for short-term parking (between 5 a.m. and 4 p.m.) and 2 stalls for handicapped parking. The 4-hour parking area is converted to 15-min passenger loading after 4 p.m. Also, parallel curbside parking may be assigned for kiss-and-ride (also referred to as passenger pick up or drop off) activities depending on the parking lot design. The quantity of parking designated as short-term (4-hour), kiss-and-ride, and handicapped parking may be increased if demand is demonstrated for additional capacity.

Role of Park-and-Ride

Although park-and-ride at LRT stations is regarded as an effective method of expanding the transit market to include automobile drivers, it is essential that an appropriate balance between park-and-ride and other access modes be maintained to sustain a viable feeder bus system and to avoid generating an undesirable impact upon adjacent residential areas.

Parking development beyond the capacity constraints of each site will create major delays at the access points and within the parking areas, thereby reducing the attractiveness of the park-and-ride travel option. This congestion would also affect the operation of the feeder bus network and the environment of the adjacent communities. Experience has demonstrated that provision of park-and-ride facilities also affects the use of other station access modes (e.g., feeder buses), thereby limiting the ridership gains achieved through parking expansion programs. A survey of northeast LRT riders indicates that approximately 60 percent of existing park-and-ride users were bus riders before LRT service began. Information obtained following the opening of the new 905-stall park-and-ride lot at Brentwood Station on the northwest LRT

TABLE 2 Inventory of Park-and-Ride Stalls on the Calgary LRT System, 1990

	Existing Parking				
Station	Total Stalls	Short-Term[a]	Kiss-and-Ride[b]	Handicapped	Future Parking
South LRT					
39 Avenue	232	6	6	8	
Chinook	309	12	12	2	
Heritage	383	7	13	2	
Southland	605	9	9	2	
Anderson	1,573	16	15	2	
Canyon Meadows					200
Midnapore					1,000
Shawnessy					1,000
Northeast LRT					
Franklin					
South	300	11	21	2	
North	284	16	16	2	
Marlborough					
West	320	13	13	2	
East	150	4	4	2	
Rundle	346	7	7	2	
Whitehorn	850	10	30	5	
Castleridge					500
Northgate					1,000
Northwest LRT					
Banff Trail	530	4	28	2	
Brentwood	905	15	15	4	
Dalhousie					1,200
Crowfoot					1,000
Total	6,787				5,900

[a]Four-hour parking.
[b]Fifteen-minute parking.

also revealed that although 37 percent of park-and-ride users were new transit customers, one-third previously made the trip by Calgary Transit bus (*2*). These high diversion rates may be partially related to the restructuring of the bus network; nevertheless it does support the conclusion that easing constraints on LRT parking may trigger some shift from other modes such as kiss-and-ride and feeder buses to park-and-ride.

The challenge presented by the park-and-ride transit option is to determine an appropriate balance of these facilities relative to other access modes. Too much parking can be detrimental to the viable operation of the feeder bus network. Too little parking merely restricts the transit market in the corridor and may result in overspill parking into adjacent communities. The appropriate balance of this option, within the spectrum of public transit services, is critical to maximize overall system efficiency.

Park-and-Ride Utilization

South LRT

Surveys undertaken by Calgary Transit of the park-and-ride facilities at the south LRT stations, indicate that park-and-ride accounts for 21 percent of the access modal share (*3*) (see Table 3). At present the demand for park-and-ride facilities on the south LRT exceeds the existing supply. All park-and-ride lots are generally full by 9 a.m. Complaints from patrons encountering a full park-and-ride lot have not been sufficient to warrant expansion of the lots.

Northeast LRT

In contrast to the popularity of park-and-ride facilities on the south LRT, park-and-ride use along the northeast LRT corridor has been lower, at 15 percent modal share (*4*). The northeast LRT line has unused parking capacity (see Table 4).

Northwest LRT

In September 1990 the northwest LRT extension to Brentwood was opened. This new station incorporates 905 park-and-ride stalls. Although current information on access mode changes resulting from the Brentwood LRT Station is not yet available, a dramatic shift has occurred in park-and-ride demand from Banff Trail Station to Brentwood Station. Parking at Banff Trail has been reduced from 100 percent to 30 percent of available capacity. Existing parking stalls at Brentwood are generally fully occupied on weekdays.

TABLE 3 LRT Park-and-Ride Access Mode Modal Share

	Access Mode	Modal Share (%)
South LRT	Feeder bus	51
	Park-and-ride	22
	Automobile drop off	5
	Walk	21
	Other	1
Total		100
Northeast LRT	Feeder bus	55
	Park-and-ride	15
	Kiss-and-ride	7
	Walk	23
Total		100

TABLE 4 Northeast LRT Park-and-Ride Occupancy Levels, November 1989

	No. of Stalls	Occupancy Level (%)
Whitehorn Station	850	80
Rundle Station	346	93
Marlborough		
West	320	82
East	150	100
Franklin		
South	300	100
North	284	80
Total	2,250	89 (average)

Customer Response to Park-and-Ride Facilities

Based on the high use of existing parking facilities at LRT stations, it is apparent that park-and-ride transit is popular with automobile commuters. The 15- to 20-percent design guideline applied to park-and-ride travel has provided sufficient parking capacity to accommodate corridor demand on the northeast and northwest LRT lines.

Recent surveys of south and northwest LRT park-and-ride users have confirmed that time savings and convenience are major considerations in choosing park-and-ride over feeder bus travel. Respondents cited a number of reasons for choosing to travel by Calgary Transit, primarily relating to the cost of travel and, in particular, the high cost of parking in the downtown area. It is interesting to note that, in spite of the parking pressure at the south LRT stations, respondents ranked additional parking below other potential transit improvements such as increased peak period train frequency, extension of the south LRT, and increased feeder bus frequency. Eighty-two percent of respondents claim that they would discontinue use of the park-and-ride facilities if a fee were charged for parking (*5*).

It is anticipated that parking pressure on the south LRT line will ease when the LRT is extended south to Midnapore (expected before the end of the decade) and additional park-and-ride is developed at the new terminal station.

GUIDELINES FOR PLANNING PARK-AND-RIDE LOTS

The following general guidelines have been developed for the Calgary LRT system (*6*):

1. Park-and-ride lots should be on major transportation corridors served by high-speed, high-quality public transit (LRT or express bus) and roadways of major arterial or expressway standards.

2. Park-and-ride lots should be located so as to intercept motorists upstream of the heavier traffic congestion.
3. Park-and-ride lots should be in corridors with good roadway access leading directly to the facility. Access and egress should be quick and easy.
4. The total transit travel time from the park-and-ride lot to the central business district (CBD) should be equal to or preferably less than travel time by car.
5. The percentage of travel time on transit should represent more than 50 percent of the total journey time.
6. Ideally the park-and-ride facility should be no closer than 5 to 6 km to the downtown, although there may be exceptions as a result of natural and man-made geographic barriers. For example, the Barlow/Max Bell Station (see Figure 2), is within 4 km of the downtown on a major escarpment and has attracted park-and-ride activity on a vacant development site.
7. Park-and-ride facilities should be in corridors and areas along corridors with a strong link to the destination zone (e.g., residential zones with a high proportion of downtown workers).
8. Park-and-ride facilities should be where the local traffic impact on residential neighborhoods would be minimal.
9. Park-and-ride facilities should be developed within a framework of an overall metropolitan planning strategy to limit long-term parking within the downtown and the provision of fast, frequent transit to the downtown.
10. Park-and-ride lots should be viewed not only as a transportation focal point but as a community asset in terms of attractive station design, landscaping, and passenger security.

Estimating the Demand for Park-and-Ride

The size of a park-and-ride facility is influenced by the estimated demand, which has been calculated in Calgary by the following method (*6*).

Commutershed Concept

The commutershed concept is used to determine the primary catchment area for estimating the demand for park-and-ride. The general shape of a commutershed is illustrated in Figure 3. The commutershed is roughly a parabolic-shaped area of varying dimensions with the park-and-ride facilities at the focus of the parabola. For the Anderson and Brentwood terminal stations, the parabola is approximately 6 km long and 8 to 10 km wide at the base. For inner stations, the commutershed dimensions will vary according to land use and geographic and man-made barriers, such as rivers, major arterial roads, and rail lines.

Primary Market

The primary market for estimating the demand for park-and-ride within a station catchment is downtown employees. Secondary markets would include downtown-destined nonwork trips or crosstown trips to destinations with a limited parking supply, such as the university, Calgary Stampede, or the Saddledome (where hockey games are played). It is the primary market, however, that is used to size park-and-ride lots.

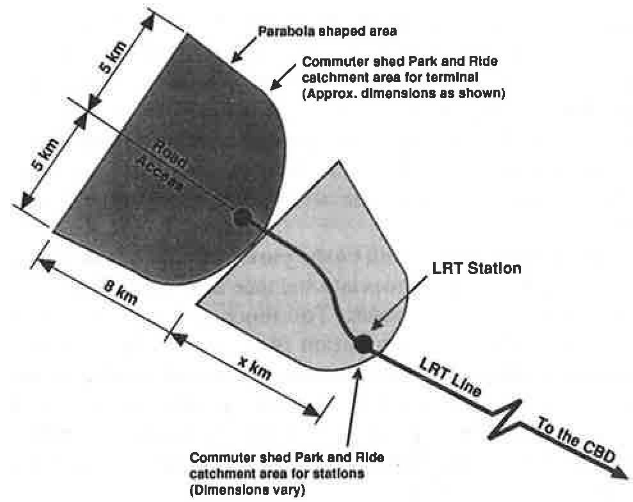

FIGURE 3 Commutershed concept for determining the catchment area for LRT park-and-ride.

Demand Forecast Procedure

The five basic steps in estimating the demand for park-and-ride are as follows:

1. Define the catchment area for each station.
2. Determine the primary market. The primary market is defined as downtown employees residing within a catchment area. In the case of Calgary the magnitude of the primary market is based on home-interview, origin-destination surveys.
3. Determine the primary demand, which is based on the observed and expected modal split for home-based work trips to the CBD. In the case of Calgary a modal split of 40 to 45 percent has been observed for CBD-oriented home-based work trips.
4. Estimate the proportion of primary demand attracted to park-and-ride. City of Calgary design guidelines for park-and-ride make provision for accommodating 15 to 20 percent of the primary demand. These guidelines are based on the observed demand for park-and-ride, an automobile occupancy of 1.2, and the lots operating at 95 percent efficiency with a stall turnover of 1.2. Accommodating 15 to 20 percent of primary demand at park-and-ride lots represents a strategy to strike a balance between satisfying the demand for park-and-ride and maintaining a viable feeder bus service. Oversupply of park-and-ride stalls is not only economically undesirable but also could result in unacceptable environmental and community effects. Undersupply of park-and-ride can also result in unacceptable community effects such as overspill parking on adjacent streets. Undersupply can also discourage potential public transit patronage by commuters presently driving to work downtown.
5. The demand for short-term parking and special needs parking (such as handicapped parking) at park-and-ride lots is taken as a proportion of long-term demand.

Northwest LRT Park-and-Ride Example

Before the extension of the northwest LRT line from the University of Calgary to the Brentwood Terminal, this method was used to estimate the park-and-ride stall requirements assuming that the line would be extended in stages beyond the University Station to Brentwood, Dalhousie, and Crowfoot. Figure 4 shows the catchment area for each station and major transportation facilities. It is noted that as the line is being extended in stages, the interim terminal park-and-ride facility must serve a larger catchment area than required when the LRT line is extended. Thus the Banff Trail park-and-ride shown in Figure 4, with a capacity of 530 stalls, served as the terminal facility for the northwest LRT for a period of 3 years. In fact before the extension of the northwest line, 85 percent of the Banff Trail park-and-ride patrons originated in the Brentwood catchment.

Table 5 gives the main assumptions used to estimate the size of the Brentwood park-and-ride facility. The catchment population of the Brentwood Terminal was estimated at 83,700 for a corresponding citywide population of 750,000. The primary market for the Brentwood Terminal was based on the number of home-based work trips originating in the Brentwood catchment and destined for the CBD. A modal split of 40 percent was used to estimate the primary demand.

Table 5 indicates that 758 and 1,008 stalls would be required for 15 and 20 percent, respectively, of primary demand using park-and-ride. A total of 905 stalls were constructed at Brentwood, which was the maximum number that could be built on the land available. The 1,200 and 1,000 stalls planned for future LRT extensions to terminals at Dalhousie and Crowfoot, respectively, were estimated by a similar procedure.

The high use of the Brentwood park-and-ride lot is attributed to the fact that it is the outermost terminal on the north-

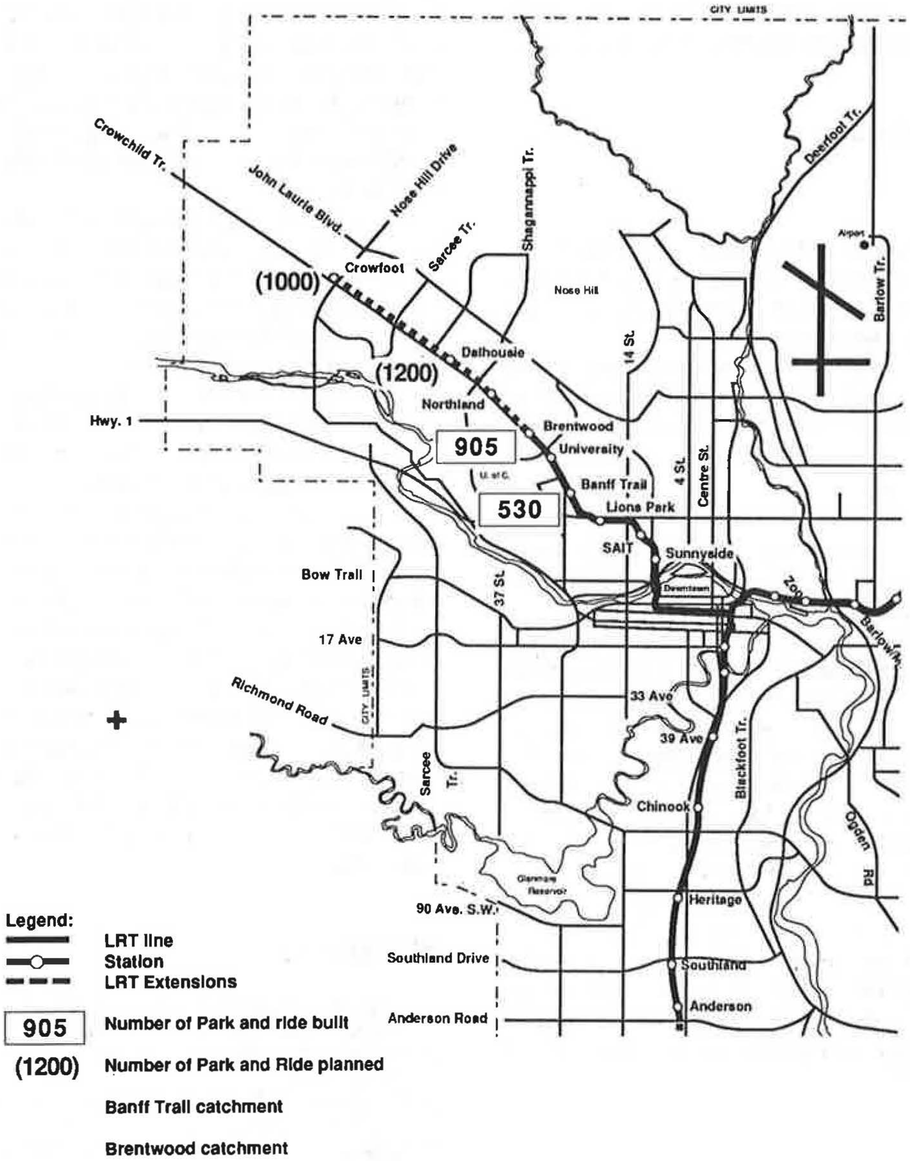

FIGURE 4 Northwest LRT park-and-ride catchment areas.

TABLE 5 Estimated Number of Park-and-Ride Stalls for Northwest LRT Line Extension to Brentwood Terminal

Station	Catchment Population[a]	Stalls Required by Percent Primary Demand[b] 15	20	Parking Stalls Constructed
Banff Trail	12,350	116	154	530
Brentwood	83,700	758	1,008	905
Total Northwest corridor catchment	96,050	875	1,162	1,435

[a]Based on city population of 250,000.
[b]Using park-and-ride.

west LRT line, which intercepts inbound traffic on Crowchild Trail, and the fact that the Brentwood catchment in reality extends approximately 50 km beyond the city limits, encompassing dormitory communities, country estates, and small towns. Recent surveys indicate that approximately 8 percent of park-and-ride commuters at the Brentwood Terminal came from outside the city.

Other Planning Considerations

Walking Distances

The attractiveness of a park-and-ride facility depends on the walking distance from the parking area to the transit boarding area. The maximum desirable and maximum walking distance are 125 m and 250 m, respectively.

Observations at the McMahon and Anderson stations, with a 5-min walk, have indicated that the distance (approximately 450 m) is undesirable and detracts from the use of the facility.

Maximum and Minimum Size

Little research has been undertaken to determine the maximum or minimum facility size. Observations of existing lots indicate that the Anderson Terminal at 1,600 stalls is larger than desirable in terms of walking distances and traffic generation. As a general guideline, the maximum and minimum size of future lots has been set at 1,200 and 200 stalls, respectively. The suggested maximum limit of 1,200 stalls is consistent with the walking distance guidelines just noted for a single park-and-ride lot. If it is feasible to develop parking in a concentric pattern around the LRT station, the quantity of parking could be increased beyond 1,200 stalls. Having determined the general location of an LRT station and the approximate capacity of parking needed, specific sites must be evaluated through more detailed analysis. Site selection must take into account factors other than the park-and-ride component. It is noted that the city of Calgary LRT design guidelines, developed in 1981, are constantly being updated to incorporate changing design parameters such as the size of the parking module (*7*).

CONCLUSIONS

Based on two decades of operating experience, Calgary's transportation department has concluded that the importance of park-and-ride is best illustrated by the fact that there is 90 percent utilization of stalls provided on a systemwide basis and 100 percent utilization at terminal stations. The primary demand for park-and-ride arises from downtown employees, and procedures for estimating demand from this market are based on a 15 to 20 percent access modal share for park and ride. Accommodating 15 to 20 percent of primary demand at park-and-ride lots represents a strategy to strike a balance between the demand for park-and-ride and maintaining a viable feeder bus service. This design guideline has been found to be satisfactory for sizing park-and-ride lots in the Calgary LRT system.

The importance of park-and-ride, not only as an access mode but in contributing to a growth of downtown work trip modal split, has been confirmed by passenger surveys. Market surveys found that 46 percent of LRT passengers using park-and-ride stated that they did so because it was faster and more convenient than a feeder bus.

The most important lessons learned are to reserve adequate space for park-and-ride facilities well in advance of line extension and to minimize neighborhood impacts. The financial burden of long-term land reservation can be minimized through joint land use or interim land use, such as a mobile home park. Local problems, such as overspill parking or increased traffic on residential streets, can be minimized by careful signing of access roads leading to the park-and-ride lot, appropriate sizing of the lot, and special attention to the location of access and egress points on major arterials.

Other factors that have contributed to the success of park-and-ride and LRT include provision of short-term and handicapped parking, kiss-and-ride, bicycle storage facilities, good signage, and lighting for safety and security.

Plans include an additional 5,900 stalls on LRT extensions, which will create a total of 12,700 long term LRT park-and-ride stalls.

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PART 3
Management and Staffing

Recent Developments in LRT Staffing and Productivity

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A number of new light rail transit (LRT) systems have come on line in the past 10 years, and several older systems have substantially renovated their physical plant. As the new systems reach maturity and the older ones adjust to new facilities, staffing changes may occur to take advantage of opportunities for enhanced productivity or to reflect the aging of the fleet and changing requirements for maintenance. System growth also may result in changed staffing needs. Analysis of current staffing and plans at a number of LRT operations in North America allows productivity factors to be derived. Definitions of labor classifications and job duties must be carefully considered when attempting to measure productivity, because the same functions are performed by staff in different classifications on different properties. The focus here is on the direct and indirect functions that must be performed to provide the transit services and on ratios of support to line operating and maintenance staff. Organizational decisions, notably the make-or-buy decision to perform functions with work force or to contract them out also play a role in productivity. Functions performed at a systemwide level on behalf of an LRT operation that is a small part of a large multimodal operation are also potentially significant in productivity. Section 15 data, although improved, still do not address these issues adequately, requiring that comparisons among properties be made with extreme caution.

A number of new light rail transit (LRT) systems have come on line in the past 10 years, and more will do so shortly. Several older systems have also substantially renovated their physical plant. It is therefore appropriate to examine current staffing and organizational arrangements to learn what productivity innovations are taking place. A related question is the way in which new LRT operations fit organizationally into transit systems that have been primarily bus-oriented.

Prior research indicated that properties differ widely in measured productivity rates (*1*). Sources of the differences include

- Equipment types,
- Labor practices,
- Environmental conditions,
- Operating procedures, and
- Errors in data reporting and differences in definitions.

To the extent that a pattern appears to be emerging, it can best be described as follows: The new LRT properties appear to be somewhat more willing to examine nontraditional ways of accomplishing the tasks needed to operate the system. A great variety of arrangements appear to exist for contracting out various work tasks and for sharing staff among operating divisions where functions performed are not unique to LRT operations. The overall thrust of these arrangements appears to be aimed at maximizing the scale economies that may exist in larger operations and thus minimizing the cost of LRT services.

The sections that follow discuss some of the staffing areas and how differences among agencies affect measured productivity. Attention is devoted to both the institutional and the measurement issues.

TRANSPORTATION STAFFING RATIOS

Operating Labor

Two measures of train operator productivity are annual average revenue vehicle hours per operator and ratio of operators to cars in peak service. Of the 10 U.S. LRT-operating properties reporting Section 15 data to UMTA for their fiscal year (FY) 1989, vehicle hours per operator ranged from 3,727 (Buffalo) to 1,100 (Pittsburgh) (*2*). However, it must be noted that several of the properties operate a multiple-unit train with only one operator, whereas others require one operator per car. Dividing the properties along those lines, a slightly different picture emerges, as presented in Table 1.

Except for San Jose, which was still in its initial stages of LRT operation, and Newark, which is a very high-frequency, short line with unusual operating characteristics, the productivity range for properties using one operator per train is completely above the range for properties with one operator per car, and the average for one-per-train operator productivity is more than 50 percent higher than for one-per-car properties. Among the unusual operating characteristics that may account for the apparently high productivity in Newark is that all cars are stored overnight at the Penn Station end of the line, eliminating deadhead trips out of revenue service. Also, qualified extra operators are drawn from the roster of a nearby NJ Transit bus depot and may not be counted in the rail operator head count. The issue of operator productivity is further complicated by the fact that some properties draw extra operators from the ranks of qualified bus operators but do not count them on the LRT operators' roster, thereby making the apparent productivity per LRT operator higher than it actually is.

It is interesting to note that the staffing plan for the St. Louis Metro Link assumes 1,668 train hours per operator per

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TABLE 1 Annual Average Revenue Vehicle Hours per Train Operator (2)

Property	Annual Hours per Operator
Properties Using One Operator per Train	
Buffalo	3726.9
San Diego	2789.7
Portland	2308.7
6-city arithmetical average	2254.4
San Francisco[a]	1745.1
Sacramento	1734.6
San Jose	1221.5
Properties Using One Operator per Car	
Newark	2008.0
Philadelphia	1546.1
6-city arithmetical average	1409.3
Boston	1298.8
Cleveland	1294.2
New Orleans	1207.9
Pittsburgh	1100.9

[a]San Francisco uses one operator per car for the surface portions of its operation and one per train in the MUNI Metro subway portion.

year. Given that the St. Louis operation will initially be composed primarily of one- and two-car consists, the productivity ratio agrees well with the reported statistics for one-operator-per-train properties.

Transportation Administration and Support

Other things being equal, the higher the ratio of operators to administration and support staff, the lower the operating cost. Table 2 presents the ratio of operators to transportation support staff, which ranges from 8.33 for New Orleans down to 1.16 for Buffalo.

Some of the variations in the ratio are readily explained. One-operator-per-car properties could be expected to have a higher ratio of operators to support than one-per-train properties, because administration and support are more a function of the number of trains on the line than the number of cars. Staffing plans for some LRT systems currently under construction indicate that street supervision will be performed by the same staff that supervises bus operations, possibly augmented by a few positions. It is not clear how the numbers reported in the Section 15 data were derived for properties that do not have a dedicated LRT supervisory staff.

It is difficult to account for doubling or halving the ratio, as occurred in San Francisco, New Orleans, Philadelphia, Pittsburgh, and Cleveland. Possible explanations include

- Inconsistencies in reporting,
- Expansion of service (more operators, no more support), and
- Adding support staff without more service.

It is interesting to note that the newer properties, as a group, appeared more stable than the older ones in this ratio.

The Baltimore Central Light Rail Line operations plan projects 2.4 revenue vehicle operators per transportation administrative/support staff member; the St. Louis Metro Link plan calls for 1.33 operators per transportation support staffer. However, the St. Louis plan includes eight people in a position classified as "operations/security supervisor." Eliminating those positions would bring the ratio up to 1.89.

MAINTENANCE STAFFING RATIOS

Cars per Maintainer

The definition of maintenance staff varies somewhat among properties. Car cleaners and hostlers, for example, are included with maintenance staff on some properties, with transportation staff on others, and are contract employees on a third group. With the exception of two outliers, however, the ratio of cars per maintainer ranges from 1.0 to 2.6, as presented in Table 3. The variations observed over time have several sources. San Diego expanded its fleet significantly. Sacramento added staff. Buffalo and Newark may have reclassified staff positions for reporting purposes.

Interpretation of the 1989 ratio of cars to mechanics is somewhat ambiguous. At first glance, one might assume that

TABLE 2 Operators per Transportation Support Staff Member

Property	Ratio 1987 Data	Ratio 1989 Data
Properties Using One Operator per Train		
San Diego	2.00	2.43
Portland	2.06	1.87
Sacramento	1.10	1.82
San Francisco	5.14	1.74
San Jose		1.46
Buffalo	0.90	1.16
Properties Using One Operator per Car		
New Orleans	4.00	8.33
Newark	2.97	5.12
Philadelphia	8.33	3.87
Pittsburgh	0.92	2.53
Boston	2.09	2.44
Cleveland	3.17	1.25

SOURCE: UMTA Section 15 Data, 1987 and 1989.

TABLE 3 Cars per Maintainer

Property	Ratio 1987 Data	Ratio 1989 Data
Boston		5.7
San Diego	1.67	2.6
San Jose		2.6
Sacramento	3.71	2.4
Portland	2.00	2.0
Cleveland		1.9
Buffalo	1.29	1.8
Philadelphia		1.5
New Orleans		1.2
Newark	3.00	1.0
Pittsburgh		1.0
San Francisco		0.7

SOURCE: UMTA Section 15 Data, 1989 (2); interviews with system representatives, 1987.

a property with relatively few maintainers (i.e., more cars per maintainer) was more efficient or enjoyed a relatively trouble-free fleet, or both. However, many other factors can influence the ratio.

Obviously the degree of contracting-out influences the staff count and thus the ratio. A more detailed financial analysis, however, would identify maintenance contract costs that could be taken into account in examining the overall efficiency of a property's LRT maintenance. Similarly if the fleet is relatively new and still under warranty, with manufacturer's staff performing some of the maintenance tasks, the ratio will appear higher than it might several years hence.

Another possible explanation for a high cars-to-mechanics ratio is a high spare ratio, which could be the result of a number of influences:

- An older fleet kept in active reserve and hence counted as part of the active fleet, but in reality used very little,
- Advance purchase of rolling stock in anticipation of system expansion,
- A shortage of maintenance bays, forcing cars to be sidelined awaiting their turn for repairs, or
- A shortage of qualified mechanics, with the same result.

Baltimore's operations plan calls for 1.94 cars per maintainer; St. Louis' for 16 vehicle maintainers for 31 cars, also a ratio of 1.94. Baltimore is open to the possibility of splitting assignments of maintenance staff between their heavy and light rail vehicles, an option not available to St. Louis.

Vehicle Maintenance Administration and Support

The ratio of vehicle maintenance staff to supervisors and support staff varies widely among properties, as shown in Table 4. Unlike transportation employees, the efficiency issue is less clear-cut in vehicle maintenance. A high ratio of maintainers to support staff may reflect, for example, any of the following:

- A large shop with a large number of employees supervised by a few managers,
- Contracting out car cleaning, reducing the number of support staff, or
- Purchasing and stores employees counted as part of central staff rather than dedicated to LRT.

In contrast a low maintainer-to-support-staff ratio may reflect the presence of supplier-furnished maintainers performing warranty work on a newer fleet. The same property in later years might have more maintainers doing running repairs, fleet overhauls, and so forth without adding to the support staff.

Baltimore's CLRL operations plan calls for 1.06 vehicle maintainers per maintenance support staff member. Support staff includes six car cleaners. St. Louis projects a ratio of 2.29 vehicle maintainers per maintenance support person. However, car cleaning is to be contracted out; the ratio would be lower otherwise. It is interesting to note that none of the "newer" LRT systems has experienced a ratio of maintainers to support staff as high as that projected for the two systems soon to come on line.

Perhaps the fairest conclusion that can be drawn from the Section 15 data is that such variables as fleet age, percent of maintenance work done under warranty, and percent of unit overhaul done by staff versus percent contracted out must be taken into account before any judgment is made about the efficiency of an individual property's staffing pattern. Simple comparisons based on the Section 15 data are not likely to be very helpful.

Nonvehicle Maintenance

The 1989 reported staffing for nonvehicle maintainers appears generally consistent with the 1987 data reported in an earlier study (*1*). Table 5 presents the ratio of nonvehicle maintainers per track mile in 1987 and 1989. The difference in the Newark data is viewed as an anomaly, possibly caused by a redefinition or an error in reporting for Section 15 in 1989. (The 1987 figure, based on a direct interview with supervisory staff in Newark, is thought to be more reliable.)

Except for Buffalo, the newer properties generally require fewer nonvehicle maintainers per track mile than the older ones. This may be attributable to low-maintenance design of track, power distribution, and facilities (including stations) in the newer systems. On the other hand, some portion of the staff ratio reduction on newer systems is caused in some cases

TABLE 4 Vehicle Maintainers and Maintenance Administration and Support (*2*)

Property	Ratio	Property	Ratio
Newark	4.11	Boston	1.09
San Francisco	2.70	San Jose	0.99
Philadelphia	2.64	Cleveland	0.94
New Orleans	1.60	Sacramento	0.85
Pittsburgh	1.22	Portland	0.73
Buffalo	1.16	San Diego	0.62

TABLE 5 Nonvehicle Maintainers per Track Mile

Property	Ratio: 1987 Data	Ratio: 1989 Data
Newark	2.35	0.05
Sacramento	0.43	0.22
San Diego	0.29	0.46
Portland	0.82	0.86
Boston		1.26
Pittsburgh		1.51
San Jose		1.59
Cleveland		1.68
San Francisco		1.72
New Orleans		1.88
Philadelphia		2.17
Buffalo	5.56	5.30

SOURCE: UMTA, Section 15 Data, 1989 (*2*); interviews with representatives of properties, 1987.

TABLE 6 Nonvehicle Maintainers per Station (2)

Property	Ratio
Newark	0.04
Sacramento	0.82
San Diego	0.86
Portland	1.04
Boston	1.15
San Jose	1.55
Cleveland	1.64
Buffalo	5.34
Philadelphia	6.20
Pittsburgh	7.24
San Francisco	10.33

by contracting out station cleaning and other nonvehicle maintenance (e.g., wayside cleaning in San Diego). Baltimore expects a ratio of 0.84; St. Louis, 0.80.

The number of stations in the system is apparently not a major determinant of the size of the nonvehicle maintenance staff. If it were, the ratio of nonvehicle maintainers per station would be expected to be fairly uniform across systems. Instead, as Table 6 shows, there is a very wide variation.

The San Francisco ratio appears extremely high because only the nine stations in the Muni Metro portion of the LRT system are counted. The system has 54.2 mi of track, however, and the ratio of nonvehicle maintainers to track miles is reasonable for an older system. Similarly Pittsburgh reports 13 stations but 62.4 mi of track. Both Philadelphia and San Francisco have a significant amount of street running, which places different demands on nonvehicle maintenance than operation on private right-of-way.

TABLE 7 Administrative Employees as Percentage of Total Operating Staff (2)

Property	Percentage
New Orleans	1.7
San Francisco	3.4
Sacramento	8.7
Newark	9.2
Pittsburgh	9.5
San Diego	11.5
Buffalo	12.5
San Jose	14.8
Philadelphia	15.1
Boston	15.8
Portland	19.7
Cleveland	19.9

ADMINISTRATIVE STAFFING

Table 7 presents the ratio of administrative to total operating employees. No pattern of older versus newer systems emerges in analyzing the statistics. The systems with lowest ratios are generally smaller parts of larger transit systems that may be somewhat more integrated into the overall agencies. However, Philadelphia, Boston, and Cleveland do not fit this explanation. Their administrative staffing ratios may reflect scale diseconomies of larger agencies.

Baltimore's staffing plan calls for no additional staff classified as purely general administrative; St. Louis' projects six employees in the operations division not assigned to transportation or maintenance. The difference may in part reflect the fact that Baltimore already has a functioning heavy rail division. St. Louis' administrative staff would represent 4.7 percent of the positions in the rail organization.

CONCLUSIONS

Staffing ratios, as reported in the last few years, appear to be somewhat more stable for individual systems than in the first years of the Section 15 program. However, the newer systems are still growing, and staffing may be expected to change as systems expand, fleets age, and new arrangements for contracting out services are attempted. The LRT systems of the United States are still a very varied lot in their staffing patterns and their needs, and are likely to remain so over time.

Although the overall quality of Section 15 data has improved somewhat in the past few years, the anomalies identified in the course of research suggest that there is still room for error and misinterpretation. It remains important for users of Section 15 data to inquire further as to the reasons for seemingly major differences in productivity measures among properties. All the reasons that have been cited, such as contracting-out decisions, the size of the LRT operation, and where it fits in a larger organization, the stage of development of the LRT service—and more—may be valid explanations for seemingly drastic differences among properties.

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Training for Success and Cost-Effectiveness in LRT

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Many factors influence the success of a new or rehabilitated light rail transit (LRT) operation. These range from car procurement, facilities construction, and infrastructure design to personnel selection and must be integrated for smooth and efficient system operation. One aspect, however, serves as the catalyst to ensure the best possible odds for system safety, success, and cost-effectiveness. That factor is training. Training efforts, both before start-up and delivery and during ongoing operations have a direct impact on safety, operational success, quality, and customer satisfaction—and the expenditures that result from inadequate or ineffective training. Training specifications, contractor liaison, instructor selection and qualification, course presentation, and evaluation and follow-up are important for both emerging and existing systems. Specific challenges are involved with start up of a rail operation from an existing "bus only" system.

Eavesdrop on a conversation on a new rail start-up and invariably financial issues, the need for community involvement, the place of federal, state, and local government, and labor concerns are mentioned, especially if the system is an adjunct to an existing bus system. Include in the discussion those people involved in the engineering, design, and construction of the system, and immediately visions are conjured up of shiny new cars, ribbons of steel rail, webs of overhead, state-of-the-art command and control systems, and facilities to handle every maintenance requirement.

Press a little and the talk will veer to the essential role of system safety, personnel needs, customer service, management information systems (MIS), and so on. But rarely does one aspect come up immediately even though it is one that ties together so many of these considerations and has a direct impact on them—training.

Why is training such an afterthought, an adjunct to primary efforts? Maybe because many people involved in light rail transit (LRT) start-ups or operations have not previously had the opportunity to witness just how crucial training really is.

Perhaps the stage can be set by the following questions: Which one common element directly bears on how well operators use those new cars, or mechanics maintain them, or support personnel troubleshoot and rectify system problems on line, power, signals, and overhead components? Or, on how satisfied customers are about the way they are treated in face-to-face moments of truth with the system? Or on how the public, press, and officials perceive the success or failure of their investment in the system? Or on how safely or cost-effectively both contract and management employees carry out their assignments in a quality manner? Again training is the one commonality.

PREOPERATION

For any of these suggestions to be viable, the newborn rail organization must be imbued with an understanding of and commitment to the importance and role of training. While these perspectives may be shared and supported by the senior management team, insinuating them into the systems approach can be helped considerably by employing at a very early stage an individual with transit management and operations experience as well as training expertise.

Such an operational background will greatly assist the selected individual in both integrating the training efforts with the overall system needs and selling training to fellow team members who are focused on other priorities. This professional must, of course, be well versed in the principles of training, adult learning theory, course design and construction, evaluation techniques, creative use of audiovisual and training aids, and effective interpersonal skills. Do not just settle for someone who was a good "train operator" elsewhere. Recruitment may be facilitated by seeking an individual with a safety/training background, because at many properties these two disciplines are intertwined.

Do not look for someone who will simply write lesson plans and produce slides and graphs. Choose an individual who understands his/her role as an advocate and catalyst, who can appreciate the system view and needs, and advance creative and innovative ways of training designed to support *all* system elements. He or she should also be excited about light rail transit (LRT). Because many other key personnel will be focused on specific system aspects, look at the trainer as a honey bee, flitting from one area to another, pollinating as he/she goes and providing cross-fertilization that may not otherwise be done. Having the trainer serve in these roles can produce unexpected results.

Indoctrinate the trainer immediately in the various aspects and considerations of the system design, so he/she has a thorough understanding of what training must support. Involve the trainer in the design of the operating plan—he/she will not only be able to provide meaningful contributions, but will also structure the training for the environment in which it will meet its true test.

Develop a training plan, and ensure it has sections for the following audiences: train operators, line supervisors, control center personnel, vehicle maintainers and supervisors, infrastructure technicians, and general management. Ensure that

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the last group includes support staff such as public relations, operational planning, customer service, claims, and labor relations personnel. Without training and an understanding of the basics of car and system operation, none of these people can do their jobs effectively once the system is carrying passengers.

Write specifications for the training to be given to each of these groups and decide if the training will be done by the manufacturers and suppliers, consultants, or in-house staff. Outside training that is inadequate or inappropriate may occur if objectives and expectations are not fully detailed. But provide a detailed specification and most contractors will say they have never had to do it that way because no one has ever asked. You'll get what you ask for.

Remember that most bids give training short shrift if the training spec is vague or incomplete, because the bidder will interpret that as a lack of importance and devote few dollars to the area. Attempting to get more or better training after the contract is signed is difficult.

Ensure that the training spec includes sections on who pays for which training-related expenses (course development, instructors, handouts and manuals, classroom needs, participant salaries); scope of training (classroom, practical work, and follow-up); objectives to be reached; course content; training plan submission and approval requirements, format, and dates; instructor qualifications; training aids and equipment and their disposition after training is completed; training materials; training facilities (who provides) and locations; hours and days of the week of training; pilot course procedures; safety; course listings and lengths; schedules for individual course design, approval, presentation, and updating; the numbers to be trained in each type of course, the number of sessions for each course, and a parameter on course duration. Final course length should be determined after vendor submissions are examined.

If the project is not too far along, seek a modification to funding line items to pay for salaries of those attending training sessions. This can avoid a substantial hit on the operating budget.

Begin early to develop the template for computerizing training attendance. Without it trying to keep track of who went to what course when becomes hopeless. This information is essential not only to ensure everyone is eventually trained in what they need, but also as a basis for refresher and retraining efforts. It can also be helpful in grievance or arbitration cases in which performance because of an alleged lack of knowledge or training is an issue.

Spend time shortly after bid award briefing the contractor on training procedures and clarifications of the spec requirements. Do not assume that the contractor read the spec the way it was intended. Press the contractor to have a full-time person responsible for training and to have it be someone who knows what effective training requires. Most suppliers and builders will try to use a tech rep who knows the equipment but not necessarily how to instruct groups on its use. If the spec was tight enough in this area, suggest they consider subcontracting the training. But be careful. The subcontractor may know how to teach but may not be sufficiently familiar with the equipment. If the training is subcontracted, make it clear to the prime contractor that it is the prime contractor who is responsible for reaching training objectives.

Work out an early understanding with the prime contractor as to its responsibility for the quality control of subcontractors. Dealing with many different suppliers or contractors is undesirable—deal only with the primary contractor. Establish that the requirements in the spec apply equally to the subcontractors, but be aware that they will be much harder to enforce.

Make a decision early as to whether the contractor will teach everyone, or focus on the LRT system's operations and maintenance instructors who in turn will do the bulk of the training. The latter approach allows company policies and procedures that the vendor is unfamiliar with to be incorporated in the training. It also fosters good student/instructor relationships that are essential in later follow-up and begins development lesson plans, handouts, and so on that will be used when the contractor is gone.

One essential to quality training is the use of a pilot session for each course after vendor's training plan, objectives, and course content (lesson plans, slides, transparencies, training aids, etc.) have been approved. Conduct one session for evaluation. Select the attendees carefully. They should be from a variety of departments and organizational levels (dependent upon the course in question) and discerning enough to give detailed, critical comments, not just on course content but on course conduct. Each pilot will help ensure that safety is being sufficiently stressed.

Schedule the pilot session with a sufficient gap (1 to 2 weeks) between it and the first production course to allow time to gather comments, meet with the vendor and pass on necessary changes, and still give the vendor realistic time to incorporate and rehearse the changes. Follow up to ensure pilot session attendees get any new or updated information.

By the way, as part of the pre-presentation checkout of what is to be taught, review actual handouts, slides, and transparencies for readability, size, content, spelling, grammar, and so on. Many suppliers will try to cut corners by extracting pages from tech manuals for handouts or slides without modifying them. These are rarely acceptable. Also, make sure (in line with the spec requirement) that all material is specifically relevant to the actual system in question, not to what the vendor previously provided to another property, which may or may not have the same equipment. Much credibility is gained when employees see their logo and system in the materials.

Once the changes resulting from the pilot session are incorporated, do not relax. Continue spot monitoring of successive courses, utilize and review written course comment sheets for all attendees, and talk one-on-one with some participants from each session. Be alert to problems and give feedback to the trainers or vendors. If problems are not corrected, do not hesitate to link further equipment deliveries and payments to corrective action. Such action will quickly get the vendor's attention.

If in-house trainers will conduct the bulk of training after they are instructed, have the vendor's lesson plans customized to include the LRT system's procedures, format, and so on. That takes some time and requires the help of an individual adept at both training program design and the system's operating plan and procedures.

It is very important that trainers remain in the loop during system acquisition and construction. They should routinely attend project meetings and updates, be part of factory visitation and inspection teams, receive change orders and meeting minutes, and so forth.

Schedule training as close as possible to actual commencement of the operation involved. There is a sliding scale; the more people to be trained, the earlier training must start; but conversely, the more material to be presented the more the earliest trained people will forget. Some formal or informal refresher training may be needed at the last minute before operation commences. The better the original training adhered to the three-stage instructional model of presentation (tell and show), application (have student practice), and evaluation (test by oral, written, and practical means), the longer the retention curve will be.

As employees begin using what they learned, do systematic follow-up. This will not only ensure they are not reinforcing their learning the wrong way, but also help pinpoint problems in the equipment or procedures. Establish a feedback loop to get this information to the engineers and designers quickly so it can be acted on.

Trainers are excellent candidates for carrying out acceptance and in-service tests. Once the manufacturer and system staff have accepted a piece of equipment, let the trainers put it through its paces with a checklist of items of most concern to the operator and passengers. They will catch some surprising things before the equipment goes in service. They will also be more effective if they make a plant visit during construction.

If a pilot car is put in test service (which I strongly recommend), ensure that operators are specially selected and are accompanied by instructors. The instructors will not only spot problems, but they can also conduct passenger surveys and act as public relations agents. The instructors will become operational experts and representatives for the operations department.

Wherever possible, before start-up and as part of the training experience, conduct simulated operations. The key is to make the simulations as realistic as possible. Running empty trains randomly up and down the line proves very little. Doing it on a schedule, with required stops, door cycling, and so on, not only tests the operator, but exercises the equipment, proves the validity of the schedule, and flushes out kinks in car components, fare collection system, signal systems, procedures, operator knowledge, and so on. This is an excellent way to minimize opening week problems and ensure system safety.

Remember that simulated service should not be limited to on-the-line operation, but should run through car washers, conducting inspections, sanding, and so forth. A true test of whether the system is ready would be a 2-day full simulation exercise before opening in which bugs are introduced into the system to test reaction time. These bugs can be real or simulated and can range from accidents to equipment failure to improper troubleshooting that spirals into more problems. Again, such a simulation not only minimizes service interruptions, but also ensures the highest reasonable level of safety. Remember, nothing is learned when the system is running well; learning occurs only when it isn't. Do not wait for the first learning experience to be with fare paying passengers.

If at all possible, conduct some limited runs with live passengers *before* start-up. If liability prevents the use of real passengers, use staff people to play the role.

Provide for thorough documentation of what is taught with detailed lesson plans and handouts, and incorporate a procedure for updating those previously trained with system changes and enhancements.

The selection of operating personnel has a major impact on training effectiveness. The better the selection, the easier the learning. Remember that those trained are a valuable source of feedback on equipment problems and flaws—encourage them and provide them with a mechanism to volunteer that feedback.

TRAINING DURING OPERATIONS

The temptation exists to downplay the importance of further training once the initial courses are all given, but that approach can be a serious mistake. First, a strategy has to be in place to disseminate information on modifications that invariably follow start-up. These modifications change the way equipment is operated and maintained and have a ripple effect on already published rules and procedures.

The challenge is to effect both the reinstruction of employees and supervisors *and* the distribution of documentation. For uncomplicated modifications, this might be done appropriately with just handouts. More complex changes may require informal explanation and handouts by instructors when employees report for work, or calling workers back to formal training and paying them.

Second, some employees may not have grasped their initial instruction, or their performance may not be up to standard. These people may require counseling by their supervisors, follow-up by an instructor, or one-on-one reinstruction. The last should usually start with on-the-job observation by the instructor and a review of the employee's record to pinpoint the exact problem, followed by customized retraining. This is especially important for postaccident training.

Third, extended absenteeism because of illness, injury, and so on, may warrant some level of retraining before the employee returns to work. Because of labor relations implications, this issue needs early input and resolution by medical staff, the labor relations department, and the union.

Fourth, make an early decision and commitment to mandated refresher training. One approach is to do it initially after 1 year of operation (to pass on the learning experiences) and biannually thereafter. This could take the form of 1 day training in core subjects that are to be repeated in every refresher program (such as emergency procedures, safety, customer relations, etc.) and other topics that change from program to program. These latter topics can address issues that have become high priority since the last program.

Remember that the presentation of training to experienced employees must be more challenging and less straight instruction, because these employees will tend to think they know it all. One approach is to use performance tests at the beginning of the day to get their attention and show what areas of weakness the instructor must focus on.

Fifth, special training programs may be needed at any time to focus on problems performance indicators have revealed. Just ensure that input on and commitment to the solutions to be taught are obtained *before* the training begins.

Finally, devise a system of follow-up tests and checks. Instructors and supervisors should regularly ride the system and observe and report on operator performance. These rides should be both uniformed and undercover (plainclothes). The system should ensure every operator gets a certain number of rides per year, and that immediate rides are taken for operators involved in accidents or public complaints.

Tests and checks should be done through wayside observation and monitoring devices for signal adherence, railroad crossing procedures (if applicable), carrying of required equipment, and so on. These not only ensure safety and reinforce training but help highlight employees who need special help.

RAIL START-UPS FROM BUS-ONLY SYSTEMS

Starting a rail system where a bus operation already exists poses some unique training considerations that will most likely need to be addressed in the context of labor agreements. Two decisions that need to be made very early are whether train operators will come from the ranks of the bus operators or be hired from outside, and whether the light rail management and supervisors will come from the bus organization or from outside.

Each option has pros and cons, and no one can definitely say which is better. However, adequate attention to the issues will ensure that the chosen direction is the best one, not only for start-up but for long-term operation.

Taking train operators from bus drivers' ranks has the following advantages *if* they are selected based on work performance and record first and seniority second—and not on seniority alone:

1. They will be proven, good-quality employees who, by their nature, will enhance the success of the operation.
2. This option provides growth opportunity and motivation to current employees, especially because train operation is generally viewed as more desirable than bus operation.
3. Recruiting costs and time are substantially reduced.
4. Union-related issues may be more easily resolved.
5. These employees already have a familiarity with company rules, personnel, procedures, and so on.

The cons are that some bus operators may not easily adapt to the more high-tech environment of light rail. Some prescreening and performance tests before selection for training help ease this situation. Further, if seniority is the only selection guideline, the best people will not be chosen for the new positions.

On the other hand, selecting the management team from outside the bus company has advantages:

1. Supervising a rail system calls for different skills than for a bus system and a bus person will try to apply approaches from his/her bus experiences.
2. Drawing from the outside produces a broader pool of candidates from many sources (other systems, consultants, etc.) rather than from one—the bus company.
3. Outside people will tend to have had wider experience than those who have spent their careers in the bus company. This wider experience relates to everything from creativity and problem solving to knowledge of light rail techniques and practices elsewhere.

An aspect of outside hiring is the real need to establish a cohesive *team* of rail and bus managers very early to gain the benefits of an integrated transit service. Otherwise, an "us and them" attitude can quickly develop.

If bus managers are chosen for rail management, send them to several existing rail properties (not just one) for some in-depth training in car operation, maintenance, and system functioning. Also provide them with contacts at as many rail properties as possible and reference materials such as the proceedings reports from previous light rail conferences.

In seeking other properties to learn from, do not ignore the long-established systems. Although they may not have the glitz of the new systems, they generally run much more frequent headways and have to cope with a greater variety of service needs and interruptions. The people there will also have a long history of rail operations. Do not limit the field to the system that opened just before yours.

Finally, in setting up the training program, do not fall in the trap of mimicking bus operator training, which may not have been reviewed or overhauled for years. If anything, a fresh design for rail training should be a stimulus to review and update of the bus training program.

These training considerations are not all that must be looked at, but they will certainly ensure that a new LRT system gets off on the right track.

Preparation and Training for First-Time Light Rail Operations and Maintenance

D. L. MacDonald

Successful revenue operation of a new light rail system depends to a great extent upon adequate preparation and training of operational, maintenance, and service staffs. The importance of early involvement by key senior operating and maintenance personnel is emphasized so that operating and maintenance requirements appropriate to the particular transit agency will be defined and addressed in the new system's design criteria. Based on experiences of several new system start-ups, an outline has been drafted that may be followed to develop the necessary skills for effective operations and maintenance. If part or all of the operations or maintenance will be carried out under contract by outside forces, it is still important that a trained, core group of the transit agency staff be developed so that they may thoroughly understand the system and be capable of monitoring the contractors' activities in the interests of the transit agency. Practices with respect to preparation of rule books, training, qualification of operators, and periodic recertification are discussed, together with the opportunities to develop operators' skills and judgment during the prerevenue stage of "running in" and commissioning the system. Basic courses in electrical propulsion and subsystems may be arranged through technical colleges for maintenance personnel training before obtaining specific training from the suppliers for the equipment installed.

Implementation of a new light rail transit (LRT) system is the culmination of a lengthy and complex process involving planning, securing approvals and funding commitments, engineering, community relations and interaction, project management, contracting, procurement, construction, testing, and eventual acceptance of the works done. However, successful operation of the line will depend upon adequate preparation, staffing, and training of the people who will manage, operate, maintain, and service the new system.

Originally, public transit systems were primarily rail transit operations—streetcar, suburban and interurban systems—but through the 1930s and into the 1950s most of these operations were discontinued or converted to rubber-tired bus systems except for a few heavy rail systems, commuter lines, and surviving street railways. Unfortunately this meant that trained, experienced rail transit personnel were lost to the industry and now, with the renewed interest in light rail and to provide staff for the inauguration of new-start LRT lines, it is necessary to develop a new generation of rail transit staffs.

Several options are available to a transit agency embarking on a new-start LRT system—hiring key personnel from one of the established light rail operations or from the suppliers, contractors, or consultants engaged in building their project (or perhaps outside specialists in train operating rules, signaling, trackwork, or electrification from a railway or electric utility company); or training their own staff in preparation for the opening of revenue service. Whether it is better or more satisfactory to train the technically competent "outsider" in the practices, procedures, and nuances of the local transit operation or to train experienced "inside" transit staff to the necessary levels of technical expertise can be argued at length and may ultimately be governed by local factors (such as a union agreement, the complexity of the equipment, a design, build, operate turnkey-type contract for the system, etc.). It is to the option of training and developing suitable expertise within the transit agency's own staff and thereby increasing the pool of skilled rail transit personnel that this paper is addressed.

It is difficult to determine the proper timing for establishing the initial light rail operating organization. Until the actual decisions to proceed with the light rail project are in place the planning process will likely be lengthy and often frustrating, particularly to operations-oriented staff who are geared to handle day-to-day activities and used to experiencing immediate results. Nevertheless it is extremely important that someone familiar with the local transit operations of the system and the community should become involved in the planning process from the outset (normally on a part-time basis) so that the line is planned as an integral part of the whole. As the plans are developed the operational needs and maintenance requirements should be carefully addressed. The early preparation of a draft operating plan is most important in this context. This draft should outline local considerations of hours of operation and policy headways desired, feeder bus connection points, timings and access routes to proposed stations, potential park-and-ride sites (and their servicing for security, lighting, snow removal, clean up, etc.), desired storage and turnback track locations, train crew relief and amenity points, resources and strategies to cope with emergencies, opportunities to integrate the light rail central control functions with those for the bus operations, as well as for certain maintenance and repair work that might be shared between the light rail and the bus shops (such as seats and upholstery, radios, and other common or similar "unit repair" components).

Such a plan can then be used to prepare initial design criteria for the proposed new LRT system and, of equal importance, the interaction with the various departments and groups involved provides excellent opportunities to introduce them to the concepts of the proposed system. Some particular security risks or locales may be identified and avoided or at least mitigated (such as by moving a station to avoid a potentially troublesome location or placing a station in conjunction with a neighborhood police precinct station as in

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Philadelphia's Penn Center). Local experience drawn from the maintenance of the bus fleet can also be useful in preparing some of the preliminary design criteria and specifications with respect to the auxiliary systems for the light rail vehicles. Although the primary systems in modern light rail equipment (e.g., propulsion, braking, lighting, ventilation, etc.) tend to be highly reliable, it is often the door systems, for example, that are more likely to cause service interruptions and extraordinary maintenance (particularly if they are sensitive and vulnerable to severe weather conditions—problems which may have already been experienced and solved in the bus fleet). In this way relatively minor changes in the designs and specifications can be incorporated that will enhance the operational features of the system in the local environment.

APPROACHING THE INITIAL ORGANIZATION

The primary qualifications for the lead LRT project person are experience and knowledge of the transit agency and its operations, adaptability to changes, enthusiasm for the project and the ability to generate enthusiasm in others, a sense of vision, and, lastly but by no means least, a great supply of patience. Familiarity with light rail equipment and operations can be acquired, usually through visits to several established light rail operating systems and discussions with their operating and maintenance staffs. In addition supplementary expertise is available through peer reviews, that is, bringing in groups of experienced practitioners from other operating LRT agencies at key milestones during the design and implementation schedule to provide invaluable assistance in avoiding problems and pitfalls encountered elsewhere.

Once the decisions and funding are established then the preparation and initiation of an appropriate operating organization should commence, even though there will likely be a relatively tight budget and time constraints. The organization for the project may take several forms—the transit agency may or may not be the agency designated as responsible for the planning function, the direction of the engineering, or the construction or procurement of the system. And it may have been decided that the future light rail system would be operated or maintained either in whole or in part by contracted forces. In any case it is important, indeed essential, to the success of the project that the transit agency develop as a minimum a knowledgeable core group of senior personnel familiar with the local operations and maintenance practices of the agency at the earliest stages of the design when the criteria are being drawn up and reviewed. The members of this group will be able to contribute their knowledge and experience to the design and engineering process while at the same time becoming knowledgeable about the proposed new system and the reasoning leading to the choice of various details.

Their colleagues in other operating light rail systems will be found to share their own experiences willingly and, through technically oriented trips to those properties, these core personnel will gain useful information about not only features that should be included in the designs but also about some that should be avoided. The information so gained can be applied throughout the development of the designs to simplify and make certain operations less critical, safer, or to facilitate future maintenance or servicing of the system (for example, in the operating rules and procedures, maintainers' safety while working on the line, shop and yard layouts, and the like).

As a further benefit, exposure to the engineering of the systems from the beginning will make the subsequent details much more easily understood during their development.

In some cases "internships" have been arranged to place selected operating and maintenance managers or supervisors in on-the-job training at one of the established light rail operating agencies.

About the time when equipment procurement contracts are awarded the formal training of the LRT operating and maintenance staffs should be under way.

MAINTENANCE PERSONNEL TRAINING

Maintenance personnel for the light rail vehicles, whether recruited from within the transit agency or from outside, will require uniform, basic, formal training in electrical circuits, devices, and controls; instruments and their proper use; safety and applicable code requirements. This training must relate to both high-power, traction voltage and to lower voltage auxiliary power equipment. Appropriate courses can be arranged through community or technical colleges or institutes, which should be contacted early enough to give them sufficient lead time to organize and set up such courses. These can take the form of night classes, part-time day classes, or more intensive semester-type sessions, depending upon the availability of instructors and facilities and arrangements made with respect to the students' time and remuneration (if any).

Satisfactory completion of such courses (or, possibly, approved equivalents) would be required as a prerequisite for the detailed, specific instruction provided by the manufacturers and suppliers on their equipment (which should be covered under their various procurement contracts as awarded). This level of instruction would include specific details on the various systems and interfaces, connections, and so forth, and their functions; testing and inspection; troubleshooting and diagnostic procedures; repair and overhaul methods. The manufacturing and testing of the system's equipment presents a valuable opportunity for key members of the maintenance staff to visit the manufacturers' shops to observe the construction, the shop facilities and testing equipment, and perhaps to participate in the activities there. Such opportunities give key staff the chance to gain hands-on familiarity with their future equipment. Finally, even though the manufacturers' representatives will be responsible for the adjustment, troubleshooting, and repair of their equipment as it is delivered, "run in," and commissioned, and for making good early failures and repairs under warranties, full and complete explanations should be forthcoming from the supplier about causes and their remedies or the modifications made to complement the staff's knowledge of their equipment. It is vital that all repairs and modifications be properly documented and in a form that enables all circuit diagrams, manuals (including parts catalogs) and service bulletins to be kept up to date and readily available to the maintenance staff for reference.

It should be noted that where the maintenance is planned to be carried out under contract it is still necessary to train key maintenance personnel to ensure that they will be able to monitor the contractor's work for adherence to the transit agency's standards and to see that the agency's best interests are being protected.

Shop Staff

Normally the need for a shop support staff during the early years of a new system's operation will be only slight and can quite possibly be supplied for the most part on an "as needed" basis from the transit agency's bus shops (for example, the services of welders, body workers, painters, upholsterers, etc.). The exception is a machinist qualified to operate a wheel lathe, which will probably see a lot of use at the outset when braking systems are being properly adjusted and operators are likely to be applying emergency braking applications more frequently than after the new line and its operations settle in.

Track, Signals, Traction Power, Stations, Buildings, and Grounds

For an initial light rail line a minimum or skeleton track maintenance force can be used to adjust minor misalignments, adjust and service track switches, and generally inspect the trackage and the trackway. When major work, such as rail grinding and resurfacing, realignment and retamping of the track is necessary, this staff can be used to supervise the work of contractors who have the equipment available to handle these kinds of jobs more effectively than the agency would likely be able to, because the investment for such equipment is very high and its use would be infrequent. Such a staff would probably be best recruited from railroads or from the track-laying contractor who built the line.

Similarly the staff required to support the traction electrification power substations are specialized and best recruited from power utility personnel (or perhaps a contract could be established with the local power utility to look after the transit substations) who would receive specific instruction on the equipment and relays, settings, and so forth supplied. They would then be capable of performing the necessary periodic inspections, checking, cleaning, and making any subsequent adjustments for the system as required (possibly on a part-time basis, allowing them to be available for other work assignments).

Arrangements must also be made for a crew to inspect the trolley overhead system regularly and to repair damaged overhead (caused by overheight loads crossing the line, a defective pantograph snagging the trolley line, etc.) in as short a time as possible. Such a crew would also most likely be recruited from either electric power utility line crews, from the contractor building the overhead system, or possibly the local power utility might contract to do this work for the transit agency.

The signal system requires a signal maintainer skilled in handling either relay or solid-state circuits and performing the necessary periodic inspections, cleaning, and adjustments as specified by the supplier. This is also likely to take up only a portion of this worker's time, and it may be possible to include maintenance of the communication system (or at least the land-line [telephone] part of it) to the duties and responsibilities of this position.

Finally the maintenance and service crews for the stations, buildings and grounds, and ancillary equipment such as fare machines, fire systems, and so forth, would primarily be an extension of those performing substantially the same work for the transit agency at present, either as the transit agency's own force or through a contracted arrangement.

OPERATIONS PERSONNEL TRAINING

Training for operators starts with the production of a comprehensive rule book. This is normally composed of elements contained in the rule books of other successful light rail operations, suitably modified for the local system and situations. (The rule book will likely have to be reviewed and approved by the appropriate regulatory authority, where one exists, or by the agency's insurance firm for risk coverage). Classes for operators, supervisors, and control center staff candidates would then follow. This instruction would include the rule book, description of the light rail and vehicle systems and equipment, and their functions so that the operating staff would understand basic diagnoses of troubles, problem description reporting, procedures for working around failures, and the operators' part in protective measures for equipment. A thorough coverage of track switching is essential, because it has been the experience in other systems that most of the accidents in the early stages of a new rail operation occur through a lack of understanding of the basic function of track switching, switch fouling points, and clearance precautions necessary in yard curves.

Certification examinations would follow the instructional sessions. Subsequently hands on experience in operating and handling single and multiple car trains, towing "dead" cars, coping with simulated failures, judging speeds and stopping distances, and driving and braking on dry, wet, or greasy tracks would be practiced. These sessions should be conducted as the cars are delivered for "running in" the equipment, commissioning it, and for prerevenue service so that operating staffs can learn their skills without the pressures of maintaining schedules and dealing with passengers and peak hour traffic situations.

Similar training should also be a requirement for the maintenance and service staffs so that they will also be able to operate the trains safely and properly in the yards and shops.

CONTINGENCY AND EMERGENCY PLANS

Finally a series of plans to cope with contingencies and emergencies that may occur on the system (collisions, derailments, fires, traffic accidents and injuries, severe storms or natural disasters, and the like) must be prepared. These plans should be drawn up and tested through simulated events to demonstrate their effectiveness and to exercise the staff and the equipment procured for such situations. (Such exercises may even be required by the regulatory authorities, local fire,

TABLE 1 Project Activities and Functions

Project Activities	Staffing and Training Functions
Initial concept for a light rail system	Obtain and inform a leader who will sponsor and support light rail for the community
Planning—identifying corridors and potential routes; determining the most suitable "starter" line	Draw on the agency's senior department heads and their staffs for positive and negative effects on the existing transit system and community relations Identify an operating and maintenance coordinator-liaison person to work with the planners
(A peer review to comment on the proposed system layout, starter line, and next steps can be very useful at this point.)	
Preparation of preliminary engineering (PE) plans and draft environmental impact statement (DEIS)	Establish the core group from transit staff to provide comment and review as the plans develop
(A peer review at approximately the midpoint of PE can be very useful in noting significant points that may have been overlooked, reviewing estimates of patronage, costs, and so on.)	
Approval of PE plans and DEIS; commencement of final engineering	Appoint a full-time project manager from the transit agency and an assistant (with complementary operations and maintenance backgrounds)
[(Frequent reviews within the transit agency are extremely important during this stage, supplemented by several peer reviews (depending on the complexity of the project).]	
	Prepare LRT-bus service integration plans
Project approval; proceed with procurement and construction	Familiarize staff with the new system in detail by observation and inspection of the work being done Select and train maintenance staff, followed by operating staff, in time for deliveries, preparation, and testing of equipment
Testing, commissioning, acceptance and prerevenue service	Suppliers provide specific, detailed training Staff gains hands-on experience with the new system during this stage (under the contractor's direction and responsibility) Operating staff (in particular) become proficient in operating the system during prerevenue service
Revenue service	Operating supervision must be particularly vigilant during the early years of revenue operation to ensure that passengers become familiar with the system, that operators progress along a steep learning curve and do not become complacent and develop poor driving habits as they become used to the system Periodic exercises of emergency plans should be carried out; as well as periodic refresher classes and recertifications

police, and disaster agencies.) These exercises also build confidence in the new system and its staff. For the public at large, some of whom may be fearful of the new rail system because of reports of misadventures and accidents on some other rail systems, the exercises provide reassurance.

REQUALIFICATION AND RECERTIFICATIONS

A requirement to requalify and reexamine operators annually is usual and, in any case, it is good practice to do so. Periodic refresher courses should be conducted to keep operators up to date on any rule changes or changes to equipment or operating procedures. (It is a common practice to require operators to sign a master sheet declaring that they have read and understood rule and procedure changes as these are promulgated.)

The various contingency and emergency plans should also be exercised and reviewed periodically in the light of experience so that those concerned remain competent to deal with situations should they arise again.

It is also necessary to establish procedures to ensure that the light rail cars are properly tested and certified for return to service whenever major work or replacement of components vital to the safe operation of the trains has been done (such as insulation levels on the traction power circuits, operation of the train controls, any work on the braking system, and so forth).

CHRONOLOGICAL OUTLINE FOR STAFFING AND TRAINING

The uncertainties in the approvals process to launch a new LRT project preclude defining a reliable schedule for the transit agency's recruitment, selection, training, and staffing. Project functions associated with certain key project activities are outlined in Table 1.

Effective Utilization of Manpower and Innovative Approaches in the Work Force at San Diego Trolley

PETER TERESCHUCK

For over a decade, San Diego Trolley, Inc., has operated and maintained one of the most successful light rail transit (LRT) systems in the world. Although the primary attention with respect to success has focused on low-cost implementation and application of proven technology, the real success has been the ability to recover an average of 95 percent of operating costs from farebox revenue since service began. From the onset management implemented a series of broad-based job descriptions and maximized the use of contract labor for the purpose of retaining tight control over operating expenses. With initial success realized, the staff expanded this concept by coordinating with the San Diego County Probation Department and the California State Department of Corrections to initiate an innovative program of using persons assigned to "community services" by local courts and trusty prisoners to perform limited maintenance functions on the system. The broad range of manpower and other innovative approaches have enabled San Diego Trolley to attain financial objectives, which have resulted in maintaining a consistently high farebox recovery ratio.

In mid-1980, the Metropolitan Transit Development Board (MTDB) was nearing completion of the initial light rail transit (LRT) line along the South Bay corridor. This first segment extended some 16 mi and connected downtown San Diego with the community of San Ysidro at the United States/Mexico border.

As construction proceeded, the next significant decision for MTDB was who would operate the system. This would ultimately be one of the most significant decisions for the agency, and one that would have the most dramatic effect on the operating system in subsequent years. The decision was not an easy one as San Diego Transit Corporation was the predominant transit operating agency in the region at the time, albeit exclusively bus oriented, and was owned by the city of San Diego.

Because MTDB was essentially an agency created by the California state legislature and there were no existing laws mandating a regional transit operator, a number of interesting options were possible for the LRT operation. One option was to obtain a contract operator for the system; another was to create an operating entity as a wholly owned subsidiary of MTDB.

The first option was explored but was quickly rejected in deference to the second option when all preliminary bids were found to be nonresponsive to the required insurance elements contained in the bid package.

San Diego Trolley, Inc., 1255 Imperial Avenue, Suite 900, San Diego, Calif. 92101.

CORPORATE HISTORY

San Diego Trolley, Inc. (SDTI), a California nonprofit public benefit corporation, was formed in August 1980. Almost immediately thereafter, MTDB hired key staff for SDTI and developed what would ultimately become the foundation of a "philosophy for conducting operations." Because the entire project had applied a philosophy of using proven technology and low-cost implementation, it seemed appropriate to extend this to the operating entity as well.

Initial Staffing Plans

Perhaps the single most significant aspect of the new corporation was its ability to start with a "clean slate." The philosophy that applied included using a private business approach to an otherwise public enterprise. The objective was to create a lean organization in terms of staffing and to develop a scope of work within various job descriptions that would allow complete flexibility in assignment and generalized work tasks as opposed to descriptions that traditionally have narrow focus.

The net effect of this plan resulted in maximum flexibility for SDTI in terms of intra- and interdepartmental employee assignments. Furthermore broad job descriptions allowed the agency to keep the number of staff in the hourly category to an absolute minimum.

Expanding this philosophy further, it was determined by board action, that part-time employees would be incorporated into the employment structure and, to the extent possible, outside contractors should perform certain work assignments. Because SDTI was not encumbered with existing job descriptions that may have been overly restrictive as a result of negotiated union contracts, many of these initial plans were considered innovative at the time.

Job Classifications

In terms of job classifications a number of unique elements were applied. Unlike most traditional transit systems, SDTI used generalized terms (e.g., electromechanic, service person, lineman, etc.). These classifications provided enough flexibility to allow varied assignments without restriction. In the position of electromechanic, the classification provided the option of assigning an employee to electronic duties as well as mechanical activities without restriction. In the employment classification associated with light rail vehicle (LRV) maintenance, descriptions even required LRV operation for maintenance purposes within yard limits.

The category of service person likewise provided management with flexibility of assigning employees to a wide range of functions that associated with varied "service." Even the term "train operator," which represented a modest departure from titles associated with persons responsible for train operations, provided flexibility. In this category all employees were required to perform revenue service operation as well as yard service.

Furthermore each job description contained words to the effect that employees would be required to "perform such other work as required" by supervision. This provision allowed flexibility such that unusual or unanticipated tasks could be assigned to existing personnel without limitations normally associated with narrow job descriptions.

Part-Time Employment Classifications

This classification allowed SDTI to determine selectively to what degree part-time employees could be integrated with the employment structure. Employees in this classification typically receive only limited benefits including pro rata share of vacation and holiday benefits and uniform allowance, but no hospitalization or other benefits that customarily cost 25 to 35 percent of an employee's wage. This has resulted in SDTI incorporating a varying number of employees for partial work assignments (usually less than 30 hr per week) with 22 percent of the hourly work force in this category (Table 1).

Contract or Temporary Labor

The board of directors also established a policy to encourage staff to maximize the use of outside contract services and temporary employees. In the contract category, the board anticipated that use of outside contractors could best be applied to seasonal work tasks and specialized work (e.g., security, LRV body repair, etc.). The temporary classification could best be used by SDTI if it were necessary to develop occasional work for limited periods in which it would be more cost-effective to hire personnel, as opposed to the substantial effort associated with advertising contract work. Personnel in this category are hired for periods not to exceed 6 months.

TABLE 1 San Diego Trolley, Inc. Personnel Report, January 1992

	Actual	Authorized	Vacancies
	Summary Totals		
Total Company	290	270	(20)
Total Hourly	238	218	(20)
Full-Time	181	171	(10)
Part-Time	57	47	(10)

Note: The greatest pércentage of part-time employees are in the classification of train operator, slightly over 50%.

Labor Organization Considerations

SDTI operated for more than 5 years without an employee labor union. This provided an opportunity to carry out board policy that may have otherwise been restricted by a labor contract. In addition many of the unique employment categories sustained 5 years of policy, which established considerable precedent in terms of how business was conducted at the trolley.

The first labor agreement at SDTI was in effect on September 1, 1986. The agreement was between SDTI and the International Brotherhood of Electrical Workers (IBEW), Local 465, and covered all hourly employees. Although the IBEW was concerned about the use of contract labor and other unique categories, the union was successful only in setting certain limitations on the percentage of the work force that was part-time. This was primarily because negotiators focused their attention on finalizing an agreement as opposed to the considerable delays that would have resulted had they attempted to dismantle the involvement of private contractors involved with the day-to-day operation.

This situation has, over the years, been considered by many to be one of the primary reasons why SDTI has been able to keep operating costs down and to continue to incorporate unique employment categories into the regular operation of the system. Unlike other transit agencies, SDTI had flexibility that was a tremendous advantage for management in applying innovative options in the work force.

EXPANSION REQUIRES MORE EMPLOYMENT INNOVATION

Throughout the mid-1980s the trolley experienced considerable growth and expansion. The first extension was a 4-mi segment to Euclid Avenue in East San Diego in March 1986. The next was a further extension of the Euclid Line some 12 mi to El Cajon in June 1989. Before long the entire system had grown to a 34-mi LRT network incorporating two routes (Figure 1).

As the system grew, it became apparent that the expanded infrastructure would require substantially more maintenance activity in a wide range of categories and thus an expanded work force to perform these functions. This situation allowed SDTI to expand on the innovative employment categories that had been incorporated into the operating plan since revenue service began. However, because the management group at SDTI was sensitive to the potential negative effects on operating costs if the staff was expanded fully to accommodate the growth that was experienced, new opportunities were explored.

Creatively Expanding the Work Force

With limits placed on the operating budget, SDTI management began to explore ways to expand the available work force yet keep costs to a minimum.

In considering other options, it was observed that the California Department of Transportation (Caltrans) had for many years augmented its work force by using individuals convicted

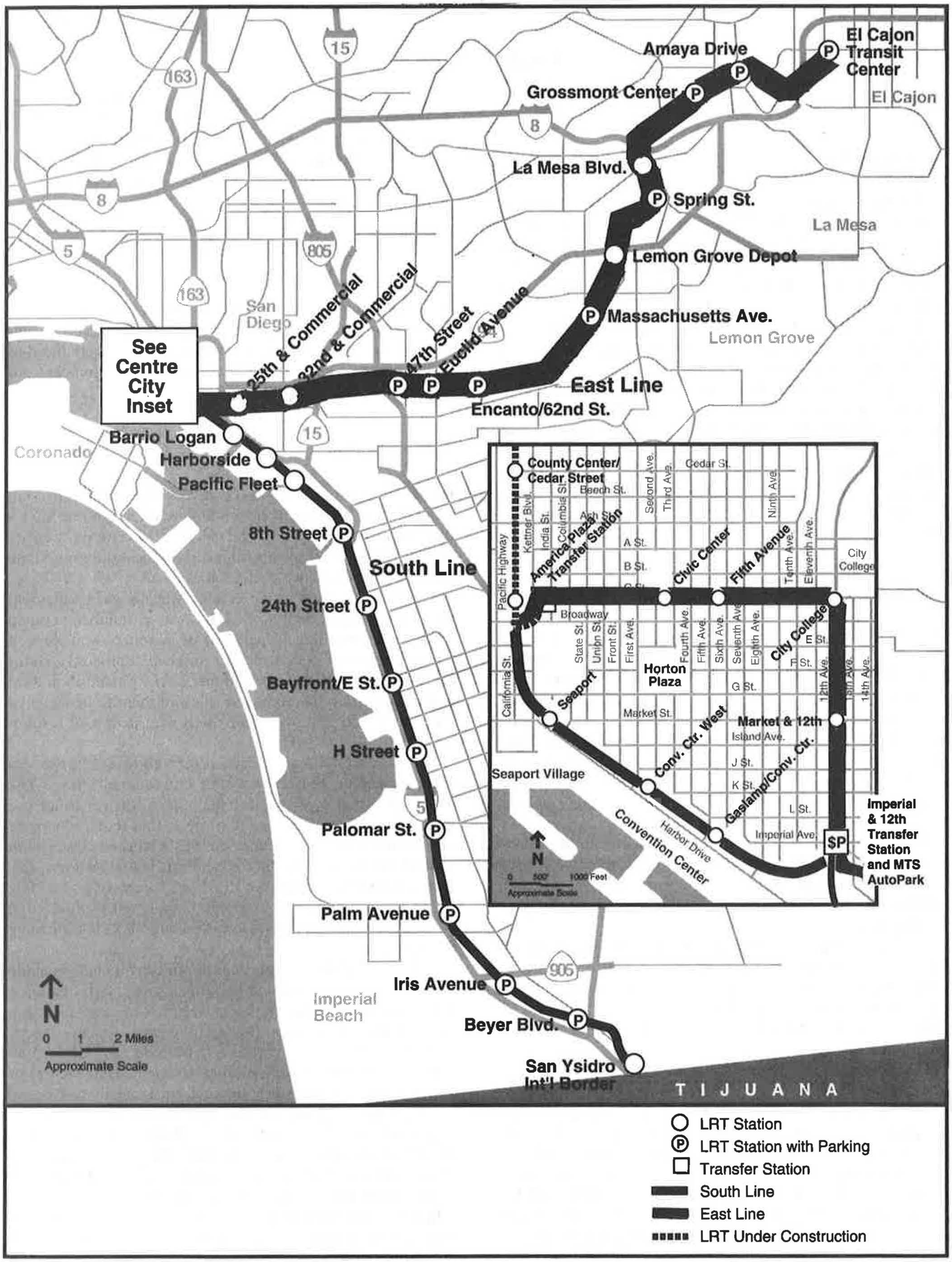

FIGURE 1 The San Diego Trolley south and east lines.

of minor traffic offenses and other infractions. SDTI implemented a successful pilot program with a local court that assigned a small work group to the trolley on a daily basis.

Local Court Workers

Under the arrangement with the South Bay Municipal Court, a small work force of 10 to 15 persons who had been convicted of minor offenses but could not pay the fine assessed were offered the chance to be assigned by the court to "community service" with the trolley as an alternative to serving a jail sentence.

The court-assigned workers report to the main SDTI maintenance facility each weekday morning. Under the general supervision of one of several facility supervisors, the workers are assigned to perform a wide range of light-duty work. These assignments typically include picking up debris at the main yard site, sweeping the shop, cleaning nearby stations, and so forth.

The amount of time an individual works at SDTI in this category depends on the court-assessed service time. It varies depending upon the offense but usually represents 24 to 40 hours.

San Diego County Probation Work Force

With the success of the original pilot program SDTI took the concept one step further. Management contacted the county of San Diego Probation Department and soon learned that an existing program was in place similar to SDTI's arrangement with the South Bay Municipal Court. This county program, however, involved persons who were assessed community service hours but who were also involved more serious offenses (e.g., child support violations, petty theft, vandalism, etc.) and thus required close monitoring and direct on-site supervision by a probation officer.

This represented a departure from the original pilot program as it required SDTI to compensate the county for costs associated with transportation of the workers to the site and supervision (the probation officer) for time they were performing service.

Despite these costs, it was still considered advantageous as the crew in this category was capable of performing more substantial work assignments and could be assigned to remote locations on the system. Because the advantages appeared to outweigh the disadvantages, the program was implemented on a trial basis.

The probation department worked closely with SDTI in terms of scheduling work and developing assignments. This resulted in a project list that represented several routine assignments (e.g., washing stations, weed abatement, etc.) and several small projects, including landscape improvements.

To date this program has been considered very successful. It has resulted in a daily work force (weekdays and weekends) of a minimum of 20 persons to a maximum of 50. Overall the comparable cost to SDTI would far exceed the annual amount incurred for a work force of equal size (Table 2).

Based on the comparison in Table 2, the probation work plan provides SDTI with a work force that is comparable to

TABLE 2 Annual Cost Comparison

Probation Plan	SDTI Comparable Cost
Monthly Cost = $9,000.	Annual Work Hours = 73,000
Aver. Daily Work Force = 25	*Full Time Equivalent = 35
Annual Cost = $108,000.	**Annual Cost = $977,412.
Annual Work Hours = 73,000	Cost/Hr/Empl. = $9.59
Est. Cost/Hr/Worker = $1.48.Hr.	

* Assumes 2080 annual hours
** Assumes 40% fringe benefits

35 full-time equivalent employees. The annual cost to SDTI for the plan represents only 10 percent of the cost for comparable services provided by employees if they were hired as replacements. This is clearly the single most significant advantage from programs such as these.

State Prison Plan

In the latter part of 1989, SDTI was approached by representatives from the R. J. Donovan State Correction Facility located near the South Line. The facility is a maximum security prison and houses criminals from various locations around the state who were convicted of felonies of all types.

The plan proposed by corrections officials was to augment SDTI's existing regular work force with a number of small teams (not exceeding 12 persons) of prisoners who were in the final stages of their sentences and had attained the status of trusty. Prisoners that attained this special classification were permitted certain freedoms that allowed them to be assigned office duty and otherwise be trusted with increased responsibility.

This plan would require each 12-person team of prisoners to be closely supervised by a state correctional officer. The other advantage was the fact that these trusties could use power tools and be assigned to projects that required a more substantial labor effort. Therefore SDTI worked closely with administration personnel at the state prison to develop a project list that included small construction projects (e.g., building retaining walls and more substantial landscaping efforts) and other labor-intensive tasks, such as waxing LRVs and cleaning the interiors.

The cost to SDTI was more substantial and included paying the full cost of the correctional officer's salary, providing a communication device (radio or telephone), and paying a nominal amount as an hourly wage for each prisoner assigned. (A portion of this hourly wage is allocated to the Crime Victims Fund, which is a local attempt to compensate victims of serious crimes with cash disbursements on a case-by-case basis.)

The program was implemented and SDTI currently has four 12-person teams. Because the work effort is more substantial, SDTI finds that there is considerable savings in terms of eliminating the use of outside contractors and other highly paid employees in new or higher-wage categories.

In some of the project work, the prison crew performs small construction-related tasks that had never been done before or required outside contract labor. Still others, such as LRV cleaning and waxing, had previously been performed by an outside contractor. In both cases it is easy to determine direct

TABLE 3 Cost and Other Comparisons

State Prison Plan	Contractor Plan
Aver. Mthly Billing = $20,110.	Aver. Mthly Billing = $32,340.
Aver. No. of Workers = 32	Aver. No. Workers = 12
Aver. Pay/Hour = $4.36	Aver. Pay/Hour = Unknown
Annual Cost = $241,320.	Annual Cost = $388,080.

Special Note: The average comparable wage in this category for an SDTI employee is $11.62/Hr. If SDTI were to hire 32 employees for comparable work per the Prison Plan the annual cost exclusive of fringe benefits is $773,427.

cost benefits to SDTI either by determining the hourly cost per worker or, as in the case of vehicle cleaning, a comparison with the previous contractor (Table 3).

HAVE THESE PLANS REALLY BENEFITED SDTI?

Based on experience to date, it is apparent that SDTI benefits significantly in terms of lowering operating costs and keeping the staff to a minimum. Figure 2 displays a breakdown, by category, of the SDTI annual budget. The personnel category is a modest 43.8 percent of the total budget. Also, 14.1 percent of the budget represents outside contractor participation, which is high by industry standards.

Other Factors

A number of cost-related categories measure the efficiency of an operating system. Two of these categories are cost per vehicle mile (CPVM) and the other is farebox recovery rate (FBRR). SDTI has, over the course of the past decade, retained an extremely low CPVM (Figure 3), averaging just $3.50. In the FBRR category, SDTI has maintained a 10-year average of recovering almost 90 percent of its operating costs

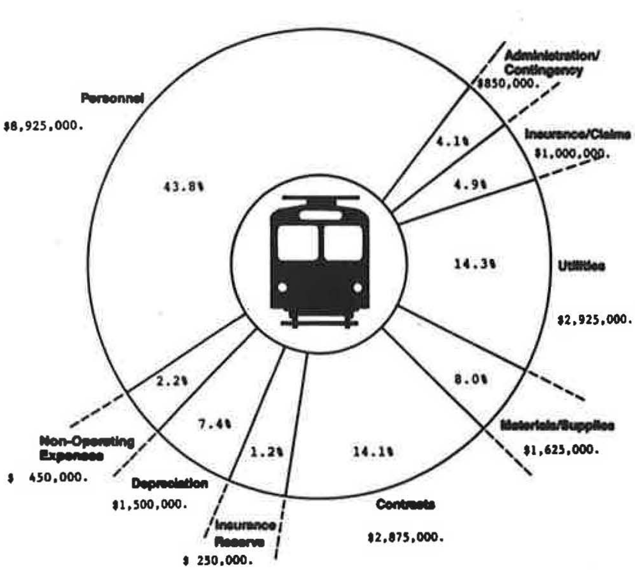

FIGURE 2 SDTI projected FY 92 operational expenses.

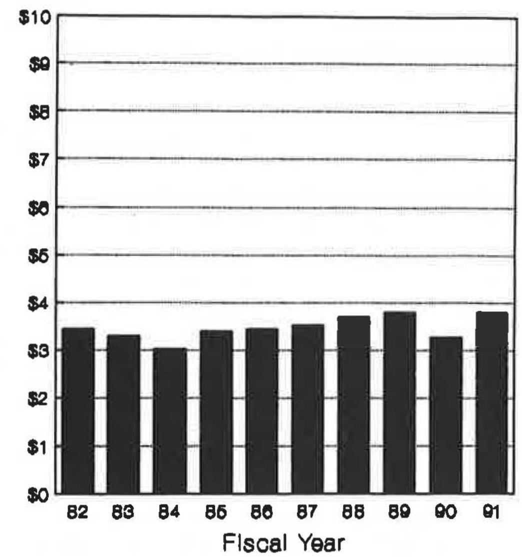

FIGURE 3 Cost per car mile, FY 82–FY 91.

from farebox revenue (Figure 4). Still other figures are equally impressive in support of the SDTI operating philosophy.

WHAT IS THE DOWN SIDE?

The programs initiated by SDTI provide an opportunity for increasing the work force and generating cost savings to an operating agency, but the potential for problems also exists if not adequately addressed.

Unlike regular employees, workers assigned to perform services because they are required to by local courts, probation agencies, or correctional facilities are clearly not highly motivated. Accordingly their activity and performance must be closely monitored to ensure compliance with safe practices

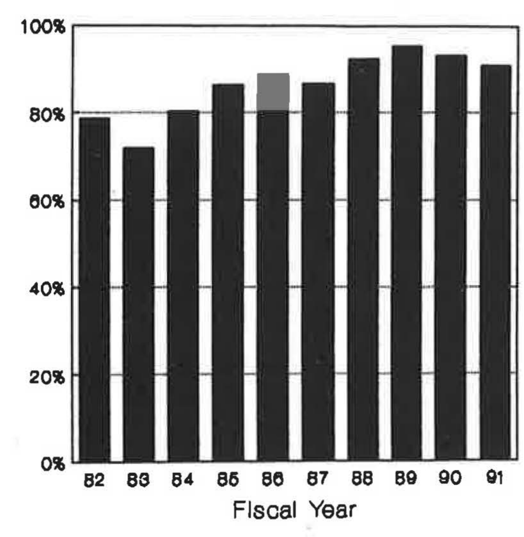

FIGURE 4 Annual farebox recovery rate, FY 82–FY 91.

and to provide oversight relative to the task assigned. In both cases, SDTI has had incidences in which participants in the program generated problems and appeared unwilling to work in a diligent manner.

The effect of these programs on regular agency employees must also be taken into account. Initially a number of employees expressed concern for their safety and security when they were performing work near individuals who were part of the prison assignment program. To date, however, no incidents involving agency employees have compromised their safety or security. Initially an occasional comment was made that was considered inappropriate, but the matter was handled by prison authorities and the individual was removed from the program immediately. Participants are advised in advance that any conduct that is inappropriate will result in a disciplinary hearing and will, in most cases, involve extended sentences.

Despite these factors, the isolated problems are not considered significant to the extent that the programs should not be continued. As with any program, a start-up phase requires corrective action and follow-up as situations present themselves.

CONCLUSIONS

It is clear that one of the most significant factors that enabled San Diego Trolley to achieve its objectives was the fact that the corporation was newly created. The "clean slate" allowed management complete latitude in terms of formulating policy and initiating a series of internal procedures that continue to pay large dividends today (*1*).

The organization, from the onset, was not encumbered by restrictive policies of an existing transit agency or limitations that were part of a labor contract. The management team established precedent and was allowed to be creative in developing unique solutions to some of the elements that have generated increased costs for transit agencies over the years.

Overall, however, it may be concluded that many of the elements applied at SDTI can potentially be duplicated at other transit agencies provided that labor contracts do not restrict using outside contractors and that state and local authorities incorporate community service or work release programs in their sentencing guidelines. Such guidelines empower authorities to initiate programs on the local level for the benefit of relieving jail overcrowding and providing an opportunity to have individuals exposed to responsible employment in the work force that they might not otherwise experience.

The more ambitious of these plans (i.e., that using state prison workers) remains relatively new and will require additional evaluation as the program matures to determine if the integrity and cost savings can withstand the test of time.

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PART 4
Design and Engineering

San Diego LRT System: Ten Years of Design Lessons

RICHARD D. THORPE

Ten years ago the San Diego light rail transit (LRT) system opened for business after 4 years of planning, design, and construction. The initial system included only the basics, a 15.9-mi (25.6-km) single-track line with three passing tracks operating at 20-min headways. The total vehicle fleet consisted of 14 light rail vehicles operating in two-car trains. Today the San Diego LRT system has undergone four separate expansions resulting in a doubling of the system to over 35 route-mi (56.3 km). Seven more mi (11.3 km) are under construction, with another 28 mi (45 km) in various stages of preliminary engineering and final design. By the year 2005 the overall system is expected to operate over 90 route-mi (144.8 km). Although the basic philosophy of low cost, high speed, and primarily at-grade is still the foundation of the design process, 10 years of design experience, together with changing socioeconomic conditions, have resulted in the design approach being modified to meet the needs of a rapidly expanding LRT system. Experience has taught lessons that have been incorporated in subsequent design efforts.

Ten years of expansion and operations have provided the San Diego light rail transit (LRT) system the opportunity to improve the design process based on experience. This process has undergone numerous modifications and refinements since its inception in 1978. However, the same basic philosophy that governed the original South Line design and construction is still used today. That philosophy was adopted by the Metropolitan Transit Development Board (MTDB) in its infancy in 1976 and is still MTDB's Board Policy No. 1 "Rail Transit Feasibility Principles (*1*)." This policy remains the backbone of MTDB's rail design efforts today. The principles contained within the policy include high-speed operation, low capital cost, primarily at-grade with exclusive right-of-way, low operating costs that farebox revenue attempts to meet, and, most importantly, use of service-proven equipment and materials.

Numerous design approaches could satisfy these basic principles. The approach selected for the South Line was developed on a bare-bones approach, offering single track with three separate passing trucks and simple, basic station amenities. However, this approach is no longer possible because of a variety of factors, including mandated state and federal regulations on seismic, air quality, and water quality conditions; varying socioeconomic needs; the MTDB and public being more demanding as the system expands; passengers expecting more amenities; and improved ride quality, security, and comfort. Thus the challenge has been to modify and improve MTDB's design approach yet still maintain the basic philosophy. The result has been a continual evaluation and updating of the basic design approach or design criteria to keep pace with these changing needs.

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LRT DESIGN CRITERIA

Fifteen years ago the MTDB considered doing something that no other city in the United States had done in more than 40 years, that was to construct an entirely new light rail system. This endeavor was the first such rail transit construction in Southern California since the streetcar days of the 1950s. The design approach used in the original design process relied upon a series of task design reports approved by the board at various workshops (*2,3,4*). When it was determined that MTDB would expand the system to the east (*5*), it was felt that a single document pulling together all the various task reports plus lessons learned from the South Line should be combined into one document. Thus in 1983 the MTDB directors adopted the San Diego Light Rail Transit East Urban Line Project Engineering Design Criteria (*6*). These criteria resulted in a very specific document related only to the East Urban Line extension. The document, therefore, addressed specific needs, such as how to redesign specific streets (i.e., Commercial Avenue) and how to handle joint freight and LRT use specific to certain shippers along that line. Future extensions, such as the Bayside Line (*7,8*), would also follow that format of revising the design criteria specifically for each new LRT extension.

However, as it became apparent that the system would continue to expand (see Figure 1), the idea of developing specific LRT design criteria for each extension was dropped in favor of developing a single set of criteria that would apply to all future San Diego LRT expansions. The goal of these newly revised LRT design criteria was primarily twofold. First, to standardize to the extent possible the design of future lines and, second, to leave the designer as much latitude as possible to address the unique aspects of each individual extension. These revised criteria were adopted by the MTDB directors on August 22, 1991 (*9*).

FACILITIES DESIGN

In reflecting over the many years of design, numerous things could have been done differently based upon today's knowledge. Although the goal of meeting the basic principles was reached successfully, lessons learned along the way should make the implementation of subsequent lines easier.

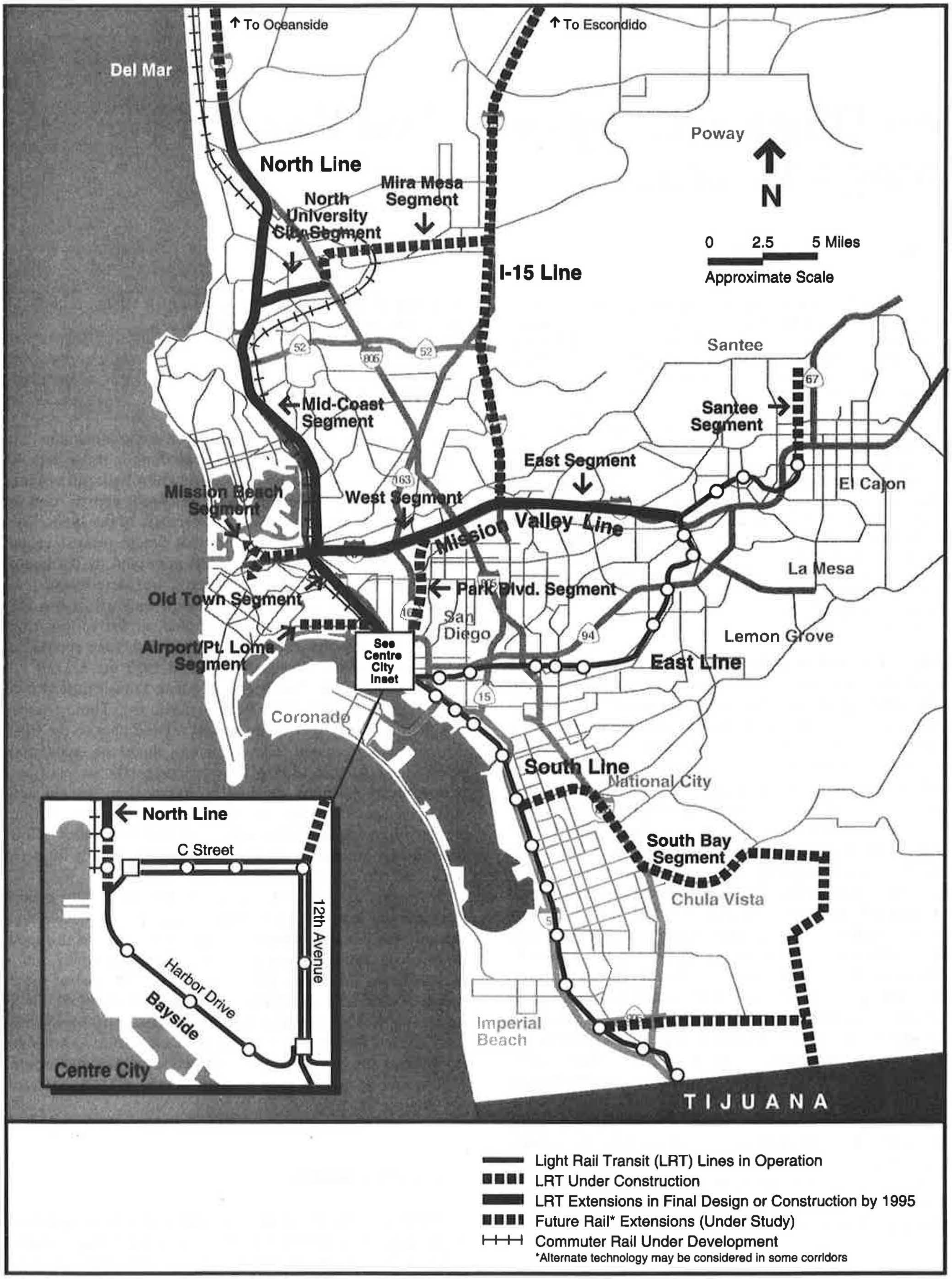

FIGURE 1 San Diego regional rail transit plan.

A prime example was the original decision to single-track the South Line and provide passing tracks where the trains were theoretically to meet. Although the concept and actual operation met with some success, a couple of important things were learned. The first, and probably most significant, was that the original design of the South Line did not contemplate double-tracking the line at a future date let alone under revenue service conditions. As a result, some major changes were necessary when it was decided that the South Line should be fully double-tracked.

A second major lesson from the South Line single-track operation was that, although such an operation does and can significantly lower the capital cost, a price is paid. Although detailed studies were performed in determining where the train meets would occur, actual operation did not follow theory. The result was that rather than operating 15-min headways on the South Line as originally planned, the operation had to be modified within weeks to accommodate a more realistic 20-min headway.

It was determined that one of the problems with precisely predicting train meets is that no two trolley operators are created equal—nor operate their trains the same. Because of these human differences, scheduled meets are almost impossible to predict accurately. However, the concept of single-track operations has not been abandoned totally by MTDB. An extension currently under construction, the Santee segment of the East Urban Line, will include a single track element near its terminal station.

For single-track operation to be successful, careful thought has to be given to the location of passing tracks, making sure to provide maximum operational flexibility whenever possible. For example, passing tracks should be extended through stations whenever possible. This feature allows a train to hold in a station while waiting for a single-track approach to clear. Also, passing tracks should be extended a significant distance beyond the theoretical meet point to allow maximum flexibility. On the East Urban Line, a 4-min allowance on either side of the scheduled meet point was provided.

Finally, and probably most importantly, any single-track operation should be designed ultimately to accommodate the second track. On the original South Line, there were significant problems with relocating substations, traction power poles, and other physical amenities because the original design did not take into account a future second track. This situation was corrected in the design of the East Urban Line. Although the East Urban Line was designed for single-track sections with passing tracks, the horizontal and verticle profile was also designed for both tracks. In fact the design went one step further, it included the construction of the embankment, crossovers instead of turnouts, and all associated civil improvements for the future second track. This initial construction avoided having to come back later under revenue operations to install major improvements close to an operating track. As it turned out, because of project cost savings, the East Urban Line was double-tracked prior to the beginning of revenue operations. Although single-track operations were never tested under this approach, the conversion to double-track during construction was certainly simplified by the process.

Another single-track feature that was a cost-saving measure was the use of existing structures. On the East Urban Line, three existing single-track bridges were used because double-tracking would have added more than $10 million to the overall project cost. In one instance, to provide maximum speed through the transition, a "gauntlet" was installed over one of the bridges. By installing the gauntlet, turnout facing points (determined to be the cause of the majority of the slowing) were eliminated. Instead only the frog was needed, allowing the operator to maintain a much higher speed through the transition area.

Another lesson was about the rail itself. Based on costs and the relative light weight of the vehicles, a consultant recommended that 90-lb (40.8-kg) rail be used. A heavier rail, such as 115-lb (52.2-kg) or 136-lb (61.7-kg), was thought to cost much more because of the significant increase in weight. Thus 90-lb (40.8-kg) rail was procured for the initial South Line operation. In preparation for the double-tracking of the South Line, it was learned that 90-lb (40.8-kg) rail was an odd size in little demand so the cost actually was the same as the heavier, more popular 115-lb (52.2-kg) rail. Because of the economies of scale, the 115-lb (52.2-kg) rail was acquired for essentially the same cost as that paid for the previous order of 90-lb (40.8-kg) rail. The special trackwork and rail have since been standardized to the more popular 115-lb (52.2-kg) rail. This standardization has not only resulted in significant cost savings, but relieved San Diego Trolley, Inc., maintenance personnel from having to stock as many spare parts (e.g., compromise joints, weld kits, etc.) and has generally simplified the overall maintenance process.

Finally there were various design options not originally taken advantage of either because they were technically not refined or were just too expensive at the time. However, in the past 10 years, the industry has made significant progress with new technology that still meets mandated service-proven requirements. An example would be the conversion from wood to concrete ties. Initially the low use of concrete ties in the industry resulted in a relatively high unit cost. Even though it was believed that concrete ties provided enhanced track stability, the high unit cost precluded their use. Now 10 years later, the cost of concrete ties has become more competitive with standard wood ties. As a result, MTDB today requires the use of concrete ties in all main-line applications in the design, except for special trackwork areas where the high cost of these special ties still dictates the use of wood ties.

Another example of cost and technology improvements changing MTDB's design approach would be the use of removable crossing material at grade crossings instead of cast-in-place concrete. Initially it was determined that cast-in-place concrete provided significant economic advantages over removal crossings, even though maintenance was more difficult. The initial evaluation was that the cast-in-place concrete provided a superior ride quality at a significantly lower cost. Again in the last 10 years significant gains have been in the use and technology of removable crossings, resulting in much lower costs. The cost and technology are now to the point where removable crossings justify consideration. Such consideration is especially applicable in open track areas where easily removable and replaceable crossings can reduce overall track maintenance costs. In paved street applications, cast-in-place concrete is still used by MTDB because of its lower cost, together with the less frequent track maintenance requirements for paved applications.

SYSTEMS DESIGN

In the systems area, lessons have been learned as well in the last 10 years. The first, and probably most significant, is the continued development of the traction power substations to be more economical, smaller, more powerful, and relatively easy to relocate. The desirability of these features rests with the resulting flexibility to interchange, relocate, and add new substations when necessary (*10*).

On the South Line, 11 low-capacity, 0.5-megawatt substations were installed. Their small size, 20 ft (6.1 m) by 23 ft (7.0 m), proved to be economical because they did not require significant additional land acquisition. When funds were granted for purchasing additional vehicles to handle growing patronage, 10 even smaller, 11 ft (3.4 m) by 25 ft (7.6 m), 1-megawatt substations were added to the system with relative ease and cost. These smaller, 1-megawatt substations can be easily picked up and moved by truck to wherever they are needed. This mobility has proven to be extremely beneficial because substations could be moved as necessary in the expansion of the overall system.

Additionally, the relatively small size makes it fairly easy to increase the capacity of the traction power system, in most cases without having to acquire additional right-of-way. For example, the overall LRT operation has gone from one line with two-car trains at 20-min headways in the downtown to two lines operating three-car trains with an average of 12 directional trains in the peak hour. Although this required a substantial increase in the traction power capacity in the downtown, the capacity was increased rather easily by adding units without having to acquire any new right-of-way. Likewise the same has happened in the yard area where the traction power capacity was designed to accommodate 14 vehicles. San Diego Trolley's fleet now has 71 vehicles with another 75 on order. The traction power capacity in the yard has been increased by substituting 1-megawatt substations in place of the 0.5-megawatt substations that were actually larger than their replacements.

When it comes to systems design, visual aesthetics have always been a significant design issue. One of the most significant problems in the public's eye is the visual impact of the overhead traction power system. This impact has been minimized in numerous ways in San Diego within the overall low-cost approach. Although the most visually appealing traction power system (i.e., an underground feeder system with a single contact wire) was used in the downtown area, this type of design has been avoided wherever possible because of the significantly higher overall cost.

On the South Line, outside of the downtown, a standard "full depth" catenary system is in place. The depth of the catenary ranges from 3.30 ft (1.11 m) to 1.10 ft (0.34 m). On the East Urban Line, because of the public's concern over visual impact, the designers developed a "low profile" catenary system. This system seemingly has a greater visual appeal than standard full depth catenary. Further the low profile design costs less than a single contact wire system in that it avoids the costly buried feeder system. The overall depth of this low profile catenary ranges from 1.50 ft (0.46 m) to 0.15 ft (0.05 m). The various cities along the East Urban Line agreed to allow this low profile system in their visually sensitive areas. The low profile has since become the standard design wherever visual concerns are identified.

Also, for aesthetic reasons, MTDB has gone to a standard traction power steel pole with the same outside diameter. For cost reasons on the original South Line, MTDB used a spun concrete pole. The outside diameter of the pole varied depending on the loads. Therefore on the South Line a number of different size poles give a cluttered, awkward look to the traction power system. Additionally those concrete poles were installed in a cast-in-place foundation. As a result, there was a complete loss of the traction power pole and foundation whenever any changes to the system were made. On the East Urban Line, MTDB used a standard cast-in-place foundation with a steel pole on a bolted foundation. Where a pole has failed, it has been a relatively simple procedure to replace it without losing the total investment in both the pole and foundation. The steel pole also allows the strength of the pole to be varied by changing the inside diameter, thus leaving a standard outside diameter and a uniform pole appearance throughout the system.

Proven technological advancements on the system's facilities have also resulted in improvements to the design approach. The most recent has been the addition of a train-to-wayside control system. This control system is being installed and, when complete, will provide for train location, automatic switching, electronic message boards at stations, and special signaling needs (i.e., nearside gate crossing hold-off and signal preemption where needed). The cost to install the system versus the overall benefits has become increasingly more attractive as the LRT operation grows. The current cost for installing this system on the existing 32 route-mi (51.5 km) is a little more than $1.5 million. This includes the cost to fit the vehicles with the vehicle transponders—a one-time investment that will not need to be duplicated on future extensions except for fitting any new vehicles.

Once the train-to-wayside control system is in operation, it will provide a relatively low-cost operational enhancement that will advise passengers at stations when trains are approaching and what route the train will be taking. Also, all switches will be thrown automatically for the specific train route, thus eliminating the basic route sequence controller. Additionally the implementation of the train-to-wayside control system will provide a low-cost train location system. When complete the location of all trains will be identified within the system automatically, eliminating the current reliance on radio communications. Finally the system will eliminate less reliable overhead mechanical switches that provide for vehicle traffic signal preemption and gate crossing hold-off control.

Alternatives to standard block signaling are also being explored by using train-to-wayside equipment. It is hoped that this approach will allow the existing train-to-wayside control system investment maximized by providing for simple LRT signaling on all future lines.

Finally, MTDB is in the midst of a sixth order of vehicles, with some significant changes to the unit's performance specifications. Although similar to the 71 existing vehicles in size and operation, a couple of key improvements have been made to the vehicle. Again in striving to meet the board's adopted principle of high speed, the new vehicles offer a power package that will provide approximately 25 percent more horsepower than the current vehicle. This added horsepower should provide for faster acceleration and a higher top-end speed. These power enhancements will become increasingly more important as the system expands into areas with steeper grades.

Additionally, the headways are at the point (i.e., 7.5-min on the South Line in the peak hours) where regenerative braking can start to provide significant power savings. Therefore all new vehicles will require regenerative braking. Thus savings will continue to increase as the system expands and headways are decreased.

CONCLUSIONS

The most important lessons learned by MTDB engineers in the past 10 years are those of standardization and incremental development. The more standardized the system is, the more economies of scale that can be gained along with reductions in inventory for spare parts and ease of maintenance. Standardization becomes more important as the system expands, allowing even greater cost savings as a result of economies of scale.

The incremental approach has provided the opportunity to refine the design approach based on experience. Lessons learned during the implementation and operation of one line were subsequently applied to new lines. This has resulted in the steady improvement of the system over the years.

Additionally it is important to keep an open, flexible mind during the design process. Too many restrictions on the designer tend to stifle their creativity and problem solving abilities. Keep in mind that LRT by definition is extremely flexible and adaptive to many different environments. What works in one place does not necessarily work in another.

Also no matter how long one has been involved in rail transit development or operations, there is always room for improvement and lessons to be learned. MTDB engineers have been able to enhance their designs and improve San Diego Trolley's cost efficiencies by learning from local experience. To this end MTDB has instituted a policy that once a job is complete, all change orders are evaluated to determine what items in future designs can be modified or changed to avoid repeating similar changes.

Lastly MTDB's experience has shown that innovation has its merits, but it is advisable to first prove that something works before implementing it systemwide. MTDB has had great success with a service-proven philosophy. However, care must be taken not to exclude all innovations. Therefore it has been MTDB's policy to encourage new ideas, but to make sure they are carefully reviewed and service proven either on other systems or by demonstration on an existing line.

In summary it is amazing to think back over all the changes that MTDB has made in its design approach over the last 10-plus years. Yet with all the changes, the overall basic philosophy has been maintained and, above all, the successful operation for which San Diego Trolley has become known has been retained.

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Light Rail/Traffic Interface in Portland: The First Five Years

GERALD D. FOX

In 1986 a new 15-mi-long light rail transit (LRT) line began operating in Portland, serving a corridor between downtown and the eastern suburb of Gresham. This line uses a variety of rights-of-way, operating in city streets, in the median of a street, and on exclusive right-of-way. Of the intersections, 55 have traffic signals, 9 are gated, and 7 use stop signs to control cross traffic. The initial concepts that guided design of the light rail/traffic interface were drawn selectively from U.S. and European concepts with emphasis on adapting existing railroad and traffic control hardware to what were perceived as the needs of LRT. Since operations began, Tri-Met has closely monitored system safety and has developed remedial measures where accident patterns have been identified. Several potential problems were identified during design and fixed before revenue service started. These included the need for LRT traffic signal aspects that would not be misread by motorists, control of right turns on red, and the limitations of changeable message signs. A number of lessons can be drawn from the Portland experience. LRT can be inserted into the street network and operate harmoniously with other traffic, achieving increases in the people-moving capacity of the central area streets. For the most part, existing traffic signal hardware and control techniques can be adapted for light rail/traffic interface in a cost-effective manner. The closure of streets for construction and the changed configurations following construction offer the opportunity to rearrange traffic patterns to diminish the impact on traffic, particularly in central areas. And saving initial construction costs by compromising traffic design (for instance, by omitting a lightly used turn lane) must be weighed against possible future operating problems.

With a population of about 1.1 million, the Portland region is the largest urbanized area in Oregon. Public transportation in Portland is provided by the Tri-County Metropolitan Transportation District of Oregon, more commonly known as Tri-Met, which operates a fleet of some 450 buses and 26 light rail cars and carries about 55 million boarding trips per year.

In 1986 Tri-Met completed a light rail transit (LRT) line serving the corridor between the Portland central business district (CBD) and the eastern suburb of Gresham, a distance of about 15 mi. This line uses a variety of rights-of-way, including on-street operation (usually in reserved lanes), street medians, and segments of exclusive right-of-way, some of them grade separated.

The concepts that guided the design can now be reviewed from the vantage point of 5 years experience along with changes made to improve operations or safety. Much of this experience is being incorporated into Portland's second light rail line, the design of which is now in progress.

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DESIGN CONCEPTS

When the design of Portland's Banfield light rail project began in the early 1980s, little precedent for modern LRT in the United States existed. Tri-Met's initial design was developed by drawing selectively from U.S. and European examples of LRT and traffic control concepts, with particular emphasis on adapting existing railroad and traffic control hardware to the perceived needs of an LRT system. Because streetcars had not operated in Portland for 30 years, it was also necessary to develop a new regulatory framework to define the powers and responsibilities of the local jurisdictions and the state public utility commissioner.

Regulatory Context

Prior to the light rail project, state law specifically exempted transit agencies from regulation by the Oregon Public Utility Commission (OPUC) with the exception of rail grade crossings. The law was silent on how typical LRT configurations, such as traffic signal controlled intersections not found on railroads, should be designed and regulated. To resolve this issue, Tri-Met and the local jurisdictions worked with OPUC to develop amending legislation that defined how the various types of crossings used on LRT should be regulated. The amended legislation states that light rail grade crossings are regulated by OPUC in the same manner as railroad grade crossings *unless* the light rail line operates within and parallel to a street right-of-way and conventional traffic control devices are used. At such locations the crossings are subject to the local traffic jurisdiction. In effect, if the LRT operates as part of the general traffic circulation system, it is governed by the general traffic circulation regulations. If an LRT crossing operates like a railroad crossing, it is regulated by OPUC in the same manner as other rail crossings.

Preempt and Traffic Circulation

The traffic design developed around preempt policies specific to each segment of the line. On the suburban segment, where intersections are generally spaced (at about 0.25-mi intervals), the LRT operates with full priority over other traffic. Both gated and signalized intersections are used, depending on site configuration and design speed.

To insert the LRT into the relatively complex traffic network in the CBD with the least impact, it was necessary to integrate train movements into the existing traffic signal progressions to the greatest possible extent. So long as the train moves with the progression, it has very little impact on traffic. However, when it stops, it becomes disconnected from the progression. Under this design concept, a train must wait for the traffic signal progression before leaving a station but, once moving within the progression, can expect to reach the next station without stopping.

As in most metropolitan areas, the local traffic jurisdictions were concerned that street capacity not be lost or traffic delayed. Therefore an important design guideline was to preserve traffic flow and capacity to the greatest possible extent. Where LRT required a change in traffic patterns, localized traffic studies were made to predict the impact and develop mitigation measures. This approach overlooked one highly important consideration. The construction of the LRT required the affected streets be closed to through traffic for extended periods, often up to a year. This forced the modification of traffic flow patterns on alternative streets. After construction, the traffic that returned to the streets where LRT operates was only the traffic that found the reopened streets more convenient. Consequently much greater flexibility could probably have been used in designing the traffic circulation concept and greater advantage derived from LRT as a tool to promote traffic calming.

Traffic Signal Hardware

An early design policy was to equip all public vehicular crossings of LRT tracks with active traffic control devices that clearly assign right-of-way between the conflicting movements. This was later modified in the downtown area to allow stop sign control at a number of minor intersections where LRT operating speeds are low.

Throughout the design, simplicity of concept and operation, avoidance of unsafe failure modes (this is not the same as fail-safe), and the selective use of off-the-shelf equipment and hardware were guiding principles. Conventional traffic signal equipment and controllers were used at all intersections. Special lenses were used in regular signal heads where necessary. Consequently most spare parts can be obtained from the city or county traffic maintenance inventory.

Where LRT operates in a traffic environment, the LRT signals at intersections are generally visible to motorists. Because the LRT signals often indicate a movement in conflict with traffic, it was very important that the LRT signals not confuse drivers. In particular it was felt that red/green signals should be avoided, even with special shapes, because a driver with less than perfect vision may not readily distinguish a blurred T or arrow signal from a round one. Signage to indicate special meanings is not reliably obeyed and should be avoided where possible. Programmed visibility heads can get out of adjustment, resulting in confusion. Therefore white bar signals, which are meaningless to motorists, were adopted. The LRT proceed signal is a vertical white bar; the LRT stop signal is a horizontal white bar. The horizontal bar was later converted to yellow to assist train operators. The use of colors that do not trigger a reaction by motorists was considered an important safety consideration and also obviates the need for special signage to indicate the function of the LRT signals to the public. To provide the equivalent of a yellow phase, the bar signals flash for a set period of 5 sec before changing. This not only provides LRT operator reaction time, but also helps operators identify their signal in a sometimes brightly lit street environment.

Failure Control

One of the concerns throughout the design period was how the LRT system could continue to operate safely in the event of a traffic signal failure at a particular intersection. Sometimes dubbed, "how it works when it doesn't work," the concept was that failure of a loop detector to detect a train or failure of individual traffic signals or controllers should not significantly delay LRT operation.

At most regular intersections this is readily accomplished by operating rule without need for additional hardware. Typically the train, on not receiving the preempt signal as it approaches the intersection, would slow down and stop. Having stopped, the train may then proceed when conditions are safe. A safe condition typically occurs when the parallel pedestrian signal is lit, or when parallel traffic is proceeding and the left turn signals are red. Because the train operator can see the traffic signals, this backup mode does not require additional hardware. At a few locations (for instance, where a train is turning in an intersection), there may be no safe phase. At these locations a backup is necessary and is typically provided by installing a pedestrian push-button within reach of the train operator's window on the approach to such intersections.

Control Software

The primary traffic controller software was developed from a fully actuated intersection program that included a railroad preempt routine. This program was modified to accommodate a number of situations peculiar to LRT:

- The pedestrian clearance phase is not truncated by the train preempt. The practical consequence is that at a few locations where the train call loop could not be set far enough from the intersection, the train phase can be delayed a few seconds if the pedestrian phase is called just before the train phase.
- The preempt phase cannot be terminated without flashing for 5 sec. This provides enough time for a train to always clear the intersection, or stop before it, should the preempt end prematurely because of a false check-out call or erroneous timing.
- With the general adoption of right turn on red, the ability to control traffic turning right across LRT tracks is severely compromised. A number of solutions were considered, including use of changeable message signs and a general prohibition of such turns at all times. The control method selected is actually a composite, including a supplementary, train-actuated warning signal. This signal consists of a pedestrian signal head in which is installed the word Train. This signal supplements a permanent no turn on red restriction, so that when the preempt phase is actuated the signal flashes. This causes motorists to either search for the train or direct more attention to the traffic signal so that they will notice the no

turn on red restriction. This system is clear, simple, and has worked well.

DESCRIPTION OF ALIGNMENT

The Banfield light rail line extends from downtown Portland to the suburb of Gresham, a distance of some 15 mi. It has 9 crossings equipped with railroad gates, 55 intersections controlled by traffic signals, 7 controlled by stop signs, and 13 pedestrian-only crossings. The line may be divided into five segments that reflect different types of right-of-way (ROW):

1. Gresham segment, constructed on an old rail ROW,
2. Burnside Street, constructed on a suburban street median,
3. Banfield segment, a grade-separated segment beside a freeway,
4. Holladay, constructed in the city street, and
5. Downtown, where a variety of in-street configurations are used.

Gresham Segment

The outermost 2 mi of the LRT line was built in a abandoned Portland Traction Company ROW. Most of this segment operates on single track, with passing tracks at two of the three stations. The rail alignment on this segment is not tied to the local street system, which it crosses at locations independent of street intersections. There are nine at-grade street crossings on this segment. With this type of alignment configuration, grade crossings come under OPUC jurisdiction. Traffic signals were considered insufficient to provide adequate grade-crossing control, and railroad-style gates were installed, actuated by track circuits. These gated crossings are identical to similar crossings used statewide on the railroads, except that OPUC allowed the mandatory warning bell on the gates to cut out once the gates are in the down position—a concession to persons living in the vicinity.

Tri-Met operates about 170 trains daily through these crossings, which carry cross traffic up to 20,000 average daily traffic (ADT). No train/vehicular collisions have occurred at the gated crossings during the past 5 years, but gate arm replacement and vandalism repairs result in significantly greater maintenance than at the signalized crossings.

Burnside Street

The Burnside segment runs for approximately 5 mi in the median of Burnside Street. For about a mile of this length Burnside is a major arterial street with four heavily used traffic lanes. For the balance Burnside functions as a minor neighborhood collector street with a single traffic lane in each direction. The reconstruction of this street for LRT required widening the former two-lane street and installing a median, bike lanes, and turn lanes at intersections. Numerous residential and commercial driveways were reconstructed. Except at intersections, the new street fitted into the available 100-ft ROW. Many minor cross streets were closed at the median, so that they now accommodate only right in-right out traffic.

Seventeen traffic signal-controlled intersections were constructed at which traffic could cross the LRT tracks and make left and U-turns across the tracks. Figure 1 shows a typical Burnside intersection. The traffic signals at all 17 intersections are fully preempted by the LRT. The eight stations, all of them at intersections, all have farside platforms for several reasons. They result in the least traffic delay (because the train arrival time can be closely predicted from the upstream detectors) and thus minimize the preempt duration. Also the station geometrics allow the platforms to balance the left turn pockets, giving a uniform ROW requirement. And, should a train overrun a platform, it does not enter a crossing.

Train operation on Burnside is restricted to 35 mph, the same speed as the parallel traffic. Trains are operated on sight, without block signals or track circuits. The only signals are the preempt signals at the intersections. Preemption is initiated by the train passing over an inductive loop detector installed on the track that requests the traffic signal controller to go to the LRT preempt routine. The traffic signal controller, depending on where it is in the cycle, selects a clearance phase and then goes to the preempt routine. The distance from the call detector to the intersection is such that the preempt phase is timed to start before the train is within stopping distance of the intersection. If the preempt phase has not occurred by the time the train has reached stopping distance from the intersection, the train then stops at the intersection using normal service braking rates. Thus failure of a preempt is not an emergency condition. To define the

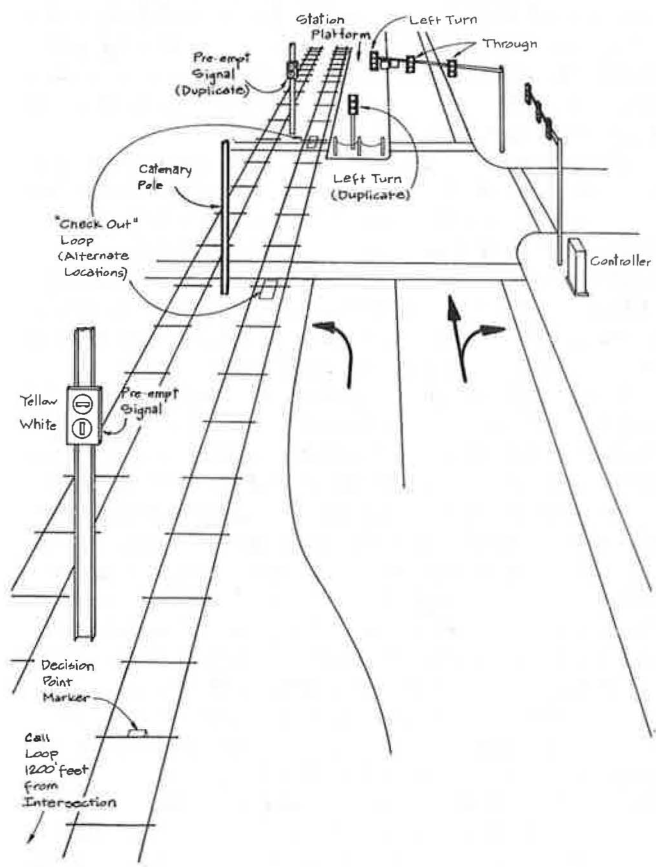

FIGURE 1 Typical Burnside traffic signal layout (half width of street).

point where the train operator should expect to see the preempt signal or begin braking, a reflective marker known as a decision point marker is installed in the track. An operating rule requires that if the preempt is not lit when the train reaches the decision point, the operator must apply the brakes. This process merely formalizes the process that all motorists use when judging stopping distance on the approach to a traffic signal.

All of the Burnside intersections are controlled by standard 170 controllers using a program customized for LRT operation. One of the features of this software is to warn the LRT operator before the preempt signal can change. The preempt signal normally rests with the horizontal bar lit, which is the LRT stop indication. If the preempt is proceeding normally this horizontal bar will flash for 5 sec before changing, thus giving the operator additional warning, and widening the decision window to approximately 7 sec in advance of the decision point marker. Similarly the preempt phase cannot revert to the stop phase without flashing for 5 sec. Thus if the preempt should accidentally terminate because of false checkout or another reason just as a train is approaching an intersection, there is no condition under which the train could enter the intersection against a signal once it has passed the decision point marker. The 5-sec flash interval, plus the 3-sec yellow and 1-sec all-red, provides enough time for the train to proceed from the decision point marker into the intersection in the available 9 sec. Once a train has passed the decision point marker, provided it is traveling at normal speed, there is no situation in which the traffic signal could change against it and allow a conflicting movement before the train has entered the intersection. Obviously if the train is traveling at less than normal speed, it can readily stop if the preempt should terminate early.

The Burnside preempt system achieves three important design goals:

- It is simple, using standard traffic signal hardware that can be maintained by the local traffic jurisdiction technicians and for which spare parts are readily obtainable. Other than the bar signal lenses for LRT and the track loops, no special parts or signs are needed.
- If the system fails to operate as intended, it creates no unsafe condition and does not require trains to make an emergency stop.
- Failure of a traffic signal or preempt does not result in delay to LRT operations of more than a signal cycle.

In addition to the signalized vehicular intersections, 13 pedestrian crossings allow pedestrians to cross the street and LRT tracks at locations remote from an intersection. These crossings are all unsignalized and have a Z-configuration, as shown in Figure 2. This simple design is found widely on European LRT systems. It provides a level, paved crossing with pedestrian refuge between the traffic and LRT lanes. It forces pedestrians crossing the street to turn towards a possible oncoming train on the adjacent track before they can cross the tracks. It enables pedestrians to cross the street without requiring a traffic-free condition across the entire street. As an additional safety precaution, LRT operators normally slow down if pedestrians are observed waiting in the Z-crossing refuges.

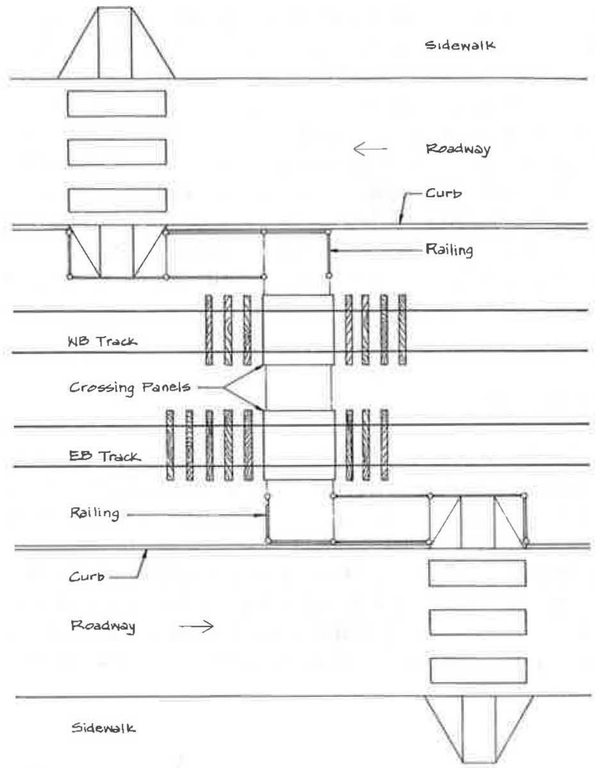

FIGURE 2 Typical Z crossing.

One of the Z-crossings serves as an access to a primary school and was a major concern to parents before operations started. The student-staffed crossing patrol that controlled the pre-LRT crosswalk now patrols the Z-crossing. If a train is sighted, the patrol retires to the sidewalk. If a train operator sees the patrol in the crossing the train will stop. This operation has worked smoothly ever since the LRT opened.

During the design of the Burnside segment the issue of fencing the median ROW was widely debated with the community. Ultimately the ROW was not fenced, although Tri-Met agreed to revisit the issue after operation began if the community requested.

Banfield Segment

At the west end of Burnside, the LRT turns out of the median, enters a short stretch of private ROW, and arrives at Gateway Station. Gateway Station is the midpoint of the line and a major transfer point for 12 connecting bus routes. The station is laid out with the bus bays forming a circle around the LRT station. This allows cross-platform transfers between bus and rail without any vertical separation. By constructing this station at grade the modal advantages of LRT are used to maximum effect. With no grade separation, the need for elevators or escalators is eliminated, and passenger transfers become faster and less onerous. For some transfers the distance between buses and trains is as little as 15 ft. Although the at-grade design results in slightly slower bus and train speeds, this is more than compensated by the reduction in both real and perceived travel time.

Continuing westward, the LRT line parallels the Banfield Freeway for approximately 5 mi. Apart from Gateway Station, this section is fully grade-separated with three intermediate stations accessed from bridge structures. At two of these stations bus pull-outs are provided on the bridges over the LRT. At the third a small transfer area is provided beside the LRT ROW. Maximum operating speed is 55 mph, and trains are protected by automatic block signals. Ironically this grade-separated segment has been the scene of the only fatalities on the system, all involving pedestrians trespassing on the ROW.

Holladay Street

The LRT leaves the Banfield Freeway and enters the downtown street system on Holladay Street, which it follows for approximately half a mile. Figure 3 shows the layout of the Holladay and downtown segments.

Holladay Street was formerly a minor arterial street carrying one-way westbound traffic from the Banfield Freeway to downtown Portland and the eastside commercial district. Because it was a one-way street, the LRT was constructed on the side of the street. On Holladay Street the LRT tracks are constructed on the north (right) side of the traffic lanes, within an 80-ft ROW, providing two traffic lanes beside the LRT tracks, one-way westbound. Although, in normal design practice, locating the tracks on the south side of this street would have been preferable (so that opposing directions would have passed on the right), this design was selected to place the Lloyd Center Station on the same side of the street as the shopping center of the same name, and because there were more numerous commercial driveways on the south side of the street. One significant traffic consequence was the need to control right turns across the tracks.

Throughout this segment the LRT tracks are constructed with girder rail, paved with concrete, and separated from the traffic lanes by a raised curb or planter. Sidewalks are on both sides of the street, with the north sidewalk between the tracks and the north edge of the ROW. Intermittent plantings are used along the LRT side of this sidewalk to channel pedestrians away from the trackway.

The 11 signalized intersections on this segment were designed to work within the preexisting westbound traffic signal progression, which in turn was tied to a north-south progression at certain intersecting streets. Westbound LRT trains

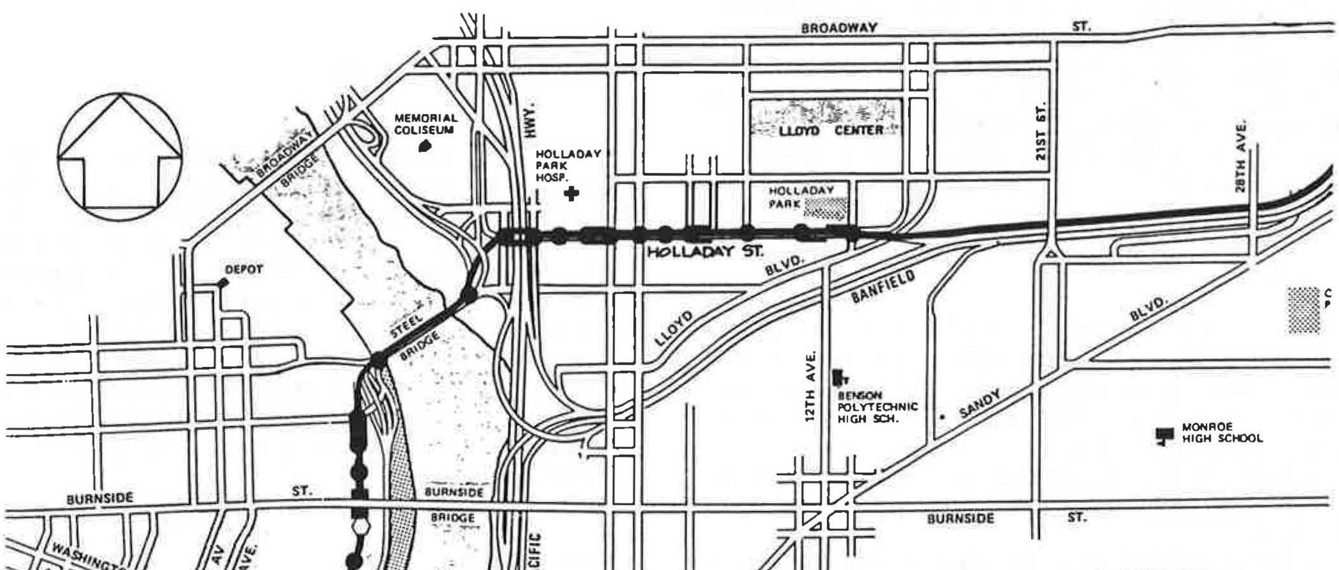

FIGURE 3 Holladay Street downtown layout.

would leave one of the two stations on this segment on a green signal and follow that progression to the next station. Because there was no eastbound progression, eastbound trains would call for a preempt (using a pushbutton at one location and a detector loop at the other) to set up an eastbound path that preempted alternate intersections to give a stop-free trip to the next station. This operation was complicated by one cross street that carried 21,500 ADT and that was not preempted in the original design. To provide a stop-free train path from station to station this nonpreempted street restricted train movents to one part of the signal cycle. The net effect of the Holladay Street design was that westbound trains had no effect on cross traffic, and eastbound trains had an impact only on alternate cross streets.

The control of right turn traffic across the tracks was a major issue on Holladay Street, and several designs were considered, including changeable message signs and turn prohibitions. In the design that was adopted, right turns were controlled by signs prohibiting right turns on red. These signs were reinforced by two flashing Train signs at each intersection. These flashing signs consisted of conventional pedestrian signal heads with the word Train used in place of the conventional pedestrian messages. Whenever the LRT preempt signal was lit, Train would flash, thus reinforcing the right turn on red prohibition.

Largely as a result of the unforeseen effects of LRT, Holladay Street has undergone significant change since the construction of the LRT. First of all, the construction of the LRT closed the street for more than a year with traffic detoured to other routes. As a result, when the street was reopened, much of the traffic that had once used it had found alternative routes and did not need to return. The delays to the parallel traffic progression caused by the all-red LRT preempts further discouraged traffic from returning to its former level.

The presence of LRT was a major factor in selecting a site on Holladay Street for the new Oregon Convention Center and development of a new traffic circulation plan for the area. One facet of this plan was the reversal of traffic direction on Holladay Street and its reduction to one lane with left turn pockets. This had the unintended effect of putting the LRT on the left side of the traffic flow instead of the right, thus removing the right turn on red problem, and making the former traffic signal progression irrelevant. Thus today Holladay Street has become a local circulation street, and the LRT now operates with full preemption in both directions. Traffic turns left across the tracks instead of right, protected by a left turn phase, so that parallel traffic can move on the same phase as the LRT.

Downtown Portland

Downtown Portland is separated from Holladay Street by the Willamette River, a major navigable waterway. To avoid constructing a new bridge, the LRT crosses the Willamette River by sharing an existing bridge (known as the Steel Bridge) with traffic. This 80-year-old structure has two decks, the lower deck carrying two railroad tracks, the upper carrying four highway lanes. Both decks have vertical lift spans in midriver to allow ocean-going ships to pass. The LRT tracks occupy the two center lanes of the upper deck of the bridge, sharing these lanes with highway traffic just as the streetcars did when the bridge was originally constructed. Sharing traffic lanes across the bridge requires a technique to merge a 200-ft train into a traffic lane at the approach to the bridge and to diverge at the opposite end. The approach merges are accomplished by train-actuated traffic signals in a similar manner to a metered freeway ramp. Normally traffic has uninterrupted access onto the bridge. When a train is detected, traffic is stopped until the train has cleared the merge point, after which traffic flow can resume, following the train onto the bridge. No active control is needed at the diverge point, which is indicated by signs and pavement markings.

The traffic signals at the Steel Bridge are overlaid by a track circuit-controlled interlocking that protects the lift span of the bridge. The bridge cannot be raised when a train is occupying the bridge, nor can a train enter the bridge approach track circuit when the bridge is raised. When the bridge is raised, trains are held at the nearest station on the approach side. Unlike the traffic signals, the bridge signals are enforced by the automatic train stop.

At the west end of the bridge, the LRT descends a 7.5 percent grade, the steepest on the system, into the downtown street network.

The downtown segment is some 1.5 mi in length, all of it in city streets. The line first runs south on First Avenue and then turns west onto a 10-block loop on Morrison and Yamhill streets. This segment passes through the retail center of the city and intersects the bus mall—two streets used by most of the regional bus service. All of the trackway is paved and is separated from traffic by contrasting paving and a rumble strip. Curb protection of the trackway in downtown is not practical because the narrow traffic lanes require that traffic be able to use the trackway to bypass obstructions in the traffic lane.

Because of the small size of the downtown blocks (200 ft) and the one-way street grid, the traffic can move within a signal progression in all four directions. The progression speed varies by time of day and is adjusted by changing the cycle lengths. The LRT was inserted into this system using the existing signal progression wherever possible to minimize the effect on cross traffic.

On First Avenue the LRT operates in two directions, although the traffic signals were set up for a southbound progression. Because First Avenue is only one block from the river, the main traffic streets pass over it on the approach spans to the river bridges. Consequently no major street crosses First Avenue at grade. As originally designed, southbound trains waited for the existing progression at each of the three stations on First Avenue and then ran with the progression to the next station. Northbound trains also waited for a green at each station and then could obtain a northbound progression by preempting alternate intersections. Thus the original design goal of stopping only at stations could be achieved.

Morrison and Yamhill streets have 60-ft ROW. LRT operates on the left side of the street in the same direction as a single lane of traffic and is tied into the signal progressions. Morrison and Yamhill streets cross all of the major north/south streets and the transit malls. By operating LRT within the existing progressions, traffic on the cross streets is largely unaffected.

VETAG

In 1990 two stations were added, one on Holladay to serve the new Oregon Convention Center and one downtown to serve a new retail development. These stations added more than 2 min to the LRT schedule, and a number of options were explored to compensate for the added dwell time. It was found that if the delays caused by waiting for progressions on Holladay Street and First Avenue could be eliminated, the 2 min could be recovered. However, this required the ability to preempt a traffic signal from a stationary train, a capability the system did not possess (except for the rather crude push-button system used as emergency backup at a few locations). After a study of system needs and available technology, a train-to-wayside communication system was defined that could not only preempt a traffic signal from a stationary train but also provide automatic track switch actuation and transmit train location to a central control. To fulfill this need, Tri-Met purchased the Philips Vetag system and installed it in 1989. Vetag is a loop- and transponder-based system originally developed in the Netherlands for bus and LRT preempt and switch actuation.

The initial Portland application was to enable stationary trains to call for preempts at stations on Holladay Street and downtown. This became possible because the city had determined that preempting signals on Holladay Street and First Avenue would not severely affect traffic and that the saving in train delays was a higher public priority. Vetag also provided the capability to retrofit Morrison Street to allow left turns across the tracks.

The Vetag installation was completed in 1990. A call button was installed on the control console of each rail vehicle, and Vetag loops and associated circuitry were installed at most of the downtown and Holladay stations. When a train pulls over the wayside loop, the call button in the cab is illuminated to inform the train operator that contact is established with the wayside. Preempt is called when the operator presses the call button. Because the preempt will not occur until the requisite intersection clearance intervals have elapsed, the train operator will call for preempt far enough ahead that the train is ready to leave by the time the doors are closed and the intersection has reached the preempt phase. The Tri-Met version of Vetag also allows the train to terminate the preempt phase by using the tail-end transponder to transmit a check-out signal. The experience with Vetag so far has been very satisfactory, and Tri-Met intends to expand its use as additional applications become necessary.

OPERATING EXPERIENCE

During the final stages of construction and preoperational testing, a number of potential problems were identified and fixes developed. Early in the project, tests were performed to compare overhead and buried loop detectors, resulting in the decision to use buried loop detectors. However when these loops were installed in the subballast they proved to be too deep to detect the trains. All of the loops installed under the initial Burnside contract had to be replaced with loops formed inside a fiberglass casing that could be bolted to track ties. These loops have provided highly reliable detection and in addition can be readily replaced should a defect develop.

In Oregon a single set of signal heads is normally used to control left turn movements. Although this arrangement is satisfactory in a normal intersection, it created an unforeseen problem at certain LRT intersections. In the event a single left turn signal loses a red light bulb or a programmed visibility head is knocked out of alignment, left turn traffic would see no signal. In this situation left turn traffic would normally proceed on the parallel green and expect to do so safely. However, with LRT operating parallel to traffic, the parallel green may also be the train phase, thus setting up a trap for the unwary. To guard against this situation a second set of left turn signal heads, at least one of which does not have programmed visibility heads, was installed at all intersections where this condition could occur.

The LRT trains are equipped with audible warning in the form of both bells and horns. The bells are used frequently in the downtown area as a method of alerting pedestrians in an inoffensive manner and to give routine signals prior to departing from a station and on similar occasions. The train horn is used primarily to warn traffic or to alert a pedestrian who has not responded to the bell. As initially installed, the horn sounded similar to an automobile horn with unintended negative consequence. When the train operator used the horn to warn traffic, traffic would sometimes believe that the driver behind them was impatient and they would therefore move ahead. Where the traffic happened to be turning traffic waiting for a train, this was exactly what was not desired. After a review of options, a new electronic horn was installed that could simulate a railroad locomotive horn. This appears to have solved the problem. The electronic horn has an additional advantage—both the notes and the intensity can be varied by the train operator to suit a particular situation.

Safe operation of the LRT system and particularly the traffic interface elements of that system has been a major concern throughout its development and early years of operation. Tri-Met's safety supervisor maintains a program of continuous review of LRT safety, including investigation of all accidents and incidents, and the compilation and review of all accident and incident information. One consequence has been the early identification of any location exhibiting unusual safety problems so that remedial measures can be investigated and implemented. For example, the high incidence of vehicles making an illegal left turn on Morrison Street and hitting a train was a major consideration in deciding to change the signal system to allow these turns. A high incidence of right turn on red accidents at 13th and Holladay was reduced by rearranging the signals, signs, and flashing train signs at that location.

Table 1 summarizes Tri-Met's accident experience in its 5 years of operation. During this period the rate of bus accidents has tended to rise, whereas the rate of rail accidents has tended to fall, with the modes currently experiencing very similar rates measured on a vehicle mile basis. Because of the greater ridership on the rail vehicles, the accident rate per passenger mile is between five and six times lower on the rail system.

Although engineering efforts have provided a foundation for safe operation, even more effective has been the defensive driving skills developed by the operators, who have learned to recognize potentially hazardous situations and have de-

TABLE 1 Summary of Transit Vehicle Accidents by Mode

	Bus	Rail
FY-87		
# Vehicle Accidents	791	45
# Vehicle Miles	21,020,000	700,000
# Passenger Miles	158,093,540	36,394,000
Passenger Miles/Vehicle Accidents	199,865	808,755
Vehicle Miles/Vehicle Accidents	26,573	15,555
FY-88		
# Vehicle Accidents	830	43
# Vehicle Miles	20,970,240	840,720
# Passenger Miles	136,663,200	38,214,000
Passenger Miles/Vehicle Accidents	164,654	888,697
Vehicle Miles/Vehicle Accidents	25,265	19,551
FY-89		
# Vehicle Accidents	776	54
# Vehicle Miles	20,935,200	842,760
# Passenger Miles	144,460,800	36,888,000
Passenger Miles/Vehicle Accidents	186,160	683,111
Vehicle Miles/Vehicle Accidents	26,978	15,606
FY-90		
# Vehicle Accidents	833	38
# Vehicle Miles	21,075,120	852,600
# Passenger Miles	159,188,658	37,981,091
Passenger Miles/Vehicle Accidents	191,102	999,502
Vehicle Miles/Vehicle Accidents	25,300	22,436
FY-91		
# Vehicle Accidents	984	41
# Vehicle Miles	21,467,040	852,000
# Passenger Miles	168,696,000	42,036,000
Passenger Miles/Vehicle Accidents	171,439	1,025,268
Vehicle Miles/Vehicle Accidents	21,816	20,780

veloped responses. Many tactics have been incorporated into the driver training program to good effect.

CONCLUSIONS

In 1986 Tri-Met opened a new LRT system with some 71 grade crossings in 15 mi, and an ROW extending from the city center to the outer suburbs. It has proved that LRT can be safely and reliably operated in a major urban area and has led to public endorsement of the eventual construction of a regional rail system. The future extensions will generally follow and build on the experience from the initial line:

- Use conventional traffic control and railroad devices, intersection configurations, and hardware to benefit from existing public familiarity and simplify design and maintainability.
- Do not provide motorists with information they do not need. Particularly do not display the train signals to motorists and then have to install signs to tell drivers to ignore the signals.
- Try not to prohibit normal traffic moves to avoid having to control them. A percentage of traffic will typically not observe the prohibition and an unsafe situation can develop. Observance of signals that permit and control movements is safer and more predictable.
- Construction of LRT requires extended street closures and forces changes to traffic flow patterns. Opportunities often exist to use this disturbance to manage traffic flow after construction and create an enhanced urban environment.

Trolley Priority on Signalized Arterials in Downtown San Diego

STEPHEN CELNIKER AND E. WAYNE TERRY

The San Diego trolley, an electrified light rail transit system, has changed its method of controlling trolley movement at signalized intersections on arterials in downtown San Diego. The previous method required a trolley to preempt, or alter, the normal operation of the traffic signals for the trolley to have uninterrupted movement at traffic signals as it traveled between stations. The new method, dubbed the trolley priority system, instead provides favorable timing to the trolley as a part of the normal operation of the traffic signals. The trolley priority system has proven to be more reliable than the preemption system and requires less maintenance. One notable drawback is that the new system sometimes requires the trolley to wait longer in the station before departing than did the previous system. However, since implementation of the trolley priority system, studies have shown that overall trip time has improved in the downtown area. Although at times a train may encounter delay beyond the normal station dwell time, by awaiting the appropriate entrance window on the next traffic signal cycle, the actual operating time between stations is enhanced.

San Diego Trolley, Inc., is a light rail transit (LRT) system serving the greater San Diego area. The system operates mostly within a railroad right-of-way serving communities on the East Urban Line between the cities of San Diego and El Cajon, 18 mi to the east, and on the South Urban Line serving communities between the city of San Diego and the United States/Mexico border, 16 mi to the south of downtown. The LRT system is controlled by an automatic block system (ABS) on the semiexclusive at-grade portions of the right-of-way.

Currently the system operates 337 daily train trips, using a fleet of 71 light rail vehicles (LRVs) to accommodate nearly 60,000 daily users of the system. Service is operated on a 15-min headway during most of the day with 7.5-min service being offered through both morning and evening peak periods.

The importance of a priority in traffic signaling for LRV operations in a mixed traffic environment is paramount in relationship to the safety and efficiency of an operating system in this medium. The mixed traffic street portion of the trolley operation encompasses 3 mi, of which 1.2 mi spans Commercial Street and 1.8 mi is combined between 12th Street and C Street in the center city.

The main concern about operations downtown is the ability of the trolley to travel between stations without having to stop at traffic signals at the intervening intersections (see Figure 1). When the trolley began operation in 1981, a method of signal preemption was established that was intended to provide the trolley with uninterrupted movement through the signalized intersections. As the trolley system expanded and the service frequency increased, it became increasing difficult to maintain adequate signaling windows at intersections shared by vehicular, pedestrian, and LRV traffic.

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PREEMPTION

The original method of serving the trolley on signalized arterials downtown was a preemption system. Traffic signals were preempted when the pantograph of the LRV initiated a preemption pulse by striking a contactor on the overhead catenary system in advance of the traffic signals to be preempted. The preemption pulses would temporarily alter the normal operation of the traffic signals and provide for one-way progressive movement for the trolley. The signals would return to normal operation after the trolley had passed. The normal operation of the signals was to favor the vehicular and pedestrian traffic crossing the track on C Street and on 12th Avenue.

Initially the trolley was a rare enough event that the traffic signals served the preemptions and returned to normal operation without causing excessive delays to the cross traffic.

As the trolley system expanded and service became more frequent, so did the frequency of the preemption pulses to the traffic signals. As an example, in 1981 using the previous preemption method, a maximum of eight trains per hour occupied signaled intersections in the downtown area. In 1992 a maximum of 27 trains per hour occupied the same intersections. This represents an increase of 238 percent in train traffic per hour in the center city zone at any given point. These numbers are exclusive of East Urban Line four-car trains that are split into two doubles for inbound peak period trips into the center city. Four-car trains are split as described because city blocks cannot accommodate the train length.

The previous preemption system was unable to accommodate the increased amount of preemption pulses initiated by trains traveling in opposite directions simultaneously. Because the preemption timing could serve trolley movement in one direction only, the trolley traveling in the opposite direction would be stopped by red lights at nearly every signal. Sometimes several trolley preemptions would be entered in rapid succession, creating significant delays for cross traffic and pedestrians as the signals departed from normal operation for several minutes at a time. In a few cases the signals received so many preemption pulses that the equipment malfunctioned, locking up with red lights in all directions, serving

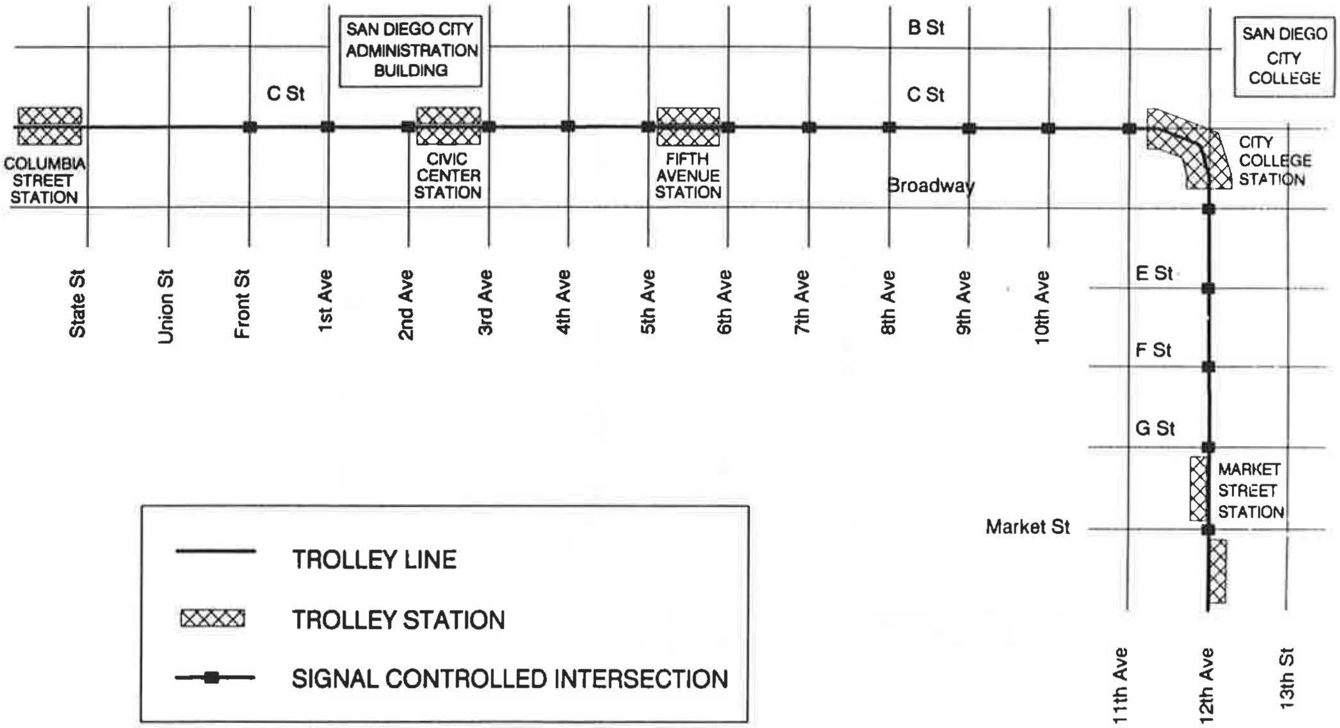

FIGURE 1 Trolley operation on signalized arterials in downtown San Diego.

neither motorists nor pedestrians nor trolleys. The success of the trolley had overwhelmed the preemption system that had been designed to serve it.

TROLLEY PRIORITY SYSTEM

The solution to the preemption problem was technically quite simple. Rather than requiring the trolley to alter the normal operation of the traffic signals to receive favorable timing, instead have the normal operation itself favor the trolley. By favoring the trolley, the system proved more effective for all users because it was time-fixed and more reliable. This concept became the basis of the trolley priority system, which was implemented in 1990 in a cooperative effort between the city of San Diego and San Diego Trolley, Inc. The system works as follows:

- The trolley dwells in the trolley station until the beginning of the next green light at the first downstream signal.
- The trolley departs within 5 sec of the beginning of the green light.
- If the departure window is missed, the trolley must wait until the beginning of the next green light.
- As long as the trolley leaves the station during the departure window, the trolley will receive green lights at all of the signals until it reaches the next station.
- The two-phase, fixed-time signal timing favorable to the trolley is always in place and is fitted into the larger network of signals.

For a time-space diagram illustrating an example of progressive timing for the trolley, see Figure 2.

With some in-the-field fine-tuning of the signal timing, the trolley priority system has proven largely successful. The major beneficiaries have been pedestrians crossing C Street and 12th Avenue. Under the preemption system, pedestrians would frequently be faced with lengthy Don't Walk lights as the signals were serving several preemption pulses in a row, overriding several normal signal cycles. With the priority system, the signal cycles are fixed and the Don't Walk lights stay within the normal range.

Two areas of concern about the trolley priority system remain. First, the waiting period for the next green light sometimes exceeds the time required to unload and load passengers at the station. Train delay is experienced if the train operator is not ready to depart the station in the initial green traffic signal cycle. Second, the departure window is not designated by any special indication, requiring the operators to guess in borderline situations, sometimes missing the window and hitting a red light before reaching the next station. The entrance window is fixed at 5 sec, which if entered properly the train will be allowed to move unimpeded through all intersections located within that particular control zone. The installation of an indicator at control zone entrances, which would signal the entrance threshold to the train operator, is being explored.

TRANSIT OPERATOR'S PERSPECTIVE

The priority system was designed and implemented on a test basis by the city traffic engineers on 12th Avenue several months prior to the system actually being adopted. Testing procedures were prepared and a test zone of five traffic signals

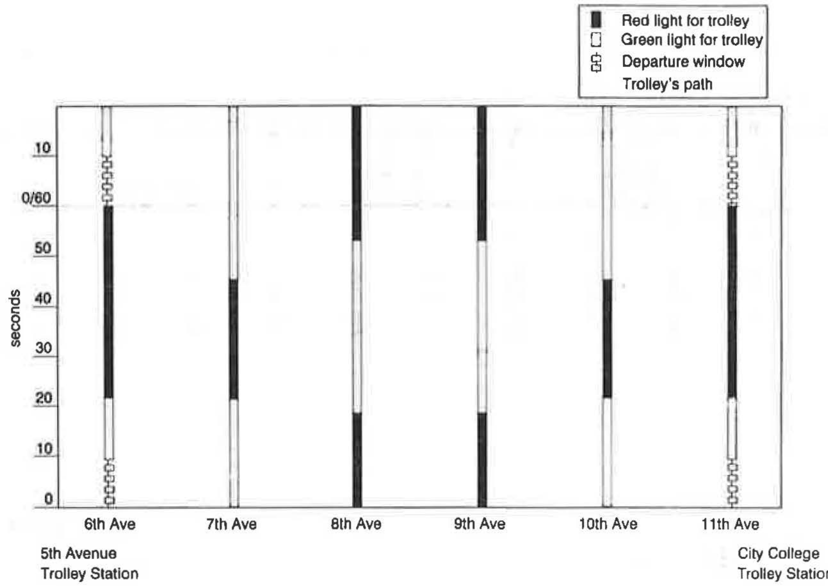

FIGURE 2 Trolley priority system (progressive movement for trolley on C Street between Fifth Avenue and City College Stations).

was established on 12th Avenue between the Market Street Station and the City College Station.

The testing plase proved to be a valuable experience in terms of using the system and monitoring the reliability of its operation. Adjustments were required as attempts were made to perfect the system during the testing phase. Trolley operating staff worked closely with city staff to effect timing changes at various intersections within the testing zone to provide for a smooth flow for trolley traffic in both directions.

During the testing phase, the following two areas of concern were under constant review:

1. The departure window the trolley operator had to enter the test zone, and
2. The length of time each signalized block in the control zone would hold favorable for trolley priority.

During the course of the testing period, the signal sequencing program was continually modified to provide the best possible operating environment for LRV, vehicular traffic, and pedestrians in shared arterials.

OPERATION

It was established that trains must enter the control zone within 5 sec from the time the green aspect illuminates on the traffic signal standard. From that point all signalized intersections in the control zone would change in succession favoring the trolley. Timing was based on an average predetermined train speed. If the control zone could not be entered within the allotted time, the operator is required to wait an entire cycle for the next green traffic signal to be displayed. If the operator disregards the departure window and enters the control zone on a stale green signal (beyond the initial 5 sec), a red traffic signal would normally be experienced at the next intersection.

Initially the traffic signal sequence timing was programmed for what was determined to be the average train speed in the downtown area. The average speed encompasses all factors associated with mixed street operation including station stops, dwell time, delay for train meets, traffic signals, and so forth. Using the time derived from these criteria, an inflated time between stations was used to calculate average train speed.

As a result, the speed used to gauge the signal sequencing proved too slow for trains to sustain the maximum 25 mph between stations, and trains were delayed unnecessarily at intersections within the control zone limits.

Control zones encompass the intersections between stations; typically, three to five intersections are located within the limits of a control zone. In most cases trains enter a control zone when leaving a station platform at the first intersection bordered by that station. If the operator is unable to accept the first green traffic signal, the train will remain berthed on the platform available for boarding until such time as the next favorable signal cycle is displayed.

FINE-TUNING

Based on the initial observations of the traffic signal sequencing plan, it was determined that additional time would be provided for trains to enter control zones. In addition to the entrance window being extended, the timing sequence for the succession of intersections within the control zones was modified to sustain an uninterrupted operation of 25 mph.

The timing sequence of priority signaling is programmed to change during the day to provide for different traffic pat-

Effective Friday, December 21, 1990, the Traffic Engineering Department, for the City of San Diego, will activate the "Center City Traffic Signal Sequencing Plan." The plan will bring all signalled intersections on-line for operation in the downtown area, between Market and Front Streets.

In recent months a test zone has been in operation between Market Street Station and City College Station, on twelfth Avenue. During this period, test results were reviewed and modifications to the system were made to enhance train operations through the zone.

The following will identify the entrance to each control zone location, and establish the procedure by which traffic signal control zones are entered and operated through:

TRAFFIC SIGNAL CONTROL ZONE LOCATIONS:

NOTE: All control zone entrances begin at intersections boardered by a station, except eastbound at Front Street.

Westbound,

1. Market Street zone includes intersections to City College Station.
2. 11th Avenue zone includes intersections to 5th Avenue Station.
3. 5th Avenue zone includes intersections to Civic Center Station.
4. 2nd Avenue zone includes intersections through Front Street.

Eastbound,

1. Front Street zone includes intersections to Civic Center Station. NOTE: Front Street traffic signals will not preempt in advance of train.
2. 3rd Avenue zone includes intersections to 5th Avenue Station.
3. 6th Avenue zone includes intersections to City College Station.
5. Broadway zone includes intersections to Market Street Station.

TRAIN OPERATION WITHIN CONTROL ZONE LIMITS:

1. Trains must enter the intersection of a control zone on a "fresh green signal." A fresh green signal is defined as within five (5) seconds from the time the green aspect appears.
2. If unable to enter the control zone on a fresh green signal, the train must be left available for boarding until the next green signal cycle appears. DO NOT move train over the in-street signal loop in an attempt to recall the signal.
3. If signal sequencing is lost while operating within the limits of a control zone, due to delays, it may be re-established after entering the next intersection on a fresh green traffic signal.

FIGURE 3 Operating procedures.

terns. Traffic signal sequence timing changes are made to accommodate the morning peak, base, afternoon peak, evening, and weekend traffic patterns. Operationally the various signal sequencing patterns work well with some delay being experienced at the transition of each traffic pattern change.

OPERATING HEADWAY

Priority signaling has adequately facilitated train service through control zones in downtown on all headways with one exception. During rush hour, because of short headways it sometimes becomes necessary to allow a train to enter a control zone on a stale green traffic signal to allow the following train to enter the station platform to discharge passengers. This occurs only in the morning peak period when the preferred direction of travel is into downtown.

CONCLUSION

The trolley priority system has proven to be successful at increasing the efficiency of trolley operations through downtown San Diego. The system has been in full service for 1 year and operators have learned to operate their trains in accordance with the standard procedures (see Figure 3). By learning the system and following procedural instructions, operators typically experience a savings in operating time throughout center city by as much as 2 to 3 min per trip.

The trolley priority system is a simple and easily implemented solution to the complex problem of motor vehicles, pedestrians, and trolleys operating together on streets under traffic signal control. Two improvements to the system that are being considered are shortening the traffic signal cycle length to reduce excess dwell time for the trolley and the installation of special T signals that would designate the departure windows to the trolley operators.

Creating a Light Rail Transitway Within Existing Arterial Street Right-of-Way

PAUL S. MCCAULEY AND JAMES W. SWANSON

The downtown Los Angeles portion of the recently opened Metro Blue Line runs south, through a short subway, then continues at grade in reserved trackways on Flower Street and Washington Boulevard to the Mid-Corridor private right-of-way and eventually to Long Beach. The light rail trackways on Flower Street and Washington Boulevard were created as part of the Blue Line project; prior to Blue Line construction, sidewalks and traffic lanes occupied the entire public right-of-way. Building the Blue Line required a series of planning and engineering decisions about how best to mix light rail, automobile, and pedestrian traffic on the streets and how to relocate utilities.

The 22-mi-long Metro Blue Line, originally designated the Long Beach–Los Angeles rail transit project, was the first rail project undertaken by the Los Angeles County Transportation Commission (LACTC). The 20-mi segment from Pico Station to Anaheim Station, including the street-running sections on Flower Street and Washington Boulevard, opened for revenue service in July 1990. The Long Beach Loop opened in September 1990, and the Seventh and Flower Station opened in February 1991 (Figure 1).

For much of its length, the Blue Line operates in right-of-way formerly used by the interurban Pacific Electric Railroad (PE). The Pacific Electric's Long Beach line, which ceased passenger service in 1961, operated from the PE station at Sixth and Main streets in downtown Los Angeles. The line ran east on a three-block-long steel elevated structure to San Pedro Street, then south and east for 2 mi in mixed traffic on city streets to Olympic Boulevard and Long Beach Avenue, where it entered private right-of-way.

One of the Blue Line conceptual design phase challenges was to find an alignment to connect the private right-of-way to downtown Los Angeles. The former PE alignment was not appropriate for several reasons. The elevated structure had been demolished and the right-of-way redeveloped; the San Pedro Street and Olympic Boulevard rights-of-way are too narrow for reserved trackways; and, perhaps most importantly, the center of downtown retail and commercial activity had moved steadily west since the PE station on Main Street was built at the turn of the century.

ALIGNMENT AND RIGHTS-OF-WAY

The Metro Blue Line begins in subway under Flower Street just south of Sixth Street in the central business district (CBD) of Los Angeles. The initial station at Seventh and Flower is a two-level underground joint station with the heavy rail Red Line. (The Red Line center platform is under Seventh Street on the lowest level; the Blue Line side platforms are under Flower Street at the Red Line mezzanine level.) The Blue Line continues south from the station in a short subway, crossing under the intersections of Flower Street and 8th Street, 9th Street, Olympic Boulevard, and 11th Street. The subway portal and trackway ramp to the surface are located on the east side of Flower Street between 11th and 12th streets.

The Blue Line crosses 12th Street at grade and proceeds south on the east side of Flower Street past Pico Station to Washington Boulevard. At Washington Boulevard the tracks swing east and proceed in the median of Washington Boulevard east past Grand Station and San Pedro Station to Long Beach Avenue. At Long Beach Avenue the Blue Line swings south into the Mid-Corridor segment private right-of-way.

Los Angeles transit planners operate under the shadow of the Pacific Electric, the transit system that "got away." At its peak, the PE Red Cars operated over more than 1,000 mi of standard gauge electrified track in the Los Angeles basin. Although the outlying sections were frequently on private rights-of-way, the PE made extensive use of street trackage in downtown Los Angeles and Hollywood. By the 1950s, street congestion had seriously compromised the PE's reliability as a rush-hour passenger carrier.

When light rail transit (LRT) shares street right-of-way with automobiles, the potential alignment classifications include the following:

- Exclusive trackway—Open tie and ballast construction,
- Exclusive trackway—Embedded track construction,
- Semiexclusive trackway—Left turn lanes on tracks, and
- Nonexclusive trackway—Mixed traffic.

One of the early Blue Line policy decisions was that the LRT system would operate in exclusive transit lanes when sharing street rights-of-way. The LACTC was not going to spend hundreds of millions of dollars to build an unreliable system, and the PE had already demonstrated the unreliability of mixed LRT/automobile lanes in Los Angeles.

On Flower Street and Washington Boulevard, the Blue Line operates in exclusive trackways with embedded tracks separated from automobile roadways by curbs. The Blue Line tracks were embedded in asphalt at the request of the city of Los Angeles so that emergency vehicles could cross or, if necessary, drive on the trackway to reach the scene of an emergency. Separate signalized left turn lanes outside of the

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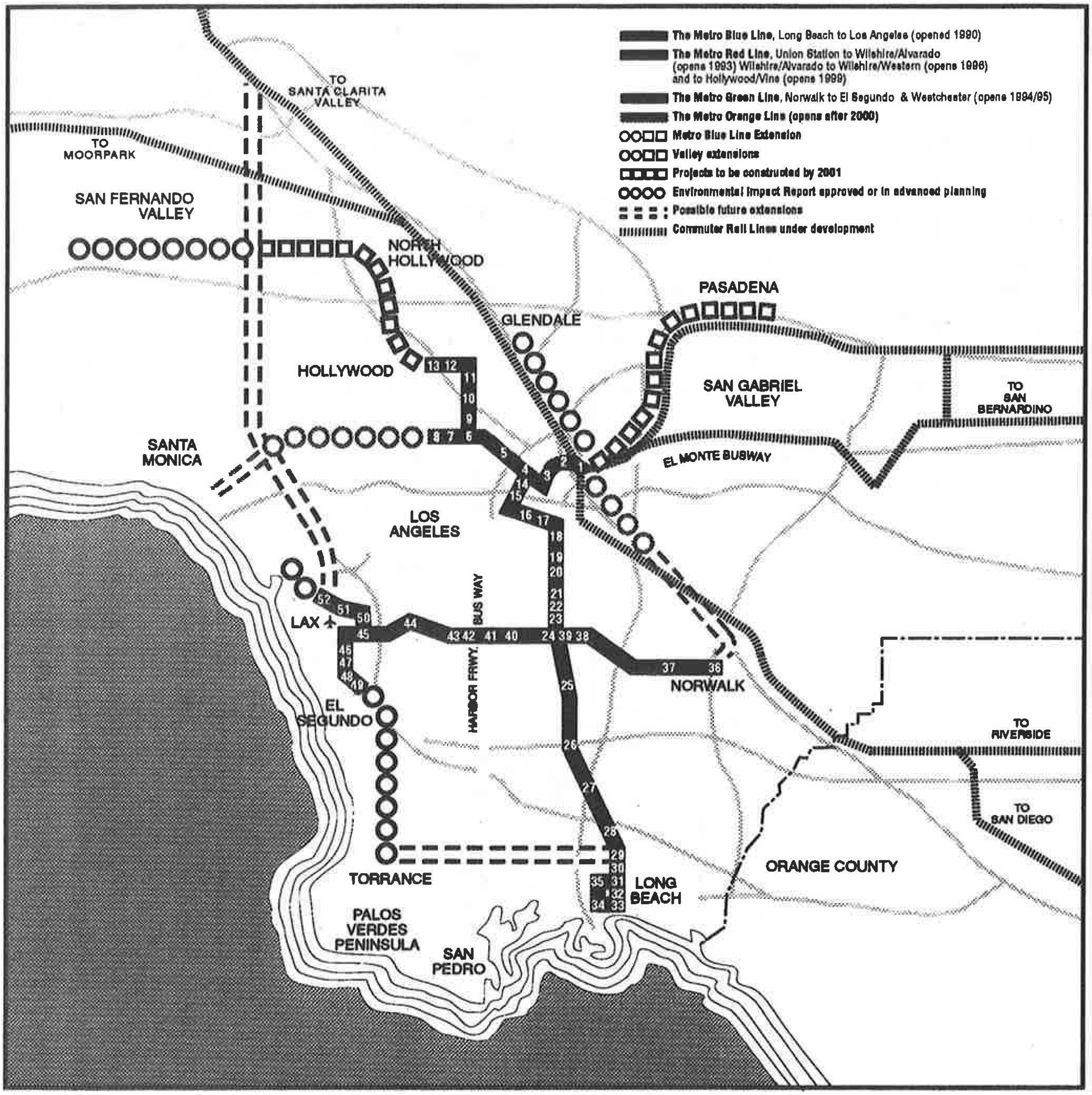

STATION LOCATIONS

***Metro Red Line**-Union Station to Hollywood/Vine*

1. Union Station
2. 1st St./Hill St. (Civic Center)
3. 5th St./Hill St.
4. 7th St./Flower St.
5. Wilshire Blvd./Alvarado St.
6. Wilshire Blvd./Vermont Ave.
7. Wilshire Blvd./Normandie Ave.
8. Wilshire Blvd./Western Ave.
9. Vermont Ave./Beverly Blvd.
10. Vermont Ave./Santa Monica Blvd.
11. Vermont Ave./Sunset Blvd.
12. Hollywood Blvd./Western Ave.
13. Hollywood Blvd./Vine St.

***Metro Blue Line**-Long Beach to Los Angeles*

14. 7th St./Flower St.
15. Pico Blvd./Flower St.
16. Grand Ave./Washington Blvd.
17. San Pedro St./Washington Blvd.
18. Washington Blvd./Long Beach Ave.
19. Vernon Ave./Long Beach Ave.
20. Slauson Ave./Long Beach Ave.
21. Florence Ave./Graham Ave.
22. Firestone Blvd./Graham Ave.
23. 103rd St./Graham Ave.
24. Imperial Hwy./Wilmington Ave.
25. Compton Blvd./Willowbrook Ave.
26. Artesia Blvd./Acacia Ave.
27. Del Amo Blvd./Santa Fe Ave.
28. Wardlow Rd./Pacific Ave.
29. Willow St./Long Beach Blvd.
30. Pacific Coast Hwy./Long Beach Blvd.
31. Anaheim St./Long Beach Blvd.
32. 5th St./Long Beach Blvd.
33. 1st St./Long Beach Blvd.
34. 1st St./Pine Ave.
35. 5th St./Pacific Ave.

***Metro Green Line**-Norwalk to El Segundo*

36. Studebaker Rd./605 Fwy.
37. Lakewood Blvd./Imperial Hwy.
38. Long Beach Blvd./Imperial Hwy.
39. Imperial Hwy./Wilmington Ave.
40. Avalon Blvd./117th St.
41. 110 Fwy./117th St.
42. Vermont Blvd./117th St.
43. Crenshaw Blvd./119th St.
44. Hawthorne Blvd./111th St.
45. Aviation Blvd./Imperial Hwy.
46. Mariposa Ave./Nash St.
47. El Segundo Ave./Nash St.
48. Douglas St.
49. Freeman Ave.
50. Century Blvd.
51. LAX Lot C
52. Westchester Pkwy.

FIGURE 1 Los Angeles Metro Rail plan.

reserved transitway are provided at all intersections where left turns are legal.

CONCEPTUAL DESIGN AND ENVIRONMENTAL DOCUMENTATION

The goal of the conceptual design and environmental documentation phase was to reach agency and public consensus on Metro Blue Line alignment.

Early in the conceptual design, the LACTC established an interagency working group to propose and screen Los Angeles CBD segment alternative alignments. The working group consisted of staff from the interested agencies, including the LACTC; the Los Angeles City Departments of Transportation (LA DOT), Public Works (DPW), Planning, and the Community Redevelopment Agency; Los Angeles County; and the California Department of Transportation (Caltrans).

In a series of workshops held in 1982 and 1983, the working group identified more than a dozen possible alignments from the Mid-Corridor right-of-way to downtown Los Angeles. The possible alignments included both alternative street routings and alternative guideway profiles (at-grade, subway, and aerial). The working group screened the list of possible alignments and recommended three alignments for conceptual design and environmental clearance. The LACTC adopted the three recommended Los Angeles CBD segment alternatives for further study in May 1983 (Figure 2):

- LA-1—Broadway/Spring Couplet, at-grade,
- LA-2—Flower Street Subway (including at-grade trackways on Flower Street and Washington Boulevard), and
- LA-3—Olympic/Ninth Aerial.

Because the Blue Line would be locally funded through the 0.5 percent county sales tax approved by the voters in 1980, no federal environmental documentation was required. A draft environmental impact report (draft EIR), as required by the California Environmental Quality Act (CEQA), was prepared for the entire 22-mi Blue Line project. The draft EIR, which was issued for public review and comment in May 1984, documented the three Los Angeles CBD alternatives. The

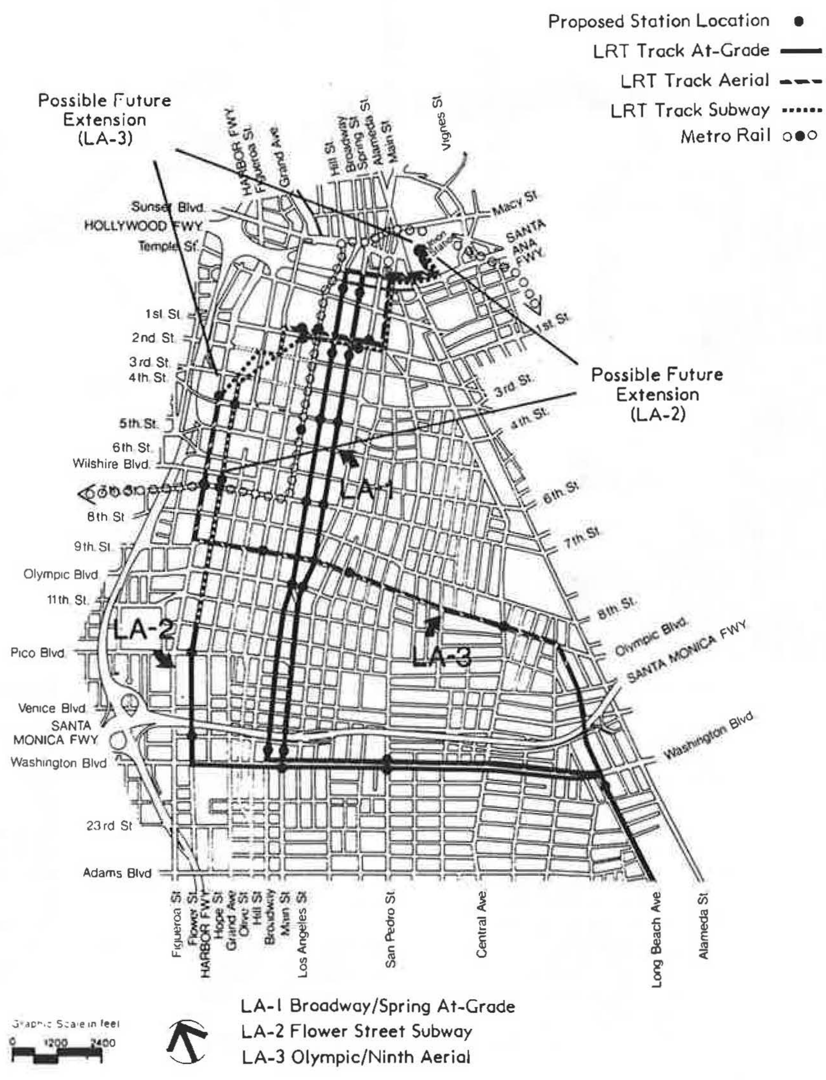

FIGURE 2 Downtown Los Angeles alignment alternatives.

LA-2 alternative was subsequently endorsed by the Los Angeles City Council and adopted by LACTC, in large part because of the transit efficiency of the joint Blue Line/Red Line station at Seventh and Flower.

PRELIMINARY ENGINEERING DESIGN

The goal of the preliminary engineering design phase was to reach agreement on how the Flower Street and Washington Boulevard public right-of-way would be shared between the roadway and the Blue Line trackway.

Flower Street: Side Running and One-Way Street Operation

The conceptual design focused on fitting the Blue Line transitway into the existing downtown Los Angeles street system. At the time both Flower Street and Washington Boulevard were operated as two-way arterial streets. With the endorsement of the LA-2 alignment by the city council, LA DOT proposed changes to the downtown street system, including conversion of Flower Street to one-way southbound operation, to improve operations for both motorists and LRT.

A limited number of one-way street couplets had been implemented in downtown Los Angeles during freeway construction in the 1950s. LA DOT had been attempting to expand the one-way street system to include additional north-south couplets for several years, but merchant opposition had stalled the conversion. The Blue Line project gave LA DOT the opportunity to reopen the issue and successfully implement two of the three proposed additional couplets.

In many respects the conversion of Flower Street to one-way operation was timely and helpful. The Blue Line was requesting that a significant fraction of the 90-ft-wide Flower Street right-of-way be dedicated to LRT operations, particularly at passenger stations. The more efficient traffic operation of a one-way street compared to a two-way street helped the city agree to that request. Another advantage was at the subway portal. With two-way street operation, northbound motorists would be driving toward the portal and might accidentally either drive into the end of the portal retaining wall or attempt to drive down the portal ramp. The conversion to one-way southbound operation diverted the automobile traffic that otherwise would be driving toward the south-facing portal.

The disadvantage of the conversion to one-way street operation was that roadways (northbound and southbound) were no longer between the transitway and the adjacent sidewalk and private property. (A median trackway between roadways operating in the same direction was judged to be unsafe because of turning movement conflicts—signs would not prevent motorists from turning across the trackway when they found themselves on the wrong roadway for their destination).

The conversion of Flower Street to one-way operation essentially forced the Blue Line to a side running alignment, placing trackway between private property and the public street. The existing driveways had to either remain in service (with motorists crossing the trackway) or LACTC would have to compensate the owners for the loss of driveway access to their property.

If the driveways were allowed to remain, a motorist turning left to enter a driveway might not see a light rail vehicle (LRV) approaching from the motorist's rear. This conflict between automobiles turning into driveways and overtaking LRVs was judged to be a significant safety problem. Automobiles exiting from a driveway cross the tracks at a right angle, then turn onto the roadway. Because the track crossing would be at a right angle, the exiting driver has a better opportunity to look both ways before crossing the trackway. The conflict between automobiles exiting driveways and LRVs was judged to be less of a problem.

Where driveway traffic was projected to be heavy, the LACTC purchased the property owner's vehicle access rights and closed the driveway. For all driveways that remained, the project installed internally illuminated No Left Turn signs facing the entering motorist (Figure 3). The normally dark No Left Turn signs are activated (illuminated) by an LRV approaching from either direction on either track. Driveway exit movements are controlled by LRV warning signs. Between driveways, handrails separate the trackway from pedestrians on the sidewalk.

As was anticipated by the designers, the one-way southbound Flower Street operates with less congestion than the two-way street experienced prior to Blue Line construction. Congestion has not increased noticeably on the adjacent one-way northbound or two-way streets. The LRV-activated No Left Turn signs at driveways are operating as planned. No LRT-related accidents on Flower Street have been reported to the city.

Washington Boulevard: Typical Section and Roadway Capacity

Washington Boulevard is an important east-west arterial street immediately south of downtown and the Santa Monica Freeway. Prior to Blue Line construction, Washington Boulevard consisted of a 70-ft- or 80-ft-wide roadway (a center continuous left turn lane plus three through lanes for each direction for a total of seven traffic lanes) and two 15-ft- or 10-ft-wide sidewalks in 100-ft-wide right-of-way. The Washington Boulevard curb lanes were signed to permit parking middays and nights, but not during rush hours. The adjacent streets are discontinuous, essentially prohibiting a one-way couplet scheme.

The conceptual design typical sections indicated that the LRT would replace traffic lanes on Flower Street and Washington Boulevard within the existing roadway—the existing curbs, gutters, and sidewalks would not be reconstructed. LA DOT commented during the environmental document review period that this would have an unacceptable traffic impact on Washington Boulevard. LACTC responded by committing to provide two through lanes plus a left turn lane for each direction of travel as mitigation.

The first preliminary engineering attempt to define a new Washington Boulevard typical section was a failure—the width of the 24-ft median trackway plus two 34-ft roadways (13-ft curb lane for buses, 11-ft through lane, and 10-ft left turn lane) plus two 10-ft sidewalks exceeded the 100-ft right-of-way by 12 feet. LACTC and LA DOT then examined various schemes to fit the roadway and transitway into the existing right-of-way, including an asymmetric design that eliminated

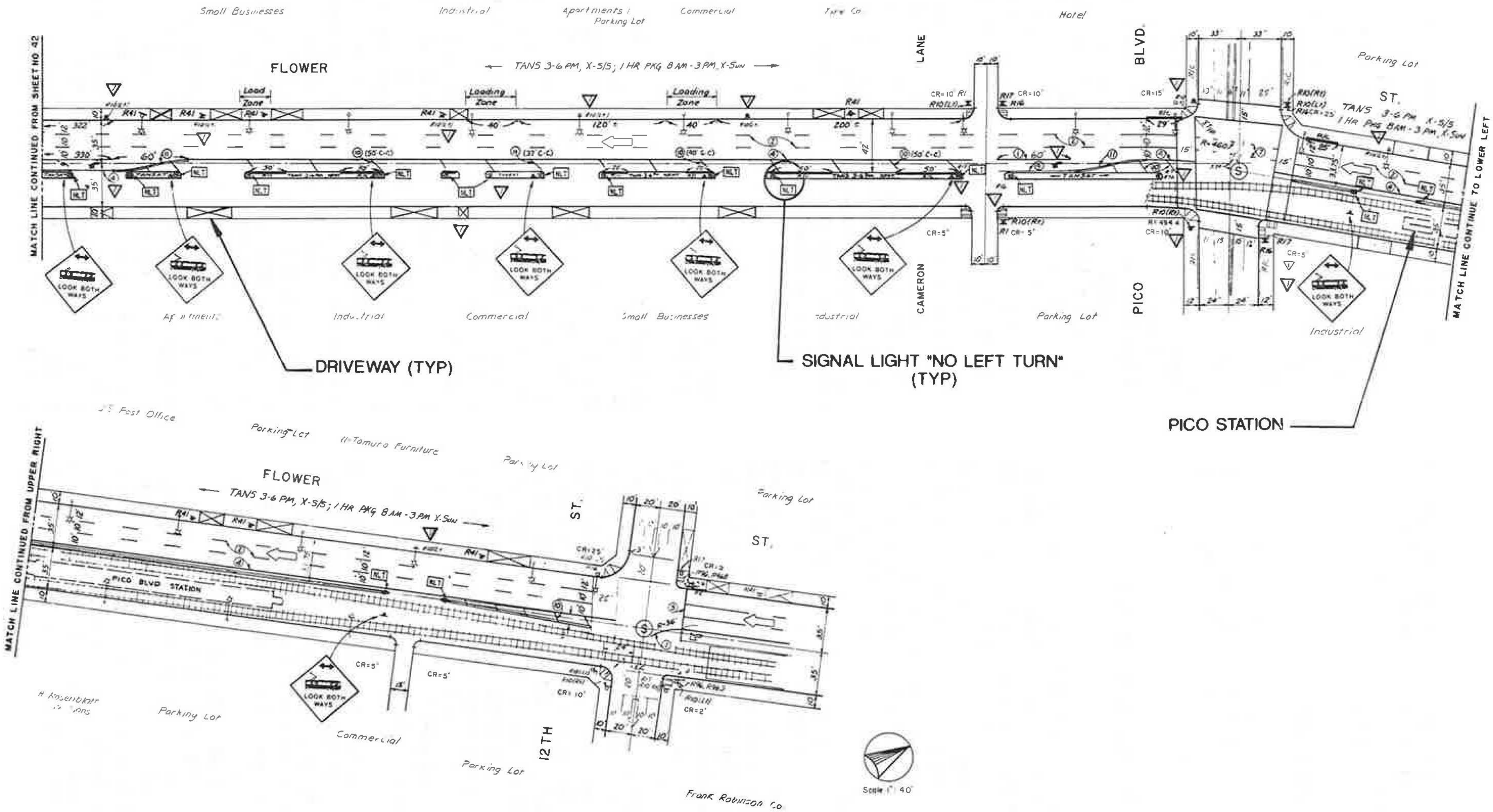

FIGURE 3 **Driveways, No Left Turn signals, and warning signs on a typical block of Flower Street.**

the westbound left turn lane and westbound-to-southbound (away from downtown) movement.

Eventually a "share the misery" program of a 22-ft median trackway, two 31-ft roadways (12-ft curb lane, 10-ft through lane, and 9-ft turn lane), and two 8-ft sidewalks was accepted with reservations by all parties (Figure 4). The agreement on a Washington Boulevard typical section was the most important decision to come out of the Los Angeles CBD approach segment preliminary engineering.

The Blue Line reduced the Washington Boulevard rush hour roadway from six through lanes to four through lanes. LA DOT took two actions to help mitigate the reduction in traffic capacity. First, all driveways and all but one of the intersections with side streets (defined as intersections that did not have an existing traffic signal) were closed to left turns. Automobiles could turn right into a side street or driveway, or could turn right from a side street or driveway onto Washington Boulevard. But automobiles could no longer turn left into or from side streets or driveways or use side streets to cross Washington Boulevard. Railings were installed between the Blue Line tracks at the closed intersections to discourage pedestrians from crossing as well.

Second, LACTC extended LA DOT's Automatic Traffic Surveillance And Control (ATSAC) system to include the traffic signals along the Blue Line portion of Washington Boulevard. The ATSAC system is used to monitor and reprogram traffic signals in real time and had proven itself in the Coliseum area during the 1984 Olympic Games. Bringing the narrowed portion of Washington Boulevard into the system gives LA DOT the ability to monitor traffic volumes and adjust signal timing from City Hall.

Somewhat to the surprise of the designers, the narrowed Washington Boulevard is now operating more smoothly than the wider street did before Blue Line construction. This is in large measure because of the reduced number of heavy trucks on the street. The trucks apparently found alternative routes during construction and have not returned to the narrower roadway. (The house movers, who also occasionally used Washington Boulevard late at night, have also had to find alternative routes.) Congestion has not noticeably increased on the adjacent arterial streets.

Three LRT-related accidents occurred on Washington Boulevard in the 6 months immediately after the start of revenue operations, but no significant LRT-related accidents occurred in the subsequent 12 months.

Passenger Stations

The 1984 Blue Line conceptual design called for low-platform passenger stations. In early 1985 during the general project review associated with the environmental clearance process, LACTC determined that high-platform passenger stations would provide better service to patrons than low-platform stations. High-platform stations allow for quicker boarding and exiting, thus reducing station dwell and total trip time. The increased convenience and reduced dwell time resulting from high-platform stations are important elements in LACTC's campaign to encourage the use of public transit rather than private automobiles. The high-platform stations have the additional benefit of making every car in a light rail train handicapped accessible.

LA DOT supported LACTC passenger station program by finding locations where left turns could be prohibited and the typical section left turn lane width used to widen the track centers around a center platform and access ramp. (Side platforms were considered and rejected for two reasons. First, a center platform could be wider than either of a pair of side platforms. Second, although any high platform in the middle of the roadway is a potentially hazardous fixed object, a center platform would be separated from the through traffic lanes by the width of the trackway. A side platform, on the other hand, would be immediately adjacent to the through traffic lanes.)

Left turns were prohibited from southbound Flower Street into Pico Boulevard, thus providing room north of the intersection for Pico Station. Station access is from the Flower Street east sidewalk. Left turns from eastbound Washington Boulevard into Grand Avenue were also prohibited, providing room west of the intersection for Grand Station. Station access is from the west intersection crosswalk. At San Pedro Street, LA DOT could not justify eliminating any of the left turn movements. The San Pedro Station was instead located 300 ft east of the intersection, east of the westbound left turn pocket. Station access is via signal-protected midblock pedestrian crosswalks from the Washington Boulevard north and south sidewalks. (The crosswalks have separate traffic signals, so that a pedestrian request to cross to the south sidewalk will not cause automobiles in the north roadway to stop.)

The Blue Line inbound and outbound tracks flare from the typical 11-ft-2-in.-track centers to 23-ft-2-in.-track centers at the passenger stations. The tracks are tangent from 50 ft before to 50 ft after the station platform to avoid any vehicle middle overhang clearance problems. All track transition curves start and end with 31-ft-long spiral curves.

Utility Relocations and Coordination with City Projects

Extensive utility conflicts were identified during preliminary engineering. Many of these conflicts were the result of narrowing the sidewalks to provide additional room between the curbs for both a roadway and a trackway.

The major utility under the trackway was a 45-in. brick sewer built at the turn of the century 10 to 11 ft under the centerline of Washington Boulevard. After reviewing videotapes of the sewer, the DPW Bureau of Engineering agreed that the sewer could remain in place. However, all of the sewer manholes had to be reconstructed as offset manholes to permit emergency maintenance access to the sewer without interfering with LRT operations.

The construction of the offset manholes required the relocation of existing utility lines that were otherwise clear of the trackway. The new structures were expensive and, because of the offset, do not allow truck-mounted maintenance equipment to be positioned over the sewer. Because the adjacent properties are already developed, few new sewer connections are anticipated. Any new connections that are made, however, will have to be mined under the LRT track slab. In hindsight, the authors feel we might have been "penny wise and pound foolish" to have worked around the existing sewers under the trackway. We might have been better off replacing

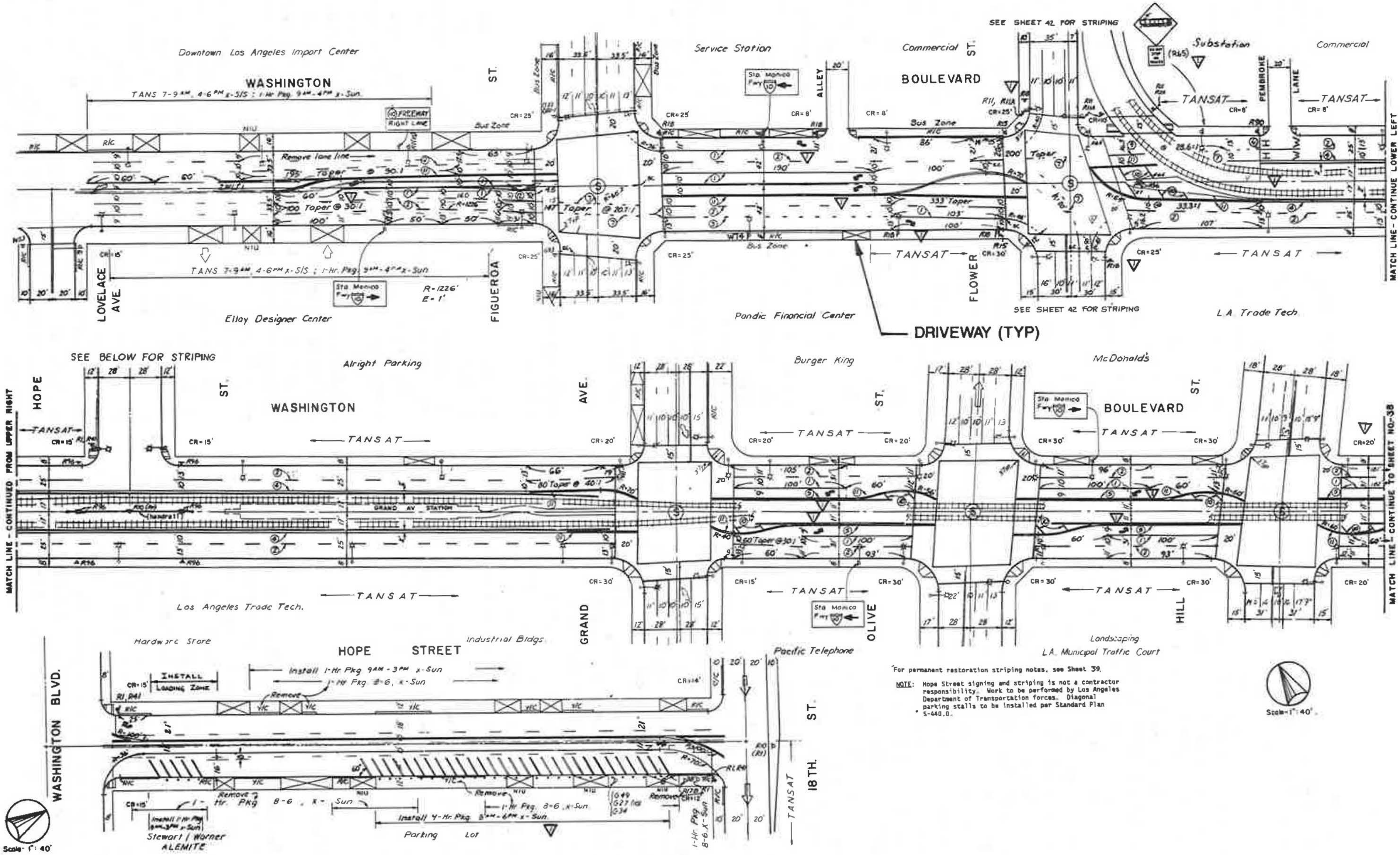

FIGURE 4 Roadway lane layout and trackway on the short blocks typical of the western portion of Washington Boulevard.

the centerline sewers with new pipes on either side of the trackway and solving the sewer problem once and for all.

The major utility conflict outside of the trackway was with a Department of Water and Power (DWP) 34.5 kV distribution line mounted on wood poles on the south side of Washington Boulevard. The existing poles would be in conflict with the widened roadway, and DWP felt that the new 8-ft sidewalk would be too narrow for a relocated pole line. LACTC built a replacement duct bank system under the street and DWP furnished and installed the new conductors as part of DWP's overhead line undergrounding program.

The DPW Bureau of Engineering had a street reconstruction project scheduled for Flower Street between Eighth Street and Olympic Boulevard. The DPW Bureau of Street Lighting had a street lighting reconstruction contract for Washington Boulevard advertised and bid. Both of these capital improvement program projects were canceled and the work assigned to the Blue Line project by task order under the master agreement between the LACTC and the city.

One conflict could not be relocated and required a special waiver from the California Public Utilities Commission (CPUC). CPUC requires that contact wire installed over public streets have a minimum clearance of 19 ft above the roadway. The Interstate 10 Santa Monica Freeway crosses over Flower Street and over an eastbound freeway on-ramp with only 16 ft of clearance. After much analysis CPUC granted a waiver to permit the Blue Line contact wires to pass under the freeway and over the on-ramp entrance. The waiver was conditioned on installation of special signs and an overheight load warning system.

Right-of-Way Acquisitions

The preliminary engineering design confirmed that the existing street right-of-way was generally adequate for the Blue Line Los Angeles CBD approach segment. Additional right-of-way was required for the curves from Flower Street to Washington Boulevard and from Washington Boulevard to the Mid-Corridor private right-of-way, and for two traction power substations. One substation was to have been located at a former service station site that turned out to have petroleum-contaminated soil; the substation was relocated to another site. Right-of-way action also was required to close several driveways on Flower Street and to remove two building canopies on Washington Boulevard that would overhang the street after the sidewalk was narrowed.

FINAL DESIGN

The goal of the final design phase was to prepare construction plans and specifications. The construction documents were subject to review and sign-off by the city to confirm that they correctly implemented the shared right-of-way strategies developed in earlier phases.

Construction documents were prepared for three Los Angeles CBD approach facilities construction contracts: an advance utilities relocation contract; a street reconstruction, station foundation, and embedded track contract; and a station finishes contract. The Blue Line systemwide traction power substation, overhead contact system, and communication/signaling contractors also worked in the segment.

Final Alignment

The Los Angeles CBD approach design speed is generally 35 mph. The design speed is reduced to 8 to 10 mph at the 90 degree turns from Flower Street into Washington Boulevard and from Washington Boulevard into the Mid-Corridor private right-of-way (between the two roadways of Long Beach Avenue). At both of these locations, additional right-of-way outside of the intersection was required to widen track centers (to permit opposing trains to pass) and to permit 120-ft to 150-ft radius curves.

At one intersection on Flower Street and two intersections on Washington Boulevard, the existing street alignment abruptly changes bearing by up to 20 degrees. The change in bearing on Flower Street at Pico Boulevard was easily accommodated in the transition from the Pico Station wide track spacing to the typical narrow track spacing. On Washington Boulevard at Central Avenue, the already narrow sidewalks on the inside of the curve were narrowed up to 6 in. more to maintain roadway width while allowing larger radius track curve. At the tighter Compton Avenue curve, LA DOT omitted the typical section left turn lanes, permitting wider track centers and larger radius curves. The Los Angeles CBD approach track curves are not superelevated, but do have spiral transition curves in advance of all circular curves of less than 10,000-ft radius.

Street Reconstruction

On both Flower Street and Washington Boulevard, the existing sidewalks had to be replaced with narrower sidewalks before trackway construction could begin. The narrower sidewalk and new curb locations forced the relocation of all of the utilities that sit immediately behind the curb, including curb outlets from roof drains; catch basins; water meters and fire hydrants; telephone splice boxes; power poles; street lighting poles; and traffic signal poles. The new foundations for the relocated street light poles and the overhead contact system support poles forced the relocation of additional utilities (such as gas distribution lines) that had been safely under the old sidewalk. All of the existing mature street trees had to be removed and replaced with young trees. Utility relocation and street reconstruction on Flower Street and Washington Boulevard cost approximately twice as much per mile ($9 million versus $4.5 million) as the sum of the right-of-way purchase and railroad relocation costs in the adjacent private right-of-way segment.

LACTC attempted to reach an agreement with the DPW Bureau of Street Lighting (BSL) for the joint use of poles on Flower Street and Washington Boulevard but failed. BSL felt there would be an unacceptable risk to BSL maintenance personnel if street lights were mounted on poles supporting the overhead contact system. (The city of Long Beach, on the other hand, insisted on joint use poles as a condition of using public right-of-way.) BSL redesigned the Flower Street and Washington Boulevard lighting systems using 50-ft tall electroliers, thus minimizing the number of street lighting poles. With the addition of contact wire support poles, however, the total number of poles per block increased.

The combination of removing mature street trees and adding contact system wires and support poles did not improve the appearance of either street. The Long Beach solution—joint-use street light and contact system support poles placed in the median between the Blue Line tracks—is a better solution where right-of-way width and utility policies permit.

As a result of the street widening, all of the traffic signals on Flower Street and Washington Boulevard were replaced. The replacement traffic signals are fitted with additional loop detectors between the rails and additional signal heads for the detection and control of LRVs. LACTC funded preparation of modified traffic signal controller software to support additional signal phases and variable levels of priority for LRVs. The new LRT phase software was installed in all traffic signal controllers along the Los Angeles CBD approach segment prior to revenue operations. The LRT priority software is still under development and is now scheduled to be installed in December 1992.

Trackway Structure and Drainage

The Los Angeles CBD approach tracks are supported by a reinforced concrete track slab. Fire trucks or maintenance vehicles driving on the trackway between intersections are supported by asphalt pavement placed between the rails on top of the track slab. At intersections, motorists crossing the trackway are supported by a second pour of portland cement concrete placed on top of the track slab.

Ballasted track needs to be maintained periodically (track realigned and the ballast rejuvenated) to maintain good ride quality. The Blue Line design criteria recognize that ballasted track is more likely to shift out of position than track supported by a concrete slab. The criteria therefore require a larger spacing (greater allowance for track shift) between parallel ballast-supported tracks than between parallel slab-supported tracks.

Embedded ballasted track is difficult to maintain because the embedding material must be removed to retamp the ballast. The Blue Line embedded track may well have been supported by a track slab even if the trackway were 24 ft wide as originally planned, just to reduce the maintenance requirements. With the "share the misery" 22-ft trackway width, the LA CBD approach trackway had to be supported by a track slab to comply with the design criteria. The 22-ft trackway is too narrow for two Blue Line tracks supported by ballast but is adequate for two tracks supported by a track slab.

The trackway is not crowned. At any longitudinal location, all four running rails have the same elevation. The trackway is separated from the adjacent roadways by a curb. Rainfall collecting on the asphalt embedment would form a large, shallow pond if some form of positive drainage were not provided.

Flower Street has sufficient longitudinal gradient so that drainage is not a problem. Water drains to the low end of any block, where it is intercepted by trackway catch basins. Washington Boulevard has very little longitudinal slope. The Washington Boulevard top-of-rail elevations match the roadway elevation at all intersections. Between intersections, the top of rail profile rises to a high point in the middle of the block, then falls to match the roadway at the next intersection. This false grading provides longitudinal slope to drain runoff to catch basins typically located in the trackway on either side of intersections.

CONCLUSIONS

The Los Angeles County Transportation Commission and Los Angeles (City) Department of Transportation were able to reach an agreement to dedicate a portion of the existing public street right-of-way to exclusive transit use. This agreement resulted in a permanent reduction in street capacity that could only be partially mitigated by transportation system management measures. That this happened in Los Angeles, arguably one of the more automobile-oriented cities in North America, should give inspiration to transit planners everywhere.

The side-running alignment on Flower Street and the median alignment on Washington Boulevard are successful. For various reasons automobile congestion on Flower Street and Washington Boulevard has decreased since Blue Line construction. No significant LRT-related accidents were reported on Flower Street or Washington Boulevard in 1991.

The construction resulting from the agreement was expensive—in the order of $20 million per mile for civil works alone. To optimize use of the public right-of-way for both LRT and automobiles, it was necessary to relocate most utilities and completely reconstruct the roadway and sidewalks. If a transit private right-of-way (not shared with an existing roadway or major utilities) is potentially available, planners should look hard at purchasing the private right-of-way. The Blue Line private right-of-way acquisition and railroad relocation costs per mile were approximately half the cost per mile of utility relocation and street reconstruction on Flower Street and Washington Boulevard.

If a transit agency plans to use street right-of-way for an LRT project, it is imperative that the traffic agency be brought into the planning process at an early phase. The traffic agency must accept the concept of reducing automobile capacity to increase the total number of riders or trips on all modes. Both the transit agency and the traffic agency will want to reduce conflicting movements to improve safety and operating speed. This common interest should be the basis for the many compromises that will be required to implement the project successfully.

Because of the removal of mature street trees and the addition of contact system wires and poles, LRT projects have the potential to diminish the appearance of the street. The transit agency and all participants in the transit project should make a commitment to aesthetic design.

Blending LRT into Difficult Traffic Situations on Baltimore's Central Light Rail Line

JACK W. BOORSE

Once a decision is made to use existing street rights-of-way as part of a new light rail transit (LRT) line, it is almost inevitable that the rail operation will have some negative impact on highway traffic. Impact of this type is likely to be more severe where the new rail line is required to pass through an intersection or other location where the existing traffic is already experiencing operating difficulties. Although this negative traffic impact usually cannot be totally avoided, it can often be reduced to a reasonable and tolerable level. At those locations where the impact is significant, mitigation often requires imaginative design that reflects sensitivity to the inherent strengths and vulnerabilities of each mode. This was the case at a number of locations on Baltimore's Central Light Rail Line.

Baltimore's Central Light Rail Line (CLRL) is a project of the Mass Transit Administration (MTA), the Maryland state agency responsible for transit service in the Baltimore metropolitan area. Now in its early stages of operation, Phase 1 of this new light rail transit (LRT) line connects the northern suburbs with those in the southeast via a route that passes directly through the heart of the city (Figure 1). In the outlying areas the tracks have been located in their own separate right-of-way. In downtown Baltimore the CLRL has been constructed largely within existing street beds.

Proponents of LRT frequently point to its ability to operate successfully in many environments. The more enthusiastic among them like to say, "Light rail goes everywhere." Although that may not be literally correct, it is close. LRT can and does operate safely in situations where other fixed guideway modes cannot. Many of these situations involve sharing the public streets. Designs for LRT operation within the public street system will often be more successful if the LRT operations are blended into preexisting traffic patterns rather than being simply superimposed upon them without full consideration of the negative effects.

The designers of the Baltimore CLRL were faced with the task of fitting a railway into a number of existing street designs that had been developed or had evolved in response to dominant traffic patterns. More often than not, some modification of street design was unavoidable, but the traffic patterns that had led to those designs could not be disregarded. This discussion will address locations in outlying areas and downtown where, for one reason or another, specific traffic patterns and LRT operation had to coexist.

Parsons Brinckerhoff Quade & Douglas, Inc., 1500 Walnut Street, Suite 305, Philadelphia, Pa. 19102.

In the outlying areas some of the interfaces between the CLRL tracks and the roadway network are simple crossings and can be controlled solely by conventional, railroad-type flashers and gates. Others, because of proximity to sensitive intersections, required some innovative redesign. The first of the two locations selected for discussion lies within Baltimore City at the Clipper Mall Industrial Park. The other is in Ferndale south of the city in Anne Arundel County. At the latter location the CLRL is still under construction and passenger service has not yet commenced.

The more difficult challenges were found in downtown Baltimore where the CLRL was constructed almost entirely within the right-of-way of existing public streets. In the central business district (CBD) the streets follow the points of the compass in a grid pattern with an occasional variation. (A few streets run diagonally for short distances.) A half-mile of one east-west street, Lexington Street, has been converted into a pedestrian mall and one north-south street, Howard Street, is closed for a few blocks to all but pedestrian and bus traffic. The majority of the streets are less than 45 ft in width and are one way in the customary alternating pattern. Two adjacent north-south streets, Eutaw and Howard Streets, were never included in the pattern and remained two way.

The street that was most closely aligned with the logical route of the CLRL to the south and also well positioned to connect with the route to the north was Howard Street. As mentioned earlier, in the heart of the CBD Howard Street carried no general traffic at all. Beginning in the mid-1980s it was restricted to bus and pedestrian traffic. This made it an inviting candidate for the CLRL route. However, both north and south of the restricted area Howard Street has quite different characteristics. At the south edge of the CBD it forms a direct, end-to-end extension of Interstate 395, a freeway spur of Interstate 95. At the north edge of the downtown district, Howard Street is a heavily trafficked arterial connector that carries traffic from Martin Luther King (MLK) Boulevard to a major bridge across the Jones Falls (which is actually a river), Interstate 83 and US-1. Following an exploration of several other north-south streets as possible routes for the CLRL and with recognition that interface with existing traffic flows would have to be addressed, the Howard Street route was selected for the CLRL.

In the southern portion of the downtown area a double-track LRT line has been built along the west side of Howard Street in a trackway created by narrowing the west sidewalk and removing one traffic lane. North of there, where traffic

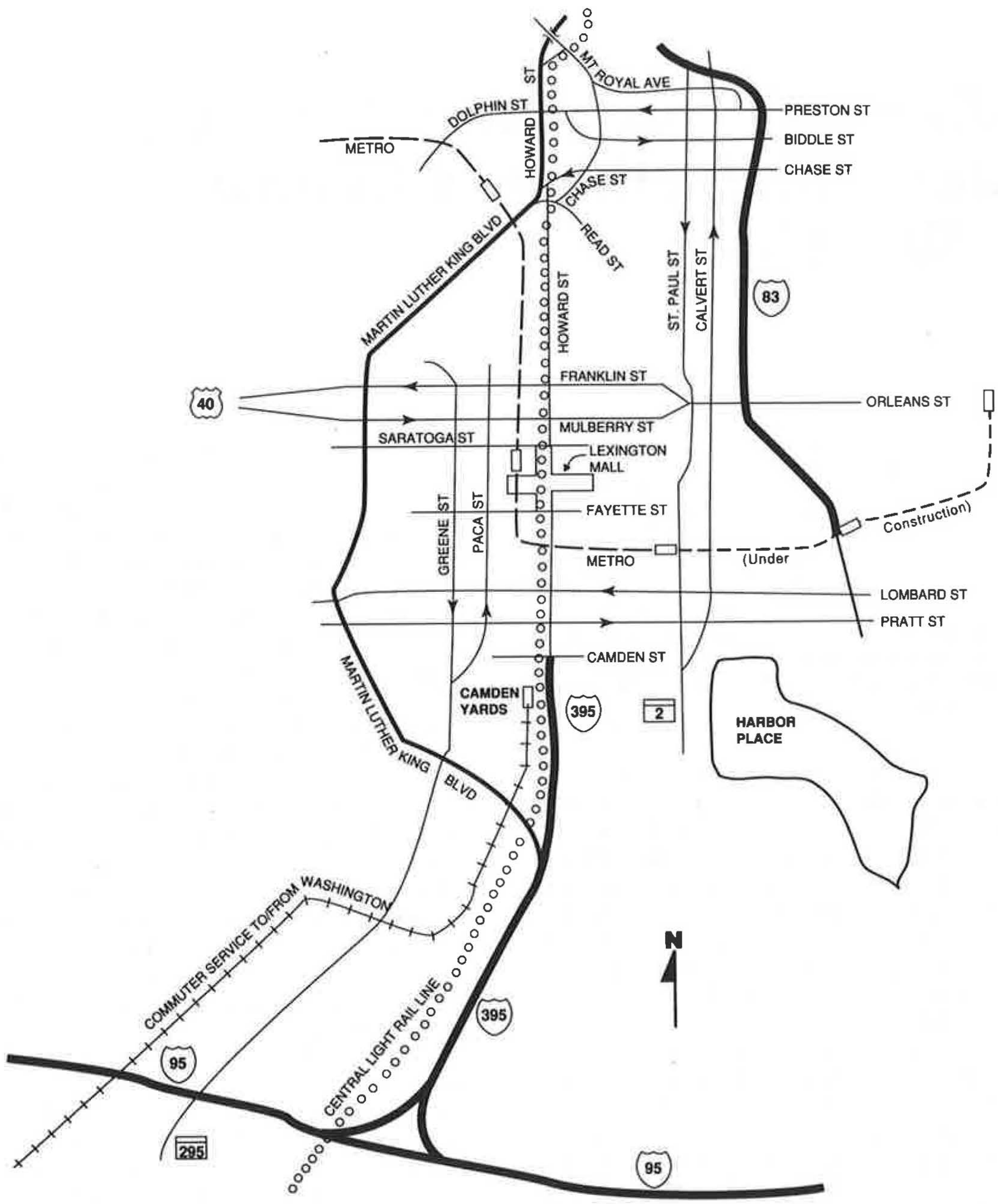

FIGURE 1 Alignment of the CLRL in downtown Baltimore.

other than buses and pedestrians was already excluded, the southbound buses have now also been diverted to make way for the southbound trains. In the northbound direction, within the traffic-free area, the trains and buses coexist, but each mode has a separate lane. To the north of that area the street widens and northbound general traffic is permitted to enter and mix with the buses whereas the tracks remain in exclusive lanes. Still farther north the trackway shifts to the center of the street and forms a median separating the two directions of general traffic. At the very north end, for the last quarter mile before they turn northeastward along Dolphin Street, the tracks move to a position east of the east sidewalk. After following a similar alignment for one block along Dolphin Street, they cross Mt. Royal Avenue onto their own right-of-way and exit the downtown area. Most of the turns from Howard Street onto cross streets that would have crossed the tracks have been prohibited. Those that remain are governed by special signal control.

Nowhere along this route will the trains operate in mixed traffic in the manner of the traditional streetcar. Nevertheless, they cross 16 intersecting streets and, at two locations, they transpose positions with rubber tired vehicles in parallel traffic lanes. Two of the more complex and challenging design problems in the CBD, Lexington Mall and Howard Street, and MLK Boulevard and Howard are discussed.

CLIPPER MILL INDUSTRIAL PARK

One special challenge was the T intersection of Union Avenue, Seneca Street, and Clipper Road in a mixed residential and industrial area a few miles north of the center of town.

The path selected for the CLRL was an existing railroad line that parallels Clipper Road and crosses Union Avenue just east of the intersection. At the time that the design effort began this line was owned and operated by the Consolidated Rail Corporation (Conrail). It was a single-track remnant of the Pennsylvania Railroad's Northern Central Line that had previously linked Baltimore and Harrisburg, Pennsylvania, with a double-track line. Following World War II both passenger and freight activity on the line diminished. Then in 1972 floods ensuing from a hurricane severed the line between the two cities and forced discontinuance of the remaining passenger and through freight service. A single track was quite sufficient to handle the surviving local freight and the northbound track was removed.

From midcentury onward the industries in the vicinity of the crossing had made increasing use of truck transport and those trucks became increasingly large. Because of their greater size it became difficult for them to turn from narrow Union Avenue onto an even narrower, privately owned industrial roadway that serves the commercial properties east of the tracks from an intersection with Union Avenue just east of the crossing. Widening of that roadway to the east was not an option because the edge of the paving was already within inches of a factory building wall. Widening to the west would also have been impossible if the railroad had remained double-tracked. However, the removal of the northbound track had rendered its bed available for other purposes. The mechanism that operated the crossing gate that controlled the westbound Union Avenue approach was a major impediment to the turning of the longer trucks and was shifted away from the aforementioned factory building to a location just east of the surviving track. Additional paving was placed on the abandoned northbound track bed to produce a wider roadway and provide more maneuvering room for the truck turn. In essence, the crossing was reconfigured to accommodate only a single track and this was the condition that existed when the MTA purchased the railroad from Conrail (Figure 2).

Although the CLRL has some single-track sections, more than half of the route will be double-tracked to provide essential operating flexibility. The Union Avenue crossing is within one of the line sections where double track is needed. This meant that, to accommodate LRT operation, the northbound track had to be restored and that the crossing had to be modified once more, this time back to a double-track configuration. The challenge was to carry this out without recreating lateral clearance restraints that would have made it virtually impossible for a modern tractor trailer to turn into and out of the private roadway.

A solution was found by providing a new location for the connection between the private industrial roadway and the public street system. In this part of Baltimore the street system has a very irregular configuration largely because of topography. Union Avenue ends just west of the crossing and, to continue farther, through traffic must turn to the north on Clipper Road. In the reverse direction through traffic must approach southward on Clipper road and turn eastward on Union Avenue. Seneca Street forms the third leg of the intersection of Union and Clipper, but leads only to a landlocked group of residential streets and is of no use to through traffic. Thus for traffic destined to or originating from businesses served by the private roadway, it was determined that a connection of that roadway to Clipper Road would serve just as well as a connection to Union Avenue. This is the design approach that was adopted (Figure 3).

In conjunction with LRT track construction and the restoration of a double-track crossing at Union Avenue, an additional crossing of the rail line was built about 100 ft north of Union Avenue. This new crossing connects the private roadway on the east side of the tracks to Clipper Road on the west side. The short section of that private road between the new crossing and Union Avenue has been abandoned.

Although the new roadway geometry creates an unorthodox double crossing of the tracks for traffic arriving from or exiting to Union Avenue, it permitted restoration of the double-

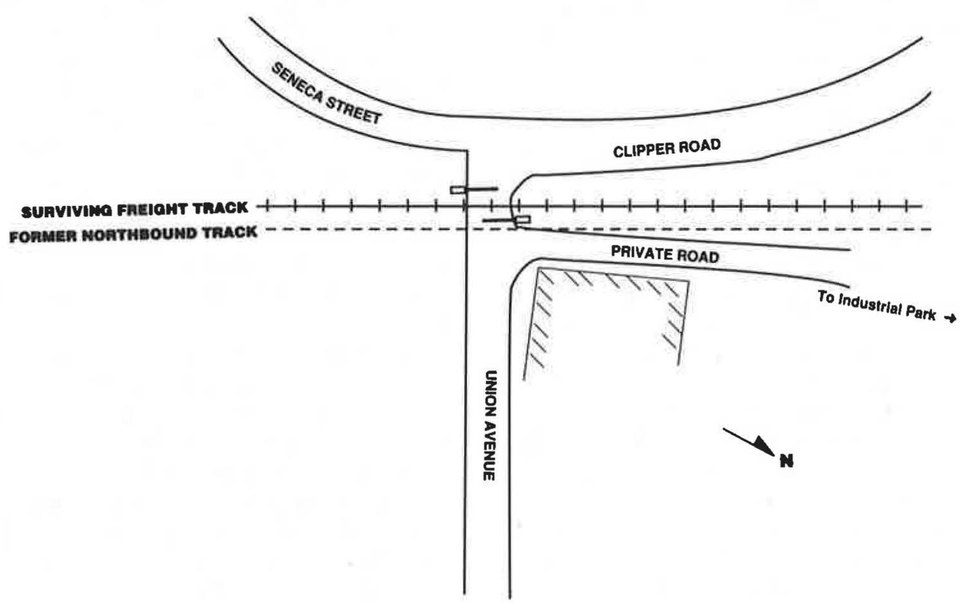

FIGURE 2 Street configuration at Clipper Mill Industrial Park when the railroad right-of-way was purchased.

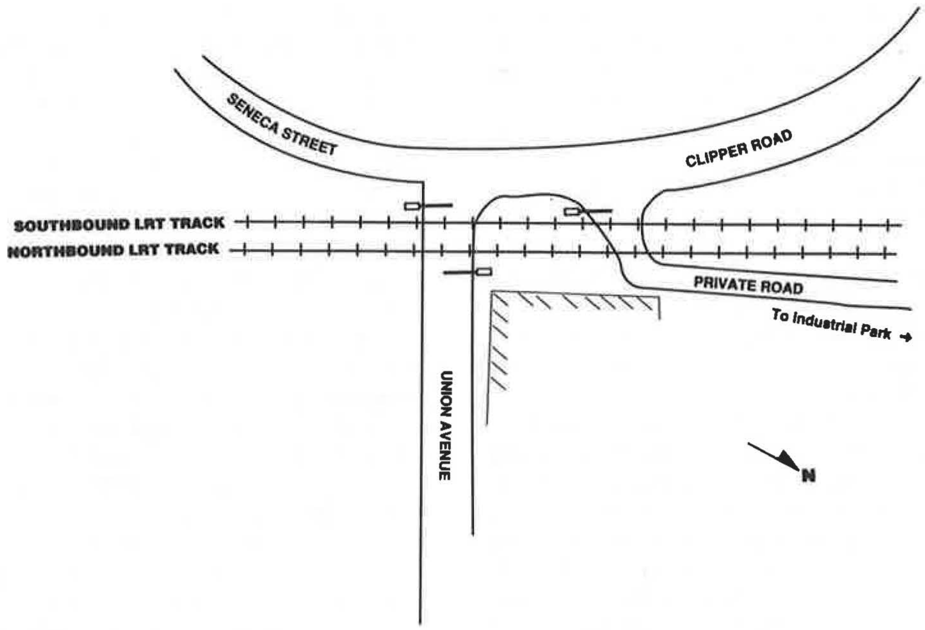

FIGURE 3 Street configuration at Clipper Mill Industrial Park when the CLRL was completed.

track crossing at Union Avenue while preserving access to the properties served by the private roadway. In fact this access is actually improved because the new crossing is designed for trailers longer than those that were able to turn, without a backup maneuver, to and from the old Union Avenue connection.

FERNDALE

Another location that required significant design modifications is in Anne Arundel County, about a mile from the south end of the line, along the Baltimore and Annapolis (B&A) Railroad in the community of Ferndale. Ironically the B&A Railroad once operated electric trains to and from downtown Baltimore, but in recent years it has served only as a local freight connector with but one significant customer. The MTA acquired the B&A Railroad and is reconstructing the trackage to accommodate LRT operation.

As the tracks pass through Ferndale they are paralleled by a public highway on each side, Baltimore-Annapolis (B-A) Boulevard on the east and Broadview Boulevard on the west. Both are two-lane roadways carrying two-way traffic (Figure 4). The traffic volume on Broadview Boulevard, a county road, is light. However, on B-A Boulevard, which is Maryland State Route 648, it is quite substantial. In the heart of the Ferndale community a cross street named Ferndale Road approaches from the west on a course perpendicular to the tracks. It intersects Broadview Boulevard, then crosses the tracks and ends in a T-type intersection with B-A Boulevard, all within a distance of less than 200 ft. Its intersection with B-A Boulevard is controlled by traffic signals, but its intersection with Broadview Boulevard is controlled by stop signs.

Over time it had become customary for eastbound traffic on Ferndale Road frequently to queue on the tracks while awaiting a green signal at B-A Boulevard. This was not problematic because of the nature of the freight operation on the B&A Railroad. Trains operated only a few times per week and approached at speeds under 15 mph. They stopped at the crossing and proceeded under the control and protection of a flagman.

When LRT operation begins passenger trains will operate four times per hour in each direction, interrupting traffic on the average of every 7.5 min for 18 or 19 hours per day, and they will carry no flagman. In light of these operating conditions attention had to be given to the queuing on the tracks.

In addressing this, the first approach was to consider some type of control that would stop eastbound traffic short of the crossing when the traffic signal for Ferndale Road at B-A Boulevard was red or about to change to red. That would have handled the track crossing itself, but it would have created a queue across Broadview Boulevard. Also, vehicles approaching from both directions on Broadview Boulevard and turning east would have needed to be stopped in some manner before they entered the intersection and the track crossing whenever they would have been unable to clear both of these potential conflicts before losing the green signal at B-A Boulevard.

All of this could not have been achieved with just signing and pavement marking. It would have necessitated signalizing the Broadview and Ferndale intersection. That in turn would have generated a new problem of westbound queuing on the tracks. To address that problem it would have been necessary during each signal cycle to stop vehicles turning from B-A Boulevard before they began to execute that turn whenever they would not have been able to clear the tracks before losing their green signal at Broadview Boulevard.

In theory, all of this would have been possible, but a five-phase signal cycle would have been required to time-separate

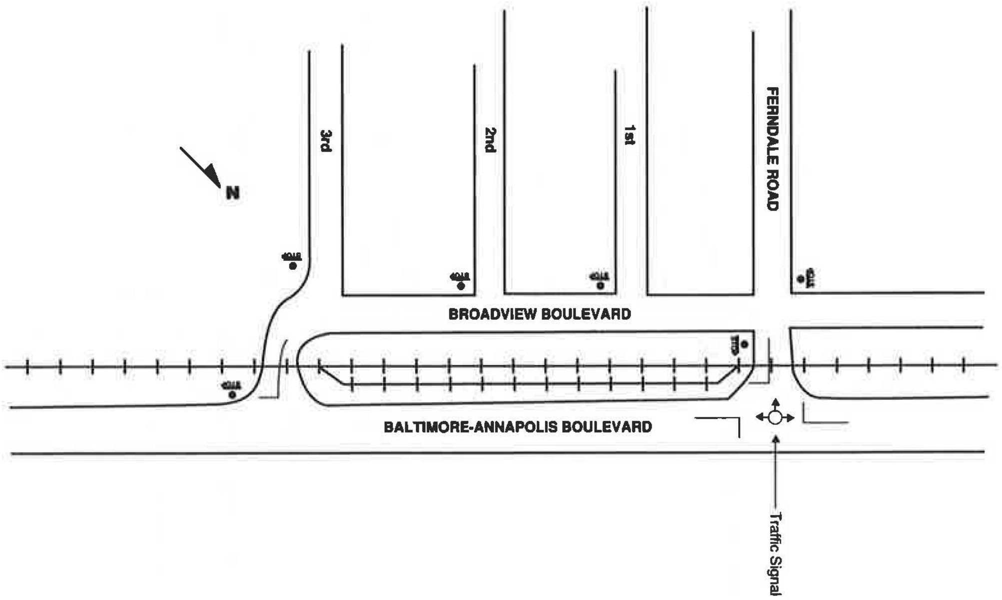

FIGURE 4 Street configuration in Ferndale when the railroad right-of-way was purchased.

all of the conflicting traffic movements. This would have resulted in an extremely inefficient signal timing that, almost inevitably, would have produced severe traffic congestion.

The root of the problem was the queuing of eastbound traffic on Ferndale Road. The method eventually chosen to eliminate the eastbound queuing was to eliminate the eastbound traffic.

The closest grade crossing to Ferndale Avenue is Third Avenue, two blocks to the south. This crossing posed no particular problem with eastbound queuing because of the roadway configuration, but with frequent LRT train operation it required new and special signalization that would hold traffic turning west from B-A Boulevard on that road whenever a train was approaching. Because B-A Boulevard is somewhat narrower there, physical widening would also have been necessary to provide separate standby lanes for the turning traffic.

In other words, the Third Avenue crossing could easily handle eastbound traffic and LRT operation, but including westbound traffic would have caused difficulty. At the Ferndale Avenue crossing, westbound traffic could be handled relatively easily, provided that eastbound traffic could be accommodated elsewhere.

Once all of this was recognized, the solution became apparent. A design was developed to discontinue two-way traffic on both crossings by making the short portions of Ferndale Road and Third Avenue between B-A and Broadview Boulevards one-way westbound and eastbound, respectively (Figure 5). The traffic displaced from each crossing could be handled at the other without difficulty. Although the two roads were farther apart than a normal one-way pair, the concept was endorsed by the county traffic engineer and was included in the final design.

As a result of these changes highway users will have better controlled and less congested movement to and from B-A Boulevard, and the trains will cross free of any traffic queues on the tracks.

LEXINGTON MALL

The exclusive bus and pedestrian section of Howard Street mentioned previously is part of what is known as Lexington Mall, a "plus sign"-shaped, traffic-free sanctuary created by removing all vehicle traffic from a three-block section of Lexington Street and all but bus traffic from a two-block stretch of Howard Street.

Howard Street has a general width between curbs of 44 ft, but where it passes through the mall area this width was reduced to a nominal 33 ft when the Lexington Mall was created (Figure 6). The purpose of this reconfiguration was to produce wider sidewalks and to facilitate pedestrian movement across Howard Street along the Lexington axis. This pedestrian-friendly design is considered by the MTA to be important and the CLRL had to be designed to retain this feature.

Equally important was the need to provide an LRT station in the mall area, the most pedestrian-oriented part of downtown Baltimore. Additionally the mall offers the shortest and most attractive walk for those passengers who transfer between the CLRL and the Lexington Market Station of the Metro, Baltimore's subway system. Not having a station on the CLRL at Lexington Mall was not an option, but the 33-ft width of Howard Street precluded any type of trackside platform.

The only way to satisfy all of these conditions was to construct the northbound track next to the east curb and the southbound track next to the west curb so that the two sidewalks could serve as passenger platforms. This design produced no problem in the southbound direction because southbound general traffic had already been removed and southbound bus operations were being relocated in favor of the rail service. The natural position for the southbound track was against the west curb with the sidewalk serving as the station platform. However, the northbound direction did present a problem.

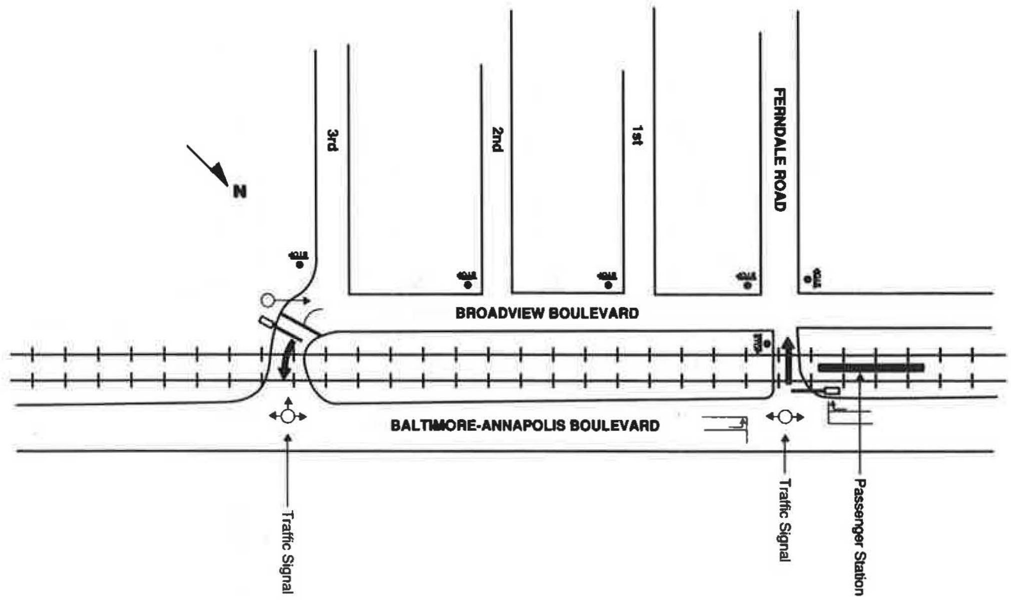

FIGURE 5 Street configuration in Ferndale when the CLRL construction is completed.

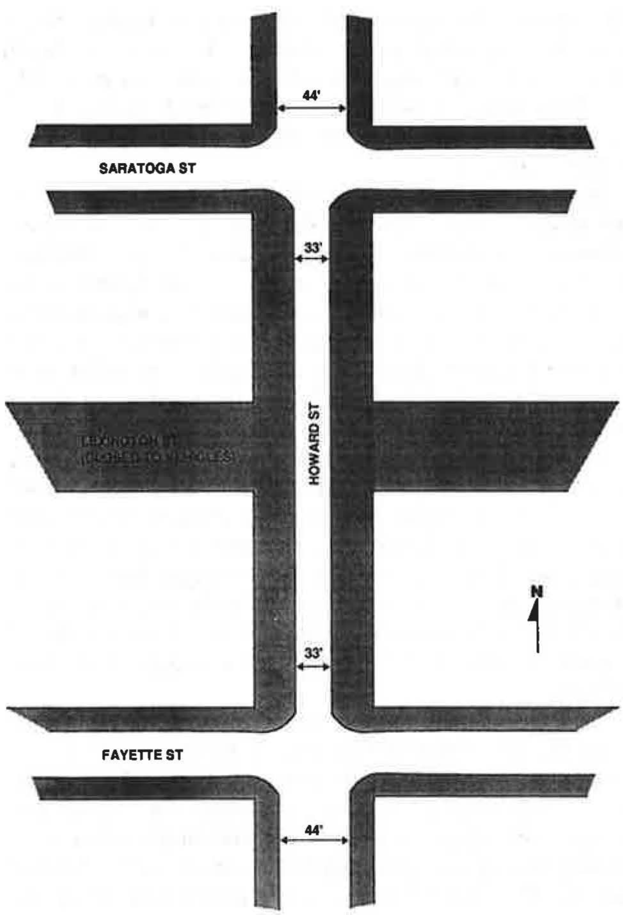

FIGURE 6 Curb and sidewalk configuration in the Lexington Mall area.

Northbound bus service was not being diverted and a stop at Lexington Mall was deemed as important for that service as it was for the LRT service. The 33 ft between curbs on Howard Street translates into three 11-ft lanes, one for the southbound trains, one for the northbound trains, and one for the northbound buses. Obviously one of those three lanes had to be positioned in the middle, not adjacent to either sidewalk. Yet both the northbound trains and buses needed access to that sidewalk to board and discharge passengers.

The solution chosen was to retain the existing northbound bus stop south of the Lexington Street walkway and to establish the northbound LRT stop north of the walkway (Figure 7). Between Fayette Street and Lexington Street, where the northbound buses load and unload from the east curb lane, the northbound trains can move in the center lane past the stopped buses. North of Lexington Street, up to Saratoga Street, the northbound trains shift to the right lane and stop at the east curb while the buses shift left and pass by in the center lane. North of Saratoga Street, where Howard Street resumes its normal 44-ft width, the trains shift back to the west side of the street and the buses, mixed with general traffic that turns on from Saratoga Street, continue northward on the east side.

Operationally this is a sound concept, but it entails crossing the paths of the trains and the northbound buses twice, once to bring the trains to the east curb and a second time to return them to the west side of the street adjacent to the southbound track. These crossings occur at intersections. The first crossing is at Lexington Street, which, although not open to vehicle traffic, is signalized to control and protect pedestrian traffic. The second crossing occurs a block to the north at Saratoga Street, which is signalized conventionally.

To control the movements of the northbound trains and buses across the paths of each other and to control the conflict

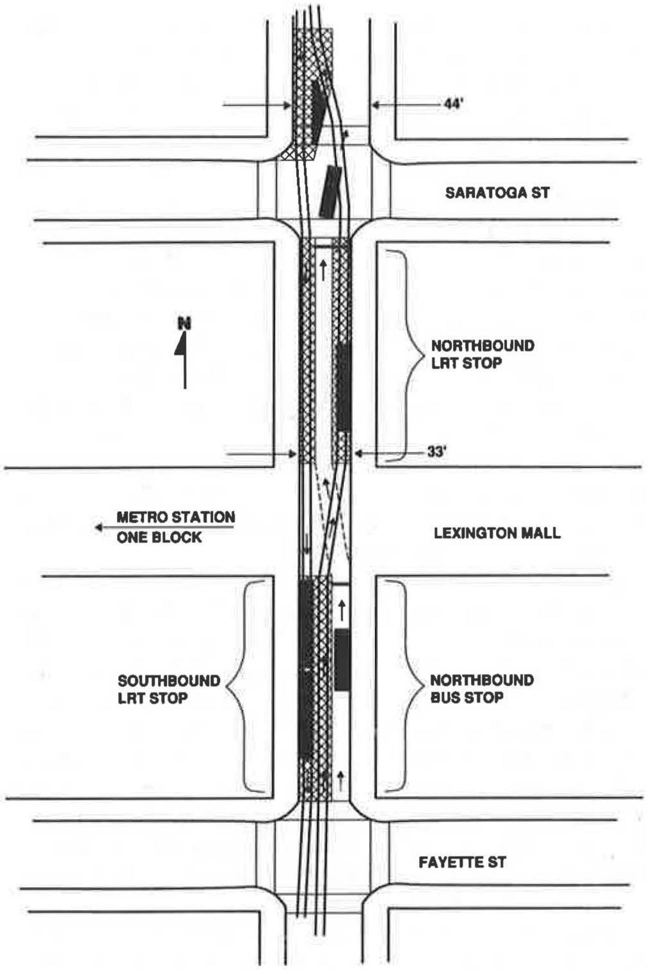

FIGURE 7 Track, lane, and transit stop configurations on Howard Street within the Lexington Mall.

of both with the cross traffic, the two-phase traffic signals have been converted to three-phase signals. Electrically this signal modification was not a problem. A number of downtown intersections require three phases and the computer-driven signal equipment can handle the extra phase.

The problem arose in the design of the signal display. The drivers of the rubber-tired vehicles and the operators of the trains approach the signals side by side in immediately adjacent lanes. When the cross street (Lexington or Saratoga) is permitted to move, both of these northbound Howard Street lanes have a stop signal. During that phase no harm would be done if the operator of a vehicle in one lane misinterpreted the signal for the other lane as his or her own because both lanes would be required to stop. However, during the other two phases, when the cross street is stopped, it is essential that each of the two northbound lanes have its own separate and discrete signals because the traffic in each must cross that in the other just beyond the intersection. Thus it is vital that the vehicles in each lane be clearly required to stop whenever those in the other parallel lane are permitted to move. The signal system had to be designed to time-separate those two movements.

The common method of restricting the lateral angle of visibility with louvers or lenses (optical programming) was considered, but the difference in viewing angle between the two lanes is insufficient to make the "wrong" signal reliably invisible. There was no choice but to accept that all northbound signals would be visible to both lanes and to provide displays that are different in appearance.

At the Saratoga Street intersection the nontrack lane is legally open to general traffic, and it was obvious from the beginning that control of that lane had to be by conventional, circular red, yellow, and green signals. This meant that the northbound track lane had to be the one controlled by some different indicator.

Very brief consideration was given to using color light signals with the lenses masked to display a special shape, such as the letter T or X. However, it was feared that this format would not be sufficient different to clearly indicate to drivers of the rubber-tired vehicles that they were not to be governed by the specially shaped signals. This general design is used on some Pacific coast systems with results that have not been encouraging. Even when white was substituted for green on one system, obedience was far from perfect because, apparently, some motorists moved when they saw a red T signal extinguished. After due consideration it was decided that for the Baltimore system the signals controlling the LRT movement must contain no colors or other elements of a conventional traffic signal whatsoever.

The design finally chosen uses a positioned bar rather than a colored light. A vertical bar indicates proceed, a horizontal bar indicates stop, and a diagonal bar warns of an impending change from the former to the latter (Figure 8). The color of the bar is the same in all positions, but that color is not red, yellow, or green. The standard railway signal color of lunar white was selected for that purpose.

The finished product displays to the highway users conventional signaling, which provides complete protection from train movements and requires no special interpretation. To the train operators it displays separate standardized indications that clearly indicate when they may move without interference. This enables the operators of both types of vehicles to determine when it is safe to enter a zone of potential conflict even though they approach the zone in parallel and immediately adjacent lanes.

FIGURE 8 The three aspects of the positioned bar LRT signals.

HOWARD STREET AND MARTIN LUTHER KING, JR. BOULEVARD

Without question the most challenging location in the entire CBD for the introduction of LRT trackage was the 350-ft section of Howard Street that encompasses its intersections with Chase and Read Streets at the south end and with Martin Luther King (MLK) Jr. Boulevard at the north end (Figure 9). The nature and function of the downtown portion of Howard Street has already been described, but from this short block northward Howard Street is quite different. It is 55 ft wide and carries significant traffic volume. A substantial portion of that volume is traffic that, south of that block, is handled by MLK Boulevard, a six-lane surface arterial that carries much of the north-south through traffic around the west edge of the city's heart. At present northbound MLK Boulevard essentially ends at Howard Street. In the long-range plan MLK Boulevard will continue on beyond Howard Street in a northeast direction, but at this time traffic must proceed over the regular street system.

Nominally half of the outbound traffic on MLK Boulevard turns northward on Howard Street. In the reverse direction an extremely high proportion of southbound Howard Street traffic turns right onto MLK Boulevard. In the initial planning of the CLRL it was hoped that this high traffic location could be bypassed entirely by the LRT route. However, problems of a different nature precluded use of the alternative path for the tracks and the Howard/MLK challenge had to be met head on.

As stated earlier, at some future date the city of Baltimore expects to extend MLK Boulevard, but a number of community and right-of-way acquisition issues will have to be resolved. At the time when the final design of the CLRL began the existing "interim" configuration of MLK Boulevard was the one with which the LRT operation had to blend.

The southbound direction (geographically southwest at this point) of MLK Boulevard is essentially completed from a point two blocks northeast of the Howard Street intersection. However, the northbound portion ends a short block southwest of Howard Street. From there outbound traffic is forced to turn eastward onto Read Street to its intersection with Howard and Chase Streets, beyond which there is a choice. The portion of that traffic destined to east and northeast continues eastward on Chase Street, at least for a few blocks, and then disperses. The portion destined for the north turns onto Howard Street but, at the time when LRT final design commenced, this was not a direct turn but rather a "jug handle"-type maneuver. Two parallel lanes of traffic, after executing the mandatory half-right turn onto Read Street then turned 90 degrees to the left, still in two lanes, onto Howard Street and proceeded northward across the completed southbound section of MLK Boulevard. Needless to say, traffic movement through these two separate, but interrelated, Howard Street intersections was less than smooth.

Constraints on property acquisition as well as both street and track design requirements meant that the tracks must remain in the center of Howard Street as far north as the Read/Chase streets intersection. North of MLK Boulevard it was possible to position them east of the east curb of Howard Street, which left the adjacent street geometry undisturbed. This required a transition from center to side that resulted in a track alignment between the two intersections that placed the rails within the paved portion of Howard Street that was also used by the traffic following the "jug handle" route from MLK Boulevard onto Howard Street and by northbound Howard Street through traffic.

Although it was not particularly desirable, a plan was developed to accomplish this but leaving the geometry of the streets untouched. This plan used signals to time-separate the two modes where they shared the same physical space in

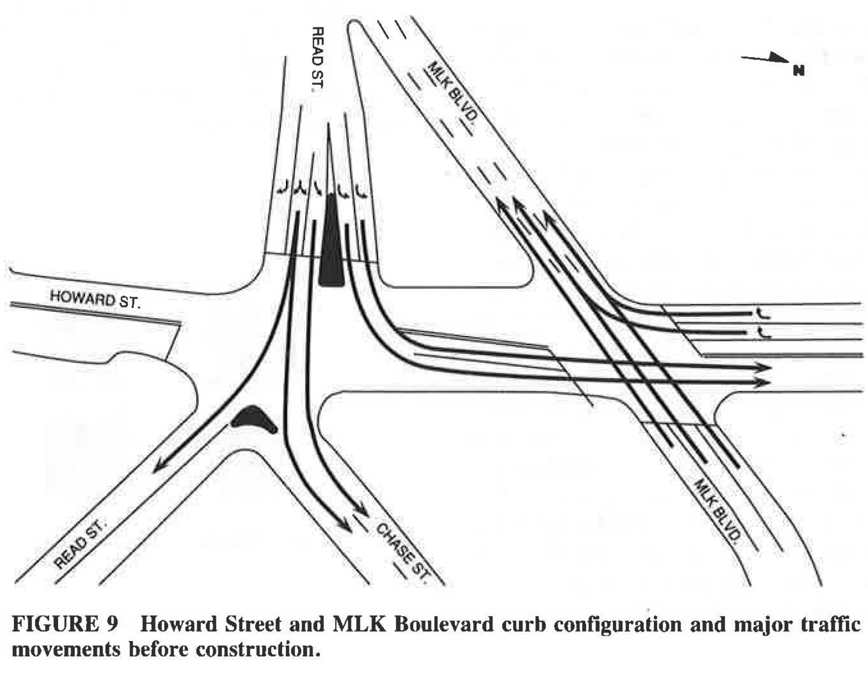

FIGURE 9 Howard Street and MLK Boulevard curb configuration and major traffic movements before construction.

the short section of Howard Street between Read/Chase streets and MLK Boulevard. These interrelated intersections were already overloaded in the peak hours, particularly in the afternoon, and adding an additional signal phase for the rail movement obviously would have exacerbated the situation. Of even greater concern was the possibility that some northbound traffic might be stranded between the two intersections during the portion of the signal cycle intended for exclusive movement of the trains through this area. This could have caused the train to lose an entire signal cycle or to enter this short block behind the stranded vehicles and possibly become stranded itself, resulting in a blockage of cross traffic.

These concerns led to the development of three alternative plans that, unlike the original plan, called for some modification of the street geometry, although they still avoided acquisition of any significant amount of private property. The three new plans were then compared against the original plan and against each other.

By the usual methods of measuring traffic capacity for signalized locations the levels of service (LOS) at the two intersections were, as implied earlier, at or near the bottom of the scale. More significantly those methods were not precise enough to measure the differences in efficiency of the four plans being evaluated. An unconventional method was developed to achieve this.

Signal phasing was developed for each of the plans, tailored to the geometry of that plan and not exceeding three phases at either intersection. (One of the plans did propose a four-phase operation at the more lightly trafficked [south] intersection by using the signal controller at the north intersection to provide the fourth phase.) Baltimore's computer-driven downtown signal system is unusual if not unique. For all intents and purposes it cannot feasibly provide more than three phases at any one intersection. Even without that constraint, the advisability of a four-phase signal timing at an intersection already operating at or above capacity was questionable.

During both peaks the traffic signals in the CBD operate on a 110-sec cycle, which is the longest cycle deemed practical considering the diversity of requirements at more than 100 other downtown intersections that are part of a common system. This translates into 33 cycles per hour.

The next step was to determine the passage time for each movement (general traffic and LRT) through one or both intersections, whichever was applicable. Based on the 33 cycles per hour, traffic volumes were translated into vehicles per cycle and from that, using industry-accepted methods for determining vehicle departure headways, the passage time was calculated. For LRT movements, trains of maximum length (three cars) were assumed and their performance characteristics when fully loaded were used to compute their passage time.

When this was completed the movement requiring the longest time in each phase was identified and the sum (under each plan) was calculated. This sum was, in essence, the cycle length for each plan that would have been necessary to accommodate all vehicles passing through the intersection(s) without requiring some to wait for the next cycle.

In all cases this sum exceeded 110 sec at one or both intersections, which came as no surprise. The purpose of the process was not to confirm that theoretical capacity was exceeded, but rather to provide a measurement of the relative efficiency (or inefficiency) of the four plans. The most efficient plans were those with their sum closer to 110 sec. Other factors, such as relative cost and the likelihood of stranding vehicles on the tracks at the end of a signal phase, were also included in the evaluation.

The plan finally selected was one that created a new, two-lane, northbound roadway on an unused piece of city-owned property at the northeast corner of Howard and Chase Streets (Figure 10). This new roadway accommodated northbound traffic and freed the northbound side of Howard Street itself for the exclusive use of the trains.

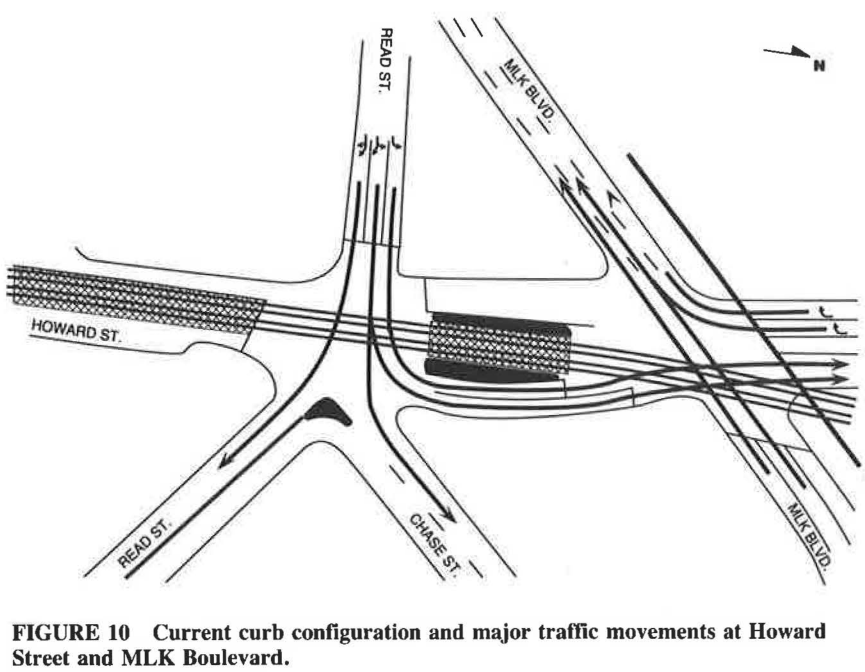

FIGURE 10 Current curb configuration and major traffic movements at Howard Street and MLK Boulevard.

Until MLK Boulevard is extended or other highway improvements are constructed to relieve pressure on this location, both the LRT and traffic operations here will have to coexist with little breathing room for either. During that time the designs that emerged from the combined efforts of the MTA, the city and its several consultants will provide a safe operating plan that maximizes traffic efficiency at this very critical location to the greatest extent possible.

CONCLUSION

One of the things that sets LRT apart from most of the modes that are sometimes considered as alternatives is its ability to interface with street and highway traffic rather than avoid it. Modes dependent upon physical elements such as guide beams, linear induction propulsion, and third-rail power distribution demand grade separation at all roadway crossings. This invariably increases capital costs severely and often creates passenger inconvenience, undesirable visual intrusion, or other environmental problems. Because of its versatility and economy it would appear that, for the foreseeable future, LRT will continue to be a mode frequently considered for new transit lines and systems. A significant percentage of these will involve design problems relating to interfacing with streets and highway traffic in some manner. Although no two problems are absolutely identical, elements of solutions that proved successful in one application may be the key to successful solutions in other applications. The locations discussed here are not the only ones in the CLRL project that contain unique elements. However they do demonstrate some of the diverse problems and solutions involved. Perhaps some elements of the solutions that evolved here will be found useful in the development of other LRT projects in the future.

Designing At-Grade LRT Progression: Proposed Baltimore Central Light Rail

GEOK K. KUAH AND JEFFREY B. ALLEN

Engineers and planners designing at-grade light rail transit (LRT) operations typically are faced with the challenge of balancing two conflicting objectives. On the one hand, the transit authority expects LRT operations to receive full priority at all at-grade crossings in order to achieve minimum travel time. On the other hand, the agency having jurisdiction over the arterial on which the LRT runs expects to maintain normal intersection operations so that peak-hour vehicle traffic delays are not worsened by the implementation of LRT services. The proposed Central Light Rail Line (CLRL) for metropolitan Baltimore was no exception to this situation. The CLRL will ultimately be 27 mi long, with a section of approximately 1.5 mi running along Howard Street through the central business district (CBD) of Baltimore. Howard Street is a two-way, north-south nonprogressive street that intersects with a number of major arterials receiving signal progression during the peak hours. The city is concerned that the proposed LRT will degrade progression on these major arterials and cause unacceptable delays to peak-hour traffic. Using the concept of traffic progression, progressive green bands for the proposed CLRL are developed to enhance its operation and at the same time minimize its effect on cross-street traffic progression. Traffic effects of LRT operations are quantified in terms of disruptions to cross-street progression, intersection level of service, and the performance of a partial CBD street network measured by systemwide criteria. The results reconfirm a previous belief that signal progression for LRT operations is available in the current computerized traffic signal network and that full priority LRT operations along Howard Street could be designed without significantly affecting cross-street progression.

The proposed at-grade light rail transit (LRT) service in central Baltimore between the Camden and North Avenue stations will likely experience substantial delays and schedule variability because of conflicts between LRT and automobile traffic unless traffic operational improvements are implemented. The problem is Howard Street, a two-way street currently receiving low priority in signal progression for automobile traffic. Although certain geometric improvements and traffic route changes are being proposed in conjunction with LRT service on this arterial, no significant signal timing changes on behalf of LRT have been scheduled. Yet the signal timing conflicts potentially cause the greatest disruption to LRT.

A previous study (*1*) of this problem demonstrated the potential for improving LRT travel times along Howard Street by establishing traffic signal progression between Camden Street on the south and Preston/Dolphin Street on the north (see Figure 1). Preliminary estimates are that 3 to 5 min travel time could be saved for LRT operations in each direction with full priority as opposed to partial priority treatment. Schedule variability could also be reduced, making transit service more attractive to users. To develop such a progression along Howard Street requires modifications to green times and signal offsets on many of the side streets currently receiving priority in traffic progression.

The city of Baltimore, however, is reluctant to retime traffic signals along Howard Street because of the perception that retiming will benefit LRT operations at the expense of city traffic. This is a common perception of municipalities involved in the implementation of street-running transit services, according to Fox (*2*). Before any timing changes can be implemented, the city has requested studies to show whether vehicular movements through the larger downtown street grid will suffer.

PROBLEM STATEMENT AND STUDY APPROACH

The computerized signal system for the Baltimore central business district (CBD) was first installed in the early 1970s. The timing plans for the signalized network were based on historic traffic patterns. Over the years, selective local intersection and arterial improvements have been implemented. Signals have not been retimed systematically for the whole downtown since the system was first installed, although patterns of commuting and midday delivery traffic have changed substantially. It is believed that progression could be accommodated on Howard Street for LRT operations and that the cross-street progression could be adjusted so that full-priority LRT treatment would not substantially degrade traffic performance relative to current conditions.

Designing at-grade LRT progression is not new; several previous studies (*2–4*) have discussed problems and operational enhancements related to at-grade LRT operations. Taylor et al. (*3*) discussed the concept of a "coordinated window" (i.e., progression) for at-grade LRT operation through two adjacent intersections at Gage and Florence in Los Angeles. Fox (*4*) used "green phase extension" techniques to provide progression for bidirectional Banfield LRT operations on one-way Holladay Street in Portland, Oregon.

The purpose of this paper is to discuss the development of a full-priority green band that enhances bidirectional LRT operations along Howard Street in Baltimore while minimizing traffic effects on major cross streets. The study approach, consistent with that of other previous studies (*3,4*), was developed after consultation with the staffs of the Mass Transit Administration (MTA) of the Maryland Department of

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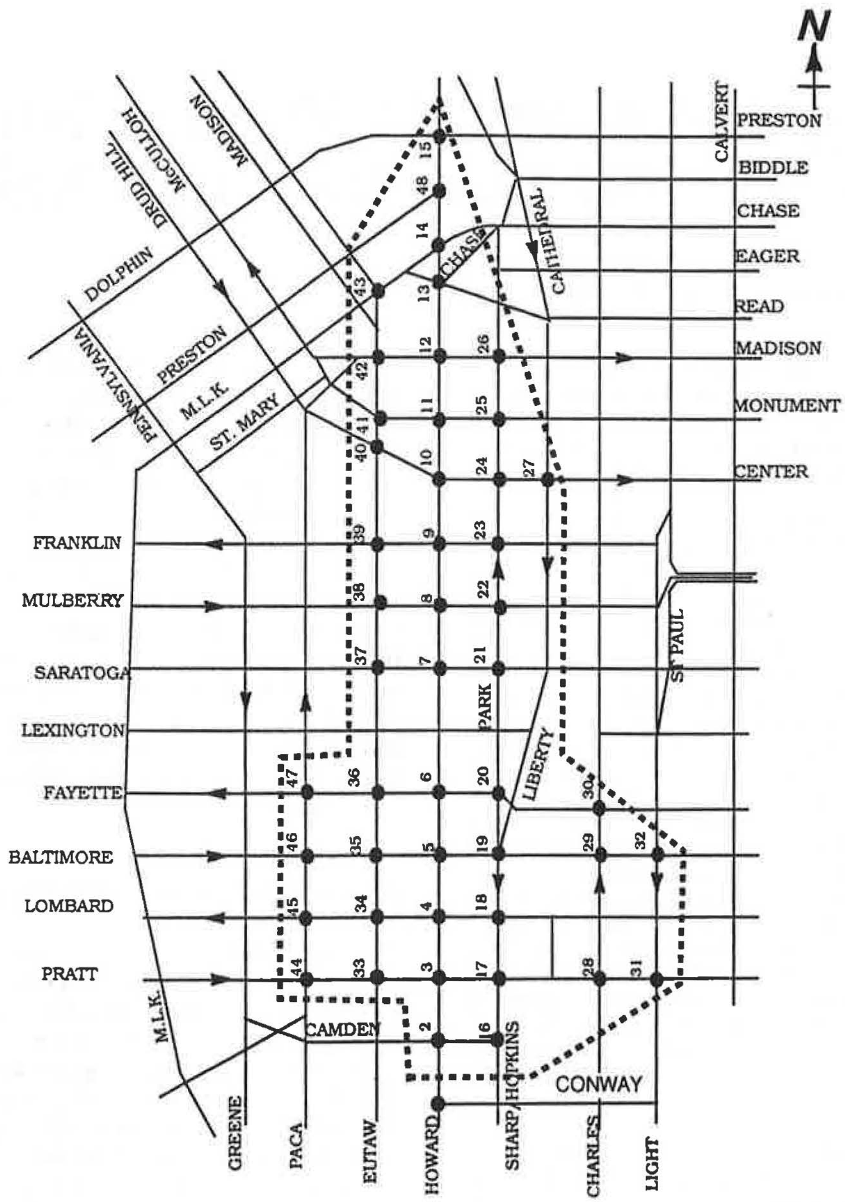

FIGURE 1 Study area.

Transportation and the City of Baltimore. The study involved the optimization of a large signalized network with about 200 nodes subject to the constraint that Howard Street signal progression be maintained to facilitate the LRT operation. Commercially available traffic network optimization programs, such as Passer II-87 and Maxband that deal with arterial progression and the microcomputer version of TRANSYT-7F that was developed originally for signalized networks, were evaluated for adaptation to the study but found to produce nontransparent results. A manual method was preferred over the "black box" computerized approach (5) for producing signal offsets and splits for LRT progression. TRANSYT-7F, however, was used to evaluate traffic impacts at the network level once basic signal timing plans for LRT had been developed. The program's simulation capabilities were used to compare two scenarios, one with and one without LRT.

In the remainder of this paper, the study area and the data requirements are described, existing conditions on arterial progression are evaluated, the progression for Howard Street LRT operation is developed, and the impact of signal timing improvements for LRT on Howard Street and on the larger signalized network are assessed. The results presented are for a.m. peak-hour conditions. The analysis could be expanded to other time periods using the same study approach, although this was not part of the original project.

STUDY AREA AND DATA REQUIREMENTS

The project study area, shown in Figure 1, includes all of the major downtown arterial streets timed to receive progression as well as other downtown arteries with significant traffic volumes but no progression. The progressive arterials, mainly one-way streets, are critical in the operation of the city's downtown grid. Study area arterials are given in Table 1, which also indicates their primary or secondary status as progressive streets.

Four types of data were required for all intersections within the study area: signal data, turning movement counts, intersection geometrics, and type of traffic control. In addition, block distances between intersections, average arterial operating speeds, bus routes and service frequency, and vehicle classification data were obtained.

To obtain existing vehicle operating speeds, studies on travel time and delay were conducted during the peak period for 19 major arterials during September and October 1989. Procedures documented in the *Highway Capacity Manual* (*6*) were followed. The existing average operating speeds were used in developing potential green bandwidth for LRT and in calibrating existing traffic conditions for the TRANSYT-7F evaluation of network effects from LRT operations.

EXISTING CONDITIONS ON ARTERIAL PROGRESSION

Most CBD signals are two-phase, pretimed signals. Several are three-phase, pretimed or semiactuated signals. For all pretimed signals, the peak-hour cycle length is 110 sec. The computer program TS/PP DRAFT was used to generate time-space diagrams and determine the green bands of the progressive streets from the signal timing data. By adjusting travel speeds within reasonable limits that ranged from 20 to 35 mph, maximum achievable arterial bandwidths were determined.

The maximum bandwidth attained through this process was designated the "potential green bandwidth," because it is based on adjusted speeds and not necessarily on the actual observed speeds. Using the potential green bandwidth ensured a more conservative assessment of LRT effects, since the potential green bandwidth for an arterial is typically wider and more apparent than any bandwidth determined from highly variable field conditions. In almost all cases, however, actual

TABLE 1 Potential Existing Green Bandwidth for Major Progressive Streets

Arterial		Cross Street From	Cross Street Through	Potential Bandwidth (Seconds)	Speed (mph)	Efficiency (Percent)	Degree of Progression
East-West Arterial							
1. Pratt Street		Greene	Gay	30	30	27%	Good
2. Lombard Street		Gay	Charles	42	30	38%	V.Good
		Hopkins	Greene	24	30	22%	Fair
3. Baltimore Street		Greene	Charles	12	35	11%	Poor
4. Fayette Street		(No Progression)		0	NA	0%	None
5. Saratoga Street (SB)		Paca	Park	20	25	18%	Fair
6. Mulberry Street		Greene	Liberty	47	30	43%	V.Good
7. Franklin Street		St.Paul	Paca	35	38	32%	Good
8. Centre Street		(No Progression)					
9. Monument Street		Paca	Park	34	30	31%	Good
10.Madison Street		Calvert	Charles	36	30	33%	Good
		Cathedral	Howard	28	30	25%	Good
11.Preston Street		Fallsway	St.Paul	27	25	25%	Good
		Charles	Cathedral	30	25	27%	Good
North-South Arterials							
1. MLK	NB	Washington	Mulberry	30	35	27%	Good
	NB	Pennsylvania	Eutaw	45	35	41%	V.Good
	SB	Madison	Franklin	20	35	18%	Fair
2. Greene Street		Saratoga	Pratt	32	25	29%	Good
3. Paca Street		Pratt	Redwood	25	30	23%	Fair
		Redwood	Mulberry	32	30	29%	Good
		Franklin	McCulloh	40	30	36%	Good
4. Howard Street		(No Progression)		0	NA	0%	None
5. Hopkins/Liberty/Cathedral		North	Preston	46	25	42%	V.Good
		Biddle	Saratoga	42	25	38%	V.Good
6. Charles Street		Mt. Vernon	North	30	25	27%	Good
7. Light/St.Paul Street		North	Centre	47	30	43%	V.Good
		Pleasant	Pratt	40	30	36%	Good
8. Calvert Street		Pratt	Lexington	25	30	23%	Fair
		Saratoga	Monument	50	30	45%	V.Good
		Madison	North	35	30	32%	Good
9. Guilford/South/Light		Madison	Baltimore	23	30	21%	Fair

Legends: Efficiency
0% - 12% = Poor Progression
13% - 24% = Fair Progression
25% - 36% = Good Progression
37% - 100% = Very Good Progression

operating speeds along CBD arterials were found to be close to the adjusted speeds. The analysis, summarized in Table 1, found that piecewise progression exists for many arterials and that several east-west arterials exhibit continuous progression over most of their length.

East-west arterials receiving good to excellent progression (i.e., green bands amounting to more than 25 percent of cycle length) include Pratt, Lombard, Mulberry, Franklin, Monument, Madison, and Preston streets. North-south streets receiving good to excellent progression include Martin Luther King Boulevard, Greene, Paca, Hopkins, Charles, Saint Paul, and Calvert streets. Baltimore and Guilford/South/Light streets exhibit only poor to fair potential progression over certain roadway segments. Howard, Centre, and Fayette streets exhibit no progression within the study area.

HOWARD STREET PROGRESSION FOR LRT OPERATION

As noted, traffic signal progression does not exist on Howard Street. The first step in developing a full-priority progression for the LRT operations was to develop a profile for typical LRT travel times between intersections. As with automobile traffic on an arterial subjected to progression, it is the expected travel time between intersections that is used to modify the signal offsets necessary for progression. For LRT, however, the situation is complicated by unique characteristics of train acceleration and deceleration, station dwells, track geometry that restricts cruise speeds, and two-way operations.

LRT Operating Characteristics and Profile

The proposed CLRL will have two lines, the North and South lines, as shown in Figure 2. The North Line will start from the north terminal at Hunt Valley, with Camden Station as its last station. The South Line will start from the south terminal at Dorsey Road, with North Avenue Station as its last station. Along Howard Street itself, the Cultural District Station is the northernmost station and Camden Station is the southernmost station. There are four other intermediate stations on Howard Street.

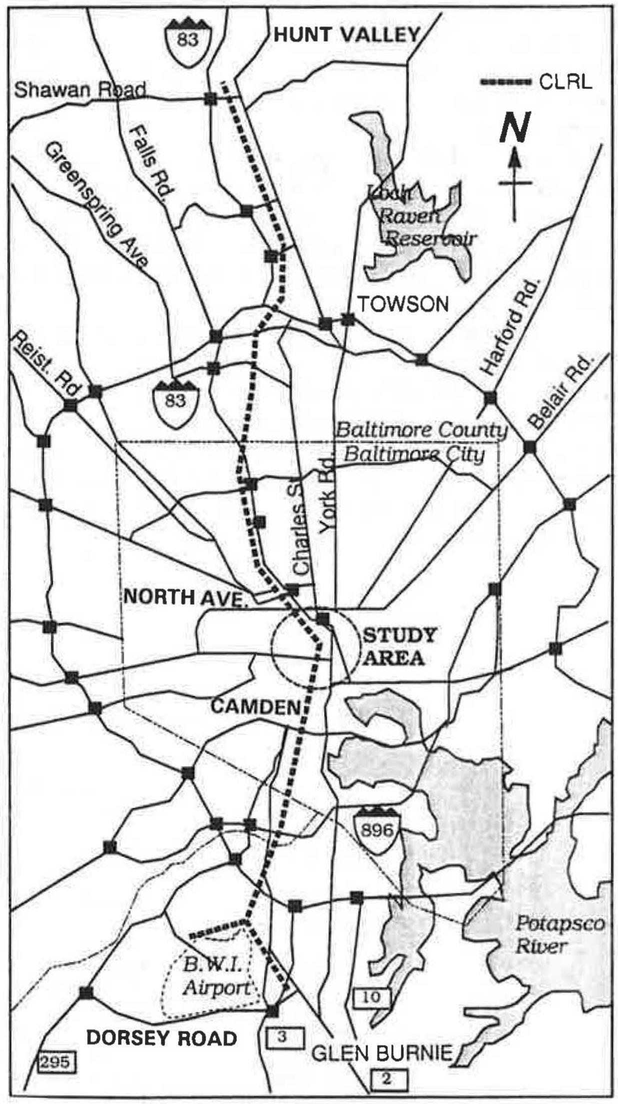

FIGURE 2 Baltimore Central Light Rail Line.

The average peak-hour headway for both lines will be 15 min. Since the two lines overlap on the section along Howard Street between the Camden and Cultural District stations, there will be a train passing through the study area every 7.5 min in each direction, on average. A combination of three-car and two-car trains, with a maximum of five train trips, will be operated during peak hours on each line. Two-car or one-car trains will be used during off-peak hours. The length of an LRT car will be 95 ft, a total of 285 ft for a three-car train.

The LRT maximum cruise speeds between intersections were obtained from the LRT track charts. Higher cruise speeds of 25 to 30 mph are possible on tangent track in the north sections of Howard Street. Lower operating cruise speeds of 15 to 20 mph elsewhere are necessary, primarily because of sharper track curvature.

The acceleration and deceleration rates assumed for the LRT were constant rates of 2.75 and 2.5 ft/sec^2, respectively. Although LRT typically has nonconstant (nonlinear) rates of acceleration or deceleration, the assumption of linear rates is reasonable for low cruise speeds. A constant station dwell time of 30 sec was also assumed. A typical LRT operating profile based on the above assumptions is presented in Figure 3. The solid line represents the front of the train, and the shaded area represents the tail of the train.

Howard Street Progression for LRT

To create a progression for LRT, the LRT operating profile needs to be "circumscribed" by a progressive green band for Howard Street. This was done by overlaying the LRT operating profile on a second time-space diagram reflecting existing signal timing for Howard Street intersections (i.e., "without LRT") between the Camden and Cultural District stations.

Figure 4 shows the existing time-space diagram on Howard Street without LRT, in which cross-street signal timing data

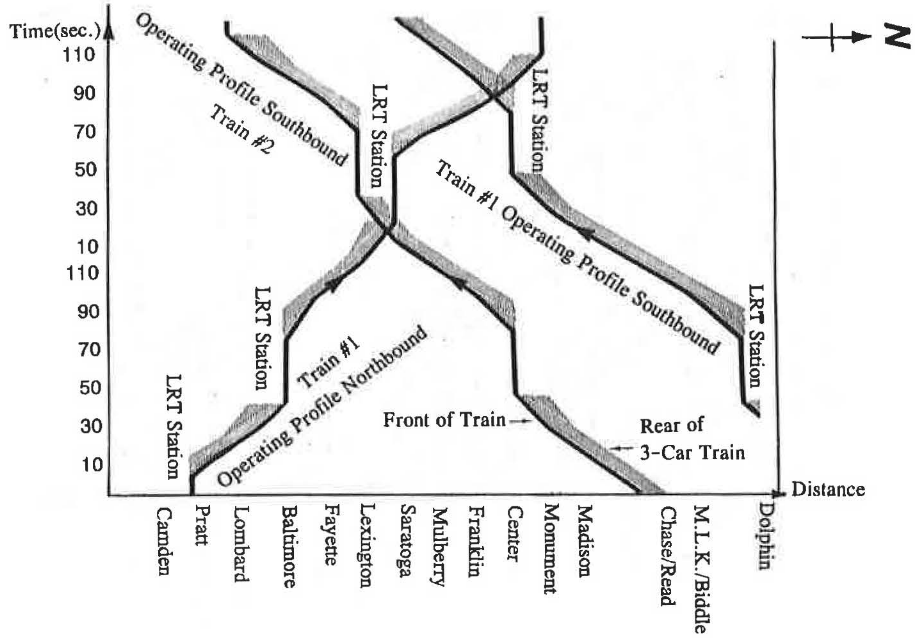

FIGURE 3 Train operation profile.

are plotted on a vertical time scale and the cross-street locations are plotted on a horizontal distance scale. The superimposed LRT operating profile was manually adjusted to achieve minimum impacts on existing cross-street progression. Cross streets given the highest priority for retaining maximum green time and progression included Pratt, Lombard, Mulberry and Franklin.

Selection of Green Band for LRT

After identification of the best location of the LRT operating profile that minimized disruption to cross-street timing while retaining LRT progression along Howard Street, a band providing adequate green time for the LRT to cross each intersection was drawn on the time-space diagram. Figure 5 shows only the southbound band, but a similar band exists for northbound trains. The resulting changes in cross-street signal offsets and green time were documented.

Since it is essential for the rear of the LRT train to pass through an intersection before the cross street receives a green phase, LRT clearance times and green intervals had to be established. LRT clearance time is the time it takes for the train to travel through an intersection and is a function of crossing speed, train length, and travel distance. The green

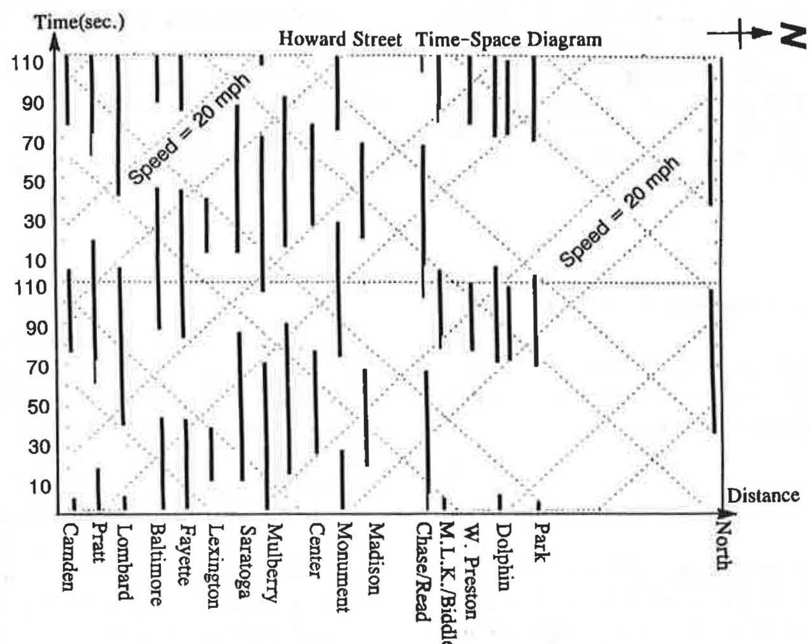

FIGURE 4 Existing signal timing on Howard Street.

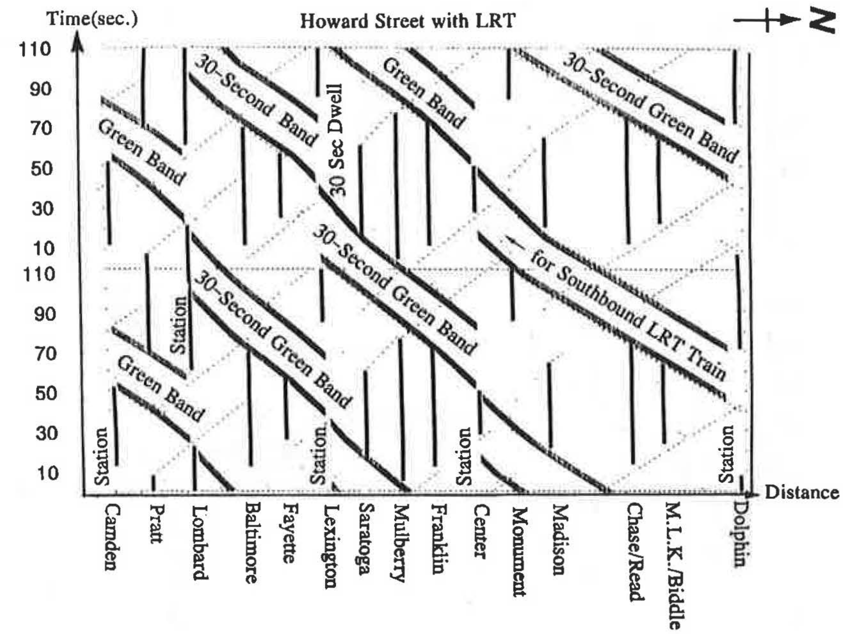

FIGURE 5 Adjusted signal timing (with LRT).

interval is defined as the time period during which the front of the LRT train can safely enter an intersection given the required clearance time (i.e., the green interval equals the green band less the clearance time).

For the best case, as defined by a 30-sec green bandwidth and a one-car train, the LRT green interval was calculated to be 19 sec for signals next to LRT stations and 24 sec for signals between stations. For the worst case, as defined by a 25-sec green bandwidth and a three-car train, the maximum LRT green interval was 9 sec for signals adjacent to stations and 10 sec for signals between stations. On the basis of these results and following discussions with LRT operations analysts, 30 sec was selected as the preferred green bandwidth for LRT. This interval accommodates the proposed longer train length and likely run time variability of the manually operated LRT system. It also allows some flexibility in protecting left turns from Howard Street onto certain side streets, turns that can only be made safely when LRT movements are restricted.

EFFECTS OF LRT ON CROSS-STREET TRAFFIC

The effects of LRT operations on cross-street traffic on Howard Street were analyzed in terms of changes in cross-street progression and intersection level of service.

Cross-Street Progression

Impacts were assessed by comparing two scenarios, with LRT and without LRT, in terms of green bandwidth. Table 2 summarizes the direct effects on cross-street green intervals and green bands as a consequence of proposed LRT operations.

The moderate to large changes in green intervals or green bandwidth or both occur on Pratt, Baltimore, Fayette, Saratoga, Franklin, Centre, Monument, and Dolphin/Preston streets. Since there is no progression on Fayette, Saratoga, Centre, and Dolphin/Preston streets, the changes in green intervals at their intersections with Howard Street will affect only the intersection level of service. For Pratt, Baltimore, Franklin, and Monument streets, a close examination of the time-space diagrams indicated that the changes in cross-street green bandwidth at Howard Street can be minimized or restored by adjusting signal offsets at the downstream or upstream intersections, or both, along each cross street.

Little or no change in green intervals or green bands occurs at other cross streets. One case receiving special study is the interconnected Chase/Read and MLK intersections. Because of the unique LRT alignment, intersection redesign involving a shift from the center of Howard Street to the east side right-of-way is under study in the area for both LRT and traffic to operate properly.

Detailed Analysis of Impacts

As an example of how cross-street progression can be maintained despite potential LRT signal timing conflicts, time-space diagrams for existing with LRT and revised with LRT conditions along Franklin Street have been included as Figures 6 and 7.

Franklin Street is a westbound-only arterial with a wide potential green band for traffic (35 sec). With improved signal timing at the Howard Street intersection to accommodate LRT, the offset shifts and narrows the green band to less than 30 sec, as shown in Figure 6. The signal timing at the Upper St. Paul and Charles Street intersections constrains the potential bandwidth.

TABLE 2 Effects on Cross-Street Green Resulting from Howard Street LRT Operation

	W/O LRT			W/ LRT			Changes In		Changes In	
Intersection	Offset	Howard Street Green	Side Street Split	Offset	Howard Street Green	Side Street Split	Side Street Green	Level of Change	Side Street Band	Level of Change [1]
Howard &										
Camden	6	70	40	59	70	40	0	None	0	None
Pratt	20	52	58	8	62	48	-10	Moderate	-15	Large
Lombard	7	34	76	22	38	72	-4	Little	0	None
Baltimore	45	42	68	69	53	57	-11	Moderate	-12	Large
Fayette	44	39	71	56	79	31	-40	Large	0	No Band
Lexington	40	84	26	0	84	26	0	None	0	None
Saratoga (SB)	86	38	72	60	68	42	-30	Large	0	None
Mulberry	71	34	76	76	39	71	-5	Little	0	None
Franklin	90	37	73	71	51	59	-14	Moderate	-11	Moderate
Centre	77	60	50	50	88	22	-28	Large	0	No Band
Monument	29	45	65	0	83	27	-38	Large	-29	Large
Madison	68	63	47	64	67	43	-4	Little	0	None
Chase/Read [2]	67	51	59	73	50	60	1	Little	0	No Band
MLK/Biddle [2]	6	78	32	63	70	40	8	Little	0	No Band
Preston (Closed)	0	77	33	0	110	0	NA	Closed	NA	Street Closed
Dolphin/Preston	8	63	47	53	83	27	-20	Large	0	No Band

[1] Level of change relative to existing band
[2] Future lane configuration still undetermined, therefore timing and phasing subject to change

The offsets on both Upper St. Paul and Charles streets can be adjusted, however, to cause their green intervals to occur sooner and consequently shift the green band and restore its original width (see Figure 7). Although the offset changes will have some effect on any progression along either Upper St. Paul or Charles Street, analysis of existing signal timing for these streets indicated that the proposed Franklin Street offset adjustments would not have significant traffic effects. Neither street has evident progression. A timing adjustment should have no effect as long as total green time is unchanged.

The other progressive streets were similarly analyzed for timing adjustments that would restore potential green bands. Except for Baltimore Street, it was possible in all cases to adjust downstream or upstream signal offsets, or both; restore the existing bandwidth; and not significantly affect other cross-street traffic. In the case of Baltimore Street, the offset change at Howard Street divided the existing progression into two pieces but did not reduce the existing bandwidth. Since existing progression along Baltimore is considered poor, the substitution of piecewise progression is not expected to have a significant effect on intersection operation. Nonetheless, monitoring of conditions would be recommended should LRT timing plans be implemented as proposed.

Intersection Performance

The effects of LRT on intersections along Howard Street were determined by performing capacity analysis for two scenarios: with LRT and without LRT. Steps required to establish future traffic conditions on Howard Street were as follows: (a) identify future lane configurations and turning movements, (b) estimate

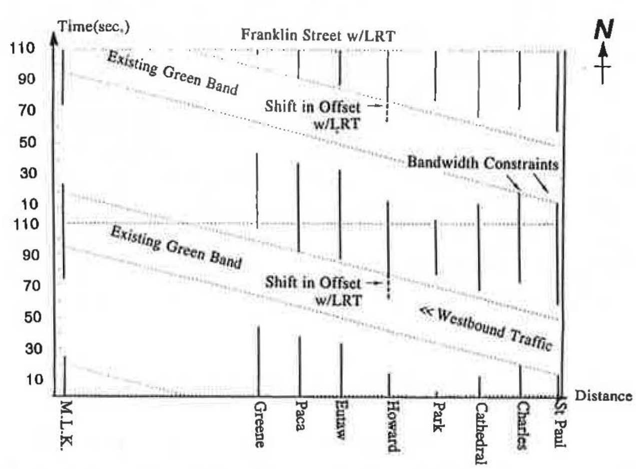

FIGURE 6 Effects of LRT signal timing, Franklin Street.

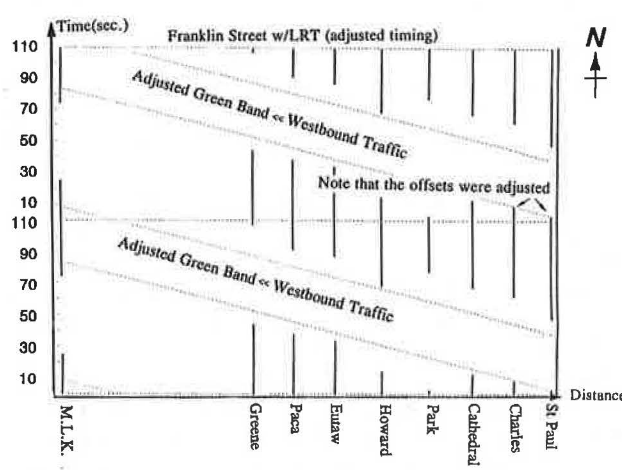

FIGURE 7 Adjusted signal timing (with LRT), Franklin Street.

future traffic volumes, and (c) establish future traffic signal timing and turning phases for Howard Street intersections.

The changes in traffic flow due to LRT implementation included converting the segments of Howard Street between Fayette and Madison to a one-way northbound street for transit buses only. Only LRT will operate freely southbound in this area.

Assumptions used to develop future traffic volumes included inflating 1988 count volumes by an annual rate of 0.5 percent; diverting southbound traffic on Howard Street to parallel north-south arterials on the basis of evaluations of existing turning movements and intersection capacity; and rerouting cross-street traffic currently turning onto Howard Street along the closest parallel north-south arterials that permit similar turning movements. Future bus traffic, modified to reflect route changes to be implemented with LRT service, was added to the automobile traffic. Using 2 sec average car headway, 16 sec maximum intersection clearance time for LRT, 2.5 passenger car equivalents for a typical bus, and an average LRT headway of 7.5 min per direction, the hourly LRT volume was converted to 26 bus equivalents per hour per direction.

Future signal timing data were obtained from the time-space diagram for Howard Street with LRT on the basis of the 30-sec (bidirectional) green bandwidth (Table 2). At five locations a third phase for protected left-turn movements required for traffic leaving Howard Street was added.

Level-of-Service Results

Table 3 shows the results of the capacity analysis for intersections on Howard Street. Level of service (LOS) is indicated for a base year (1988) and the target opening year (1991) for LRT. Cross-street LOS is calculated, in addition to intersection LOS, in order to isolate the operational impacts on the downtown east-west arterials carrying major automobile traffic volumes.

Only one intersection was found to suffer a major degradation in service as a result of signal timing changes for LRT. Centre Street at Howard Street will fail (LOS F) with significant reduction in cross-street green time. An additional 15 sec in green time for Centre will bring the LOS up to an acceptable level (LOS D). The eastbound approach for Pratt Street at its intersection with Howard Street was found to degrade to LOS D in 1991 from an existing LOS B. A few additional seconds in green time for eastbound traffic will improve the LOS to C.

The performance of the Dolphin-Preston/Howard Street intersection was found to fail under both existing and future conditions. The westbound and eastbound approaches tend to worsen in the future with LRT signal timings. It is clear that intersection performance cannot be improved without modifying intersection geometry.

Three other intersections, at Fayette, Saratoga, and Monument, were found to experience modest deterioration in LOS, all going from an LOS B to C. For the remaining Howard Street intersections (Lombard, Baltimore, Mulberry, Franklin, and Madison), effects of LRT timing changes were found to be insignificant.

TABLE 3 Level of Service for a.m. Peak Hour

Intersection		1988 Base Year	1991 Opening Year
Camden	Whole Intersection	C	B (1)
	Side Street (WB&EB)	C	C
Pratt	Whole Intersection	C	C
	Side Street (EB)	B	D (2)
Lombard	Whole Intersection	B	B
	Side Street (WB)	B	B
Baltimore	Whole Intersection	C	B
	Side Street (EB)	B	B
Fayette	Whole Intersection	B	C
	Side Street (WB)	B	C
Saratoga	Whole Intersection	B	C
	Side Street (WB)	B	C
	Side Street (EB)	B	C
Mulberry	Whole Intersection	B	B
	Side Street (EB)	B	B
Franklin	Whole Intersection	B	B
	Side Street (WB)	B	B
Centre	Whole Intersection	B	FAIL (3)
	Side Street (EB)	B	FAIL (3)
Monument	Whole Intersection	C	B
	Side Street (WB)	B	C
	Side Street (EB)	B	C
Madison	Whole Intersection	B	B
	Side Street (WB)	B	B
Chase/Read	Whole Intersection	C	(4)
	Side Street (EB)	C	(4)
MLK	Whole Intersection	Fail	(4)
	Side Street (WB)	E	(4)
Dolphin/Preston	Whole Intersection	Fail	Fail
	Side Street (WB)	E	Fail
	Side Street (EB)	C	D

(1) Assumes no RT from SB Howard Street in opening year
(2) By adding 3 seconds to Pratt Street the LOS will be "C"
(3) By allocating an additional 15 seconds to Centre Street the LOS will be "D"
(4) Intersection improvements still uncertain; addition of separate LRT or combined LRT/SB Howard phase to existing geometry will likely result in intersection failure at both MLK and Chase/Read

EFFECTS OF LRT ON STREET NETWORK AS A WHOLE

To evaluate the effects of LRT operation on the street network and on Howard Street as a whole, the simulation capability of TRANSYT-7F was used. Three simulation runs were performed: existing conditions, target year without LRT, and target year with LRT.

Network Definition

The network for TRANSYT-7F simulation, as shown in Figure 1, included Howard Street and the portion of the street network that will be affected directly by LRT operations. North-south intersections along Eutaw Street and Park Avenue, and selected east-west intersections along Pratt, Lombard, Baltimore, and Fayette streets, were included because signal timing at these intersections will need to be modified to produce the desired green band for the LRT. The resulting network, consisting of 47 total intersections with LRT passing through 15 intersections, represents a manageable network size that can reasonably be used to assess LRT effects.

Model Calibration and Development of Scenarios

The base year was simulated by using intersection signal timing, lane configurations, and observed arterial operating speeds for existing traffic conditions. Individual link performance, as measured by the degree of saturation flow and the length of maximum queue, was examined. The maximum calculated queue length for a selected number of links was compared with field conditions.

The scenario of 1991 without LRT differed from the base-year scenario only in the traffic volumes. The without-LRT scenario, required to isolate the effects of LRT, was created by increasing the base-year traffic volumes by 0.5 percent for 2 years. For the with-LRT scenario, the new signal timing data proposed for LRT progression were used. LRT movements were modeled as bus traffic by inserting additional transit links into the network and assigning 26 bus equivalents per hour per direction. A dwell time of 30 sec at the predetermined LRT stations was also used. To further account for the increased friction between LRT and vehicle traffic, the platoon dispersion factor of the model was changed from the default value of 0.35 to 0.45. Modifications to the traffic volumes were also included to reflect changes in traffic rerouting resulting from the LRT operations.

Effects on the Network

Nine measures of effectiveness (MOEs) for system performance were used to evaluate the effects of LRT on the street network. The MOEs were (a) total distance traveled by all vehicles per hour, (b) total travel time by all vehicles per hour, (c) total vehicle delays per hour, (d) average vehicle delay, (e) total number of vehicle stops per hour, (f) total fuel consumption in gallons per hour, (g) total estimated operating costs in dollars per hour, (h) average system speed, and (i) performance index.

The results, as shown in Table 4, quantify the effects of LRT operations relative to the scenario of 1991 without LRT. LRT was found to increase the total distance traveled, travel time, delay, number of stops, and operating costs. On average, individual vehicle delay will increase by 2.3 sec (or 14 percent), and average operating speed will decrease by 0.8 mph (or 7 percent). However, the magnitudes of change in the systemwide MOEs indicate only moderate traffic effects from LRT.

SUMMARY, CONCLUSIONS, AND FUTURE ACTIVITIES

The feasibility of enhancing bidirectional movements of LRT trains along Howard Street while keeping the traffic effects to a minimum has been examined. The focus was on identifying a potential green band for LRT operations and quantifying potential changes in cross-street traffic progression, intersection LOS, and network performance.

The existing cross-street progression was analyzed using existing signal timing data by graphically showing the potential green band along each major east-west arterial intersecting Howard Street from Camden Street (south) to Preston/Dolphin Street (north). Future with-LRT cross-street progression was similarly analyzed using the revised offsets and green times that resulted after imposing a 30-sec LRT green band along Howard Street.

Four cross streets—Pratt, Baltimore, Franklin, and Monument streets—were found to experience significant changes in progression following the introduction of LRT along Howard Street. It was shown, however, that satisfactory progression could be restored to Pratt and Franklin streets by making moderate adjustments to the signal timing at selected intersections, either east or west of Howard Street. The loss of progression along Monument Street was found not to be significant for traffic operations. The proposed with-LRT signal timing at the Baltimore and Howard intersection blocks the progression, dividing it into piecewise progression.

Intersection operations for Howard Street and major cross-street intersections were determined by comparing levels of service for existing without-LRT and future with-LRT (1991) conditions. The analysis found that the proposed with LRT signal timing changes did not significantly reduce intersection performance, with one exception: Centre Street at Howard Street. The poor performance of the Dolphin/Preston Street intersection, both for existing and future conditions, appeared to require improvements to intersection geometry or a redesign of traffic operations before changes in LRT signal timing plans would be warranted.

Certain traffic treatments along Howard Street are still under review. The LRT station between Lexington and Saratoga

TABLE 4 Changes in Systemwide Measures of Effectiveness Resulting from the LRT Operation

Scenario	Measure of Effectiveness								
	Total Distance Traveled (veh-mi/h)	Total Travel Time (veh-h/h)	Total Delay (veh-h/h)	Average Delay (sec/veh)	Total Uniform Stops (veh/h)	Total Fuel Consumption (gal/h)	Operating Cost ($/h)	Average Operating Speed (mi/h)	Perfor-mance Index
Base Year Condition	7,940	758	406	16	46,722	850	2,550	11	419
1991 without LRT	8,017	767	412	16	47,314	860	2,580	11	425
1991 with LRT	8,139	840	477	19	52,983	933	2,767	10	492
% Change from 1991 w/o LRT	2%	10%	16%	14%	12%	8%	7%	-7%	16%
% Change from Base Year	3%	11%	17%	14%	13%	10%	9%	-7%	17%

streets has been split, with the southbound platform moved one block south between Lexington and Fayette, in order to better serve commercial uses along Howard Street. Further changes in turning movements and station locations will likely require reconstruction of the LRT green band and revisions to signal offsets and green time.

ACKNOWLEDGMENTS

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New Standards for Control of At-Grade Light Rail Transit Crossings

HANS W. KORVE AND PATRICK M. WRIGHT

Guidelines and standards for traffic control devices for at-grade light rail transit (LRT) crossings are needed. With the advent of several new LRT systems in the past decade (Calgary, San Diego, Buffalo, Portland, Edmonton, Sacramento, San Jose, Los Angeles, Baltimore) and more systems planned for the future, LRT systems are no longer isolated in a few areas in North America and need to be governed by a consistent set of standards. Up to this point, each system has been developing its own set of standards for traffic control devices with no uniformity from one city's system to the next or even within cities. This fact was discovered by ITE Committee 6Y-37 (Light Rail Transit Traffic Engineering), when researching the operation of at-grade crossings in various cities. Specifically the committee found that there were inconsistencies or no standards for at-grade crossing warning signs for roadway traffic; vehicle signal types and locations for operators; and midblock-crossing railroad gates, location and type. It was also recommended that a new committee be formed to research and develop guidelines for these traffic control devices. The new committee, ITE Committee 4D-2 (Guidelines for Traffic Control Devices for At-Grade Light Rail Crossings), will survey existing devices used in LRT systems throughout North America and Europe, and recommend a set of guidelines for these devices. It is also the intent of the new committee to have the guidelines adopted by the National Committee on Uniform Traffic Control Devices to create a national set of standards for LRT systems.

No standards exist for traffic control devices at light rail transit (LRT) at-grade crossings with surface streets. Systems from Baltimore to Portland and from San Francisco to Los Angeles have their own sets of standards for light rail vehicle (LRV) signal types, signal placement, the warrants for and placement of railroad gates, and other traffic control devices. ITE Committee 6Y-37, Light Rail Transit Traffic Engineering, has studied the problem and issued recommendations as a first step toward crafting a solution. Also, ITE has formed a new committee, 4D-2, Guidelines for Traffic Control Devices for At-Grade Light Rail Transit Crossings, which is studying a variety of different traffic control devices, to determine which are most appropriate and to develop a set of guidelines for the traffic control devices. The ultimate goal of the new committee is to have the guidelines adopted by the National Committee on Uniform Traffic Control Devices (NCUTCD) and published in the *Manual on Uniform Traffic Control Devices* (*1*).

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NEED FOR GUIDELINES

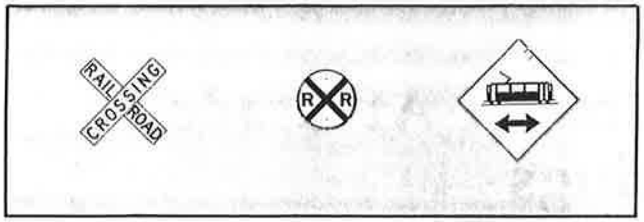
ITE Committee 6Y-37 researched at-grade operations and light rail systems throughout North America. One of its principal observations was that no standards exist for traffic control devices for light rail crossings. Each system examined, from Philadelphia to Los Angeles to Calgary, has developed its own set of guidelines for traffic control devices over the years. Inconsistencies were found not only within North America but within states (e.g., California), and within cities (e.g., San Francisco). Some examples are described in the following sections.

Why no current set of standards governs LRT crossings is not very apparent and needs to be researched further. In the earlier half of this century, when rail transit systems were more prevalent throughout North America, uniform national guidelines were never established. Thus systems evolved their own sets of guidelines based on their own experiences. After World War II, and throughout the 1950s and 1960s, the use and construction of rail systems declined, and the creation of national standards was probably thought to be unnecessary. In the mid1970s, however, UMTA, made an effort to develop guidelines for LRVs. Unfortunately, this attempt at standardization failed, and funding for the project and development of standards for other traffic control devices was dropped.

CURRENT WORK ON GUIDELINES

Since that experience, no concerted effort at standardization has been attempted—until now. In addition to the new ITE Committee 4D-2, the NCUTCD also has a Railroad Highway Grade Crossing Technical Subcommittee working toward establishing a new LRT section of the traffic control devices manual. This new section would contain standards for traffic control devices for both LRT and motorists for at-grade crossings.

Standards for LRT traffic control devices are clearly needed. Standards would help the public by conditioning expectations at crossings and by presenting a uniform set of clear messages, and would improve overall safety at crossings by making a safer design the standard. Standards would also help reduce costs by allowing economies of scale in design and manufacture of devices. Another highlight of this effort will be resolving the issue of whether to use existing traffic control devices (such as those for heavy rail) or develop an entirely new set of devices solely for LRT (e.g., devices currently being used for LRT systems).



CROSSBUCK R15-1 | ROUND ADVANCE WARNING SIGN W10-1 | DIAMOND WITH LRV

FIGURE 1 LRT grade crossing warning signs.

The ITE Committee 6Y-37's findings on the use of different traffic control devices throughout North America cover three categories of traffic control devices:

- LRT at-grade crossing warning signs for roadway traffic,
- LRV signal types and locations for LRV operators, and
- LRT midblock crossing railroad gates, location and type.

Light Rail Grade Crossing Warning Signs

Presently at least three different types of signs are being used to warn motorists and pedestrians of a light rail crossing (see Figure 1). One is the standard railroad crossbuck (R15-1), another is the round railroad sign (W10-1), and the third is the diamond-shaped yellow warning sign with a representation of an LRV on it. It is clear that there is a need for standardization. NCUTCD has already established a subcommittee to develop standards for other signs and traffic control devices at LRT crossings. This subcommittee is considering recommending that the diamond-shaped yellow warning sign become the standard sign. This is definitely a step in the right direction. The new ITE Committee 4D-2 has begun to work with the subcommittee to help define the problem and develop solutions for the advance LRT crossing warning sign and the many other nonstandard signs that exist.

Signal Types for Light Rail Vehicles

ITE Committee 6Y-37 found that LRT systems throughout North America and Europe used a wide variety of signal aspects, signal types, signal locations, and signal phasing for LRVs. Some systems even used different signals for LRVs along the same line (e.g., MUNI, San Francisco).

The signal type used for LRVs is very important because of the potential for motorists to confuse LRV signals with traffic signals. The signal type refers to the signal aspects, or lenses; the shape of the signal; the size of the signal; the color of the signal lenses; and the size and shape of the housing. Several LRV signals are being used that are very similar to standard traffic signals; other systems use LRV signals that are unlike traffic signals.

In addition to the signal type, the location of the LRV signal is very important. The location must be readily visible to the LRV operator to ensure safe operation of the LRV. However, the LRV signal should not be visible to motorists, especially if the LRV signal could be confused with a traffic signal. The LRV operator, a trained, professional driver, does not need to have LRV signals located with the same visibility criteria as traffic signals. The LRV signals can be located out of sight of the motorists, yet in a conspicuous and consistent location where LRT operators can be trained to expect them.

Signal Aspects

Initial research has shown that several different signal aspects are being used to control the movement of light rail vehicles across at-grade intersections. These range from standard traffic signals to Ts, Xs, bars, and dots. Figure 2 shows a sample of some of the different signal aspects. Colors range from the standard green, amber, red, to lunar white.

As part of the new ITE Committee 4D-2's work, a survey form is being sent to each LRT system throughout North America and Europe to gather more information on, not only the type of signal aspect, but also on the operation record and experience of the signal aspect. Figure 3 is a sample of the survey form. The purpose of the survey is to find out which signal aspect best meets the needs of the LRV operator without providing conflicting information to motorists.

The authors' initial research leads us to believe that the nonstandard traffic signal aspects, such as the lunar white bar, would be least likely to be perceived and misread by motorists. Other signal aspects, such as the T and the X, especially in the traditional green, amber, red colors, could be mistaken by motorists as an arrow or other indication. Because this problem has been experienced by LRT systems, these signals are typically accompanied by a sign, Trolley Signal, in an attempt to lessen the confusion (e.g., Blue Line, Los Angeles).

Signal Size and Shape

In addition to the variance in signal aspects, a similar variance was also found in the signal size and shape, which range from the standard 8-in. and 12-in. traffic signal heads to square and pedestrian signal heads. Some of the different signal shapes are also shown in Figure 2.

As with the signal aspects, the signal sizes and shapes are also being surveyed by ITE Committee 4D-2. Again, the purpose is to find the signal shape and signal aspect that meet the needs of the LRV operator without confusing motorists and that has a good safety record. At this time, the authors think that to lessen potential motorist confusion, the signal size and shape should also not resemble a typical traffic signal head, just as the signal aspect should not be similar. Thus the rectangular signal heads would seem more appropriate.

Signal Location

The last major issue concerning signals that control LRV movements across at-grade intersections is the actual location and mounting of the signal. ITE Committee 6Y-37 found that the location and mounting varies considerably from near-side/

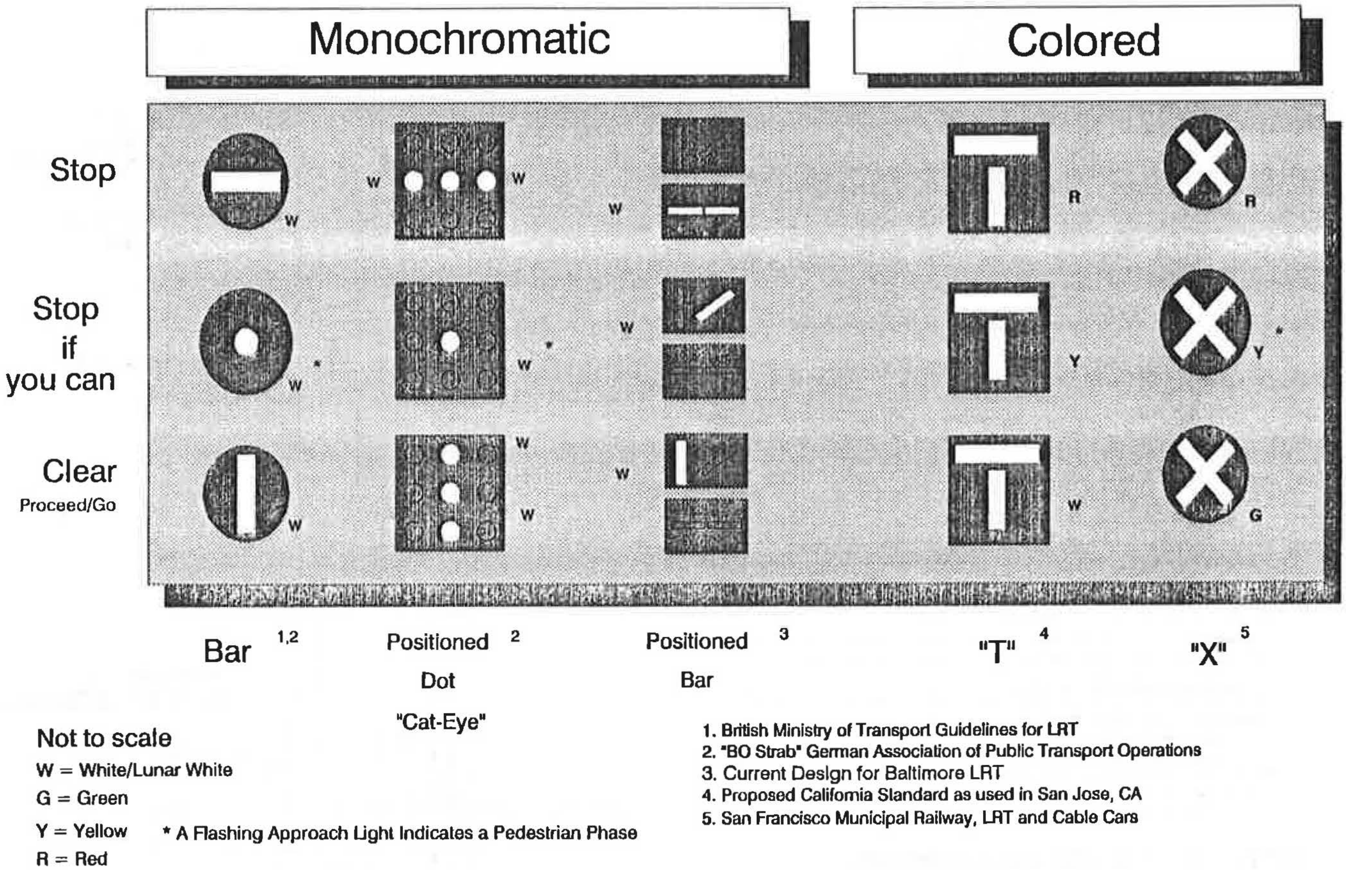


FIGURE 2 LRT signal aspects.

far-side combinations, to far-side only, near-side only, mounted on mast-arms with vehicle traffic signals, pole-mounted separately, mounted vertically, and mounted horizontally to name a few. Some systems locate the signals in a way that treat the LRV operator as an untrained motorist, putting LRV and traffic signals side by side. In fact the ITE Committee 6Y-37 has found inconsistency for different LRT systems to be *the* consistent pattern throughout North America.

The new ITE committee is also surveying LRT systems on signal locations and experiences related to signal locations. Initially the authors believe that the best location for the LRV signal is out of the main viewing area of a motorist. Installing additional signals, some of which may be similar to traditional traffic signals, in plain view of motorists can only cause additional confusion. For example, a typical location would be pole-mounted on the near-side of the at-grade crossing. Near-side LRV signals also help reduce the "creep factor"—LRVs slowly creep into an intersection. Of course, depending on the specifics of the actual crossing, other locations may be more appropriate.

What's Being Used Now

Today, no clear consensus exists as to what is the most appropriate LRV control signal. Both San Jose and Los Angeles are using the T. Portland, following the lead of the European light rail systems, is using the positioned lunar white bar signal in a rectangular frame. Baltimore, which will open soon, is using a similar signal. The San Francisco Municipal Railway is still using the green, yellow, red X. The new Dallas system (DART) is considering using the lunar white bar signal (similar to Portland's). The DART system is in the design stages and will greatly benefit from a consistent set of national guidelines.

Midblock LRT Crossings

From the information gathered from the ITE Committee 6Y-37, several safety-related issues were uncovered related to at-grade midblock LRT crossings. The first issue deals with the protection of pedestrians. The second issue deals with the problem of vehicles driving around gates that are down. Both issues are critical at midblock crossings, because midblock crossings typically have only railroad gates with no traffic or pedestrian signals.

Current design practice for railroad gates calls for flashing lights and gates on the approaches to the crossings. Occasionally older installations may have traffic signals or other devices. The gates are typically located between the sidewalk and the street with the sidewalk areas protected by flashing

DRAFT ITE
COMMITTEE 4D-2
QUESTIONNAIRE
LRT TRAFFIC CONTROL DEVICES

LRV CONTROL SIGNALS

Please describe signals to control LRV movements at locations where they could possibly be viewed by motor vehicle drivers. You can describe up to four different signal types used for your LRT system.

LRV CONTROL SIGNAL TYPE 1

1. PHYSICAL DESCRIPTION OF LRV SIGNAL

Please sketch on Figure 1 the LRV signal type, including housing shape, aspects, colors, and associated meanings.

2. LOCATIONS USED FOR LRV SIGNAL

Please sketch on Figure 2 the LRV signal locations used for different types of LRT crossings. If different locations are used at the same crossings, please sketch as many that apply.

3. COMMENTS ON LRV SIGNAL DESIGN AND LOCATION

AGENCY RESPONSIBILITY FOR MAINTENANCE: ______________________

SOURCE FOR DESIGN: ______________________

BENEFITS VERSUS OTHER DESIGNS: ______________________

POTENTIAL PROBLEMS: ______________________

FIGURE 3 ITE Committee 4D-2 questionnaire.

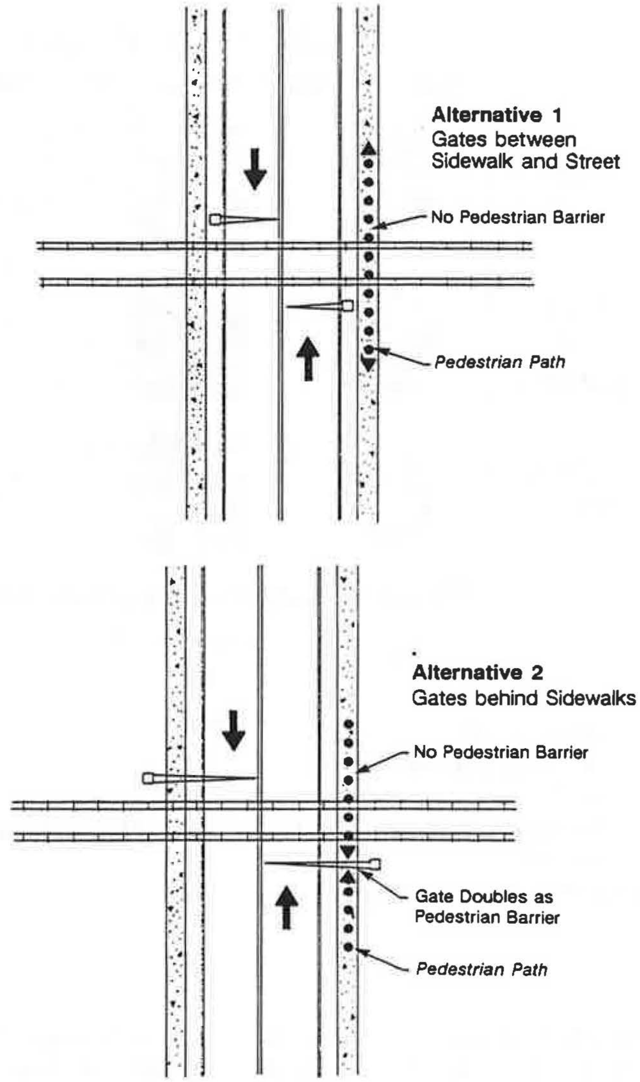


FIGURE 4 LRT gates at midblock crossings.

lights. Some systems locate the railroad gates behind the sidewalk, in which case the railroad gates serve as a physical barrier for the automobile approach as well as the sidewalk in one direction. The Blue Line in Los Angeles does not have gates across the sidewalks but does use pedestrian signals. The RT light rail system in Sacramento has the gates located behind the sidewalks (see Figure 4).

Pedestrians

As can be seen in the examples displayed in Figure 4, the railroad gates, depending on how they are located, do not provide a barrier to prohibit pedestrians from crossing the tracks while the gates are down. Alternative 1 provides no protection, whereas Alternative 2 provides protection in one direction but not both. Other than the flashing red lights intended to warn vehicles, pedestrians have no direct barrier or symbol warning them not to cross the tracks. Depending on the volume of pedestrians at the crossing special measures may be needed. In Palo Alto, California, a pedestrian accident with a commuter rail train prompted the California Public Utilities Commission to reverse an earlier position and recommend installation of pedestrian gates (*2*).

A possible solution to the problem would be to add a short railroad gate for the sidewalk only, as shown in Figure 5, Alternative 1. With the addition of fencing, and the other railroad gates located behind the sidewalk, pedestrians would be faced with a physical barrier to prohibit dangerous crossings. Other potential solutions include four-quadrant gates or special pedestrian signals that are activated along with the railroad gates. Some European systems even go so far as hanging "skirts" from the gate arms to discourage pedestrians from circumventing the gates.

One potential problem with four gates is trapping pedestrians or vehicles within the crossing. However, by sequentially lowering the upstream (near-side of the crossing) gate first and then the downstream gate, this entrapment problem can be lessened.

Note that the design of the fencing is also important. The diagram in Figure 5 indicates the fencing height at 3 ft. Fencing higher than 3 ft tends to block the view of both motorists and LRV operators, reducing sight distance (e.g., Blue Line, Los Angeles).

The goal for the new ITE committee will be to develop a recommended strategy for protecting pedestrians at midblock crossings, possibly including the establishment of guidelines to install gate arms or pedestrian signals. The guidelines could be based on the volume of pedestrians, the type of area, frequency of LRVs, and other factors. The use of pedestrian signals alone could be a first-step measure with gate arms being added to more critical crossings.

An underlying issue to all this is the actual design of the pedestrian signal—should it be a standard pedestrian signal or should it be a new design with a message referring to the coming LRV—Train Coming/Don't Walk? Another good example of this debate between existing devices and new designs is the advance warning crossing sign. Why create a new sign (the diamond-shaped sign with LRV on it) when all drivers are familiar with the existing round railroad crossing sign (W10-1)? This debate is an important one for the new committee to tackle to limit the already vast array of traffic control devices presented to motorists yet still properly inform and protect the motorists.

Driving Around Gates

A common problem with the exclusive use of a railroad gate to protect the approach to the LRT crossing is that it invites motorists to drive around the gates in the down position (see Figure 6). This is a problem with at-grade LRT and railroad crossings throughout North America. The problem is less serious when the crossing is frequented by slow-moving freight trains, especially trains involved in switching operations. However, with LRT come higher speeds and more frequent train operations. A typical railroad crossing may experience 5 to 10 trains a day, whereas a light rail crossing may experience that many trains in an hour. The problem gets worse when a train in one direction is followed very closely by a train in the other direction and the gates stay down. Motorists and pedestrians get lulled into thinking that after the first train has passed and the gate does not rise, the gate has malfunctioned and it is safe to drive around the gate. Such maneuvers can lead to serious accidents. The Blue Line in Los Angeles experienced two of these drive-around-the-gates accidents in late 1990. Both accidents involved drivers circumventing lowered gate arms only to be hit broadside by an LRV. The results of one of the accidents are shown in Figure

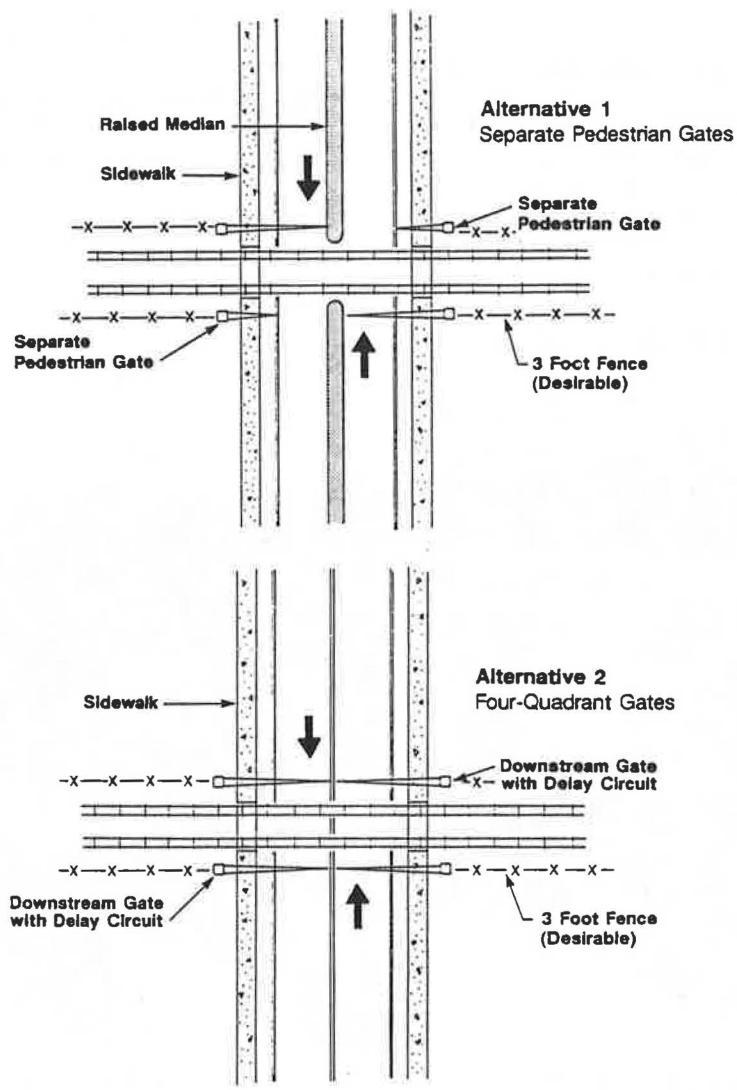


FIGURE 5 Proposed guidelines for LRT gates at midblock crossings.

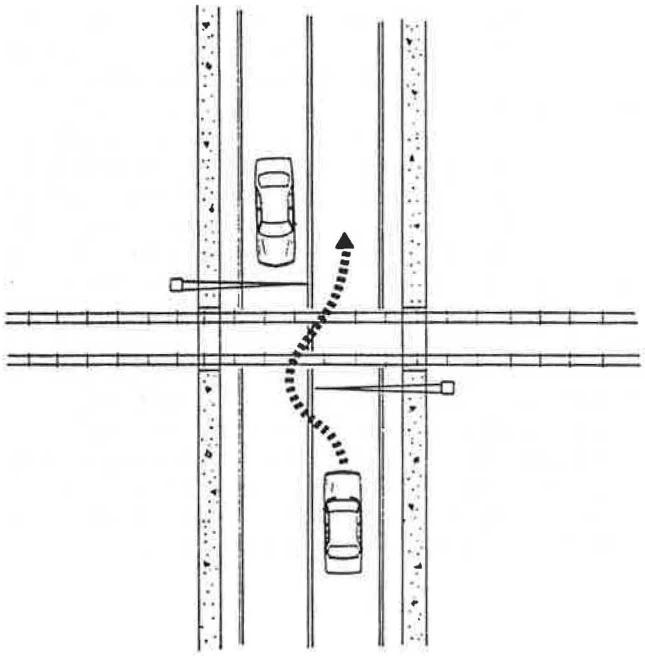


FIGURE 6 Automobile driving around lowered crossing gates.

7. In all, the Blue Line has experienced collisions with 37 vehicles in its first year and a half of operation.

Several solutions to this problem are possible. One is to install a median on the approach to the rail crossing as shown in Figure 5, Alternative 1. The median would physically prevent motorists from driving around the gates in the immediate vicinity of the approach. Circumventing the median would require either driving over the raised curb or driving around the median at an upstream opening. But constructing a median may require widening the street and it may require acquisition of some right-of-way.

Another way to solve the problem is to completely seal off the crossing. This typically requires a minimum of four gates, two for each side of the street on each side of the crossing, as illustrated by Figure 5, Alternative 2. This approach is commonly used in Europe with great success. A concern of the FRA is that vehicles or pedestrians may become trapped. This problem can be minimized by the sequential lowering of the railroad gates. The upstream railroad gate closes several seconds before the downstream railroad gate. With such an installation, the crossing, including the sidewalks, is completely closed during the train movements. Violation would require a driver to crash through the gates. A further refinement frequently used in Europe is to attach a skirt to the bottom of the gates and to fence off the rail right-of-way sealing off the crossing to anyone unless they climb over the fence or over the gate.

The use of the median to seal off the crossing completely is being used in Dallas by DART to make the at-grade crossings of the planned system as safe as possible. At one location where right-of-way is limited, the large Texas-style buttons (large raised pavement markers made of metal that act as a barrier to crossing over the double yellow line) will be used instead of a median. DART is monitoring the results of a safety study by the Los Angeles County Transportation Commission of the accident experience on the Blue Line to help make DART decisions. The ITE committee is planning

Caught on the Tracks

THOMAS KELSEY / Los Angeles Times

The driver of this car was critically injured when he apparently drove around lowered gates and was hit by a Long Beach-bound Blue Line commuter train at Willowbrook Avenue and Elm Street in Compton. The accident occurred at 5:35 a.m. Thursday.

FIGURE 7 Results of driving around lowered crossing gates.

to deal with this issue and develop recommendations by mid-1992.

ITE COMMITTEE 4D-2 GUIDELINES

As mentioned earlier, one of the principal recommendations of ITE Committee 6Y-37 was to establish a new committee to develop standards for traffic control devices at LRT crossings. ITE Committee 4D-2 has been formed to do just that. Its charge is to develop guidelines for traffic control devices controlling light rail crossings. Specifically, the committee is focusing on developing guidelines for LRT crossing warning signs for roadway traffic, guidelines for LRV signal types and location, and guidelines for the location of railroad crossing gates at midblock at-grade crossings.

The Committee is surveying the different LRT systems throughout North America to determine what is being used. The survey is also gathering the operational experience of each of the devices, including the effectiveness, safety, and potential problems. The second step for the committee will be to categorize the devices, and evaluate the experiences of each device type. The final step will be to develop recommended uniform guidelines for the devices and have the guidelines adopted as standards by NCUTCD.

CONCLUSION

With the advent LRT in the past decade—expansions of existing systems and more new systems being planned—the development of standards for LRT traffic control devices is an important task. ITE Committee 4D-2 will tackle this task with the goal of improving the safety and smooth operation of LRT systems throughout North America by providing a uniform set of guidelines.

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Traffic and Light Rail Transit: Methods of Analysis for DART's North Central Corridor

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Since 1986 three methods have been used to evaluate the traffic effects of at-grade light rail transit (LRT) operations in Dallas' North Central Corridor. The objective was to determine the need for and location of any grade separations. The technical data was subsequently entered into the grade separation decision making process that included other factors such as aesthetics, ability to pay, and community opposition or support. The first of the methods calculates the decrease in cross street capacity resulting from the reduction in the progression band caused by preemptive LRT operations. The second method has four modules that estimate the reduction in cross street capacity, the impact of motor vehicle queuing, motor vehicle stopped delay, and reduction in cross street travel speeds resulting from preemptive at-grade LRT operations. The third method estimates the change in various measures of effectiveness by simulating traffic operations with and without priority at-grade LRT operations. The model used for this third method is the TRANSYT-7F traffic signal optimization and simulation model. In addition to these methods, the cost-benefit analysis used for the North Central Line is discussed, along with the potential application of the NETSIM and Traf-NETSIM models.

The Dallas Area Rapid Transit Authority (DART) was created by the voters of Dallas, Texas, and surrounding communities on August 13, 1983. The 20-mi starter system approved by the DART board of directors in June 1989 (see Figure 1) consists of four legs radiating from the Dallas central business district (CBD). On the Oak Cliff, West Oak Cliff, and South Oak Cliff lines, most of the street crossings of the LRT guideway will be isolated, midblock, at-grade crossings or within the median of a major arterial street. The North Central Line will be in a subway tunnel from the northeastern edge of the CBD to a point just north of Mockingbird Lane. The potential at-grade section of the North Central Line, which is the subject of this paper, traverses what is, and is expected to continue to be, one of the most congested corridors in Dallas. Bounded by Park Lane on the north, Greenville Avenue on the east, Mockingbird Lane on the south, and US-75 (North Central Expressway) on the west, DART's North Central Line will cross nine major east-west thoroughfares—five of these feed ramps serving US-75—and are expected to carry traffic volumes in excess of 20,000 vehicles per day (vpd).

To determine the technical need for and location of grade separations, it was necessary to estimate the effect of at-grade LRT operations on cross street motor vehicle traffic at each potential crossing. To do this, DART initiated a series of planning studies that, with the passage of time, have become more intense and refined. Between January 1986 and July 1991 three distinct methods of analysis were used:

1. The options analysis method—a method used by DART and Parsons Brinckerhoff/DeLeuw Cather (PBDC) planners from January 1986 through mid-1986 for a quick but intensive systemwide evaluation of a large number of alternative systems and alignments.
2. The grade separation analysis method—a refinement of the options analysis concept used for detailed planning between mid-1986 and July 1989. The method can be used by itself on simple crossings as an analysis tool or on more complex crossings as a screening process to determine potential problems and solutions.
3. The TRANSYT-7F evaluation method—a logical progression from the second method, it permits areawide traffic impact studies of at-grade LRT operations in complex corridors. TRANSYT-7F work on the North Central Line began in August 1989.

As a supplement to the TRANSYT-7F evaluation method, a benefit-cost analysis was performed for each potential at-grade crossing to determine the cost-effectiveness of constructing a grade separated facility.

OPTIONS ANALYSIS METHOD

This method was developed to make quick estimates of the effect of fully preemptive LRT operations on motor vehicle traffic at potential at-grade crossings. Four major assumptions are made:

1. LRT operates with full, unconditional railroad-type preemption across crossings protected by flashing lights and railroad-type gates.
2. Close-by street intersections restrict, or meter, traffic flow on the roadway link containing the rail crossing.
3. The crossing is blocked by light rail vehicles (LRVs) for a percentage of time equal to the following:

$$r/C_D = TPH \times BT/H \quad (1)$$

DeShazo, Starek, & Tang, Inc., 330 Union Station, Dallas, Tex. 75202.

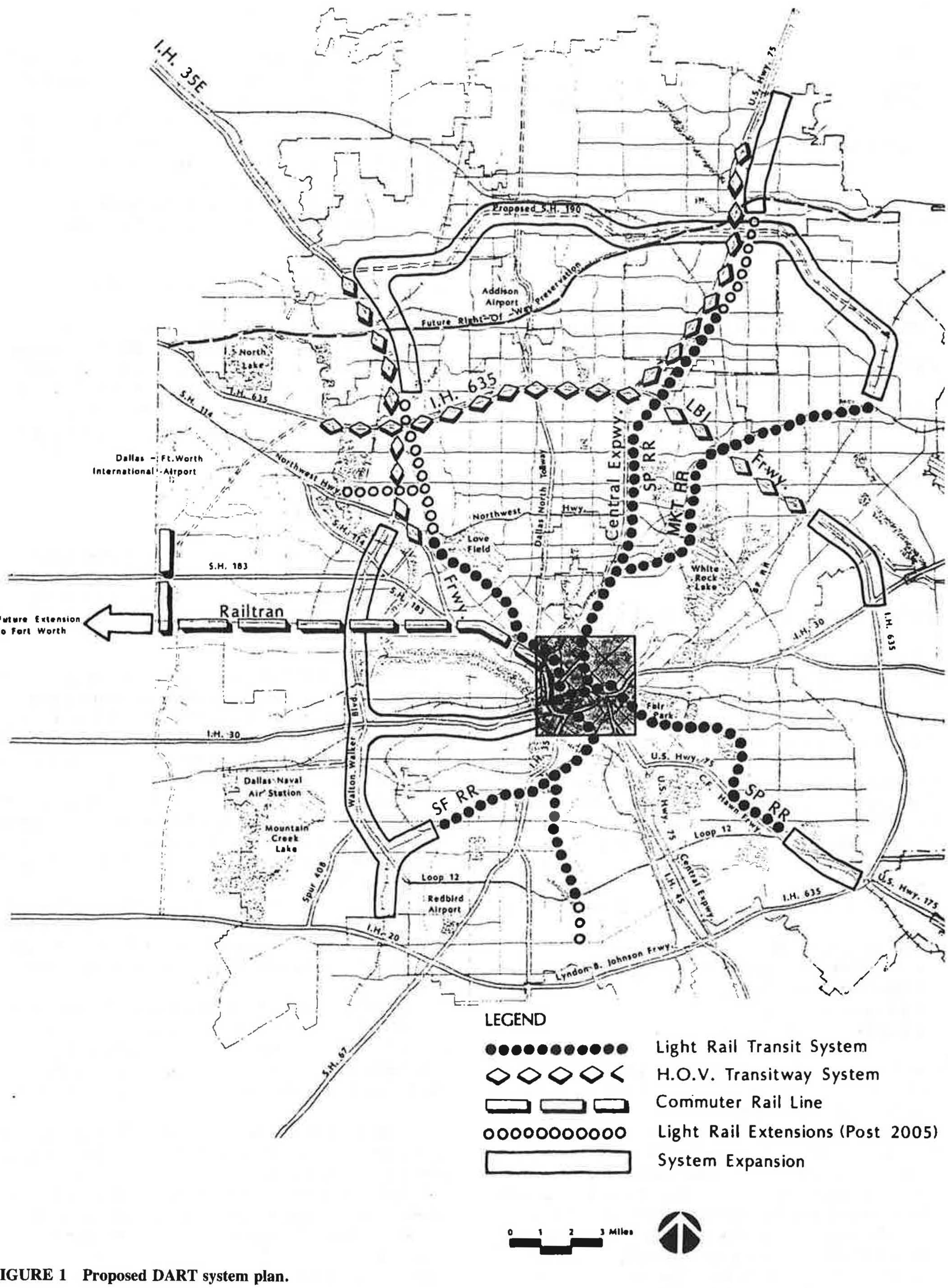

FIGURE 1 Proposed DART system plan.

where

r/C_D = blockage ratio of the street by transit operations,
TPH = trains per headway period (two-way operation = 2, one-way operation = 1),
BT = time per train that the gate blocks the street (sec), and
H = train headway time (sec).

example

r/C_D = 2 trains × 30 sec/150 sec = 0.40

4. The traffic service volumes on the link containing the at-grade crossing are reduced by the blockage ratio to reflect the additional delay resulting from the fully preemptive rail operations:

$$MSV = (1 - r/C_D) \times ISV \qquad (2)$$

where

MSV = maximum service volume at a given level of service (LOS), and
ISV = upstream intersection service volume at a given level of service.

example

MSV at LOS D = (1 − 0.40) × 2,115 vph = 1,269 vph

The options analysis method draws upon *Special Report 87: Highway Capacity Manual* (1965 edition) (*1*, Ch. 6)—in which levels of service (LOS) are defined by the load factor associated with the particular intersection approach under study. The load factor is the ratio of the number of green phases on an approach that are fully used (loaded) by traffic to the total number of green phases available. Graphs from *Special Report 87* were used to determine the approach volumes (*MSVs*) for the upstream intersections for each LOS. Key assumptions for the upstream intersections were as follows:

- No turns,
- Ratio of cross street green time to cycle length (g/C) of 0.42,
- 60-sec cycle length,
- 60/40 directional distribution of hourly demand volume,
- Peak hour factor of 0.85,
- 8 percent trucks, and
- 12-ft lanes and no parking.

Additional assumptions include a metropolitan area population of more than 1 million, location in the fringe or outlying area, and no local bus stops.

A table was constructed that showed maximum service volumes at each LOS for two-, four-, and six-lane cross streets versus 2.5-, 5.0-, 10.0-, and 20.0-min light rail headways. Two-way peak hour traffic volumes at each proposed grade crossing were compared with the appropriate maximum service volume to determine the LOS that will be provided by a crossing.

Although this method was appropriate for a quick analysis of a large number of alternative alignments, it has a number of limitations, including the following:

1. Use of fixed parameters such as the peak hour factor, the directional distribution of motor vehicle traffic, and the g/C ratio of the upstream intersection,
2. Use of measures of effectiveness (MOEs) based on volume/capacity ratios rather than the average vehicle stopped delay values contained in *Special Report 209*, the third edition of *Highway Capacity Manual* (*2*),
3. No specific assessment of crossing capacity, and
4. No assessment of motor vehicle queue magnitudes.

GRADE SEPARATION ANALYSIS METHOD

Engineers and planners from DART, the city of Dallas Department of Transportation (DOT), and DART's consultants recognized that the assumptions of the options analysis method were too restrictive for DART's more detailed project planning and design phase. Alternative methods with greater flexibility were evaluated, resulting in a series of spreadsheets referred to as the "grade separation analysis method."

Overview of Method

The grade separation analysis method is an iterative multiple analysis technique designed to assess peak hour traffic effects of LRT operations with and without specific traffic mitigation measures in place. The major elements of the process are as follows:

1. Identify candidate streets—Each street crossing the LRT line was initially examined. Major highway facilities currently grade separated from the proposed DART rail alignment were assumed to remain grade separated. Streets not on the Dallas thoroughfare plan as secondary thoroughfares (or higher classifications) were eliminated from the study by policy.
2. Data collection—Field data included roadway geometrics, traffic signal parameters near the crossings, 24-hr traffic volumes, peak hour directional distributions, and the percentage of the 24-hr traffic volumes occurring during the peak traffic hours (K factors).
3. Forecast of design year demand—estimates of 24-hr traffic volumes were forecast for the year 2010 using the MicroTRIPS traffic model developed by the city of Dallas with assistance from the North Central Texas Council of Governments (NCTCOG).
4. Preliminary analysis—The microcomputer spreadsheet estimated the a.m. and p.m. peak hour directional LOS of the roadway segments next to the proposed LRT crossing, as well as vehicle queues upstream and downstream of the crossing. Crossings were classified into one of three categories:

- At-grade crossing indicated—If the LOS estimates were A through C and the estimated vehicle queues did not exceed available storage, no further analysis was necessary.
- Grade separated crossing indicated—If the LOS estimates were F or the vehicle queues greatly exceeded the available vehicle storage or both, no further analysis was necessary.
- Crossing subject to further analysis—Where the LOS estimates for at least one approach during one of the peak

hours was D or E or the estimated queue length exceeded the available vehicle storage by less than 100 ft or both, a second level of study noted as "detailed analysis" was initiated.

5. Detailed analysis—Two evaluations were performed: first, an estimate of vehicle stopped delay at the LRT crossing to determine crossing LOS and, second, an estimate of cross street through travel speeds to determine arterial LOS. Comparing the arterial LOS with and without the at-grade crossing determined its relative impact. If queuing problems were found, solutions (auxiliary turning lanes, dual left turn lanes, channelization, and signal phasing modifications) were examined.

6. Findings—If, after examining a particular crossing at the various levels of detail noted above, the crossing operated at acceptable levels of service, it was not subject to further study. At those locations where the analysis indicated significant traffic impacts, a grade separation was considered if suitable traffic mitigation measures could not be found.

Key Traffic Characteristics of Method

In applying this method, estimates were made of four key traffic characteristics: The K-factor, the directional distribution, the g/C ratio for the upstream and downstream intersection approaches (g/C_s), and the ratio of green time to cycle length for the DART rail crossing (g/C_D). A consensus was reached with city of Dallas DOT staff that existing traffic characteristics would be used for projected conditions within the following limits:

1. K-factor—If the existing factor was less than 0.08, use a projected factor of 0.08; if the existing factor was greater than 0.10, use a projected factor of 0.10.
2. Directional distribution—If the existing directional distribution was between 85 percent/15 percent and 99 percent/1 percent, use a distribution of 85 percent/15 percent.

The g/C_D of the cross street assumed the street was blocked by rail operations for 35 sec. This time approximates the time required for a 300-ft-long train to cross 100 ft of right-of-way at 20 mph with the advance warning requirements for fully gated railroad crossings contained in the *Texas Manual on Uniform Traffic Control Devices* (*3*). The following example illustrates the means of arriving at the g/C_D value for each crossing.

given

DART vehicle headway = 5 min in each direction, and

gate down time = 35 sec.

let

number of hourly gate activations $= Nt$

gate blockage time (sec/hr) $= G_{Bl}$

effective g/C ratio of crossing gate $= g/C_D$

then

$$\begin{aligned} Nt &= 2 \times \text{number of one-direction trains per hour} \\ &= 2 \times (60\,\text{min/hr}/5\,\text{min headway}) \\ &= 24\,\text{activations} \end{aligned} \tag{3}$$

$$G_{Bl}\,(\text{secs/hr}) = (35\text{ secs/gate activation}) \times (24\text{ activations in peak hour}) = 840\text{ sec/hr} \tag{4}$$

$$r/C_D = (G_{Bl})/(3{,}600\text{ sec/hr}) = (840\text{ sec/hr})/(3{,}600\text{ sec/hr}) = 0.233 \tag{5}$$

$$g/C_D = 1.0 - (r/C_D) = 0.767 \tag{6}$$

In this example, the gate is estimated to be up an average of 77 percent of the time. Conversely, the gate down time, or blockage time r/C_D, is estimated to affect traffic flow 23 percent of the time. The value for g/C_D is dependent only on the train headways and the assumed gate down time.

Street Capacity Estimation

The method used to estimate the capacity of streets crossing DART LRT guideways was the result of an evolutionary process beginning with the options analysis method. The most restrictive traffic flow constraint (either DART rail operations or the signal timings associated with signalized intersections on the cross street) was assumed to establish the capacity of the cross street.

A microcomputer spreadsheet was constructed to perform the calculations. Twenty-four-hour design year volumes were converted into directional peak hour demand estimates that could be compared with the most restrictive capacity constraint in the vicinity of the crossing—either an up- or downstream traffic signal, or the light rail crossing itself.

The capacity estimates for the cross street were based on the number of lanes indicated on the Dallas thoroughfare plan for a LOS E saturation flow rate. The spreadsheet provided capacity estimates for street cross sections of one to five lanes in each direction. Specific levels of service were related to the capacity of the segment using these relationships:

- LOS A—60 percent of capacity,
- LOS B—70 percent of capacity,
- LOS C—80 percent of capacity,
- LOS D—90 percent of capacity,
- LOS E—100 percent of capacity.

Traffic signals near the North Central Line operate both as isolated signals and within coordinated signal systems. At the time this method was used, it was generally assumed that traffic signals were not coordinated if they were located more than 0.5 mi apart because of platoon dispersion. Because of this assumption, the treatment used for each crossing was dependent on the distance from the nearest signalized intersection and whether it was within a coordinated signal system. Crossings within 0.25 mi of a signalized intersection were assumed to be affected by the cross street traffic signals. To determine the most restrictive capacity constraint, the following rules were applied:

1. When adjacent traffic signals were within 0.25 mi of a crossing and operated as isolated signals or in two uncoordinated systems, the lane group saturation flow rate was reduced by the most restrictive g/C of the cross street. Usually the high g/C_D ratios of the at-grade crossings do not reduce cross street capacity and $g/C_{\text{eff}} = g/C_s$.
2. When adjacent traffic signals were within 0.25 mi of a crossing and operated in a coordinated traffic signal system, the lane group saturation flow rate was reduced by the product of the g/C_D and the smallest g/C_s for the through movement of the cross street. As time increases, the amount of reduction in average band width converges toward the product of g/C_D and the smallest through movement g/C_s value. Consequently $g/C_{\text{eff}} = (g/C_D) \times (g/C_s)$.
3. When adjacent traffic signals were more than 0.25 mi from the crossing, the lane group saturation flow rate was reduced by g/C_D. Therefore, $g/C_{\text{eff}} = g/C_D$.

The relationship between the demand volume and street segment capacity determined the LOS. Capacity and LOS were also calculated without an at-grade crossing to determine the incremental traffic impact of the crossing.

Although developed independently, the street capacity estimation procedure is similar to the method Gannett-Fleming/Schimpeler Corradino (*4*) used on the Bayside Line in San Diego, California.

Queue Length Estimation—Signalized Intersections and DART Rail Crossings

Two cases of vehicle queuing are estimated by the method. In the first case LRT operations block the cross street for a period of time that causes motor vehicles to spill back into an upstream intersection. This case is dependent upon the gate blockage time at the crossing (G_{Bl}) and the average LRT cycle length (C_D). In the other case the queues at the downstream signalized intersection encroach on the at-grade rail crossing. They are directly related to the signal timing of the downstream intersection which is defined by the g/C_s of street approach analyzed and the cycle length of the traffic signal. In either case the average number of vehicles arriving during the appropriate effective red period was estimated assuming constant vehicle arrivals. A factor of 1.5 was applied to this value to compensate for differences in the motor vehicle arrival patterns. This resulted in a probability estimate of being exceeded of 15 percent for low approach volumes and 5 percent for high volumes. The derived queue formula is as follows:

$$\begin{aligned} X_a = {} & 1.5 \times (r/C_{\text{eff}}) \\ & \times \{[(PHV/\text{no. lanes})]/[(3{,}600 \text{ sec/hr})/C_{\text{eff}}]\} \\ & \times 25 \text{ ft/veh} \end{aligned} \tag{7}$$

where

X_a = queuing distance in feet rounded to the next highest multiple of 25 ft,
r/C_{eff} = $(1.0 - g/C_{\text{eff}})$,
C_{eff} = C_D for Case I, where upstream intersection may be blocked because of DART operations,
= C_s for Case II, where downstream intersection timing may cause the LRT crossing to be blocked, and
PHV = total estimated directional peak hour demand volume for the design year.

Available queue storage distances were estimated from aerial photography and preliminary alignment studies. Comparisons were made between the anticipated queue lengths and storage distances to determine the adequacy of the storage area. Where turning movement counts were available, the estimated directional peak hour demand volumes were divided among the approach lanes in accordance with the percentage of turning movements, resulting in an improved estimate of projected queue length.

Queue Length Estimation—Unsignalized Intersections

The method used to estimate motor vehicle queues at unsignalized intersections downstream from at-grade crossings used a combination of capacity analysis and queuing theory. Capacity analysis was used to estimate the available gaps in the conflicting traffic streams. Single channel queuing was then applied to estimate queue length on the minor street approach.

In the study area most low volume cross streets are subject to wide variations in traffic flow rates during the peak hour. In addition unsignalized intersections will not be subject to measures that can be used to clear vehicles from crossings. These factors suggested using a higher than average demand volume for study purposes to account for short term operational fluctuations. A poisson arrival distribution was therefore assumed. The average peak hour demand volumes were increased so that the probability of being exceeded was no greater than 15 percent. This adjusted demand volume was used as the arrival rate.

The capacity of the unsignalized intersection was estimated using unsignalized intersection capacity techniques (*2*). The sum of the demand volume and reserve capacity for a particular movement is the capacity of that specific approach movement and was used as the average service rate. The number of vehicles in the queue was estimated using a formula derived from work by Wohl and Martin (*5*, Eq. 11.51a):

$$x = \{\ln[1 - P(n < x)]/\ln(R_a/R_s)\} - 1$$

where

x = estimated number of vehicles in queue,
R_a = arrival rate in vehicles per hour,
R_s = service rate in vehicles per hour,
$P(n < x)$ = probability of x vehicles in queue exceeding n vehicles in queue, and
x = n for study purposes.

Note that R_a divided by R_s is equivalent to the v/c ratio of the approach movement. The probability that x will be greater than n vehicles was set at 0.95. The final form of the equation was as follows:

$$X_a = 25 \text{ ft/veh} \times \{[\ln(0.05)/\ln(R_a/R_s)] - 1\} \quad (10)$$

Crossing Delay Estimation

The method to estimate delay at DART rail crossings used the delay equation contained in the 1985 *Highway Capacity Manual* (*2*, Ch. 9). Factors in the equation were developed from estimates made for the street capacity estimation module and once again, a microcomputer spreadsheet was constructed to perform the calculations.

Total estimated directional peak hour demand volumes were calculated in the street capacity estimation module and used as input for the crossing delay calculations. These volumes were multiplied by the lane utilization factor to determine lane group volumes. The critical lane volume is the lane group volume divided by the number of travel lanes on the crossing approach. The saturation flow rate estimates used in this module were consistent with those of the street capacity estimation module. The crossing capacity per lane was calculated by multiplying the saturation flow rate estimate by the g/C_D. The v/c ratio of the crossing was calculated by dividing the critical lane volume by the lane capacity. Average individual stopped delay was estimated using Equation 9-18 from the 1985 *Highway Capacity Manual* (*2*). Berry and Williams (*6*) validated use of this equation for LRT crossings. The equation is as follows:

$$d = \{0.38\, C[1 - g/C_D]^2/[1 - (g/C_D)(X)]\} + 173X^2\{(X - 1) + [(X - 1)^2 + (16\, X/c)]^{0.5}\} \quad (11)$$

where

d = average stopped delay per vehicle for the subject lane group (sec/veh),
C = cycle length (sec),
g/C_D = ratio of the estimated green time for motor vehicle traffic to average DART cycle lengths at a specific DART crossing,
X = v/c ratio for the subject lane group, and
c = capacity of the through lane group.

The delay estimate is for an assumed random arrival condition. Where the arrival of an LRV could not be predicted in terms of a coordinated traffic signal system, the calculated delay was adjusted. It was multiplied by the progression factor for pretimed signal control and a Type 1 vehicle arrival type (*2*). This arrival type conservatively assumes that 50 percent to 100 percent of the vehicle platoons will arrive at the crossing just as the gate lowers for an LRV. The at-grade crossing LOS was estimated using the following criteria:

- LOS A—less than 5.0 sec of average individual stopped delay,
- LOS B—from 5.1 to 15.0 sec of average individual stopped delay,
- LOS C—from 15.1 to 25.0 sec of average individual stopped delay,
- LOS D—from 25.1 to 40.0 sec of average individual stopped delay,
- LOS E—from 40.1 to 60.0 sec of average individual stopped delay, and
- LOS F—over 60.0 sec of average individual stopped delay.

The total approach delay accounting for the deceleration/acceleration before and after a motor vehicle stops at an at-grade crossing was calculated as follows:

$$D = 1.3d \quad (12)$$

where

D = intersection approach delay (sec/veh), and
d = intersection stopped delay (sec/veh).

Travel Speed Estimation

The method used to estimate travel speed impacts of DART rail crossings on motor vehicle traffic was taken directly from the 1985 *Highway Capacity Manual* (*2*). Each cross street studied included an at-grade crossing and the adjacent signalized intersections.

Intersection delay estimates were developed using projected intersection volumes. Overall intersection LOS was maximized by minimizing total intersection delay. The result was used to estimate the arterial LOS (*2*) with the FHWA highway capacity software (*7*). The arterial LOS was estimated with and without the additional vehicular delays resulting from DART rail operations. The LRT related delay was input as "other delay" and default values were used for initial speeds. A microcomputer spreadsheet was used to display the results of the analysis.

Evaluation Criteria

Street capacity level of service and queue length calculations were examined in the preliminary analysis stage and allowed the crossings under study to be classified as follows:

1. At-grade crossing indicated,
2. Grade separated crossing indicated, and
3. Crossing subject to further analysis.

Additional studies were identified for all crossings classified in the latter category. A summary of the evaluation criteria for each type of analysis is shown in Table 1 and represent the values used in the grade separation analysis method for assessing traffic effects of the DART rail crossings.

Portions of the grade separation analysis method were included in drafts of ITE Committee 6A-42's report on LRT grade separation guidelines (*8*). Although this method is su-

TABLE 1 Evaluation Criteria for DART At-Grade Rail Crossings

Type of Analysis	Evaluation Criteria		
	Finding for At-Grade Crossing	Detailed Study Needed	Finding for Grade Separation
Preliminary			
Street Capacity	LOS = A - C	LOS = D - E	LOS = F
Rail Crossing Queuing	Storage > Queue	Storage ~ Queue	Storage << Queue
Signalized Intersection Queuing	Storage > Queue	Storage ~ Queue	Storage << Queue
Unsignalized Intersection Queuing	Storage > Queue	Storage ~ Queue	Storage << Queue
Detailed Analysis			
Crossing Delay	LOS = A - D	Not Applicable	LOS = E - F
Travel Speed	LOS = A - D	Not Applicable	LOS = E - F

perior to the options analysis method, it still had major limitations including the following:

1. No assessment of the effect of preemption on areawide traffic signal operation,
2. Limited assessment of the effect of cross street progression on LOS and queuing,
3. No assessment of the effect of train operations on diamond interchange operation,
4. No assessment of the effect of "late" trains on traffic signal operation, and
5. Serious deficiencies within the street capacity estimation module resulting from the reliance of level of service on the most restrictive g/C ratio and not on at-grade crossing capacity and delay (*9*, Ch. 4).

TRANSYT-7F EVALUATION METHOD

Following a review of the results of the grade separation analysis method, the city of Dallas requested additional detail on the effect of the proposed LRT operations on traffic operations. TRANSYT-7F was selected to simulate systemwide traffic signal operations under a condition of restricted on-demand traffic signal preemption in the corridor.

TRANSYT-7F can be used to account for systemwide traffic effects of nonpreemptive at-grade crossings and is especially useful for studying the nonrandom traffic flow often resulting from progressive traffic signal systems. Specific MOEs calculated by the TRANSYT-7F model and important to this effort included estimates of average vehicle delay for each intersection and "maximum back of queue" estimates for individual intersection approaches.

Initially a 50-node network was developed that encompassed most of the major traffic signals in the corridor. As at-grade crossings were removed from the network, the number of nodes was slightly reduced. At present the evaluation network (Figure 2) includes 25 signalized intersections, 9 diamond interchanges on US-75, and 5 at-grade crossings of the LRT guideway.

To date three TRANSYT-7F studies have been made, although the latter two were substantially the same and will be described as a single study. During the first TRANSYT-7F study the following steps were generally used to apply the optimization and simulation features of the model to the problem:

1. Study networks were identified and coded for base and light rail scenarios.
2. Initial traffic signal phase sequences for individual intersections were input as provided by the city of Dallas.
3. Diamond interchange traffic signal sequences were developed from PASSER III-88 optimization studies.
4. At the insistence of the city of Dallas no traffic signal preemption was allowed. Therefore train operations in the corridor were assumed to abide by a strict progressive green window operating concept.
5. At the time of the study, DART had not fully developed a train operations scenario. Therefore it was assumed that each train would operate through the corridor at 30 mph on 5-min headways, have a single 30-sec station stop at the Lovers Lane Station, and have a 2.5-min layover at the Park Lane Station. These assumptions resulted in a symmetrical time-space diagram through the corridor.
6. To regularly and predictably operate a train in the green window through the corridor, the traffic signal cycle length was set at 150 sec. There were two traffic signal cycles for each 5-min (300-sec) train headway.
7. The crossing blockages were modeled using two-phase traffic signal operations, a 40 sec blockage time, and a crossing saturation flow rate of 1,600 vphgpl (*9*). No clearance phases were provided.
8. Two simulations were made for each light rail scenario. One included train blockages at the Yale Boulevard, University Boulevard, and Blackwell Street crossings. The second included train blockages at the Southwestern Boulevard, Caruth Haven Lane, and Blackwell Street crossings. The symmetry of the proposed train operation simplified the study considerably. Except for the traffic signal timing at the light rail crossing nodes, both networks were identical. The first

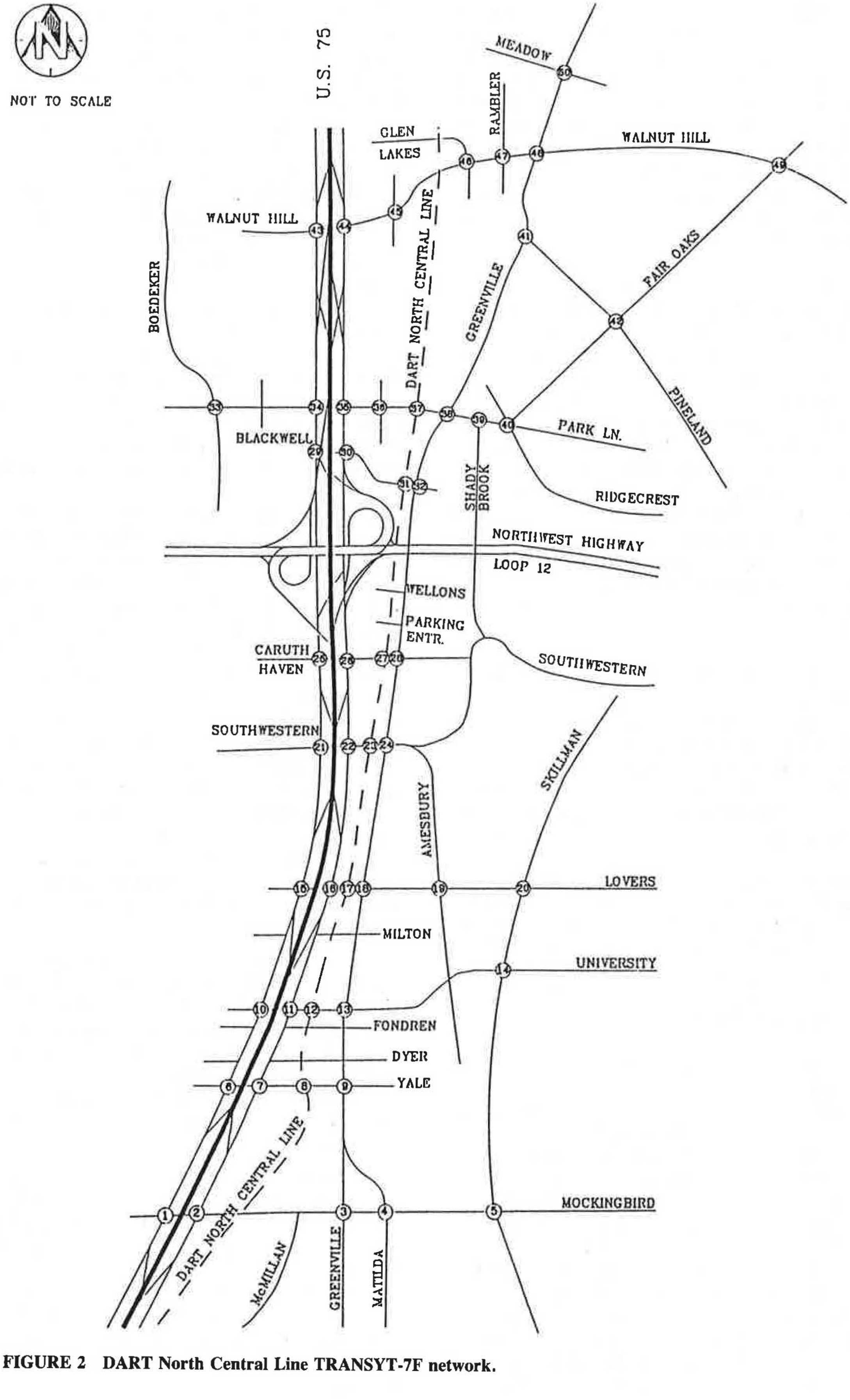

FIGURE 2 DART North Central Line TRANSYT-7F network.

network was optimized using TRANSYT-7F. Optimization of the second network would have resulted in conflicting traffic signal offsets. The second network therefore was not optimized. Instead the optimized timings from the first network were coded into the second network (except at the light rail crossing nodes) and simulation runs were made. Minor adjustments were made to both networks to balance the impacts of the LRT crossings on the traffic signal system.

9. Individual nodal MOEs were determined by either taking the largest value, averaging the results, or summing the results of the two networks, depending upon the MOE.

The technique was generally satisfactory. The resulting traffic simulations provided MOEs for traffic signal phase sequences that could accommodate LRT operations in every single traffic signal cycle. No priority or preemption was provided. However, both the city of Dallas and DART wanted to modify some of the key assumptions. Traffic volumes were modified at some locations, a second train headway option was introduced into the problem, clearance phases were added to the traffic signal sequences, and peak priority train operation was introduced. These changes resulted in a second, completely different, set of TRANSYT-7F runs. From the standpoint of applying TRANSYT-7F, three modifications were significant: the change in train headway, the addition of clearance phases, and the introduction of priority operation.

The change in train headway from 5-min to 10-min meant the following:

- The traffic signal cycle length did not have to be 150 sec—it could be optimized.
- The phase sequence in each traffic signal cycle did not have to be identical—they could be optimized.
- Many more combinations of train meets were available between northbound and southbound trains, and, consequently, the traffic signal phase sequence requirements were increased significantly.

The addition of clearance phases meant that flexibility would be lost during that one signal cycle. It also complicated the application of PASSER III-88. The introduction of priority operation in the peak direction added combinations of train meets, and hence, complexity.

For the second TRANSYT-7F study the following steps were used to apply TRANSYT-7F:

1. Study networks were identified and coded for base and light rail scenarios.
2. Initial traffic signal phase sequences for individual intersections were input based on PASSER II-87 optimizations.
3. Diamond interchange traffic signal sequences were developed from PASSER III-88 optimization studies.
4. A systemwide traffic signal cycle length was chosen for the base and light rail scenarios based on the PASSER II and III studies. The best MOEs were obtained for the base scenarios when eight of the nine diamond interchanges were double-cycled with respect to the remainder of the evaluation network. For the light rail scenarios, these interchanges were only double-cycled when clearance phases were not in the traffic signal sequence. Addition of the clearance phases in the phase sequences necessitated longer cycle lengths.
5. For this set of TRANSYT-7F studies DART reviewed a number of suggested train operations scenarios. Simulation studies by DART consultants indicated that the most reliable train operation in the corridor resulted from operating speeds between 35 and 45 mph on 10-min headways, with a single 35-sec station stop at the Lovers Lane Station and a 12-min layover at the Park Lane Station. This scenario resulted in a meet between northbound and southbound trains near the Lovers Lane Station. It is referred to as the "X" Case because of the pattern of its time-space diagrams. Five other scenarios with other meet locations were also studied.
6. The optimal systemwide traffic signal cycle length determined in the PASSER studies was 120 sec. This resulted in five traffic signal cycles for each 10-min (600-sec) train headway. Depending on the type of meet between northbound and southbound trains, one or two of the signal cycles in each five-cycle set had to accommodate LRT operations.
7. The crossing blockages were modeled using two-phase traffic signal operations, a 50-sec blockage time, and a crossing saturation flow rate of 1,600 vphgpl (*9*). Ten- to 15-sec clearance phases were provided at traffic signals adjacent to the crossings.
8. Two simulations were made for each of five scenarios. One included northbound train blockages and, if applicable, blockages from simultaneous crossings of north- and southbound trains at each of the five crossings. The second simulation included the southbound blockages. Except for the traffic signal timing at the crossing nodes, both networks were identical. The first network was optimized using TRANSYT-7F. The second network was not optimized. Instead the optimized timings from the first network were coded into the second network (except at the light rail crossing nodes) and simulation runs were made. After the initial traffic signal timings were determined, the clearance phases were manually fitted into the appropriate signal cycles at the affected locations. Minor adjustments were made to balance the effects of the crossings on the traffic signal system.
9. Individual nodal MOEs were determined by either taking the largest value, averaging the results, or summing the results of the five traffic signal cycles, depending upon the MOE.

This second technique was also generally satisfactory. The resulting traffic simulations provided MOEs for traffic signal phase sequences that included clearance phases that could accommodate LRT operations as necessary. The priority operation defined by these TRANSYT-7F simulations was accepted by the city of Dallas.

The two TRANSYT-7F methods are not without shortcomings, however. The primary ones identified include the following:

1. This method is labor intensive for large networks. Significant time is spent setting up the networks, finding the optimal phase sequences and cycle lengths, adding the clearance phases, and compiling the composite results of the multiple runs.
2. TRANSYT-7F does not account for queue spill back into upstream intersections. The Stop line flow profiles and platoon progression diagrams should be inspected to ensure that the LOS of nearby upstream intersections is not compromised by queue spill back.

3. TRANSYT-7F does not provide the queue length at the end of the red phase. These data would be helpful in evaluating the adequacy of queue storage areas.
4. TRANSYT-7F does not always give results comparable to PASSER III-88 when modeling diamond interchanges. A wide disparity may exist between the results of each model even after the differences in the delay calculations are accounted for.
5. TRANSYT-7F does not allow for sufficient signal intervals to double-cycle a four-phase diamond interchange signal sequence. This limits the model's utility.
6. TRANSYT-7F cannot explicitly model the traffic signal preemption that typically occurs at light rail or railroad-highway grade crossings.

TRANSYT-7F is a powerful tool for evaluating the traffic effects of at-grade LRT crossings when time and funding are adequate, and a sophisticated analysis within a complex corridor is needed. It provides insight into the operation of a traffic signal system in much more detail than can be obtained with the options analysis or the grade separation analysis methods.

GRADE SEPARATION BENEFIT-COST ANALYSIS

As a supplement to the TRANSYT-7F evaluation method, DART consultants used a benefit-cost model to determine the cost-effectiveness of grade separations at each potential at-grade crossing. The model, originally developed in 1986 and 1987 by staff of the NCTCOG (*10*), quantifies the point at which the benefits of a grade separation outweigh the costs. Benefits of grade separation included the annualized dollar value for reduced person-hours of delay, reduced accidents, and reduced automobile idling costs at grade crossings. Costs of grade separation included the annualized cost difference between an optimized and fully protected at-grade crossing and grade separation. When the benefits exceed the costs, grade separation may be warranted at a crossing.

OTHER METHODS—NETSIM

Between 1986 and 1988, other methods of analysis were studied. NETSIM and Traf-NETSIM evaluations, for example, were used with limited success to evaluate the traffic effects of at-grade crossings in the North Central Corridor. Version 1.0 of NETSIM was used in 1987 to study isolated at-grade crossings modeled as two-phase pretimed intersections with no variability because of train operations. Studies by Cline et al. (*11*) suggested additional ways to model at-grade crossings using NETSIM. A validation study performed by Berry (*9*), however, casts some doubt on the validity of the regression model developed by Cline et al.

Traf-NETSIM has features that make it ideal for studying a priority operation such as the one developed in the second TRANSYT-7F study. The primary feature is the ability to transition from one traffic signal cycle type to the next. The at-grade crossing would have, again, been modeled by a two-phase traffic signal in the pretimed mode. Validation would have been performed using data contained in Berry (*9*). Although not implemented in the corridor, initial results looked promising. Potential shortcomings of NETSIM and Traf-NETSIM are as follows:

1. The limited number of vehicles, links, and nodes accommodated by the model,
2. The complexity of coding the model, and
3. The significant computational time—even using fast microcomputers.

SUMMARY AND CONCLUSIONS

Since 1986 three methods representing an increasing level of effort have been used to evaluate traffic impacts of at-grade LRT operations in the North Central Corridor:

1. The options analysis method is useful for sketch planning studies in which traffic data are limited to 24-hour volumes. It will provide an indication of which cross streets may have capacity constraints.
2. The grade separation analysis method is useful for evaluating at-grade crossings where nearby traffic signals may create queues. It is also useful for midblock isolated grade crossings. Although the data requirements are more rigorous than for the options analysis method, the intersection capacity estimates are more refined. In addition this method also provides an indication of potential queue spill back and travel time and delay impacts. Judgment is required in its application, however, to ensure that spurious results are not obtained from the street capacity estimation module.
3. The TRANSYT-7F method provides the most detailed indication of traffic effects. It is, however, labor intensive and should be applied only when detailed results are necessary. This method provides a wide array of MOEs and consistency for one simulation to the next. It does not, however, explicitly provide for traffic signal preemption. Although this type of operation can be modeled with TRANSYT-7F, it is difficult.

NCTCOG's benefit-cost analysis model was used to determine the cost-effectiveness of constructing grade separations in the North Central Corridor in which many traffic mitigation measures were assumed to be in place. A benefit-cost analysis is useful when extensive mitigation measures affecting the cost of at-grade operations are expected. If extensive construction is not expected, this method may not be necessary because motor vehicle delay at grade crossings is seldom significant.

The Traf-NETSIM method was never fully applied to DART's North Central Line but does show great promise for the evaluation of complex crossing problems. The primary shortcomings of this method are the limited number of nodes and the limited traffic volume that the model can handle. For detailed analysis of small areas, however, this method should work well.

Any of the methods could be adapted to other LRT systems. The basic approach of starting at a sketch level of planning and continuing on in more detail is similar to the process ITE Committee 6A-42 has identified. Starting at the sketch level with a conservative method such as the options analysis method will usually result in an overestimation of the number of grade separations—which is not necessarily bad when initially setting capital budgets. As budget reductions occur, as they are prone to do, the additional levels of refinement provided by the more sophisticated methods typically will result in fewer grade separations and more mitigation measures at a lower capital cost.

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Light Rail Transit Direct Fixation Track Rehabilitation: The Calgary Experience

SIEGFRIED FASSMANN AND AZIZ S. MERALI

Shortly after the south leg of Calgary's light rail transit (LRT) system went into revenue service in May 1981, the portland cement grout plinths supporting the rail began to show signs of deterioration. By 1988 the direct fixation plinths, particularly on the approaches to tunnels, required immediate attention, but shutting down LRT service for the repairs was problematic except during narrow windows when the LRT was lightly used or was out of revenue service. After criteria were drawn up for the replacement material and materials testing was conducted—including field tests—a particular cementitious grout was selected and bids were solicited for the repair work, which involved the construction of some 3,600 new plinths during the narrow windows when LRT operation was suspended. The material selected and the method used to make the repairs both proved successful despite the time constraints.

The 12.2-km south leg of the Calgary light rail transit (LRT) system was opened to revenue service in May 1981. The double-track system was constructed on an exclusive right-of-way with entry to a transit mall at Seventh Avenue and Third Street and the southern terminus at Anderson Station. A shop and maintenance facility was also constructed at the south terminus. This leg has seven center-loading platform stations with connections to the bus system via transit terminals.

The second leg constructed was in the northeast part of the city. This 10.2-km double-track station also uses an exclusive right-of-way and was opened to revenue service in September 1984. The northern terminus is at the Whitehorn Station and connects also to the transit mall at Seventh Avenue and Third Street S.E. This leg of the LRT has seven center-loading station platforms.

The northwest leg was completed by September 1987 in time for the 1988 Winter Olympics. This double-track system is 8 km long and extends from the west end of the Seventh Avenue transit mall in downtown Calgary to the northern terminus at the University of Calgary and has two center-loading platform stations and five side-loading platforms.

The section of Seventh Avenue in downtown between Third Street S.E. and 10th Street S.W. is common to the three legs of the LRT system and has 11 side-loading platforms.

A short 2-km extension of the northwest line was completed in 1990. This extension was from the University of Calgary Station to Brentwood Station and included a parking facility at the terminus.

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DETERIORATION

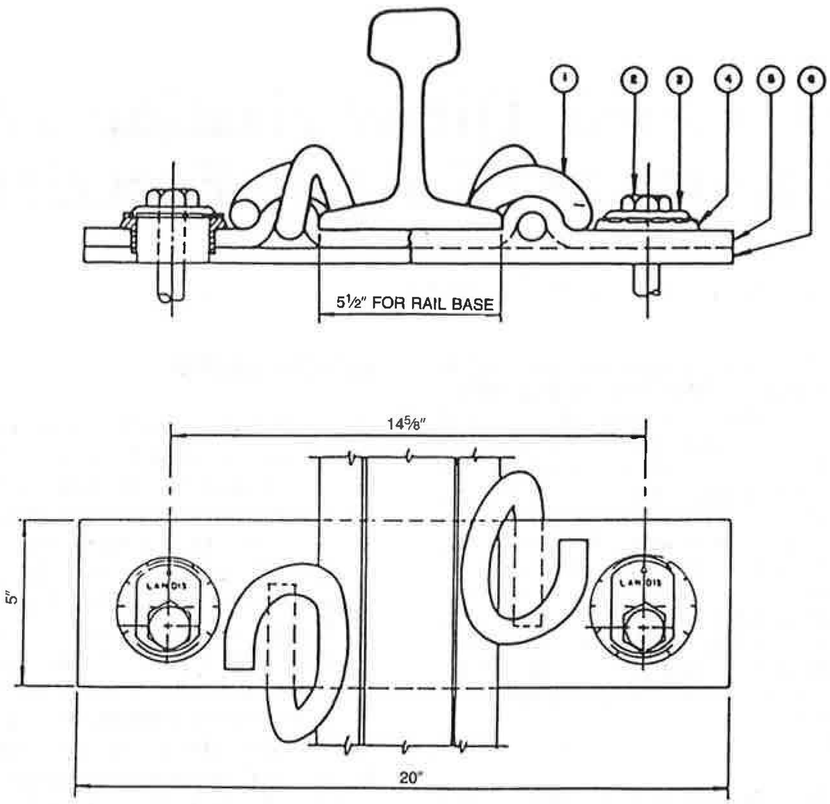
The south leg of the Calgary LRT system utilizes 100-lb ARA continuous welded rail. In the ballasted section this rail is fastened to concrete ties with the Landis-Pandrol fastening system. The direct fixation sections (2.5 km) used the Landis-Pandrol 5301 fasteners supported on portland cement grout plinths at 750-mm intervals. A detailed drawing of this direct fixation system is included as Figure 1.

Shortly after entering revenue service in May 1981, the portland cement grout plinths supporting the rail began to show signs of distress. The deterioration appeared in the form of cracking of the cement grout, delamination from the primary concrete invert, and anchor bolts pulling out. The extent of the deterioration varied depending on the location of the plinths. The majority of the deterioration was found at the tunnel approaches and on the Elbow River Bridge. By 1984 one tunnel, namely the 42nd Avenue S.E. tunnel, had reached a point where rehabilitation work was mandatory. At this time the northwest leg was nonexistent and the northeast leg was under construction. Based on the systems requirements at that time and the emergency nature of the plinth pad failures, it was decided that a steel-reinforced concrete plinth system be used. The standard Lord fastening system was used to replace the Landis-Pandrol System. The portland cement grout plinths in this area were replaced with 40 Mpa portland cement concrete plinths and steel reinforcing. A shutdown of each revenue track was required for 3 weeks to complete this repair.

By 1988 the direct fixation plinths, particularly on the approaches to tunnels in the remainder of the south leg, required immediate attention. The northeast and the northwest legs of the Calgary LRT system were in service at this time.

A shutdown of one revenue track for an extended period was no longer feasible. Because all three legs utilized the Seventh Avenue transit mall, a change in the headways along one route would create a considerable operations problem on Seventh Avenue. The single train maintenance and storage facility is located at the south terminus of the south leg of the LRT system, and trains are dispatched to the northeast and northwest legs from there. A slowdown on the south line would have an impact on the other two legs.

The need to carry out this rehabilitation work with minimum impact on the train operation presented a significant challenge in the engineering design and construction. The longest period that a section of track could be taken out of service was set at 68 hr (from 9 a.m. Friday to 5 a.m. Monday). This period was not available at all times but only for the weekend when a concrete pour was scheduled. However, one



ITEM	TITLE	MATERIAL	QTY
1	PANDROL CLIP	601-A	2
2	BOLT	7/8" DIA. – NOT INCLUDED	2
3	ECCENTRIC POST	SINTERED SD2-1 STEEL MAT. DENSITY 6.1–6.4	2
4	INSULATOR	URETHANE – POLYETHER BASE DH94–	2
5	TRACK PLATE	STEEL	1
6	PAD	NEOPRENE RUBBER	1

FIGURE 1 Original Landis-Pandrol 5301 fastener assembly used on the south line direct fixation areas.

track was available every weekend from 7 p.m., Friday to 5 a.m., Monday.

The material selection criteria included the following:

- Structural capability,
- Long-term durability
- Construction under various site conditions,
- Set time and strength gain, and
- Economics.

To be able to satisfy the basic engineering requirements as well as the constraints imposed by various external factors, the ideal material had to have the following characteristics:

- "Quick set" characteristics,
- "Nonshrink" type,
- Rapid strength gain—20 MPa in less than 12 hr,
- Long-term durability to freeze-thaw cycles,
- Be readily available,
- Be economically viable,
- Be capable of being placed on dry as well as wet substrates, and
- Be capable of being placed in cooler temperatures—around 5°C.

EVALUATION

In 1988 the city of Calgary, in conjunction with the Civil Engineering Department of the University of Calgary, evaluated two potential plinth construction materials, Icosit KC and a modified epoxy grout. Both materials exhibited desirable properties but required further field testing for applicability to this project.

Reid Crowther & Partners Ltd. of Calgary were retained to undertake an independent assessment of all potential plinth repair materials and the related construction procedures (including the two evaluated at the University of Calgary) that would have minimal impact on the train operation.

The evaluation used in the assessment of the numerous repair methods included the following major criteria:

- Meet structural design requirements.
- Provide a durable long-term repair.
- Meet construction constraints imposed by the existing site conditions.
- Meet constraints imposed by revenue service operation.
- Be economically viable.

It became evident early in the evaluation that a single repair material would not rank number one in all five of the major criteria established. The four types of plinth pad materials and their construction procedures that ranked highest were the following:

- Portland cement concrete (uses the same construction procedures as for new construction),
- Modified epoxy grout,
- Cementitious grout, and
- Icosit KC—a polyurethane rail compound.

The plinths were to be designed to withstand lateral, longitudinal, and vertical forces generated by the passage of many trains as well as the internal forces generated by the torquing of the plinth anchor bolts. Each of the four products had physical properties that governed the plinth design and preset construction procedures.

The Lord fastening system had been implemented in the direct fixation sections of the northeast and northwest legs and was performing as expected. To maintain system consistency, the Lord fastening system was to be used on the south leg rehabilitation project. The Lord fastening system was approximately 20 mm thicker than the existing Landis-Pandrol system. This difference in height along with the restricted vertical clearance on approaches to tunnels established the design criterion of the vertical geometry of the rehabilitation track. There was no change in the horizontal geometry.

PORTLAND CEMENT CONCRETE PLINTH

The portland cement concrete plinth method is similar to that specified for the construction of new rail plinths. This system consists of a high-strength (40-Mpa) concrete plinth bonded to the existing concrete invert and reinforced internally with steel rebar or wire mesh. Female inserts are embedded in the concrete and are used to anchor a Lord fastener to the top of the concrete plinth surface. To withstand the pull-out force generated by the bolt torque of 260 ft·lbf, the female insert had to be embedded 145 mm into the concrete plinth. This, along with providing room for the steel reinforcement and the vertical geometry, resulted in plinth heights of between 100 and 200 mm. Concrete is relatively weak in bond strength. Therefore the plinths were recessed into the concrete invert to resist lateral and longitudinal loads and mechanically anchored in the recess to resist uplift forces. The recess was also used to minimize the amount that the rail had to be lifted. The recess depth was limited to 50 mm so as to only expose the reinforcing and not cut through it.

The general construction procedure would be as follows:

1. Release and remove the rail.
2. Hydromill 50 mm recess.
3. Install anchors, mechanical or epoxy.
4. Install steel reinforcing.
5. Install forms.
6. Check alignment.
7. Pour concrete.
8. Strip forms.
9. Grind plinth tops to achieve desired bearing surface.
10. Check alignment.
11. Install fastener assembly.
12. Install and fasten rail.

The compressive strength gain of normal concrete is relatively slow, and therefore the time between the concrete pour and allowing loads on the plinths was set at a minimum of 3 days. On the south line rehabilitation project this procedure would require that one revenue track be shut down completely for a period of 1 week for each area of work.

But this does not satisfy the 68-hr maximum shutdown time criterion. Various train and train/bus simulations were run to determine if there was any possible way that one track could be taken out of service for the required week.

This method was subsequently dropped and a field evaluation was not performed.

MODIFIED EPOXY GROUT

The modified epoxy grout plinth system consists of a high-strength epoxy grout mixed with specially graded aggregate. Female inserts would be embedded in the parent concrete invert and be used to anchor the Lord plate to the top of the plinth.

Epoxy grouts can have higher tensile strength and relatively high compressive strength. The plinths can therefore be kept reasonably thin (±50 mm) above the surrounding concrete invert and do not require steel reinforcing. Because of the high bond strengths a recess depth of 25 mm was considered sufficient. Where the change in profile is restricted, the female insert would be embedded into the existing concrete invert. The compressive strength gain is rapid for this type of material and therefore the new plinths could be stressed and loaded after 12 to 24 hr of curing if the ambient temperature were above 20°C.

Epoxy grouts are self-leveling until they reach initial set. This property of the material makes it more difficult to finish the top surface of the plinth on a slope as would be experienced on the inclined tunnel approaches and superelevated sections of the track system. The solution was to use a steel shim plate between the top of the plinth and the bottom of the Lord plate. The shim plate in combination with the forms could be used to completely enclose the plinth, leaving only a small opening on one side (the high side) to pour the grout in. See Figures 2 and 3 for details. The grout is poured slowly into the opening to ensure that all of the air escapes from the

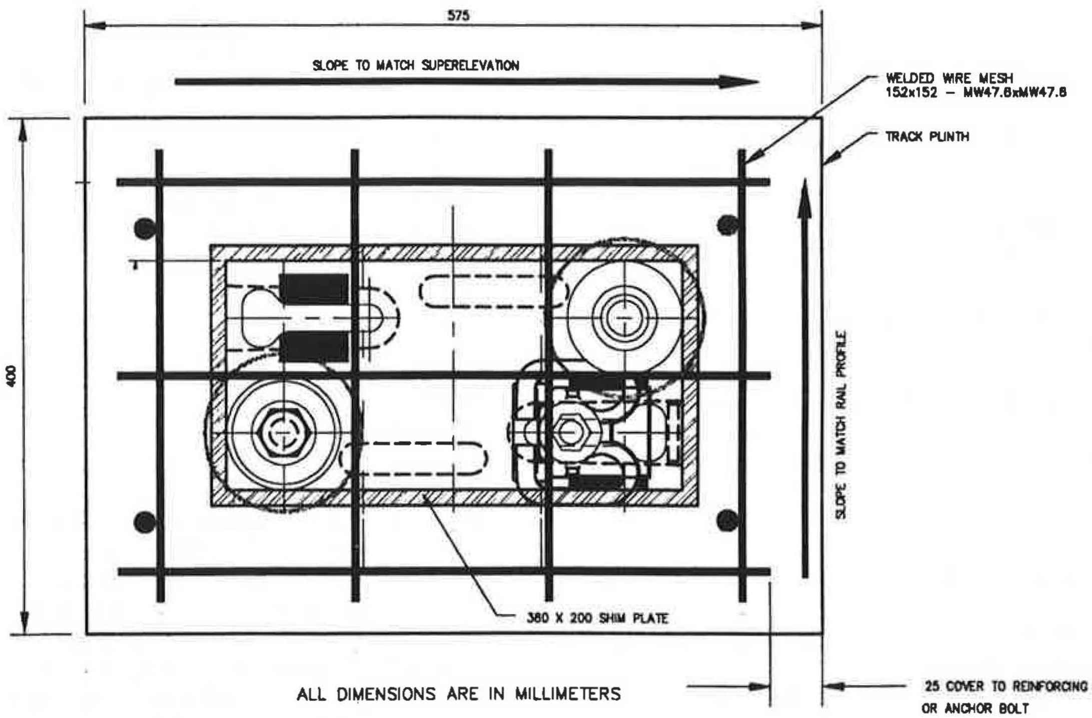


FIGURE 2 Plan view of the direct fixation assembly.

bleed holes. The general construction procedure would be as follows:

1. Hydromill a 25-mm recess.
2. Core holes for female inserts.
3. Check and adjust alignment.
4. Install forms.
5. Suspend Lord fastener assembly.
6. Pour epoxy grout.
7. Remove forms.
8. Final track fastening.

This material satisfied the five general criteria set for material selection. Therefore this material was carried through to the next phase of material testing.

CEMENTITIOUS GROUTS

The cementitious grout plinth system consisted of a Lord fastener anchored in a cementitious grout pad. The grout mix was derived from one part cement to one part of 10-mm nominal size aggregate and a water-to-cement ratio of 0.28. The cementitious grout material exhibited good physical characteristics and could be suitably placed under the field conditions experienced on the south line track. However, the rate of strength gain was not acceptable and concerns were raised as to its performance at cooler temperatures.

Of all the materials tested to this stage, not one of these had satisfied all of the requirements. Therefore it was decided that the cementitious grout not be eliminated at this time.

ICOSIT KC

The Icosit KC plinth consists of a two-part elastomeric polyurethane plinth bonded to the existing concrete invert and a Krupp fastener assembly. In addition steel studs are epoxied into the existing concrete invert to hold the Krupp fastener in place.

Icosit KC has good tensile strength, compressive strength, and bond strength; therefore the plinths do not require reinforcing. However, the Icosit KC material is not rigid and exhibits some deformation in the direction of an applied lateral load.

The plinth heights must not exceed 100 mm, and all plinths should be roughly the same height to maintain the same material stiffness properties. For adjacent plinths with varying plinth heights, the material stiffness should be modified. By bonding the Krupp fastener to the Icosit KC material, the design does not permit any future adjustments to the vertical alignment without removal of the plinth.

The strength gain of the Icosit KC material is rapid, and the new plinths could be constructed in between existing plinths using techniques that allow the rail to remain in place.

The Icosit KC material exhibits self-leveling characteristics, which make it difficult to finish the top surface of the plinth on a slope as would be experienced on the inclined tunnel approaches and superelevated sections of the track system.

The general construction of these type of plinths would be as follows:

1. Hydromill or scabble the top of the existing concrete invert.

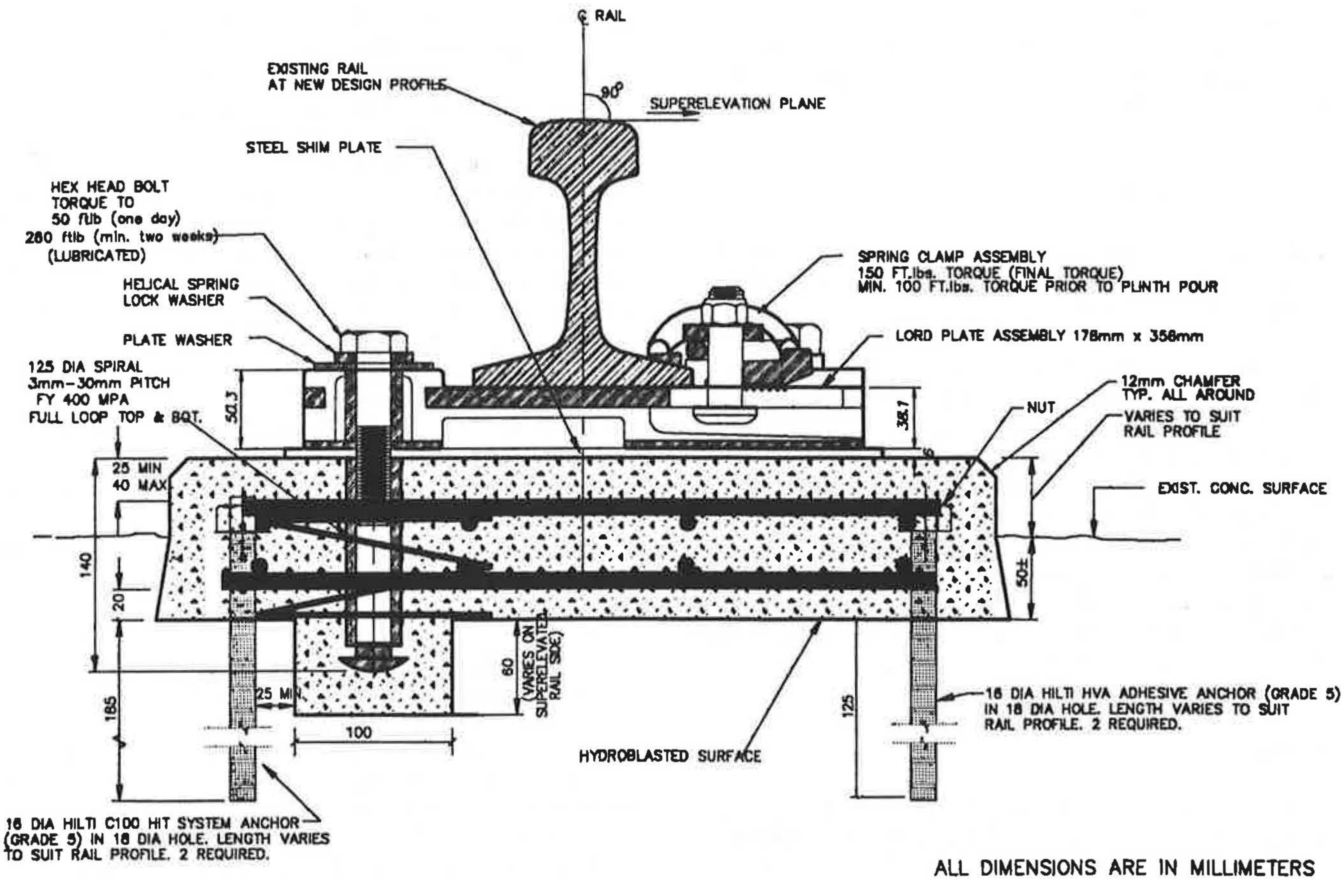


FIGURE 3 Section through the south line direct fixation assembly.

2. Check and adjust alignment.
3. Core holes for anchor studs.
4. Epoxy anchor studs.
5. Install forms.
6. Suspend Krupp fastener assembly.
7. Install forms.
8. Pour Icosit KC.
9. Remove forms.

MATERIALS TESTING

Various materials were tested and evaluated under field conditions to determine their compressive strengths and bond characteristics to wet and dry·concrete substrate. The materials' behavior when placed on sloped surfaces was also investigated.

Working with the suppliers of various materials and their product specifications, the following materials were best suited.

Portland Cement Concrete

The portland cement concrete and plinth system had to be used on the northwest and northeast legs of the LRT system as new construction. These plinths have performed as expected to date and there was no reason to perform any further lists with this material.

Modified Epoxy Grouts

Four epoxy grouts that were evaluated were Sikadur 43, Cappar HLP/VLT, Talleygrout 200 (modified), and Kammacrete 17. The grouts were tested as follows:

- Sikadur 43 is an epoxy-based resin grout that was mixed to the manufacturer's recommendations. This material used a sand as the mineral filler with an aggregate-to-resin ratio of 3:1.
- Cappar HLP/VLT is a polymer-modified grout that was mixed using prebagged 10-mm aggregate. The aggregate-to-resin ratio was approximately 7.75:1 mixed to the manufacturer's specifications.
- Talleygrout 200 (modified) is an epoxy-based resin that was modified to achieve a faster set time. The mix was batched as follows:

Part A, resin, 4.22 kg/batch;
Part B, hardener, 0.98 kg/batch; and
Aggregate finer than No. 8 sieve, 3.75 kg/batch.

- Kammacrete 17 is a polymer-modified grout that was mixed to the manufacturer's requirements with coarse 10-mm concrete aggregate and concrete sand. The aggregate-to-resin ratio was approximately 8.5:1.

Cementitious Grouts

Two cementitious grouts were evaluated: Elsro X-L flowable grout mixture and Pyrament PBC-XT cementitious grout. The grouts were tested as follows:

- Elsro X-L premix grout is a flowable, nonshrink cementitious grout that was mixed as follows: 1 part Elsro X-L permix grout, 1 part 10-mm concrete coarse aggregate, and a water-to-cement ratio of 0.28 calculated based on the aggregate being in saturated surface dry condition.
- Pyrament PBC-XT cementitious grout is a modified hydraulic cement with nonshrink characteristics. The mix was batched in the following proportions: 1 part Pyrament PBC-XT, 1 part clean natural sand, 1 part coarse aggregate (clean, well-graded, 20-mm top size), and 0.28 water-to-cement ratio including free and absorbed water.

Icosit KC

Icosit KC was tested extensively at the University of Calgary in 1988. The Krupp fastener and Icosit KC 330 combination performed reasonably well at above 10°C temperatures and when constructed on dry substrate. The manufacturer recommended that this material should not be used on damp or wet substrate. The university testing also concluded that a 100-mm-high plinth did not perform as well as a 50-mm-high plinth. In the case of the 100-mm-high plinth, excessive swelling of the mastic had occurred during the early stages of the curing process and there were indications that mechanical properties had been impaired. At low loads (up to 20 kN) the 100-mm-high plinth exhibited acceptable stiffness but became too flexible at higher loads. Therefore it was recommended that the plinth heights be limited to 50 mm.

Because of these limitations, it was decided that the Icosit KC 330 would be eliminated from the field testing program.

FIELD TESTING

Various blends of coarse and fine aggregates were tested to determine the optimum ratio that would result in good workability and placement of the mix.

For each material, modified epoxy grout and cementitious grout, a 325 mm × 550 mm × 13 mm-deep recess was created using an electric chipping hammer. A 13-mm recess was used to expose the concrete aggregate and provide the same texture as would be achieved with a 25-mm- or 50-mm-deep recess. A 50-mm-high plinth was then constructed in the recessed area. During the test the ambient temperature was approximately 3°C with the grout mix temperature of 6°C. Material core samples were taken after 24 hr, 7 days, and 28 days. These cores were used to determine the bond strength at the interface between the grout and the concrete substrate. The bond strengths were a measure of the direct tensile load capacity of the core. In addition the compressive strengths of the various grout materials cured under field conditions were determined. Table 1 presents a summary of these data.

Generally the modified epoxy grouts exhibited excellent compressive strength gain characteristics. In most cases, the specified minimum compressive strength requirement of 55 Mpa was achieved in 7 days. These grouts also exhibited good bond characteristics to a dry concrete substrate with the 7-day bond strengths in excess of 1.5 MPa. In all cases the failure occurred at the bond line. In all cases the bond developed to a wet substrate by the modified epoxy grouts was poor and in some cases there was no bond. When poured onto a damp substrate the entire plinth delaminated after 24 hr making it difficult to obtain a core sample. At lower temperatures (of less than 5°C) some of the modified epoxy grouts did not set up in the first 12 hr.

As a result of the low bond strength data obtained for the modified epoxy grouts and the longer set times required in colder temperatures, attention was diverted to the cementitious grouts.

The cementitious grout plinths exhibited excellent compressive strength gains with acceptable bond strengths. The Elsro XL-Premix grout exhibited excellent strength increases under ideal conditions (ambient temperature of 20°C). However concerns regarding the freeze-thaw durability of the material and the strength gain characteristics at cooler temperatures were raised. This material was not considered further in the testing program. The Pyrament PBC-XT exhibited excellent strength gains—10 MPa in 4 hr with 32 MPa compressive strength achieved in 3 days. The excellent bond characteristics were demonstrated by the difficulty experienced in removing some overflowed material that had set up on the concrete floor.

Therefore only the Pyrament PBC-XT was tested further. Various blends of coarse aggregate and sand were investigated in terms of compressive strength and placability. It was observed that flowable mixes could be obtained while maintaining a water-to-cement ratio of 0.265. Exceeding a 1:2 ratio of cement to combined aggregate blend resulted in either a stiff mix or lower-than-specified compressive strengths or both.

DESIGN MIX

As a result of this testing program it was decided that the Pyrament PBC-XT mix would be used for the repair of the

TABLE 1 Modified Epoxy Grout Evaluation Results

	COMPRESSIVE STRENGTH (MPa)		TENSILE STRENGTH (MPa)			
Product	1 Day	7 Day	1 Day Dry	1 Day Wet	7 Day Dry	28 Day Dry
Sikadur 43	6.5	31.8	0.89	0.80	2.12	1.20
Cappar HLP/VLT	65.0	80.0	0.87	...	0.97	0.85
Talleygrout 200 (Modified)	42.1	67.5	1.92	0.21	1.76	1.08
Kammacrete 17	80.0	83.0	1.28	...	1.42	0.64

Calgary LRT system. The design mix is summarized as follows:

	Volume	*Weight*
Pyrament PBC-XT cement	1.0 parts	25.0 kg
Concrete sand	0.6 parts	6.3 kg
Coarse aggregate	1.4 parts	45.0 kg
Water	6.6 L	6.6 L
Water-to-cement ratio (based on total water)	0.265	0.265

The material gradation for the concrete sand and coarse aggregate used on this project is shown in Table 2.

CONSTRUCTION

To carry out the rehabilitation work, changes were required to the LRT operations and schedules. The construction was carried out on one track while the trains ran on the other. The hours of reverse running during week nights as specified in the contract were from 7 p.m. to the end of revenue service at 1 a.m. After revenue service work could be carried out on both tracks until 5 a.m. when both tracks were returned to revenue service. During the weekends the construction was carried out continuously on one track from 7 p.m., Friday to 5 a.m., Monday.

The rehabilitation project was divided in two phases:

- Phase 1—North approach to C.P. tunnel.
- Phase 2—Big 4 slab, Elbow River Bridge, north approach to the Cemetery Hill Tunnel, and south approach to the Cemetery Hill Tunnel.

Bids were requested for Phase 1 of this project in July 1989 with the construction starting in August 1989. This phase consisted of the construction of 1,200 new Pyrament PBC-XT direct fixation plinths and removal of the old plinths. Bids were requested for Phase 2 in March 1990 with construction starting in June 1990. This phase consisted of approximately 2,400 new plinths.

Hydromilling

The system of plinth construction as suggested in the contract documents included creating a 50-mm recess in between adjacent plinths. A 50-mm recess was used to reduce the amount that the rail had to be lifted to accommodate the new plinth system. A hydromilling system was specified exclusively to eliminate the problems that may arise from the microcracks caused by pneumatic hammers. In this system water at 36,000 psi pressure is used to wash away the cement binder in the concrete, thus creating the desired recess. The recess has a rough texture with some aggregates exposed. A rail-mounted hoarding system was used to contain the cement and aggregate that was removed from the concrete substrate as well as to keep the water from contacting the catenary that was live with a 600-V direct current.

The hydromilling work was completed during the weeknights and on weekends. The time required to hydromill a 525 mm × 350 mm × 50 mm-deep recess was approximately 25 min, excluding downtimes because of equipment failures.

TABLE 2 Cementitious Grout Evaluation Results: Pyrament PBC-XT

			COMPRESSIVE STRENGTH (MPa)				
W/C RATIO	10 MM COARSE AGGREGATE BY VOLUME	SAND BY VOLUME	1/2 DAY	1 DAY	3 DAY	7 DAY	REMARKS
0.28	1.4 C.	0.7 C.	19.1	28.6	42.5	47.7	Stiff
0.28	1.4 C.	0.6 C.	35.7		60.7		Stiff
0.28	1.3 C.	0.7 C.	22.6		40.4		Flowable
0.265	1.4 C.	0.6 R.M.	25.7	35.4	52.4	59.9	Flowable
0.265	1.4 C.	0.65 R.M.	19.9	28.8	46.0	51.5	Flowable
0.265	1.4 C.	0.625 R.M.			37.1	44.6	Flowable

			COMPRESSIVE STRENGTH (MPa)				
W/C RATIO	10 MM COARSE AGGREGATE BY VOLUME	SAND BY VOLUME	1 DAY	1 1/2 DAY	7 DAY	28 DAY	REMARKS
0.265	1.2 R.M	0.8 R.M.	41.2	48.1	55.9	67.2	Flowable
0.265	1.4 R.M.	0.7 R.M.	30.5	36.2	39.55	50.3	Flowable
0.265	1.6 R.M.	0.7 R.M.	47.9	59.3	70.0	77.5	Stiff

Note: R.M. = Aggregate Supplied by Rolling-Mix of Calgary
C. = Aggregate Supplied by Consolidated Concrete of Calgary

Coring of 75-mm Holes

The 75-mm holes were cored to allow for the embedment of the female insert. The holes were cored with diamond-tipped coring bits capable of cutting through steel reinforcing when encountered. The contractor converted an old tamping machine to core these holes. This equipment was rail-mounted and produced very even, accurately placed cored holes at constant depths. The concrete core was then removed with the aid of a cold chisel and a hammer.

Install Anchor Studs

The 18-mm diameter core holes were cored using a specially designed rail-mounted, self-propelled drill capable of coring two holes at the same time. Diamond-tipped bits were used that were capable of cutting through steel reinforcing when encountered. The Hilti HVA cartridge and Hilti HIT system were used to epoxy the 16-mm-diameter threaded rods into the substrate concrete.

The hydromilling, coring, and anchor stud installation were completed prior to the weekend when the remainder of the plinth construction, including the concrete pour, was to take place.

Plinth Construction

The longest period that one track could be taken out of revenue service had been set at 68 hours. Therefore the work was scheduled on long weekends whenever possible.

During this period the spring clips on the existing Landis-Pandrol fasteners were removed and the rail was raised to the designed elevation. Mechanical jacks and wood bracing were used to ensure that the rail remained at its designed alignment, both vertically and horizontally. Two layers of steel reinforcing were installed along with wax-treated metal forms. The steel reinforcing was tied to the Hilti anchor studs with a minimum of 25-mm cover provided on the top surface and on the sides. Construction details are shown in Figures 2 and 3. The Pyrament PBC-XT was preblended with the required amount of aggregates and was delivered to the site in 35-kg bags. To produce the Pyrament PBC-XT in 70-kg batches, 0.25 cu.m. grout mixers were used. The Pyrament mix was very sensitive to water; therefore great care was taken to ensure that the mix was the desired consistency. The Pyrament PBC-XT mix was placed into the formed plinths using a tapered chute. Pencil vibrators were used to consolidate the mix. Finishing was completed using conventional concrete finishing tools. The quality assurance program for this project included full-time supervision at the mixers and concrete test cubes were cast every 3 hr or at the engineer's discretion. The concrete compressive tests were carried out at 8 hr, 12 hr, 24 hr, and 28 days. Table 3 shows the results of these tests.

The mechanical jacks and wood bracing were removed after the concrete had cured for at least 4 hr. The rail was fastened to the new Lord fasteners anchored to the Pyrament PBC-XT plinths. The horizontal and vertical alignments were checked and adjusted to comply with the design requirements. After the Pyrament PBC-XT plinths had cured for minimum of 8

TABLE 3 Test Results

Material: Pyrament PBC-XT
Area: C.P. Tunnel, North Approach - Inbound Track
Date: 16th September 1989 - 17th September 1989

COMPRESSIVE STRENGTHS IN MPA					
	Time				
Test #	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	26.0	29.5	36.3	65.7	78.2
C2	30.8	31.1	40.0	66.9	91.7
C3	26.1	28.3	35.8	67.6	86.4
C4	31.6	34.9	43.5	74.3	86.8
C5	31.9	36.0	43.7	71.4	101.4
Avg.	29.3	32.0	39.9	69.2	88.9

Material: Pyrament PBC-XT
Area: C.P. Tunnel, North Approach - Outbound Track
Date: 19th May 1990 to 20th May 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	25.6	31.4	39.2	73.8	94.3
M1	25.8	-	-	-	-	72.5
C2	-	18.4	22.0	26.7	57.1	66.2
M2	20.4	-	-	-	-	59.7
C3	-	20.2	21.5	32.8	47.9	59.7
M3	18.9	-	-	-	-	61.7
C4	-	34.4	40.1	43.5	73.7	84.6
M4	28.3	-	-	-	-	70.9
C5	-	17.9	18.3	22.0	46.0	55.6
M5	25.5	-	-	-	73.5	77.0
C6	16.6	-	18.2	-	49.3	56.6
C7	20.0	-	23.0	-	55.0	65.8
Avg.	22.2	23.3	24.9	32.8	59.5	68.7

Material: Pyrament PBC-XT
Area: Cemetery Hill Tunnel, South Portal - Inbound Track
Date: August 4th, 1990 to August 8th 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	14.4	18.8	25.0	46.2	55.3
M1	20.4	-	-	-	-	60.0
C2	-	24.8	26.8	37.8	57.7	69.4
M2	19.1	-	-	-	-	58.1
C3	-	24.9	32.9	45.7	61.0	73.5
M3	10.7	-	-	21.7	-	41.9
C4	-	23.9	26.8	32.8	50.7	57.4
M4	9.0	-	-	20.4	-	30.2
C5	-	18.8	27.1	40.3	54.7	68.6
M9	17.0	-	22.9	30.2	50.9	60.0
C10	13.2	14.3	-	25.0	32.3	46.3
C11	-	23.8	27.1	32.9	50.5	-
Avg.	14.9	20.7	26.1	50.5	56.4	51.7

Material: Pyrament PBC-XT
Area: Cemetery Hill Tunnel, South Portal - Outbound Track
Date: September 15th 1990 to September 16th 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	6 Hrs	8 Hrs	12 Hrs	24 Hrs	7 Days	28 Days
C1	-	25.9	36.3	44.4	77.6	91.0
M1	-	16.4	-	-	-	62.0
C2	-	22.8	30.5	34.4	69.1	74.1
M2	-	25.8	-	-	-	78.9
C3	-	13.3	16.7	22.8	43.4	45.6
M3	-	25.4	-	-	-	83.9
C4	-	27.4	32.7	36.1	69.8	80.6
Avg.	-	22.4	29.0	34.4	65.0	73.7

(continued next page)

TABLE 3 Test Results *(continued)*

Material: Pyrament PBC-XT
Area: Elbow River Bridge - Inbound Track
Date: August 7th 1990 to August 8th 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	**6 Hrs**	**8 Hrs**	**12 Hrs**	**24 Hrs**	**7 Days**	**28 Days**
M5	21.6	-	-	-	-	66.8
C6	-	14.7	21.7	32.8	48.7	57.6
M6	19.6	-	-	-	-	68.9
C7	-	17.9	21.7	25.6	41.2	50.6
M7	25.6	-	-	-	-	71.2
C8	29.2	33.7	35.4	40.6	-	71.5
M8	20.8	-	28.9	42.7	54.6	70.0
Avg.	23.4	22.1	26.9	35.4	48.2	65.2

Material: Pyrament PBC-XT
Area: Elbow River Bridge - Outbound Track
Date: September 17 1990 to September 18 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	**6 Hrs**	**8 Hrs**	**12 Hrs**	**24 Hrs**	**7 Days**	**28 Days**
M4	22.7	-	-	-	-	80.1
C5	-	19.9	28.9	29.6	63.1	76.6
M5	24.5	-	-	-	-	85.7
C6	-	31.7	35.7	46.6	74.2	82.8
M6	27.3	-	-	-	-	101.3
C7	-	25.6	29.6	40.4	73.9	87.5
C8	26.0	28.9	33.3	37.9	59.7	72.3
M8	25.7	-	-	-	-	77.5
Avg.	25.2	26.5	31.9	38.6	67.7	83.0

Material: Pyrament PBC-XT
Area: Cemetery Hill, North Portal - Outbound Track
Date: October 14th, 1990

COMPRESSIVE STRENGTHS IN MPA						
	Time					
Test #	**6 Hrs**	**8 Hrs**	**12 Hrs**	**24 Hrs**	**7 Days**	**28 Days**
C1	-	27.2	31.9	-	-	83.2
M1	30.9	-	35.3	-	-	90.7
C2	-	24.8	28.1	32.2	76.5	94.1
M2	17.9	-	23.2	-	-	84.5
Avg.	24.4	26.0	29.6	32.2	76.5	88.1

hr and attained a minimum compressive strength of 20 MPa, a final rail gauge check was performed. The Lord fastener anchor bolts were torqued to 50 ft·lbf and the track was returned to revenue service. The main anchor bolts were torqued the designed 260 ft·lbf after 14 days.

CONCLUSIONS

The material selection program was carried out independent of the design during the initial stages. After having selected the most suitable material, the Pyrament PBC-XT in this case, a complete testing program to simulate plinth construction under field conditions was carried out. As a result, the plinth dimensions were modified slightly to make the plinth construction procedure simple with good quality control.

The testing and evaluation of the materials to simulate the construction of the new plinths under field conditions were also key to the success of this project. The Pyrament PBC-XT material worked as expected. The material is very sensitive to water content and therefore close attention is required to ensure that the quality of the mix is maintained. The approximate working time available is 90 min but varies with temperature. The material worked well in colder temperatures but the resulting compressive strengths were considerably lower than those of the mix that was placed at higher temperature (around 20°C).

The constraints imposed by the train operations and schedule, the fixed horizontal alignment, and a vertical alignment that could not be changed appreciably presented challenges that were successfully conquered by the design team. The proof is exhibited in the successful completion of the south line rehabilitation project within the scheduled time and allocated budget. There were also no disruptions to revenue service recorded on the project.

Further testing of the new Pyrament concrete plinths was carried out after the curing period. Table 4 displays the results.

TABLE 4 Pyrament Plinth Test Results After Curing

Location	**Strength MPa**	**Density Kg/m^3**	**Air %**	**Spacing Factor**	**Permeability**
Elbow River	56.3	2219.3	11.4	0.148	2.15
	27.7	2000.0	9.98	0.189	32.5
	71.3	2180.6	6.78	0.194	3.90
	59.0	2226.9	6.25	0.248	0.97
	69.5	2246.2	5.87	0.189	1.60
	63.8	2241.6	9.43	0.138	1.79
Cemetery Hill - South	73.1	2282.6	5.17	0.279	0.75
	75.1	2339.0	6.76	0.200	0.73
	53.4	226.1	8.55	0.134	2.81
	45.4	2130.3	7.69	0.167	3.54
	44.5	2117.9	9.17	0.157	3.05
C.P. Portal	55.8	2287.0	6.19	0.229	0.53
	58.8	2234.6	6.45	0.202	1.61
	87.8	2503.7	3.31	0.316	0.53

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Light Rail Transit Bridge Design Issues

ROBERT D. NIEMIETZ AND ANTHONY W. NIEMEYER

With the advent of numerous light rail projects being developed in North America, the need to construct bridges to carry these systems over waterways or existing facilities has made designers aware of issues concerning these particular structures that require focus on items not typically associated with railroad or highway bridges. The design of these bridges has required bridge engineers to review the applicability of existing railroad and highway bridge codes to the design of bridges that carry only the transit vehicles or specialized maintenance vehicles and that are not also to carry freight railroad traffic (that is, dedicated light rail bridges). These bridges also require consideration of items that are not typically associated with freight railroad or highway bridges such as power support systems, aesthetic themes, stray current mitigation, and other issues. Two systems currently under construction in St. Louis, Missouri, and Dallas, Texas, have been reviewed to ascertain what light rail transit bridge issues are typically encountered in design and how they may be resolved.

The choice of design codes to be used as criteria for the design of light rail transit (LRT) bridges is an important decision that requires careful consideration of many factors. In the United States, the most familiar bridge design codes are the AASHTO and the American Railway Engineering Association (AREA) design specifications that apply to highway and heavy railroad bridges, respectively (*1,2*). Most light rail loads are significantly greater than the current HS20 truck load used by AASHTO, but not nearly as great as the Cooper E80 Loading prescribed by the current AREA code. Figure 1 depicts the bending moments produced by the Cooper E80 train, the AASHTO HS20 truck or lane load, and the transit vehicles used on the St. Louis Metro Link system and the Dallas Area Rapid Transit (DART) system. This graph shows that, for 100-ft spans, the light rail vehicles (LRVs) produce approximately 50 percent higher bending moments than the HS20 truck, but less than 20 percent of the Cooper E80 moment. These relationships suggest that both the AASHTO and AREA bridge codes should be evaluated for their applicability for light rail bridges that will carry only LRVs or specialized, weight-restricted maintenance vehicles and not freight railway loads.

BRIDGE DESIGN CODES FOR LRT BRIDGES

The AREA bridge specifications (*2*, Chs. 7, 8, and 15) were developed for the heavy freight rail systems of the United States, Canada, and Mexico. The service conditions, frequency, and types of loadings that are applicable to bridges for freight railroads are not mirrored in dedicated LRT systems. The AREA specifications do form a basis for light rail bridge design, but sound engineering judgment should be used in the application of those specifications to LRT bridges and should modify them in certain instances. For example, the AREA steel specifications contain a statement that, for steel deck plate girders, the web-to-flange weld should be a full penetration groove weld. This is certainly applicable to an open deck (ties supported directly on the girder, Figure 2) bridge subjected to the heavy axle loads of a freight railroad that would cause significant impact and torsional loads to be applied to this weld and that haul live loads that may require the greater part of the bridge's load carrying capacity. For an LRT ballast deck, concrete slab on steel deck girder bridge (Figure 3), a significantly cheaper double fillet weld may be appropriately substituted for the groove weld specified. This is because of the relatively light impact and torsion loads applied to the light rail flange-to-web joint and also because of the fact that this type of bridge would use its carrying capacity mostly to carry dead load and therefore would not experience the wide level of stress range that a freight railroad bridge of a similar span would.

Similarly the AREA specifications require that all steel deck spans greater than 50 ft in length have a bottom flange lateral bracing system. This is logical for the two-girder per track, open deck system typically employed for freight railroads for high lateral forces from dynamic train effects (nosing). This requirement may not be applicable for relatively light axle-loaded LRVs on well-maintained, ballast deck, concrete slab on steel girder-type bridges. The majority of the load for these bridges will be transferred to the substructure at the span bearings via the stiff concrete deck in a manner similar to the accommodation of horizontal live loads by highway bridges. The AASHTO specifications are much less severe regarding the need for a lower lateral bracing system. The need for this bracing system should be evaluated carefully before adding the expense for this system to LRT bridge costs. Similar type modifications to the AREA specifications for use on dedicated light rail systems may also be warranted for these particular items:

- Impact loads,
- Height of application of centrifugal force,
- Continuous steel bridges,
- Fatigue stress limitations for steel bridges, and
- Steel transverse stiffener requirements.

If a particular LRT system being designed is to only carry LRVs and system maintenance vehicles, then to be cost-effective the design should not strictly follow AREA E80 design requirements, but should be tailored for the loads that will actually be used on the system.

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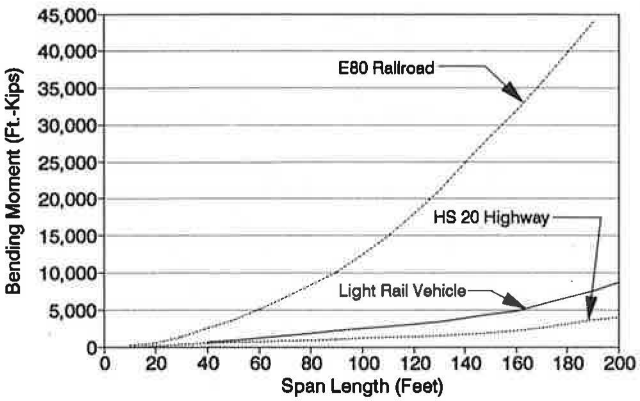


FIGURE 1 Vehicle bending moments on simple spans.

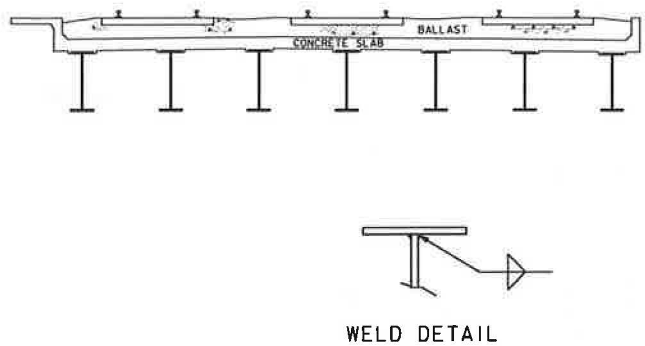


FIGURE 3 Section through ballast deck bridge and weld detail.

Where the LRT system is to carry only the LRV and system maintenance vehicles, two bridges design approaches may be taken:

- The bridges may be designed for the most severe of loadings produced by stipulated transit vehicle loads and stipulated maintenance vehicle loads. This was the design approach used for the St. Louis Metro Link.
- The bridges may be designed for the stipulated transit vehicle and the maintenance vehicles will be restricted to axle loadings that will not overstress the transit vehicle designed bridges. The Dallas Area Rapid Transit (DART) system used this methodology for the design of its bridges.

The first listed method for tailored LRT bridge loadings specify the axle loads and spacing for the passenger consist to be employed and for the various types of maintenance vehicles and their arrangements that will service the system. Often it is the practice to substitute the maximum of these loads for a particular bridge for the E80 load of the AREA specifications and then to follow the remaining provisions of that specification. This method of applying the AREA code should be used with care to preclude expensive, overly conservative designs. Overly conservative designs may result when using the Metro Link design approach from the following:

- Blanket application of AREA impact formulas,
- Blanket application of centrifugal force formulas, and
- Strict compliance with steel fatigue requirements.

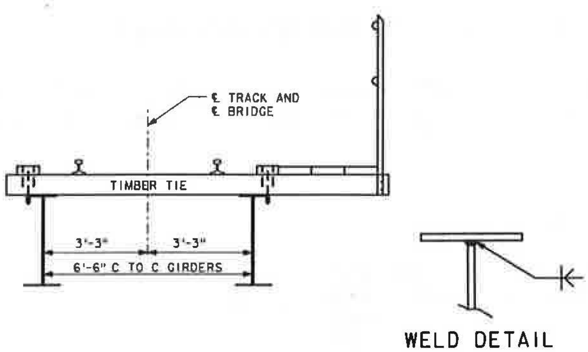


FIGURE 2 Section through open deck bridge and weld detail.

These items generate overly conservative designs if they are applied, without modification, to relatively slow, infrequent maintenance vehicle axle loads, which frequently produce much greater static stresses in a given bridge than the stipulated passenger consist. For example, if the system design life is 60 years, it would be illogical to apply the allowable fatigue stress range for 2 million cycles of live load for a maintenance consist when that consist can reasonably be expected to operate at most monthly over the system, even when that consist produces the greatest static loads. The same reasoning may be applied for the impact forces and centrifugal forces that are speed dependent. To apply the basic AREA formulas to these forces without compensating for the realistic speed at which vehicles will be operated is an unwarranted penalty. Conversely, in regard to fatigue, it is possible that, for a heavily used system, the actual number of loading cycles from the passenger consist may exceed the AREA stipulated number of loading cycles to be designed for. This is of special concern when the DART method of using the LRV as the controlling loading is used.

For LRT bridges that have significantly lower axle loads than the normal AREA E80 loading, it is often cost-effective to use continuous steel bridges, especially where a ballast deck on concrete slab is to be employed. The current AREA specifications do not extensively address the use of continuous bridges because the heavy freight axle loadings often produce high stress ranges in continuous bridge configurations that negate their beneficial reductions in dead loading bending stresses. For LRT bridges, however, the ratio of live load to dead load may more closely approximate that of highway loadings than freight railway loadings (see Figure 4) and the benefits of continuous steel bridges are therefore more likely to be realized. The AASHTO *Standard Specifications for Highway Bridges* (*1*) is a source that may be used for guidance for continuous light rail bridges and for other light rail bridge items that are not explicitly covered by the AREA specifications or for which the AASHTO specifications may be more applicable. A number of these items are as follows:

- Live load impact,
- Load factor design for steel bridges,
- Segmental concrete bridge construction,
- Curved steel bridge girder design, and
- Seismic design.

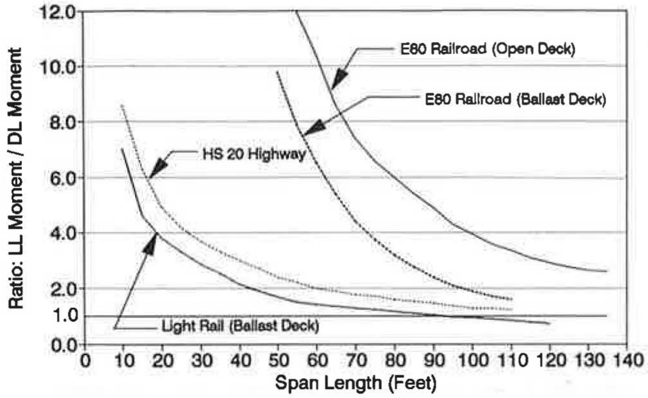


FIGURE 4 Typical bridge live-load-to-dead-load ratios.

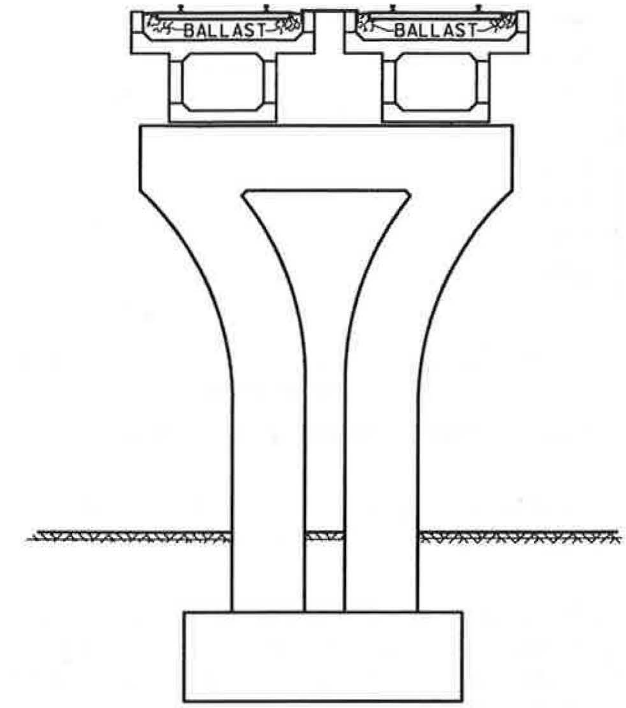


FIGURE 5 St. Louis Metro Link delta bridge pier elevation.

BRIDGE AESTHETICS

The Metro Link light rail system under construction in St. Louis had, from the inception of design work, a partnership of engineers, architects, and artists that gave the system structures a theme that made them attractive and readily recognizable to the public. One part of this theme was the delta bridge pier configuration shown in Figure 5. This was one of a number of items that resulted from work by the partnership to achieve its goal of distinctive structures that were functional and within the construction budget. Another design feature that was attempted to be maintained on the system was the use of haunched, cast in place, concrete box girders wherever possible when new structures were to be constructed. Figure 6 depicts the elevation view of this type of bridge. In some instances, however, these types of girders were not practical to construct. Where grade separation structures required that traffic passing underneath the light rail bridge be maintained, either precast concrete girders or steel spans were sometimes required. The partnership tried to retain the haunched effect on these bridges by developing a handrail that mirrored the cast in place box girder effect in elevation. This handrail is shown in Figure 7.

Of particular concern on the Metro Link project was the visual interface of new structures to be built adjacent to the historic Eads Bridge across the Mississippi River. To avoid any visual discontinuity, the new structural steel spans were designed to appear as vintage late 19th century steel structures. This included the use of exterior vertical web stiffeners, black finish paint coat, and two girders per track framing system. The piers on the east approach to the Eads Bridge were designed as arch-type structures to be consistent with the existing bridge architecture.

The DART system in Dallas did not have a theme that the many bridges to be designed on that system were to follow. Consequently, with the variety of designers on this project, there are a variety of bridge types and forms to be constructed. Figures 8–12 show a number of the structures to be built for DART.

The cost penalty for establishing and maintaining a bridge theme is difficult to determine. Typical costs for the St. Louis Metro Link cast in place concrete girder bridges range from \$1,600 to \$2,200 per track foot for spans between 80 and 100 ft long. Bridges of similar span length for the DART system range from \$1,200 to \$2,300 per track foot. For any bridge, many of its costs are site-specific, therefore direct cost comparisons between the bridges of the two systems should be done with care.

LIGHT RAIL BRIDGE MAINTENANCE ISSUES

Maintenance of LRT bridges must be considered at the beginning of the design process. Tie replacement is one issue

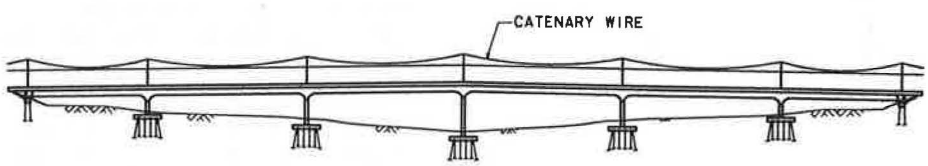


FIGURE 6 Metro Link cast-in-place concrete box girder bridge.

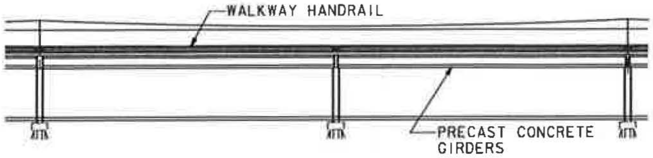


FIGURE 7 Elevation showing handrail used to simulate the haunched effect called for by Metro Link's design criteria.

that requires attention and should be studied in conjunction with what types of ties are to be employed, their fastening system, available times for scheduled maintenance, and ease of making emergency, unscheduled repairs. Bridge deck designs should account for storage of replacement ties, ease of tie removal and insertion, and tamping of ties on ballast deck bridges.

Other maintenance items that should be considered in design are the use of ballast deck, open deck, or direct fixation deck bridges. These types are shown in Figures 13–15. Each has it own particular advantages and disadvantages:

	Advantages	*Disadvantages*
Ballast deck	Good ride quality Impact damping Good live load distribution Good track support Standard track maintenance Good retainage of track debris	Heavy dead load Deck drainage Greater deck depth Waterproofing may be required
Open deck	Light dead load Low first cost Ease of tie replacement Low deck depth	Specialized track restraint required Relatively poor ride quality High live load impacts Poor retainage of track debris
Direct fixation deck	Low maintenance Low deck depth Relatively good ride quality Relatively good live load distribution Relatively low dead load	High first cost Tight construction control required Susceptible to wheel damage Specialized rail fasteners required

WELDED RAIL ON BRIDGES

The wide use of continuous welded rail (CWR) requires the consideration of its effect on LRT bridges, especially in how temperature-induced forces in the rail are transmitted to the bridge and what effect a rail break may have on the structure.

For the bridge to be influenced by temperature changes on the rail, the rail fastening system on the bridge must be able to transmit the lateral forces applied to the rail, both live and any buckling restraint forces, to the deck and through the entire superstructure system to the bridge bearings. Rail restraint longitudinal forces are also transmitted in this fashion.

For ballast deck bridges, the typical rail track fasteners are usually employed. These range from the standard cut spike and separate rail anchor system for timber ties to spring-type

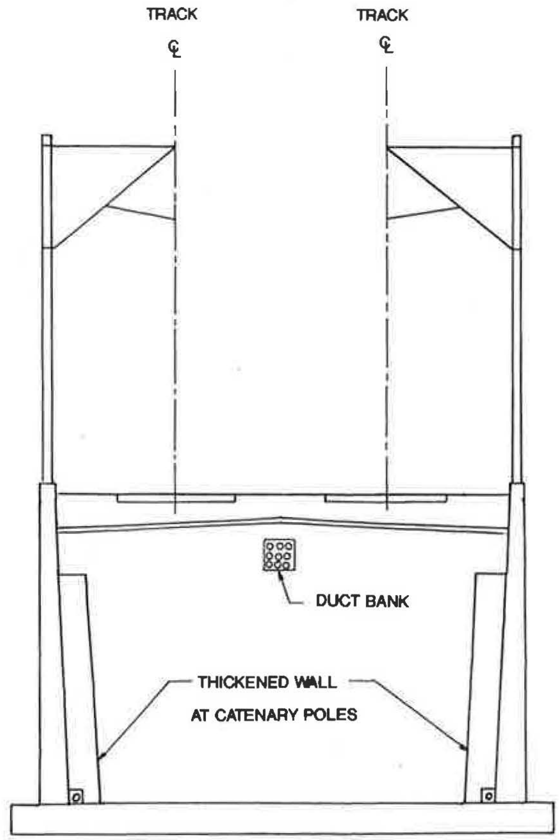


FIGURE 8 Typical section, retained fill bridge approach at catenary poles.

fasteners most often used for concrete ties. These systems transmit rail forces to the tie and then through the ballast to the bridge deck and then to the substructure. Experience has shown this to be satisfactory for bridges composed of simple spans of moderate length.

For longer bridges, where CWR is used, rail expansion joints are often used to reduce problems related to rail movements on the bridge. Figure 16 shows the typical rail expansion joint configuration. Rail expansion joints are relatively expensive and constitute an added maintenance expense.

For open deck bridges, special methods of longitudinal rail restraint are used. One major railroad had recommended that, for simple spans, the third part of the bridge adjacent to the fixed bearing end should have the rail fully box-anchored and that blocks be inserted between the ties to prevent bunching.

The use of CWR on bridges also has created concern over the forces that it may impart to the bridge. For example, a 115-lb rail, completely restrained, develops a force of 191,000 lbs when subjected to a 90°F temperature rise or fall. There is considerable concern over the effect that rail thermal forces may have on the bridge if, for example, the 191,000-lb force noted above is developed and applied to the bridge superstructure. As the rail attempts to contract or expand, the motion of the rail transfers part of this force through the rail fasteners into the bridge deck and then into the bridge structure. Although these forces should be considered, it should

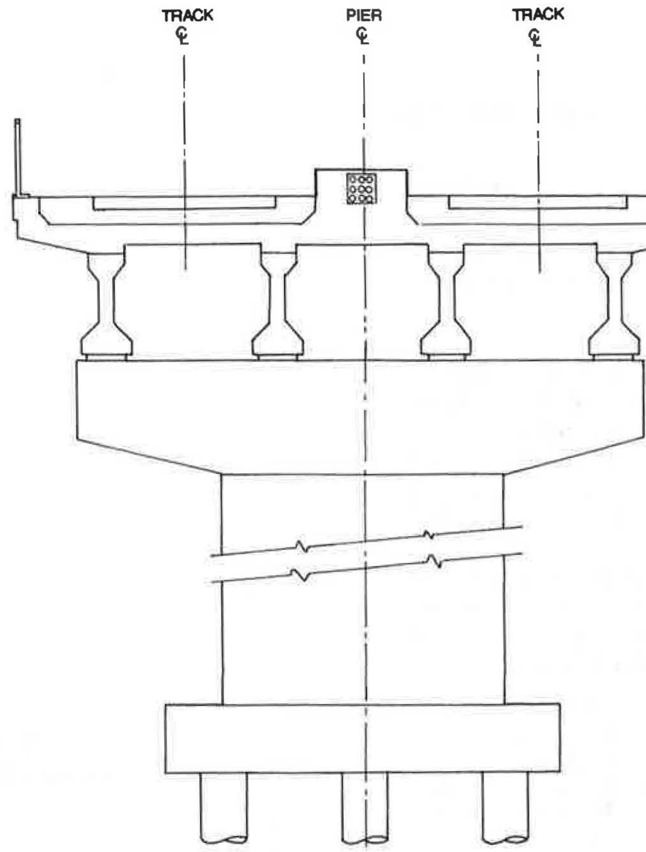


FIGURE 9 Typical section, AASHTO beam span ballast deck.

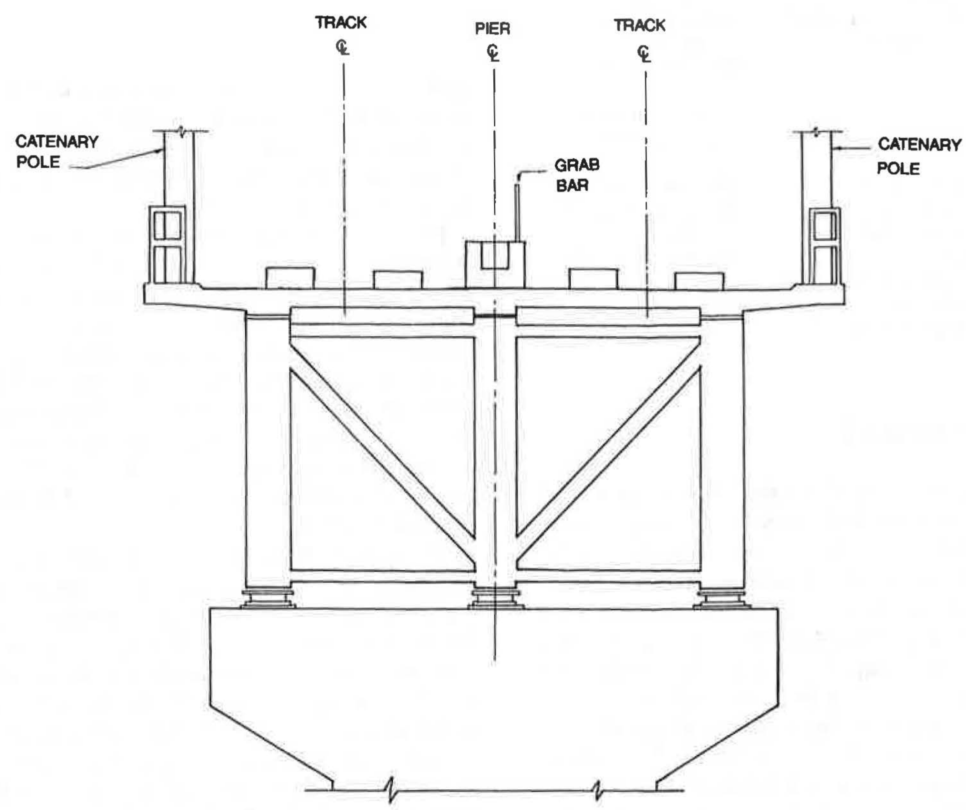


FIGURE 10 Typical section, steel girder span.

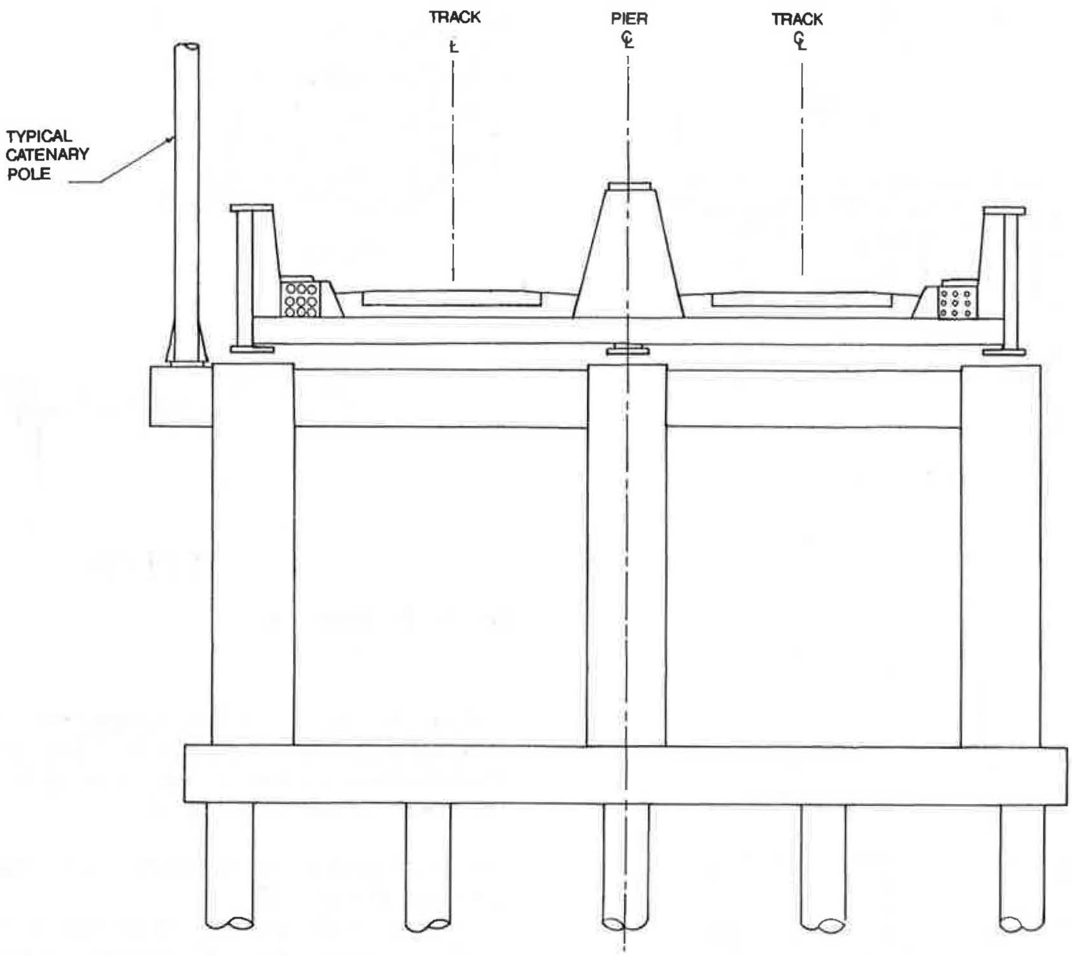


FIGURE 11 Typical section, typical girder span.

be noted that the transfer of forces applied to the rail and then to the bridge structure is a complex procedure. For example, the AREA specifications concerning the transfer of longitudinal tractive or braking forces reduces the 15 percent of applied vertical load to the rail by friction by a factor of the bridge length (in feet) divided by 1,200. This reduces longitudinal force to a negligible effect for most bridge lengths. The commentary to Chapter 15 of the AREA specifications (*2*) notes the reason for this reduction to be the tendency for rail forces to be transmitted off the bridge to the at-grade track structure. This shifting of the rail forces was empirically derived and is applicable only where the rails are continuous or are continually fastened together by joint bars. If rail expansion joints are used on the bridge, or the rails are otherwise not continuous, this substantial reduction in longitudinal force is not to be applied. This same reasoning may be used when considering rail thermal forces in unbroken rail.

Broken rail on LRT bridges is an issue that requires consideration because of the potential large transfer of force to the bridge and for the possibility for derailments because of rail gap formation. It is theoretically possible that, for a particular combination of rail laying temperature, rail restraint devices, span length, bridge expansion bearing configuration, and rail temperature at time of break, a relatively large (2 to 3 in.) gap may develop. The possibility that the rail may break under a wheel of the transit vehicle is a concern that has received much attention on several LRT systems that have been recently developed. Although this is an issue that should be considered, its importance may be mitigated by the following factors:

- Length of gap formation may not be more contributory to derailment than broken rail vertical deflection, which is not gap size dependent;
- Broken rail most often does not occur under load and will give a signal indication of a track defect to alert the transit vehicle; and
- Modern methods of rail inspection, both before and after installation, can detect rail defects or detect flaw growth before they are of a size to precipitate a crack or break. Broken rail results primarily from defects and not rail overstress.

Concern has risen over the possibility of rail gaps and the transfer of thermal-induced rail forces to the bridge structure that would theoretically result when CWR breaks at a low ambient temperature if that rail was installed at a relatively

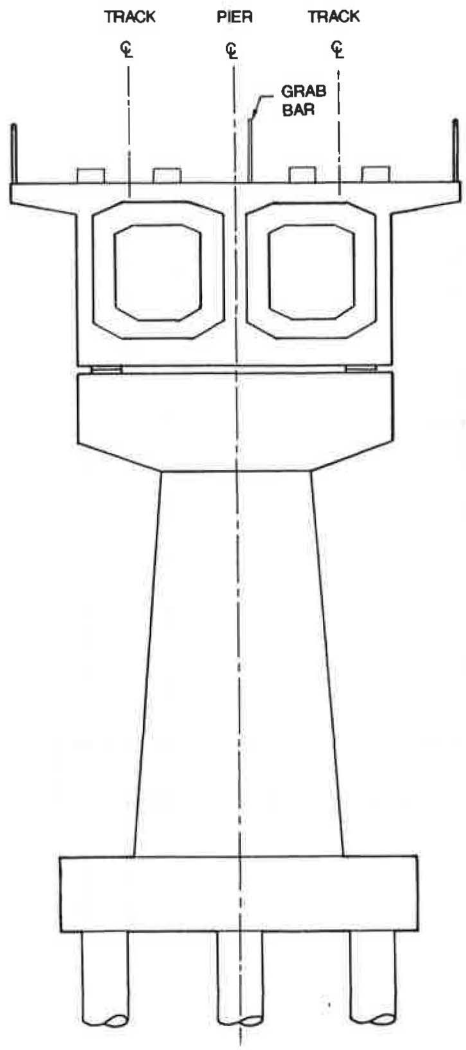


FIGURE 12 Typical section, concrete segmental bridge.

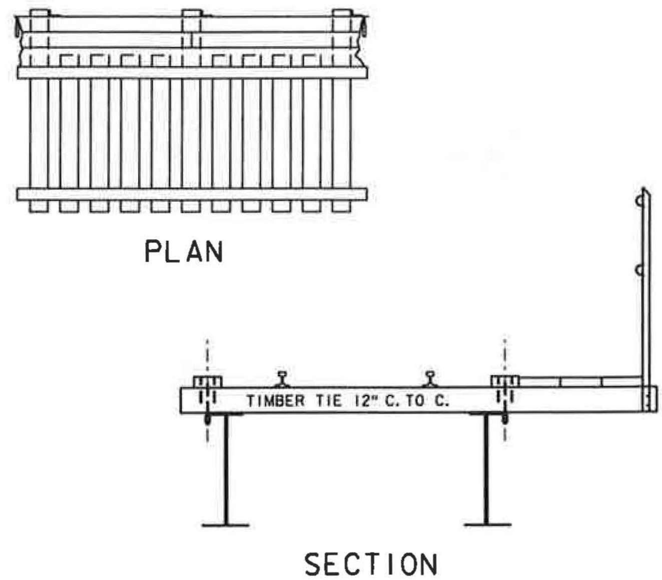


FIGURE 14 Open deck.

high neutral temperature. This has caused some designers to request that, when CWR is used on a bridge, that it be laid at a lower than normal neutral temperature. The rail neutral temperature is the rail temperature that would theoretically result in zero rail thermal stress. Welded rail is typically installed at a neutral temperature that is in the upper 15 to 20 percent of the historical air temperature range of a particular locale. This is to forestall the more dangerous and prevalent susceptibility of the rail to buckle.

Unless there are extraordinary circumstances or a bridge is unusually long, CWR on bridges should be installed at the neutral temperature used for the rail installation on grade. The reasons for this are as follows:

- Experience has shown that rail neutral temperature shifts downward with time (*3*).
- In regard to the effect on a bridge that the breaking of a rail in tension may have, it should be noted that AREA has not included this as a bridge design criterion.
- Rail buckles noted above are just as apt as broken rail to cause derailments and do not give a signal indication of this track defect as does broken rail.
- "Tight rail," which is caused by excessive rail compressive stress, is a rail maintenance problem that can cause rail corrugations, alignment defects, and rail fastener failure. Maintenance of the correct neutral temperature will reduce rail compressive stress.

POWER AND SIGNAL SYSTEM CONSIDERATIONS

Most light rail systems are powered by overhead catenary systems. On bridges, the pole support is typically placed on the bridge piers. If the bridge is a double-track structure and

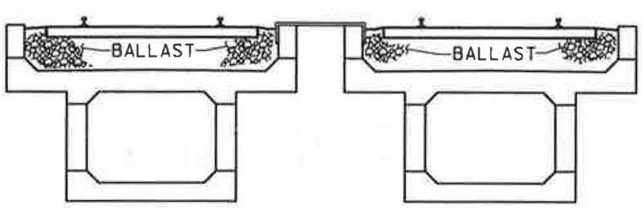


FIGURE 13 Ballast deck.

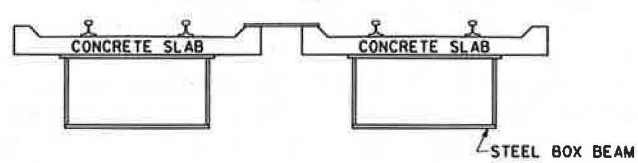


FIGURE 15 Direct fixation deck.

there are no conflicting circumstances, poles are usually placed at the center of the pier. This is to reduce the effect of the relatively large moments that may occasionally be applied to the bridge from the catenary poles and to minimize the number of poles required.

For single-track line segments, some curved bridges where pole clearance is a concern, elevated stations between bridges, or other special situations, side-supported catenary poles must be used. Bridge piers are again the typical location for the pole location. Figures 17 and 18 show typical pole mounting details on piers.

In some situations, it may not be possible to place the poles on the piers. Figure 19 illustrates details used on the DART system to mount the catenary poles on the side of the bridge deck. These side slab locations require extensive reinforcing to satisfy the large eccentric loads.

Another concern relating to the catenary electric power system is that of stray current mitigation. Stray currents can cause corrosion of steel and reinforced concrete. All bridge decks should have their reinforcing steel connected and grounded. Details of the method used on the Metro Link system are shown in Figure 20. On this system, the grounding of slab reinforcement is carried off the bridges by cable contact with a buried scrap rail off each end of the bridge.

Signal and communication lines must also be carried on the structures. For the Metro Link system, these lines are typically accommodated by placing them in a cable tray beneath the center walkway of the double-track structures. For the DART system, these lines are placed in ducts and either cast into the concrete bridge deck or placed under the walkway grating for certain steel bridges (see Figures 8–12). For long bridges where signals must be installed, and to maintain proper interface intervals between the track and signal lines, it is necessary to provide access openings in the bridge for proper connections between the track and signal lines. It is necessary then to have close coordination between the system signal and bridge designers to ensure the proper location of these openings.

SUMMARY

The design of bridges for dedicated light rail transit systems requires careful analysis of a variety of issues. Of significant

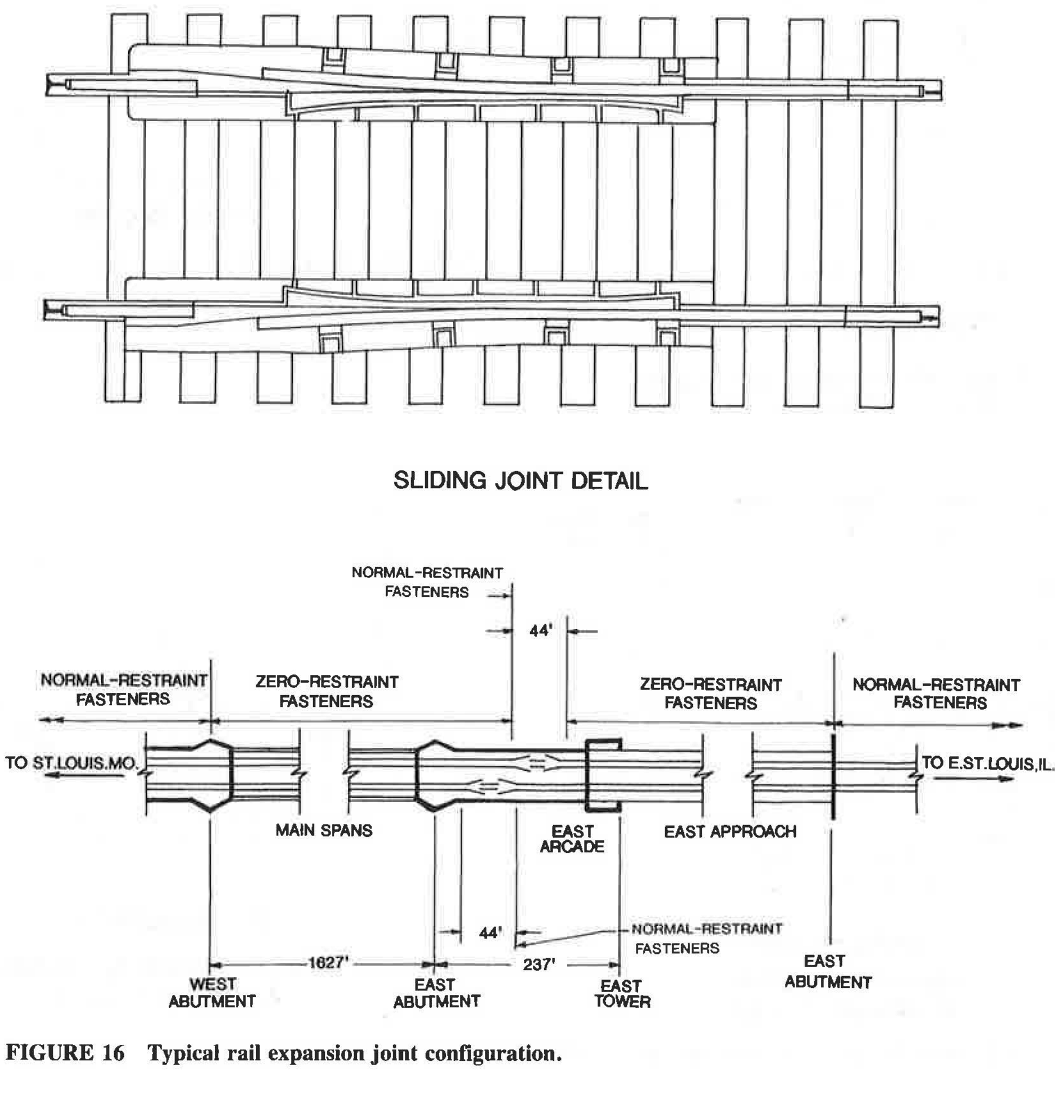


FIGURE 16 Typical rail expansion joint configuration.

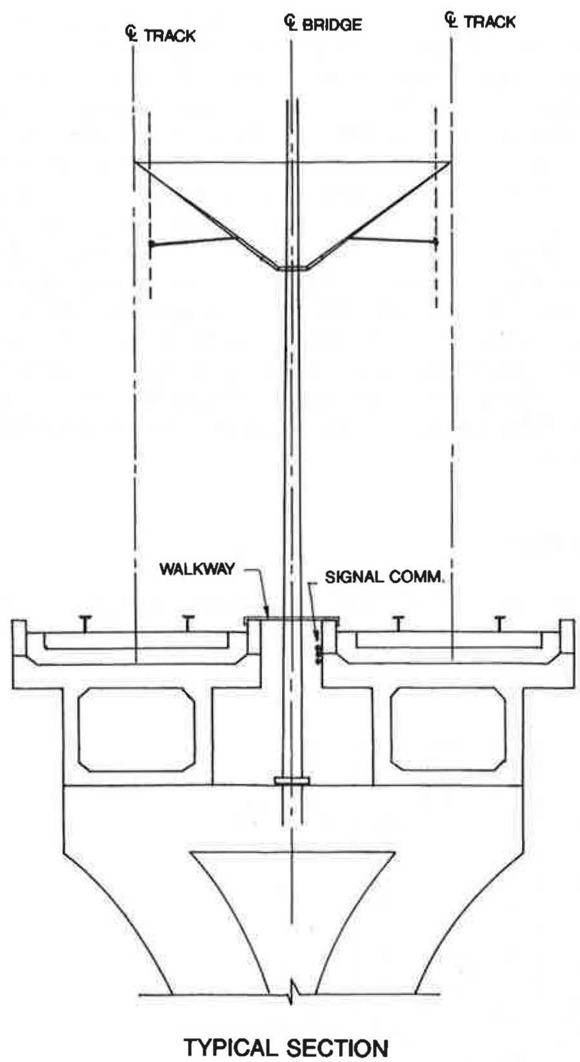


FIGURE 17 **Typical pole mounting details on piers: cast-in-place concrete span ballast deck.**

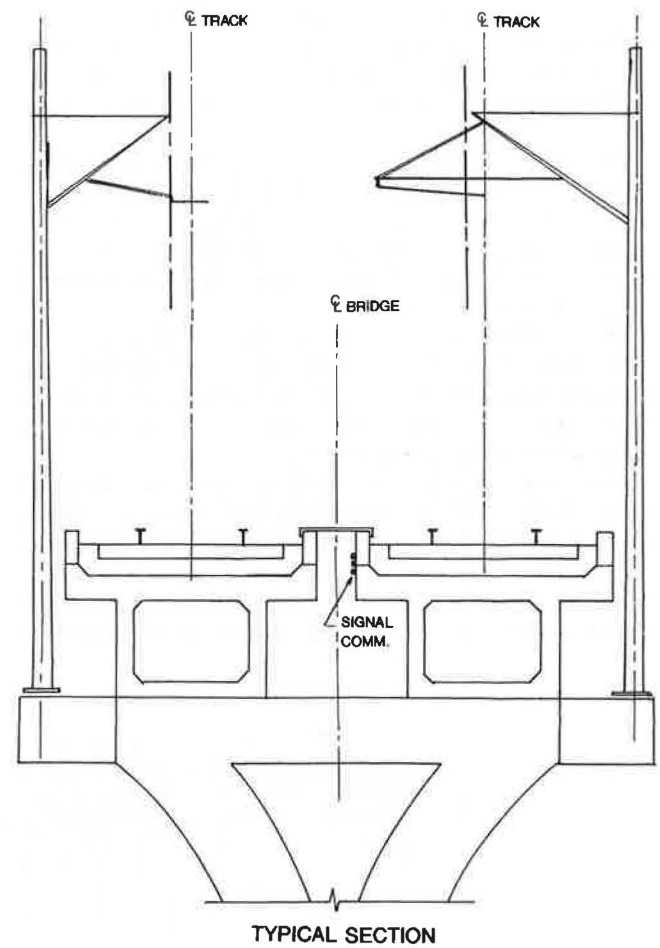


FIGURE 18 **Typical pole mounting details on piers: ballast deck plan.**

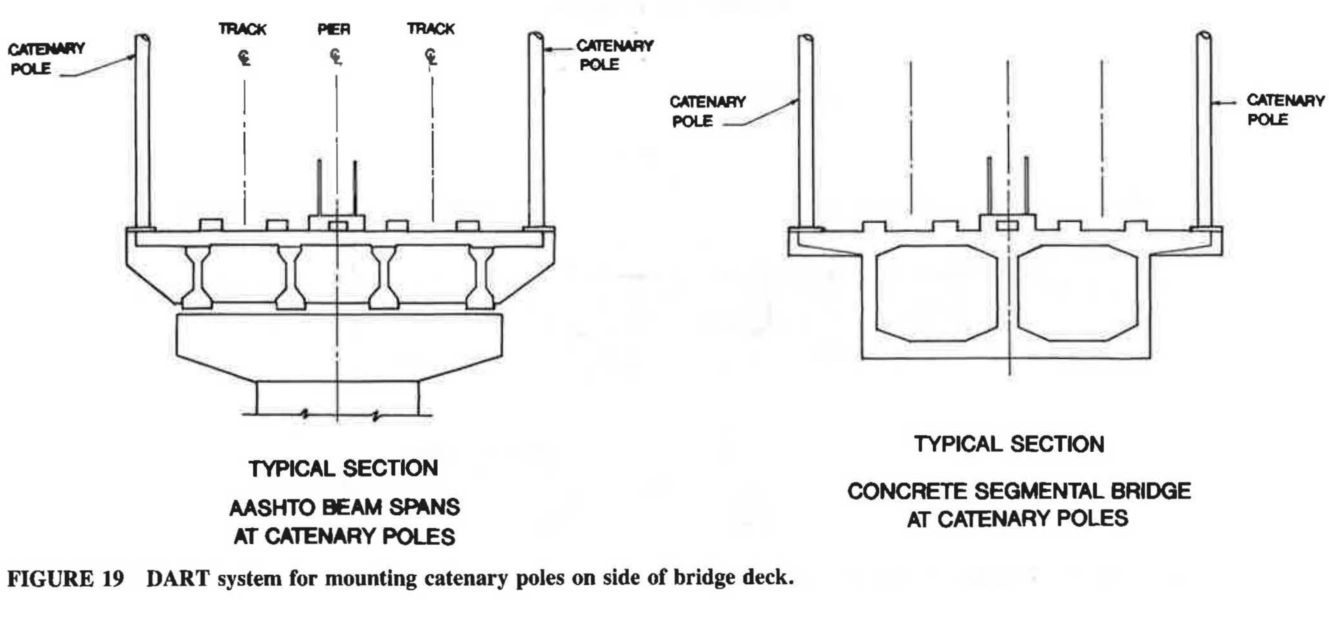
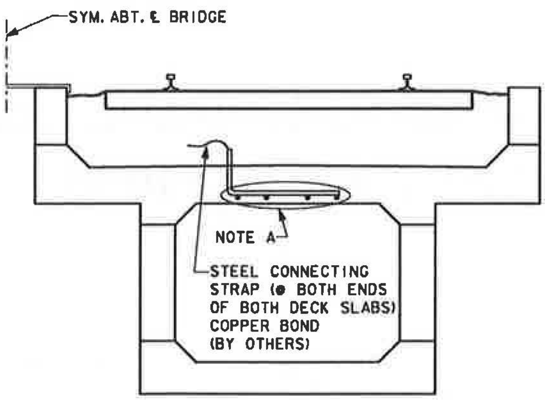


FIGURE 19 **DART system for mounting catenary poles on side of bridge deck.**



NOTE A: ALL LAPS SHALL BE TACK WELDED TO MAKE REINFORCEMENT ELECTRICALLY CONTINUOUS THROUGHOUT LENGTH OF EACH DECK SECTION. AT BOTH ENDS OF EACH DECK SECTION THESE 4 BARS SHOULD BE CONNECTED TOGETHER BY A 1½" x ¼" FLAT STEEL SECTION WELDED TO THE BARS AND BROUGHT TO THE SURFACE OF THE CONCRETE.

FIGURE 20 Metro Link system for stray current grounding.

importance is the recognition that no current bridge design code exists that is completely applicable for the design of light rail bridges. Modification of current AREA and AASHTO bridge design codes is required to address the design of these bridges adequately and economically. Other design issues, such as aesthetics and the use of CWR on bridges, may be site-specific and also require consideration.

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1. *Standard Specifications for Highway Bridges*, 14th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 1989.
2. *Manual for Railway Engineering*. American Railway Engineering Association, Washington, D.C., 1990.
3. J. M. Sundberg. Union Pacific Railroad—Laying and Maintenance Policies for CWR. *AREA Bulletin 717*, Vol. 89, 1988.

Building Bridges: Artists Collaborate as Designers for a Light Rail System

ANN R. RUWITCH

For the first time on a large public works project (Metro Link, the St. Louis light rail system), visual artists worked as equal partners in a collaboration with engineers and architects to design all aspects of the infrastructure, including the design of new bridge structures. Arts in Transit, the sponsoring organization, is a national model and project of the Bi-State Development Agency. A team of visual artists critiqued preliminary engineering for Metro Link and developed aesthetic criteria for the project. Subsequently the artists worked on design development for all the functional elements of the system. In collaboration with the civil engineers, the artists designed a distinctive new bridge structure featuring a slingshot pier and haunched superstructure. This design is part of a unified concept that ties together various parts of Metro Link and relates them to structures in the St. Louis region.

The Bi-State Development Agency in St. Louis has pioneered a new concept in the building of a large rail system by using visual artists in integrated design collaborations with engineers. This unusual working relationship has produced excellent results and changed the thinking about building infrastructure.

Art has been included as an integral part of the construction of new transit systems for many years. For the most part artists have been commissioned to create objects for specific sites and to decorate or design artwork that complements and relates to the architecture. Both large and small systems, Boston, Pittsburgh, Detroit, Miami, Atlanta, Sacramento, Toronto, and Stockholm, have all been enhanced by the addition of artwork, lately referred to as "plop art."

For the 18-mi, 20-station Metro Link light rail system, which is scheduled to begin operation in mid-1993, an entirely new approach was developed by Arts in Transit, in itself an unusual group to be associated with a public works project. Organized in 1986 Arts in Transit (AIT), a group of entrepreneurial and energetic civic leaders, responded to the request of the regional planning agency then responsible for the light rail system to develop and implement a program that would change the negative perceptions of mass transit that existed in the St. Louis region and to maximize a very limited design budget. As a result of the vision of some 30 volunteers, a very ambitious but highly successful program has developed, part of which is the design collaboration.

Bi-State assumed responsibility for the design, construction, and operation of Metro Link in early 1988 and was committed from the beginning to having artists influence the look of the entire system. At that time, preliminary engineering was complete and final design not scheduled to begin for more than a year.

Bi-State Development Agency, 707 North First Street, St. Louis, Mo. 63012.

The journey from the preliminary engineering to the final design (Figure 1) was a complicated one because no practical models existed for a design collaboration of this type. Both the artists and the facilities designers were new to the project. The learning curve was an issue for AIT staff and Bi-State management as well. But most important was the fact that no overall aesthetic criteria or aesthetic goals existed for the system.

Six artists were selected for the design team in a highly publicized national competition many months before requests for proposals were issued to engineers for the project. Grants from the National Endowment for the Arts, a federal agency, and the Regional Arts Commission, a St. Louis agency, paid the fees and expenses for the artists before Bi-State was able to issue contracts under the capital grant from the FTA.

During this interim period the artists critiqued the preliminary engineering design drawings and documents, familiarized themselves with the site, and recommended overall aesthetic design concepts.

The six artists did not know each other before this project and come from different cities with vastly different experiences. But after many days of discussion and debate they were almost of one mind on how they approached this project. Their major concerns with the preliminary engineering were that it seemed fragmented and disconnected, had no sense of place, that it did not relate to St. Louis, and that the system, through its design, was self-contained, emphasizing a linear, unfriendly approach.

Environmental artists are interested in philosophy, metaphor, shapes, forms, relationships, and feelings. "There is something wonderful about Stonehenge," observed Leila Daw, lead artist for Metro Link and primary design collaborator on the new bridge structures. "Most modern bridges are also post and lintel construction, but they almost always look awful." Daw also observed that "highway bridges with curvatures seem more satisfying somehow."

The curve, with the artists' input, has become the strongest design element present in Metro Link. The station canopy shape is a curve. The tunnel station ceiling is curved. Park-and-ride lots have curved contours that follow the natural line of the landscape. According to the artists, repeating the curve gives the system a sense of unity so that not only does it function as a whole, but it also relates to and reminds the public of some of the most familiar and best-liked structures in the St. Louis area—the Arch, Union Station, Eads Bridge, and the Airport Terminal Building, all of which are part of the Metro Link alignment.

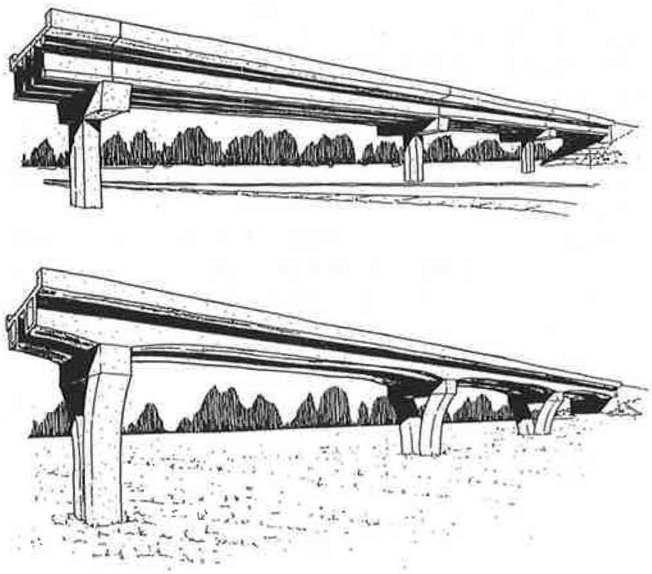

FIGURE 1 Metro Link bridge: (*top*) preliminary engineering phase—post and lintel bridge with constant depth beam on hammerhead piers; (*bottom*) final design—cast-in-place slingshot piers with haunched beamed curved superstructure.

The riders will relate to the surrounding topography and perceive the new bridge structures in a dynamic way as they ride on the train or go gently up and down the hills along Interstate 70, which parallels the train tracks. Equally important are the perceptions of the viewers from the highway as they see the slingshots cropped to existing groundlines, giving a sense of movement as the grade changes.

Leila Daw has worked in a variety of media in sizes ranging from small paper objects to temporary outdoor pieces encompassing many acres. Her work focuses on concepts of time travel and motion. Other artists on the team include St. Louisan Michael Jantzen, who has received considerable attention for innovative designs in living and recreational structures; environmental sculptors Alice Adams and Gary Burnley from New York; Anna Valentina Murch from San Francisco; and Jody Pinto, also from New York. Pinto is best known for her steel footbridge in Pennsylvania, also a collaboration between artist and engineer.

The engineering community knew from the requests for proposals (RFPs) and a series of meetings Bi-State had with firm principals that artists would have a major role in design development. The scope of work for the artists, with their range of responsibilities, was included in the RFP and hours for the collaboration were included in all design consultant contracts. Also mentioned in the RFPs was the existence of an external design review committee that advised Bi-State on aesthetic issues.

All of the artists were involved in preliminary engineering review and aesthetic criteria development. They were also assigned in pairs to station finishes, systems design, and facilities design. These work assignments enabled them to cover most of the functional elements of Metro Link and at the same time preserve the sense of the whole in design, which was the most important of their design criteria.

Engineers from Booker Associates, Inc. (the design consultant) and their subconsultants and Sverdrup Corporation (the Metro Link project management consultant) worked with Leila Daw and Anna Murch in analysis and facilities design. In their 30 percent review report, which also evaluated cost, Booker Associates included the following: "There is a consensus that the bridge structures as proposed in preliminary engineering, although structurally functional and cost effective, are not aesthetically attractive." Through numerous meetings between the design engineers and AIT, several objectives and goals were developed:

- The structures should have a dynamic, flowing appearance.
- The structures should have a neat, clear, uncluttered appearance.
- A central theme should be used for all structures throughout the project.
- The proposed alternatives should carry no more than a minimal increase in cost.
- Structural shapes should be distinctive so as to be identified as part of the Metro Link system.
- The structures should present a three-dimensional appearance.

Leila Daw participated as a team member until the construction package went out for bidding. Sometimes, during the later stages of design, she felt her role had changed from designer to defender of the basic concept. Value engineering produced ideas for saving money on the superstructure that would have destroyed the delicate balance between it and the piers. Other requirements for earthquake protection and maintenance were incorporated late in design development. These involved considerable compromise, but did not negate the essential concept.

The Metro Link bridges weave through a spaghetti interchange of highways with significant changes in grade. The slingshot form of the bridge piers (Figure 2) is the appropriate solution because it is functional, distinctive, and aesthetically balanced with the existing environment. Because of the light

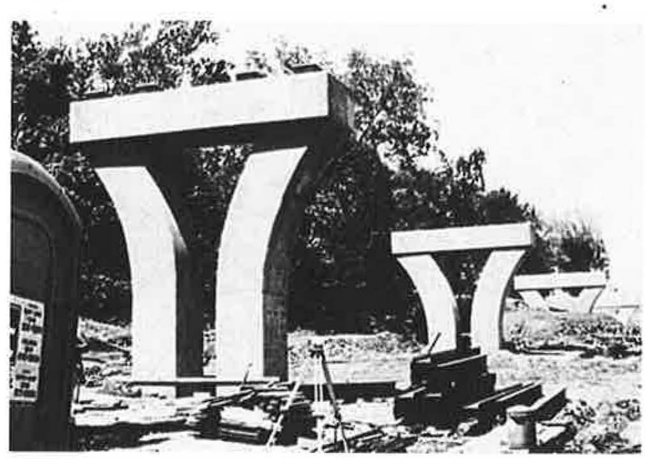

FIGURE 2 Metro Link bridge piers at University of Missouri-St. Louis.

rail construction schedule, the bridge piers were the first highly visible sign that Metro Link was a reality. Their aesthetically pleasing and unusual shape received positive media attention and considerable community response and have served as a marketing tool.

Arts in Transit also markets Metro Link through a series of public arts projects that for 2 years have marked station neighborhoods and the alignment. AIT will continue its marketing efforts with a program based on other elements of the system design besides the new bridge structures.

Metro Link is starting its system with an 18-mi, 20-station route. Much of this alignment has been recycled, using the Eads Bridge railroad deck and tunnel and 9 mi of existing railroad right-of-way. But more than four very visible miles are new construction and include 10 new bridge structures. The bridge going into the main terminal of the airport is three-quarters of a mile long and will utilize a modification of the slingshot pier. Because of site constraints the haunched superstructure could not be used on this section but other elements, such as handrails, were designed to give the sense of the curve.

"The infrastructure of St. Louis will look different in the future," said Stephen E. Willis, P.E., deputy general manager of Metro Link. "I knew we had started something by having engineers work with artists, but I was cautious with my expectations. I was wrong. It's terrific!"

PART 5
Operations and Maintenance

Cleveland's Light Rail System in the 1980s: The Ongoing Revolution

ROBERT J. LANDGRAF

In the early 1980s, the light rail lines in Cleveland were completely reconstructed and equipped with a new fleet of radically different cars not at all suited for street running, effectively converting the line to a low-platform semi-metro and thus realizing much of the long-term intention of the original builders. But these projects, costing upwards of $100 million, were not the end of the matter. Despite the damage to riding volume caused by the disturbances of reconstruction, the revolution resumed near the end of the 1980s. Five recent, basic changes have been made to the system: conversion to right-hand running in the formerly left-hand area, installation of a cab signal system on the western portion, construction of a combined end-to-end high-low platform station downtown as part of an indoor shopping center, evolution of the two boulevard center strips into linear parks, and retrofit of the new car fleet to overcome two major problems. The work reveals much about tolerable levels of deviation and disruption in planning and construction of new or revamped light rail lines. The lesson is derived that operations management must be more assertive early in the planning process when rail transit systems are being altered for purposes not directly related to their performance.

In the early 1980s, the former Shaker Heights Rapid Transit, now known as the Blue and Green Lines of the Greater Cleveland Regional Transit Authority (RTA), was completely reconstructed at a cost approaching $100 million, with all new track, new overhead electrical distribution, two additional substations, new retaining and guard walls, new platforms and shelters, refurbishing of the sole downtown terminal, a huge new shop (shared with the heavy rail system), and a fleet of specialized articulated light rail vehicles (LRVs) 80 ft long and weighing 90,000 lb, which were a radical departure from the various adapted streetcars that had always been used on the lines from their 1913 beginnings. The system was transformed into a true semi-metro, with only the old signal system, parking lots, and two substations built in 1968 remaining. These changes are well described in the literature (*1–3*). For the most part, the reconstruction and refurbishment has proved to be a first-class job and easily maintainable. From the passenger's viewpoint, the far more comfortable and quiet ride with air-conditioning was nothing short of a revolution.

The reconstruction drew to completion with an afterthought: the second complete rerailing of the shared trackage that had been rebuilt with 100-lb ARA-A continuous welded rail in 1955 to accommodate the new heavy rail line. Selected curves had been rerailed again, but this type of rail had become hard to obtain. Instead of using 100-lb ARA-B as had been done on the light rail construction, making procurement compatible with New York's subways, it was decided to go top-drawer with the popular, more rigid, 115-lb AREA, which rested well on the existing tie plates. The result is a very stable roadbed, better coping with the forces caused by frequent operation of two very different types of cars. Unfortunately, this project dragged on over a period of 5 years because the first contractor had problems.

These radical innovations with their large investment were far from the end of the matter. The revolution once set in motion took on a life of its own. Ideas that had seemed like pie-in-the-sky took form without thought as to whether the system had undergone enough already—enough investment, enough change, and perhaps too much disruption.

The inner end of the system just had to be switched over to right-hand running, even though it was converted to left-hand when street-running downtown ceased in 1930 and had worked well enough. A sophisticated cab signal system has been installed on the 3 mi of line shared with and approaching the heavy rail route, replacing a dilapidated three-aspect light system with automatic stop trip-arms installed in 1955 that had not been maintained properly since its youth. Moreover, this older technology depended on assuming a level of competence among drivers not experienced since the RTA began in 1975.

The two separate downtown stations for light rail (low-platform) and heavy rail (high-platform), which had high capacity for future growth and for dealing with special situations, have been taken out and combined into one through station with high and low platforms end-to-end. The new station has a strained capacity, little capability to cope with problems, and a costly turnaround operation. Its stairways and escalators have the appearance of a Dantesque pit in the midst of a very sophisticated major downtown shopping mall and entertainment area.

The above three projects affect only the western 3 mi of the light rail system and are no direct benefit to the rest. They are intertwined in that the change to cab signals and right-hand running had to be coordinated with the work of combining the downtown stations. The cab signal system was planned in the 1970s and would have been installed eventually without the new station.

Landscaping was greatly enhanced along the boulevard center strips in Cleveland and Shaker Heights, with RTA assuming the cost of maintenance in Cleveland. The two light rail branches were, in effect, converted to linear parks with little or no benefit to the riders.

Acquiring the radically different car fleet in the first phase of the revolution brought in a new set of troubles, with snow choking electrical ventilation systems and nearly complete premature failure of the original gear drive sets. These prob-

2927 Weymouth Road, Shaker Heights, Ohio 44120.

lems are not all corrected yet, and further major headaches may be expected from cars now a decade old. But, from the rider's viewpoint, these cars are the crowning achievement of the system's renaissance.

It is hoped that planners and operators of light rail systems will learn from the ongoing Cleveland experience.

CONVERSION OF SHARED TRACKAGE TO RIGHT-HAND RUNNING

Combining the light rail and heavy rail stations in Cleveland Union Terminal into one end-to-end facility, as described later, necessitated the change of light rail's western terminus to right-hand configuration, with passengers alighting and boarding on the left sides of the cars (except for the single stub track, which allows either side of a car to be used). That portion of the line from the junctions east of East 55th Street into Union Terminal had been left-hand long before the heavy rail line was built. The reason for that strange operation lies with the types of cars.

From the time the first parts of the Shaker Heights lines were opened in 1913, single-end streetcars had been the mainstay of the rolling stock. With the exception of seven interurban cars purchased in the 1930s, all cars on the light rail system had doors only on the right. The original fleet, in fact, had only a pair of center doors. All operation was right-hand (with all platforms on the outside) until operation into Cleveland Union Terminal began in 1930.

To minimize trackwork in the terminal and to maximize space for platforms, the "temporary" track arrangement of 1930 (Figure 1) consisted of an inbound track at the left, a clockwise semicircle loop to an outbound track, and two stub tracks in between to be used by backing in or out. In the 1950s one of these stub tracks was extended to cross the loop into a "tail track," permitting easier filling after cars had

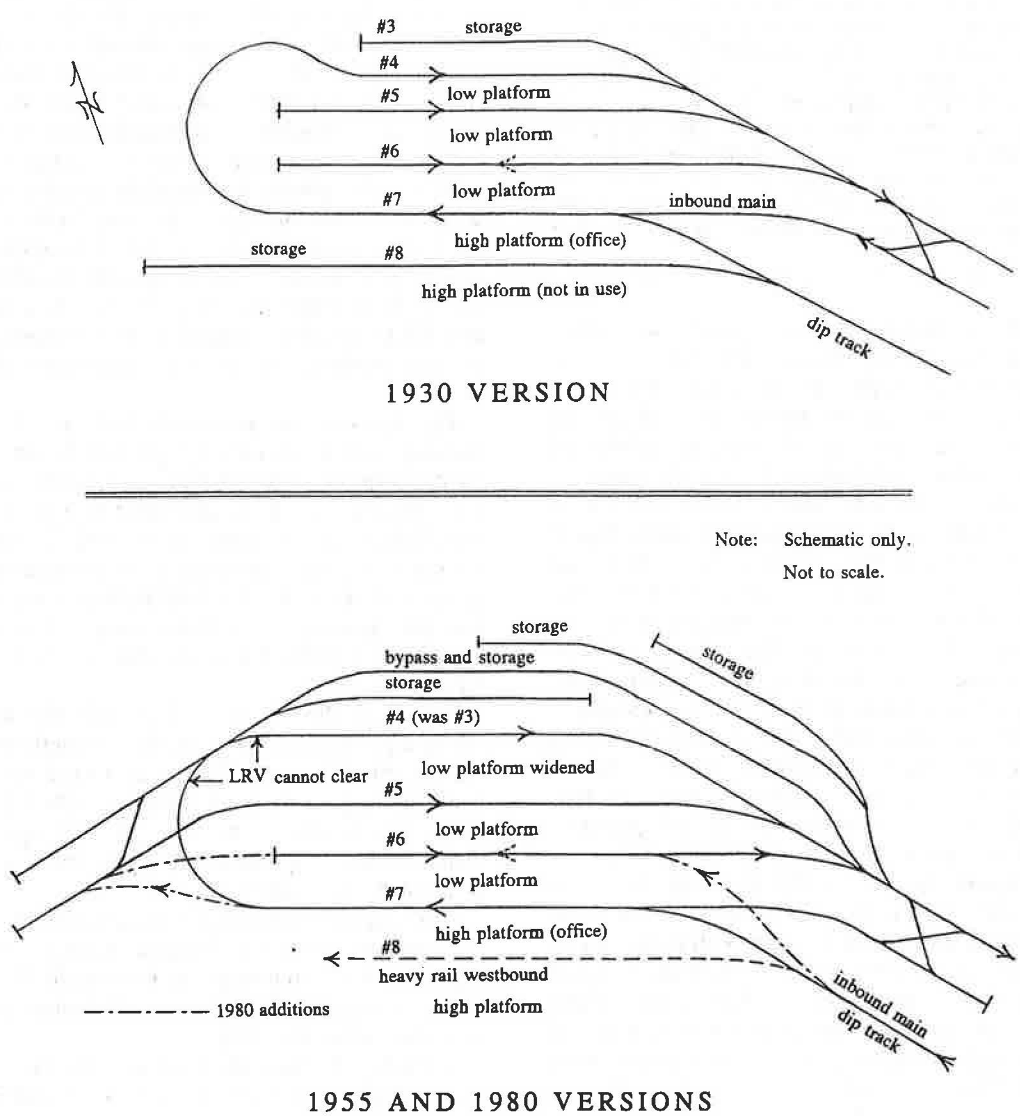

FIGURE 1 Light rail station in Cleveland Union Terminal.

passed around the loop, backing and then pulling forward. This compact arrangement produced a very flexible loading operation (Figure 1, lower part).

The change to left-hand running was made with an over-under braiding move at the new junction tunnels structure east of East 55th Street (Figure 2). This was easy to do after the project constructing the (heavy rail) line to East Cleveland was abandoned in 1930. The westbound line was redirected over the top of the tunnels, and the planned westbound tunnel became the eastbound. The planned eastbound tunnel was used only for switching and an approach to the new Kingsbury Yard and Shop. A center island station was built at East 55th with a very strange shelter at high-platform level, steps leading out of it to the "temporary" cinder low platform. All signals between the junction tunnels and the new 1930 trackage at East 34th Street had to be relocated for left-hand running.

In 1955 when the heavy rail line to East Cleveland was finally completed, it was decided to retain the left-hand configuration east of the downtown terminal, simplifying the junction problem at East 55th. An existing dip track in the terminal was used for both lines to "duck under" the Cleveland Transit System (CTS) eastbound as it changed from right to left (Figure 3). The West Side (of Cleveland) CTS line was constructed right-hand as the easiest way to use this dip for the blending of the two lines at the terminal with no crossing at grade. The first fleet of CTS cars (the "blues") was built with the cab on the right because it was guessed (wrongly) that left-hand running with center platforms would predominate, especially in a downtown subway that was never built. As time went on and the right-hand downtown and West Side operation became more important, this decision was regretted. From the time of the 1967 airport extension, all heavy

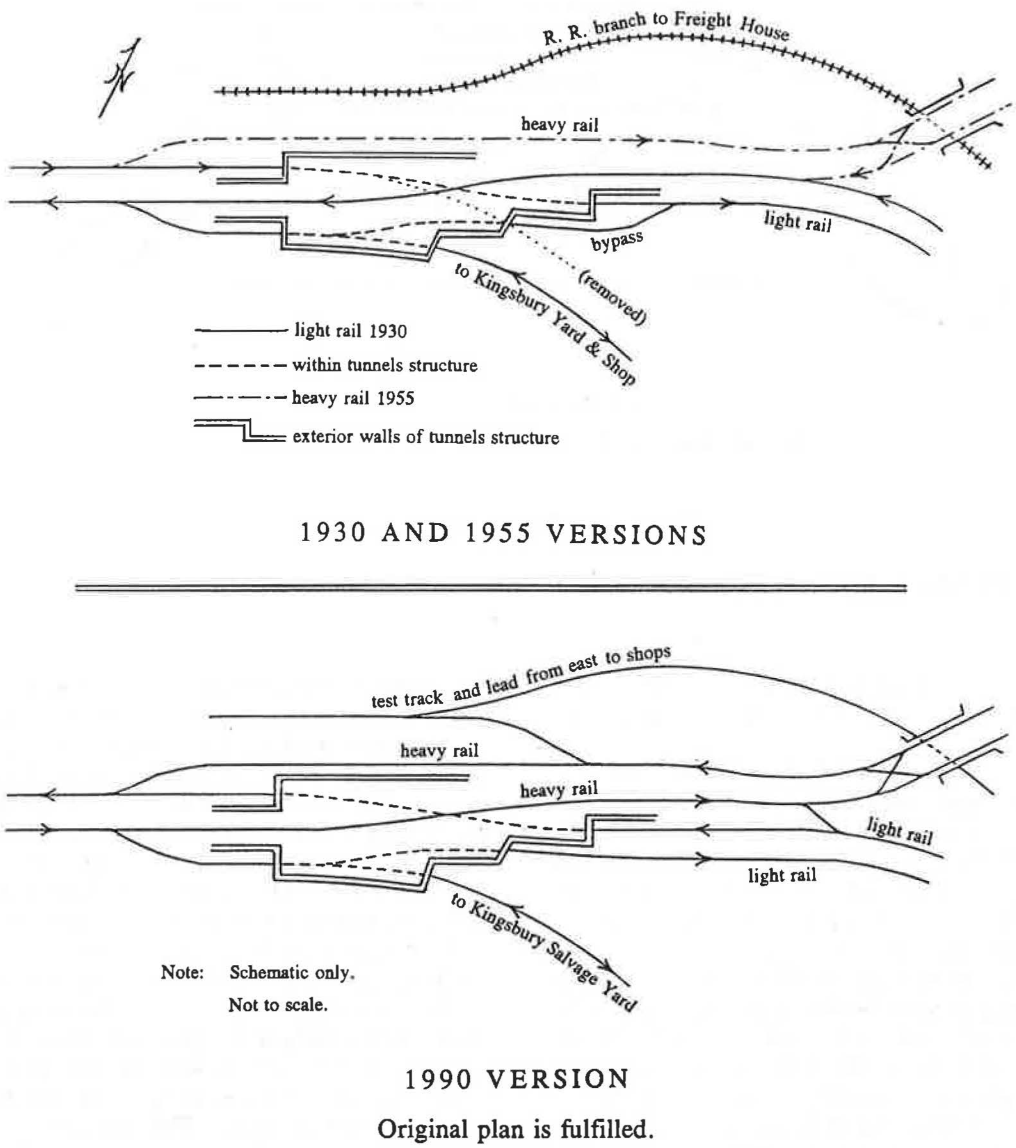

FIGURE 2 Transit junction east of East 55th Street in Cleveland.

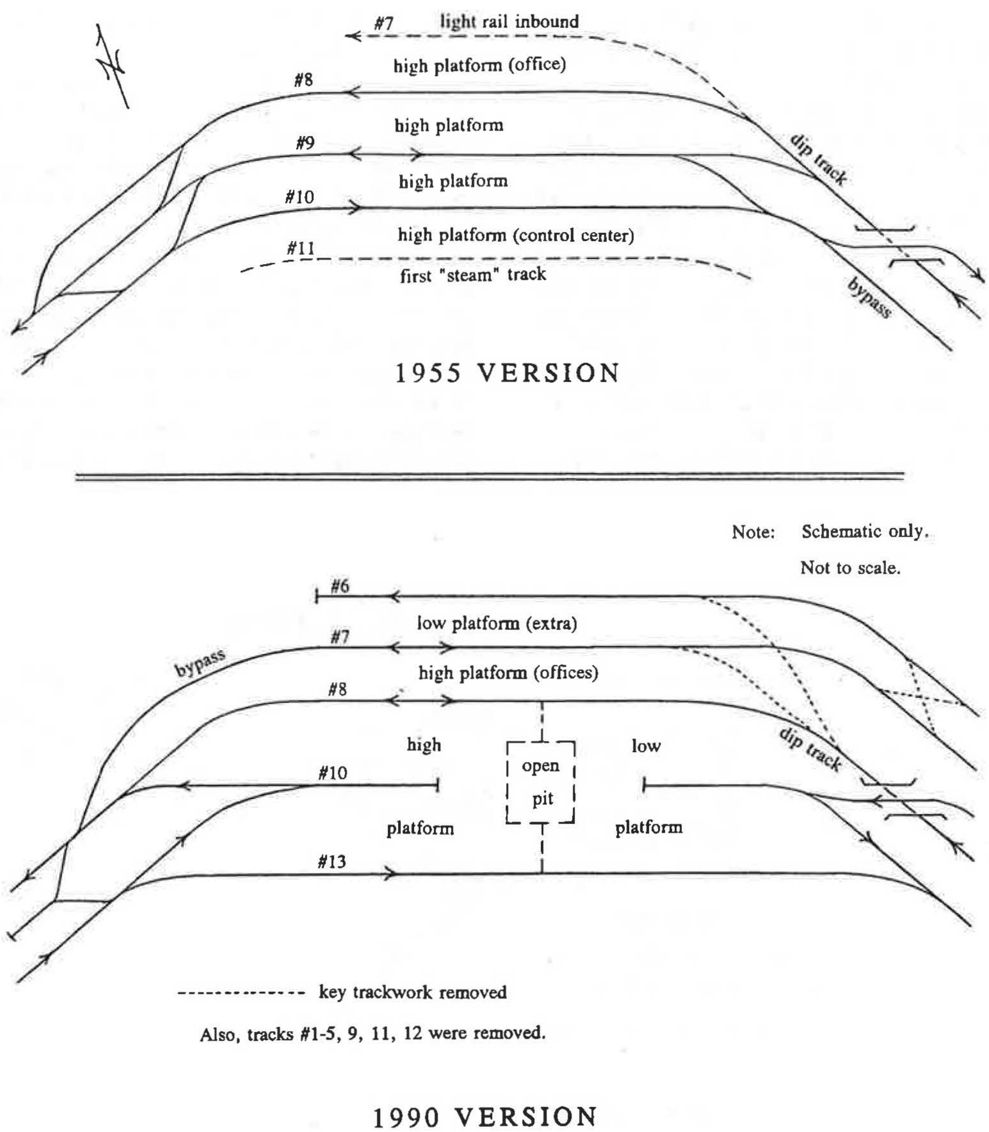

FIGURE 3 Heavy rail and later combined station in Cleveland Union Terminal.

rail car orders have been for vehicles with cabs on the left. Except for East 55th, no heavy rail stations used outside platforms.

With the retirement of Shaker's President's Conference Committee (PCC) car fleet and discontinuance of the separate light rail station, all reason for the left-hand operation has gone. Along with the new Tower City Station, a conversion to cab signal operation (discussed separately) provided the opportunity to go right-hand without having to relocate existing block signals and automatic stops. They were being removed anyway. The new cab signal system is operational on all the heavy rail lines, on the shared trackage for its entire length, and on the light rail system nearly to East 79th Street. By restoring the light rail tracks at the junction tunnels to their original configuration, right-hand running has been resumed, as shown in lower part of Figure 2. The meeting of the light and heavy rail systems at that point even looks more normal.

One feature of the "temporary" junction arrangement (which lasted for 60 years) has been retained. A part of the old westbound over-the-top track has been converted to a crossover from the westbound light rail to eastbound heavy rail, providing an escape operation for light rail in case the tunnels are flooded (which has happened many times). This feature plus the "test track" and shop lead from the east provided as part of the 1980s reconstruction produce an alternate flood-free route that is almost entirely double-track.

A powerful incentive to convert the East Side portion of the heavy rail line to right-hand operation arises from an arbitration finding: all heavy rail trains of more than one car were required to have two-person crews in the left-hand territory because the cabs were on the left away from the platforms. Management's wish to change to one-person operation was carried out east of East 55th Street recently as right-hand running went into effect. Conversion to right-hand running and installation of the cab signal system discussed below are all part of one project. Total capital cost is $15 million, including completion of the Red Line change to Windermere.

CHANGEOVER TO CAB SIGNAL SYSTEM

The CTS (and later RTA) has had a long history of unfortunate experience with block signals having automatic stop, including unauthorized entry of occupied blocks, failure of trip-arms, and years of undermaintenance. Several bad accidents and many minor ones occurred, especially as the system aged. Operator failure and equipment deterioration combined to produce a hazardous riding environment. This system had negative return current in only one rail of each track, shutting down the line if the return rail broke too far from a cross-bond.

After RTA took over, the light rail system had problems with its own very old three-aspect block signals (no automatic stop), arising primarily from operator disrespect of occupied territory. A number of used signals from the Chicago Transit Authority were installed to divide some of the very long blocks on the main stem (Shaker Square to the shared trackage with heavy rail) and make the system more operationally meaningful by having the operator encounter the red aspect more reasonably close to the train in front. This helped, but the system is very old (mostly 1924 vintage) and costly to maintain. It does allow negative return in both rails, an essential feature in the old days of jointed rails. At this point, the only apparent "original" appurtenances that remain are these signals, surely an anachronism in 1992.

The shared trackage with heavy rail has been recently converted to cab signal operation with reverse running capability, making easy the changeover to right-hand running discussed earlier. Both rails are now used for negative return, decreasing power loss. A plethora of three-aspect lights and trip-stops (all made to subway quality and not meant for a long life outdoors) has been removed, eliminating a lot of clutter. Furthermore, the original placing of those signals (at side or in center strip) seemed almost arbitrary, brought about in some cases for ease of installation rather than for operator visibility. For the light rail operation, this conversion virtually eliminates the use of trip-stops, which are retained only at certain stub ends and in three places on each through track in the downtown station. The new system is much more foolproof and frankly does not require as dedicated and disciplined a driver as the former.

Cab signals extend on light rail to west of East 79th Street, well beyond the junction with heavy rail and past the point where the third or "test" track joins in. Thus the entire area where the two lines meet and operate together is now under control of the latest very safe type of control. The chance for collision of two different types of trains (outside of yard operations) is nearly eliminated. All main line crossovers in this territory are under the control of a central "tower."

It is planned to extend cab signal operation on the remainder of the 3-mi "main stem" (to Shaker Square from East 79th) shared by the Green and Blue Lines. This part is a candidate for conversion because of its frequent trains, long steep grades, no grade crossings, and history of a bad accident on its only blind curve. The operation should no longer depend on very old simple three-aspect block signals to govern what is really a rapid transit operation despite its light rail styling. At this time, funding is not available for that project.

The branches east of Shaker Square, with 24 grade crossings, are a different problem. Signal territory now stops 1.5 mi west of the terminus of the Green Line and 0.6 mi before the end of the Blue Line, leaving the outer parts a strictly line-of-sight operation. Every street intersection is governed by traffic lights arranged primarily for motor traffic. All but two stops at grade are nearside, and there is no signal preemption. A marvelous opportunity to go to farside stops at grade crossings with signal preemption was lost when these lines were completely reconstructed a decade ago. One major grade crossing was converted to farside stops to provide room in the median for left-turn lanes, and it works better than nearside stops even without preemption.

It is questioned whether the type of cab signal system now installed would function well in an area with numerous grade crossings, being more sensitive to current leakage than block signals are. Moisture is almost always present in the rail grooves, and some of the rails installed in rubberized crossings in 1980 have already worked loose. Without preemption, one school of thought says that the traffic lights for automobiles will control the trains well enough. But that view does not settle what to do about the 1.3 mi of the Green Line at the east end that have no intersection grade crossings and thus no traffic lights. Certainly a case can be made for leaping from line-of-sight operation to cab signals on that straight stretch, which has undulations restricting visibility.

A great advantage of the cab signal system compared with any type of lights system even with automatic stop is the ability to control speed. In this application, the cars had control points for 15 mph maximum, 25 mph maximum, 35 mph maximum, or full speed (about 60 mph). Thus a positive control can be enforced at stations, sharp curves, turnouts, and anywhere else where full speed would be dangerous. Unfortunately, in retrospect the 35 mph top restriction did not allow enough choice, excessively slowing running time. Another control zone at 45 mph maximum is desirable, and the shared track and heavy rail line have been refitted with such restrictions where needed. The cars have now been modified to add a 45 mph control point. The running schedule in the areas controlled by cab signals is noticeably slower than before, and the light rail has a substantially longer running time than when it first pulled into Cleveland Union Terminal in 1930. In fairness, some of that slower running results from the need to "baby" the gear drives on the new rolling stock when running downhill, as described later. That long hill is not yet under cab signal control, so it is up to the operator to use restraint.

COMBINING THE DOWNTOWN STATIONS END-TO-END

Certainly the most controversial and obvious-to-the-consumer improvement to the light rail system since reconstruction is the combining of heavy rail and light rail stations end-to-end in the Tower City redevelopment of Cleveland Union Terminal and the former arcade area of Terminal Tower. An indoor regional shopping center and entertainment areas fill the old traction and "steam" concourses, with two elaborate fountains and multitiered balconies for shops. That part of the cost assignable to the transit station is $60 million. Although this is all very grand and glamorous, certain major sacrifices have been made that are not apparent to the rider until something goes wrong.

First, a background description of each station (they were side by side) is necessary. The heavy rail station had three through tracks (Nos. 8, 9, and 10) and two very long, fairly narrow platforms, as shown in the upper part of Figure 3. Two trains 300 ft long could be simultaneously berthed at each track, with the center track able to load and unload on both sides of the train. The station was intended to handle through service or reversal of trains to the East Side or the West Side or any combination. Reverse signaling was installed to allow this; in practice, the center track was normally used only for terminating and originating some rush hour trains to the West Side, the more heavily patronized line (a line, incidentally, not having any shared light rail operation).

The best part of the three-through-tracks feature was the ability to get around problems in the station, such as a dead train. The center track often was used as a siding for disabled equipment, while the operation could proceed normally.

The light rail station just before the combining took place was an improved version of the 1955 station shown in the lower part of Figure 1. After RTA took over, all the tracks except lightly used storage tracks were renewed in situ, with three key tracks added that had been called for in the original plan 50 years earlier. These are shown as 1980 additions.

The principal inbound track No. 7 was given a turnout just where the turning loop began, allowing the new double-end cars, which cannot clear the loop, to go out in the "field" and reverse ends. Track No. 6 was extended across the loop, as had been done for track No. 5 in 1955. These improvements gave the new cars access from the back end to tracks Nos. 6 and 5. Furthermore, a disabled PCC car could be pushed into the field without having to take it around the loop, always a derailment risk when pushing.

A track with a crossing frog was installed from the regular inbound track to track No. 6, creating a second easily reached unloading opportunity instead of only the one that had been regularly used for 50 years. With doors on both sides of the cars, trains could berth at the regular inbound platform and deposit passengers from both sides. This feature saw a lot of use under RTA.

The new cars could not enter track No. 4 from the field because of clearance problems; they could use the bypass and be backed in from the departure end, though this was rarely done. PCC cars were stored there for a while and also on the storage tracks Nos. 1, 2, and 3 as before. When the PCC cars were discontinued, these four tracks were removed to begin constructing an additional underground auto parking area as agreed to by RTA.

The light rail station functioned extremely well under RTA after these improvements. There were two inbound tracks, Nos. 6 and 7, and potentially three outbound tracks, Nos. 5, 6, and 7, with access at both ends and no interference from heavy rail trains. The tracks, overhead wires, and platforms had all been rebuilt as a key part of the light rail reconstruction.

This well-operating, highly flexible station proved its worth time and again when problems or overloads arose. It was especially valued in sending out large crowds after major downtown events, an important feature in a system having only one downtown terminal at one end.

All these tracks except Nos. 6 and 7 were removed in the zeal to combine both rail stations end-to-end and add more parking, with this area now providing 415 spaces. No. 7 was retained as an emergency bypass of the main station, with a long stub remainder of No. 6 and one low platform providing an extra load and unload point for special events. Key connecting trackage was arbitrarily scrapped. Trains can no longer cross between No. 7 and No. 6, nor go from the dip track to No. 7 and No. 6. See lower part of Figure 3 for these removals and a diagram of the combined station described next.

Track No. 8 serves as one of two inbound tracks for light rail and the westbound track for heavy rail. Track 9 has disappeared altogether in the interest of making the platforms vastly wider than before. Track No. 10 has metamorphosed into two stub tracks, one serving the heavy rail to and from the West Side only and the other serving light rail only. Plans for a second light rail stub to allow trains from either the Blue or Green Lines to berth simultaneously out of the path of through traffic were unfortunately dropped to cut costs.

A new eastbound track was built at approximately the location of long-gone "steam" track No. 13. The positions of tracks Nos. 11 and 12 were filled in for the eastbound platforms. Originally an eastbound bypass track was planned for about the location of former "steam" track No. 14, but this was eliminated to cut costs and provide still more automobile parking. The large south parking area now has 2,230 spaces. There is talk of someday restoring Nos. 14 and 15 for the National Railroad Passenger Corporation (Amtrak) or for intrastate high-speed trains.

The approach from the Public Square level to the rapid transit platform level is now via a pair of long escalators that bypass the old station concourse level, now a major shopping area. Other escalators connect the concourse and track levels. The four long ramps that connected the concourse to Public Square have been eliminated to the great relief of heart patients.

Combining the passenger platforms into one giant (with two stubs penetrating it) has made possible a very dramatic opening from the concourse and Public Square levels right into the bottom level of the terminal. The rapid transit facilities, especially light rail, are a lot more visible at the upper levels than they ever were before. Also, large sheltered waiting rooms have been added on the platform level, an amenity much appreciated by those who remember how the wind howled through the track level, especially on the light rail side.

It was planned originally that only one fare collection point would be provided for both rail services at track level, but this has not been done. Fare collection for the lines differs in that the light rail line is pay-leave westbound, pay-enter eastbound, resulting in most fares on light rail being collected at its west end downtown in the terminal. Heavy rail is always pay-enter. Management has yet to come up with a way to save personnel by collecting fares for both systems from one set of gates; each line's fare method works very well for its characteristics. Passenger volume transferring between the systems is still very light despite the highly convenient combined station. Good riding has never developed from the Heights area eastern suburbs to Cleveland's major airport at the west of the heavy rail line.

A major drawback of the new station arrangement is the elimination of tail tracks for light rail in the immediate vicinity. It was necessary to construct a long tail track with two long approach turnouts on the viaduct over the Cuyahoga River valley, well beyond normal walking distance from the station. Trains in the tail are much more exposed to severe weather conditions than formerly, and turnaround time has lengthened by 9 min. Movements into and out of the tail interfere with the through operation on the heavy rail system, in effect greatly extending the shared trackage. Moreover, a blockage has been placed in the way of someday restoring passenger railroad service across the viaduct. Maximum use is made of the one stub track to minimize the delay and other problems caused by using the tail. However, inbound trains sometimes have to wait for outbound trains to clear the stub.

All these changes have combined to radically reduce system capacity, especially for light rail. The statement is frequently made that the old agreed-upon capacity of 43 trains per hour in each direction on the shared tracks east from the terminal was never needed anyhow, so why not sacrifice capacity for amenities and convenience? Now the maximum capacity is 30 trains in and 30 out in the peak hour if all goes without a hitch. Breakdown of a train in the station on the through tracks leads to chaos with the present arrangement, whereas the old stations coped well with some extraordinary train failures and derailments. It is clear that experienced operating people were not given a strong voice in deciding on the new design. Good railroad practice was sacrificed to help create a remarkable and impressive regional indoor shopping center with a maximum of auto parking on the lower level. Much of the cost, of course, is tax dollars spent for a nongovernmental purpose, enhancing the value of the investment made by those who got control of the railroad terminal from Penn Central and the Consolidated Rail Corporation (Conrail). Clearly the shopping center people were the dominant party in this arrangement with RTA negotiating from a position of seeming weakness.

LANDSCAPING ALONG BOULEVARD MEDIANS

When the system was still owned by the city of Shaker Heights, some of the residents along that part of Shaker Boulevard having a 60-ft-wide median approached the city with a plan to screen the tracks visually and reduce sound. In those days the tracks on that stretch of the Green Line were very worn and noisy, and the cars of that time rumbled more loudly than the present fleet.

It was decided to plant a screen of Washington hawthorn trees halfway between the inner curb and the rails along certain stretches where the residents raised the money. Some of these trees have been there for over 20 years and now must be trimmed regularly so that they won't scratch the cars. The plastic windows are especially vulnerable. The residents in one block did not care for the hawthorns and had flowering crab trees with a vase-like shape planted instead. This stretch has been photographed heavily; in fact, a photo by Lee Rogers was featured years ago in a magazine article about light rail.

After the reconstruction was completed, the city (at no capital cost to RTA) greatly extended the plantings, covering the rest of Shaker Boulevard that had the 60-ft median. The same type of hawthorns were used. In fact, at locations where crab trees have died, they have been replaced by hawthorns. The landscaping now serves its purpose, but it creates the impression that the rail line should be barely seen and not heard.

Along the Van Aken Boulevard Blue Line, which had a 90-ft median laid out for potentially four tracks (narrowed to 86 ft by lane widening right after the reconstruction), landscaping treatment was quite different. At each surface station, at least one parking lot is in the median strip and complete screening was not possible. The city of Shaker Heights has converted more than 2 mi of the line into a linear park with clusters of flowering fruit trees, tall gingkos, and ornamental pines and spruces. The rail line is not especially hidden by this arboretum, and the effect enhances rather than detracts from the operation. Again, the maintenance is handled by the city. RTA pays a proration of the cost of maintenance based on the space in the medians occupied by the transit easement, generally 42 ft wide.

On the short westerly stretches of the two branches that lie within the city of Cleveland, RTA had similar landscaping installed, using a simple screen of hawthorns on Van Aken and placing hawthorns at the station on Shaker Boulevard, which has a 90-ft median at that point. West of that station, a double row of pin oaks borders a center-siding area with six turnouts. Maintenance is done under the same contracts for care of the RTA grass median and station landscaping in Shaker Square.

The result of all this tree planting illustrates the law of unintended consequences. Many of the hawthorns have grown quite large, while some in waterlogged areas have died. This type of tree is a menace to anyone running wildly because of the plethora of sharp thorns. To this point, no person has been struck by a train while running between trees. Certainly there is a heavy burden on various taxpayers to maintain all this, and a splendid rail line is screened from beautiful homes. Leaf removal from the tracks will be a yearly problem, especially in the oak tree area. The fact that most stations are nearside does reduce the cross-traffic hazard caused by not seeing the train for the trees. In one farside location, the first few trees have been removed, because motorists complained about the trains darting out.

MODIFICATIONS TO NEW LIGHT RAIL CARS

The fleet of radically different light rail cars built by Breda in Pestoia, Italy, has been thoroughly described elsewhere in the literature (*2–4*). The cars went into service in 1981 and 1982. After some of the initial "glitches" had been worked out, the entire light rail service was operated with these cars. The remaining PCC cars saw their last emergency use in 1985, and all but four have been disposed of.

The new fleet still has major problems, and filling the service is only possible because the volume of ridership is far below predictions when 4,000 seats (working out to 48 cars) were specified in the 1975 agreement between Shaker Heights and RTA. Today 47 cars remain, car No. 849 being cobbled from the undamaged A and B halves of two other wrecked cars. However, the schedule calls for only 30 cars, providing a shocking spare ratio of 56 percent! Only this surplus makes it possible to cope with two major problems.

The first problem to show up was the matter of powdery snow being ingested into the chopper control ventilation system far beyond any capability to filter it out (*2*). A host of solutions were tried, including spin filters, quick change filters, modifications to the ductwork, but all to small avail. The problem has become tolerable the past few winters because Cleveland and the Heights area have not experienced much powdery snow. Cars that overheated simply shut down and were taken out of service until the systems could be thawed out.

A proven "fix" has been developed that requires the chopper intake air to come in at the roof (the best location) rather than under the car (the worst location). However, ductwork must be run from floor to ceiling in the body of the car just ahead of the articulation area. It was necessary to remove two double seats, reducing seating capacity from 84 to 80 and gaining a little standing area. No one objected to this loss of capacity, even though the 4,000-seat requirement was violated. Sixteen cars have been modified, and retrofit kits are available to convert half the fleet. Eventually, all cars will have to be reworked. Cost of the kits to RTA will be near $1 million with installation being done in-house.

The second—and more serious problem—has been excessive wear and premature failure on the hypoid bevel gear trains, which convert longitudinal rotating motion of the monomotors to lateral axle turning power (*2*). The demands of Cleveland's light rail system may well be the most severe anywhere imposed on monomotor trucks. The difference in elevation from end to end is more than 500 ft, much of it concentrated in 3 mi of mostly tangent track with a few gentle curves. The desire to go fast downhill is very strong; after all, the line was called "rapid transit" before it was built and had better running time 60 years ago than it does today.

Gears began to fail within months after the cars were placed into service. It was quickly found that the hypoid offsets in the gearboxes were out of limit in most of the failures. The German gear supplier had subcontracted the gear cutting and assembly to an organization in Ontario, which had not satisfactorily observed quality requirements. When the trouble became acute, the supplier expressed amazement at the profile of the line and the sudden changes from high downhill speed to full service braking approaching stations, information that had been given to the carbuilder. (This high demand did not bother the original fleet built in 1914 and intended to be mere streetcars.)

After many experiments with different lubricants, greater frequency of servicing, and imposition of operating restrictions on speed and severity of braking, it was decided that 100 gearboxes would be overhauled by the gear supplier and fitted with new gears, using the facilities in Germany instead of those of a subcontractor. Cost of this work is about $1.4 million with RTA paying the bill. In the meantime, the operation is hard pressed to meet the schedule of 30 cars in service from a fleet of 47. At four gearsets per car, it is doubtful that many of the original 192 will still be in use by the time this report is published.

Some of the replacements made better to the same design are also showing problems, and the horrible conclusion is sinking in that the design may be simply inadequate for the service demand. One complete set of four gearboxes made by a different supplier for the Los Angeles cars will be tried as an experiment. In the end, it may be necessary to change to the largest possible gearbox that can be crammed into the space. With modern slip-slide control available, it is questionable whether monomotor trucks had enough advantage in the first place to justify their use in this rigorous application.

CONCLUSIONS

Virtually complete reconstruction of the old Shaker Heights Rapid Transit, carried out in the early 1980s, was by no means the end of the story. The great portion of change favorable to the passenger had already been achieved at that point, and riding volume improved to 19,000 per weekday. All this did was to bring the volume back to near the levels enjoyed before the disruption caused by rebuilding.

The later projects did very little for the rider and were justified by an assortment of unrelated values. At a cost of about $80 million (in the same league as the original reconstruction but in later, deflated dollars) the operation has been made safer, more attractive at the inner terminal, and seemingly less complicated.

At the same time, sacrifices have been made in capacity, speed of operation, and labor efficiency. A sophisticated signal system has been introduced that might in the long run prove more costly to maintain than its predecessor. Most significantly, riding volume, now down to 12,000 per weekday, may never return to the level enjoyed in 1979 before this renaissance began. Of course, things could not go on indefinitely in the old way, and fare increases of 1980, 1981, 1982, and finally again in 1991 had a lot to do with the poor results.

Nevertheless, the lesson can be drawn that enough may be too much. Improvements that degrade the running speed and have the potential to worsen delays should not be made without far greater justification than was shown here. Great expense devoted to creating a shopping palace and underground parking out of an old railroad terminal should not passed off as providing a transit benefit when it actually increases costs for the operating agency and robs it of terminal capacity enjoyed for 60 years. Certainly the last thing any rail transit system should want is more auto parking in its downtown terminal.

After more than a decade of disruptions, Cleveland's light rail system may now enjoy a period of relative calm, during which the management should be able to concentrate on trying to bring the riding volume back up to levels that will begin to justify the total investment since 1979 of around $180 million. Certainly the experience of earlier eras with this system showed that clockwork performance at good speed with a very high reliability level was the way to achieve a riding volume justifying rail operation in a low-density setting. Passenger amenities were of secondary or little importance for such short trips at rather high speed. That may no longer be true in today's market with competition from luxurious automobiles.

Those responsible for planning new light rail systems or for carrying out the reconstruction of old ones can learn much from the experience in Cleveland. Negotiations with outside parties must always be done from a position of strength, insisting that the needs of the transit system always come first, now and in the future. Performance specifications for cars need constant follow-on to see that all components and systems meet demands. The sophistication level of equipment and appurtenances should be kept as low as can be to do the job needed. That old engineering lesson that less can be more must always be kept in view. Every dollar saved in this way may be a dollar available for expansion that otherwise could never be funded. Certainly the great spending in Cleveland with so little tangible result has put the damper on support for any expansion of the rail systems.

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Paris New Light Rail System: Operation Strategy

HAROLD H. GEISSENHEIMER

As existing large-scale bus and metro systems reinaugurate light rail transit (LRT) service, organizational opportunities may present themselves to simplify and increase the productivity of the new light rail service. Such a situation will exist in Paris with the opening of the new Saint-Denis/Bobigny LRT. The first phase of this new 21-stop, 9-km line opens June 29, 1992, and is projected to carry 15.5 million annual passengers. Seventeen low-floor articulated light rail cars will be operated on this new tram line. Paris has been without trams since the late 1930s. A decision had to be made whether to operate the new rail line as a separate entity or as part of the Paris Metro system, the bus system, or some combination of the two. It is now proposed that the LRT line will be operated by the bus department and that the vehicles be maintained in the existing Bobigny Metro workshop. A private company will provide daily cleaning services. The new LRT line will be operated through a central control room by bus division supervisors. Fifty-five bus drivers selected through a volunteer seniority process and especially trained for the LRT will operate the cars. During their careers, they will remain both bus and LRT drivers. Functions performed at a systemwide level, such as administration, marketing, and so forth, will further increase LRT productivity. The next step in creating a circumferential tramway around Paris is a second line, Tram Val de Seine, which is now in design and scheduled for completion in 1995.

As existing large-scale bus and metro systems reinaugurate light rail transit (LRT) service, organizational opportunities may present themselves to simplify and increase the productivity of the new light rail system. Such a situation will exist in Paris with the opening of the first section of the new Saint-Denis/Bobigny LRT on June 29, 1992.

The new line will be operated by the Paris Transit Authority (Régie Autonomes des Transports Parisiens, or RATP). Paris, which has been without trams for 54 years (and nearby Versailles for 34 years), presently operates 15 Metro lines, 2 RER-Regional rail lines, and 202 bus routes. Some 3,899 buses are now in service operated from 23 bus garages. More than 2.96 billion riders used the combined system in 1989.

SAINT-DENIS/BOBIGNY TRAMWAY PROJECT

The modal choice of the tramway between Saint-Denis and Bobigny in the Ile de France region was made to suit site conditions and to create a direct link between outlying communities. The creation of this circumferential route will link 3 Metro lines, 30 bus lines, the RER D line, and the Société Nationale des Chemins de Fer (SNCF) commuter rail system and strengthen the use of the existing infrastructure. The tramway is entirely innovative in its design and impact on the environment and was selected for its reasonable cost and the economic and social advantages that it provides. The first Ile de France Tramway represents a new concept for travel between suburbs.

LS Transit Systems, Inc., 1515 Broad Street, Bloomfield, N.J. 07003.

RATP based its decision to install the tramway on the success of new or modernized LRT systems in Grenoble, Lille, Marseilles, Nantes, and Saint-Etienne. The Saint-Denis tramway has many advantages:

- Its price is competitive. It is four times less expensive than an underground railway. The total cost less equipment is approximately 650 million francs (4.94 francs = $1 1992 U.S.).
- It runs on its own tracks within a specific right-of-way. This results in more reliable service.
- With a maximum speed of 60 km/hr, it is a fast means of transport.
- It is silent.
- It is electric and therefore nonpolluting.
- The technical systems (track, wire, etc.) are fully integrated into the urban scene.
- It serves an ever-increasing demand for travel between suburbs without passing through the center of Paris itself. Today 70 percent of all trips in the region take place between suburbs, although public transport carries only a small proportion.

The line will serve 91,000 inhabitants in Saint-Denis and 43,000 in Bobigny as well as 34,000 in La Courneuve and 60,000 in Drancy enroute. There are an estimated 110,000 jobs in the LRT corridor. Daily ridership is estimated at 55,000 travelers.

Seventeen low-floor, standard French tramway, articulated light rail cars (based on the Grenoble car design) will be built by Alsthom at a cost of 13 million francs per car. The first car was delivered in February 1992. Access to the car is convenient both for the disabled and all riders. Car floors and platforms are at the same level. No sliding "gap" filler is needed. Two wheelchair places are in each car without safety attachments. Fourteen cars operated in one-car trains will be required for peak hour service. Cars will carry up to 180 passengers with 52 seated.

There will be 21 stops on the 9-km line, which will be opened in two sections (Figure 1):

- Bobigny (Metro Line 5) to La Courneuve (Metro Line 7), June 29, 1992, and
- La Courneuve to Saint Denis (Metro Line 13), end of 1992 (construction took 2 years).

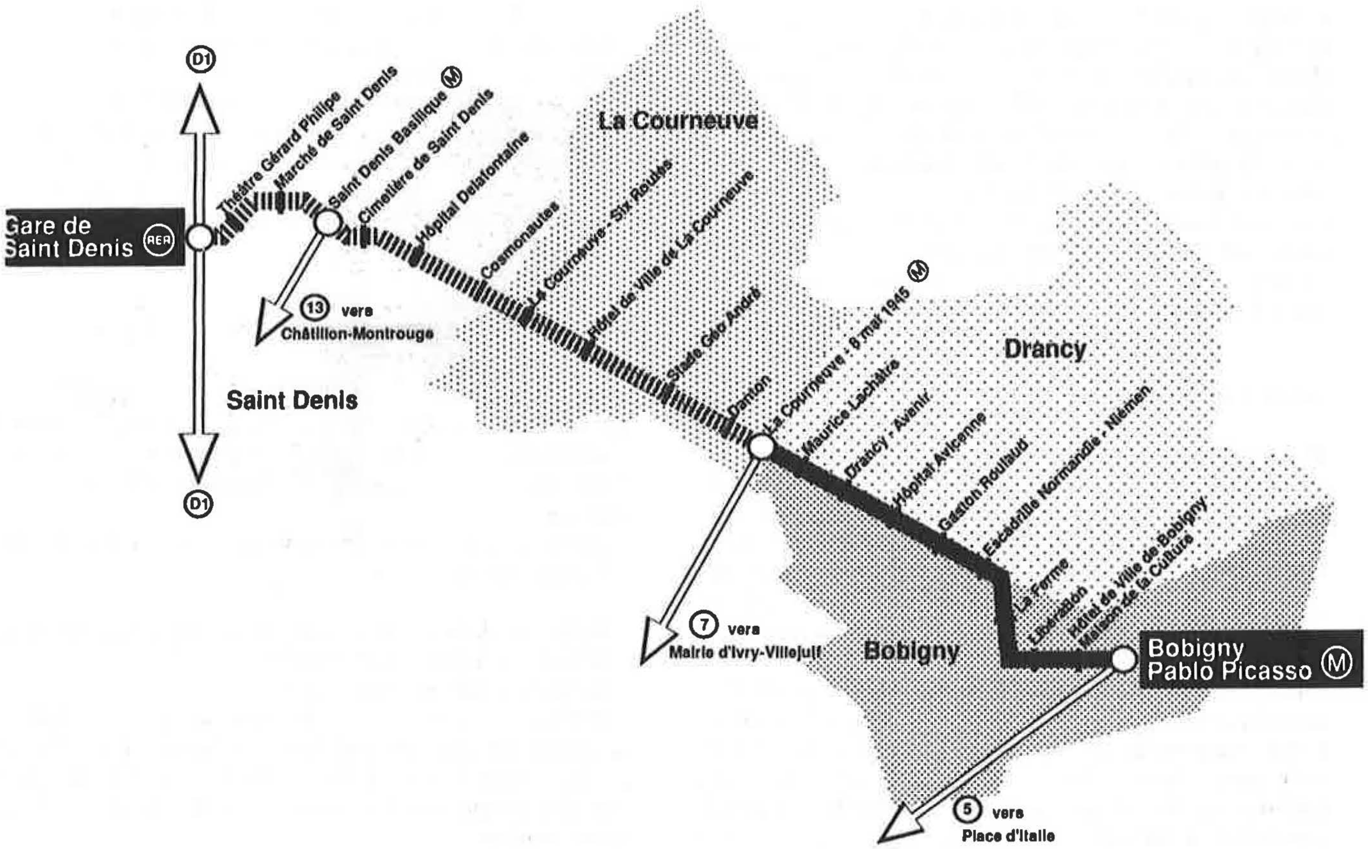

FIGURE 1 Map of Paris light rail system.

Service will be provided from 5:30 a.m. to 12:30 a.m. The tramway will operate every 4 min at the peak of the peak hour. Running time will be 30 min each way with a 75-min cycle time. The commercial speed is 19 km/hr.

The line is designed as part of an urban boulevard. It runs on dedicated track parallel to rebuilt National Road 186. Water and gas pipes, drains, electrical and telephone lines were adapted to the new construction. The Seine Saint-Denis local authority and the region took special care to ensure architectural consistency with the environment. The landscape was remodeled to provide absolute safety for users and pedestrians within pleasant surroundings. Pedestrian areas will stimulate the trade that the tramway traffic initiates. The track area is paved with paving blocks to improve appearance and reduce maintenance. Traffic signals at crossroads and along the line are integrated with the tramway. The LRT was considered to be part of a total urban improvement project.

LIGHT RAIL ORGANIZATION

In February 1990, the RATP's president-director general, Christian Blanc, announced a new organization plan favoring decentralization and simplification of lines of responsibility. The new organization realigns the RATP under five deputy general managers. Two of these deputy general managers (operations and maintenance/construction) share major responsibilities for the new light rail line.

President-Direct or General

- Security
- Public Communications
- Director General Services

Deputy General Manager: Operations and Commercial

- Metro Department
- RER Department
- Bus Department
- Commercial Department

Deputy General Manager: Maintenance, Construction, and Manufacturing

- Equipment and Electrical Systems Department
- Infrastructure Department
- Rolling Stock—Rail
- Rolling Stock—Bus

Deputy General Manager: Development, Finances, and Logistics

Deputy General Manager: Human Resources and Social Policy

Deputy General Manager: International

Within the new organization plan, a choice was open to operate the light rail as a separate entity, as part of the Metro or RER, as part of the bus system, or some combination. The final operating plan eliminates all possible duplication within the overall RATP system and results in improved system productivity. The new line will be operated by the RATP bus department, the vehicles will be maintained by the rail rolling stock department, the line will be maintained by the infrastructure department, and electrical by the equipment and electrical systems department. Other functions such as finance, administration, marketing, and so forth will be performed at the systemwide level by the appropriate deputy general manager and department involved.

TRANSPORTATION AND OPERATIONS

The RATP bus department will be the responsible unit for operations under the direction of Ph. Ventejol, project manager, assisted by P. Lenormand and Ph. Isenbeck. Following the concept of decentralization, the light rail line will be administered from the bus garage at Pavillon Sous-Bois. This garage has 220 buses and more than 500 drivers assigned. The manager of the garage, M. A. Thoule, will be responsible for the LRT start-up and operations.

Fifty-five RATP bus drivers selected through a volunteer seniority process will receive training as light rail operators. In full operation the line will require 32 operator runs. During their careers, the selected operators will remain both bus and LRT drivers. They may return to bus operator duties but their selection for LRT is regarded as a moral contract. Driver pay is the same as for articulated buses with a 150-franc monthly bonus.

The main training staff of seven from the bus department received operating experience and training in Grenoble. They will be assisted by 12 regular bus trainers. The training program for drivers will last 3 weeks and consist of equal classroom and road instruction. The rule book and operating procedures are in accordance with French Ministry of Transport regulations and procedures and are now being reviewed and refined.

The new line will be controlled by bus department supervisors through an expansion of the central control room shared with local bus operations control located at the Bobigny/Pablo Picasso Terminus (Metro Line 5). This terminus will serve 13 bus routes (more than 120 buses per hour) and the LRT. The control room is at the bus platform level, glass enclosed, and visible to passengers. The LRT control position will monitor line operations, 10 closed-circuit television cameras, and traction power. Radio communication with all cars and a public address system at each stop is provided. Line supervision will be provided by bus supervisors.

The line is to be operated "on sight" without a train stop signal system. However, traffic signals are integrated with the LRT operation.

FARE COLLECTION

The fare collection system will be a proof-of-payment self-service system now in use on Paris bus lines served by a 283 articulated bus fleet. A magnetic ticket reader will be at each door of the light rail car and 41 ticket vending machines, one at each platform, will dispense single ride, reduced fare, and 10-ride tickets. These machines will be serviced by outside contract. The entire line is in Fare Zone 3.

No dedicated security staff will be used. Operationally this is another bus line. Fare checkers in the bus department will check approximately 5 percent of the passengers based on the experience on bus lines operated with articulated buses. Police in the four municipalities are on call through the control center when required.

VEHICLE MAINTENANCE

The fleet of 17 light rail cars will be maintained by the RATP rail rolling stock department at the Bobigny Metro Line 5 maintenance base. This facility is connected to the Bobigny/Pablo Picasso Terminus by a 2,400-ft partial single-track connection.

At this location, the following facilities are provided for the light rail system:

- New single-track inspection and running repair building,
- New single-track wash building,
- Outdoor storage tracks, and
- Within the 10-track main Metro maintenance building, 2 tracks are set aside for LRT heavy maintenance and 1 track is shared with Metro. A unique three-truck hoist has been installed for the articulated cars along with a shared wheel-truing machine.

M. Barrandon is in charge of maintenance with C. Le Brun managing the Bobigny facility. A final maintenance staffing has not been determined pending discussions with the union.

The general maintenance plan is for a *petit noyau* (small core group) of ex-Metro mechanics to specialize in tram maintenance. Working with this group would be a larger group of mechanics who would split their time between tram and Metro cars. This group would receive less tram maintenance training. It is planned to have both a morning and afternoon work shift.

The vehicle driver will operate the car to the parking location in the yard, including driving it through the wash building.

Light rail vehicle painting and body work will be performed off site at a Metro paint shop. Vehicles would be transported by highway truck.

Vehicle cleaning will be privately subcontracted, as at Metro.

TRACK, WAY AND STRUCTURES, TRACTION POWER

Track, way, and structures would be maintained by the RATP infrastructure department. No rail maintenance vehicles will be used as the line is accessible by road vehicle.

Traction power and overhead catenary maintenance will be provided by the RATP electrical systems department. They will use the same personnel as they now use on the RER. A staff of 70 cover 26 km of RER Line A. The overhead catenary for the 750-volt direct current traction power system is much simpler than the 1500-V RER line, so technical training will be minimal. But they have received extensive safety training because working on the public street is new to them. The planned work load is 1 week every 2 months (4 hr per night, 5 nights per week) for three to four workers (two technical, one or two traffic control).

Passenger shelter maintenance and cleaning will be similar to that for bus stop shelters and paid for by advertisers.

Systems maintenance, including radio and telecommunications, will be provided by the RATP systèmes d'information et de télécommunications department under the RATP development and finance assistant general manager.

THE NEXT STEP

The Saint-Denis/Bobigny light rail line will serve as a model for the second new tram line to be constructed in Paris using the same type of low-floor car. This will be the Tram Val de Seine located to the west of Paris and now in design. Important details are as follows:

Length of line: 11.3 km
Number of stations: 12
Average distance between stations: 1,020 m
Number of LRVs: 13 plus 3 spares
Cost per LRV: 14 million francs
Total construction cost (excluding rolling stock): 572 million francs
Start of construction: mid-1993
Start of service: End of 1995

This line will use the right-of-way and trackage of SNCF's last remaining third-rail electrified line in Paris between Puteaux and Issy-Plaine with an extension from Puteaux to La Défense and a possible future extension from Issy-Plaine to near Boulevard Victor.

It will connect the major business development at La Défense (RER Line A, Metro Line 1 extended, and SNCF Commuter Lines) with Issy-Plaine Station (Interchange with RER Line C) in the southwest of Paris.

This new tram will modernize an old rail line serving a busy corridor, extend it to a major employment and transportation center at La Défense, and provide another section of a series of orbital links in the near Paris suburbs. The rail infrastructure will remain SNCF property but the RATP will provide the equipment, operate the line, and build the storage yard and workshop, which will be located in the SNCF Moulineaux-Billancourt freight yard near Issy-Plaine.

The Saint-Denis tram was the first of these orbital links designed to connect radial rail lines in the suburbs and eliminate the need to transfer in the center of Paris. Longer-term circumferential projects for the Tram Val de Seine include an extension eastward from Boulevard Victor along the route of the Petite Ceinture to either Porte d'Orleans or Cité Universitaire, where it will connect with the new Meteor automated rapid transit line. At the other end, from La Défense, there are two possible routes: northeast via Colombes or Le Stade to Gennevilliers and continuing to the Saint-Denis tram. This will form a linked circumferential tram for three-quarters of a loop around Paris. Another link in the southeast will consist of a dedicated Trans Val de Marne guided busway between RER Saint-Maur-Creteil and Chevilly-La Rue to open in 1993. This will later be upgraded to light rail. Two other noncircumferential busways are also under construction. Last, there is a possibility of LRT on an underutilized SNCF branch line between Dolnay-Sous-Bois and Bondy.

SUMMARY

The operating strategy developed for the new Paris light rail line is appropriate for an integrated medium-sized light rail start-up by a large bus and Metro system. It maximizes the use of existing staff, prevents unnecessary duplication, and builds on the concept of decentralization.

A number of cities, such as Chicago, New York, London, and Hamburg, could be faced with similar decisions as new light rail systems are opened. In some ways, it is similar to the operation of the Newark City Subway by NJ Transit bus operations. It is also similar in terms of driver staffing to several North American bus systems that opened new light rail lines. Older U.S. light rail systems developed from an even older trolley car network may also have integrated bus-LRT management and operations.

This strategy cannot be adapted by cities establishing separate light rail systems outside the existing transit organization or cities such as Manchester that are following a privatized design-build-operate concept.

Thus the Saint-Denis/Bobigny light rail line is not only a model state-of-the-art rail system fully blended into its urban environment, it is also a new and innovative management operating strategy to increase operating efficiency, prevent duplication, and contain costs. The Paris transit authority has been long known for its transit leadership. The proposed management strategy certainly reflects this long-standing tradition of cost-effectiveness and excellence.

As Fast as a Speeding Bullet: Rebuilding the Norristown High-Speed Line

RONALD DEGRAW

The Norristown High-Speed Line of the Southeastern Pennsylvania Transportation Authority, formerly the Philadelphia & Western Railway, is a 13.5-mi high-speed, grade-separated, high-platform light rail line that opened in 1907 but had fallen on hard times in recent years. Its rolling stock, although revolutionary at the time of its construction 60 years earlier, was in growing need of replacement, and virtually every aspect of the little commuter line required replacement or rebuilding. Less than 10 years ago, the decision was made to rebuild the entire line, and nearly $160 million has been expended or committed to once again make the Norristown High-Speed Line the showpiece of light rail lines. The rebuilding of the line includes new cars, a complete reconstruction of the maintenance shops, renewal of the substations, a new signal system, a new terminal on one end and a renovated terminal on the other end, new pedestrian bridges and some new highway bridges, improvements to other bridges, and major track improvements.

The Southeastern Pennsylvania Transportation Authority (SEPTA) Norristown High-Speed Line began service in 1907 as the Philadelphia and Western (P&W) Railway. It had been incorporated 5 years earlier as a steam railroad with grandiose plans to become a major competitor of the mighty Pennsylvania Railroad. When it finally opened on May 22, 1907, it was a mere 11 mi long. Its eastern terminus was 5 miles from Philadelphia's City Hall, via a connection with the newly opened Market Street elevated railway, and its western terminus at Strafford was in the middle of a field, the exact location chosen principally because an existing farmhouse could be cheaply turned into the terminal station. During the course of its 11 mi, the line managed to avoid every single town along Philadelphia's prestigious Main Line.

Its eastern terminus was at 69th Street Terminal, which was in Upper Darby, just west of the city limits. Sharing the terminal with P&W were four rail routes of the Philadelphia & West Chester Traction Company, the Market Street subway-elevated line, and a long streetcar line operated by Philadelphia Rapid Transit Company.

Although P&W's electric interurban railway operated with a third rail and had all high-level platforms, no highway crossings, and gentle curves and grades, for some reason its management saw fit to purchase a fleet of 22 wooden passenger cars with a top speed of 44 mph.

The poor little P&W, vastly overshadowed by the huge and powerful Pennsylvania Railroad's four-track speedway, was almost immediately in danger of financial failure.

It struggled along for 5 years and was then redeemed by a branch from Villanova Junction to Norristown, opened August 26, 1912 (Figure 1). Although this branch had more curves than the original main line, it, too, was completely grade separated with high-level platforms, built to be a speedway but encumbered with a 44-mph fleet.

Norristown was a substantial-sized suburban city and was the county seat of Montgomery County. The Lehigh Valley Transit Company at the same time was building southward toward Norristown, upgrading and relocating much of its Allentown to Lansdale right-of-way. High-speed cars of the Liberty Bell Limited route, as it was called, began operating the 55 mi from Allentown through Norristown to the 69th Street Terminal on December 12, 1912. The Norristown extension and the connection with the Liberty Bell cars was just the remedy that P&W needed for financial stability. It prospered well until the Great Depression.

With the Depression came a new management headed by Thomas Conway, Jr., who had made a name for himself rebuilding interurbans such as the Chicago, Aurora & Elgin, and the Cincinnati & Lake Erie.

Conway immediately ordered a fleet of 10 radically different cars from the J. G. Brill Company. The resulting "bullet" cars, which went into service in November 1931, were the first aerodynamically designed railroad cars in the world and the first built entirely of aluminum. They were capable of 85 mph.

Conway vastly improved P&W's track and superelevated all curves by as much as 8 in., creating a 70-mph speedway for his new "bullet" cars that reduced the running time from Norristown from 24 min to 17 min in one schedule change. Eleven steel passenger cars purchased during the 1920s, but which had the same 44 mph impediment as the old wooden cars, were rebuilt to match the speed of the "bullet" cars.

Conway was forced out in 1946 when control of P&W was acquired by the neighboring Philadelphia Suburban Transportation Company, better known as Red Arrow Lines. Red Arrow's management continued to run P&W as a prestige, high-speed operation, although P&W as a corporate entity officially ceased to exist when it was merged into Red Arrow on January 1, 1954.

The Liberty Bell Limited route was abandoned in 1951 and the Strafford branch in 1956, but otherwise the little interurban line soldiered on with the incredible "bullet" cars providing the bulk of the service.

SEPTA acquired Red Arrow Lines on January 29, 1970, and continued to operate it separately from its larger system, the old Philadelphia Transportation Company. In 1971, the Norristown line's schedule was speeded up and it was boasted that it was now "the fastest suburban electric railway in the world," with the fastest peak hour trains making the 13.5-mi Norristown to 69th Street run in 19 min.

Southeastern Pennsylvania Transportation Authority, 841 Chesnut Street, Philadelphia, Pa. 19107-4484.

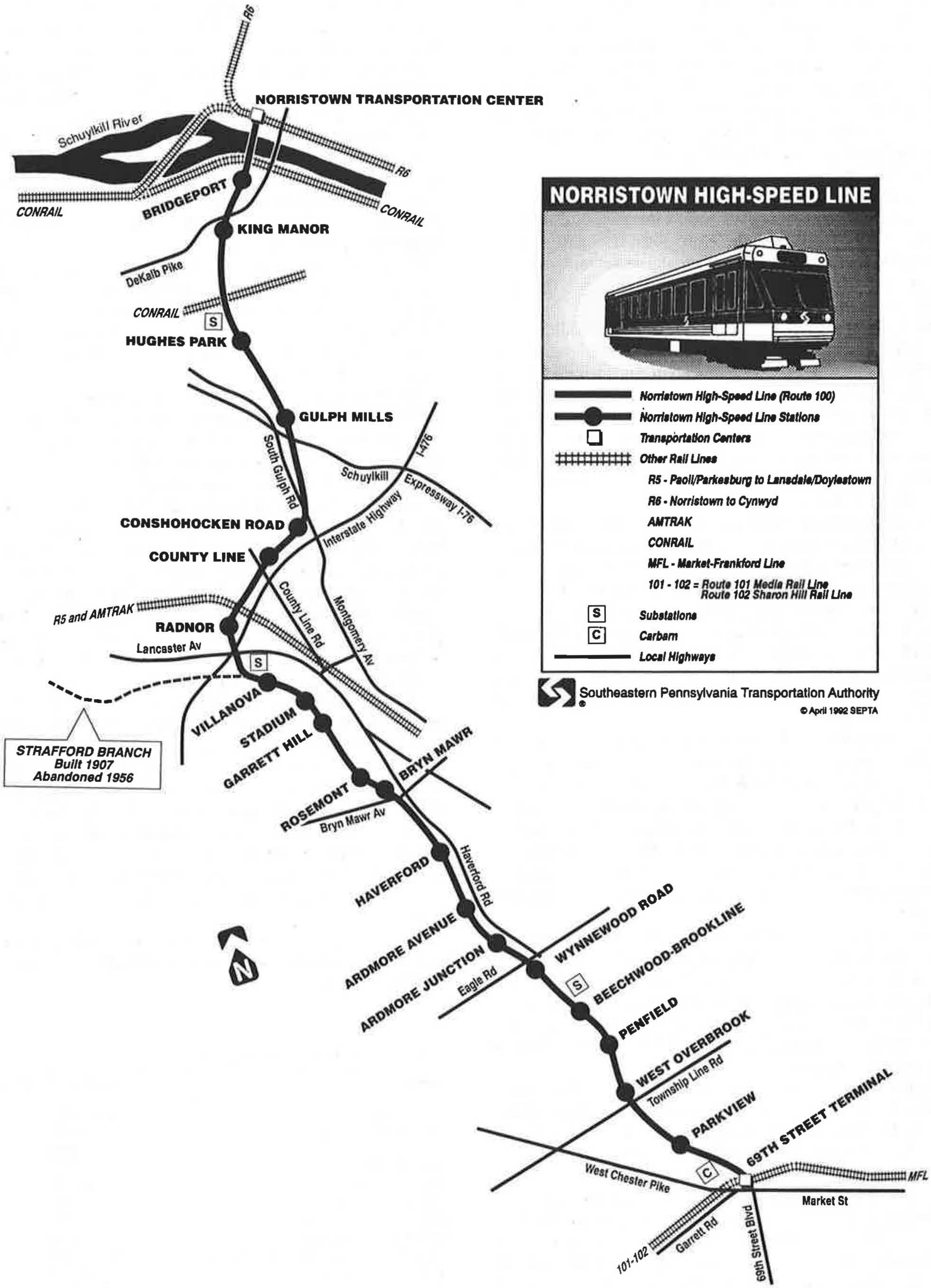

FIGURE 1 Norristown high-speed line.

SEPTA began ordering new equipment for its other electric lines. New light rail cars arrived in 1981 and 1982 to replace all of the older cars on the city's five subway-surface routes and on Red Arrow's Media and Sharon Hill lines. New Broad Street subway cars arrived in 1982, and the entire trackless trolley fleet was replaced with new vehicles in 1979. A total of 232 new Silverliner cars for the regional commuter railroad lines had arrived in 1974 through 1976.

But there were no cars on order for the Norristown line, despite the fact that the bullet cars were older than many of the electric vehicles that had been replaced. The principal reason seemed to be that the Norristown cars had received reasonably good maintenance over the years and were operating with fewer breakdowns and problems than the other fleets despite their age.

But age was beginning to catch up with the "bullets" and the older 160-series cars. Finally in 1983 the manager of SEPTA's suburban system succeeded in convincing everyone that the Norristown Line had become a tired, wornout railroad that needed to be completely rebuilt if it were to remain viable. Not only were the cars nearing the end of their lives, but so was much of the track, the substations, the signal system, the bridges, the shops, both of the terminals, and some of the stations.

The most pressing need was for new rolling stock, and SEPTA's own staff wrote the specifications for the new cars. The need for new cars became even more urgent after a series of collisions in 1985 and 1986 considerably reduced the fleet size. The last collision, when a 160-series car ran into the 69th Street Terminal waiting room, resulted in closing the entire railroad for about 6 weeks and offering only partial rail service for another 2 months. Buses were substituted for the rail cars but took about twice as long to travel between 69th Street and Norristown.

Ridership fell from its normal 9,000 trips per day to a low of 2,800 during the bus substitution. Nearly 6 years later, daily ridership hovers around 7,000. P&W's reverse-peak ridership, which had grown quickly during the 1960s and 1970s, continued to expand during the 1980s. It was primarily the prevailing-direction commuters with other options who deserted the line. By the late 1980s, the rail line was carrying more reverse-direction commuters than it was traditional prevailing-direction commuters.

Seven two-car sets of Chicago Transit Authority elevated cars built in the early 1950s began operation on the Norristown line in December 1986 and were followed in 1990 by five single-unit standard-gauge Market-Frankford subway-elevated cars. The last of the old cars was retired from passenger service in 1990 with the remarkable "bullets" falling a year short of their 60th anniversary.

Twenty-six new cars costing $55 million were ordered from Asea and the National Railroad Passenger Corporation (Amtrak) in 1987 but have been delayed after problems at Amtrak's Beech Grove assembly plant. Meanwhile Asea merged with Brown Boveri to become A.B.B. Traction. A.B.B. is now using Morrison-Knudsen in Hornell, New York, instead of Amtrak to assemble the cars. The first car arrived at 69th Street on May 22, 1991, far behind schedule and is still undergoing testing. It has still not operated in revenue service. The other 25 cars are now finally under construction and will begin arriving later in 1992.

The new cars have been designated as the N-5 cars, because they are the fifth series of new cars to operate on the line. The cars will have a stainless steel body and will be 65 ft long and 9 ft 10 in. wide, seating 60 passengers. They will continue a P&W tradition of railcar innovation. The new cars will feature the first three-phase alternating current (AC) drive to be used in a production fleet in the United States. Each truck will be driven by its own DC-AC inverter with two 208 hp motors per truck. The high horsepower will allow the cars to maintain 70 mph on the several 2.5 percent grades on the line. The normal running speed of the car will be 70 mph, with a top speed of 80 mph.

These specially designed interurban cars should be a match for the old bullet cars, and it is SEPTA's intention to operate a public timetable that gets passengers from Norristown to the 69th Street Terminal just as fast as a speeding bullet used to.

In addition to new cars, most other aspects of the railroad are being rebuilt (Table 1).

The Norristown cars are still being maintained in the original 1907 car barn just outside 69th Street. The structure, which is basically sound, will be completely rebuilt, with a new roof and floor. The overhaul of the structure will begin after the new fleet of cars is in service.

The Norristown High-Speed Line has three substations, Beechwood, Villanova, and Hughes Park. The first two date back to 1919, when the railroad ceased manufacturing its own power, and the Hughes Park facility replaced a Norristown substation in the mid-1950s. All three are being completely rebuilt with solid-state equipment replacing the old rotary generators. The result is that the previous 5,200-kW output is being replaced by a more reliable 8,400-kW output. The substations are nearing completion.

The original substation buildings have been retained, and the two 1919 buildings have been handsomely renovated.

P&W originally used two- and three-position semaphore signals. These were converted to three-aspect block signals in the early 1930s but have received no major overhaul since then. An entirely new signal system now being installed will use a cab-signal system with overspeed control. Such a system would have prevented most of the collisions that have occurred in the railroad's history. The system will authorize operation of six different speeds: 0, 15, 30, 45, 55, and 70 mph.

A Vetag system will permit train operators to remotely control interlockings used regularly, including terminals and turnback switches.

TABLE 1 Modernization Program

Project	Approximate Cost ($)
New rail cars	54,800,000
Shop modifications	21,300,000
Renewal of substations	8,900,000
New signal system	28,800,000
Highway bridges	3,900,000
Pedestrian bridges	1,700,000
Schuylkill River bridge	3,000,000
69th Street Terminal	14,800,000
Norristown Transportation Center	11,700,000
Track Improvements	10,000,000
Total	158,900,000

Most of the bridges date back to the line's opening, and several were in need of major renovations. The bridge over the former Ardmore trolley line at Ardmore Junction was completely rebuilt, and others have been renovated. Five pedestrian bridges have been replaced with new concrete structures.

Major efforts were devoted to improving both terminals on the line. 69th Street Terminal, which opened in 1907, was completely renovated at a cost of nearly $15 million. The Great Hall was restored to its original grandeur, including restoration of the skylight that had been painted over during World War II so it would not provide a bombing target. The rebuilding of 69th Street Terminal was a far greater effort than just P&W's portion of the building.

At the other end of the line, nearly $12 million was spent to construct a completely new Norristown Transportation Center with a bus terminal on the ground floor and an elevated train terminal and second track. The new structure was more than a block short of the previous terminal, and the unused elevated structure was demolished. SEPTA's regional rail station at DeKalb Street in Norristown is also tied into the new Norristown Transportation Center. The new facility is the only suburban transportation center in North America that combines regional rail commuter trains, high-speed light rail, and bus service.

Much of the track has been renewed since SEPTA took over Red Arrow Lines in 1970, with the old 85-lb bolted rail being replaced by new 115-lb continuous welded rail. Most of the third-rail has also been replaced with new 150-lb rail. Unfortunately not all of the track will have been renewed by the time the new cars arrive, and renewal of all the superelevation also remains to be done.

Several stations still need to be rebuilt, and some parking lots need to be improved or expanded.

Ideally the rebuilding of the Norristown High-Speed Line would have been coordinated to coincide with the new car delivery. Parts of it were begun as capital funds became available, and a few improvements have still not been funded because of the lack of capital.

Part of the Norristown High-Speed Line covers territory that is served by two other SEPTA regional rail commuter lines. Despite this, the Norristown line is considered a valuable transportation asset in the Philadelphia region, carrying large numbers of reverse commuters to destinations not properly served by the regional rail lines and intersecting with numerous bus and rail routes at its two terminals and at other points. To some, transferring at 69th Street Terminal to the Market-Frankford subway-elevated is an unpleasant trip to be avoided. To others, however, the numerous stations on the subway-elevated offer more convenient delivery than do the three downtown Philadelphia stations of the regional rail system.

With a fleet of new air-conditioned cars and other major improvements, the Norristown line's ridership is expected to increase substantially over its old daily figure of 9,000. Possible future extensions of the line near the northern end would further boost ridership.

With a transit system the size of SEPTA's, there are always many demands on the relatively limited capital funds that are available. The investment of about $160 million in rebuilding the old P&W, however, demonstrates a major commitment on SEPTA's part to once again operate one of the most impressive suburban electric railways in the nation. Trains will again speed from Norristown to 69th Street in 21 or 22 min, down significantly from the 35-min running time of a few years ago.

The new vehicles will be among the most modern interurban cars in the world, worthy successors to the famous bullet cars. An extension of the line to King of Prussia and perhaps farther west is under discussion, and the future looks bright for the little railroad once nicknamed the "Pig & Whistle."

Multiple-Phase Start-up: Headache or Opportunity?

PAUL O'BRIEN

Two distinct approaches to the start-up of light rail systems have been used over the last decade. Certain properties, such as San Diego (the South Line) and Portland, have begun operating the entire line at once, whereas others, such as Los Angeles and San Jose, have chosen a multiple-phase start-up. A few of the major aspects of a multiple-phase start-up are managing the media, coordinating operations and construction, the cut-over of a new phase, and maximizing windows of opportunity. A multiple-phase start-up can be a great opportunity to "sell" the system and work out some details of operations and maintenance if the potential pitfalls are effectively managed.

The last decade has seen a constant stream of new rail properties begin service in North America. Although most were light rail, heavy rail and automated guideway systems were also well represented. The next decade is unlikely to see a slowdown in the introduction and expansion of rail service. At last count, at least 10 urban areas were actively planning new rail systems. Ultimately these areas, and even some systems considering expansion, will be faced with the dilemma of a project in which one or more pieces lag behind the project as a whole. Given the enthusiasm shown for rail in most areas, managers will soon be faced with a choice of offering less than full service on a segment of the project or offering no service until the project is complete. If the decision is made to open one portion of the project ahead of another, the specter of a multiple-phase start-up presents itself. Is this phased start-up a great opportunity to whet the area's appetite for rail, or is it a challenge destined to become a major headache for agency personnel and contractors alike?

Starting up a new rail system is an exercise in tension for all concerned. As the day of operation approaches, the pressure is on the contractors to finish up and on the operator to be ready. Resolution of these two goals is a stress-inducing juggernaut. It is in this arena that a decision has often to be made whether to introduce part of the system or wait until the entire system is complete. In the cases of San Diego's South Line and Portland, the decision was to open the entire line at once. Buffalo and Los Angeles chose to begin operating pieces of the line and bring the complete line into service in three phases. Ultimately each system became a rousing success but they each reached that point in a different manner.

Once a decision is made to attempt a multiple-phase start-up, two major aspects must be considered. First is public perception, which includes political perception. How will the public and the media perceive the phased start-up and what effect will it have on existing travel patterns. Second is the technical and professional aspect. What hardware, training, and staffing issues have to be addressed?

Sacramento Regional Transit District, P.O. Box 2110, Sacramento, Calif. 95812.

IMAGE AND EXPECTATIONS

Because no rail system is entirely self-supporting, the support of the public and political representatives can make a difference in the ability of the agency to carry out its transportation mandate. What is put on the street is the reality of the operation to people outside the transit agency. What is seen then needs to be managed to present the best image of the rail system. Expectations must be realistic and well communicated. Each start-up phase must be clearly labeled as to its role as a part of the entire project.

For example, the opening of 6 mi of line in San Jose, operating in basically an industrial area, was sold as introductory service. No bus routes were changed and no ridership expectations were created.

When the rail vehicles begin rolling, the public will begin to judge performance. Empty trains, delayed trains, or trains that function improperly begin to create an impression. A train that takes 40 min to reach its destination rather than the 20 min the customers expected has already created an impression. The fact that a traction motor was "lost" or a switch failed to throw is academic.

What the public sees needs to be managed by the rail operator. If a phase involves use of a temporary terminal, for example, strategies should be developed ahead of time to deal with any problem that could arise. If stations are in an unfinished state, consideration should be given to managing noise and dust that may be created from continuing construction. If the car wash is not functioning properly, ensure that alternate methods are available for car cleaning.

For example, Los Angeles used temporary terminals at each end of the initial phase. A strategy was developed to deal with the loss of the single crossover at one terminal and with the necessity of having return passengers alight from the train at the terminal.

COMMUNICATION

Expectations of each phase must be realistic and clearly communicated. If the purpose of Phase 1 is simply to get the public used to the idea of rail, sell the service as demonstration, or preliminary, or as a test to avoid customer disappointment if the equipment does not work as well as expected. On the positive side, Phase 1 could be billed as a festival sort of operation where the public is invited to help work out the "bugs." If regular revenue service is proposed, bite the bullet and pad recovery time and begin operation with a realistic and, most likely, conservative definition of operating hours.

Each phase of start-up must be clearly labeled. If the reason for operating is to demonstrate the technology, then the operation should be presented as a demonstration and not linked with the existing transit network. If, initially, temporary facilities or restricted operating hours will be in force, this should be conveyed to the public ahead of time. The public must be made aware that the railroad is not in its final form and expectations should not be raised and then dashed because of a poor customer experience.

For example, Buffalo began demonstration service during the midday periods on weekdays on the surface portion of the line. Experimentation took place with headways and operating strategies.

TECHNICAL ISSUES

From a technical and professional standpoint, phasing in parts of a project provides an opportunity to test equipment and procedures under near operating conditions when public expectations are low. Different operating and maintenance strategies can be explored and tested. On the other hand, close coordination between operations and construction is necessary and the cut over of each phase must be carefully monitored.

A new system invariably has "bugs" that need to be worked out. Even the best prerevenue simulation can not compare to actual revenue service. Operating revenue service in a first phase is a good opportunity to learn a little more about true system capabilities. Single-track operation, troubleshooting, and discovering whether the staff has a true sense of the urgency of rail operations can be uncovered during the first phase of operation. By using temporary terminals, one can discover their positives and negatives prior to the full line being in operation. The advantage to the public is that they have an opportunity to "touch and feel" the railroad and get a sense of what it is about. Phasing in a portion of the operation is also a way to focus attention away from the years of construction disruption and gear up to the excitement of an operating rail system.

For example, San Jose began operating on the transit mall prior to the opening of the south line. This let the staff become familiar with turnback strategies and the uniqueness of mall operation prior to heavy customer traffic.

Phasing in the operation allows operating and maintenance strategies to be tested. Hours of service, headways, and running time can be tested in revenue service and adjustments made prior to opening the full line. Preventive maintenance strategies can be explored and a better feel for the performance of equipment under operating conditions can be gained.

Staffing requirements can be worked out based on the operating history of the first phase. Actual operation can reveal staffing adjustments that may need to be made prior to full line operation.

For example, Los Angeles was able to fine-tune operating, maintenance, and staffing issues so that when service was expanded into the tunnel the resulting major increase in travel was easily accommodated.

CUT-OVER

The physical cut over from one phase to another is an area of critical importance to a smooth phased start-up. The first situation to be encountered is that everyone wants to work weekday, daylight hours. Unfortunately it is just not possible to complete construction, testing, and training all at once.

Windows of opportunity have to be identified and taken advantage of to ensure efficient use of facilities and personnel. Close coordination will have to take place between the operating group and the construction group. It is advantageous to have a single point of contact on each side who will be the final arbiter of all disagreements. Operating personnel should be prepared to work odd hours to handle the transition smoothly from one phase to another. However, once construction is complete, the operating personnel need an appropriate length of time to operate prerevenue service over the new phase.

For example, Buffalo operated nearly all prerevenue service during the tunnel activation phase on the graveyard shift. Daily hand offs from construction to rail control ensured that daily transitions went smoothly.

FULL LENGTH VERSUS MULTIPLE PHASE

Although a multiple-phase start-up allows rail operators the opportunity for experimentation, a full-length start-up permits most problems to be visited just once. Only one grand opening is held, permanent terminals are established immediately, and the public does not have to adjust to different scopes of rail services.

On the other hand, Portland's air-conditioning situation or San Diego's single-track inadequacies may have surfaced with less negative feeling if they had been discovered prior to full operation. In Sacramento full operation of the North Line avoided delaying the introduction of rail service by 6 months while waiting for completion of the East Line. This approach, also used to a certain extent in Miami, was a full-length start-up in that each leg of the system was self-supporting. This approach eased many of the problems of dealing with unmet expectations.

CONCLUSION

In summary, multiple-phase start-up has been used successfully by rail operations from Buffalo to Los Angeles and has paid dividends ranging from increased awareness of rail on the part of the public to better preparedness on the part of the system operator.

However, the challenges of start-up in this manner require attention to many aspects both of a public perception and a technical nature. A full-length start-up has the advantage in that many situations are visited only once.

San Diego Trolley: Performance Trends

DENNIS J. WAHL AND LARRY A. HUMISTON

Revenue service on the San Diego light rail transit project was inaugurated on July 26, 1981. From the project's inception, planning for the San Diego Trolley placed primary emphasis on cost-effective operations. The intent was to create a system that attracted the maximum number of riders while minimizing operating cost. The San Diego trolley was, in a sense, a pioneer in light rail operations. Although off-the-shelf technology was used and light rail systems are not new to most of the world, the San Diego trolley was a first in the automobile-oriented environment of Southern California. Since the 1981 opening, the system has more than doubled in size, both in terms of route miles and ridership. After 10 years of operation, it is now time to review the performance of the trolley and look to the future.

"Please Hold Tight" is written inside all San Diego trolley vehicles to remind passengers that they are riding in a high-performance vehicle. Indeed, the same advice could be given to decision makers, as the trolley has been a high-performance addition to San Diego's regional transit system. The trolley has taken single-occupant vehicles off the road, while increasing transit ridership in its corridors. Its high level of performance is reflected in its cost-effectiveness—the lowest farebox recovery ratio for any fiscal year has been more than 70 percent; the highest has been over 95 percent.

The Metropolitan Transit Development Board (MTDB) was created in 1976 to plan and construct transit guideway facilities in the southern urbanized portion of San Diego County. With the use of existing rights-of-way in well-developed areas and strong support from the California legislature and the local community, MTDB has built a successful light rail transit (LRT) system. It is operated by San Diego Trolley, Inc., a wholly owned subsidiary of MTDB.

The first trolley line was the South Line. Opened on July 26, 1981, it runs 15.9 mi (25.6 km) from downtown San Diego to the international border with Mexico. It was constructed in one of the region's fastest growing employment areas where, according to census statistics, jobs have grown by 54 percent and population has risen by 29 percent between 1980 and 1990. The line currently carries approximately 32,000 riders per day.

The second line to be built was the East Line, which opened in phases to El Cajon between March 1986 and June 1989. In June 1990 the Bayside extension of the East Line was opened in Centre City, connecting the core of the downtown with the new convention center and other developments along the harbor. The East Line is now 19 m (30.4 km) long and connects eastern suburbs to downtown. Ridership has exceeded expectations and the line currently carries approximately 18,000 daily riders. The South and East lines together include 34.9 route miles (56.0 km) and 33 stations.

Numerous extensions are in various stages of development, ranging from alignment studies to construction (see Figure 1). As the trolley rolls into the next century, extensions will be taking on a new form. Most of the usable, existing railroad right-of-way, which allowed in the past for low-cost construction with relatively little impact on communities, has already been tapped. As a result, more new rights-of-way will be established, including running on, above, or below existing streets.

One future trend in San Diego will be to incorporate the trolley into existing and new developments whenever possible. MTDB's efforts in existing communities will be not to intrude, but to serve. Developers are beginning to incorporate trolley right-of-way into their plans. Many of them hope to use proposed trolley lines as a selling point for their property. Development has increased near existing trolley lines and people are moving to areas where they can use the trolley. A substantial amount of undeveloped land still remains in San Diego that affords MTDB the opportunity to work with developers. Some are even planning transit-oriented developments that incorporate transit stations as a major focus of the project. The aim is to design areas that do not rely solely on the automobile because they have a viable transit alternative, the trolley.

RIDERSHIP PERFORMANCE

Across the board, the trolley's numbers are positive. Ridership figures indicate continuous growth, farebox recovery rates that are among the highest of any transit system, passengers riding by choice (i.e., they have a car available for the trip) and 70 percent of them highly satisfied with the service.

The annual number of boarding passengers on the trolley has increased continuously since the first day of operation (see Figure 2 and Table 1). Not only has trolley ridership grown, but so has the ridership on the transit system as a whole, dispelling the notion that the trolley serves only passengers who would have ridden the bus anyway (see Figure 3).

Many of the suburban bus operators have rerouted their service specifically to connect with the trolley. They have cited this integration of service as a reason for the increase in transit passengers in the region and on their systems (see Figures 4 and 5). The increase in ridership for the smaller operators since the trolley began operation has been dramatic. In the South Line corridor, Chula Vista Transit has had a 158 percent increase in total passengers between FY 81 and FY 91, while miles of service increased 42 percent. National City Transit, in the same corridor, had a ridership increase of 179 percent

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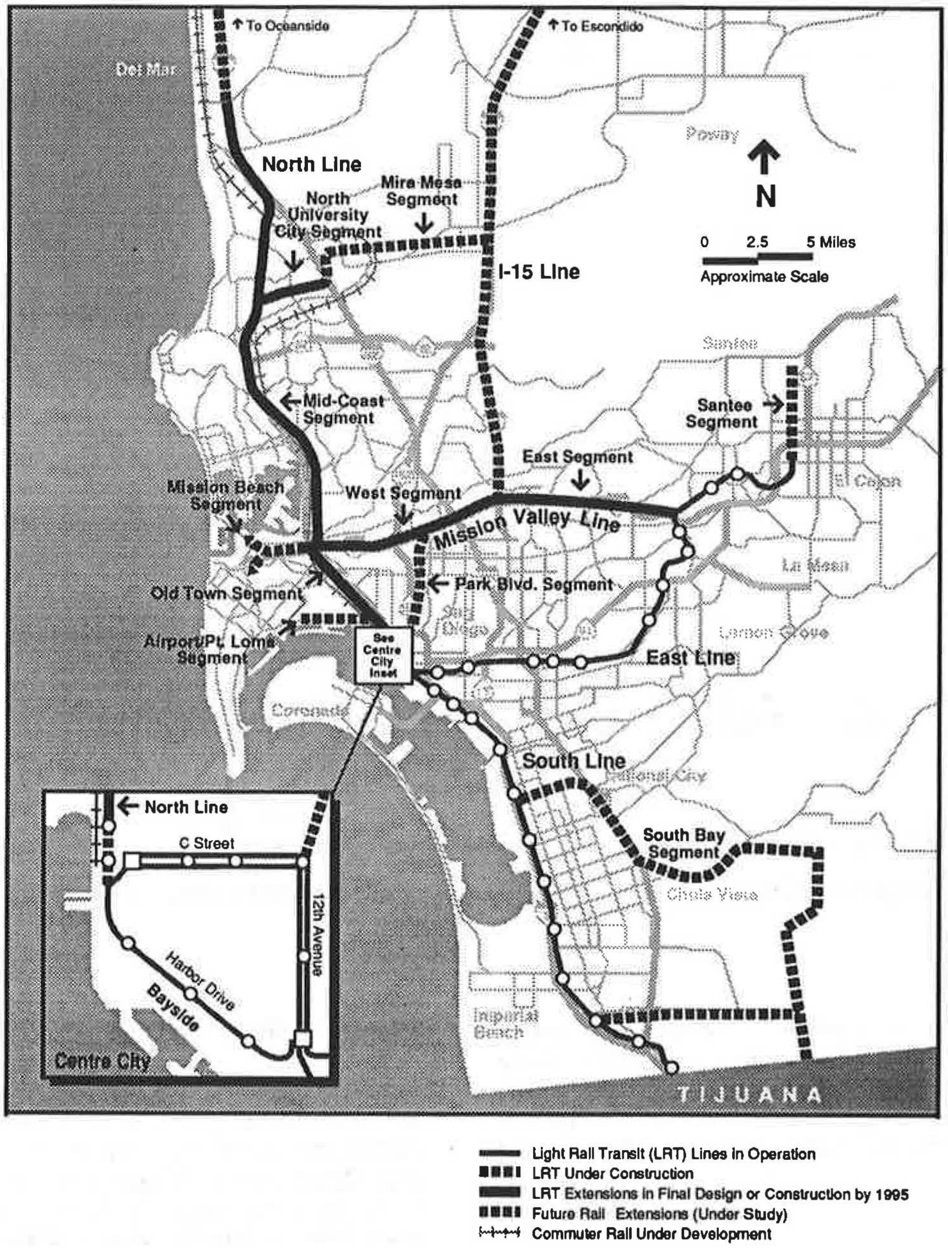


FIGURE 1 San Diego's regional rail transit plan.

in the same period, with miles of service up only 25 percent. In the East Line corridor, San Diego County Transit System has experienced an 161 percent increase in ridership between FY 89 and FY 91, while miles of service went up 89 percent.

The growth in LRT ridership can be related to certain key events as depicted in Figure 6. The two most significant factors were improving frequency from 20 to 15 min on the double-tracked South Line in FY 83 and completing the East Line to El Cajon in FY 89.

The trolley is in fact luring people who would have otherwise made their trips by car. Figure 7 indicates that 41 percent of trolley passengers ride by choice, compared to only 26 percent for all transit users. Figure 7 also indicates that the number of passengers who have an automobile available has increased significantly from 1985 to 1990. Figure 8 indicates that 37 percent of trolley passengers previously made the trip by driving alone. San Diego Transit Corporation, the largest bus operator in the region, has not shown as great an increase in choice riders as the systemwide average. This may be in part because of a diversion of riders from bus to LRT, but the data seem to indicate that the boost in choice riders for the region depends heavily on LRT service.

As indicated in Table 2, most riders walk or transfer from a bus to access the trolley. Between 1985 and 1990, the primary change in mode of access has been a small increase in transfers and a small decrease in walking. This may be because of the increase in feeder bus service and more auto access on the East Line.

Figure 9 indicates that the primary trip purpose of people using the trolley is to commute to work, approximately 52

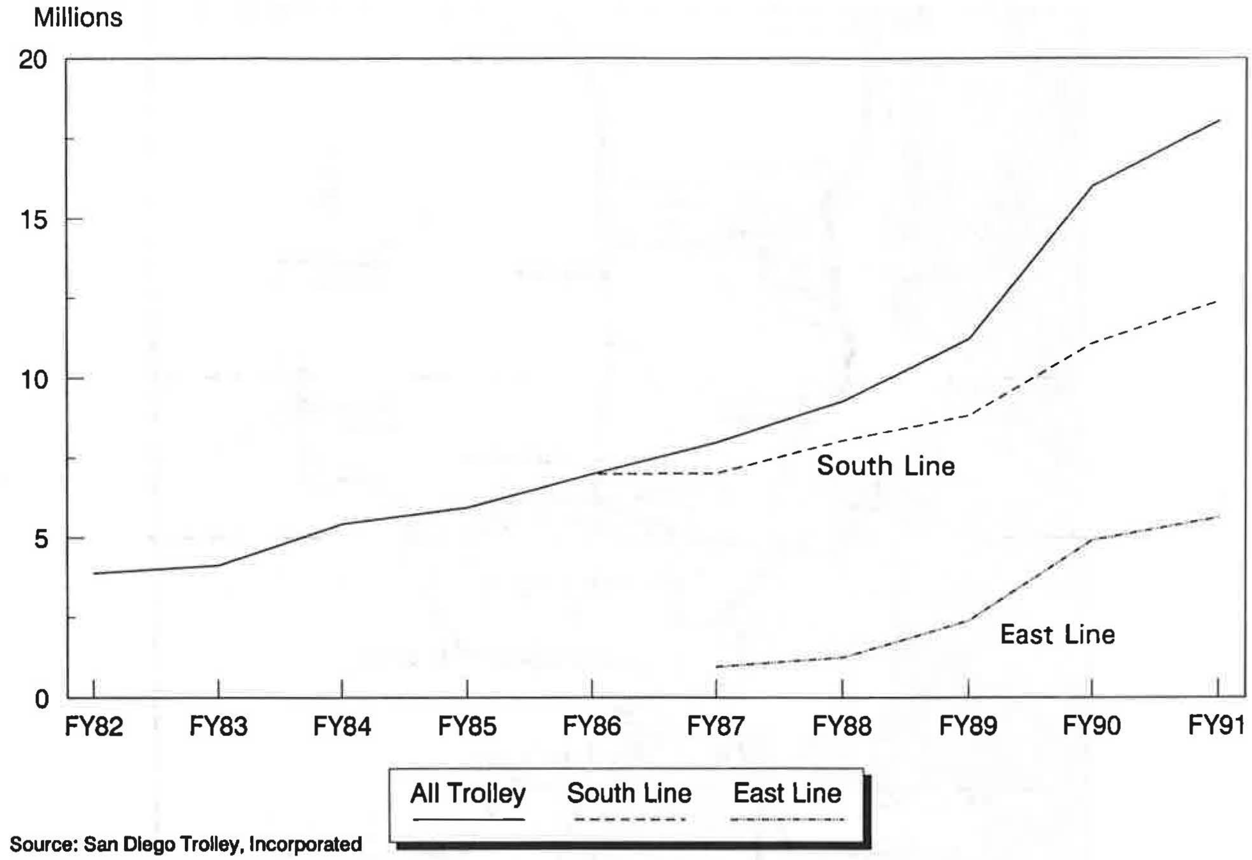


FIGURE 2 Passenger comparisons between the South and East lines and the trolley service as a whole.

percent. Table 3, in its demographic information, indicates that a higher proportion of trolley riders earn $30,000 or more than the riders of transit system as a whole. Taken together, these data seem to indicate that the trolley attracts middle- and upper-middle-income workers, even though they could drive to work.

TABLE 1 San Diego Trolley: Total Passengers

	Total	South Line	East Line
FY82	3,885,703	3,885,703	
FY83	4,137,928	4,137,928	
FY84	5,437,091	5,437,091	
FY85	5,942,858	5,942,858	
FY86	7,003,283	7,003,283 (Includes East line)	Information for FY 86 not available
FY87	7,974,058	7,013,035	960,782
FY88	9,280,612	8,033,660	1,246,952
FY89	11,216,631	8,816,736	2,399,895
FY90	16,005,726	11,088,328	4,917,398
FY91	18,029,669	12,401,549	5,628,120

Source: San Diego Trolley, Incorporated

FINANCIAL PERFORMANCE

Passenger fares provided 36.7 percent of the total operating revenue for transit systems in the United States in 1990. By contrast, the farebox recovery rate for the trolley has exceeded 70 percent since it began operations. Figure 10 displays revenue and operating costs since FY 82. The closest the trolley came to breaking even overall was in FY 89 when the recovery ratio reached 95.31 percent (see Figure 11). In FY 89, 90, and 91, the South Line actually ran at a profit, with farebox revenues higher than operating costs. The farebox recovery rate has declined since its high in FY 89 for two primary reasons: the recent extensions are not yet as productive as the South Line and power consumption has increased considerably with the entire fleet now air-conditioned. (The South Line opened without air-conditioned vehicles.)

To accommodate the ridership growth of the past 10 years, the trolley has more than doubled its route miles, from 15.9 (25.6 km) to 38.3 (61.4 km). The light rail vehicle (LRV) fleet has grown from 14 to 71. This growth has been accompanied by service frequency increases, train size changes, and all of the other operational measures associated with service improvements. Operating costs have, of course, increased accordingly.

Has operating cost-effectiveness been sacrificed as a result of growth? This question can be answered by examining op-

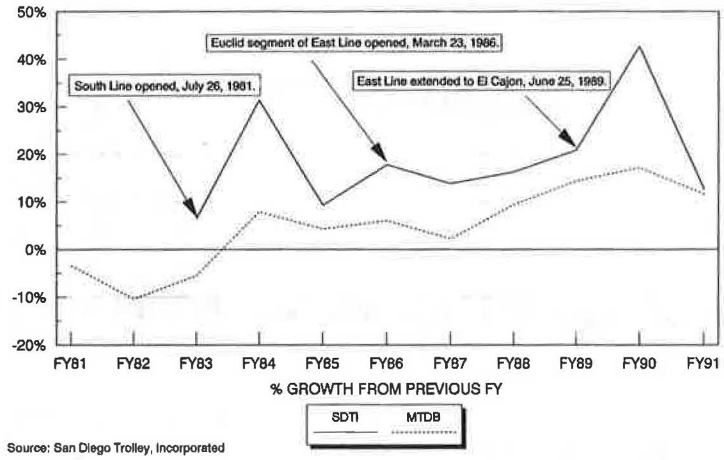


FIGURE 3 Ridership growth comparisons between the trolley and the MTDB area fixed route.

erating costs through the 10-year period compared to the amount of service (defined as number of riders) provided to passengers. When the audited operating cost for each fiscal year is divided by the number of passengers carried each year, a cost per trip is calculated for each trip provided during that year. Without considering revenue collected and capital cost, it can be seen whether the trolley has remained cost-effective even during a period of major growth.

Current year and 1982 base-year figures are displayed in Table 4. It is evident that the actual cost per passenger has remained about the same (average $0.91) over the 10 years of operation. However, when the figures are converted to 1982 dollars, the real cost per passenger has actually decreased to $0.56. The San Diego Consumer Price Index (CPI) for all consumer goods for the FY 82–91 period averaged 4.68 percent per year, one of the highest in the country. If costs had increased at the same rate as the San Diego CPI, then a cost of $1.28 per passenger trip could have been expected in FY 91.

The same kind of cost-efficiency test can be applied to cost per train mile and cost per car mile, as displayed in Table 4. Once again, if costs had increased at the rate of 4.68 percent per year, the FY 91 cost per train mile would have been $9.57, and the cost per car mile would have been $4.87.

Therefore, when examined from the perspective of three factors, cost per passenger trip, cost per train mile, and cost per car mile, it can be seen that the trolley has shown a distinct

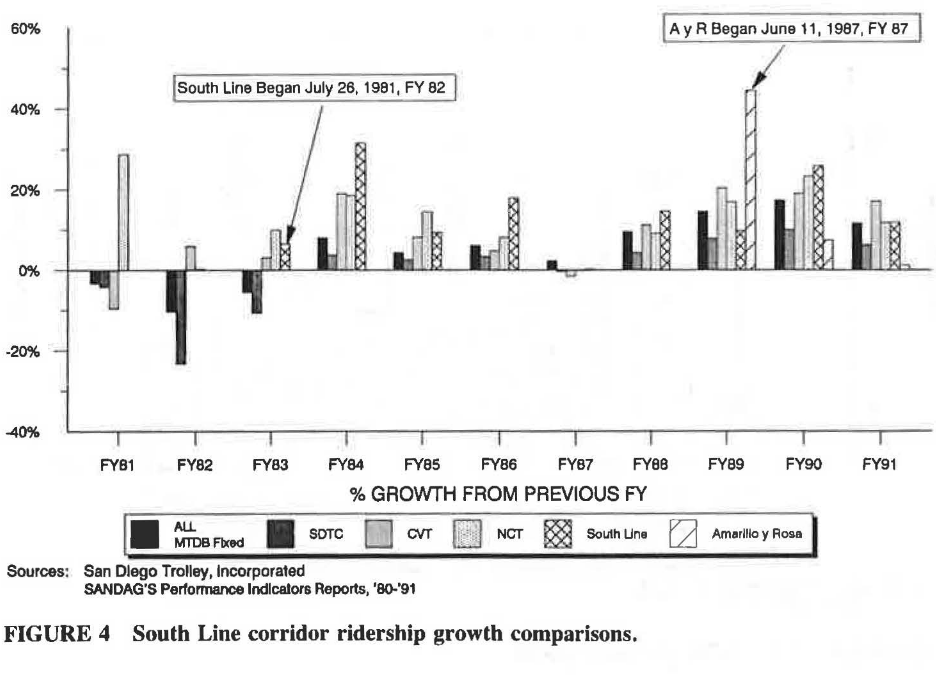


FIGURE 4 South Line corridor ridership growth comparisons.

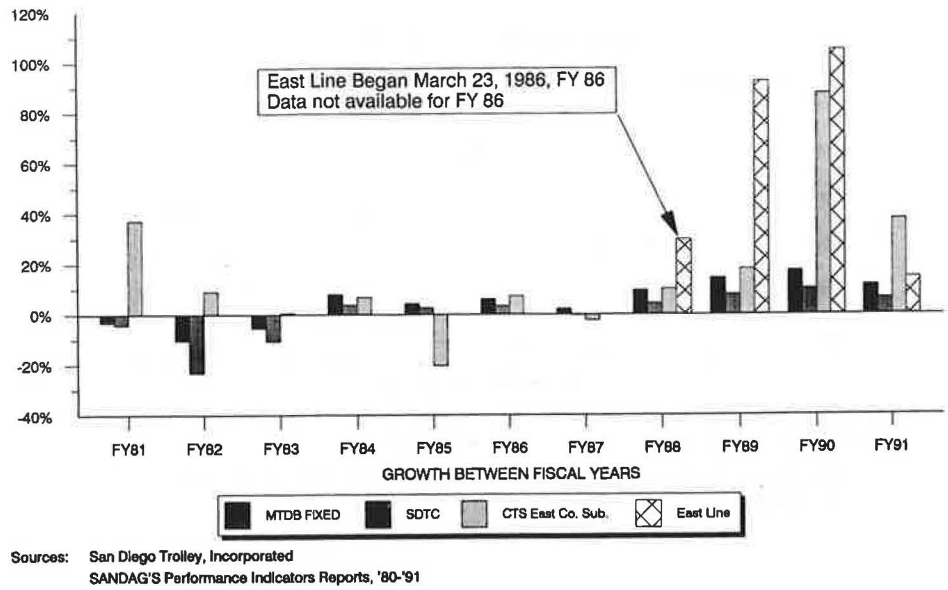


FIGURE 5 East Line corridor ridership growth comparisons.

pattern of improvement in operating cost-efficiency over the first 10 years of operation.

Two other financial items of interest include the change from a flat fare to a distance-based fare structure and the capital depreciation account. When the South Line opened, the basic fare was $1.00, with a $0.25 fare for trips within Centre City. In an effort to increase passenger revenue and match the fare more closely to distance traveled, a distance-based system was implemented in July 1984 for the trolley. (A similar system for bus fares was initiated in July 1989.) Modest increases in both ridership and revenue were achieved with the change.

When the South Line opened, MTDB established a capital depreciation account for the future replacement of system components. MTDB Policy No. 16 covered the amount to be paid to the account and the use of funds. A formula based on asset value, depreciation period, and the Consumer Price Index is used to calculate the annual payment with a minimum payment of $500,000. A reduced payment can be made when actual farebox recovery falls below the budgeted amount.

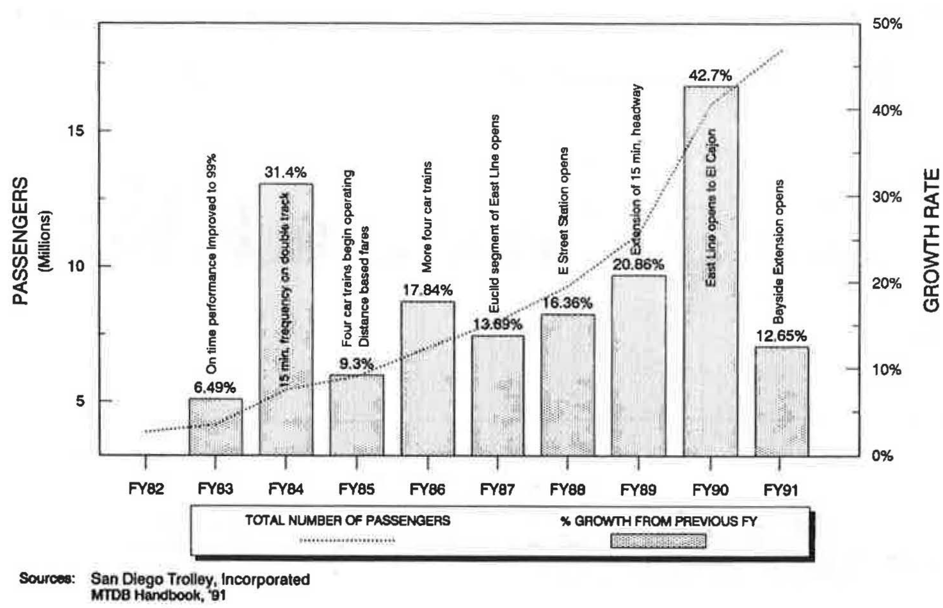
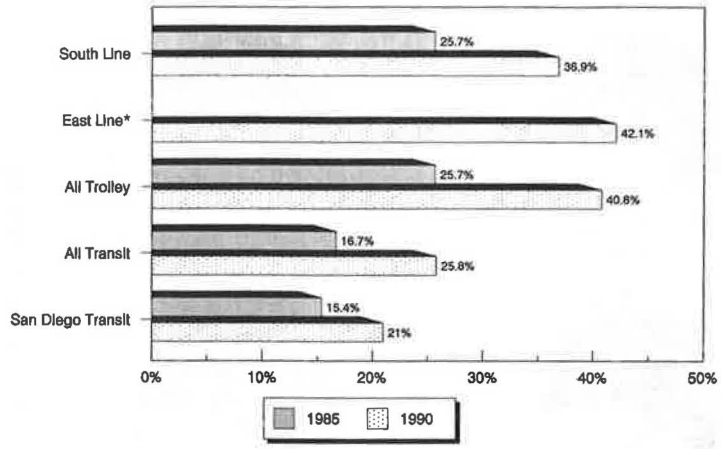
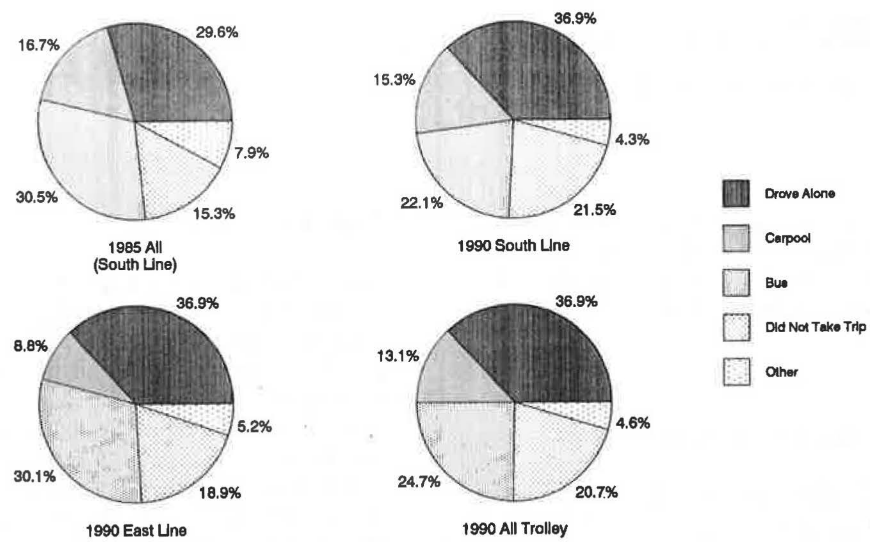


FIGURE 6 Total trolley passenger growth.



* East Line began March 23, 1986.
Source: 1990 SAN DIEGO REGIONAL TRANSIT SURVEY, VOLUME 2, SANDAG, 1991.

FIGURE 7 Automobile availability of transit passengers.



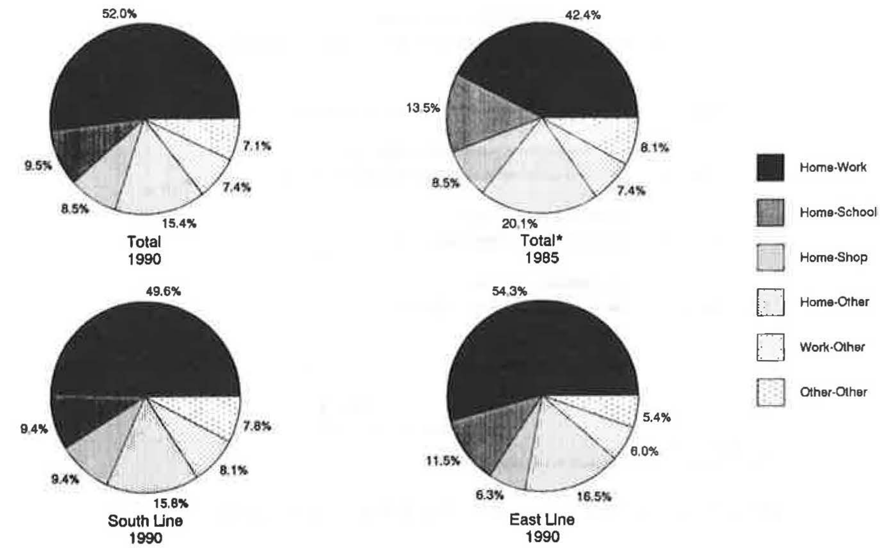
Source: 1990 SAN DIEGO REGIONAL TRANSIT SURVEY, VOLUME 2, SANDAG, 1991.

FIGURE 8 Mode of travel prior to trolley service.

TABLE 2 Mode of Access to Transit Stops in Percentage of Boardings by Operator

	TRANSFER		WALK		AUTO		OTHER	
OPERATOR	1985	1990	1985	1990	1985	1990	1985	1990
SAN DIEGO TROLLEY	17.0%	21.6%	59.7%	56.5%	20.1%	20.7%	3.2%	1.2%
SAN DIEGO TRANSIT	25.5	26.2	70.4	69.4	3.3	3.7	0.8	0.7
NATIONAL CITY TRANSIT	33.8	40.3	63.2	56.0	2.3	2.7	0.7	1.0
CHULA VISTA TRANSIT	33.6	37.9	62.9	59.0	2.5	2.8	1.0	0.5
SD COUNTY TRANSIT	19.5	25.4	69.9	62.4	10.2	11.5	0.3	0.8
MTDB CONTRACT ROUTES	28.9	25.6	59.8	68.7	5.9	5.0	5.4	0.6
NORTH COUNTY TRANSIT	22.8	26.9	70.0	66.4	5.5	5.5	1.8	1.2
TOTAL	24.4	25.6	68.3	65.1	5.9	8.3	1.4	1.0

SOURCE: 1990 SANDAG REGIONAL ONBOARD SURVEY



* East Line Began 3/23/86
Source: 1990 SAN DIEGO REGIONAL TRANSIT SURVEY, VOLUME 2, SANDAG, 1991.

FIGURE 9 Passenger trip purpose.

Items with short life spans (e.g., trucks and communication equipment) have already drawn on the account for replacement. The trolley continues to pay into the account each year and will thus be able to replace more expensive items when necessary.

TABLE 3 1990 MTS Bus and Trolley Rider Profile and Performance Trends

HIGHLIGHT	SAN DIEGO REGION	SAN DIEGO TROLLEY ONLY
Weekday Ridership	200,000	53,000
Commuter Weekday ridership	86,000	31,000
Trip Type		
Work	49.0%	58.3%
Visitor/Recreation	14.0%	17.9%
Shopping	14.0%	12.5%
School	18.9%	12.3%
Other	11.1%	6.8%
Riders who had car available	25.9%	41.8%
Persons/Household (p/h)		
1 p/h	16.5%	13.5%
2 p/h	23.4%	19.7%
3 p/h	19.0%	20.3%
4 p/h	18.3%	21.0%
5 p/h	22.7%	25.4%
Rider Type		
Male	50.4%	55.0%
Female	49.6%	45.0%
12–18 Years of Age	12.3%	7.6%
19–24 Years of Age	42.1%	22.9%
25–44 Years of Age	22.6%	49.9%
45–59 Years of Age	11.2%	13.7%
60+ Years of Age	9.2%	5.9%
Earn $30,000+	28.9%	34.7%
Earn Up to $19,000	54.4%	49.6%
Military	5.5%	7.9%
Visitor	8.3%	13.9%

Based on 1990 SANDAG REGIONAL ONBOARD SURVEY
December, 1991

LESSONS LEARNED

Several lessons can be learned from the first 10 years of operation. Some of the effects of LRT service have already been discussed. The trolley clearly attracts people from their cars, it induces new trips, and all transit systems gain ridership because of its presence. In addition, several other observations are worth mentioning that may help guide future LRT development.

The low-cost design aspects, such as self-service fare collection and simple stations, have paid off in long-term operating cost savings. Although, for example, some of the future stations may be more elaborate when part of a joint development project, the basic concepts employed in building the South and East lines will continue to be followed.

The trolley has been fortunate to have two strong trip generators to serve, downtown San Diego and the international border with Mexico. These two areas have helped ensure strong ridership even when other factors have dampened ridership growth. Future lines will attempt to serve activity centers as witnessed by plans for the Mission Valley Line to serve San Diego Jack Murphy Stadium and San Diego State University.

The trolley has spawned several joint developments including the MTS Tower (which houses MTDB and San Diego Trolley, Inc. offices), American Plaza (across from the Santa Fe Depot), the Trolley 8 Cinemas at the Grossmont Center Station, and a housing/day care project at the 47th Street Station. Discussions are under way with numerous developers on the Mission Valley and Mid-Coast lines for even more joint developments. Thanks to the trolley's proven benefits and supportive local jurisdictions, more of these projects are expected in the future. In this way, the trolley may help shape urban development in much the same way Toronto's system has.

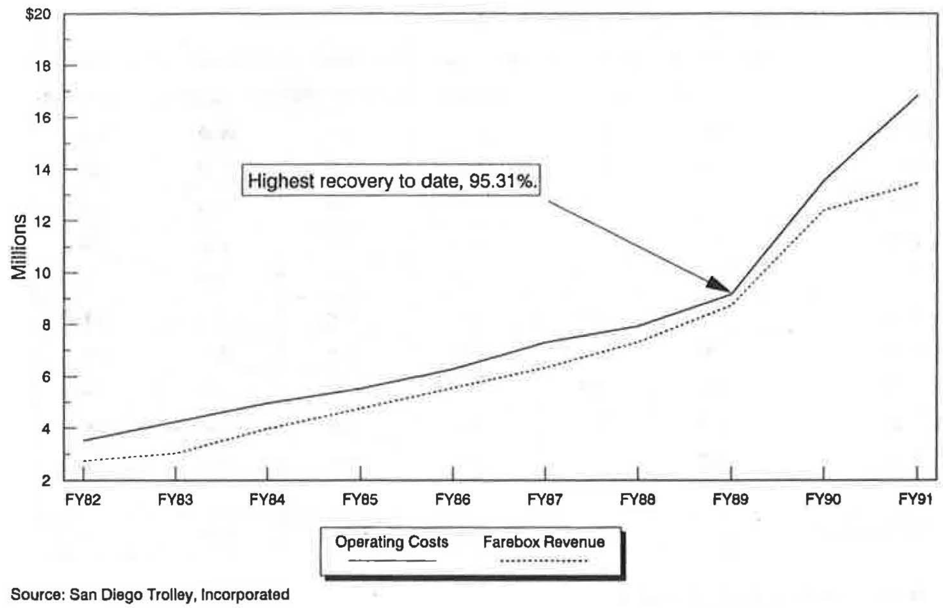


FIGURE 10 Trolley operating costs versus farebox revenue.

On the operational side, double-tracking was found to be essential to on-time operations. The South Line opened as a single-track line and on-time service could not be provided at 15-min frequency. As a result, 20-min service was operated until double-tracking could be completed. Double-tracking is now our design standard. Only in a few special situations, such as at the suburban end of a line, is single-tracking considered. All planning and environmental work assumes a double-tracked right-of-way.

Also, immediate graffiti cleanup has been effective in keeping the problem under control. Marked-up vehicles are cleaned when they come in before they return to service. Wayside facilities are cleaned as soon as possible. Vehicles have even been cleaned while in service, with a crew waiting for them at a station. As a result, the San Diego trolley has remained virtually graffiti free.

Looking toward the future, MTDB and San Diego Trolley, Inc., will have to try harder to maintain the success they have enjoyed in the first 10 years. New lines will be built in more suburban areas where major trip generators like downtown or the border crossing are harder to find. Planning for the expansions is becoming more difficult as new rights-of-way must be found. The system is aging, requiring a higher level of maintenance and, thus, greater expense to keep things in

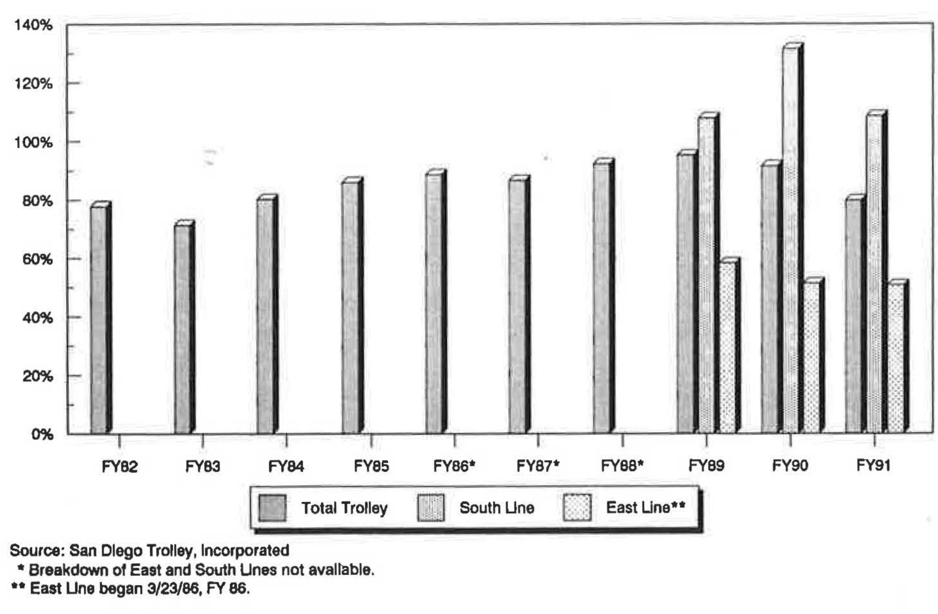


FIGURE 11 Trolley farebox recovery ratio.

TABLE 4 San Diego Trolley Financial Indicators

	Operating Cost/ Passenger	Operating Cost/ Train Mile	Operating Cost/ Car Mile	Operating Cost/ Passenger (1982$)	Operating Cost/ Train Mile (1982$)	Operating Cost/ Car Mile (1982$)
FY82	$0.91	$6.82	$3.47	$0.91	$6.82	$3.47
FY83	1.03	8.16	3.32	1.00	7.92	3.22
FY84	0.91	6.40	3.01	0.84	5.89	2.77
FY85	0.93	7.16	3.38	0.81	6.21	2.93
FY86	0.90	7.45	3.42	0.75	6.21	2.85
FY87	0.92	7.35	3.50	0.74	5.88	2.80
FY88	0.85	7.52	3.70	0.64	5.68	2.79
FY89	0.82	8.01	3.79	0.57	5.59	2.66
FY90	0.85	7.91	3.31	0.54	5.05	2.12
FY91	0.93	9.38	3.74	0.56	5.60	2.23
10-YEAR AVERAGE	$0.91	$7.62	$3.46	$0.74	$6.09	$2.78

Sources: San Diego Trolley, Incorporated
Bureau of Labor Statistics

a like-new condition. San Diego Trolley, Inc., itself will grow to operate the expanded system, presenting the challenge of maintaining its high standards within a larger organization. Marketing efforts will probably have to increase to keep ridership growing in the existing corridors.

Fortunately, trip making restrictions emanating from air quality efforts will likely be helpful in boosting ridership.

Yes, the future will be challenging, but the experience of operating the system for over a decade, the support of the community, and the continued commitment of MTDB and San Diego Trolley, Inc., to high standards should enable this LRT success story to keep growing.

ACKNOWLEDGMENT

The authors are thankful for the assistance of MTDB staff members Bob Robenhymer, Principal Transportation Planner, and Tony Mendoza, Transportation Planner, in preparing this paper.

Dwell Time Relationships for Light Rail Systems

TYH-MING LIN AND NIGEL H. M. WILSON

Vehicle dwell time is an important determinant in the capacity and performance characteristics of high-frequency, high-ridership light rail lines that are common in Europe. In the United States these systems are best exemplified by the Green Line of the Massachusetts Bay Transportation Authority (MBTA). In such systems cumulative dwell time can represent a significant proportion of total train running time and can contribute greatly to headway variability, which in turn affects passenger service quality. Models are estimated for both one- and two-car trains based on data gathered for the MBTA Green Line. These models explain about 70 percent of the observed variation in dwell times using three explanatory variables: passengers boarding, passengers alighting, and passengers on board. The effect of passenger crowding is statistically significant in most models, and adding crowding variables to reflect congestion on board the vehicle significantly improves the explanatory power of most models. Nonlinear forms of the crowding effect were also estimated, and generally these forms performed better than the corresponding linear forms.

Vehicle dwell time is an important determinant of system performance and passenger service quality in many forms of urban public transportation. Dwell time directly affects vehicle trip time and hence number of vehicles required to operate a given timetable and most measures of productivity. Beyond this obvious effect, dwell time may govern line capacity in systems that have on-line stations with no overtaking permitted such as most urban rail systems. Furthermore dwell time is generally accepted to be the major factor causing vehicle pairing (bunching), which results in variability in headways. Headway variability itself results in higher than necessary passenger waiting times and uneven vehicle passenger loads, both of which are sources of user dissatisfaction with transit service.

Although dwell time will have some effect on transit operations, the extent of this effect varies across mode and service type. At one extreme is commuter rail operation in which headways are typically relatively long and cumulative dwell time represents only a small fraction of total trip time. At the other extreme is a long, high-frequency, high-ridership bus line. In this case dwell time may be a substantial fraction of running time, dwell time for a particular bus is quite sensitive to passenger movements, and difference in cumulative dwell time over the route can readily exceed initial headway between successive buses. In most North American bus systems, fare payment is on board, resulting in boarding through a single door in a single stream, which contributes to the longer dwell time.

Rail rapid transit and light rail transit lie between these two extremes in terms of the impact of dwell time on operations. Rail rapid transit systems are designed for high-volume operations, with fare payment off the vehicle, and use vehicles designed for rapid passenger boarding and alighting. At the same time, because headways are usually short, differential dwell times have the potential to induce variable headways. Light rail transit operates under quite a wide range of circumstances so that dwell time may, or may not, be an important determinant of overall operational performance. For example, some newer light rail systems operate with relatively high headways, low passenger loadings, and off-vehicle fare payment; in these systems dwell time should not be a critical factor. On the other hand, in light rail systems that operate at high frequency and with high passenger volumes, dwell time is likely to be important even with off-vehicle fare payment.

Dwell time models for light rail systems that use off-vehicle fare payment have been estimated and can be used to address for the first time the relationship between dwell time and train length. After a review of prior work on dwell times, the theoretical aspects of dwell time modeling are discussed. This is followed by a description of the MBTA Green Line system on which data for model estimation were gathered, and finally the models themselves are presented.

PRIOR WORK

Prior work on vehicle dwell times (or the related measure, passenger service times) has been focused on bus systems, not surprisingly given its critical importance to bus operations, with relatively little attention paid to light rail dwell time relationships. Typically these studies have used ordinary least squares regression to relate vehicle dwell time to the numbers of passengers boarding and alighting, with separate models estimated for different operating characteristics likely to affect dwell time, such as restrictions on door usage for boarding and alighting, fare payment method, one- versus two-person operation and vehicle design. In at least one study (*1*) the passenger service time was also found to increase when the passenger load exceeded the seating capacity of the bus. More about prior bus dwell time research can be found in the *Highway Capacity Manual* (*2*), as well as papers by Levinson (*3*), Guenther and Sinha (*4*), Boardman and Kraft (*5*), Kraft and Bergen (*6*), Kraft (*7,8*), and Cundill and Watts (*9*).

In terms of light rail studies, Fritz (*10,11*) estimated models for the MBTA Green Line with the President's Conference

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Committee (PCC) cars in use. Linear relations were estimated between the number of passengers boarding per unit time and concurrent passenger counts (or density) both on board the car and on the platform. These models showed that boarding rates declined markedly with increasing passenger crowding, especially as the space per standee fell below the often used nominal standee space allocation of 2.7 ft^2 and approached crush capacity density of 1.5 ft^2. At lower levels of congestion these models produced results quite similar to predictions from constant service time models. These results cannot be applied to a modern, articulated light rail vehicle (LRV) because of the radically different vehicle design, including number and size of doors. Fritz's models were estimated only for single-car trains and did not consider the general case of boardings and alightings occurring simultaneously.

In the most closely related prior work to this, Koffman et al. (*12*) collected two data sets on the MBTA Green Line and another on the San Diego Trolley to estimate the effects of the self-service fare collection system being used in San Diego. One MBTA data set referred to outbound operation in which no fares were collected, whereas the other referred to inbound operation with on-vehicle fare collection. All models estimated used independent variables, passengers boarding, passengers alighting, and passengers on board to estimate the dependent variable dwell time. All three variables were found to be statistically significant in all data sets with the model explaining between 43 percent and 84 percent of the variation in the observed dwell times. Although these results are suggestive, they cannot be directly applied to a high-ridership, high-frequency operation because of the low level of passenger movements and low passenger loads (the MBTA observations were made on the surface portion of the line, not the high-density central subway portion). The MBTA Green Line observations were also made only for one-car trains. However Koffman's MBTA model results will be compared with those developed here later in this paper.

THEORY

Dwell time of a train at a station may be affected by many factors, grouped by Kraft (*7*) into seven categories: human, modal, operating policies, operating practices, mobility, climate/weather, and other system elements. However, for a given property and system, most of these factors are constant, and the principal determinants of dwell time are likely to be various aspects of passenger demand and human behavior as it affects both operators and passengers.

Differences in operator characteristics, such as how long the operator might wait with the doors open for someone who may want to alight from a crowded car, will clearly lead to dwell time differences, but even if such characteristics could be captured in a mathematical model, they could not be used to forecast future system performance because the future composition and assignment of the operating work force is unpredictable. Similarly although passenger characteristics, such as the number of mobility-impaired passengers, is likely to affect dwell time, they cannot be used to predict dwell time for a specific train in the future. For these reasons no attempt will be made to incorporate human factors into the models to be estimated, and the influence of these factors will simply be included in the error term: the larger the error term, the more significant are those factors that are not included explicitly among the independent variables.

Thus the somewhat predictable factors likely to affect dwell time are simply the numbers of passengers boarding and alighting from a train and the number of passengers on board the train, as well as the number of cars in the train. These are referred to as being "somewhat predictable" because their mean values may be known from passenger counts per unit time, although their specific values will vary on a train-to-train and day-to-day basis. If mean passenger boarding and alighting rates are known from observation of the system, then mean numbers of passengers boarding and alighting at a station can be estimated given the train headway. Mean number of passengers on board can be estimated in a similar fashion given passenger boarding and alighting rates at all stations on the line.

In developing the theory underpinning dwell time one can think first about the way each independent variable would be expected to affect the time required to move passengers through a single door and then about the relationship between door open times and the total dwell time for the train. Consider first the time required for a given number of passengers to move through a single door in both directions. First assuming constant boarding and alighting rates without interference between boarding and alighting, and without interference with passengers standing on either side of the door, the following simple linear model might apply:

$$DOT = a + b(DONS) + c(DOFFS) \tag{1}$$

where

DOT = door open time,
$DONS$ = number of passengers boarding through door,
$DOFFS$ = number of passengers alighting through door, and
a,b,c = estimated parameters.

If interference with passengers on board is included, then the boarding and alighting rates would be expected to decrease as the crowding level on board increases. Furthermore it might be reasonable to expect that this term would be negligible until there is a standing load on board. Assuming the simplest case in which the passenger service time increases linearly with number of standees and the congestion effect on boarding and alighting service times is identical, the following model results:

$$DOT = a + b(DONS) + c(DOFFS) + d(DONS + DOFFS)(STD) \tag{2}$$

where STD is the number of standees.

This further assumes that passenger congestion on the station platform is not significant relative to that on board the vehicle (this will typically be true) and that interference effects between boarding and alighting passenger streams either are small or exist in all cases, in which case they will be included in the constant term a.

Although this model may be a reasonable description of the boarding and alighting process through a single door, the question of how this relates to total dwell time for a train remains. Consider a single car that has three doors, such as an articulated LRV. The dwell time for a single LRV would be as follows:

$$DT = \max(DOT_1, DOT_2, DOT_3) \tag{3}$$

where DT is the dwell time and DOT_i is the door open time for the ith door.

Equation 3 simply states that the dwell time for a single car is the longest door open time for any of its doors, where each door open time could be represented by Equation 2.

Clearly the minimum dwell time will occur when both boardings and alightings are evenly divided between all doors (assuming further that any standees are evenly distributed around the doors). In this case dwell time for a single car is as follows:

$$DT = a + b/3(CONS) + c/3(COFFS) + d/3(CONS + COFFS)(STD) \tag{4}$$

where $CONS$ is the number of passengers boarding the car and $COFFS$ is the number of passengers alighting from the car.

At the other extreme, where all boardings and alightings occurred through a single door, Equation 2 would apply at the car level; however, this is very unlikely to be true except for very low levels of boardings and alightings. The true dwell time process for a single car will be bounded by Equations 2 and 4, but is likely to be much closer to Equation 4. Furthermore, because in most LRVs all three doors cannot be operated independently, Equation 2 cannot be estimated directly, whereas Equation 4 can. The structure of these equations is, of course, identical; the only difference would be in the size of the estimated parameters b, c, and d.

Turning finally to the topic of multicar trains, the dwell time model would be analogous to Equation 3, but the maximum would now be taken over the dwell times of individual cars:

$$DT = \max(DT_1, DT_2, \ldots, DT_n) \tag{5}$$

where DT_i is the dwell time for the ith car of an n car train.

In typical North America light rail operations, the maximum train length is two cars, so dwell time for the train is simply the maximum of the individual car dwell times with each car dwell time being represented by Equation 4. Once again the minimum dwell time for the train will occur when boardings, alightings, and standees are evenly split between the two cars, leading to the following train dwell time:

$$DT = a + b/6(TONS) + c/6(TOFFS) + d/6(TONS + TOFFS)(STD) \tag{6}$$

where $TONS$ is the number of passengers boarding the train and $TOFFS$ is the number of passengers alighting from the train.

At the other extreme, with all passengers boarding and alighting from the same car, Equation 4 would hold. Thus Equations 4 and 6 represent bounds on the dwell time for a two-car train with the actual coefficients reflecting the degree of imbalance in passenger movements and loading between the cars.

EMPIRICAL STUDY: MBTA GREEN LINE

In this section dwell time functions are estimated for one- and two-car trains on the MBTA Green line, a light rail line operating with articulated LRVs (*13*). The Green Line operates over a branching network of 28 mi and 70 stations with much of the line fully grade separated, including the central portion that operates in a subway. Trains operate on four routes with separate surface alignments but which converge in one central subway tunnel (from Lechmere Station to Kenmore Station) with trains from all routes operating on the same tracks. Within this subway section, fares are paid upon entering a station rather than on board the train, which is the rule on the surface branches of the line.

In the 1970s, PCC cars were the principal vehicles running on the Green Line; but today they have been replaced with 52-seat (practical capacity is about 150 passengers) articulated LRVs. There are six doors per car, three on each side; the middle and rear doors are 35-in. wide, whereas the front door is 32-in. wide. The great majority of trains are composed of either one or two cars, depending on time of day, although some three-car trains are now being introduced. Virtually all stations have single (low-level) platforms for passenger movements, thus three doors are available for passengers alighting and boarding in any one-car train and six doors in any two-car train. Typical scheduled headways in the central subway are in the range of 1 to 2 min, depending on time of day.

For this analysis, a special detailed data set was gathered, with each observation including the following data: the number of passengers boarding and alighting through each door, the time the front door was opened and closed for each car, and the departing passenger load for each car. Because of the unusual level of detail required, it was necessary to have a two-person team per car, or a four-person team for a two-car train, to collect the data. For the two-car observations, the train dwell time was taken to be the larger of the dwell times observed for each car. A total of 122 observations of one-car train dwell times and 51 samples of two-car train dwell times were taken in April 1988 and 1989 at two subway stations.

A preliminary analysis was carried out that confirmed that dwell time is related to the number of passengers boarding and alighting as well as to the passenger load. This analysis also determined that the hypothesis that the mean dwell times were equal for one- and two-car trains that had similar levels of passenger movements or similar passenger loads could not be rejected. For the two-car trains this conclusion was based on the passenger movements and passenger load observed for the car having the longer dwell time. Tables 1 and 2 summarize the dwell times observed for one- and two-car trains as a function of the (leaving) passenger load and the sum of boarding and alighting passengers.

Based on the preliminary analysis and theory, two major factors, the number of passengers boarding and alighting, and crowding on board, were expected to enter into the dwell time function. However each factor can be represented in different forms and may interact in different ways. Accord-

TABLE 1 One-Car Train Dwell Times

Total Sample:	n = 122	Mean = 23.31	Standard Deviation = 11.41	
a) Analysis based on leaving passenger load (LPL)				
LPL	< 53	53-80	81-108	> 108
Sample Size	41	37	16	28
Mean LPL	32	65	94	132
Mean TONOFFS	10	15	20	21
Mean (Dwell Time)	16.83	20.60	24.00	36.00
Std. Dev. (Dwell Time)	5.65	8.35	6.68	13.31
b) Analysis based on sum of passengers boarding and alighting (TONOFFS)				
TONOFFS	< 10	10-17	18-25	>25
Sample Size	37	39	30	16
Mean LPL	47	75	89	101
Mean TONOFFS	6	13	21	32
Mean (Dwell Time)	15.81	20.03	27.10	41.56
Std. Dev. (Dwell Time)	6.65	6.32	5.90	14.98

TABLE 2 Two-Car Train Dwell Times

Total Sample:	n = 51	Mean = 26.57	Standard Deviation = 8.40	
a) Analysis based on LPL for longer dwell time car				
LPL	< 53	53-80	81-108	> 108
Sample Size	11	13	16	11
Mean LPL	41	69	98	132
Mean TONOFFS	11	15	21	27
Mean (Dwell Time)	20.36	23.15	27.50	35.46
Std. Dev. (Dwell Time)	5.68	7.39	6.81	6.31
b) Analysis based on TONOFFS for longer dwell time car				
TONOFFS	< 10	10-17	18-25	>25
Sample Size	12	14	11	14
Mean LPL	61	74	97	109
Mean TONOFFS	6	14	21	32
Mean (Dwell Time)	19.33	22.79	28.73	34.87
Std. Dev. (Dwell Time)	5.69	4.87	6.81	6.56

ingly a series of linear regression models of passenger processing were estimated to identify the strongest functional form. In the following discussion of the estimation results, the variables used to explain the variation in the dependent variable *DT* (dwell time measured in seconds) are as previously defined, with the following additions:

TONOFFS = sum of *TONS* and *TOFFS*,
AS = number of arriving standees,
LS = number of departing standees,
TOFFAS = product of *TOFFS* and *AS*, i.e., *TOFFS***AS*,
TONLS = product of *TONS* and *LS*, i.e., *TONS***LS*, and
SUMASLS = sum of *TOFFAS* and *TONLS*.

In all cases of two-car trains, the variables refer to passenger movements and loads on the entire train.

As discussed in the theory section, the dwell time processes for one- and two-car trains are different and so separate models were estimated for the one-car train data set and the two-car train data set. The statistical packages SST (*14*) and MINITAB (*15*) were used for the regression analysis. The resulting models shown below include *t*-statistics (in parentheses) and corrected coefficient of determination (R^2). The *t*-statistics are used to determine the contribution of each variable used in model estimation, and the corrected R^2 is used to measure how well the model estimation fits the sample data.

ONE-CAR TRAIN MODELS

Although the one-car train data set was collected at two stations, a dummy variable introduced in the regression analysis to reflect possible differences between the stations was not statistically significant, and thus is omitted from all models shown here.

Models were estimated based on three approaches: all data together, the data set with *TONS* being equal to or greater than *TOFFS* ($TONS \geq TOFFS$), and that with *TOFFS* being greater than *TONS* ($TOFFS > TONS$). The available sample points for these three approaches are 122, 83, and 39, respectively. In the following analysis, model estimations are conducted based on these three approaches, with the second and third approaches referred to by subscripts *a* and *b*, respectively.

Model A: $DT = f(TONS, TOFFS)$

Model A assumes that only the number of passengers boarding and alighting affect the dwell time and that there is no effect of passenger crowding on board. The resulting models are shown below:

$$\text{A1: } DT = \underset{(5.96)}{9.07} + \underset{(8.46)}{1.15} * TONS + \underset{(5.58)}{0.63} * TOFFS \quad (R^2 = 0.48) \tag{7}$$

$$\text{A1a: } DT = \underset{(3.91)}{8.67} + \underset{(4.03)}{0.90} * TONS + \underset{(5.28)}{1.41} * TOFFS \quad (R^2 = 0.52) \tag{8}$$

$$\text{A1b: } DT = \underset{(8.51)}{11.98} + \underset{(4.61)}{0.88} * TONS + \underset{(3.82)}{0.43} * TOFFS \quad (R^2 = 0.64) \tag{9}$$

Although all coefficients are strongly significant in all three models (as indicated by the t-statistics), the models have rather low coefficients of determination (corrected R^2). It does appear, however, that Models A1a and A1b using two data sets based on the relative magnitude of *TONS* and *TOFFS* are a significant improvement over A1, which pools all data. In light of the poor overall goodness of fit measures, all subsequent models include terms representing passenger crowding, and all three modeling approaches are retained.

Model B: $DT = f(TONS, TOFFS, SUMASLS)$

Model B recognizes that movement of alighting passengers would be affected by arriving standees, whereas movement of boarding passengers would be affected by departing standees. Therefore the crowding effect may be represented by the variables *TOFFAS* and *TONLS*, which are combined in the variable *SUMASLS*, producing the following results:

$$\begin{aligned} \text{B1:}\ DT = {} & \underset{(8.94)}{12.50} + \underset{(3.76)}{0.55} * TONS + \underset{(2.03)}{0.23} * TOFFS \\ & + \underset{(6.70)}{0.0078} * SUMASLS \quad (R^2 = 0.62) \end{aligned} \tag{10}$$

All coefficients are strongly significant in this model with an R^2 of 0.62 showing that adding the variable *SUMASLS* to reflect the effect of crowding on board significantly improves the explanatory power of the model. The marginal boarding time in this model is more than twice the marginal alighting time and the contribution of the crowding term is that dwell time would be increased by about 7 sec at a typical stop when half the train passengers are standing.

When boardings are greater than alightings:

$$\begin{aligned} \text{B1a:}\ DT = {} & \underset{(6.33)}{12.32} + \underset{(2.78)}{0.56} * TONS \\ & + \underset{(8.25)}{0.01} * SUMASLS \quad (R^2 = 0.65) \end{aligned} \tag{11}$$

In this model the term for alighting passengers has been dropped because of its low statistical significance, although the contribution of alightings is included in the *SUMASLS* term. All remaining coefficients are significant at 0.05 level with an R^2 of 0.65, which implies that adding the variable *SUMASLS* to reflect the effect of crowding on board is a significant improvement over model A1a.

When alightings are greater than boardings, however, the effect of on board crowding is much less significant and the overall goodness of fit changes little as shown below:

$$\begin{aligned} \text{B1b:}\ DT = {} & \underset{(8.60)}{12.46} + \underset{(2.43)}{0.65} * TONS + \underset{(3.43)}{0.39} * TOFFS \\ & + \underset{(1.25)}{0.002} * SUMASLS \quad (R^2 = 0.65) \end{aligned} \tag{12}$$

Model C: $DT = f(TONS, TOFFS, LS)$

The Model C form assumes that the effect on dwell time of crowding on board could be represented simply by the leaving standees (LS). A rationale for this is that for a very crowded car (train) the operator may wait longer to see if any passengers are trying to alight—even if none finally do. In this case the contribution of crowding to dwell time may not be a function of the number of passengers boarding or alighting:

$$\begin{aligned} \text{C1:}\ DT = {} & \underset{(7.19)}{9.24} + \underset{(5.40)}{0.71} * TONS + \underset{(5.35)}{0.52} * TOFFS \\ & + \underset{(6.98)}{0.16} * LS \quad (R^2 = 0.63) \end{aligned} \tag{13}$$

$$\text{C1a:}\ DT = \underset{(4.13)}{8.10} + \underset{(4.65)}{0.88} * TONS + \underset{(7.61)}{0.22} * LS \quad (R^2 = 0.62) \tag{14}$$

$$\begin{aligned} \text{C1b:}\ DT = {} & \underset{(8.37)}{11.46} + \underset{(2.64)}{0.60} * TONS + \underset{(4.38)}{0.48} * TOFFS \\ & + \underset{(2.09)}{0.066} * LS \quad (R^2 = 0.67) \end{aligned} \tag{15}$$

As indicated by the t-statistics, all coefficients are strongly significant in all three models of this form. Overall goodness of fit statistics are quite similar to those for Model B, and it is clear that, statistically at least, using the variable LS to reflect the crowding effect is a reasonable approach. However, if there were standees, but no passengers boarding or alighting, the number of standees should not have as significant an impact on dwell time as if there were passenger movements. For this reason, Model B may be preferred over Model C.

NONLINEAR MODELS

The previous models have assumed that the effect on dwell time of crowding is linear; however, it may well be nonlinear. To investigate this possibility, various nonlinear forms for the variables reflecting crowding were also estimated. Several of the more interesting nonlinear models are shown below:

$$\begin{aligned} \text{D1-1:}\ DT = {} & \underset{(8.78)}{11.43} + \underset{(5.38)}{0.69} * TONS + \underset{(4.99)}{0.48} * TOFFS \\ & + \underset{(7.41)}{1.35 * 10^{-5}} * TONS * LS^{2.5} \quad (R^2 = 0.65) \end{aligned} \tag{16}$$

$$\begin{aligned} \text{D1-2:}\ DT = {} & \underset{(8.32)}{10.05} + \underset{(6.70)}{0.78} * TONS + \underset{(5.51)}{0.50} * TOFFS \\ & + \underset{(8.50)}{2.0 * 10^{-4}} * LS^{2.5} \quad (R^2 = 0.68) \end{aligned} \tag{17}$$

$$\text{D1a}: DT = \underset{(5.44)}{9.71} + \underset{(5.69)}{0.94}*TONS + \underset{(9.34)}{1.1*10^{-4}}*LS^{2.7} \quad (R^2 = 0.69) \tag{18}$$

$$\text{D1b}: DT = \underset{(8.47)}{11.45} + \underset{(3.17)}{0.66}*TONS + \underset{(4.46)}{0.49}*TOFFS + \underset{(2.26)}{7.7*10^{-4}}*LS^{2.0} \quad (R^2 = 0.68) \tag{19}$$

These models show that nonlinear forms of the crowding term with passenger load raised to a power of about 2.5 gives a slightly better representation of observed dwells than the standard linear form.

TWO-CAR TRAIN MODELS

Model A: *DT* = *f*(*TONS*, *TOFFS*)

Model A assumes that only the numbers of passengers boarding and alighting affect the dwell time, so there is no effect of passenger crowding on board. The resulting models based on the three approaches discussed earlier are referred to as A2, A2a, and A2b, respectively, in this (and subsequent) specifications:

$$\text{A2}: DT = \underset{(7.44)}{11.73} + \underset{(7.59)}{0.42}*TONS + \underset{(6.22)}{0.49}*TOFFS \quad (R^2 = 0.68) \tag{20}$$

$$\text{A2a}: DT = \underset{(4.32)}{9.69} + \underset{(4.49)}{0.42}*TONS + \underset{(3.99)}{0.66}*TOFFS \quad (R^2 = 0.71) \tag{21}$$

$$\text{A2b}: DT = \underset{(7.46)}{14.39} + \underset{(6.29)}{0.56}*TOFFS \quad (R^2 = 0.68) \tag{22}$$

As indicated by the *t*-statistics, all remaining coefficients are strongly significant in all three models, with high R^2-values, although it should be noted that the boardings term was dropped from Model A2b because of its low significance.

Comparing these models with the corresponding one-car train models, several points should be noted. First, the constant terms imply that there is a greater station "overhead" for a two-car train. Second, the coefficients for the variables *TONS* are much lower, because twice as many doors are available to boarding passengers. Note that this effect does not necessarily apply to the alighting process because passengers cannot move between cars once on board, and so imbalance between cars is more likely to arise in alighting than in boarding. It also appears that these two-car models better explain the dwell times using only two variables than the corresponding one-car models, implying that the crowding effect is less significant in the two-car train dwell process.

Model B: *DT* = *f*(*TONS*, *TOFFS*, *SUMASLS*)

Model B introduces the variable *SUMASLS* (the sum of *TOFFAS* and *TONLS*) to express the marginal effect on dwell time of crowding on board:

$$\text{B2}: DT = \underset{(7.43)}{13.93} + \underset{(2.92)}{0.27}*TONS + \underset{(3.79)}{0.36}*TOFFS + \underset{(2.03)}{0.0008}*SUMASLS \quad (R^2 = 0.70) \tag{23}$$

$$\text{B2a}: DT = \underset{(3.83)}{11.31} + \underset{(2.62)}{0.34}*TONS + \underset{(2.23)}{0.52}*TOFFS + \underset{(0.85)}{0.0005}*SUMASLS \quad (R^2 = 0.70) \tag{24}$$

$$\text{B2b}: DT = \underset{(8.10)}{15.69} + \underset{(3.50)}{0.41}*TOFFS + \underset{(1.88)}{0.0008}*SUMASLS \quad (R^2 = 0.72) \tag{25}$$

In Model B2, all coefficients are significant at the 0.05 level, and adding the variable *SUMASLS* is an improvement over Model A2. In Model B2a, the crowding term coefficient is not statistically significant, and it is only marginally significant in Model B2b.

Compared with the corresponding one-car train models, the most striking difference is the ratio of marginal boarding to marginal alighting time between the corresponding models. The boardings coefficients for the two-car train models are about half the values for the corresponding one car models, as would be expected given twice as many doors through which boarding can occur. However, the alighting coefficient is greater for two-car trains than for one-car trains. This can only be explained by passengers who are getting off at a specific station being concentrated in one of the two cars—presumably the most convenient to the station exit.

Model C: *DT* = *f*(*TONS*, *TOFFS*, *AS*, *LS*)

The only Model C that produced interesting results was for the cases in which there were more alightings than boardings:

$$\text{C2b}: DT = \underset{(8.43)}{15.00} + \underset{(4.23)}{0.43}*TOFFS + \underset{(2.11)}{0.037}*AS \quad (R^2 = 0.74) \tag{26}$$

As indicated by the *t*-statistics, all coefficients are significant at 0.05 level in this model with an R^2 of 0.74. Compared with Model A2b, it is clear that adding the variable *AS* to reflect the effect of crowding on board significantly improves the explanatory power of the model.

NONLINEAR MODEL FORMS

As for the one-car train models, various nonlinear models were estimated to reflect possible nonlinearities in the crowding effect. Several of the more interesting nonlinear models are presented below:

$$\text{D2-1: } DT = \underset{(8.06)}{13.54} + \underset{(3.70)}{0.28}*TONS + \underset{(5.65)}{0.44}*TOFFS + \underset{(2.41)}{6.0*10^{-6}}TONS*LS^2 \quad (R^2 = 0.71) \qquad (27)$$

$$\text{D2-2: } DT = \underset{(7.94)}{12.72} + \underset{(6.08)}{0.36}*TONS + \underset{(5.01)}{0.42}*TOFFS + \underset{(2.03)}{1.3*10^{-6}}*AS^{2.5} \quad (R^2 = 0.70) \qquad (28)$$

No interesting nonlinear model forms were found for the separate data sets in which boardings or alighting dominated.

It is clear from these results that passenger crowding has a lesser effect on dwell time in two-car train operations than in one-car operations.

COMPARISON OF ONE- AND TWO-CAR TRAIN MODELS

Tables 3, 4, and 5 compare the parameter estimates for the one- and two-car linear models for all three model series.

Table 3 indicates that the constant terms in the two-car dwell time models are greater than those in the corresponding one-car models, but the marginal dwell time for boarding is significantly smaller. The coefficient of *TONS* for the two-car model is half that for the corresponding one-car model because there are about half as many *TONS* per door when the same passengers board a two-car train compared with a one-car train. The marginal dwell time for alighting varies between the one- and two-car models, depending on what model form is chosen, but it depends on the passenger load distribution between cars. It is also clear that the coefficients of the variables reflecting the crowding effect in the one-car train models are greater and more significant than those in the two-car models, implying that the marginal dwell time

TABLE 3 Comparison of Parameter Estimates for All Observations

	One Car Trains			Two Car Trains		
Model	A1	B1	C1	A2	B2	C2
Constant	9.07	12.50	9.24	11.73	13.93	12.37
	(8.87)	(8.94)	(7.19)	(7.44)	(7.43)	(7.73)
TONS	1.55	0.55	0.71	0.42	0.27	0.35
	(8.46)	(3.76)	(5.40)	(7.59)	(2.92)	(5.20)
TOFFS	0.63	0.23	0.52	0.49	0.36	0.41
	(5.58)	(2.03)	(5.35)	(6.22)	(3.79)	(4.46)
SUMASLS		0.0078			0.0008	
		(6.70)			(2.03)	
LS			0.16			0.027
			(6.98)			(1.61)
Corrected R-Square	0.48	0.62	0.63	0.68	0.70	0.69

TABLE 4 Comparison of Parameter Estimates for Net Boardings Only

	One Car Trains			Two Car Trains		
Model	A1a	B1a	C1a	A2a	B2a	C2a
Constant	8.67	12.32	8.22	9.69	11.31	9.90
	(3.91)	(6.33)	(4.37)	(4.32)	(3.83)	(4.21)
TONS	0.90	0.56	0.69	0.42	0.34	0.41
	(4.03)	(2.78)	(3.55)	(4.49)	(2.62)	(3.98)
TOFFS	1.41		0.73	0.66	0.52	0.60
	(5.28)		(2.83)	(3.99)	(2.23)	(2.67)
SUMASLS		0.01			0.0005	
		(8.25)			(0.85)	
LS			0.18			
			(5.67)			
AS						0.01
						(0.36)
Corrected R-Square	0.52	0.65	0.65	0.71	0.70	0.70

TABLE 5 Comparison of Parameter Estimates for Net Alightings Only

	One Car Trains			Two Car Trains		
Model	A1b	B1b	C1b	A2b	B2b	C2b
Constant	11.98	12.46	11.46	14.39	15.69	15.00
	(8.51)	(8.60)	(8.37)	(7.46)	(8.10)	(8.43)
TONS	0.88	0.65	0.60			
	(4.61)	(2.43)	(2.64)			
TOFFS	0.43	0.39	0.48	0.56	0.41	0.43
	(3.82)	(3.43)	(4.38)	(6.29)	(3.50)	(4.23)
SUMASLS		0.0022			0.0008	
		(1.25)			(1.88)	
LS			0.066			
			(2.09)			
AS						0.037
						(2.11)
Corrected R-Square	0.64	0.65	0.67	0.68	0.72	0.74

effect of crowding is greater in one-car trains than in two-car trains. Part of this difference is explained by the implied difference in passenger movements and crowding at each door, but this would account for only a factor of four difference in the terms. The remaining difference is most likely because of load imbalances between cars, allowing boarding passengers to board the less crowded car, thus experiencing less congestion. As indicated by the corrected R^2 shown in Table 3, it is clear that adding either proposed crowding variable significantly improves the explanatory power of the one car train model.

The most striking observation from Table 4 is that the crowding effect is insignificant in the two-car train models, whereas it is highly significant in the one-car train models for the net boarding sample. The second observation is that the alighting time coefficient is greater than the boarding time coefficient. This again reflects the greater imbalance in alightings than in boardings, and the sequential nature of alightings and boardings through the governing door.

Table 5, for the net alightings sample, clearly shows the higher constant term for all two-car train models. In the two-car train models boardings are accommodated in parallel with alightings (presumably at other doors), whereas in one-car trains the marginal contribution of boarding time is significant. The marginal alighting times are very similar in one- and two-car trains, again reflecting imbalance in alighting load between cars in the two-car trains. Finally although the crowding terms are only marginally significant, their magnitude is very similar for one- and two-car trains when the variables are interpreted on a per door basis.

To provide a better understanding of the differences between the dwell times for one- and two-car trains, Table 6 uses Model Form B to estimate dwell time for some hypothetical train movements, for both one- and two-car trains. By comparing dwell times along a single row, one can see the difference in dwell time between a one- and two-car train with identical passenger movements and passenger load. This difference in dwell time increases with number of passengers boarding and alighting, and with passenger load, indicating the substantial dwell time reductions that result from operating two-car trains when the alternative would be a heavily loaded one-car train. These time savings can be half a minute, or more when the one-car train is operating close to practical capacity.

TABLE 6 Comparison of Predicted Dwell Times for Models B1 and B2

Boardings	Alightings	Passengers on board	One Car Trains Model DT (sec)	Two Car Trains Model DT (sec)
0	0	any #	12.5	13.9
10	10	<53	20.3	20.2
10	10	100	27.8	20.2
10	10	150	35.6	21.0
20	20	<53	28.1	26.5
20	20	100	43.1	26.5
20	20	150	58.7	28.1
30	30	<53	35.9	32.8
30	30	100	58.4	32.8
30	30	150	81.8	35.1

COMPARISON WITH OTHER DWELL TIME MODELS

The only directly comparable model found in the literature was a study by Koffman et al. (*12*) that included the following dwell time model for single-car, surface, outbound (no on-board fare payment) MBTA Green Line operations (the parameters presented are averages of those obtained separately by Koffman on two different branches of the Green Line):

$$DT = 3.0 + 0.75(TONS) + 0.56(TOFFS) + 0.035(PASS)$$

where *PASS* is total passengers on board arriving at the stop.

For comparison purposes the most similar model developed under this study is Model C1:

$$DT = 9.24 + 0.71(TONS) + 0.52(TOFFS) + 0.16(LS)$$

Comparing these models, the marginal boarding and alighting times are quite similar, with the slightly lower times estimated in the model developed under this study most likely resulting from the significantly higher observed boardings and alightings in the data set (15.3 versus 9.4). The other striking differences are in the size of the constant term and in the structure of the crowding term. These differences are somewhat offsetting given the structural difference in the terms.

Table 7 compares predicted dwell times using both models for some hypothetical operating circumstances. Substantial differences exist between the model predictions, particularly with respect to the effect of heavy passenger loads on dwell

TABLE 7 Comparison of Predicted Dwell Times for Koffman Model and Model C1 from This Paper

Boardings	Alightings	Pass on Board (Leaving Standees)	Lin, Wilson Model DT	Koffman Model DT
0	0	10 (0)	9.2	3.3
0	0	60 (8)	10.5	5.1
0	0	110 (58)	18.5	6.9
10	10	10 (0)	21.5	16.4
10	10	60 (8)	22.7	18.2
10	10	110 (58)	30.8	20.0
20	20	60 (8)	35.0	31.3
20	20	110 (58)	43.1	33.1
30	30	60 (8)	47.2	44.4
30	30	110 (58)	55.3	46.2

time. This effect of heavily loaded trains is even more pronounced in some of the nonlinear dwell time models and would be even more marked for trains operating closer to capacity.

OPERATIONAL IMPLICATIONS

The sensitivity of dwell time to both numbers of passengers boarding and alighting and the number of standees on the train has several important implications on operations. First the difference in dwell times of up to half a minute, or more, between heavily loaded trains and lightly loaded trains for the same number of passenger boardings and alightings means that an initial ideal headway of (for example) 1 to 2 min can rapidly deteriorate if initial train loadings vary greatly. This deterioration becomes much more rapid as the shorter headway results in fewer boardings and alightings and the longer headway results in greater boardings and alightings. Furthermore the whole line is slowed by the heavily loaded train operating with a long headway. Thus effective real-time operations monitoring and control become a critical requirement for maintaining high quality service on this type of high-frequency, high-ridership light rail system.

Another observation is the difficulty of running different length trains on the same service at the same time. Unless headways are closely controlled there will be a strong tendency for the shorter trains to become heavily loaded and thus run more slowly than the longer trains. This leads to bunching and poor service quality.

CONCLUSIONS

This research has estimated dwell time models for one- and two-car light rail operations. The resulting models showed that both the numbers of passengers boarding and alighting and the level of passenger crowding on board the train significantly affect dwell times. Several forms of the crowding variable were shown to be effective, all based on the number of standees. Evidence was also found that the crowding effect may be nonlinear with the marginal delay increasing with the number of standees. A basis for formulating and estimating dwell time models for multicar trains was also laid out and showed that important differences exist between dwell time models for one- and two-car trains as a result of typically uneven distribution of passenger movements and passenger loads between cars in a two-car train. Finally some of the implications of the dwell time models for maintaining high-quality service on high-frequency, high-ridership light rail lines were pointed out.

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Improving Service on the MBTA Green Line Through Better Operations Control

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The Massachusetts Bay Transportation Authority (MBTA) Green Line is a four-branch light rail network that includes the nation's oldest subway section. It is operated with one- and two-car trains using articulated vehicles at trunk headways of less than 90 sec. Although a major investment has been made in track reconstruction, upgrading the power distribution system, and vehicle acquisition over the past decade, the high-frequency, high-ridership nature of the system makes it difficult to maintain good service quality given the myriad disruptions in service that routinely occur. Until now the critical operations control function has been performed principally in the field by supervisors located at key points in the system deciding whether and how to intervene in ongoing operations. Currently an automatic vehicle identification system is being implemented for the Green Line that will eventually provide the opportunity to restructure the operations control process.

The performance of any transport system is most strongly influenced by its infrastructure and vehicles, the operations plan, and operations control procedures. In the short run, because infrastructure and vehicle characteristics cannot be changed because of the associated long lead times and high capital costs, improvements in performance are most likely to come through changes in the operations plan and through better operations control. The operations plan, which includes routes, service frequencies, and vehicle and crew schedules, should reflect typical operating conditions in terms of both demand characteristics and vehicle operating characteristics. Although a well-designed operations plan is essential for good system performance for any public transport service, in general it is rare that the plan is executed exactly because of inevitable major and minor events that disrupt operations. Dealing with these deviations from the operations plan is the function of the operations control process.

Operations control is the general description of actions that are determined dynamically, in real time, to minimize the negative effects of disruptions in operations and to maintain high service quality despite these unexpected events. Although operations control is necessary in any public transport system, its importance will vary depending on the frequency and magnitude of deviations from the operations plan. The Massachusetts Bay Transportation Authority (MBTA) Green Line is a high-frequency, highly constrained branching light rail system in which operations control is critical in determining system performance.

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MBTA GREEN LINE

The MBTA, the dominant public transport operator in the Boston metropolitan area, provides service on four major interconnecting rail transit lines, the Red, Orange, Blue, and Green lines, and on an extensive bus and commuter rail network. Of these four lines the Green Line, the major light rail line, provides perhaps the critical element in the whole system. It runs south then west from the Lechmere terminus to the branch termini at Boston College, Cleveland Circle, Riverside, and the Arborway, interconnecting with all three rapid transit lines. Thus the Green Line serves a vital collection and distribution function for the transit system as a whole, as well as providing the rail commuter network for the inner western suburbs (see Figure 1).

The Green Line has four branches, referred to as B, C, D, and E, that converge into a common central subway in the downtown area of Boston. The D Line is the longest line (only about one-half of the D branch is visible in Figure 1), its stops are spaced the farthest apart, and it is the only line operating on a fully reserved right-of-way. The B, C, and D lines meet at Kenmore station, whereas the E Line joins the central subway at Copley. Operation in street traffic results in running time uncertainty on the B and C lines especially, and to a lesser degree on the E Line, while the length of the D line also contributes to running time variation.

Within the central subway, turnback tracks exist at Park Street, Government Center, and North Station, providing some flexibility in both route design and real-time control actions for the different branches. The current Green Line operating route structure is as follows:

- B line—Boston College to Government Center,
- C line—Cleveland Circle to North Station,
- D line—Riverside to Government Center, and
- E line—Heath Street to Lechmere (the section from Heath Street to Arborway is closed for reconstruction).

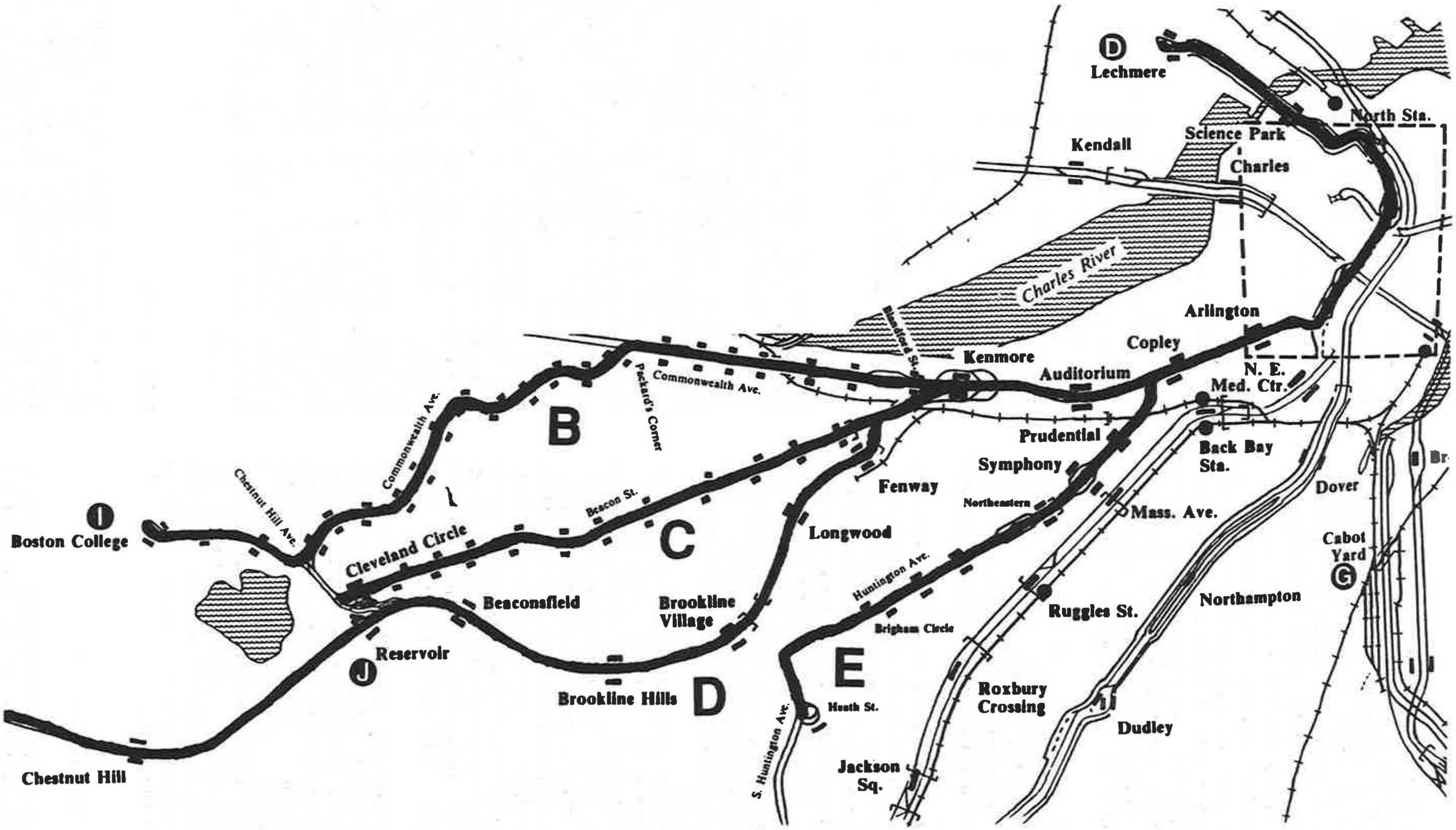

FIGURE 1 Green Line subway and branch lines (source: Boston Track Map, © 1986 Boston Street Railway Association, reprinted with permission).

North Station and Lechmere serve as termini for the C and E lines, respectively, and these lines have scheduled departure times at both ends. In contrast, B and D line trains in the central subway simply turn around at Government Center without any recovery time built in, because there is no place to store trains. Thus C and E line running time variation can be corrected at each end of the line, whereas inbound B and D variations, if left alone, propagate to the outbound direction because they are essentially dispatched from their western termini as loop systems. Park Street Station, the interchange point between the Red and Green lines and the highest volume station on the line, is particularly important because the Red Line frequently generates large surges in passenger volume, and much of the Green Line operations control is focused here.

The Green Line operates one- and two-car trains using articulated light rail vehicles (LRVs), at scheduled headways of 5 to 10 min on the four branches (see Table 1), which, when combined, produce central subway headways of 1 to 2 min for much of the day. These short headways are required to serve an estimated 189,000 daily riders.

The structure and ridership of the Green Line both create significant operations problems and afford (to some extent) the opportunity to intervene to correct these problems as (or even before) they occur. It is the combination of mixed street traffic, merging branch lines, passenger surges from connecting lines, low headways, and high ridership that presents a considerable challenge to Green Line management. The question is not whether to intervene to improve operations—the line requires constant monitoring and intervention—only where and how the intervention should occur to maximize benefits to the riders.

Before turning to the operations control function, it is appropriate to indicate to what extent actual operations correspond to the operations plan. Table 1 presents information on schedules and actual headways for a randomly selected day (January 20, 1988, the winter 1988 schedule) at the start of this study for each line by time of day at Boylston Street Station (northbound) in the central subway. Actual headways were derived from the log kept by the chief inspector stationed at Boylston. Mean headways may vary from scheduled headways because of trips not run (thus increasing headway) or two-car trains being run as two single-car trains (thus reducing headway).

Of particular interest is the standard deviation of the headway. Ideally the standard deviation would be at, or very close to, zero, indicating evenly spaced trains. As the table indicates, typical headway standard deviations are in the range of 4 to 6 min, or about 75 percent of the mean scheduled headways. This clearly suggests that passengers will see the service as being much less reliable than the schedule promises.

With such variation in headways, average passenger waiting times will be several minutes higher than the ideal case, and in a significant number of cases some operations control intervention may be appropriate.

TABLE 1 Headway Analysis for January 20, 1988

	Time Period		
Line	7 - 10 a.m.	10 a.m. - 3 p.m.	3 - 6 p.m.
B Line			
Scheduled Headway	5.0	5.0	6.0
Mean Headway (H)	5.3	5.2	6.1
Std. Deviation (H)	5.0	4.9	7.0
C Line			
Scheduled Headway	6.5	5.0	7.0
Mean Headway (H)	6.4	5.3	6.8
Std. Deviation (H)	4.0	3.7	5.5
D Line			
Scheduled Headway	5.0	5.0	6.0
Mean Headway (H)	5.8	5.1	6.8
Std. Deviation (H)	4.1	4.2	4.6
E Line			
Scheduled Headway	6.0	6.0	6.0
Mean Headway (H)	6.3	6.1	6.4
Std. Deviation (H)	4.0	2.7	5.0
Central Subway			
Mean Scheduled Headway	83 secs	78 secs	93 secs

OPERATIONS CONTROL OPTIONS

The general aim of operations control actions is to optimize system performance given the system state. Although system performance includes both the authority's and the passengers' perspectives, in the case of real-time decisions, effects on operating costs are likely to be relatively unimportant because the labor costs are fixed, except for possible incremental overtime payments as a result of delayed trips, and the incremental direct operating costs associated with different decisions should be small. From the passengers' perspective, however, there are likely to be effects on a range of service quality attributes, including passenger waiting time, riding time, and additional transfers required, and the issue of how to weight these in evaluating alternative actions is not trivial. In general, however, the aims of operations control intervention will be to minimize waiting and riding time for all passengers and to minimize the number of the passengers negatively affected (*1*).

Four types of control actions aimed at improving service quality can be made on the Green Line: holding a train, short-turning, expressing, and deadheading (*2*). Each of these actions is briefly discussed below with emphasis on the ideal scenario for making such a decision in the specific context of the Green Line. Because of the low Green Line headways, and the resulting assumption that passengers arrive at stations independent of the schedule, maintenance of even headways is a more appropriate proxy for service quality than is schedule adherence. Hence the control actions are analyzed in terms of rebalancing headways rather than correcting schedule deviations per se.

Holding a Train

Holding a train is the simplest operations control action, consisting of delaying a train in a station, usually when there is a short preceding headway and a long following headway. This reduces the headway variance and hence reduces passenger waiting time at all stations down the line. Within the

Green Line central subway, Park Street Westbound is the most common holding point because it is a double-tracked station with very heavy boardings. Because most of the Green Line is one track per direction, holding a branch train within the central subway at stations other than Park Street is likely to delay following trains of other branches, negating any benefit.

Holding selected inbound trains just before entering the central subway may be beneficial, especially in the p.m. peak (low inbound volume, high outbound volume) and avoids any inter-branch–line effects.

Short-Turning

Short-turning is the decision to turn a train before it reaches its terminus with the aim of reducing headway variance in the reverse direction by filling in a large headway gap (*3*). The ideal scenario for a short turn is to select a train with a low passenger load, a low preceding branch headway, a high branch headway further up the line (the large gap to be filled in the reverse direction), and a low following headway. In this situation a few passengers will be negatively affected by the short-turn (primarily those passengers forced to transfer to reach their destinations), but their additional waiting time will be small, and the benefit to riders in the reverse direction will be large. Short-turning, of course, can occur only where special turnback or crossover tracks exist. In the case of the Green Line, short-turning is the principal form of operations control with most short-turns involving northbound B and D line trains destined for Government Center being turned one stop early at Park Street.

Expressing

A decision to express a train reduces the number of stops for this train and hence also reduces running time and preceding headway beyond the express segment (*4*). Before expressing, affected passengers must be notified and allowed time to alight. The ideal scenario for an expressing decision is to have a long preceding headway, a short following headway, and high passenger load past the end of the express segment. In the case of the Green Line, expressing decisions are made occasionally, principally involving westbound trains in the central subway, such as from Park Street to Kenmore, but also on the surface portions of the network.

Deadheading

Deadheading (also known as running light) is similar to expressing except that no passengers are carried over the deadhead segment. To avoid forcing passengers to alight, deadheading is typically initiated at a terminus when there is a long preceding headway and a short following headway. Its principal advantage over expressing is that it does not require notifying passengers at the beginning of the deadhead segment, thus potentially reducing dwell time and passenger confusion.

CURRENT OPERATIONS CONTROL STRATEGY

In this section the current operations control strategy is described for short-turning, expressing, and deadheading. Holding is also used, principally at Park Street westbound, but is not documented and thus is hard to evaluate.

Short-Turning

The decision whether to turn trains at Park Street has traditionally been a "judgment call" by the Boylston inspector. Inspectors have not been expected to apply strict criteria, and different inspectors may make decisions differently, following their own sense of what will best maintain service quality. A skillful inspector will develop an ability to notice and keep track of several relevant pieces of information simultaneously and may or may not be able to explain his or her decision process. Years of practice result in a complex view of the problem that may not be easily reduced to a statement of the formal decision process.

According to Deckoff (*3*), "the best inspectors at Boylston appear to use evenness of westbound headways as the chief objective in deciding when to short-turn." If, for example, several B Line trains have bunched together over the course of their inbound trip and have a large headway gap preceding them, the Boylston inspector may short-turn one of them to reduce the size of the gap, thereby producing more even headways on the B Line outbound.

It takes some skill to achieve this objective. Even so, many of the passengers waiting on the outbound platform at Park Street will be destined to other stations within the central subway (63 percent in the morning peak period and 39 percent in the afternoon peak). These passengers will not be concerned about the branch line headway because they can take any train to reach their destination. Hence, a short-turn decision that benefits branch line passengers may not provide much benefit to passengers traveling only within the central subway. In addition short-turning reduces the level of service for passengers traveling in either direction between Park Street and Government Center stations. Thus between 10 percent and 24 percent of passengers on a short-turned train are likely to be forced to transfer at Park Street (the remainder would have alighted at Park Street in any case), while some passengers at Government Center westbound will have a longer wait.

Analysis of a week's worth of data recorded by the Boylston inspector in March 1989 showed that of 1,956 B and D line trains observed, 270 (16 percent) were short-turned at Park Street. In most cases short-turning resulted in reduced overall passenger delay (measured in total passenger minutes), but 26 percent of short-turns actually increased passenger delay. In other words, under the current decision process—which varies from inspector to inspector—one in four short-turn decisions leads to poorer system performance based on total passenger minutes.

Expressing and Deadheading

Like the short-turn decision, expressing and deadheading decisions are generally made by an inspector on the station platform, and the decision is based on his or her judgment without formalized rules. Although inspectors at fixed locations such as Park Street keep a record of their control decisions, express or deadhead trips ordered by field inspectors on the branch lines are generally not recorded and thus not available for evaluation.

An analysis was made of 2 weeks of records from Park Street inspectors for weekday rush hours (both a.m. and p.m.) during June 1989 (*4*). Inspectors will sometimes express a train from Park Street to Kenmore Station, and trains may be deadheaded to intermediate stations. During this period 64 decisions were recorded to express or deadhead a train from Park Street Station. Only 10 of these actions were to express a train; the other 54 were to deadhead. B and D line trains are also on occasion deadheaded the one stop from Government Center to Park Street. It is not surprising that deadheading is preferred by inspectors over expressing, because expressing requires public address announcements and induces delay and general disruption as passengers sort themselves out once the announcement has been made.

Some patterns were found in the inspectors' decision making. First, when two (or more) trains on the same line arrived consecutively at Park Street, one of the trains was usually deadheaded to separate them. It could be surmised that one of the simultaneously arriving trains is likely to have been short-turned. Second, when the preceding branch headway was very long (16 min or greater), deadheading was not used; trains would either be expressed or no action would be taken. In these situations large numbers of passengers are likely to be waiting for service, which makes deadheading less attractive because of the associated reduction in line capacity. Control actions were about twice as likely to be taken during the p.m. peak period when more passengers are destined for the surface portions of the branch lines, than during the a.m. peak.

INFORMATION FOR OPERATIONS CONTROL

The ability to make good operations control decisions depends heavily on the availability of accurate real-time information. These decisions are sensitive to train length, train positions, passenger loads, and the expected future positions of trains with and without the intervention, and to a lesser extent, passenger volumes at various stations, occurrences of delays or breakdowns, train schedule adherence, and train congestion at track switches (*3,4*).

The information needed can be obtained from a variety of sources, including direct observation, radio and telephone communication, computerized information systems, and, if necessary, analyzed historical data. Although using predicted values based on historical data is less desirable than using real-time data, it is possible, with careful attention to the resulting uncertainty, to generate information from historical data that closely matches actual data and is substantially superior to random guessing (*3,4*).

In the past Green Line operations control decisions have been based on communications among field personnel and personal observations, though more recently some of the analysis described in this paper has been used to formulate decision guidelines (see Figure 2 for an example). However, additional improvements in decision making are expected to result from the installation of a new automatic vehicle identification (AVI) system on the Green Line (*2,5–8*). This system, which is now operational, performs automatic routing of trains through track switches, records detailed information on train movements, and drives a model display board in the MBTA operations control center (OCC).

Green Line AVI System

The AVI system transmits train identification information from 33 detectors located at various points along the network to the MBTA control center (*6–8*). The information is transmitted from transponders mounted at each end of every vehicle, to the wayside detectors, to the central control computer, and then to both video terminals (text display) and colored lights on a model board.

When a train passes a detector, the central computer records the car number(s), route number, destination, detector location, and the time of detection. This information can be viewed on a video terminal and is used to indicate approximate train positions, color-coded by branch, on the model board.

Using AVI for Operations Control

The original intent of the AVI system was to provide automatic switching at track junctions and, to a lesser extent,

<u>B Line – During the AM Peak and Midday periods</u>:

- Both the preceding headways on the line are short: ≤ 1 minute each (i.e., three trains appear in a row -- turn the third one), or
- The preceding headway is ≤ 1 minute, but the second preceding headway was between 8 and 10 minutes, or
- The second preceding headway was 10 minutes or longer and the inspector can see the candidate train (in other words, after a ten minute gap, two trains show up at once -- in this case turn the second of the two), or
- The preceding headway is ten minutes or longer and the candidate's follower is not in sight. Note that in this case many passengers would be dumped.

<u>B Line – During the PM Peak Period</u>:

- The preceding headway ≤ 1 minute and the second preceding headway ≤ 3 minutes, or
- The preceding headway ≥ 8 minutes.

<u>B Line – During the Evening Period</u>:

- The first preceding headway is ≤ 3 minutes and the second preceding headway ≤ 1 minute, or
- The first preceding headway is ≤ 3 minutes and the second preceding headway is between 10 and 12 minutes, or
- After a 12 minute gap two trains show up at once, in this case turn the second train, or
- The first preceding headway ≥ 12 minutes and the follower is not visible.

<u>D Line – During the AM Peak, Midday or PM Peak Periods</u>:

- Short-turn if the previous headway ≥ 8 minutes.

<u>D Line – During the Evening Period</u>:

- Short-turn if the previous headway ≥ 10 minutes.

FIGURE 2 Proposed short-turning decision rules.

collect maintenance data. Although the system works as designed quite reliably, for other uses, such as operations control, the system lacks some features that might be helpful and possibly worth adding in the future. For example, the number of detectors is adequate for train routing, but not really sufficient for effective operations control. With the short headways on the Green Line, accurate train position information is needed to ensure good decisions, but the 33 detectors cannot provide the necessary resolution.

Secondly, the video display terminals show only sorted and filtered AVI transmissions, rather than information derived from the data, such as headways, which must be manually calculated. This restricts the ability of OCC personnel to monitor headways at multiple keypoints and anticipate problems. Lastly no related information is provided, such as schedule data, run number, or operator badge number, that might be helpful when analyzing, either manually or automatically, the AVI data for operations control purposes.

Although these factors limit the maximum use of AVI data for operations control, additional features could be added in the future to overcome these limitations. In addition the new AVI system does give OCC personnel a broad system level view of the Green Line and, through voice communications, assists existing line personnel with operations control decision making. Although future enhancements will likely expand the AVI system's role in operations control, current decision making will still rely heavily on direct observation and voice communication, but with the added element of the AVI-provided system level view.

APPLICATIONS

Green Line operations control is evolving from a decentralized, direct observation-based system to a more centralized, AVI-directed system, but for many reasons, including those discussed above, the transition will be gradual. Although more information is usually better than less, good decision making still can be achieved with many different levels of information as long as the accuracy and meaning of the information is well understood.

In this section the potential benefits of improved operations control, based both on applying decision rules with current limited information and decision making with more complete AVI information, are illustrated for the short-turn and express decisions.

Short-Turning

The short-turn decision of whether to turn, at Park Street, an inbound train destined for Government Center is made by the Boylston inspector based on experience and judgment without strict criteria being applied. Deckoff (*3*) investigated different decision rules for this short-turning decision with an objective of minimizing total passenger minutes of travel time, including both wait time and ride time, weighted equally. From examining a week's worth of Boylston inspector records, estimates of the passenger time effects resulting from a decision to short-turn or not to short-turn were made for each observed train, and these results were generalized to identify conditions under which an inspector could be confident that a short-turn decision would result in a net decrease in total passenger minutes.

Four groups of passengers are affected by a short-turn decision:

- Skipped segment alighters—those passengers bound for Government Center who would be dumped off a short-turning train (passengers destined beyond Government Center are not counted because they would need to transfer in any case);
- Short-turn point boarders—passengers waiting at Park Street for Government Center who would have boarded the short-turned train had it continued;
- Skipped segment boarders—passengers who, if the train had not been short-turned, would have boarded it at Government Center for a westbound trip, including passengers destined to the surface portions of the B or D lines who must wait for a train running on the appropriate line, as well as those with central subway destinations who can take any train; and
- Reverse direction passengers—those traveling westbound including both branch line and central subway riders.

The last group benefits from a short-turn decision, whereas the first three groups are inconvenienced. Because passengers bound for different destinations face different choices of trains, each group was further divided by destination. Headways were calculated between successive trains, and passenger accumulations for each group were estimated using accumulation rates derived from data collected in 1985 by the Central Transportation Planning Staff (CTPS). For each trip, passenger minutes of delay were calculated twice for each of the affected groups, once assuming that the train (and only that train) was short-turned, and the second time assuming that the train followed its regular route. A great deal of care was taken to account for cases in which vehicle capacity would be exceeded and passengers delayed until the following train.

Among the model inputs required to compute the passenger minutes saved (or lost) in short-turning each train are the various passenger accumulation rates, the headways of outbound C and E line trains, train lengths of the C and E line trains, and the number of minutes saved by short-turning. Not all these inputs are known by the Boylston inspector at the time the short-turn decision must be made for each train; the other variables are, from the inspector's point of view, essentially random. Therefore, the model uses randomly generated, normally distributed values for the unknown variables, based on observed values.

The most crucial and available items of information available to the Boylston inspector for determining the suitability of a particular train for short-turning are the headways preceding the candidate train on the same line. Passenger minute effects from the model were grouped according to the headways preceding each candidate train to determine the circumstances under which a train can be short-turned with roughly a 95 percent confidence that aggregate passenger travel times will improve. Given only the first and second branch preceding headways, it is proposed that trains should be short-turned in the circumstances shown in Figure 2.

These short-turning guidelines differ by line and by time period because of different passenger flow rates and different line service frequencies. For example, on the B Line in the morning peak and midday periods, a majority of outbound passengers are headed to destinations within the central subway, whereas during the afternoon peak and evening more passengers are bound for the surface portions of the line. Because it is the branch line passengers who benefit most, more liberal use of short-turning is justified when the branch passengers predominate.

In the morning peak period on the B Line, of the 146 cases examined, applying the proposed criteria, only 32 short-turns would have been performed as opposed to the 44 trains turned by the Boylston inspector during the week examined; yet the number of passenger minutes saved by short-turning was estimated to increase from 9,400 to 13,000 despite the smaller number of short-turns. Likewise, the "success rate," or the percent of short-turns that cause a reduction in passenger delay, was estimated to increase from 73.8 percent to 93.6 percent using the guidelines.

With implementation of an enhanced AVI system, additional information on which to base short-turn decisions would be available. Specifically knowledge of both C and E line outbound headways and of headways following the candidate inbound train should enable short-turn decisions to be made with greater confidence about the outcome. However, even in this case the outcome will still depend on unknown factors and unpredictable future events, and so there will still be a non-zero probability of a negative outcome. The analysis showed that incorporating this increased information would allow a greater use of short-turning than that suggested by the proposed criteria. Specifically during the a.m. peak for the week analyzed, some 43 short-turns would have been made, almost the same number as those actually made by the Boylston inspector, but with a much higher expected success rate (92.7 percent) and higher estimated passenger minutes saved (17,200 versus 9,400 min).

Thus in the case of short-turns it appears that although the existing real-time decision making based on limited information and experience results in substantial net passenger benefits, these benefits could be increased by about 40 percent through the application of more consistent decision guidelines without additional information and further increased by a similar amount through the use of more comprehensive AVI data.

Expressing

Macchi (*4*) developed a set of mathematical models to determine which strategies for expressing trains would result in minimizing total passenger travel time, again expressed in passenger minutes. These models were applied to the expressing decision in the p.m. peak period westbound from Park Street with the express segment ending at Kenmore.

Again, four distinct groups of passengers are affected by an expressing decision:

- Expressed passengers—those who remain on an expressed train—these passengers will have a reduced travel time,
- Passengers waiting downstream who will benefit if headway variance is reduced,
- Passengers skipped—this includes passengers who would have boarded the train had it made all stops, both those waiting at the station where expressing is initiated and those waiting at intermediate stations, and
- Passengers dumped—those passengers already on the train and bound for stations in the express segment—they must leave the train and wait for another.

Given passenger accumulation rates for each set of passengers (again based on 1985 CTPS data), preceding and following headways, and an expected time savings as a result of expressing, a set of equations were developed to predict the cost and benefit in passenger minutes that would accrue to each group because of a decision to express a train. By summing the effects on the four groups, total net benefits to passengers of a decision to express were calculated.

The expected time savings is defined as the express segment travel time if the train is not expressed minus the express segment travel time if it is expressed. Both travel times include station dwell times. Because the time savings is defined as a travel time difference, if the travel time for the nonexpressed train would have been longer than usual [as a result of long dwell times as passengers squeeze on and off the crowded car and jam into the door wells (*9*)], the time savings from expressing can, in fact, be greater than the preceding headway.

Assuming a 1.5-min preceding headway (the headway between the express candidate train and the nearest preceding train) and a 2-min time savings for expressing, the model indicated that expressing would produce net benefits over a 250 passenger minute threshold on the B Line in the p.m. peak period in the circumstances indicated in the top half of Figure 3. Assuming instead a preceding headway of 3 min and a 4-min time savings, the model shows expressing to be beneficial for almost any above average preceding branch headway, given that the following branch headway is not greater than average (see bottom half of Figure 3). Comparing the net benefit tables produced by the expressing model under these two sets of assumptions shows the staircase pattern in the latter table to be steeper, indicating that confidence of a good decision increases when the preceding any-line headway is longer and the time savings is increased.

The same model was applied to the C and D lines during the same period and under the same two sets of assumptions. Again the net benefit tables formed a staircase pattern that was steeper in the case in which the previous headway was longer and time savings greater, but the benefits produced by expressing were greatest on the B Line, and least on the C Line, with the D Line in between—roughly proportional to the passenger volumes on each line.

Initially, the expressing models did not account for limited passenger capacity on any train, although given a long preceding branch headway, a train is likely to be crowded if not crush-loaded. In this case the cost of expressing to passengers waiting at intermediate stops is zero, because, as a result of capacity limitations, they could not have boarded the train even if it had made all stops. Likewise, the number of passengers who can ride the express train is limited to available capacity.

Incorporating capacity constraints into the B Line model, when the previous branch headway exceeds 12 to 16 min, beneficial expressing decisions can be made with significantly longer following branch headways than before, and expressing will virtually always be beneficial when the previous branch headway exceeds 18 min. The results indicate that expressing based on expected values may be warranted when train capacity is likely to be constraining, and it will not always be necessary to know the following headway to almost guarantee that the express decision will be beneficial.

The subject of deadheading trains was investigated only briefly, but the trade-offs are relatively straightforward. Deadheading a train, rather than expressing it, results in less delay and confusion for passengers and is easier for inspectors. But it shifts one group of passengers from being positively affected to being negatively affected: those who would have benefitted by riding the express train must instead wait for the next train as do skipped passengers.

The results of the expressing model were compared with current practice as observed from 2 weeks of Park Street inspectors' reports for weekday a.m. and p.m. peak periods during June 1989. As described earlier, 64 control actions were taken by inspectors during this period: 54 trains were deadheaded and 10 expressed. Of these, 10 were likely to have been good decisions according to the expressing model, 12 were likely to have been bad decisions, and the remainder

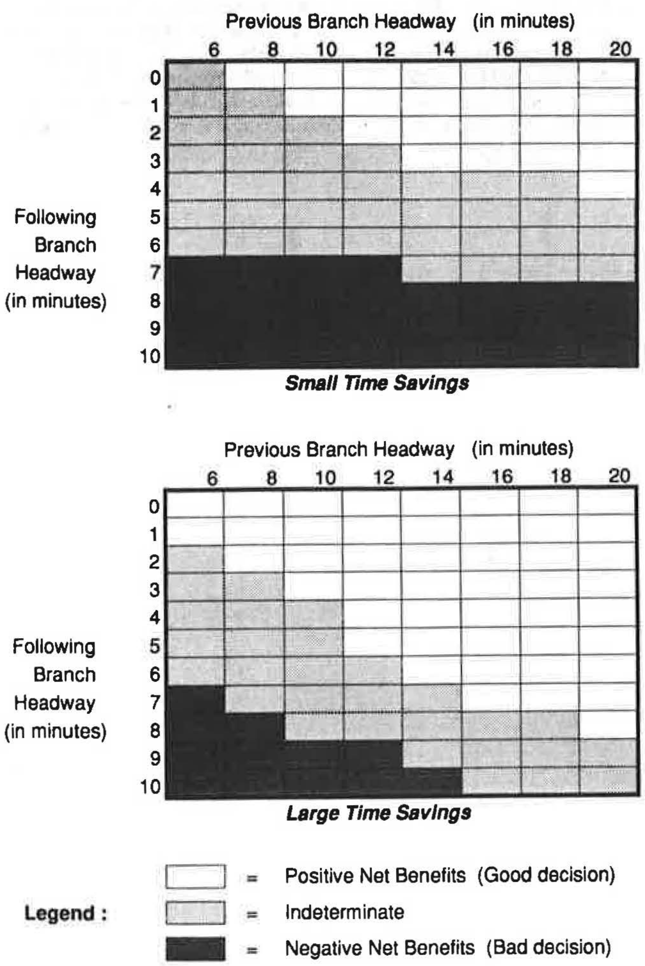

FIGURE 3 Benefit regions: B Line p.m. peak express decision—small and large time savings.

(42) were probably slightly beneficial. A decision to deadhead a short-turned train that arrived simultaneously with another train on the same branch line, given an average (or less) preceding branch headway, would be an example of the "slightly beneficial" category. Looking at expressing actions separately, of the 10 express actions taken, 4 were probably good decisions, 4 probably bad, and 2 slightly beneficial. The bad express decisions were typically characterized by 5- to 8-min preceding branch headways possibly with blocking trains ahead, and an average following headway. It is not clear why these actions were taken.

Again using the same 2 weeks of data, there were 45 instances in which a B, C, or D line train entered Park Street with a 12-min, or greater, preceding branch headway. In these instances, inspectors took action in eight cases, sending three trains light and five express. All of these actions would have been recommended by the expressing model. In addition, the model would have strongly suggested one more express trip and moderately recommended taking action in 31 other cases. So although the situations in which action was taken were also situations in which the model most strongly recommended action, the model suggests greater use of expressing in some more marginal cases in which the preceding branch headway is long. But of the 45 trips with preceding headways exceeding 12 min, 10 had following branch headways of 6 to 9 min, so the risk of a bad decision is not insignificant.

As with short-turning, express decision making could be greatly improved with the information that would be available given full AVI system implementation. The express decision is sensitive to the time savings and the neighboring headways, and AVI could provide the headways and an estimation of the probable time savings. Much of the ambiguity in the model analysis of the 45 instances of headways of at least 12 min results from the uncertainty of the external conditions—the records kept do not provide a complete and precise picture. By using the AVI system as the source of the important variables, much improvement could be made in decision making. In fact the AVI system, by recording the running times from Park to Kenmore of expressed trains, could be used to derive an empirical formula for time savings estimation, which in turn could be used in future express decisions.

The AVI system could be used not only to help make decisions, but to make them sooner, such that when a B or D train is at Government Center, passengers there could be notified that the train will be expressed from Park, minimizing annoyance. More importantly, Government Center passengers waiting for a B or D train could be told to take any train to Park, when a combination short-turn and express is planned. To do this properly, significant coordination is required: short-turn decision at Boylston, Government Center passengers notified to travel to Park, and passenger notification and coordination of other trains at Park Street. This requires both a central line controller to coordinate personnel and an information system to relieve the controller of time-consuming data analysis. Only with a very effective AVI system is such a scenario possible.

CONCLUSIONS

Currently the MBTA uses a decentralized operations control system on the Green Line, relying principally on the judgment and experience of field inspectors to decide when to hold, short-turn, express, or deadhead trains. The outcomes of these decisions are subject to great uncertainty because of lack of information about some critical inputs, most notably following headways. Analysis of short-turning and expressing decisions suggests that although most current decisions are beneficial, a minority result in worse overall performance. Decision guidelines were developed that can be applied with the current limited information and to improve the operations control function significantly.

An AVI system has now been implemented on the Green Line and holds the promise to improve substantially the information base for operations control. Although the initial AVI system will have some significant shortcomings as an operations control instrument, particularly in terms of processing the AVI data into information suitable for a controller to assimilate, the additional information will eventually result in better real-time control decisions, and better service to passengers.

The type of analysis presented here would be directly applicable to other high-frequency transit systems that routinely experience headway variability. Examples that come readily to mind are the branching light rail networks in San Francisco and Philadelphia. Analyses can be used both to evaluate the effectiveness of current operations control practices and to estimate the benefits of installing an AVI system in terms of improved operations control.

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Practical Limits of Single-Track Light Rail Transit Operation

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Increasing urban traffic congestion continues to stimulate interest in exclusive rights-of-way for new transit projects. Today's increased concern with cost-effectiveness, however, has focused attention on light rail transit (LRT) and other transitway technologies that are less capital-intensive than traditional heavy rail rapid transit. For these systems, planners have sometimes turned to single-track operation. Such operations have their limits, however. A planning-level method can identify whether single-tracking is appropriate for a particular application. The spacing and length of passing tracks depends on a number of factors, primarily the scheduled headway and the variability in vehicle travel time. Generalized design conditions, analogous to some levels of service can be considered in terms of maximum running times over single-track sections. For situations in which single-track operation is found to be feasible, the effects of additional practical considerations can be explored. Guidelines can help determine whether these practical considerations are likely to invalidate a solution originally determined to be feasible. Modern LRT and traditional street railways can also be compared in terms of the defined conditions.

Increasing urban traffic congestion continues to stimulate interest in exclusive rights-of-way for new transit projects, including high-speed commuter rail and rapid transit systems. Today's increased concern with cost-effectiveness, however, has focused attention on transitway technologies that are less capital-intensive than traditional forms. These include light rail transit (LRT), other guideway-based technologies, and busways. When the available right-of-way width is constrained by cost, physical obstacles, or other factors, planners have turned to single-lane or single-track operation to avoid the constraints. Single-track operation has its limits, however. A planning-level method can identify whether single-tracking is appropriate for a particular application.

SINGLE-TRACK APPLICABILITY AND PRINCIPLES

It should be noted at the outset that the use of railroad terminology is not intended to suggest that the techniques proposed are appropriate exclusively for rail vehicles. The terms are generally transferable to other guideway-based systems. The techniques are intended to be applicable to busways as well; when each "railroad" term is first used, a substitute term applicable to busways is either shown in parentheses, or a definition of the term applicable to bus operation is presented.

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When traffic density is low enough, a single-track (lane) main line with appropriately located passing tracks (sections of two-lane roadway or two dedicated parallel single-lane roadways) can accommodate bidirectional operation with little or no delay. Vehicles running in opposing directions pass each other on double-track sections; these "meets" may require one or both vehicles to reduce speed or stop. As the frequency of operation increases, delays increase as well up to a point at which they become unacceptable, and a full double-track system is warranted.

Safe operation on single-track sections requires positive control of access. Railroad signaling technology has provided such control for decades, using the proven techniques of block signaling and interlocking logic. For a single main-line with passing tracks, control points at each end of each passing track are established to control access to the single track. The operation of signals and track switches is often electrically interlocked to ensure safe operation (e.g., to prevent the simultaneous display of signals to trains in opposing directions). Control points so equipped are generally referred to as interlockings.

The nearest common highway analogue to such operation is the use of traffic signals to control access to single-lane bridges, underpasses, and temporary work zones; in these cases, a single traffic signal controller ensures that conflicting signals are not displayed. Unlike railroad interlockings, however, these systems rely on the passage of time from the beginning of a red signal as the basis for an assumption that the single-lane section has cleared. The lack of a positive indication of block occupancy limits the applicability of this approach to sections that are entirely within line of sight from both control points.

The recent trend toward cost-effective rapid transit, however, has led to the development of bus presence detection technologies that can effectively function as signal systems. Elements of these technologies are already in service in a joint bus-LRT exclusive transit tunnel in Pittsburgh and in Germany. Busway planners should not, therefore, necessarily avoid single-lane sections.

ANALYTICAL MODEL OF SINGLE-TRACK OPERATION BETWEEN MEET POINTS

Techniques can be used to examine characteristics of a single-track section between specific meet points or to assess route-wide requirements.

Major Assumptions

The location and length of passing tracks depends on a number of factors. On North American railroads these generally include acceleration and braking characteristics; horizontal and vertical alignment; differences in train operation by direction; type of signal system; acceptable delays; train priorities; and train frequency. In a transit application, a number of simplifying circumstances are generally present, and were incorporated in this analytical model. They are as follows:

1. Vehicles have similar performance on successive trips in the same direction.
2. Service is scheduled on a fixed headway (i.e., the time interval between successive vehicles is constant).
3. All vehicles have the same priority.
4. Signal systems are optimized for the particular vehicles operating on the line.
5. Use of the single-track sections is on an alternating basis (i.e., successive occupancies of the block are by vehicles traveling in opposing directions).

Analytical Framework and Definitions

The analytical technique of the model is built around the concept of a "design early vehicle" and a "design late vehicle." The technique allows for estimation of passing track lengths for three basic design conditions. These are intended to approximate levels of service in the sense popularized by the 1965 and 1985 editions of the *Highway Capacity Manual*. These design conditions are as follows:

1. Condition B, under which there would be little or no delay to vehicles in either direction under normal operating conditions;
2. Condition C, under which some vehicles leaving double-track sections would be delayed, but few would be required to come to a complete stop; and
3. Condition E, under which all or most vehicles would experience delays waiting to enter single-track sections, but it is still possible to move the required traffic.

In the author's opinion, it is inappropriate to identify a design Condition A for systems employing single-track sections. Operating conditions analogous to highway Level of Service A (e.g., "individual users are virtually unaffected by the presence of others" and "extremely high freedom to maneuver" (*1*, pp. 1–3) can only be approached by an entirely double-track system.

Given the assumptions above, it is possible to analyze a single-track operation to determine what the primary factors are controlling the maximum single-track length. Figure 1 is a diagram of a typical bidirectional transit operation in what is usually called "stringline" form. With time on the horizontal axis and location on the vertical, the trajectories of individual vehicles in motion appear as lines or curves with non-zero slope; station dwell times have zero slope.

Figure 1 shows the on-time operation of two succeeding vehicles in each direction; the vehicles have been designated

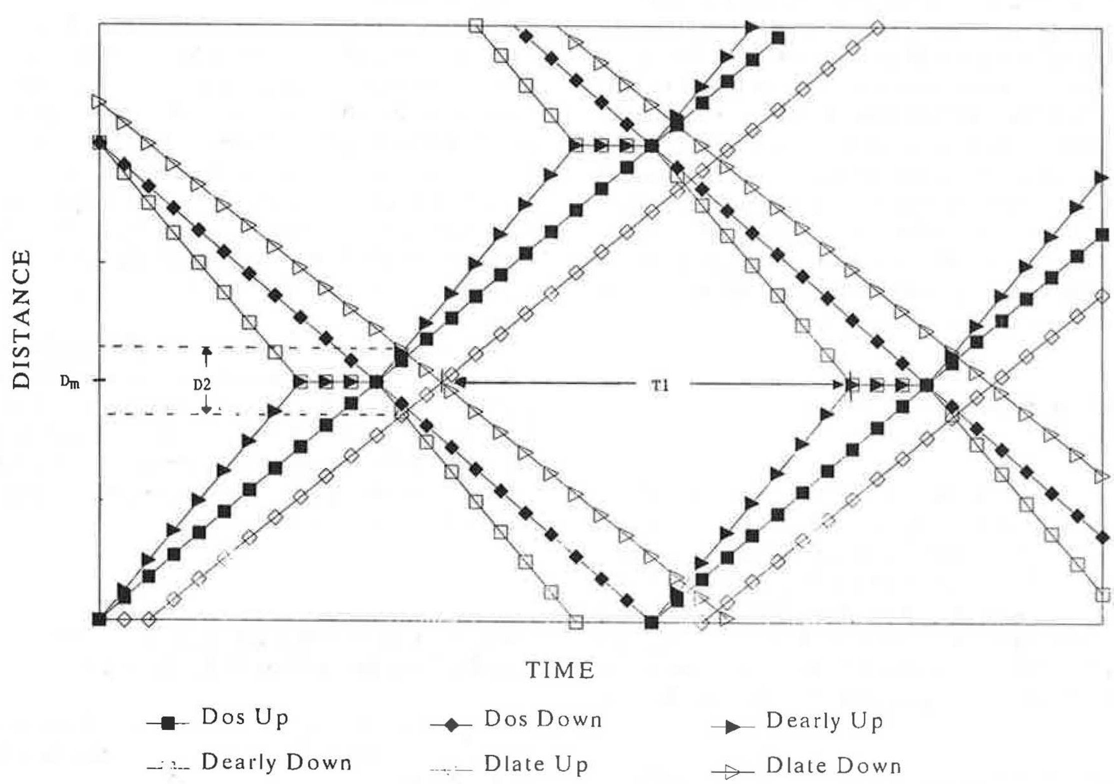

FIGURE 1 Stringline diagram.

"up" and "down," which will appear as superscripts to distinguish terms applicable to each direction. The stringline trajectories for the leading vehicles shown on this figure are defined as follows:

$Dos^{up}(t)$ = location of head (front end) of an on-time upbound vehicle at time t, and

$Dos^{down}(t)$ = location of head of an on-time downbound vehicle at time t.

The trajectories for the following trains are shown separated by the scheduled headway, H. Points at which the scheduled upbound and downbound trajectories intersect are the meet points, or centers of double-track sections. These are normally separated in time by one-half the scheduled headway (i.e., $H/2$).

Figure 1 also shows trajectories for design early and design late vehicles in each direction. These are the trajectories that govern the extent of double-tracking that should be provided. The double-track length, $D2$, around a meet point must be sufficient for the design early vehicles in each direction to pass each other on double track, and for the design late vehicles in each direction to do likewise. The scheduled running time over the single-track section, $T1$, is also shown.

To simplify the model, the following assumptions are made:

1. Trains arriving early at meet points will depart on time. Although this is not strictly true in all cases, most transit operations do have time points at which vehicles may be held to regain schedule. Some railroad operating rules actually prohibit early departure from stations.
2. The design late vehicle will accumulate lateness from the beginning of its trip to the meet point. Unlike an early vehicle, which can be returned to schedule by holding, it is relatively difficult for a late vehicle to recover schedule.

Single-Track Limitations—Conditions B and C

In Figure 1, the following trajectories are indicated:

$D^{up}_{early}(t)$ = design early trajectory for the head end of upbound vehicles,

$D^{up}_{late}(t)$ = design late trajectory for the head end of upbound vehicles,

$D^{down}_{early}(t)$ = design early trajectory for the head end of downbound vehicles, and

$D^{down}_{late}(t)$ = design late trajectory for the head end of downbound vehicles.

From Figure 1 it is now possible to describe the maximum allowable scheduled single-track running time. This is evaluated at the meet point (Dm on the vertical axis). The governing late vehicle is the one which passes the point later in time. The design lateness, Tlate, at the meet point is as follows:

$$T^{meet}_{late} = \max\left(T^{down}_{late}, T^{up}_{late}\right) \quad (1)$$

where

$$D^{down}_{late}\left(T^{down}_{late}\right) = Dm \quad (2)$$

and

$$D^{up}_{late}\left(T^{up}_{late}\right) = Dm \quad (3)$$

Through a similar process, the design early time can be identified:

$$T^{meet}_{early} = \max\left(T^{down}_{early}, T^{up}_{early}\right) \quad (4)$$

where

$$D^{down}_{early}\left(T^{down}_{early}\right) = Dm \quad (5)$$

and

$$D^{up}_{early}\left(T^{up}_{early}\right) = Dm \quad (6)$$

The above quantities are critical to the analysis. For convenience, their sum is designated as the critical time, T_{crit}:

$$T_{crit} = T^{meet}_{early} + T^{meet}_{late} \quad (7)$$

Two additional steps must be taken before defining solutions. First, because the trajectories defined are for the head ends of vehicles, a deduction from the remaining time must be made for passage of the early train:

$$T_{pass} = L/V \quad (8)$$

where L is the vehicle length in meters and V is the operating speed through the control points in meters per second.

A second allowance, T_{clear}, is required for operation of the signal system protecting the single-track section. The system must recognize that the block is clear, perform any conflict checks required, and display the signal for the opposing direction. If the operation is dispatched manually, an allowance must also be included for dispatchers who may not immediately recognize that display of a signal is required; this is usually only true for commuter or intercity railroad operation.

With the above adjustments, the time value for Condition C is obtained by subtraction as follows:

$$T^{C}_{1} = (H/2) - T_{crit} - T_{pass} - T_{clear} \quad (9)$$

Derivation of a value for Condition B requires an additional allowance of time for the following vehicle to decelerate to a stop from the authorized speed; this is denoted as T_{stop}. Therefore

$$T^{B}_{1} = (H/2) - T_{crit} - T_{pass} - T_{clear} - T_{stop} \quad (10)$$

The maximum single-track time T_1 can now be seen to be dependent primarily on both the scheduled trajectory of vehicles, the headway H, and the inherent variability in operating time, as represented by T_{crit}.

Estimation of T_{crit} for Conditions B and C

The model's technique for estimating T_{crit} is based on several underlying premises:

1. For any particular type of vehicle, there is a minimum "dead time" at stations, designated T_0, which is not available for loading passengers. This includes the time required for door operation, brake release, and so forth. This is supported both by data collected by the author (*2*) and the "lag time" referenced in the 1985 *Highway Capacity Manual* discussion of transit capacity (*1*, pp. 12–20).
2. The passenger service time is proportional to passengers boarding and alighting.
3. Passenger boarding times for individual passengers are statistically independent.
4. Passenger boarding times at successive stations are statistically independent.
5. Successive vehicle run times between stations are not statistically independent. At least two major mechanisms for dependence can be identified: first, operators are generally aware of whether they are early or late and can often take measures to compensate; second, transit schedulers often build in schedule recovery time to account for variations.
6. For successive trains, the distributions of both run times between stations and of station passenger service service time exhibit a characteristic asymmetrical probability distribution function. The following equation was estimated by a least squares fit to a cubic polynomial to generate simulated run or dwell times:

$$T_{sim} = T_{min} + T_{var} * (3.15*R - 6.2*R**2 + 5.75*R**3) \qquad (11)$$

where

T_{sim} = a randomly occurring value of a time to be simulated,
T_{min} = a minimum observed or possible value for the time to be simulated, presumed to be invariant (e.g., T_0),
T_{var} = a variable component of time, computed as the difference between the mean value of T_{sim} and the value of T_{min}, and
R = a randomly generated number with a uniform probability distribution, ranging between 0 and 1.0.

Based on the above premises, an expression for estimating the earliest likely arrival relative to the timetable, assuming an on-time departure from a point from which the timetable shows a travel time of T_{ref}, was constructed:

$$T_{early}(T_{ref}) = \{6.25*[Fd*T_{ref} - N*T_0] + 0.0004*[(1 - Fd)*T_{ref}]**2\}**0.5 \qquad (12)$$

where

T_{ref} = the scheduled travel time upstream of the meet point. For late vehicles, this is the total travel time from the upstream terminal; for early vehicles, it is one-half the headway (i.e., $H/2$),
N = number of station stops within scheduled travel time T_{ref} upstream of the meet point,
Fd = fraction of T_{ref} that is scheduled station dwell time, and
T_0 = station stop dead time for the particular equipment and station configuration under analysis.

Equation 12 implies that, for planning purposes, an amount equal to 1.7 times the early allowance would account for late operation not resulting from equipment failure or other major occurrences. Therefore

$$T_{late}(T_{ref}) = 1.7 * T_{early}(T_{ref}) \qquad (13)$$

Development of Basic Input Parameters

Application of the model described above for any proposed meet point requires the following information:

- H, the design headway,
- T_{clear}, the signal clearance time,
- T_{stop}, the vehicle stopping time (for Condition B),
- Fd, the scheduled station dwell time as a fraction of total scheduled time,
- T_0, the station stop dead time, and
- T_{pass}, the time required for an entire vehicle to pass a control point.

The design headway is strictly a user input. The values for T_{clear}, T_{stop}, T_0, and T_{pass} should, where possible, be derived from the actual operating characteristics (e.g., speed, braking characteristics, and vehicle lengths) of the proposed transit service. For planning-level feasibility assessments, however, an assumed value may be desired. Table 1 provides suggested typical values for these parameters, assuming commonly found operating characteristics for each of several modes. It is strongly recommended that values for *Fd* be specifically estimated for the particular operation under analysis; in the case of bus operations, considerable guidance is available from the *Highway Capacity Manual* (*1*, pp. 12–19); in principle, these techniques are also probably valid for LRT systems using low-platform stations. For high-platform stations and railroad op-

TABLE 1 Typical Model Parameters for Various Transit Modes

Parameter	Busway	LRT	HRT(1)	Railroad(2)
Tstop (seconds)	25	25	30	45
Tclear (seconds), manual dispatching	25	25	25	35
Tclear (seconds), automatic dispatching	6	8	8	10
To (seconds) "dead time"	3	5	8	15
Tpass (seconds)	1	3	10	10
Fd, ratio of dwell time to travel time (3)	0.25	0.25	0.30	0.20

(1) "heavy" rail rapid transit
(2) Diesel locomotive with passenger coaches
(3) Derivation of application-specific values for Fd is strongly recommended.

erations, dwell time is highly dependent on vehicle door configuration and other factors; the values for these modes in Table 1 represent approximate averages only, and should be used with caution.

Single Track Limitations—Condition E

In most cases it is possible to decrease the extent of double-tracking implied by Conditions B or C and continue to provide service on a fixed headway. There is, however, a maximum single-track occupancy time which can be scheduled for a given headway, assuming each trip through the single-track section follows one in the opposing direction. Values of T_1 above this limit, designated as Condition E, or capacity, will result in either accumulating delays or the need to "fleet" (i.e., dispatch more than one vehicle at a time in the same direction through single-track sections). This limit is as follows:

$$T_1^E = (H/2) - T_{\text{clear}} - T_{\text{pass}} \tag{14}$$

EXTENSION OF MODEL TO ROUTEWIDE ANALYSIS

Assumptions and Methods

The model described above can be extended to complete lines or routes by suitably defining the variables to be representative of an average or typical condition. To do this, the following assumptions were made:

1. For a given mode, the location-specific default values from Table 1 for the model parameters would apply.
2. The value of T_{crit} will, on average, grow as the square root of distance from the terminal. This implies that the value any point will be the larger of two values (see Equation 1), one proportional to the square root of the value from each terminal.
3. T_{ref} for design early trains will be $H/2$.

An electronic spreadsheet was developed to calculate location-specific values for T_{crit} according to Equations 1 through 7, and was then exercised for a wide range of relative locations along routes of various length for each set of modal parameters. Functions proportional to the square root of relative location were then fitted to the results via linear regression. Based on the coefficients of these functions, standard curves for various values of Fd were developed, as well as mode-specific adjustment factors.

Application of Routewide Technique

The most convenient form for using these results requires successive use of two sets of curves, or nomographs. The first set, appearing as Figure 2, represents a typical value for T_{late} (see Equation 1). This value depends primarily on the one-way scheduled travel time along the line (T_{ref}) and the route-wide average dwell time ratio (Fd). A mode-specific adjustment factor is also provided. A second curve, appearing as

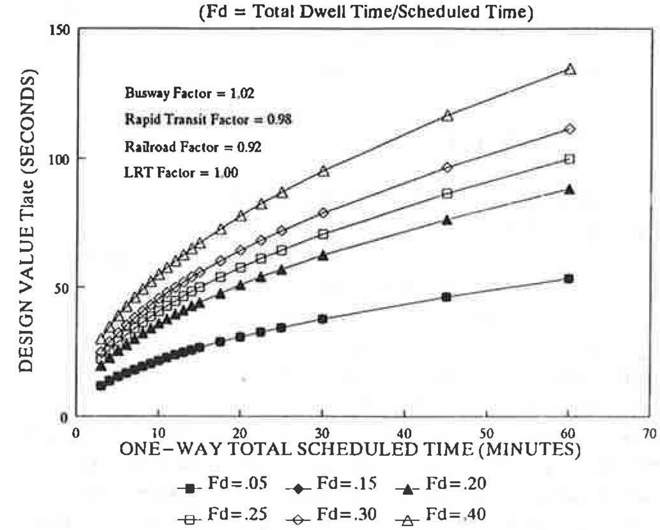

FIGURE 2 Routewide assumptions for T_{late}.

Figure 3, allows the effect of the headway H on T_{early} (as specified in Equation 4) to be considered, and therefore the effect on T_{crit}. This curve provides a factor by which T_{late} can be multiplied to provide a value for T_{crit}.

Once T_{crit} is determined, the equations governing T_1 for Conditions B and C (Equations 10 and 9, respectively) can be applied. Equation 14 remains applicable for Condition E, and does not require use of the nomographs.

VALIDATION AND COMPARISON WITH ACTUAL SYSTEMS

The techniques described have been compared with both present and historical North American rail systems. Table 2 com-

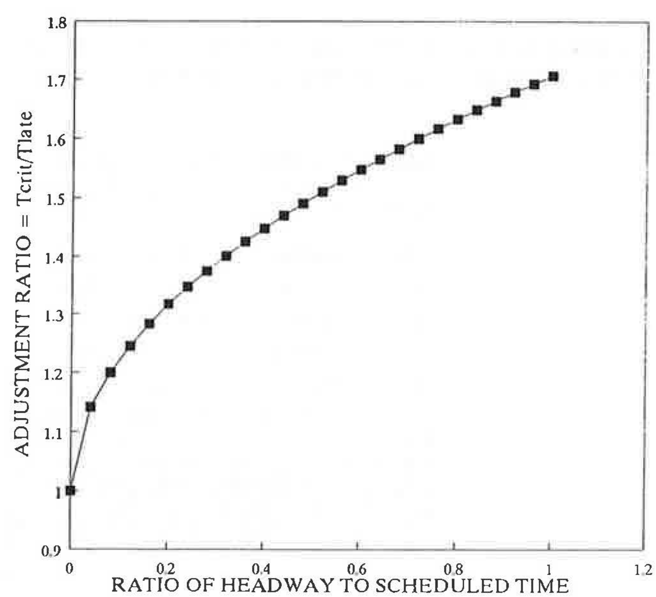

FIGURE 3 Estimation of T_{crit} from T_{late}.

pares key parameters and T_1 values, derived for selected current systems with single-track sections, using the routewide method described above, against actual values.

Segment-Specific Data

The data in Table 2 suggest that the technique described in this paper is indicative of the actual performance of the routes or branches represented. Operation of the LRT starter line in Sacramento and the Needham commuter rail branch line are generally satisfactory for the scheduled headways; these systems are indicated as being in the range of Conditions B and C. The Media and Sharon Hill LRT lines (in metropolitan Philadelphia) were studied by Transportation and Distribution Associates (TAD), Inc., in 1987. TAD's report (*3*) concluded that the single-track operation on Sharon Hill (approximately Condition C according to the model) was acceptable, but that the Media Line (approximately Condition E) required improvement. Pittsburgh's single-track 2-km Drake extension, which is similar to the Philadelphia lines in that the single-track section lies entirely at the outer end of a route, is scheduled at less than capacity. Of some interest is the Overbrook segment of Pittsburgh's South Hills LRT, which operates a section of single-track midroute with frequently spaced short passing tracks. As of 1987 the Port Authority Transit (PAT) was actually operating this segment over its capacity (i.e., Condition E) by "fleeting" two or three trains at a time in one direction.

System or Routewide Data

A second indication of the general validity of the model is provided in Figure 4. In this graph, the vertical axis represents the ratio of physical track kilometers to route kilometers for a particular light rail system or route. The horizontal axis represents the actual or estimated average number of trains per hour per direction. Six sets of information are shown on Figure 4:

1. Points represent those North American LRT routes operating with at least some single-track as of 1989, according to a recent survey conducted by the Institute of Transportation Engineers (*4*). They are labeled individually.
2. Points represent *systemwide* average values for street railway companies operating in Massachusetts in 1916, according to a Public Service Commission report (*5*). Average frequencies were estimated based on reported fleet size and typical operating speeds.
3. Values represent Condition B, according to the model, from the default parameters assuming that the fraction of single-track length would be proportional to the fraction of single-track time.
4. Values represent Condition C under assumptions similar to No. 3 above.
5. Values represent Condition E under assumptions similar to No. 3 above.
6. A straight line represents a fit to the 1916 data.

Several interesting conclusions can be drawn from Figure 4: First, on a routewide basis, all the recently constructed LRT systems with single-track sections appear to be able to meet Condition B. Second, with the exception of PAT's Drake extension, all existing single-track operations appear to at least meet Condition C. Third, the points representing 1916 operations suggest that the private companies of that era designed to a fairly consistent practice lying somewhere between Conditions C and E. This might almost be regarded as a de facto condition D.

Condition D—Historical/Empirical

Based on the discussion in the previous two sections, it may be appropriate to add the concept of Condition D to the set of conditions that can be evaluated. This is probably a more realistic practical upper limit than E, even though it cannot be directly derived from the analytical method. Given the statistical fit to historical data, however, it can be estimated once the other T_1 values have been calculated according to the procedures described above:

$$T_1^D = 0.66 * T_1^C + 0.39 * T_1^E \qquad (15)$$

TABLE 2 Comparison of Actual Designs and Model Results

System	Line	Tref	H	Fd	Tcrit	T1/"B"	T1/"C"	T1/"E"	Actual T1's
MBTA(1)	Needham	2400	1500	0.21	104	542	582	686	555
SEPTA(2)	Sharon Hill	1330*	900	0.20*	85	334	354	439	360
SEPTA(2)	Media	1440	900	0.22	90	329	349	439	420
SDTA(3)	Starter	3240	900	0.30	145	269	294	439	240,285,310,325,325
PAT(4)	Drake	2340	1260	0.25**	90	504	529	619	240
PAT(4)	Overbrook	2400	240	0.25**	100	(16)	9	109	N/A

(1) Based on field observations by author
(2) Data from Media/Sharon Hill Productivity Study, Transportation and Distribution Associates, Inc., for Southeastern Pennsylvania Transportation Authority (SEPTA), April 1987.
(3) From "Light Rail Transit X-T diagram" dated March 7, 1983, for Sacramento Transit Development Agency, by Foster Engineering, Inc.
(4) Port Authority Transit (Pittsburgh, PA) public timetables effective 1987.

* Estimated value based on station spacing vs. Media
** based on default values from Table 1.

Security for Los Angeles Metro Blue Line

Louis Hubaud

The Metro Blue Line is a 22-mi light rail system that operates through three cities and unincorporated areas of Los Angeles County. The line was designed and constructed by the Los Angeles County Transportation Commission (LACTC) and is operated by the Southern California Rapid Transit District (SCRTD). The Blue Line is in one of the highest crime areas of Los Angeles County. Early on, LACTC recognized the importance of providing for effective security in the design, construction, and operation of the system with features such as communications, fare collection, security hardware, closed circuit television, parking policies, open stations, lighting, fencing, and security studies to determine staffing levels. During construction, contractors were required to maintain secure work sites by using lights, fencing, locks, roving guards, and security patrols. The contractors were also required to keep the work site and property free of graffiti. As LACTC assumed responsibility for completed works, security levels were increased with the cooperation of the local police departments and by contracting with the Los Angeles County Sheriff's Department, Los Angeles County Safety Police, and private security guard services. When prerevenue testing began, security levels were increased again. The SCRTD board of directors elected to contract with the Los Angeles County Sheriff's Department to provide police services for the revenue operations. By using the sheriff's department, the board believed that perceived and actual security levels for the line would be maximized. To date few security-related problems have occurred. Sheriff's deputies are highly visible on station platforms and on trains, and the high level of security has served to discourage criminal activity on the line.

In late 1982 the Los Angeles County Transportation Commission (LACTC) began its planning process for the Long Beach–Los Angeles rail transit project, since named the Metro Blue Line, with detailed route evaluation and environmental studies. In early 1985 LACTC approved the start-up of the project, and detailed design work commenced. Property acquisition and preliminary construction activities were started later in 1985. The line was opened for revenue service in July 1990.

The total route, shown in Figure 1, is approximately 22 mi long; about 15 mi follows an existing Southern Pacific railroad right-of-way. Much of the line's route is the same as the last line operated by the Pacific Electric Railway Red Cars, which ceased operation in 1961. The Blue Line includes 22 stations and incorporates conventional light rail vehicles (LRVs) powered from overhead electrical catenary wires. After 1 year's operation, the line's average daily ridership is approximately 30,000 passengers.

Since the inception of the Blue Line project, LACTC has been aware of the potential for problems associated with the security. It was recognized that portions of the line would operate through some of the historically highest crime areas in the Los Angeles region and that the security of the patrons, employees, equipment, and facilities must be a primary concern throughout the design, construction, and operation of the system.

Rail Construction Corporation, 818 W. Seventh Street, Los Angeles, Calif. 90017.

Generally the Blue Line runs through areas with average to high crime rates. Nearly half of the Blue Line runs through areas with high crime rates, from the Artesia Freeway/S.R.-91 north roughly to Firestone Boulevard, then from Slauson Avenue north to the line's terminus in downtown Los Angeles. Eleven of the line's 22 stations are located in high crime areas, including the five stations in downtown Los Angeles. Certain sections of the corridor are characterized by high rates of crime that is violent, gang-related, and drug-related.

Furthermore, LACTC recognized that the Blue Line would be a pilot for the county's entire rail transit systems development program. The 30-year program for light rail, heavy rail, and commuter rail systems development was, to some extent, dependent on the success of the Blue Line and on how the line's success was perceived by the residents of Los Angeles County. Personal safety and security were identified as critical factors influencing how individuals perceived the line and its success as a mode of transportation.

EXISTING BLUE LINE LAW ENFORCEMENT

Planning and providing security for the Blue Line's construction and operations required cooperation and coordination among LACTC, the Blue Line's police services provider, and the police departments with primary jurisdiction in the various communities traversed by the line from Los Angeles to Long Beach. Four police departments have primary jurisdiction along the Blue Line corridor:

- City of Los Angeles Police Department (LAPD),
- Los Angeles County Sheriff's Department,
- City of Compton Police Department, and
- City of Long Beach Police Department.

In addition law enforcement agencies with limited jurisdiction operate in the Blue Line corridor, including the Southern California Rapid Transit District (SCRTD) Transit Police Department and the California Highway Patrol (CHP). The SCRTD Transit Police Department functions as a specialized law enforcement agency with concurrent jurisdiction for routine criminal matters affecting SCRTD passengers, employees, equipment, and facilities. CHP has primary responsibility for traffic and related matters on state highways and freeways.

In the Blue Line corridor, the LAPD has primary responsibility for police services for approximately 6.9 mi of the

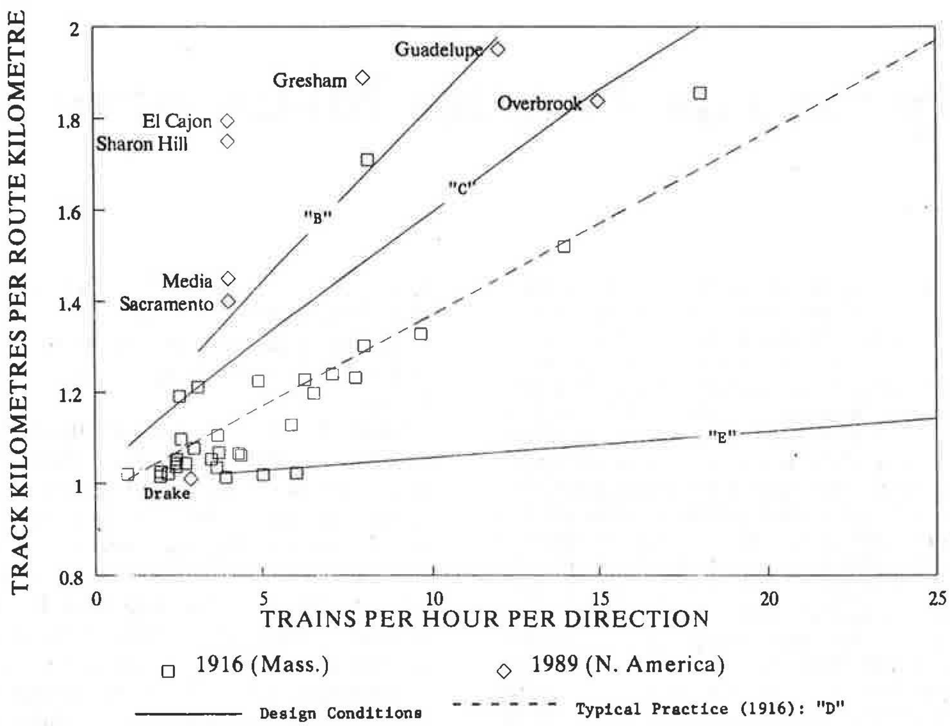

FIGURE 4 Track ratio versus frequency (1916 values estimated).

PRACTICAL PLANNING AND DESIGN CONSIDERATIONS

Adjustments may be required before using T_1 as a basis for determining the actual lengths of single-track sections. Ideally a route should require running trackage determined as follows:

$$TK = 2.0 * RK * (1.0 - T_1/H) \quad (16)$$

where TK and RK are track kilometres and route kilometres, respectively. In planning or designing a particular route, however, a number of other considerations may emerge to constrain single-track solutions. These constraints and some of the techniques applicable to them, are outlined below:

1. Specific locations may not be able to accommodate double track because of topography, cost, environmental impact, or other factors. These locations must be taken out of consideration as possible passing track locations. Where necessary, a lower design condition (i.e., larger T_1 value) may have to be accepted at specific locations.
2. It may be necessary to accommodate more than one headway or service type (e.g., local and express). This may require a solution valid for several different values of H and T_{crit}, and even for different time-space trajectories. In this case, design values of T_1 and H should be established for each service required, and passing tracks should be located to meet all the requirements. Maximum sharing of common passing tracks can be identified by testing different relative departure times from terminals.
3. Very short single-track sections cannot be justified economically; costs for trackwork and signals can exceed the cost of extending two tracks through the section. Current maintenance costs for rail systems suggest that single-track sections shorter than 500 m should be carefully examined to see whether they will offer a true saving in total annualized costs.
4. The location of passing tracks should include a consideration of the time-space trajectory of a typical vehicle trip, as shown in Figure 1. If single-track sections are located to avoid as many station stops as possible, they can be physically longer than sections that include many stops.
5. For some types of service, particularly commuter rail, the assumption of equal service priority in each direction may not be applicable. The values of T_1 between Conditions C and E, for example, can usually provide a very satisfactory level of service for heavily loaded peak direction vehicles, provided that fairly long scheduled "meet" delays can be accepted by lightly loaded off-peak direction vehicles.

In actual application, several iterations or adjustments may be required to reach a satisfactory solution. It is also important to remember that once constructed, the guideway layout will governs the kinds of services that can be operated.

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4. Technical Committee 6Y-37, Institute of Transportation Engineers. *Guidelines for Design of Light Rail Grade Crossings.* No date.
5. *Fifth Annual Report of the Public Service Commission.* Wright and Potter Printing Company, Boston, Mass., Jan. 1918.

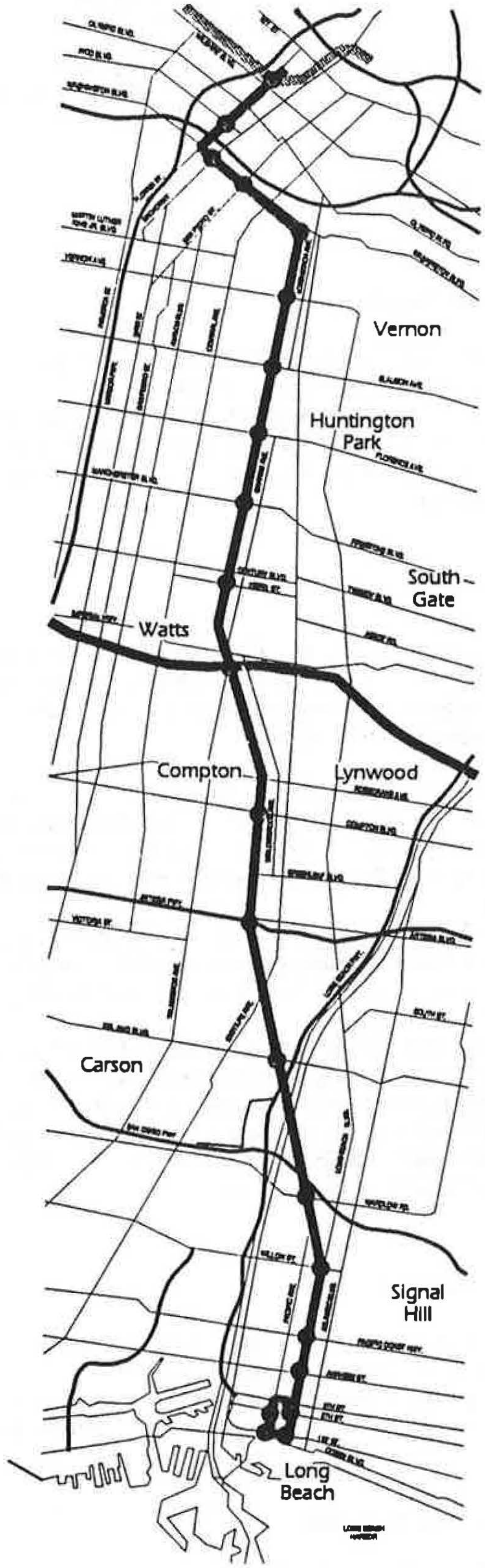

FIGURE 1 Blue Line system map.

route, including the line's subway section in downtown Los Angeles and seven station areas. The stations in the LAPD's jurisdiction are located in the department's Central, Newton, and Southeast service areas.

The Los Angeles County Sheriff's Department has primary law enforcement jurisdiction for approximately 5.5 mi of the route including five of the line's 22 passenger stations. The stations in the sheriff's department jurisdiction are located in the areas served by the department's Firestone, Lynwood, and Carson stations. The system's central control facility (CCF), located next to the Imperial Highway Station, is also in the jurisdiction of the sheriff's department Lynwood Station.

The Blue Line's Slauson Avenue and Imperial Highway stations are located at police service area boundaries. The area on the north side of Slauson Avenue is served by the LAPD's Newton Station, whereas the area on the south side is served by the sheriff's department Firestone Station. The Blue Line station is located on an elevated structure just on the south side of Slauson Avenue. The Imperial Highway Station is located where Imperial Highway forms the boundary between the LAPD's Southeast service area and the sheriff's department Lynwood Station service area.

The city of Compton Police Department has primary jurisdiction along approximately 3.1 route-mi, including two stations located in Compton.

The city of Long Beach Police Department has primary jurisdiction for eight of the line's 22 stations and approximately 6.5 mi of the route. The system's main yard and shop facilities are located next to the line about 4 mi from the line's downtown Long Beach terminal. These facilities are in the jurisdiction of the Long Beach police.

SECURITY PLANNING APPROACH

LACTC's approach for planning and providing security for the Blue Line involved the following elements:

- Establishment of goals for system security,
- Establishment of a security subcommittee of LACTC's safety and security committee made up of representatives from the sheriff's department, LAPD, Long Beach police, Compton police, and SCRTD transit police,
- Conduct of an analysis of system security risks,
- Implementation of system design features to mitigate security risks and areas of concern where possible,
- Development of a plan and program for implementing police and security services during construction, prerevenue service testing, and revenue operations, and
- Implementation of the recommended plan and program for police and security services.

Each of these security planning elements is discussed in detail in the following sections.

SYSTEM SECURITY GOALS

LACTC recognized the need for effective security early on and developed three security program goals:

1. Provision of a high level of security and well being for patrons, employees, and the general public;
2. Protection of facilities and equipment; and
3. Incorporation of provisions for deterrence, detection, and response to criminal acts in the planning, design, and operation of the rail system.

SECURITY SUBCOMMITTEE

As preliminary design work for the Blue Line commenced, LACTC established a security subcommittee of its safety and security committee to identify areas of concern and to evaluate and make recommendations about system design features. The subcommittee consisted of representatives from each of the four law enforcement agencies having primary jurisdiction along the Blue Line's route, a representative from SCRTD's transit police, and consultants familiar with rail transit-related security problems and solutions.

The subcommittee evaluated and made specific recommendations concerning the following system design elements:

- Vandal-resistant train window materials;
- Landscaping that would not serve as hiding places for persons illegally entering the right-of-way or station areas;
- Security fasteners requiring the use of a special tool to loosen for vehicles, ticket vending machines, and other accessible locations; and
- Location and type of fencing along the right-of-way.

The subcommittee compiled a photo catalog of all equipment and components made of materials with scrap value, such as copper or brass. Photos were taken from all sides of the equipment and components, taking care to record any manufacturer's markings. This catalog was distributed to LAPD, the sheriff's department, and Long Beach police, and the Scrap Dealers Association. The Scrap Dealers Association cooperated in advising all its members that the catalog was available and requesting that dealers not buy any of the cataloged items. When any thefts did occur, flyers were prepared and distributed through the Scrap Dealers Association, requesting that information on anyone attempting to sell the stolen items be reported to the appropriate law enforcement agency.

SECURITY RISK ANALYSIS

LACTC developed a security risk analysis methodology for the Blue Line's security planning. It has since been applied to the Green and Red lines currently under development. The methodology presents a structured approach to the identification of potential risks and to the specification of potential solutions and mitigations that might be invoked for each of the identified risks.

System Elements and Subsystems

The security risk analysis addressed risks related to the following system elements and subsystems:

System Element	*Subsystems*
Stations	Platform/passenger waiting areas Fare vending equipment Equipment rooms Parking areas Elevators
Yards, shops, and facilities	Main yard and shops Satellite vehicle storage yard Central control facility Parking areas
Vehicles	
Trackways and structures	
Wayside equipment	

Risks and Targets

For each system element and subsystem, risks likely to result in crimes or infractions were identified.

For each identified risk, the potential target of any resulting crime or infraction was specified as being one or more of the following: passengers, employees, revenue, and equipment and property.

Severity of Crime

Security risks may be categorized according to the severity of the potential criminal activity resulting from the problem. Specifically the following categories were used for identified risks included in this analysis:

- Serious offenses including homicide or attempted homicide, forcible rape, burglary, robbery, aggravated assault, theft, auto theft, and arson—These offenses are referred to as Part I offenses, according to the Uniform Crime Reporting (UCR) system;
- Less serious offenses such as drug violations, simple assault, vandalism, drunkenness, and disorderly conduct—These offenses are referred to as Part II offenses, according to the UCR methodology;
- Local ordinance violations, including traffic and parking infractions and "quality of riding" violations related to smoking, eating, and playing radios aboard transit vehicles; and
- Incidents such as harassment and abuse, lost children, and stalled automobiles blocking traffic lanes, which do not necessarily involve criminal acts.

Causes and Effects

Events or conditions contributing to the existence of the identified security risk were listed for each risk.

The potential effects of the criminal acts on rail transit system operations also were listed for each identified risk.

Solutions and Mitigations

Potential solutions and mitigations for the security risks were organized in the following four areas:

- System design features and criteria,
- Equipment and products designed both to deter and detect criminal activity,
- System operations and scheduling, and
- Police service activities by fully sworn peace officers, uniformed security guards, or fare inspectors not having full police powers, and undercover spotters.

SYSTEM DESIGN FEATURES

The Blue Line was designed with security systems and elements to enhance security. Design criteria and standards relating to system security were developed and applied. Key security systems and system design elements implemented for the Blue Line were as follows.

Station Areas

Materials

Materials used for finishing the stations are graffiti- and vandal-resistant, and designed to be easily cleaned or maintained.

Lighting

Station platforms and waiting areas are illuminated adequately during hours of darkness and reduced visibility.

Facility Intrusion Detection System

Sensors have been installed for train control communications and other equipment rooms located in each station, for the end of platform gates at each station, and for doors at train control communications buildings. The sensors are monitored at the CCF by train operations control personnel.

Public Address System

The public address system provides the capability to give routine announcements and emergency warning information from the CCF to one or more passenger stations.

Closed Circuit Television System

The closed circuit television (CCTV) system provides visual surveillance of each station's platform, fare vending equipment, and other designated areas. The CCTV system provides for passenger assistance and for enhanced safety and security under certain circumstances. The system permits the images from any one CCTV camera to be viewed at a police dispatching call-up monitor.

Passenger Assistance and Emergency Telephones

Telephones in the platform and fare vending equipment areas permit passengers to talk directly with operations personnel at the CCF to obtain assistance or report emergencies.

Fencing

Steel picket fencing has been installed along the line's at-grade sections and at other selected locations.

Vehicles

Materials

The materials used for vehicle seating, interior finishes, and exterior finishes are resistant to graffiti and vandalism, and easily cleaned or maintained.

Windows

Vehicle windows are sized as large as possible and located so that passengers can easily see outside the cars, and persons outside are able to see inside the cars. The windows are made of an impact-resistant, hard-surfaced material.

Radio System

The radio system provides frequencies for both data and voice transmissions between the CCF and all vehicles. Supervisory and selected control data for train control functions are provided by radio data transmissions. Voice transmission capabilities provide for communications between the CCF and operations and maintenance personnel on trains, at stations, and along the trackway.

Silent Alarm

A train operator may activate a silent alarm to alert CCF personnel to a problem on the train.

On-Train Passenger Intercom System

The intercom system permits passengers on a train to have two-way communications with the train operator.

On-Train Public Address System

The on-train public address system permits the train operator to make routine announcements and provide emergency warning information to passengers.

CORRIDOR SECURITY EVALUATION

Figure 2 illustrates the crime rates in the cities and unincorporated areas along the Blue Line's route. For security planning, annual crime rates were calculated for each of these cities and unincorporated areas, which were then ranked as low, average, or high crime areas. An "average" crime area has crime rates that are roughly the same as those for Los Angeles County as a whole. A similar analysis of crime rates was done for individual station areas.

The statistical data summarized in Figure 2 illustrate why LACTC became concerned about taking the necessary steps to ensure personal and property security on the Blue Line trains and at its station areas. Without adequate attention to security, projected ridership levels could not be attained. For many of the station areas on the line, the rate of violent crimes, including homicides, rapes, aggravated assaults, and robberies, was found to be at least three times and as much as five times greater than for comparable areas in other parts of the metropolitan area. In portions of the midcorridor, the high rates of crime were found to be generally gang- and drug-related.

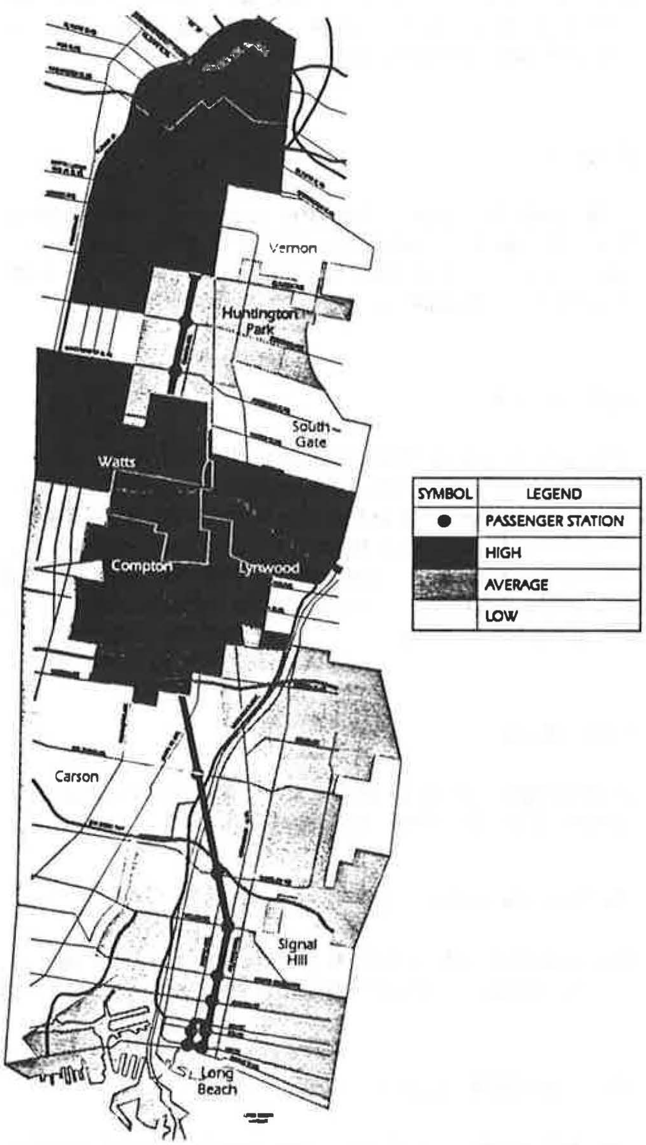

FIGURE 2 Crime rates for cities and unincorporated areas along the Blue Line corridor.

The findings derived from statistical data were confirmed by interviews with law enforcement personnel responsible for police services in the corridor as well as by observations made of security measures implemented by other organizations in the corridor. For example, a recently constructed neighborhood shopping center adjacent to the line's 103rd Street Station has been protected by CCTV cameras, some mounted on high poles to prevent vandalism of the cameras; 8-ft steel picket fencing with electrically controlled gates; an observation "tower" to provide security guards with an unobstructed view of the center and its parking areas; and four uniformed, armed security guards on duty for each shift, 24 hr per day, 7 days per week. In midcorridor areas, numerous buildings, walls, and street curbs were found heavily marked with graffiti. It was anticipated that station facilities in these same areas would also be defaced unless appropriate security measures were implemented.

A representative of one of the law enforcement agencies serving the corridor suggested that the "transit police ride shotgun" on trains operating on the line. Although this response may be viewed as "colorful" or perhaps even "overzealous," it was consistent with LACTC's conclusions from statistical data and other investigations concerning security requirements for portions of the corridor.

CONSTRUCTION SITE SECURITY

When the design and construction phase of the Blue Line began, LACTC made a commitment to the residents of Los Angeles that the construction and operation of the system would not unnecessarily cause a safety hazard to the neighborhoods traversed by the system nor would the system cause an increase in crime in the areas. To uphold this commitment, security was as vital a part of the construction phase as it is now in the line's operations phase.

LACTC's construction and systems installation contractors were responsible for providing adequate security for all improvements as they were being constructed. Most major construction contracts mandated that contractors be responsible for the security of their personnel, tools, equipment, and the site in general. Depending on specific site security requirements, contractors were required to provide the following elements to ensure construction site security: fencing, lighting, signs, security personnel, police patrols, and intrusion alarms.

When a contractor was relieved of responsibility for completed or partly completed improvements, LACTC, as the owner, assumed responsibility for protecting and maintaining the improvements. Security was provided by contract security guards at the stations and at the yard and shops area. In addition, the Los Angeles County Safety Police provided patrols for the station areas, the yard and shops area, and the right-of-way as well as police support to the contract security guards.

IMPLEMENTATION OF POLICE SERVICES

The Blue Line's operator, SCRTD, has contracted with the sheriff's department for police services. The first year's cost for security services was approximately $12 million. The sheriff's department has established a transit services bureau for the contract, headquartered at the Blue Line's CCF adjacent to the Imperial Avenue Station in central Los Angeles.

To date, there have been few security-related problems. Sheriff's deputies are highly visible on station platforms and on trains, and the high level of security being maintained has served to discourage criminal activity on the line.

Blue Line Police Services Staffing

The sheriff's department transit services bureau has 136 positions, including 123 sworn deputy positions, authorized for Blue Line police services. The authorized positions are as follows.

Position	*No.*
Sworn deputies	
Captain	1
Lieutenants	3
Patrol sergeants	11
Support unit sergeants	3
Supervising line deputies	5
Watch (dispatch) deputies	6
Detective deputies	5
Foot and car patrol deputies	89
Civilian	
Supervising secretary	1
Clerks	4
Captain's secretary	1
Crime analyst	1
Dispatch room assistants	4
Service assistants	2
Total	136

Contract security guards have also been employed for certain security work assignments. The security guards work under the "on the street" supervision of the sheriff's department. Sheriff's deputies and contract security guards have been deployed generally as follows for Blue Line security functions.

Sheriff's Department Deputies

Car patrols are scheduled for the day and p.m. watches. Each patrol operates in one of four predefined patrol zones along the line. One- or two-car patrols may be assigned to each zone.

Deputies are assigned to random foot patrols in each of the patrol zones along the line for the day and p.m. watches. Generally one of the deputies in each zone is responsible for fare inspections.

Deputies are assigned to station area foot patrols at selected stations only on the day and p.m. watches.

Contract Security Guards

Security guards are posted at four park-and-ride lots for the day and p.m. watches.

A security guard is posted at the CCF building's main entrance to monitor persons entering and leaving the building's second floor areas. The transit services bureau occupies the building's first floor.

Two security guards are posted at the main yard and shops facility in Long Beach. The guards are on duty for three shifts per day, 7 days per week.

Blue Line Crime Experience

As already noted, little transit-related crime has occurred during the line's initial 12 months of operations. A total of 1,351 arrests were made for felony and misdemeanor offenses on the Blue Line during its first year of operation. The number of arrests made by month has varied from 59 in February 1991 to a high of 164 in May 1991.

Few violent crimes, including homicides, rapes, aggravated assaults, and robberies have occurred. Most of the violent crimes reported for the line's initial 12 months have been for aggravated assaults, primarily in connection with fights on trains and at stations, and assaults on deputies during arrests for other crimes. A total of 3 burglaries, 19 thefts, and 2 automobile thefts have been reported on the Blue Line during the line's first year of operations (see Figure 3).

In the first 12 months 19,106 citations were issued for infractions such as fare payment violations, quality of riding violations, and traffic-related violations. Figure 4 provides a breakdown. The fare evasion rate has averaged 0.39 percent. Deputies have been checking between 30 and 40 percent of the passengers on trains. In June 1991, deputies identified 1,702 passengers not paying fares on the line. Of this total, 785 passengers were cited for fare evasion or misuse of fare media, and the remainder were warned and advised about the line's fare payment requirements. The fare evasion rate increased to a high of 0.66 percent in May 1991 and was estimated to be 0.64 percent for June 1991. The fare evasion rate has increased as ridership has increased following the opening of the line's subway segment into downtown Los Angeles.

Gang-related problems have not occurred on the line, although the line runs through areas where there are numerous gangs and frequent gang-related criminal activities.

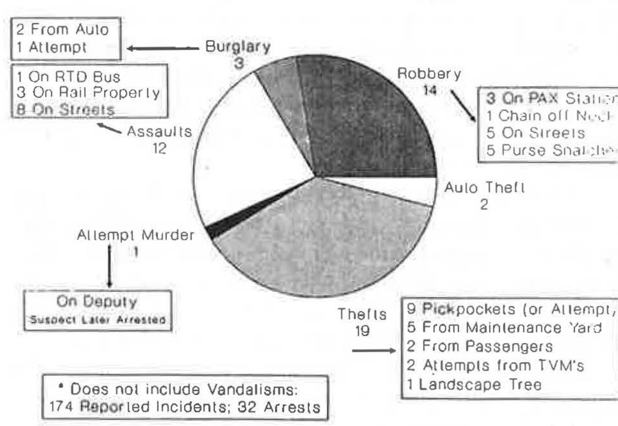

FIGURE 3 Summary of Blue Line crimes, 1990–1991.

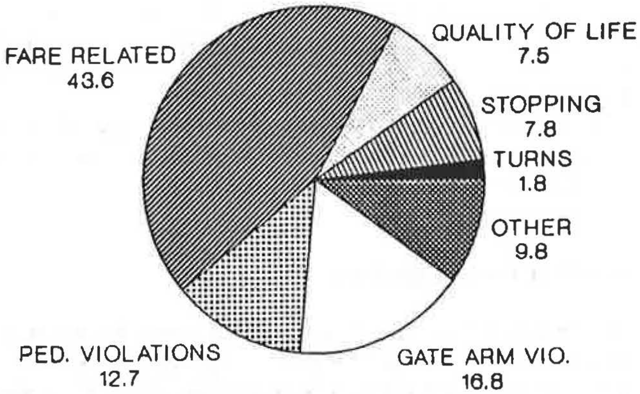

FIGURE 4 Blue Line citations percent by type, 1990–1991.

No particular problems have arisen with graffiti on the trains or the stations, but the sheriff's department is making arrests for vandalism and related property damage offenses when it has been possible to identify the persons responsible for the damage. In June 1991, 23 incidents of vandalism were reported by the sheriff's department, 19 for marking vehicle windows.

To enhance perceived security, LACTC has established an aggressive antigraffiti policy. Maintenance crews have been contracted to inspect for graffiti along the line and to remove it.

LACTC recognized that the perception of adequate security on the Blue Line would have a significant impact on the line's ridership. The perceptions of residents in the Blue Line corridor concerning "fear of crime" decreased from 16 percent in 1989 before the Blue Line's opening to 4 percent in 1991 after the line had been in operation for several months. Clearly the security program has changed the attitudes of the general public markedly concerning the possibility of risks to personal safety.

Coordination with Local Police Departments

Providing police services for the Blue Line has required cooperation and coordination among the sheriff's department transit services bureau and the local police departments with primary jurisdiction in the communities traversed by the line. The sheriff's department has executed a memorandum of understanding (MOU) with each of the three city police departments working in the corridor. The MOUs call for general and traffic law enforcement responsibilities to be separated generally as follows.

The sheriff's department is responsible for handling crimes or incidents occurring on the trains or in station areas; thefts of rail system property and any vandalism to rail system property; accidents involving trains and pedestrians not at controlled crossings or intersections and only at locations where the right-of-way is fenced to restrict access to the tracks.

The city police departments are responsible for handling crimes or incidents not originating on trains or rail system property, but that continue onto trains or rail property; crimes occurring on the right-of-way that do not involve train passengers; accidents at grade crossings involving trains and vehicles; and accidents involving trains and pedestrians at controlled crossings, intersections, or at other locations where the trains are running in a roadway.

FUTURE RAIL SYSTEMS DEVELOPMENT

LACTC has embarked on the development of a countywide rail transit system consisting of more than 300 mi of light rail, heavy rail, and commuter rail services to be completed by the year 2020.

Security will be needed for each of the transit lines as they are constructed and then during revenue operations. Planning is underway that takes into account the fact that each line has certain unique operating and design characteristics that result in varied security risks. For example, one of the lines will provide parking spaces for nearly 7,700 automobiles in 25 parking lots at 13 of the line's 17 stations. Providing security for parked cars will be a major concern for this line's security services provider.

In addressing the security requirements of the transit lines under development, LACTC has identified several key areas of concern and issues to which special attention is being directed.

Level of Security

How much security is necessary for the Blue Line? And for the rail transit and commuter rail lines under development? The first year's cost for police services on the Blue Line was approximately $12 million or nearly $1.50 per passenger transported. LACTC Executive Director Neil Peterson has summarized LACTC's view of the need for adequate security:

> We have to have the respect of the public. Polls say people want [security] regardless of age, ethnic group or income . . . we hope to overinvest in security (*1*).

Police Services Provider

As already noted, SCRTD has contracted with the sheriff's department for Blue Line police services. It is likely that other law enforcement agencies, perhaps including the SCRTD transit police and LAPD, will become the primary police services providers for other transit lines.

Fare Inspections

The Blue Line system is barrier free, and uses a self-service approach for collecting fares. Fare inspections are done by sheriff's deputies. Both the Red and Green lines will use the same approach. For all three lines fare inspection duties may be carried out by deputies or other sworn police officers, as is currently done for the Blue Line, or alternatively by uniformed fare inspectors who are responsible only for checking fares.

Each approach has advantages and disadvantages. The use of fully sworn and trained deputies for fare inspections may be an inappropriate use of their time. Fare inspections are most effectively done as a separate function because of the need to maintain controls on the number of fare inspections being done in a random manner, and because fare inspections cannot be done in an effective manner at the same time as other police duties. In addition the cost of using fully sworn police officers for making fare inspections is significantly higher than the cost of using inspectors.

The use of nonsworn inspectors provides greater flexibility for scheduling split and short work shifts, so that the desired inspection rates can be obtained for all hours of operation. A force of inspectors could be effectively assigned to any of the transit lines as necessary without the need to consider which law enforcement agency was providing primary police services for the line.

However, passengers will probably be more inclined to refuse cooperation to fare inspectors than to deputies, which could result in higher fare evasion rates and an increased number of disputes on trains and station platforms. In addition, the presence of additional deputies on the trains for fare inspections increases both the actual and perceived level of security for the system.

Furthermore police officers inspecting fares may observe more serious offenses and infractions and be able to immediately take appropriate actions.

And finally certain supervisory and clerical functions may need to be duplicated if fare inspections are done by a separate force of inspectors.

Coordination with Police Departments

With the continuing growth of public transit services in the county, the need to ensure that all public transit services are safe for passengers and as crime-free as possible is increasing. Furthermore sales tax revenues from the recently passed Proposition C will provide $20 million a year specifically for improved and expanded rail and bus security in the county. Currently more than 80 operators provide public transit and paratransit services in Los Angeles County. They operate through areas policed by nearly 50 different law enforcement agencies. Only the SCRTD, the county's largest transit provider, maintains its own security force, which consists of approximately 160 officers.

LACTC is exploring approaches to coordinate transit-related police services throughout the county, possibly through the establishment of a metro police management group. Special attention will be directed to requirements for transit-related crime reporting.

Construction Security

In early 1991 LACTC elected to make its Red and Green line's construction management contractors directly responsible for construction security at locations and for time periods when finish construction and systems installation contract work is under way. This approach was implemented to eliminate confusion over security responsibilities for completed work, for areas where several contractors are working at the same time, for periods of time when no contractors are working in an area, for systems being installed by one or more contractors, and for other circumstances in which security provided by construction and systems installation contractors might not be adequate, resulting in additional costs and possible delays.

CONCLUSION

LACTC is proud of its success with the Metro Blue Line, which is being operated with an extra emphasis on security. The emphasis on security has been significantly greater than for typical transportation projects.

The Blue Line is an example of how security can be provided and maintained despite negative public perceptions, crime statistics, and press reports. The Blue Line is a nearly crime-free ribbon of transportation, carrying more than 30,000 passengers per day through some of the most notorious crime areas of Los Angeles County.

REFERENCE

1. N. Peterson. Building a Rail Line Means Making Passengers Happy. *Metro Magazine*, May/June 1990.

PART 6
Vintage Trolley Operations

Vintage Trolleys: A National Overview

S. David Phraner

This overview introduces vintage trolley (VT) case studies and premieres VT as a valid transit concept to transportation professionals. VT is defined and compared with other transit modes. Its characteristics and applications are analyzed relative to the communities in which it is an integral element. VT successes and shortcomings are highlighted.

The talk today is often about returning to basics; embracing the fundamentals that provide reliable, no-frills, user-friendly products and services. This principle (and sometimes its opposite) is aptly demonstrated in public transportation and specifically in light rail transit (LRT). Vintage trolley (VT) equipment and facility design demonstrate the practice of basics in transit.

VT appears to be more than a momentary gimmick, supplying nostalgia for tourists and rail buffs. VT is growing more rapidly than any other form of urban rail transit: 23 VT new starts in 20 years.

DEFINITION

This is an opportunity to define VT for the first time. VT as a transit mode is now established enough to qualify for a standard definition, but young enough that no one has yet given it an official designation.

The term "VT" is carefully considered. The *T* applies to either "tram" or "trolley" quite well. Other terms popularly applied to VT include "heritage trolley," "historical streetcar," and combinations of these terms. Use of trolley car replicas in some VT reduces the validity of applying "historical" or "heritage" to describe such operations. Other elements of VT properties may not be authentically historical or part of local or national heritage. "Vintage" is a more flexible word that describes age or the frequent perception of age. A vintage wine, for example connotes quality as well as a significant era that may not necessarily be "old."

A universal tendency seems to be to define VT using the trolley vehicle as the sole identifier. Even the fledgling VT systems now in operation demonstrate that VT is better defined by a combination of features, including rolling stock, service, infrastructure, management, and operating environment.

One thing VT is not is a minibus or truck/van chassis with a body decorated to resemble a San Francisco cable car or traditional streetcar. The term "vintage trolley" is also proposed for common usage to avoid confusion with rubber-tired highway vehicles that attempt to mimic rail cars.

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What then is VT? A short definition of vintage trolley is offered as a standard for the genre: Vintage trolley is a variant of light rail transit that provides year-round urban transit service using genuinely historical or replica vintage rail equipment with heritage-compatible infrastructure.

Though considered part of the VT family, urban funiculars and cable lines such as in San Francisco, Pittsburgh, and Dubuque are excluded from this analysis. Admittedly, they exhibit most of the characteristics of VT but differ in geometry and propulsion. Tables 1–3 attempt to show the fine line between electric traction museums and VT properties. Trolley museums and museums that feature trolley displays, such as San Jose's Kelley Park or Calgary's Heritage Park, are relegated to Table 3 and are otherwise not treated in the analysis.

Consider existing transit President's Conference Committee (PCC) streetcar operations such as those in Philadelphia, Pittsburgh, Toronto Harbourfront, and Newark in a VT context. But are they VT? The cars qualify as historical vehicles if one uses the motor vehicle department eligibility criteria for issuing historical license plates. Within the transit spectrum, however, these PCC properties are treated as modern operations with dated but hardly obsolete technology. As their transit managers clearly do not wish to impart an image of vintage equipment or nostalgia, most PCC operations do not quite fit the VT mold. Similarly Fort Worth's Tandy Subway uses PCC car apparatus with replacement contemporary-design bodies and amenities. Tandy's LRT rail transit property is clearly not vintage by intent.

Proposed trolley operations in Buffalo's Tonawanda Corridor and San Francisco's Embarcadero will employ second- or third-hand PCCs and reclaimed infrastructure and right-of-way. Although this appears at first glance to be a financial expedient rather than an intent to create a vintage image, both the vehicle and right-of-way are of some historical value. San Francisco's Muni, for example, plans to take advantage of the PCC car's appeal by applying historical paint schemes of various PCC operators across North America. Hence they qualify as VT.

PCC cars do have other potential to further the VT concept. Surplus PCC components are being used to construct replica VT cars as recently demonstrated on Portland's four-car order from Gomaco. Nelson, British Columbia, is using an ex-Toronto PCC to supply parts to rebuild a vintage car. In some cities that once operated PCCs on the surface, there are proposals to return cars to their original habitats as they are retired by their current owners. Minneapolis, Vancouver, Detroit, Dallas, San Diego, and El Paso reportedly are active in such efforts for promotional, historical, and perhaps even transportation reasons. Surplus PCCs are being purchased by fledgling VT operators (Cincinnati, Frederick, Keokuk, and Johnstown). These circumstances make a strong argument for treating recycled PCCs as VT.

TABLE 1 VT Properties in North America, March 1992

Location	Operator/Name	No. of Cars[a]	Route Miles
Chattanooga, Tenn.	Chattanooga Choo-Choo	1	<0.5
Dallas, Tex.	McKinney Ave. Transit Authority	5 (4)	1.4
Denver, Colo.	Platte Valley Trolley		
	Denver Rail Heritage Inc.	1 R	3.5
Detroit, Mich.	Detroit Citizens Ry./DDOT	9 (3)	1.2
Ft. Collins, Colo.	Ft. Collins Mun. Ry. Soc.	2 (1)	1.5
Ft. Smith, Ark.	Ft. Smith Trolley Museum	2	<.5
Galveston, Tex.	Galveston Island Trolley,	4 R	4.7
	Galveston Park Board		
Lowell, Mass.	Lowell Nat'l Historic Park		
	DOI, National Park Service	3 R	1.5
Nelson, B.C.	Nelson Electric Tramway Soc.	2 (1)	1.4
New Orleans, La.	Riverfront Trolley		
	RTA/Riverfront Transit Coal.	7	2.2
New Orleans, La.	St. Charles Line, RTA	35	6.5
Orlando, Fla.	Grand Cypress Resort, Hyatt	4	3.5
Philadelphia, Pa.	Penns Landing Trolley		
	Buckingham Valley Trolley Inc.	7 (4)	1.1
Portland, Oreg.	Vintage Trolley Inc./Tri-Met	4 R	2.5
Portland, Oreg.	Willamette Shore Trolley	1	6.0
Sacramento, Calif.	Regional Transit		
	(temporary service, discontinued)	0	2.0
San Antonio, Tex.	San Antonio Museum Assoc.		
	(service discontinued)	1+(0)	>1.0
San Francisco, Calif.	Historic Trolley Festival Market		
	St. Ry. Inc.	16 (13)	3.6
San Jose, Calif.	Santa Clara County Transit	5	4.5
Seattle, Wash.	Seattle Metro	5	2.0
Toronto, Ont.[b]	Toronto By Trolley Car/TTC	3	—
Tucson, Ariz.	Old Pueblo Trolley Inc.	1	—
Yakima, Wash.	Yakima Interurban Lines Inc.	4	7.0

NOTE: VT-like cable and funicular lines are excluded. This inventory totals 23 VT properties, of which 16 are representative for comparison and analysis; these are underlined in the table.

[a]*R* = replica.

[b]Toronto's newly opened Harborfront LRT Line uses overhauled PCCs. It is not classified as a VT in this analysis because its operator, TCC, clearly wishes to impart an image of a modern, new facility in new development. Toronto's tour trolley using pre-PCC and PCC equipment is included above for purposes of this analysis.

TABLE 2 VT Properties Planned, Committed, or Under Construction in North America, March 1992

Location	Name/Operator	No. of Cars	Route Miles
Algiers, La.	Algiers Landing Rest.	1	<.5
Aspen, Colo.	Aspen St. Ry. Co.	6	N/A[a]
Brooklyn, N.Y.	Waterfront/Atlantic	1	N/A
Buffalo, N.Y.	Tonawanda Corridor/NFTA	12	5.2
Charlotte, N.C.	Charlotte Trolley Inc.	2	1.3
Chattanooga, Tenn.	Downtown Trolley/CARTA	0	3.0
Cincinnati, Ohio	Cincinnati St. Ry./CTHA	7	2.5
Cleveland, Ohio	Flats Trolley/RTA	0	.5
Edmonton, Alberta	High Level Bridge/ET	1+	<2.0
El Paso, Tex.	El Paso City Lines	5+	<4.5
Frederick, Md.	Frederick Trolley Comm.	1	4.0
Memphis, Tenn.[a]	Mid America Mall/MATA	11	2.4
Mexico, D.F.	Tour Tram STE/STC (disc)	—	N/A
New Orleans, La.	Canal St.		3.9
	Loyola/Rampart (proposed)	38	1.1
New Orleans, La.	Riverfront Extensions	0	6.3
Orlando, Fla.	"OSCAR" City of Orlando	1	3.0
Orlando, Fla.	Disney World	0	N/A
Portland, Oreg.	River Place/Union Sta.	0	2.3
Richmond, Va.	Electric Trolley/GRTC	1	0.6
San Diego, Calif.	Gas Lamp Dist. Trolley	—	N/A
San Francisco, Calif.	F Market St./Muni and	12+	3.6
	Embarcadero/Muni	—	1.7
Vancouver, B.C.	False Creek Waterfront	3	2.0

NOTE: Of the 24 VT proposals in 21 cities inventoried above, those shown underlined are under construction or are in other stages of advanced implementation. Proposals in early planning: Johnstown, Pa.; Glendale, Calif.; Pottstown, Pa.; Omaha, Nebr.; Lincoln, Nebr.; Newark, Ohio; Hagerstown, Md.; Tampa, Fla. Gordon Thompson's unpublished inventory of VT and LRT proposals lists another 45 proposed projects.

[a]N/A = proposed route mileage not available or determined.

[b]Opens in 1992.

TABLE 3 North American Electric Traction Railway Museums, March 1992

Location	Name/Operator	No. of Cars	Route Miles
Baltimore, Md.	Baltimore St. Railway Museum	13	<1
Boone, Iowa	Boone & Scenic Valley	4+	15
Branford/E. Haven, Conn.	Shore Line Trolley Museum	80+	1.5
Calgary, Alberta	Heritage Park	2+	1
Clear Lake, Iowa	Mason City & Clear Lake Railway Historical Soc. (Iowa Traction)	3	12
Cleveland, Ohio	Trolleyville USA	20+	<2.0
Delson, Quebec	Canadian Railway Museum	15+	1.5
Duluth, Minn.	Lake Superior Museum of Transportation	3	<.5
East Troy, Wis.	E. Troy Railroad	10+	7.2
Edmonton, Alberta	Ft. Edmonton/ERRS	13	1.1
Elgin, Ill.	Fox River Trolley Museum	10+	1.5
French Lick, Ind.	Indiana Railway Museum	2	>1
Glenwood, Oreg.	Trolley Park/OERHS	5+	1.5
Golden, Colo.	Colorado Railway Museum/RMRRC	2	<.5
Hibbing/Chisholm, Minn.	Iron World USA	2	2.5
Kennebunkport, Maine	Seashore Trolley Museum/NERHS	200+	2
Kingston, N.Y.	Trolley Museum of N.Y.	8+	1.5
Minneapolis, Minn.	Como-Harriet/Minn. Transportation Museum	7	1
Mt. Clemens, Mich.	Michigan Transit Museum	4	4.0
Mt. Pleasant, Iowa	Midwest Electric Railway	6	1.1
Noblesville, Ind.	Indiana Transportation Museum	3+	1
North Prairie, Wis.	N. Prairie Electric Railway	5	1
Orbisonia, Pa.	Shade Gap Electric Railway	20+	1
Perris, Calif.	Orange Empire Ry. Museum	130	2.5
Rio Vista, Calif.	Bay Area Electric Ry. Museum	80+	1.5
Rockford, Ill.	City of Rockford Parks	1	—
Rochester, N.Y.	NY Museum of Transportation	3	<1
Rockwood, Ontario	Halton County Radial Railway/OERHS	10+	1
San Jose, Calif.	Kelley Park (City of San Jose)	2	.3
St. Louis, Mo.	National Museum of Transport	10+	—
Union, Ill.	Illinois Railway Museum	30+	>2
Vancouver, B.C.	Burnaby Village Museum	5	—
Warehouse Pt., Conn.	CT Electric Railway Association	50+	1.5
Washington, Pa.	Arden Railway Museum/PRMA	20+	1
Wheaton, Md.	Nat'l Capitol Trolley Museum	15	2
Worthington, Ohio	Ohio Railway Museum	13+	1.5

NOTE: Including major railway and general purpose museums featuring operating trolleys (four museums are static displays). These 36 museums, holding over 750 cars, constitute a network that interacts with VT properties in complementary ways. Most notable is the exchange of parts, equipment, and technical advice. Some, like the Kelley Park VT shop, provide restoration skills. Other urban electric railways and traction museums like Baltimore could become VT.

VT Versus LRT

The above definition of VT has been scrutinized and modified to suit a panel of VT operators, designers, and planners. Yet it is not quite enough to differentiate genuine VT from tourist rides, LRT, trolley museums, or hybrid transit operations that happen to employ trolleys. Describing VT as a submode of LRT invites comparison of their general, mostly qualitative, characteristics (see Table 4).

Additional Features and Tendencies

An inventory of North American rail properties yielded a list of 23 operations that exhibit some strong VT characteristics. Of these, 16 are selected as best representing the VT ideal as defined above. Clearly these VT properties were placed and designed by their sponsors to support certain community purposes, civic facilities, and commercial land uses. VT, once built, also tends to attract and nurture complementary urban features, such as historical districts, gentrifying neighborhoods, sightseeing attractions, and trendy shopping areas. These downtown features are some of the strongest techniques for renewing urban "main street" America. Their presence with VT suggests that VT itself is a powerful tool in improving, or at least helping to stabilize, downtowns. Table 5 shows these features measured against the 16 representative VT properties.

The 16 representative VT properties also demonstrate some common physical characteristics that help reveal the nature of VT. They are expressed in aggregate terms as averages in Table 6.

Electric freight railways not now routinely used for revenue passengers, like Keokuk Junction Railway, Gomaco's test track, and some noncommon carrier electric railways are not included here. Some of these freight railways host vintage trolley and interurban rolling stock.

Like each of their LRT brethren, every VT property is unique. Some, like Seattle's, are integrated with the local transit system in terms of fares, labor, schedules, and other aspects of operations. Others, such as the McKinney Avenue Transit Authority in Dallas, are fully independent from the metropolitan transit operator. Yet others, like the New Orleans Riverfront, are partially integrated. Funding and op-

TABLE 4 Light Rail Versus VT Characteristics

Characteristic	LRT	VT
Infrastructure	New equipment; some reuse of rights-of-way	Reclaimed ROW track, equipment
Labor	Paid	Part time, paid, volunteer
Technology	Leading edge	Traditional
Capital cost	Moderate >$10 million/mile	Low <$10 million/mile
Car performance	High (55 mph, 3 mphps)	Low (30 mph)
Functions	Line haul, distribution	Distribution, CBD shuttle
Route distance (shortest/longest)	>3 mi (Denver, 3.5)	<5 mi (Galveston, 4.7)
Image and perception	Modern/advanced	Traditional/nostalgic
Demand features	Sharply peaked	Uniform loading
Peak use	Rush hours (7–9 AM, 4–7 PM)	Nonpeak (10 AM–4 PM, 7–10 PM)
Predominant users (travel motivation)	Commuter (routine)	Tourist/shopper (discretionary)

NOTE: Although these characteristics are indeed generalities and may not apply in all cases to all LRT and VT operations, they are offered here to help distinguish some of the less obvious, less visual differences between LRT and VT.

TABLE 5 Features of 16 Representative VT Properties

Percentage	Feature
81	Serve one or more major tourist attractions/districts
63	Serve a CBD shopping district
63	Of North American VT host cities are located west of the Mississippi River. Considering all 23 VT properties, 70 percent are located in the West. Of those VT properties being proposed, slightly over half would be located in the West. The siting tendency of VT is coastal, not directional. This appears to be related to centers of commerce being on water and VT's affinity for waterfronts.
50	Serve a riverfront or waterfront area
50	Serve convention, civic, or sports center
50	Have expanded or are actively planning to do so
50	Use reclaimed streetcar or railroad track and/or right-of-way
44	Use exclusive right-of-way for all or a portion of their route distance
31	Operate jointly with LRT [Portland, San Jose, San Francisco, Toronto (Tour Tram), Sacramento (disc.)]
25	Use replica cars exclusively (Galveston, Lowell, Denver, Portland); none now uses a combination of historic and replica VT cars; only 10 percent of the total North American VT fleet is replica; including one demonstrator and two in museums, the total is 15
6	Have cars employing on-board internal combustion power generation; Of the 16 representative VT properties, only Galveston's four Miner-built cars feature this means of propulsion; of the total of 23 VT properties, Denver's single Gomaco-built open car is the only other diesel electric VT

NOTE: Of a total of twenty-three vintage trolley properties now in North America, sixteen are selected in this paper that best embody the features of VT as defined herein. These sixteen VTs reflect very diverse local conditions. Though each is different, they display some commonalties that may provide guidance to those considering a VT in their area. As we learn more about what works in VT, the common features could become means of predicting VT project success.

TABLE 6 General VT Physical Characteristics

Characteristic	Average Value
Car fleet size	5.5 cars (82 cars on 15 properties, minus New Orleans St. Charles' 35-car fleet)
Route miles	2.9 mi (40.8 total miles on 14 VT properties, Toronto and San Francisco operations excluded)
Fare	$1.36 (ranging from $0.25 to $3.75 over 12 representative VT lines)
Capital cost	$3.4 million/mi (includes 7 properties ranging from Galveston's $2.6 million/mi to New Orleans Riverfront's $3.4 million/mi, and St. Charles total rehab at $7.2 million/mi. VT costs are rising. Seattle's initial 1.4-mi former rail line cost $2.6 million/mi. Its 0.6-mi extension in street cost $10.8 million/mi.

NOTE: These are averages of selected VT.

erating arrangements vary though nearly all VT has the support and some financial assistance of local business, corporate, and retail commercial interests.

Vulnerabilities

Detroit's Downtown Trolley, San Antonio's Brewery Line, and Dallas' McKinney Avenue Transit Authority demonstrate VT's vulnerability, just as the VT operations in Seattle, New Orleans, and San Jose demonstrate VT successes. VT patronage is more discretionary than conventional transit or LRT use, which is based largely on daily commuting. VT typically is linked to shopping, tourist travel, sightseeing, restaurants, and a host of other particularly recession-prone enterprises. A depressed downtown needs more than just a VT to revive it. A VT alone in an economically depressed central business district (CBD), absent other active economic remedies, is doomed. VT financial performance varies and defies comparison. None, however, appears to be self-sustaining using conventional accounting criteria. (For a list of VT properties planned, committed, or under construction, see Table 2.) Experience in early VT operations suggests a few conditions that contribute to VT popularity and success.

First, strong and consistent political will, endowed in a single dynamic leader or group of leaders is an ingredient for VT success. It is essential for VT new starts. Seattle's and Santa Clara's VTs demonstrate the power of strong and persistent individual leadership such as that of City Council President George Benson and Supervisor Rod Diridon, respectively.

Second, commercial and business interests' endorsement and support reflected in a willingness of retail establishments to tolerate momentary interruptions of trade during VT construction is important. Other support measures include forming special assessment districts, corporate VT car sponsorship, and volunteerism of various forms. Businesses appear to demonstrate more tolerance toward VT than other rail transit because costs are lower and VT is perceived as serving as an attraction in addition to a means of transportation. VT also has the potential to help place and manage CBD parking least disruptively. Memphis' Mid-America Mall and San Jose's downtown promise to provide examples of the mutual benefits of VT and traditional retail downtowns.

Third, a well-defined transportation mission is essential to VT to differentiate it from an amusement ride or solely as a tourist attraction. San Francisco's three cable car lines demonstrate the importance of a transport function in the context of an historical (and in this case a landmark) property. Insufficient route length to reach or link downtown attractions betrays a flawed transportation mission.

And fourth, an already strong CBD is desirable, but not essential.

PAST AND FUTURE OF VT, AN EVOLVING PHENOMENON

The first "new" VTs appear in the mid-1970s. Previously, San Francisco Muni's three cable lines and New Orleans' St. Charles line were regarded merely as survivors of a past era. However, both demonstrated the lasting appeal and value of VT to the extent that their advocates prevented nationally publicized attempts to replace VT with "modern" bus transit. San Francisco and New Orleans were prototypes for early VT. (Like urban inclines, Muni's VT cable system is excluded here.)

The next step in the evolution of VT was Toronto's and Mexico City's vintage tour trams of the early 1970s. These were vintage, pre-PCC cars operating on relatively modern streetcar and LRT properties, primarily for sightseeing.

Next, projects imported vintage trolleys and trams from Portugal, Argentina, Australia, and other nations. The domestic supply of vintage trolleys had been scrapped, placed on static display, or preserved in operating trolley museums, of which more than 30 are located in the United States and Canada. (See Table 3 for a list of major traction museums and museums featuring early street transit.)

Yakima opened its VT line in 1976 and Detroit's VT project started in the same year, introducing what Julien Wolfe has termed "purpose built lines." Seattle's Waterfront Line appeared in May 1982. Lowell's VT followed in 1985 and Orlando's Grand Cypress Resort VT in 1986, representing VT in recreational environments. Since then, the number and variety of VTs has increased. Galveston, New Orleans, Riverfront, and McKinney Avenue VTs opened within a year of one another (1988–1989).

At least 24 major new VT projects are now proposed, in planning, or under construction. Some are in areas where VT is already present. Of these, five are committed in property acquisition or under construction. Some of these may assume the complexion of operating museums. Others, like Memphis' VT and Orlando's "OSCAR," will become transit-type VTs.

The future of VT is promising on several counts. The landmark federal ISTEA (Intermodal Transportation Efficiency Act of 1991) legislation contains alternatives analysis funding for two VT projects: the downtown Orlando VT distributor for OSCAR and Chattanooga's CBD loop. At $5 million and $2 million, respectively, these study funds are in the capital cost magnitudes for VT. Federal funds, matched by local public and private resources have already been expended in New Orleans, Portland, San Jose, Galveston, Seattle, Lowell, and Dallas' McKinney Avenue. One might cite federal funding eligibility by Federal Transit Administration (formerly UMTA) as a sign that VT has arrived as a bonafide transit mode.

The first generation of VT properties are already considering expanding their routes. Seattle, Detroit, Lowell, and New Orleans have already done so.

A small VT family of enterprises has arisen specializing in various aspects of implementation. Three firms offer vintage trolley vehicles, two building replicas from scratch and one importing and adapting foreign trams. A modest consulting business has emerged to advise prospective VT operators and to plan and design VT facilities.

VT is not only a North American phenomenon. It exists elsewhere with tour trams mixing with state-of-the-art light rail vehicles. Melbourne, Hong Kong, Bern, and Zurich provide special vintage trams that serve meals and receptions while traveling their streetcar systems. Fares and revenue are premium.

A profile of the initial phase of New Orleans' Riverfront Streetcar Line provides a good case study of successful VT practice. Funding was a blend of private sources (22 percent),

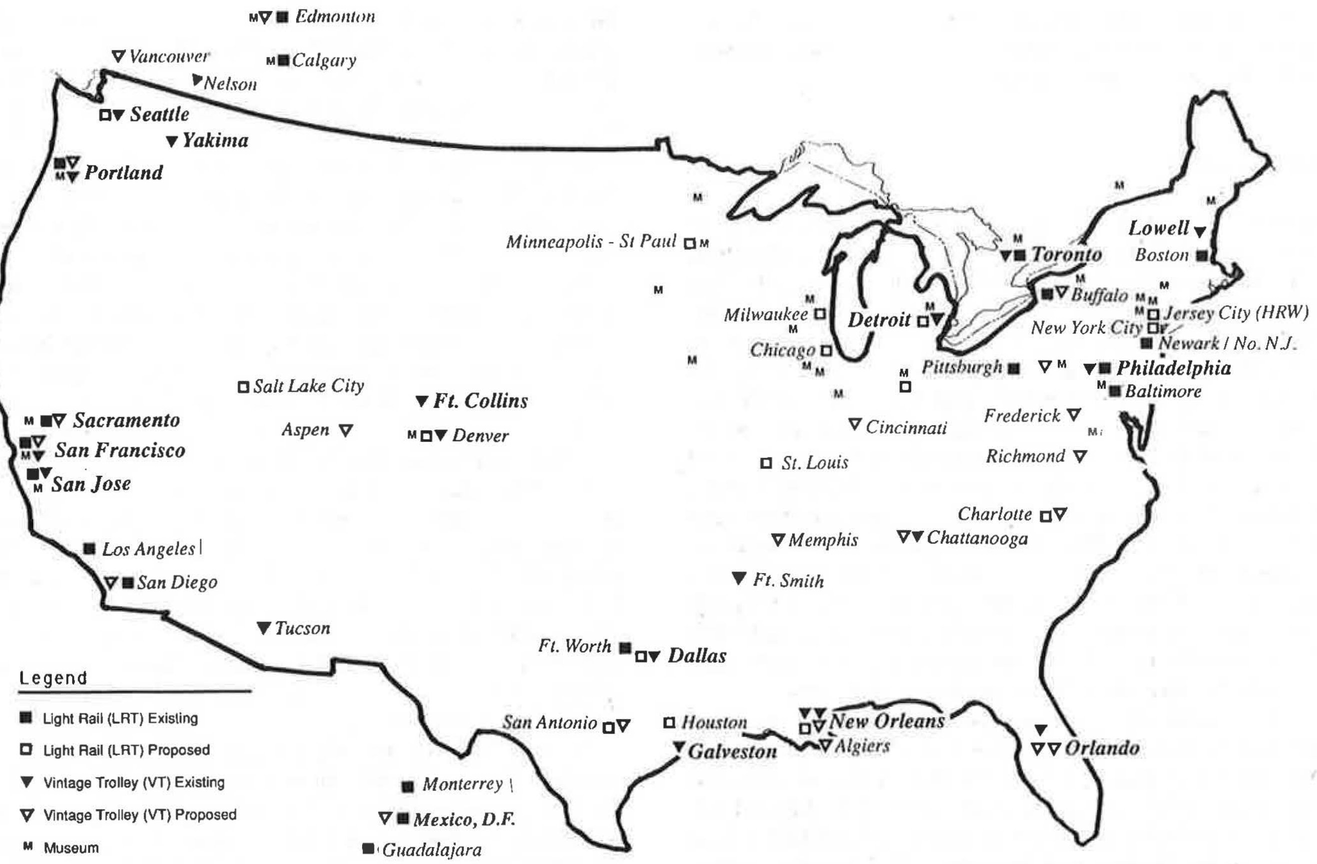

FIGURE 1 North American VT and LRT properties and proposals.

transit operator (22 percent), redevelopment district (5 percent), and UMTA (51 percent). The 1.5-mi line was built in a matter of months at a cost of $3.9 million a mile on reclaimed railroad right-of-way. The New Orleans Belt Railway continues to use adjacent tracks on common right-of-way. The streetcar line officially opened on schedule and on time for the Republican National Convention, 48 days after ground breaking. Daily ridership was forecast at 2,100 fares. Typical operating days yielded around 5,000, with peak holiday and weekend daily fares hovering around 7,000. The facility was expanded with additional cars and track. Now ambitious plans include extensions beyond both extremities of the Riverfront Line up to 8 mi and standard gauge extension up Canal Street and across Loyola and Rampart Streets using newly built replicas of the distinctive Perley-Thomas streetcars of New Orleans.

RESEARCH AGENDA

Some lessons can be learned from VT basics that may be applied to other transportation facility planning. Further, the data presented here suggest that VT merits serious consideration for more research and understanding. If one considers the number of properties alone and the astonishing average of one VT "new start" per year for the last two decades, then VT qualifies as the most popular and fastest growing of the rail modes being built in North America. By some counts, more than 60 light rail proposals are now being considered, many of which are VT. As the map (Figure 1) shows, VT is ubiquitous and should not be ignored by transit professionals.

Will VT encourage LRT or does it confer a stigma of obsolescence to rail transit? Does VT demonstrate a new approach to pedestrian-scaled and traffic-compatible transit distribution in downtowns? How does VT relate to CBD parking infrastructure? What is the real cost-benefit performance of VT? How does VT help comply with new initiatives in energy, clean air, historical preservation, and disabled access? Is VT a valid, less costly substitute for downtown people movers? How is VT best financed? Can it ever be self-sufficient? Should VT merit separate treatment as a subcommittee in the TRB hierarchy? These are just a few of the issues that demand attention in a VT research agenda.

ACKNOWLEDGMENTS

Little is formally written about VT. Although some VT properties are featured in trade and fan magazine articles, most VT information appears in news columns, newspaper articles, and promotional material provided by VT operators. In its present state, VT defies assembling a bibliography.

Practically no serious research has surfaced. The technical literature, financial and technical feasibility studies, to the extent that they exist, have not found their way into publishing channels. Those papers that exist are not research in nature, but tend to be expositions of "how we did it." These experience-sharing documents are useful in their comprehensiveness, but they do not focus on specific VT issues.

All of this means that to produce an overview of a subject like VT, one spends a lot of time on the phone, verifying details and interviewing operators. First drafts of this paper were circulated to a peer group of nearly 20 professionals representing varied interests in VT. The author appreciates their information, constructive comments, and suggestions. Thanks go to J. Aurelius, G. Benson, H. Botzow, E. Clark, J. Graebner, W. C. Graeub, M. Gaddis, R. Landgraf, J. McCall, F. Miklos, D. Minister, A. Morrison, M. K. Murphy, T. Parkinson, R. Roberts, F. Schultz, G. Thompson, J. Wilkins, and J. Wolfe.

Seattle Vintage Trolley Operations

GEORGE BENSON

The Seattle Waterfront Streetcar currently operates along a 2-mi (3.2-km) route through the city's central waterfront and Pioneer Square historical district. The Waterfront Streetcar uses a former freight line of standard-gauge track running north-south along the central waterfront and then proceeding east-west on new rail to Seattle's International District, where it links with the southern portal of the city's new downtown transit tunnel. Development of the initial 1.6-mi (2.6-km) leg of the system cost \$3.6 million. A 0.4-mi (640-m) extension in 1990 required new track and special engineering at a cost of \$6.5 million. The system operates five double-ended Melbourne Class W-2 streetcars dating from 1924 with up to three cars running at one time. The cars are electrically powered through overhead lines, and each can carry a total of 93 seated and standing passengers. The initial leg of the system entered operation in May 1982 and was extended in 1990 as part of a comprehensive downtown Seattle transit project. In 1991 the system recorded a ridership of 174,000 fares (during 6 months of operation) and generated revenues of \$130,000 against operating costs of \$863,000. Conceived in 1974 as an easily implemented tourist amenity, the system's development quickly encountered a series of political, regulatory, financial, and technical obstacles. Among these were obtaining permissions for use of a former freight line from multiple owners and contract users; locating suitable rolling stock; upgrading the route; soliciting financial participation from local taxpayers; and overcoming the skepticism of local and federal transportation planners. Although ridership has declined from a peak of 278,000 fares in 1983, the system is deemed a success. Use of the streetcar has suffered to a degree from the failure of the new downtown transportation system to reach planned operating capacity. Market research shows that streetcar use would benefit from active and sustained promotion. Developing vintage rail systems is probably never as easy as it seems at first blush, but the results can provide an attractive visitors' amenity and useful component in a comprehensive transit circulation system.

The Seattle Waterfront Streetcar began operation on May 29, 1982, and ranks as one of the United States' first experiments with creating and operating a vintage rail system. Initially intended to link visitor attractions along Seattle's central waterfront, the original 1.6-mi (2.6-km) line was extended by 0.4 mi (640 m) in 1990 and integrated into a comprehensive downtown transit system the central feature of which is a new crosstown transit tunnel (Figure 1).

It required 8 years to move the streetcar from a deceptively simple idea to an operating system. Along the way, the concept encountered a daunting succession of political, bureaucratic, financial, and engineering obstacles, and its development costs ballooned from a few hundred thousand dollars to nearly \$10 million for the extended system. Despite this, the streetcar has become a popular fixture and currently serves some 200,000 riders annually. Many Seattle citizens would sooner chop down the Space Needle than scrap the streetcars.

Seattle City Council, Seattle Municipal Building, Seattle, Wash. 98104.

GEOGRAPHICAL AND HISTORICAL CONTEXT

The Seattle Waterfront Streetcar service occupies a unique niche in the history of both Seattle's central waterfront and its transit services. Because trends and investments in waterfront development and transit planning will exert a major influence on the streetcar service's future role as a transportation amenity, they are reviewed briefly here to aid the reader.

Evolution of Seattle's Central Waterfront

Seattle's central waterfront stretches approximately 1.5 mi (2.4 km) along the eastern shore of Elliott Bay. It features a series of oblique piers originally designed to accommodate the steamers and ferries that were the principal vessels for the Pacific and Puget Sound prior to the 1960s. These piers were once served by a planked roadway built for rail and wagon traffic over tide flats. Most of the downtown piers and the appropriately named Railroad Avenue were built by private railroad companies that vied with each other for lucrative and exclusive public right-of-way concessions. These routes were used primarily for freight after the 1906 opening of a rail tunnel from the foot of Virginia Street to Union Station on the southern edge of the downtown business district (National Railroad Passenger Corporation [Amtrak] passenger service to Seattle currently terminates at the adjacent King Street Station).

When the Port of Seattle was organized as a public port district in 1911, many of the downtown piers and Railroad Avenue were turned over to public ownership. The railroads retained their rights-of-way as the port and city government filled in the shoreline with material from inland regrades and constructed present-day Alaskan Way for automobile traffic. An elevated double-deck viaduct was added in the 1950s as part of U.S.-99. This viaduct straddles the remaining waterfront rail lines and defines the western boundary of downtown Seattle, which rises to the east up a steep ridge.

The Port of Seattle's early commitment to container shipping technology had a profound impact on the character of the central waterfront. The construction of large truck-container piers south of Yesler Way diverted maritime activity away from the central waterfront's piers, and railroad traffic declined accordingly, except for north-south through-traffic beneath the Alaskan Way viaduct. Many piers were abandoned, and city planners began to shift priorities for the area from maritime to housing and entertainment uses. This transition was slowed by passage of the Washington State Shorelines Protection Act in the early 1970s, which emphasizes preservation of maritime commercial uses. But the economics of modern shipping has all but rendered the central waterfront obsolete for such purposes.

FIGURE 1 Axonometric map of downtown Seattle showing Waterfront Streetcar route and related transit facilities. (© 1990, Pocket Concierge Publishing).

As maritime commerce and employment shrank during the 1970s and 1980s, tourism activity increased, spurred by private development of new shopping arcades in pier sheds and the Waterfront Place neighborhood, and public investments in the Seattle Aquarium, Waterfront Park, Myrtle Edwards Park, and the nearby Pike Place Market and Pioneer Square historical districts. This trend is expected to continue in the 1990s with the port of Seattle's development of a major trade center, marina, and hotel complex adjacent to its headquarters at Pier 66.

Evolution of Seattle's Transit Planning and Services

Seattle's transit services began with development of private street railways in the late 1800s. These lines were often ancillary to private real estate or utility enterprises and followed no predetermined plan. Seattle's first attempt to adopt a comprehensive land use and transportation plan, crafted by Olmsted protégé Virgil Bogue, was frustrated by voters in 1912. The electorate was more receptive to public ownership of key utilities and in 1919 approved acquisition of private tracks and rolling stock to form the Seattle Municipal Street Railway. As in other American cities, the rise of the automobile doomed tracked trolleys in Seattle. The last of the lines was discontinued in 1941 in favor of diesel buses and trackless trolleys operated by the reorganized Seattle Transit System.

Comprehensive transit planning continued to languish until the late 1960s, when rampant suburban growth spurred development of a visionary plan for metropolitan heavy rail transit as part of a countywide "Forward Thrust" package of bond issues submitted to voters in 1968. Everything passed except the transit plan and a scaled-back version fared no better at the ballot box in 1970. The events of 1912 and 1919 seemed to repeat themselves, however, when county voters approved acquisition of private bus lines and the Seattle Transit System by the Municipality of Metropolitan Seattle, a countywide water quality utility formed in the 1950s.

The newly created Metro Transit immediately embarked on a series of ambitious service improvements and long-range planning. Its most significant capital investment to date is the downtown Seattle transit project, which features a transit tunnel running beneath the central business district between a northern terminal at the Washington State Trade and Convention Center and a southern terminal in the International District. This facility features three large stations along its 1.3-mi route and is linked by exclusive busways to Interstates 5 and 90.

The tunnel opened in 1990 and is currently served by dual-mode buses that convert from diesel to electric power when underground. Rails were installed in anticipation of future conversion to light rail service, and Metro Transit is developing a new comprehensive transit plan, which may include both light and heavy rail components for submission to county voters as early as November 1992.

GENESIS AND DEVELOPMENT OF THE WATERFRONT STREETCAR

The origin of the Seattle Waterfront Streetcar had nothing to do directly with the plans for either the central waterfront or metropolitan transit services in which it would later figure so prominently. Rather, it grew out of the enthusiasm of a local butcher, Robert Hively, who happened to own two Brill Master Unit streetcars salvaged from Yakima Valley in eastern Washington. Mr. Hively approached the author in January 1974 with the idea of operating these cars on switching tracks beneath the Alaskan Way Viaduct.

As a newly elected member of the Seattle City Council, the author naively believed that this should be a simple proposition. Take two vintage streetcars, secure a right-of-way on existing waterfront tracks, and recruit a handful of retired transit operators as motormen and—voilà!—a streetcar system in a few months at the cost of a few thousand dollars. Events quickly derailed this pleasant fantasy.

At that same time, Seattle Mayor Wes Uhlman and Councilmember Bruce Chapman were advocating a trolley line down First Avenue to link Pike Place Market on the north with Pioneer Square. Seattle, it should be noted, was a national leader in creating and financing preservation of historical districts, and a vintage trolley link between its two main attractions, which effectively bracket the downtown core, seemed to be a natural complement. When the First Avenue proposal proved to be costly (as a result of utility relocation and other necessary capital outlays), the waterfront line became the preferred route, but it was not without its own problems, fiscal and otherwise.

First, Hively's cars failed to meet FRA safety standards, which applied because the tracks the cars would run on were part of the transcontinental rail system. Estimates revealed that upgrading each car could cost $60,000.

The rail line itself had a tangled ownership dating back to the railway "wars" of Seattle's early history. Approvals for its use were required from Union Pacific, Milwaukee, and Burlington Northern, which actually operated the line and raised a host of technical objections to the idea. Additionally, individual pier owners had to waive their long-unused rights to service off the main line.

Finally, the railroad workers union had to approve an exception to the standard labor rules that required a three-person crew for any engines operating on interstate railways, even a trolley. After indicating an initial interest in a special arrangement for the streetcar line, the union decided to go by the book.

Despite Mayor Uhlman's public support for the streetcar concept, his planning staff decided that the line would be prohibitively expensive and irrelevant to the larger transit schemes then being developed by Metro Transit. As a newly elected member of the City Council, the author was oblivious to these bureaucratic maneuvers and blithely enlisted the support of U.S. Senators Warren Magnuson and Henry Jackson, who then ranked among the most powerful members of Congress. They in turn prevailed upon Burlington Northern to take a more flexible approach toward the notion. This support effectively switched the staff onto a dead-end spur, and the streetcar line got a political green light. (It should be noted that the city's planning staff was reorganized shortly after a new mayor, Charles Royer, took office in 1978.)

Burlington Northern officials, led by a regional vice president, Richard A. Beulke, suggested using the railroad's western-most running-tracks, which could be legally disengaged from the transcontinental system and federal regulation. This also cut the Gordian knot of union jurisdiction, putting the more flexible transit workers union in the "driver's seat" rather than the railroad workers union. Unfortunately, it did nothing to untangle the welter of historical rail rights-of-way dating back to the old Railroad Avenue and it took 2 years to obtain all of the necessary permissions.

As these negotiations progressed, the author took up the problem of finding suitable rolling stock, specifically standard-gauge, double-ended trams powered with 600 volts and built some 50 years ago. A national request for proposals elicited only two bids: one from Robert Hively and a lower bid from Paul Class, based in Glenwood, Oregon, who undertook a worldwide search for appropriate streetcars.

These were ultimately found in Melbourne, Australia. The author crossed the Pacific to examine these cars prior to purchase, which was fortunate because officials there had reserved inoperable cars for Seattle in the mistaken belief that the city was only building a museum display. Upon learning that Seattle meant to run the cars, they graciously gave the city the pick of their rolling stock. To date, Seattle has purchased a total of five Melbourne Class W-2 streetcars (Figure 2). Each car cost $18,000 ($5,000 for the car and $13,000 for shipping). Compare this with the $150,000-plus cost of a standard diesel coach or the $1 million-plus cost of a modern light rail car!

Although the cost of the streetcars proved a pleasant surprise, estimates for line improvements ballooned into the millions of dollars. At the same time, jurisdictional disputes arose between the city government and Metro Transit over financial and operating responsibilities. Newly adopted rules for handicapped access also imposed new costs in designing stations and reconfiguring rolling stock, but these also led to the first fully accessible surface rail system in the nation.

Matters were further complicated by the skepticism of the UMTA, to whom Seattle looked for about one-third of the $3 million construction budget (Senators Magnuson and Jackson again helped to overcome this resistance). With persistence, each of these obstacles was overcome, but on the eve of commencing construction in 1981, the city council balked at approving the local funding.

In an abrupt change of heart, the council demanded that as the streetcars' "primary beneficiaries," the downtown and waterfront business communities should shoulder the burden of local funding. The business and property owners rallied at a meeting on January 11, 1981, and gave their overwhelming endorsement (by a 72 percent majority) to a local improvement district to raise $1.2 million for construction through special tax assessments. This in turn required amendment of state law governing such tax districts during that year's session of the legislature. Even with this support, completing the system required enormous private assistance and volunteer labor from every stratum of the community. Even Bruce Nordstrom, principal in the fashion retail chain, pitched in to help paint the first streetcars for their inaugural run.

That came on May 29, 1982, and 3,000 citizens lined the route for the Waterfront Streetcar's first trip. The line was an instant success with tourists, waterfront businesses, shoppers, employees, and even city and Metro Transit bureaucrats. The journey from Bob Hively's simple idea to a functioning system had taken 8 years, cost more than $3 million, and spanned the Pacific Ocean from Melbourne to Seattle—all for a 20-min streetcar ride along 1.5 mi of waterfront (Figure 3).

PHYSICAL FEATURES OF WATERFRONT STREETCAR SYSTEM

Original Line

The initial route of the Seattle Waterfront Streetcar extended 1.6 mi (2.6 km) from Broad Street on the north to Main Street on the south. The system uses a single line of track located between Alaskan Way, a four-lane arterial, on the west and

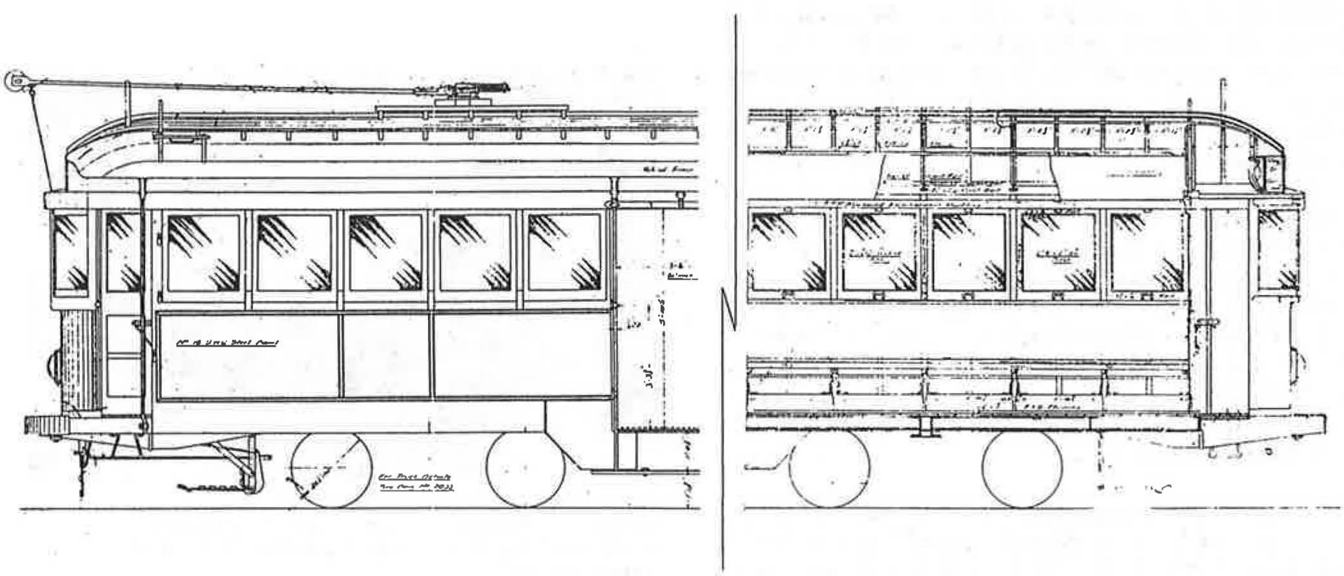

FIGURE 2 Schematic drawings of the Melbourne Class W-2 streetcar.

FIGURE 3 Melbourne Class W-2 streetcar in operation along Seattle's central waterfront.

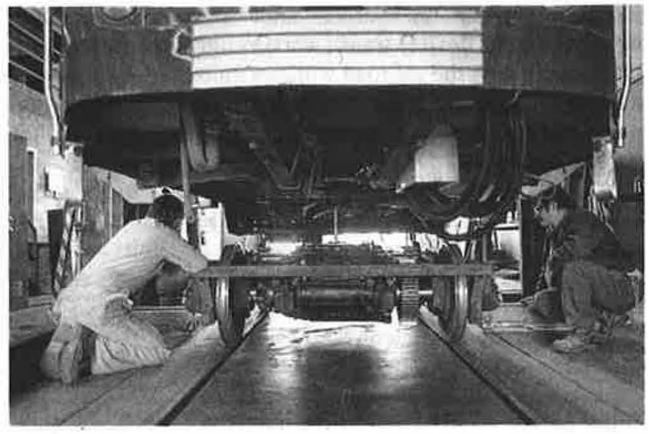

FIGURE 4 Seattle Waterfront Streetcar maintenance facility.

the Alaskan Way Viaduct on the east. One short passing track was constructed just south of Pike Street.

The northern terminus is 400 ft north of Broad Street and Pier 70, which marks the northernmost limit of the central waterfront and has been remodeled as a shopping and restaurant arcade. This terminus lies at the entrance to Myrtle Edwards Park, a popular shoreline greensward that continues another mile to the north. The streetcar barn for storage and maintenance is also north of Broad Street (Figure 4).

Following the line south, there are five "carstops" or stations spaced approximately four city blocks apart along the route: Vine Street, Bell Street, Pike Street, University Street, and Madison Street. Each carstop features a raised, handicapped-accessible, concrete platform with a steel and glass pergola shelter and benches (Figure 5).

The interim carstops correspond to major activity centers along the waterfront:

- Vine Street serves the Edgewater Inn, a large convention hotel on Pier 67.
- Bell Street serves the port of Seattle's headquarters at Pier 66, a site slated for major redevelopment by 1995.
- Pike Street serves the Seattle Aquarium and Omnidome Theatre on Pier 59. This station is also linked via a "hillclimb" system of stairs and elevators to the Pike Place Market, a landmark farmers market and tourist hub perched on the ridge top to the east.
- University Street serves Waterfront Park, a large, passive viewpoint that forms a crescent between Piers 59 and 57 and a converted pier shed retail arcade on Pier 57.
- Madison Street serves the Pier 52 terminal of the Washington State Ferry System, which provides transportation across Puget Sound for thousands of commuters and visitors each day. Madison Street also serves the new Waterfront Place complex of new and restored condominiums, apartments, offices, and retailers on the east.

The original southern terminal for the line was Main Street at the western edge of the Pioneer Square Historical District and adjacent to the Washington Street Boat Landing, a small public day-moorage for pleasure boats. Main Street also lies about five blocks north of the Kingdome, King County's sports and exhibition stadium.

Several design features of the system deserve mention:

- The tracks are bonded to limit wandering currents that might affect railroad switching systems and underground utilities.
- Grade crossing signals were added for cross streets north of Bell Street because of heavy truck use and limited visibility in this area.
- The Melbourne cars measure 48 ft (14.4 m) in length and 8 ft (2.4 m) in width and weigh 16 tons each. A motorman station is located at each end, and the cars are partitioned into three discrete passenger saloons for up to 52 seated riders and 41 standing riders. The saloons feature upholstered longitudinal benches and latitudinal benches crafted from Tasmanian mahogany. The cars are accessed via sliding doors on the western side behind the motorman station. Although dat-

FIGURE 5 Waterfront Streetcar at one of the fully handicapped-accessible carstops featuring steel and glass pergola shelters.

ing as far back as 1924, the Melbourne cars did not require major upgrading. Primary improvements included addition of a radio communication system, public address system, and warning whistles to each car.

Construction of the original system, including acquisition of the first three streetcars and grade crossing signals, cost \$3.6 million in 1982. Of this, \$1 million was provided by UMTA through Metro Transit; \$1 million was provided by the city of Seattle; \$1.2 million was raised by the local improvement district tax assessment; \$370,000 for signalization was provided by the Federal Arterial Safety Board; and the balance was donated by Burlington Northern Railroad and other private benefactors.

1990 Extension

Although initially scorned as little more than a toy by transportation planners, the Waterfront Streetcar was made an integral component in development of Metro's downtown Seattle transit project (DSTP) during the late 1980s. The DSTP faced two primary hurdles: how to expedite commuter and crosstown routes through Seattle's narrow downtown core (which is pinched to as few as seven blocks between Interstate 5 and the waterfront) and how to increase internal circulation via transit feeder services.

After much debate, a north-south transit tunnel beneath Third Avenue was adopted as the best solution for commuter and through services. Metro then turned to two "vintage" systems to supplement the existing "Ride Free" downtown zone within which a rider may travel via any coach at no charge. The Alveg Monorail, an artifact of the 1962 Seattle World's Fair, provided a link to Seattle Center, the former fairgrounds and now the city's principal performing arts complex that lies 1 mi north of downtown. The monorail's southern terminus was integrated into the new Westlake Mall shopping arcade, which, in turn, opens on to the Westlake Station of the transit tunnel.

The Waterfront Streetcar offered a second link to the waterfront that lies four blocks west and down a steep ridge from the tunnel. In 1990, the streetcar line was extended eastward on Main Street through the heart of Pioneer Square and then southward on Fifth Avenue to terminate at the International District portal of the tunnel. Two carstops were added at Occidental Park in Pioneer Square and at the International District terminus, and two additional Melbourne cars were acquired and modified for service.

Construction through Pioneer Square required stabilization of the subterranean areaways (the famous "Underground Seattle" catacombs left over from turn-of-the-century landfilling) and laying track on the Main Street automobile bridge over the Burlington Northern tracks leading to the downtown rail tunnel.

The extension required fabrication of new track, which was performed in Luxembourg. At street crossings, hard rubber tracks are used out of consideration to bicyclists.

These special engineering solutions raised the cost of the 0.4-mi (640-m) extension to \$6.5 million—nearly twice the cost of the original line. This cost was borne almost entirely by Metro Transit as part of the DSTP budget. The extended line entered full operation on June 23, 1990, and the entire DSTP system was inaugurated the following September.

PERFORMANCE AND OPERATING EXPERIENCE

The system operates 12 hr per day year-round with a minimum of two cars with 30-min headways. One car is added during peak times and the summer, reducing headways to 20 min. Each car is manned by a motorman and conductor.

Between May 1982 and this writing, the system had experienced no major accidents or breakdowns. Liability claims over the past 8 years total \$300—including a \$100 claim for a pair of eyeglasses broken during an emergency stop.

The streetcar (like the monorail) is not subject to the downtown "Ride Free" zone. Metro charges its standard one-zone fare (currently 75 cents) and issues a transfer that allows each rider to board any Metro vehicle, including the streetcar, at no charge for 1 hour.

The streetcar's first full year of operation in 1983 registered its best ridership to date with 277,801 fares. Novelty and a strong tourism season played an obvious role in this initial success. Ridership declined to 232,000 fares over the next 3 years, rose to 242,000 fares in 1987, and then declined anew to 201,000 fares in 1989. Allowing for the system's shutdown for a full quarter during its extension, this ridership level was maintained during 1990. Total ridership in 1991 registered a further drop to 174,000 fares, but the system operated for only 6 months because of storm sewer work along the waterfront. Thus the extension appears to be reviving ridership to earlier levels.

Table 1 compares streetcar and total Metro Transit ridership between 1982 and 1991. Causes for these ridership trends are difficult to pinpoint. It should be noted that overall Metro ridership declined steadily from 1982 to 1988. Further, all of downtown Seattle was disrupted by a major public and private building boom (including construction of the DSTP) during the late 1980s, which discouraged tourists, shoppers, and employees from circulating through the district.

Streetcar ridership no doubt suffers from the failure of the DSTP to achieve its full service level because of mechanical problems and delivery delays for its dual-mode coaches. The transit tunnel is also closed on Sundays, a prime tourism day when riders might be expected to use the tunnel-streetcar link. Additionally, marketing research shows that streetcar ridership is very responsive to promotion, but promotion has been sporadic at best.

Farebox revenue in 1991 totaled \$129,600 against operating costs of \$862,000. Table 2 breaks revenues and costs down per passenger, hour, and mile. The revenue shortfall is made up from a variety of sources, including advertising sales and an UMTA operating grant of \$200,000 per year. It should be noted that the streetcars' operating costs are partially offset by elimination of conventional coach service along the central waterfront.

TABLE 1 Comparison of Waterfront Streetcar and Metro Transit Ridership and Revenue

Year	Streetcar Ridership	Streetcar Ridership % Change from Previous Year	Transit System Ridership % Change from Previous Year	Streetcar Hours	Streetcar Revenue	Streetcar Miles
1991*	174,000	12%	0.5%	12,400	$129,600	47,500
1990	154,886**	-23%	4.2%	9,128	$108,003	N/A
1989	201,531	-12%	4.1%	5,784	$100,303	"
1988	228,375	-6%	0.8%	6,269	$112,036	"
1987	242,596	4%	-3.5%	5,840	$121,089	"
1986	232,194	0%	-2.2%	5,897	$116,864	"
1985	232,058	-2%	-2.1%	5,833	$120,359	"
1984	237,350	-15%	5.0%	N/A	$123,790	"
1983	277,801	14%	-1.6%	"	$145,896	"
1982	244,179			"	N/A	"

*1991 Estimates based on Year-to-Date through November 1991

** Waterfront Streetcar was not in service for most of the first quarter. Bus service was substituted, for which service hours data are available but not passenger trips data.

TABLE 2 Comparison of Waterfront Streetcar Operating Costs and Revenue

1991 Projected Total Streetcar Operating Expenditures = $862,930 ***

	1991 Total Oper. Costs	1991* Farebox Revenue
per Hour	$69.59	$10.45
per Mile	$18.17	$2.73
per Passenger	$4.96	$0.74

*1991 Estimates based on Year-to-Date through November 1991

*** Metro 1992 Budget. Includes Salaries, benefits, materials, supplies, and services.

CONCLUSIONS AND EXPECTATIONS

Vintage transit systems are necessarily unique propositions wherever they are undertaken. This means that critical factors of popularity, political support, potential use and funding, and physical characteristics will vary dramatically with locale. Thus it is difficult if not impossible to fashion a general prescription out of any single city's experience. This said, at least a few helpful tips can be gleaned from Seattle's experience with its Waterfront Streetcar.

First, do not assume that re-creating or simulating an older system is as simple as it may sound. Reviving an older transit technology can be just as daunting as pioneering a new approach. Adapting older machinery to a modern transportation context presents its own set of special engineering and operational problems. Be especially alert to the layers of legal and regulatory arrangements in which older commercial rail lines may be entangled.

Second, although integration of a vintage system into a new transit system is a self-evident virtue, it creates problems as well as opportunities. The danger, as Seattle has experienced so far, is that the vintage component may be dragged down by shortcomings of the larger system.

Third, unlike supernatural baseball fields, the formula, "build it and they will come," does not guarantee ridership for vintage rail. Aggressive and ongoing promotion is needed to generate passengers and farebox revenue.

The author believes that the Seattle Waterfront Streetcar faces a bright future. Its ridership will benefit as the bugs are worked out of the total downtown Seattle transit project, and use can be expanded through targeted promotion (e.g., as a shuttle between outlying parking and the Kingdome for major sports events).

Foremost, the author is gratified by the outpouring of public sentiment in favor of the streetcar. Like other famous Seattle "follies," such as the Space Needle and the monorail, the streetcar has become a beloved fixture of the city's landscape and in her citizenry's hearts. A steep grade had to be climbed in taking the Waterfront Streetcar from idea to reality, but it was worth it.

Vintage Trolleys in Santa Clara County

MALCOLM R. GADDIS

The Santa Clara County Transportation Agency, light rail division, has a 21-mi system operating from the Great America area of the city of Santa Clara to the Santa Teresa area south of San Jose. Vintage trolleys operate over the downtown track for a distance of about 4.5-mi, providing alternate local service from the Civic Center to the downtown mall, serving various shopping and restaurant areas. The historical trolleys used include four early California-type cars constructed primarily of wood that originally served the local area. These cars were all restored from vehicles found nearby. Two international cars are on the roster, one from Melbourne that operates regularly and a Milan car that is still being restored. Trolleys are operated by regular light rail vehicle (LRV) operators who receive additional special training for this service. Special overhead trolley hardware was installed when the original light rail contact wire was put up; this avoided changes at a later date. The transit mall was opened for LRV service on June 17, 1988, and the vintage cars went in service on November 18, 1988. Both trolleys and LRVs use the same stations and connect with various bus routes in the downtown area. The regular fare for vintage trolleys, which operate from 9:30 a.m. to 3:00 p.m., is 50 cents.

Electrified streetcars first appeared in San Jose, California, in the early 1890s. The first electric system was a narrow-gauge line from San Jose to Santa Clara. Various power collection methods were tried, including an underground system that was quickly replaced by overhead wire. First Street was successfully electrified, and service was initiated on February 20, 1891. From this beginning, branches radiated south to the cemetery, east to Alum Rock Park, west to Saratoga, Campbell, and Los Gatos, then finally north to Palo Alto.

By 1915 there were 126 mi of trolley wire in the Santa Clara Valley, and the streetcars were at the height of their popularity. By this time, two systems were operating, one of which was the Peninsular Railway that ran to Palo Alto, Congress Springs, Los Gatos, Saratoga, Campbell, and Alum Rock Park. The most popular ride in this period was the "Blossom Trolley Trip" usually operated with the "Big Palys" series of cars, numbered 105–112, built by Jewett in 1913. These cars were the same as the 1000-series of the Pacific Electric (PE) Railway in Los Angeles, and, after abandonment, they were sent to the PE where they lived out their lives as cars 1050–1057 until they were scrapped in the 1950s.

The other company operating streetcars in the area was the San Jose Railroad. It was related to the Peninsular, with which it sometimes exchanged cars, and the two systems also shared some track. However, the San Jose Railroad operated primarily within the city limits of San Jose, with the exception of a northern extension to the city of Santa Clara.

The Peninsular Railway abandoned all service with the closing of the Mayfield Line in October 1934. The remaining equipment included some city cars, a box motor, wrecker, and line car, along with about 12 mi of track in city streets, which were conveyed to San Jose Railroad. The San Jose Railroad continued to operate until April 10, 1938, at which time all of the South Bay area bade farewell to their once-proud streetcar system.

Following the end of trolley service in San Jose, rails in the street were paved over, car bodies were stripped of all usable metal and the remains sold to farmers for storage sheds, while some went for living quarters. In the late 1950s, the body of Peninsular Railway Car 61 was lifted out of a backyard and taken to Lou's Village Restaurant, where it was partially restored as a museum piece. It and the body of Car 52 eventually made their way to Rio Vista Junction, where they are now in the Bay Area Electric Museum.

REBIRTH OF THE TROLLEY SYSTEM

With the surge of interest in building a new light rail line in San Jose, a few rail enthusiasts remembered the vintage cars that operated downtown; they hoped to find an old trolley car body that could be restored.

The first car located was actually a Sacramento car, No. 35, which had been in operation until about 1948 when its body was sold for use as a storage shed. This car was picked up by Charles Smallwood, placed on a pair of dummy trucks, and stored at Rio Vista in the trolley museum. It was later donated to the San Jose Trolley Corporation with the stipulation that it be numbered Car 129 and be painted the yellow and red of the San Jose Railroad.

In the early 1980s, two former San Jose trolley cars were located along Almaden Road. They had been used for farm worker housing and had badly deteriorated over the 40-plus years they had sat on the ground. These car bodies (Peninsular No. 73 and San Jose Railroad No. 124) were moved to the Kelley Park/San Jose Historical Museum in 1982. About the same time, it became apparent that some sort of organization was needed if these cars were going to be properly restored and made suitable for operation.

TROLLEY CORPORATION ESTABLISHED

The San Jose Trolley Corporation was formed in 1982 for the purpose of restoring vintage trolley cars. Restoring trolleys is a very complex operation, starting with an old termite-eaten car body and ending up with a fully operational vehicle that will meet all Public Utilities Commission (PUC) requirements for revenue passenger service. Without an organization, the cars remained in the dirt, and little progress was made to restore them.

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Fans took a look; some sanded a little to see what the other colors of paint were that had covered the bodies over the years. It soon became apparent that if these cars were going to be restored, a lot of work had to be done, and a lot of money would be needed. Buildings would be needed where qualified workers could turn axles, weld underframes, wire the high voltage systems, replace the roofs, put the air brakes back on—the list went on and on.

The new San Jose Trolley Corporation included charter members, such as Rod Diridon, a well-known Santa Clara County Supervisor, with a great interest in rail transportation. He was joined by a group of community leaders, including lawyers, businessmen, labor leaders, skilled workers, and numbers of very willing (though not quite so skilled) volunteers.

One of their first projects was to build a trolley barn in Kelley Park in south San Jose. Pacific Gas and Electric (PG&E), along with several building contractors, donated materials and labor to construct this three-track building with several work areas. Old machine shop equipment was donated along with woodworking tools, all of which seemed to find their way to the building along with people who wanted to help.

LEADERSHIP FOR THE TROLLEY SHOP

The next task was to search the country for an experienced master car builder, a full-time position. The person needed to have streetcar restoration experience and also had to be someone who could direct volunteers as woodworkers, painters, electricians, machinists, pattern makers, upholsterers, and glass cutters. At the same time, this person needed to be able to work with high school and college students, make drawings of any part on the car, while knowing how to repair air brakes.

Fred Bennett was hired from the Branford Museum in Connecticut, and for more than 5 years he has patiently overseen the work as the cars have changed from rotted sheds to beautiful works of art—comparable to trolleys just delivered from the American Car Company.

Each of the first trolley cars took more than 3 years to bring back to life. This represents a lot of hand labor, but that is only part of the reconstruction. Each restoration takes a lot of money. For example, the two car bodies recovered from Almaden Valley had been resting on the ground for 50 years. Much of the work body was rotted away or full of termites. Nearly every metal part had been removed before the car body was sold at the San Jose Railroad's scrap yard on San Carlos Street. The wheels and axles were gone, along with the traction motors, air compressor controls, and air brake equipment. When used as houses, sides were removed and bathrooms were installed, holes were cut in the floor, windows were knocked out, and roof lines were changed.

What was left was not much to work with, but with a closer look and a little imagination, an old streetcar could be seen. Looking for new hardware for a car built 90 years ago is a full-time job in itself. New wheels and axles were purchased so that the cars could run on the Santa Clara County Transportation Agency (SCCTA) light rail system and meet railroad standards. K-35 controllers were purchased from Milan, Italy. Air compressors were purchased or traded from other trolley museums. Many wooden patterns were made and taken to the local foundries to get parts for seats, couplers, queen posts, brakes, handles, and numerous other pieces of hardware. New high-voltage wire was purchased along with heavy-duty steel air piping. Trolley poles are still made as well as whistles and bells. But all this adds up, and the cars probably cost about $200,000 each.

PARTS FOR RESTORATION

Obtaining parts to reconstruct vintage trolleys is an endless task.The first car was delivered with a body in reasonable shape, and it also had a pair of turn-of-the-century Brill 27G trailer trucks. The wheels were worn beyond condemning limits, so it was necessary to purchase new wheels from Standard Steel, Burnham, Pennsylvania. These were bought to match the LRVs with Association of American Railroads (AAR) standard contour, but slightly more clearance back-to-back to allow for operation on down to 80-ft radius curves. With only the set of trailer trucks, it was necessary to obtain matching power trucks. As a result, a pair of Brill 27G American-built power trucks was purchased from a museum in Minnesota. The two trucks differ in some respects, such as wheel base, axle diameter, and hardware; however, only a sharp traction fan would notice the difference.

It was decided to keep two motors in one truck and run the other as trailer truck, rather than one motor in each truck as had been the operation standard in the early days in San Jose. Cars 124 and 129 now operate with mixed Brill trucks and full 5-1/2-in.-wide tires.

The next trucks that were available were two pairs from Melbourne, Australia. These trucks are very similar to American-built M.C.B. types as used in many high-speed cars and locomotives. When these trucks were received from Melbourne, they had narrow transit-type tires and would have dropped through the frogs on the LRV system, so it was necessary to replace the old tires. During a study of the truck frames, it was determined that a wheel set with 5-1/2-in. tires would not fit without contacting the equalizer or other truck hardware.

Early electric interurban cars designed to operate partially over steam railroads had a "compromise" wheel that would operate on street railways as well as steam main line. These cars had tires measuring nearly 4-1/2-in.-wide. Tests were made through the light rail yard and over various switches, and it was determined that the 4-1/2-in.-wide tire would operate safely and had several years of reserve metal to keep it from dropping into No. 4 switch frogs. As a result, four of the vintage cars will have compromise 4-1/2-in. tires. In more than 2 years of regular operation, Car 73 has shown little wear on any of the tire surfaces. This particular car also has composition shoes.

The first vintage streetcar was placed in service in November 1988; to date, no wheel turning on the Hegenscheidt lathe has been required. A few minor slid flat wheels have been experienced; however, they have all been small enough to wear back round or to true up with hand grinding.

All cars are equipped with GE K-35 controllers, whereas all but the Australian car have LB-2 line breaker control handles. The Australian car is equipped with an older ratchettype line breaker control that has provided very reliable service.

A slight reverse movement on the operating handle of either controller unlatches the power to the overhead line breaker, immediately dropping the power to the traction motors. This safety provision has been used as a near equivalent to a "dead man" system for nearly a century. In addition to the controller-power off provisions, vintage cars are all equipped with a series of overhead line breaker switches at each end of the car. This allows the conductor in the rear of the car to also cut off power in an emergency.

UPGRADING FROM MUSEUM STANDARDS

Most vintage streetcars are restored to a museum standard that is usually a thing of beauty with much polished wood, bright brass, and glistening paint.

To operate a historical trolley in revenue service, much more work is required. The window glass at the ends of the car must be safety plate, seats and gates must always operate properly, the brakes must pass strict stopping distance tests, steps must have the required clearance, trucks must be completely overhauled and meet operating railroad requirements. The whistle and bells must work at 75 to 85 dB(A), and the hand brakes must be able to hold a full car on the steepest grade.

When operating in revenue service, vintage cars come under the California PUC, and they are subject to the same rules as LRVs.

POWER

Overhead power for Santa Clara County's light rail system is supplied at 840 volts direct current (dc) to the overhead. Historically, most vintage trolley systems operated from 550 to 600 volts dc. Therefore a voltage dropping device is required to protect the traction motors and other electrical equipment. Several exotic devices were investigated, such as multiple groups of MOSFETS (a semiconductor circuit for dropping voltage and maintaining uniform output with various loading). Reducing dc from 900 to 600 volts at 200 amps with electronic circuit has not yet been developed to meet trolley car requirements. Vintage cars in San Jose use a heavy-duty 2 ohm dropping resistor for the power circuit and other combinations of resistors for the compressor and controller latching. The power resistor arrangement is made up of sixteen 0.89 ohm Milwaukee resistor elements, part No. 792. This provides eight even steps of power, five in series parallel and three in straight parallel.

Current limiting is handled by a GE DB-986 overhead line breaker set to trip at 200 amps. This setting provides overload protection to the traction motors and will trip if the operator advances the K-35 controller faster than 1 sec per position.

The air compressor (CP-25) has a 90-ohm resistor in series to drop the dc voltage to about 575 volts. Amperage in the circuit is less than 5 amps.

Lighting circuits are made up of two sets of seven GE 56-watt 120-volt street railway lamps in series. A headlight switch directs power either to the headlight or to an overhead lamp above the operator. When the overhead lamp is on, it is an indication that the headlight is off. Each vintage car has a total of sixteen 120-volt lamps, with the location of lamps varying with the style of car. Some have step lights if steps are at the corners and light at night will help passengers.

OVERHEAD WIRE CHANGES

Integrating vintage trolleys with LRVs in the transit mall area of downtown San Jose was considered before the contact wire was strung in that area. Trolley wire frogs were installed as the overhead was being put up; also, additional tie wires were installed and circuit isolators were revamped to accept trolley poles. In the downtown area, all of the Siemans insulator clamps were replaced by Ohio Brass hollow screw clamps so that the trolley car J-type shoes would not contact the large Siemans bolt heads.

Regular routes were established for trolley cars in and out of the shop area so that all the overhead wire involved was equipped with the required trolley frogs. The downtown area is completely equipped with overhead frogs so that vintage cars can continue to loop the mall or pull out of the way of LRVs on the northbound loop off First Street.

SCHEDULING

Vintage cars are scheduled to follow right after LRVs whenever possible. When departing from the shop holdover point, trolleys wait for scheduled LRVs to pass before entering the main line. If an LRV is in sight on the downtown loop heading back north, the trolley will hold up to let it pass, avoiding any possible delay on First Street. Figures 1 and 2 show the route.

Heaviest usage of vintage cars usually occurs between 11:30 a.m. and 1:30 p.m. when office workers take the vehicles downtown for lunch. During the Thanksgiving and Christmas holidays, patronage is high when the cars are running later at night to accommodate shoppers and people who want to visit the downtown holiday displays.

SERVICE HOURS

Normal trolley service hours are from 9:00 a.m. to 3:30 p.m. weekdays and 11:00 a.m. to 6:00 p.m. weekends and holidays. Trolleys run every 20 min between the Civic Center Station and downtown.

FARES

Regular vintage trolley fares are 50 cents for adults (18–64 years) and youth (5–17 years). Seniors (65 and older) and disabled passengers pay 25 cents. Tickets have a 2-hr time limit. Tickets may be purchased from ticket vending machines at the transit mall or Civic Center Light Rail Station. A button on the vending machine is marked Historic Trolley. Valid Santa Clara County Transit District bus and light rail passes

FIGURE 1 San Jose transit route.

FIGURE 2 Historic trolley service route.

are good on vintage trolleys, but vintage trolley tickets are not valid for travel on LRVs or buses.

PUBLIC ACCEPTANCE

The combination of vintage cars with the streamlined LRVs provides an attractive contrast in transportation. Local residents enjoy taking a step back in history by climbing on the old-fashioned cars that served their city 50 years ago. Tourists enjoy a ride on the San Jose vintage trolleys and make the cars a part of their trip—just like their planned tour on the San Francisco cable cars.

TROLLEY CARS IN SERVICE

Each of the five vintage trolleys in service has an individual history and its own set of distinctive features. Table 1 summarizes this information.

Car 1 was built by the Sacramento Electric, Gas, and Railway Company and ran in Sacramento from 1903 to 1906. It was sold to the new standard-gauge Union Traction Company in Santa Cruz, California, in 1907, going into service after the 1906 earthquake. In 1923 it was taken out of service and used as living quarters behind a laundry on lower Pacific Avenue. The laundry owner donated the deteriorated car body, which was then in two pieces, to the San Jose Trolley Corporation. A new steel underframe replaced the rotten wood floor and the body areas. The car was then reconstructed one board at a time with wood sides and brass hardware. The car body was restored to its original "convertible" configuration. For summertime at the beach, the windows and sides could be removed—making it a completely open car. The interior of the car is solid ash. It was returned to service in San Jose on August 3, 1990.

Car 73 was built by the Jewett Car Company in Newark, Ohio. It ran in San Jose for the San Jose Railroad from 1913 to 1934. Then it was sold for use as housing on Old Almaden Road. Car 73's exterior is bright yellow (similar to Car 129's) that contrasts with a rich mahogany interior that is almost identical to Car 124's. Car 73 returned to service on May 12, 1989.

Car 124 was built for the San Jose Railroad by the American Car Company in St. Louis, Missouri. It ran in San Jose from 1912 to 1934. Then it was sold with Car 73 for use as housing. In 1920 its original red paint scheme was changed to yellow and windows were added to the open sections. Car 124 was

TABLE 1 Vintage Trolley Data

CAR #1		CAR #129	
BUILDER	Sacramento Gas & Electric Co. 1903	BUILDER	American Car Co. 1913
WEIGHT	34,000	WEIGHT	38,000
SEATS	48	SEATS	36
TRUCKS	Milan 1928	TRUCKS	Power - Brill 27G 4 '6" wheel base Trailer - Brill 27G 4 '10" wheel base
MOTORS	4 Milan 27 HP	MOTORS	2 Brown Bouarie, 65 HP
CONTROL	GE K-35KK	CONTROL	GE K 35KK
COMPRESSOR	CP25	COMPRESSOR	CP 25

CAR #73		CAR #531	
BUILDER	Jewett Car Company 1913	BUILDER	(M&MTB) Melbourne, Australia 1928
WEIGHT	38,000	WEIGHT	36,000
SEATS	36	SEATS	56
TRUCKS	Melbourne	TRUCKS	Melbourne
MOTORS	4-40 HP	MOTORS	4-40 HP
CONTROL	GE K-35 KK	CONTROL	GE K-35 JJ
COMPRESSOR	CP 27	COMPRESSOR	CP25

CAR # 124		CAR #2001	
BUILDER	American Car Co. 1912	BUILDER	Officine Neccaniche Lodigiane-Lodi 1929
WEIGHT	38,000	WEIGHT	36,000
SEATS	36	SEATS	29
TRUCKS	Power- Brill 27G 4'6" wheel base Trailer- Brill 27G 4'10" wheel base	TRUCKS	Milan 1928
MOTORS	2 Brown Bovarie 65 HP	MOTORS	4-Milan 27 HP
CONTROL	GE K-35KK	CONTROL	GE K-35KK
COMPRESSOR	CP25	COMPRESSOR	CP 27

restored and returned to service in San Jose on November 18, 1988.

Car 129 was built by the American Car Company for Sacramento Gas and Electric. It operated in Sacramento as Car 35 from 1913 to 1948 and is identical to cars that ran in Santa Clara County. After 1948 the car was used as a storage shed before being acquired by Charles Smallwood and leased to the San Jose Trolley Corporation for restoration. Before his death in 1986, Mr. Smallwood requested the corporation renumber 35 to Car 129 and paint it the yellow San Jose Railroad colors. It returned to service on November 18, 1988.

Car 531 was built in 1928 by the workshops of the Melbourne and Metropolitan Tramways Board (M&MTB) in Melbourne, Australia, and ran on the 200-mi Melbourne trolley system from 1928 to the mid1980's. It was retired from service during an upgrade of M&MTB's trolley fleet. The San Jose Trolley Corporation bought the vintage trolley in 1986. Restored to its original factory-fresh chocolate-and-cream paint scheme, Car 531 features Tasmanian mahogany and polished chrome accents. It began service in San Jose on January 26, 1990.

Car 2001 was obtained from Milan, Italy, and was part of the group numbered 1993 to 2002 built for Azienda Transporti Municipali. The car was built for single-end operation and had three doors on the right side, unlike all of the other vintage trolley equipment in San Jose, which is equipped for double-end operation with doors on both sides.

The underframe appeared to be weak at the ends, and it was desirable to rebuild this car into a special charter car for possible service north to Santa Clara. The reconstruction of this car involves extensive steel work, the exchange of ends from Car 1943, new doors on the blind side along with heavy collision posts, and removal of many old and rusted structural parts. When completed, it will resemble a double end Peterwitt.

OPERATING FIXED COSTS

Operating costs for the vintage trolleys are shown on Table 2. In 1991, they totalled $641,500. Fixed costs, such as the initial cost for construction of maintenance and storage facility for six vintage trolleys and necessary improvements for their operation including powered switches, trolley pole provisions, and transponders, total $1.9 million.

LEASE AGREEMENT FOR SIX TROLLEY CARS

The Santa Clara County Transit District board of supervisors leases completed trolley cars from the San Jose Trolley Corporation at a nominal $1 per year. The district is also responsible for all operations and maintenance. Trolleys run on the San Jose transit mall and other such sections of the Guadalupe Corridor light rail system as permitted by the district. All operations of the trolleys are solely under the direction of the district, including, but not limited to, general purpose

TABLE 2 Approximate Annual Trolley Operating Costs, 1991

PERSONNEL - SALARIES & BENEFITS		
6.0	Operators	$275,000.00
1.0	Manager / Supervision	80,000.00
2.0	Elector-Mechanics	100,000.00
Administrative Support and Overhead		115,000.00
SERVICES AND SUPPLIES		
Insurance		$16,000.00
Traction Power		21,000.00
Vehicle Parts		20,000.00
Tools and Equipment		4,000.00
Vehicle Delivery		2,500.00
Miscellaneous		8,000.00
Total		$641,500.00

and function; method of operation; fare structure and method of collection; and charter usage. Although the district is unable to alter the appearance of any vintage trolley in any way without approval by the San Jose Trolley Corporation, the collection of fares, operational procedures, and security measures are the responsibility of the district. The district is also encouraged to implement programs to discourage the use of the trolley vehicles for any purpose other than public transportation.

If a vintage trolley should be totally destroyed, the insurance payment covering the necessary parts, components, wheels, body, motor frame, and brake system is to be remitted to the San Jose Trolley Corporation. It will be their decision whether to obtain and rehabilitate another similar vintage trolley.

FINANCING

The cost for all materials and parts needed to equip a car body probably rounds out to about $200,000. To this is added a few thousand hours of volunteer labor and supervision. After the vintage car is assembled at Kelley Park Trolley Barn, it is moved on a flatbed trailer and taken to the light rail maintenance facility where the shop crew usually spends 3 or 4 weeks completing detail work and checking safety appliances. Lengthy tests are made to ensure that the car is ready for revenue service.

Money to purchase wheels, motors, controllers, air brake equipment, and all the other required hardware is obtained from various sources. Many local business people have contributed generous sums, including The Fairmont Hotel, San Jose Mercury News, Heritage Cablevision, Hugh Stuart Center Charitable Trust, Collishaw Corporation, Pacific Gas and Electric, California Engineering, UTDC, Peninsula Crane and Rigging, and Kearny Pattern Works, along with many donations from the volunteer workers who developed more of an interest as they worked restoring the cars.

DOWNTOWN OPERATION

Operating vintage streetcars on downtown streets has generated a great deal of public pride by providing visible ties to the community's past. With a mixture of old and new building styles in the downtown, the combination of old and new transit cars presents a compatible blend of styles (Figures 3 and 4).

The pleasant attitude of the regular vintage car operators gives old and new passengers a warm feeling as they board and ride through the downtown area. Both types of cars make the same stops, with maximum speed in the mall held to 15 mph. Trolleys tend to stay at 15 mph; however, in separated center sections of track on North First Street, vintage trolleys may increase their speed to 25 mph or more.

Rail fans and tourists find riding on and photographing the vintage cars a great pastime, but the largest share of the riders are locals. At noontime several large surges of working people ride downtown for lunch. Many shoppers just ride a stop or two and then later catch an LRV or a bus home. At nearly any time of the day, families, school groups, business people, and others can be found just taking a ride or two for the pleasure of the trip. During the Christmas season, with the increased shopping push, two cars are usually operated continuously, and the cars remain generally full.

FIGURE 3 Modern light rail vehicle at a station.

FIGURE 4 Vintage trolley at a station.

The vintage cars have been involved in two minor accidents with automobiles. No one was hurt in either accident. All vintage cars have a standard-height anticlimb bumper that also locks with an LRV if bumped together on the end. The anticlimber holds the cars together and prevents them from climbing over each other and wiping out the end of the car. All the trolleys have reinforced ends to protect the passengers and operators. Vintage cars are not designed for high-speed, main-line service; the only exception to this is the Milan car now being converted from single-end to double-end operation. When this steel car is completed, it will have heavy collision posts at both ends with reinforced end platforms and a pantograph. It will then be able to operate north to Santa Clara in the median of First Street and Tasman. Here, trolley speed will be governed by the trucks and low gear ratio of the traction motors, probably not exceeding 25 mph. When operational, this car will be available for charters in addition to regular downtown service.

TRAINING

Prior to running a vintage trolley at SCCTA, an operator must have a Class B commercial driver's license, must have taken the necessary bus operation training to get that license, and completed LRV operator training. The 1-week "Historic Trolley Training Course," which starts with a special "Book of Rules" section and test, includes a review of car equipment and operating procedures. A hands-on examination is given, including use of air brakes, the controller, trolley pole power pickup, running lights, transponder, and emergency stops without air brakes. All this is followed by an operation qualification test. Scores on portions of the examination must be 100 percent correct or the course must be taken over.

INCLEMENT WEATHER

During inclement weather, ridership on the vintage trolleys usually drops. In addition, four of the trolleys are California Cars and have open ends with much exposed finished wood and rattan seats, so these cars are kept inside during the rainy season. However, Car 531 is totally enclosed and has windshield wipers and is usually operated during the rainy season. When completed, the Milan Car 2001 will also be enclosed and have windshield wipers.

CONCLUSION

Vintage trolley supplements to LRV systems should be encouraged. These cars add so much personality to the system, especially if the cars are authentic to the area. If not, one or two of the cars should be similar to former system cars. These can then be supplemented with authentic streetcars from other countries—especially those countries with cultural or economic ties to the community.

The cost of such a system may sound high. But when the civic pride that these pieces of transportation history bring is considered, and the way a trolley program can strengthen visible ties to the community's past, it is well worth the cost. Local dollars can usually be found for an investment in living history.

Evolving Vintage Trolley Projects

JAMES H. GRAEBNER

Ten years ago, on May 29, 1982, the Municipality of Metropolitan Seattle began operations of the Waterfront Streetcar. Arguably the prototype for the vintage trolley lines that have followed, Seattle's pioneering installation has been one of the most successful. During the past decade vintage trolley lines have become important transportation elements in several cities and are being considered in many others. Some key lessons have been learned from professional experience in planning, implementing, and operating vintage trolley services. Systems in San Jose, Denver, Memphis, and Orlando, where the author has been closely involved, are highlighted here. In reviewing various existing and planned lines, it will be obvious that not all desirable features will be met in every case. Happily, vintage trolleys can succeed given a wide range of physical and operating conditions. However, in assessing the likelihood of success of a given proposal, it appears that the closer the line can come to meeting the ideals outlined here, the more chance of its community acceptance and a long-term role within the community.

To a large extent, the current vintage trolley movement can be traced to the advent of trolley museums, which have preserved examples of this colorful mode of transportation since the late 1930s. However, a vintage trolley property differs significantly from a museum and it is critical that vintage trolley proponents and trolley museum members understand this difference. First, the vintage trolley operates to provide transportation to the general public. It usually operates 7 days a week, adheres to a published schedule, and relies on a full set of policies and procedures. Thus the service must be reliable and dependable. In effect it functions like any other public transit mode except that it uses an unusual and colorful variety of technology. Trolley museum operations, by contrast, tend to be relatively relaxed as to schedules, which are often confined to weekends.

A vintage trolley must often operate in a crowded downtown, sharing streets with automobiles and pedestrians alike, whereas the typical trolley museum operates on its own right-of-way in a suburban or rural environment. The museum labor force is composed of volunteers whose interest in the equipment is that of true hobbyists. By contrast, vintage trolleys are usually operated by transit system employees who, although fully qualified for their work, do not necessarily have the affection and care for the equipment that a typical museum member does.

The vintage trolley line must serve as an accommodation to the entire public, which leads to differences in liability exposure and care for the handicapped when compared to the typical museum operation.

Finally, museums tend to restore equipment as museum pieces. This often means that a given car will have its own particularities that, although they may be fully understood by museum personnel, would render such a vehicle unacceptable to the typical vintage trolley operator who must insist on a reliable and dependable vehicle. The nature of the service also means that the meticulous and painstaking restoration of a museum piece is somewhat inappropriate to the operating conditions of a vintage trolley for which easy maintainability and resistance to the ravages of rugged use are more important.

In summary, the philosophy of a vintage trolley operation—a full-fledged transportation mode for an urban area—is significantly different from the philosophy of a museum installation. To attempt to operate a vintage trolley service under the philosophy of a museum would almost certainly result in a service that, in the end, would disappoint the majority of the community.

TRANSIT FUNCTION

A vintage trolley must serve a legitimate transportation function. This function can range from that of a shuttle within the central business district (CBD) to a connection between parking and retail or amusement areas to serving a sports venue, but in any event the system must provide mobility for users. The ride should be a means of getting from Point A to Point B and back and not exclusively an amusement ride.

Nonetheless, much of the attraction of a vintage trolley ride is in the ride itself. In some cases, this means that people will take a ride on the trolley just for the experience of riding a historical or "old-time" vehicle. However, this kind of ridership is not strongly repetitive. A family that takes a ride on the trolley just for the experience will not repeat that ride as often as if the same trip linked a parking lot to a major attraction that the family could enjoy regularly. Thus several of the existing vintage trolley operations are actively seeking to extend their lines to tap potential trip generators to increase their ridership. Furthermore, some vintage trolley lines have had severe difficulties because their routes were not sufficient to provide a useful transportation link within the communities served.

COMMUNITY SUPPORT

Obviously a vintage trolley project cannot be implemented nor can it succeed without strong community support and backing. Yet in the frantic efforts to get the line built and keep it going on a day-to-day basis, several systems have neglected to continuously cultivate the community support so vital to ongoing success. This has meant that ridership has

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slipped as has financial support. By contrast, in communities that have actively sought a widespread basis of involvement, the support for the vintage trolley has helped the system to become a significant local attraction. The New Orleans St. Charles Line and San Francisco cable cars epitomize how community support can make a system into an icon of the community.

FUNDING

Strong, widespread community support and the recognition of the system as a transportation provider is needed for an adequate funding base that covers both operating and capital costs. Although it is true that some systems have functioned for several years on a "shoestring" budget, the more successful examples have managed to achieve permanent and ongoing funding sources that allow them to provide a high level of quality service.

Funding has typically been from a combination of public and private sources. Perhaps uniquely among fixed-guideway transit projects, vintage trolleys have attracted significant private participation for both capital and operating costs. Examples include the following:

- In San Jose and Memphis, vehicles have been wholly or partially funded by local corporations. Typically, this takes the form of an outright cash grant to the vintage trolley sponsoring organization. The grant is dedicated to a particular car. Acknowledgment of the donor appears on print material and a plaque on the car. Sponsorship of vehicles is probably the easiest way to attract large chunks of private investment, because the money yields a very tangible and visible product.
- The Kelley Park Facility in San Jose (where cars have been restored) was funded partially by donations of time and materials from local contractors and suppliers.
- In Galveston, it was the guarantee that operating deficits would be covered by a private organization for a multiyear period that was critical to implementation of the project.
- Close relations with served attractions—and an appreciation of the value of the Platte Valley Trolley's contribution to patronage—has brought operating assistance from several popular entities in the Denver area for the past 4 years. Similarly, car card advertising for restaurants, bars, and shops along the line is a salable—or tradable—commodity.

Public funding is somewhat more conventional in nature. In most systems the local transit system has been a participant at some level. This may be as basic as in San Jose, where the physical plant for the vintage trolley is the Guadalupe Corridor light rail project, which was planned, engineered, and built by the Santa Clara County Transit District. (The fact that both the transit district's board chairman and general manager were founding directors of San Jose Historic Trolley, Inc., was fortuitous in this situation.) In a similar vein, the latest Portland vintage trolley operation uses the facilities of Tri-Met's MAX system. On the other hand, lines in Lowell, Galveston, and Dallas are operated independently of the local bus system; whereas in Seattle and Memphis the entire property is owned *and* operated by the local transit provider. In Denver, the Platte Valley Trolley has received annual contributions from the transit agency and operates in part on an old railroad right-of-way owned by the agency. In addition, after the Platte Valley Trolley purchased the original portion of its trackage from the Burlington Northern, it was able to sell its interest to the transit agency for potential future use and in return received a guaranteed contribution for the next 5 years. There are undoubtedly other possible mechanisms, but the point is that the local transit system can often play a role in vintage trolley implementation.

ORGANIZATION

The previous sections lead to the inescapable conclusion that a vintage trolley operation must be organized in a businesslike manner. In terms of organizational structure, a great deal of variety is represented by the more successful systems in operation. Most such lines feature a partnership between public and private interests, an arrangement that tends to maximize support, increase potential funding, and reinforce strong ties to community constituencies, such as the preservationists and downtown neighborhoods.

Operations and maintenance functions must be crisply run. In some cases the degree of volunteer participation is an issue. Most operations have some or all paid staff. However in many cases volunteers are also encouraged to participate, the relative proportion ranging widely among properties. To the extent consensus exists, it would appear desirable that management personnel and operators plus one or two key maintenance personnel be paid staff and volunteers serve primarily as tour guides, conductors, and restoration assistants for vehicles. It should be noted, however, that there is sufficient variety in the specific employment arrangements of the various systems and those under construction to render this judgment no more than a gross generalization. The relationship between paid and volunteer staff should be determined on a case-by-case basis and should consider such factors as these:

- Funding constraints,
- Relationships with local transit providers and their represented employees,
- Liability considerations, such as insurance coverage,
- Availability of personnel (volunteer staffing requires more people than paid staffing), and
- Size and scope of the operation.

It is axiomatic that safety is paramount in the operation. Most vintage trolleys have enviable safety records. This is the result of a combination of good training, including periodic refresher courses, well-defined policies and procedures, and competent staff. No compromise can be made in this important area.

As mentioned, many vintage trolley operations combine public and private representation so as to secure not only community support but also to tap various funding sources. Indeed, vintage trolley projects by their nature tend to be fertile grounds for public-private funding initiatives. Thus the organization structure should include the private sector, either in a direct board relationship or as part of an advisory committee or its equivalent. In several cases, the vehicles have been purchased or restored by private interests. In other cases, the operational deficit is born in part or entirely by the private sector. Marketing tie-ins and promotions between retailers and vintage trolley operators are extremely common, indeed, de rigueur for well-run systems. Similarly the local transit agency and local historical preservation groups can provide strong support and helpful political constituencies.

In summary the organization to build and operate a vintage trolley system must be a businesslike organization whose operating code is safety first, closely followed by reliable and dependable service to the public. Whatever organizational model is adopted, a blending of private and public interests should be strongly considered to maximize the support of community constituencies and funding sources.

FITTING INTO THE COMMUNITY

A vintage trolley must fit into the community it serves, both in terms of the physical plant and the service it provides. In the case of the former, it is helpful if the line can be linked to a historical district or to an area whose theme is compatible with that of vintage trolleys. Mining the lode of nostalgia that exists in most communities is a serendipitous exercise for many vintage trolley operations, inasmuch as the historical preservationists can play a major role in implementing the project and can be a base of long-term support. As mentioned above, it is important to the life of the organization that it become part of the community it serves. This involves people who will interact with the community to educate its citizens to the value of the vintage trolley installation in providing customers, retailers, attendees to museums and entertainment venues, happy conventioneers, and so forth. Although the purpose of the ride must be transportation from one point to another, the experience itself should be memorable for the rider and promote the community of which the system has become an integral part.

The degree to which the vintage trolley project reaches out to the community and imaginatively promotes itself and attractively positions its service will be the measure of its adoption by the community as a civic symbol.

PHYSICAL PLANT

The "hardware" of the vintage trolley system is often the image created. Although it is true that the cars are the primary symbol of the system, considerations of the physical part of the system have been relegated to the last element in this paper to emphasize the criticality of other issues. Good-looking cars, smooth track, and nonintrusive overhead can enhance any vintage trolley project. However, they cannot by themselves turn a poorly conceived and inadequately funded project into a winner.

The past decade has not been without its share of lessons on how to physically assemble a high-quality vintage trolley project.

An important consideration in planning a vintage trolley is whether the community has or is planning to have a light rail transit (LRT) system. If such a system is contemplated, the physical parameters of that system will govern most of the engineering considerations applicable to the vintage trolley. For example, in San Jose the vintage trolley vehicles were configured to operate on the LRT system. This resulted in wheel profiles, voltage, and other design practices compatible with the LRT but that, in some cases, required modification to the vintage trolleys or application of modern appliances. Similarly where a vintage trolley line precedes potential LRT application, as in Memphis, it is prudent to design the physical plant to accommodate proposed LRT operation. Not only does such a practice permit the future joint use of facilities where appropriate, but it is also a more comfortable approach for the engineering consultants who will, in large part, design the physical plant. Finally such a practice allows the system to comply with the various codes and practices now in effect that have been implemented since the halcyon days of the old-time trolleys.

Notwithstanding all of this, instances may well exist where no LRT operation is contemplated (as, for example, smaller cities) or where the vintage trolley line's route need not be shared by LRT vehicles. In such cases, more traditional vintage trolley standards may be used, including tighter radii for curves.

Whether the vintage trolley line uses an LRT system, is intended as a precursor to LRT, or functions as a stand-alone system, it is important that system designers and engineers have a feel for vintage trolleys. Many aspects of vintage trolley design and construction were thoroughly understood years ago by track workers, linemen, and car repairmen with no more than a grade school education. Somehow in the intervening years much of this heritage has been forgotten, and despite high-powered computers, computer-aided design systems, and Ph.D.s to run them, matching the product of three-quarters of a century ago is often unattainable.

Track

Modern street railway track design is reasonably well understood by most qualified engineering firms. LRT practice may be used for either street trackage or private right-of-way trackage. The relative advantages of girder versus T-rail, wood versus concrete versus street ties, direct fixation, and so forth can and should be argued in the context of an individual community and with the background of the cost and the system versus the benefits sought in terms of aesthetics, noise, and community acceptance.

In some cities, the use of abandoned track has been put forward as a cost-saving advantage. This scenario states that simply scraping off the asphalt from Main Street to expose the long-buried streetcar track underneath will provide a ready-to-run roadbed at minimal cost. This concept is often a snare for several reasons. First, unless the tracks go where people want to go, any saving in track construction will be more than offset by diminished ridership and revenue. Second, when streetcars were abandoned, the rail on which they rode was often close to the end of its economic life. Decades of being buried under asphalt have not helped in terms of corrosion. Railbonds are usually completely gone and must be replaced, crossties may well be thoroughly rotted out, and public works projects such as sewer line replacements and other utility relocations may well have caused sections of track to be torn up. If streetcar or railroad track of relatively recent vintage can be found along the desired route, and if the track can be put into reasonable shape at relatively low cost, it may be desirable to rehabilitate such track.

Overhead

The design and construction of an overhead wire system should be simple and easy. However, numerous examples exist around the country of both vintage trolley lines and LRT systems with overhead design that resulted in massive, ugly, and intrusive cobwebs of copper. Because of the strong need for community acceptance, it is very important to spend significant time in designing and building overhead that is as aesthetically pleasing as possible as well as being properly installed. Some potential design features for consideration include the following:

- Vintage trolley overhead can be integrated with existing street fixtures. It is both physically practical and historically correct to use line poles for more than one purpose. In some cases, joint use agreements have been negotiated that allow multifunctional use of line poles. Another possibility—equally authentic—is to anchor span wires directly to building fronts in downtown areas.
- Simple suspension, as opposed to catenary, is almost universally appropriate. This results in fewer visible wires. Where possible, various types of "masking" can be used to render even the single 4/0 copper wire nearly invisible. Trees are a commonly used method, as seen in San Jose and Memphis. Building fronts also provide a backdrop that masks the wire.
- Attractive and eye-catching line pole bases and bracket arms can help to enhance the feel of the streetscape. Fortunately a wide variety of appropriate pole bases is available.

Vehicles

Basically three vehicle choices exist for vintage trolley systems. The first, a restoration vehicle, is generally defined as one that actually ran in the city where the vintage trolley system is being built and that is restored to the condition in which it was once operated in that city. Such vehicles tend to be the "star of the show" within the local community. Excellent examples are Car 124 and its sister, Car 73, operating in San Jose. Both were restored over a period of several years using lots of tender loving care with a large dollop of seasoned trolley restoration skills furnished by an individual who is truly a master car builder. The advantage of the restored car—if a suitable candidate can be found—is that it truly is part of the heritage of the community it serves. The disadvantage is the length of time required for restoration and the difficulty in finding the car to be restored. In terms of costs, this option is often the least expensive in dollars, although if restoration labor is not volunteer any cost advantage can quickly disappear. It is possible that as a landmark such a car could be exempt from Americans with Disabilities Act (ADA) requirements, assuming such an exemption is politically acceptable locally.

The second vehicle option, rehabilitation, is commonly used and examples are found in the majority of vintage trolley systems. Typically a streetcar from another nation is purchased and required modifications are made to adapt it to its new home. Melbourne, Australia, and Oporto, Portugal, have furnished many cars for U.S. vintage trolley projects. The advantage of this option is that the cars are usually close to reasonably operable condition (if one is extremely careful in selecting the vehicle to be purchased) and the cost of rehabilitation is usually relatively low. On the other hand, if extensive modifications are required to meet local conditions, the cost can escalate quickly. Further the vehicles are, in most cases, several decades old and thus may quickly become maintenance nightmares unless they are fully rehabilitated. The low first cost of the rehabilitated car may turn into a high life-cycle cost as the car ages and various problems come to light. Wood-bodied cars are particularly notorious in this respect. A further consideration to this option is the degree to which the car can readily be adapted to handle ADA requirements. Although there are no absolutes as yet in terms of ADA regulations for vintage trolley operations, it is reasonable to assume that all such vehicles will be required to be fully accessible either by regulation or through local political pressure (with a possible exception of restored cars, which fall under the historical exemption clause of the act). One can easily envision the difficulty in engineering appropriate modifications to a single-truck wooden car to enable it to handle powered wheelchairs and their occupants adequately. A final consideration when considering rehabilitation as a vehicle option is the availability of suitable equipment. The fleet of good Melbourne W2 cars is largely exhausted and many of the remaining Portuguese vehicles are in extremely poor condition. Cars from other cities such as Milan and St. Petersburg (Leningrad) may become available in the future but, as has been mentioned, the operating constraints of these vehicles (single-ended cars in Milan, for example) may make them unsuitable for some installations.

The third vehicle option is that of mounting a new, replica body on rehabilitated trucks and electrical gear. Because of safety, engineering, and conformance to modern design practices, this option is becoming preferred. It is, however, also the most expensive although such vehicles are typically one-third the cost of a new light rail vehicle. The vehicles that have been delivered to date grace the rails in Portland, Lowell, Denver, Galveston, and Mason City, Iowa. Experience with these vehicles, such as the car in Denver, has shown them to be extremely reliable with minimal maintenance requirements. The advantages of this option also include the known contract price at award, the relatively fast delivery, and the provision of warranties on the car body and major components as well as reliability and conformance to modern design codes and practices. The drawback is that these advantages are purchased at a price.

Maintenance Facility

The maintenance facility for the vintage trolley system is often relegated to a minor position in the design and construction process. This is unfortunate because not only is the system's reliability and dependability in part a function of the design of the maintenance facility, but the facility itself can become an attraction. The proliferation of light rail maintenance facilities in the past decade has generally led to an appreciation of the design elements of such a building. Although certain functional requirements for vintage trolleys are particular to that vehicle and must be carefully considered by the shop designer, the basic layout and tool list is fairly straightforward and several experienced design firms can handle this work adequately.

A few vintage trolley systems have considered the shop facility as an attraction in itself. This concept probably originated with the restoration of the San Francisco Municipal Railway's cable car barns with the attendant provision of balconies, lighting, and so forth, to allow tourists to witness the operation of the cable driving mechanism. In San Jose, the shop at Kelley Park was designed to permit viewers to watch cars under restoration. Memphis will have similar provisions, and designs for Denver are incorporating this feature. Detroit's barn features glass swing panels. The process can become an educational one when accompanied by appropriate lectures and so forth. Such an arrangement allows a small shop to be provided for sale of incidental merchandise having a connection with the vintage trolley system. It should also be noted that several museums, notably the Trolley Museum in Baltimore, have taken the "visitor center" design element and made it a very attractive part of the overall system. Such an option should strongly be considered when designing the maintenance facility for any modern vintage trolley installation.

CONCLUSION

The vintage trolley movement has gained ground rapidly during the past decade. Originally positioned by many transportation professionals as an amusement park gimmick, vintage trolley service has gradually gained respect as a transportation mode to assist communities in meeting certain specialized mobility requirements in a manner that brings fun and excitement to the process of moving about. Such systems are not confined to any one geographic area or to large cities. Indeed, actual examples and planned installations can be found in communities of 50,000 as well as in cities of well over 1 million population. It is important to apply sound transportation principles and good engineering and design practices in implementing such systems, rather than to simply let them be "cute" interpretations of civic nostalgia. Properly done, vintage trolleys have been extremely successful. With the knowledge gained from a decade of growth, new systems can look forward to similar results.

McKinney Avenue Transit Authority Experience

FRANK A. SCHULTZ III AND JOHN B. MCCALL

Dallas' McKinney Avenue Transit Authority (MATA) was an early participant in the growing renaissance of vintage trolley systems in the United States. With a majority of its construction funding—and all of its operating subsidy—sourced in the private sector, MATA is perhaps singular in its public/private relationship. For more than 2 years, four vintage trolley cars have been maintained and operated over nearly 3 mi of reclaimed city trolley trackage by a largely volunteer labor force. This experience has application to present or planned vintage trolley and light rail operations. Promoted by commercial property owners adjacent to its route, MATA secured endorsements from city and state governments, as well as a federal construction grant, and began operation on a daily schedule in July 1989. The start-up process of construction, maintenance, personnel management, and initial operation revealed both unique opportunities and special problems that are associated with realization of an operating vintage trolley system. Farebox revenues have been influenced by both seasonal factors and economic trends that have not been sufficient to cover system costs. Hindsight reveals that MATA's initial route plan fell short of an important traffic generator that would have significantly improved system results. During 1991, a 2-year federal operating grant to supplement declining private-sector subsidy and reduced revenues was indefinitely forestalled. Failure to fully comply with Federal grant regulations, positions taken by employees of Dallas Area Rapid Transit (DART), as well as the intrinsic nature of MATA's operation created this result. As a result, in fall 1991, MATA eliminated all but one part-time paid employee, reduced its operating schedule to evenings and weekends, and began to cope with the problems created by deferred maintenance.

Major cities, by nature, are intensely competitive for both convention and tourist business. Innovative attractions, things for people to do and to see—properly promoted—can be a deciding factor for success in this competition. A well-planned and executed vintage trolley (VT) operation can be a key part of a city's attraction. A successful city government will attract millions of dollars each year to the local economy. These dollars will be respent approximately twice locally. Local taxes upon this activity alone can arguably justify city subsidy to VT. VT management must compete effectively for these funds before city government, as well as before private-sector firms that benefit from conventions and tourism.

Most civic leaders have little initial appreciation of the benefits that a properly placed and efficiently operated VT can bring to a city economy. The impact upon convention and tourist business aside, VT can also stimulate local activity in redeveloped or historic areas and its route can help "focus" additional development. VT can introduce citizens to an alternative to private automobile, city bus, traffic congestion, and air pollution. And VT can also suggest the possibilities of light rail transit (LRT). If operated on regular, publicized schedules, VT will also serve as local transit.

Dallas' McKinney Avenue Transit Authority (MATA) is a joint public/private-sector venture.The first 2 years' operation were funded by a combination of farebox earnings and private-sector sources. MATA's survival has required that fundamentals be addressed; failure to produce reasonable results from any one of these fundamentals will place the entire operation in doubt. VT in North America, today, is a concept attracting interest among cities and within the LRT community. MATA's experience is applicable to extant and proposed organizations within the rapidly growing VT sector of public transport.

THE BEGINNING

Organization and Planning for Political Approval

In 1981 a Dallas area along McKinney Avenue, characterized by restaurants and specialty shops, was being redeveloped. The effort included excavation and renovation of the brick street paving. Removal of the asphalt revealed a double-track streetcar line that appeared to be in generally sound condition. A local businessman, with restaurant interests along this route, decided that trolley service on that portion of McKinney Avenue would enhance both the ambiance and commercial success of the redevelopment project. His observation that, "Wouldn't it be nice to have some old streetcars running down our street?" drew local media attention. After screening vintage Dallas trolley movies (supplied by a local VT enthusiast), the businessman organized MATA as a nonprofit corporation—Section 501 (c)(3) of the Internal Revenue Code—to build and operate the line. Two local trolley enthusiasts joined the board to oversee technical aspects of the project.

The businessman funded a professional feasibility study that supported the concept. He arranged pro bono public relations and advertising services, conducted fund-raising events, secured local business funding pledges, achieved city support, and applied successfully for two UMTA construction grants. MATA's early initiatives addressed mainly political hurdles. The businessman headed a small team that promoted MATA steadily before Dallas' city government for several years. This major effort finally produced the city's official endorsement and passage, in the Texas Senate, of a bill that limited the liability of city-contracted private transport firms to that of

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the city itself. Once these hurdles were cleared, MATA began to develop a physical plant.

A Public/Private Partnership

MATA's $5.5 million construction costs were divided between $3 million in private-sector grants and $2.5 million from UMTA (now the Federal Transit Administration). City government spent about $200,000 for signs, pavement marking, and the relocation and modification of traffic signals. The businessman bought, and donated to MATA, a 1906-vintage Brill-built car from Portugal. Private grants to MATA funded the purchase of a large Model W-2 car from Melbourne, Australia. One of MATA's board members donated a restored Stone and Webster car body (on Melbourne trucks purchased with MATA funds). The same man also purchased, restored, and leased an ex-Dallas single-truck Birney car to MATA. The businessman bought, and leased to MATA for $1 per year, a warehouse to be converted to a carbarn. During this conversion, other private space was loaned to MATA for initial restoration work on the rolling stock.

Operating agreements were negotiated with the city, paid and volunteer personnel were selected and trained, and the 2.8-mi route construction was finished. With media coverage, a parade, and a crowd of about 30,000, MATA began daily service on July 22, 1989. From that date, through the summer of 1991, MATA produced a daily ridership load factor that was approximately double that of the surrounding public bus system (5.13 passengers per car-mile, versus approximately 2.60).

PLANNING THE SYSTEM

Route Constraints and Characteristics

MATA was conceived and developed primarily to stimulate lower McKinney Avenue restaurant and specialty shop business, as well as to enhance the historical ambiance of the surrounding turn-of-the-century neighborhood just north of Dallas' central business district (CBD). The idea was to both provide a magnet for convention and tourist activity and to attract a regular lunchtime trade from downtown. Hindsight revealed that the initial feasibility study greatly overstated traffic potential on the route. The same study also considerably underestimated both the construction and operating requirements.

Even though there was some discussion, during the planning process, that the 2.8-mi route was "Phase 1" of some undefined larger project, the founders had no real vision of a more extensive operation outside the vicinity of their own property holdings. Active consideration of route extension began after more than a year in operation, when both the pattern of public comment and problematic load factors began to be acknowledged by top management. Unfortunately the UMTA construction grants, generally available through the middle 1980s boom, were no longer an option by 1990. Downward economic trends foreclosed additional private-sector grants or city supplements for the same purpose.

The resulting 2.8-track-mile route used the revived double-track lines down McKinney Avenue with short segments of new construction at each end. At the north end, new track construction connected the McKinney Line with the new carbarn and looped around an adjacent block for returning cars. At the downtown south end, new single track was constructed that turns, from double-tracked McKinney Avenue, onto St. Paul Street for a 0.5-mi stretch that terminates at Ross Avenue on the northern edge of the CBD. The Ross Avenue terminus requires a multiblock walk for any CBD lunchtime traffic. This terminus also stops six blocks short of a major, well-developed restaurant, specialty shop, and restored warehouse attraction named The West End. MATA's lack of access to, and visibility within, this area was, in retrospect, a major planning mistake. Extension to The West End would have created an extensive, attractive, magnet for Dallas convention and tourist traffic.

MATA could have accessed The West End by either six blocks of new street trackage from its Ross Avenue terminus or by soon-to-be abandoned freight railway trackage. This latter route would pass a third developed leisure area (The Quadrangle) and traverse a large parcel of undeveloped commercial real estate. It would also allow some express running through a greenbelt area. Together, both route expansion options would allow MATA to loop its route with double track. Without these West End connections, the route—as built—concentrates nearly all MATA's traffic generators on that half of the route that is remote from both the CBD and The West End. Well-developed parking facilities at The West End would also minimize the lack of such facilities along MATA's as-built route.

Rolling Stock Planning

From the beginning, MATA's founders had a keen sense of trolley heritage and identified transport of the public in carefully restored vintage cars as a major objective. In retrospect, choice of old cars over replicas was the correct approach. The traditions of MATA's steel car body designs, one of which is nearly 90 years old, have proven to be extremely reliable. It was the attraction of the genuine article that drew the large, skilled volunteer restorative force that did much of the work on the project. Even if the labor had been purchased, a restored car would still have been less expensive than an estimated $450,000 reproduction car. With the volunteer force, the cost of restoring a double-truck car was approximately $185,000. Additionally, MATA has tied its promotion and marketing to "genuine antique streetcars."

When planning a route, the equipment must be considered, particularly when planning curves and special work, given VT truck wheelbase and car overhang. The decreasing availability of VT cars dictates that the track geometry conform to the cars and not the opposite. MATA was under a design handicap in that special work and some curves were salvaged from the original system long-buried under the pavement. This resulted in the route being designed around available preexisting trackwork. Additionally, some of the newly constructed curves failed to take into account the wide variation in truck wheelbases (5 ft 6 in. to 8 ft). As a consequence, some of the cars (particularly the single-truck cars) bind up or are technically derailed on some of the curves. Car overhang must be carefully considered on sharp curves when locating poles. Degree of truck swivel must be adequate for the sharpest curve. Failure to consider route and equipment as an integrated system is an error. Design routine in LRT becomes the exception in VT.

Personnel

In addition to the two trolley enthusiasts who joined the board at the onset, there were several interested people in the Dallas area who brought some technical depth and mechanical expertise. Likewise, a larger group of more casual enthusiasts expressed strong interest in donating their time. MATA's planning, therefore, visualized a labor force drawn mainly from volunteers.

Ridership and Promotion

Although the initial feasibility report's ridership estimate was overoptimistic, MATA's novice management accepted these projections. Little formal discussion was held about the necessity to "buy" riders with a carefully thought-out, ongoing promotion campaign. Lacking a place on the initial budget, early promotion was informal and virtually nonexistent. Charter possibilities, likewise, were not considered to be an appreciable source of revenue in the initial planning.

Deficit Financing Options

During the planning process, UMTA funds were thought available and the then-strong local economy suggested that supplemental private grants could also be secured. No advance planning was done to have other sources (such as emergency city funding) in place should initial funding sources prove inadequate or evaporate. When negative economic trends in the real estate and oil sectors later eliminated large private pledges, this planning omission had severe consequences.

Board of Directors

The board of directors was assigned the functions of securing private grants, developing public grant proposals, and maintaining liaison with government at all levels. The chairman was to be the initiator in these functions.

NEAR-TERM RESULTS

Costs, Revenues, and Output

In 1990 MATA recovered 46 percent of its costs at the farebox; not bad for transit but inadequate for an independent VT. These costs included debt service to the bank line-of-credit that was secured by private-sector sources. Inclusion of other revenues—individual donations, membership dues, and merchandise sales—expanded cost recovery to 85 percent. Farebox recovery, for the first half of 1991—as this paper is drafted—increased to 48 percent because of a fare increase and vigorous cost reductions. Through the end of 1991, no public subsidy of MATA's operating expenses has been received. Supplemental private guarantees of the bank credit line, and other private grants, have covered the deficit. Adult tickets are $1.50 and children under 12 ride for $1, round trip. Charter business has accounted for nearly 30 percent of MATA's revenues and, during some weeks, has exceeded the regular farebox revenues. Charter rates are based on a 2-hr minimum, priced from $150 to $400, with $100 for each incremental hour purchased.

MATA's 1990 passenger load factor was nearly double that of the area public bus system that surrounds it. MATA carried 236,074 passengers that year and produced 45,991 trolley car miles, with an average one way trip load of 7.19 riders. Average passengers per car-mile was 5.13. MATA's average variable direct cost was $1.43 per car-mile, 20 cents of which was for electricity. In its first 2 years of operation, MATA has carried over a half million passengers. These results were produced with four vintage cars, 2.8 mi of track, volunteer labor, and seven paid employees. Paid employees included those identified in the planning process, an office/operations manager, an advertising director, and an additional shop person.

Ridership Profiles

MATA has undertaken no formal surveys of ridership. However, some informal assessments are held with some confidence. Well over 90 percent of the traffic is pleasure-related and, therefore, highly discretionary. Ridership is almost evenly split among males, females, and children. Essentially all of the traffic is round-trip, with about one-fourth of the passengers departing, then reboarding a car with a return coupon at some point during the journey. The split between local and out-of-town riders is heavily convention-dependent, and this is further influenced by the level of preconvention planning that has been done jointly between MATA and the Dallas Convention Bureau. Generally the younger the age group of the conventioneer, the more traffic MATA gets.

Whatever the source of the traffic, one-half go for a trolley ride, and the others use the cars to visit stops around the route. Ridership is also highly weather-dependent. Even though the cars are heated in winter, cold weather kills ridership. Moderately hot weather does not seem to appreciably affect traffic. Very little lunchtime traffic from the CBD has developed. Commuter ridership is nil. Among the local riders, all age groups are represented, with senior citizens accounting for a small proportion of the total, relative to other groups. Although MATA's old cars are not modified for wheelchair lifts, those few passengers with wheelchairs have been accommodated informally and lifted on board.

More than 90 percent of MATA's first-time riders have never before taken city transit of any type. They are either transit-ignorant or transit-hostile and must be cultivated with friendly and gentle handling by the crew. These riders are generally apprehensive and intimidated about their first-time ride. They are afraid of getting lost and of looking foolish because they do not know how things "work." Everything is a new experience, from boarding, paying the fare, and finding a seat to managing a return to the vicinity of their automobiles. Car crews must ensure that these riders do not take a trip to the "twilight zone."

Charter business is solicited from any organized group. MATA has chartered for school groups, reunions, corporate functions, birthdays, "murder-mystery" dinner groups—and even one memorable prewedding groom's party (that probably will not be repeated). MATA provides basic car decoration, including tables and bar (if needed), and the buyer is encouraged to arrange any on-board catering of food, drink, or music.

Labor Profiles

MATA's time sheets reveal that two-thirds of the operating labor hours are volunteer. This volunteer group includes the chief of cardiology at a major hospital, a retired public utility chairman, a bus driver's union president, educators, business owners, wage earners, and college students. Generally they are reliable, motivated, and professional in demeanor. Their accident rate is lower than that of MATA's paid employees. Volunteer motormen and women undergo the same training and recertification programs required of the paid employees. Volunteers also work a variety of other jobs, from shop work and housekeeping to administrative assistance. VT jobs cross craft lines. VT volunteers will work at several different tasks during the month, limited only by their skills and attitudes. MATA's policy assigns each volunteer to a specific task or project that is defined with specific beginnings and completions. Once the volunteer is matched with the job, they usually carry out the assignment with minimal supervision. The volunteer has both the responsibility and the personal recognition for a job well done. The key to volunteer motivation is organization, individual responsibility, recognition, and praise. This policy does not vary with the paid employees, who, because of their comparatively low pay, tend to consider themselves semivolunteer anyway. Though scheduling of volunteers during weekdays may be difficult, MATA could not exist in its present form without these people.

Though MATA has not sought an all-male volunteer force, that has almost been the outcome. At any given time, there has never been more than one regular female car operator nor more than one female conductor (one of MATA's four cars requires a conductor). The rail enthusiasts' movement, from which MATA's volunteers are largely drawn, tends to include few female participants. MATA's agreement with the city requires car operators to have, or obtain, a commercial driver's license. Although seven or eight female students have enrolled in the operators training course, all but two have dropped out rather than undergo a state driving test with MATA's line truck. Additionally the prospect of operating an empty car at late hours, alone, along a nearly deserted urban street may have deterred greater female participation. As a result, MATA's few female volunteers have usually elected office projects.

Advertising and Public Relations

Although MATA has been the subject of a number of media features, the public's memory is short, and few residual benefits occur. It is estimated that more than half of the metropolitan area population has yet to learn that MATA exists. Management subsequently agreed that consistent promotion was needed, although the board's concerns about reduced cash flow precluded allocation of any significant funds to the effort. Lack of systematic, ongoing liaison with city convention hosts cost MATA many riders; those conventions for which VT personnel worked closely with the convention bureau, in advance, business was good. Available funds were used to hire an in-house public relations person who worked almost exclusively to promote, sell, and coordinate charter business and, here, modest success was forthcoming.

Souvenir merchandising is an important advertising, as well as revenue, adjunct to MATA's operation. MATA policy requires that the inventory be unique, of good quality, and related to MATA or to Dallas. This part of the enterprise needs floor space, sales personnel, a keen eye for product selection, and good inventory control. As most of the cars are one-person operations, it is not feasible to do more than advertise these items on board and suggest the operator direct interested riders to the carbarn sales area.

FINANCIAL DISTRESS AND REACTIONS

On opening day, July 22, 1989, MATA began service with $156,000 of its bank credit line spent. When negotiating the initial project with city government, MATA represented as a condition of the city's approval that it did not expect to seek future public subsidy. Also, when MATA applied to UMTA for its two construction grants, DART's Amalgamated Transit Workers Union believed that MATA would not seek future UMTA Section 9 operating assistance grants. Distress in the local oil and real estate sectors triggered private-sector pledge defaults of $1.1 million.

By early 1990, with MATA's cumulative deficit exceeding $300,000, the executive department acknowledged that no backup deficit financing plan was in place. A new chief operating officer was hired and charged with reducing the rate at which this deficit was accelerating. Formal advertising and public relations were addressed by the creation of a new paid position in the office.

By midyear, it was evident to the executive department that new fund-raising efforts were mandatory. Concurrently they began to recognize the impact on farebox revenues of MATA's inadequate route length (and lack of access to The West End). In July the most popular car was indefinitely withdrawn from service, reducing the fleet by 25 percent. Its repair was estimated at $37,000 and 1 year's work. MATA applied for $200,000 in unused UMTA Section 9 operating assistance funds. In November two full-time and one part-time motormen were laid off and subscription to Workmen's Compensation was terminated. By the end of the year, the executive department imposed a general moratorium on restocking any merchandise and tokens, and imposed severe restrictions on the already conservative advertising and promotions program.

In early 1991 adult fares were increased in the face of an unmistakable decline in ridership that exceeded seasonal variances. By mid-1991 the approved budget was suspended and all advertising ceased. Deferred maintenance of both track and overhead began to accumulate, and the inventory of major spares for the rolling stock was depleted. Three weeks prior to MATA's scheduled receipt of its requested $200,000 UMTA operating grant, DART's Amalgamated Transit Workers Union declined endorsement under the required 13C Provision. The funds were withheld. By the end of August MATA had reached the $400,000 limit of its bank line of credit and service on this debt, $42,000 per year, became MATA's third-highest expense, after insurance and payroll. September operation was funded directly by board members. At the end of this month, all employees were laid off, except for one caretaker shopman; MATA reduced weekday operation to evenings only and began an all-volunteer operation. Rough calculations suggest that, if MATA had ceased operation at that time, each of its passengers would have been subsidized slightly more than $12 from public and private grant monies over those 26 months of operation (excluding proceeds from salvaging the operation).

VINTAGE TROLLEY AS AN INTRODUCTION TO LRT

Whether VT can favorably introduce a transit-ignorant rider to the possibilities of LRT—in the abstract—will depend upon how serious VT management is about the proposition. The trolley ride itself will probably do little more than create impressions about riding streetcars among automobile and bus traffic. This alone is not enough. The missing ingredient is a proactive, on-board educational program with, perhaps, attractive souvenir handouts. Passengers must be led to recognize both differences and similarities between VT and LRT. This program is a sales effort designed to leave the rider with a favorable disposition toward LRT.

PERSONAL PERSPECTIVES AND EXPERIENCE

Based on personal involvement on MATA's staff, some views have been developed as to the applicability of the MATA experience to VT in general.

Can VT Support Itself?

No, VT cannot support itself. The convenience, cultural, and emotional appeals of automobile possession, as well as its generally unacknowledged full costs, present a formidable hurdle for any for-hire passenger transport operation. Philip Locklin long ago opined that passengers, unlike pigs, can never be carried for a profit because the value of humans, per unit weight, is so high. If the unit fare is set high enough to cover all true costs of the service, traffic volume will be inadequate to produce a profit; someone will have to cover the deficit.

What Is an Optimal VT Organization?

The issue of what an optimal VT organization is will be influenced by unique considerations of each potential VT. A public/private venture such as MATA's, with its emphasis on volunteer labor, offers potential benefits in the form of both lower unit cost and operational flexibility that might not be obtainable if the VT were organized as an adjunct to other city services.

What Are Essential Planning Elements of VT?

Before planning can proceed, a clear definition of the VT's mission must be developed. If transportation is not the only mission, if property development or job creation—or any other competing goals—are determined, a careful assessment of the trade-offs among these goals is required and costs shared accordingly.

Route planning may be influenced by available abandoned trackage. Nevertheless, some flexibility probably always exists in route choice and length. Three generic route types emerge. Route Type 1 is anchored at one end by a traffic-generating attraction. Initial demand results from the strength of the terminal and from the number (and strength) of intermediate stops along the route. Route length is a function of the number of such intermediate attractions.

Route Type 2 is anchored at each end by terminals. So long as their strength will provide at least threshold ridership, the extent of the terminals' separation will generally determine the length of the route.

Route Type 3 approximates MATA's case; both ends are weak attractions. This type of route concentrates destinations along its length such that traffic density is "bell-shaped" and traffic thins out quickly on either side of this bell. Unless new attractions can be developed and the amplitude of the bell increased, failure of the project is likely. The best probable route outcome would be a combination of Types 2 and 3.

Can VT Planning Prompt Further Economic Development?

VT route planning and promotion turns transport history inside out. Early transit routes were the engines that drove development. Today the attractions drive VT success. VT, in turn, can augment the attractions and, with luck, synergy will evolve.

What Are VT Rolling Stock Considerations?

The location of restorable VT bodies, as well as the parts needed to resurrect an operable car, can be a formidable task. Realistic survey of each restoration candidate is the essential precondition for the acquisition of such relics. The survey requires a person versed in both general streetcar repair and with experience in the restoration of VT technology. Hidden problems can be located if the surveyor has the trained eye that only hands-on experience can develop. Europe is a source of fairly complete VT cars. MATA's experience discloses that vintage car bodies should be avoided in the direct proportion to the amount of wood, as opposed to metal, contained in the car construction.

Restoration and maintenance of genuine vintage cars requires people who have learned obsolete skills and who understand both obsolete techniques and technology. Local job shops with intrepid master workers in both machining and woodworking are necessary. Take nothing for granted; inspect or rebuild everything. Shortcuts do not save money. If restoration is not feasible, reproduction VT cars of excellent quality are available from two domestic suppliers. Expect them to cost from twice to three times the outlay for a practical restoration.

What References Exist for VT Construction?

Although VT and LRT may share a common, contemporary route design, old reference materials can be highly useful as a substitute for "organizational memory." For a project manager new to VT, a most useful reference is the *Electric Railway Handbook* by Albert S. Richey, published by McGraw-Hill in 1924. Reprints of this volume are available from the Association of Railway Museums. The volume is of value as a compendium of considerations to be dealt with rather than a source of absolute data, because materials and standards have changed over time. Much of the information, however, concerning cars, carbarn, overhead, and track design is still valid.

What to Look for When Reclaiming Abandoned Track

MATA experience indicates that revival of abandoned track in-place can be done at 10 percent of the cost of new track on a new route. Two factors influence this potential saving: location of public utility distribution systems above and below the street surface and the condition of the old track. An early survey of the entire track structure is a must. Each rail joint must be excavated to reveal the condition of ties, hardware, bonds, and rail. A rail flaw detection car should be run over the line to ensure mechanical, as well as electrical, integrity. Broken rail should be thermite welded and rail bonds must be double-checked. Expect to replace rail sections where utility cuts have been made. Bridge all these cuts with reinforcement, otherwise subsidence of the subgrade will occur soon after service begins.

Expect to find that some of the old rail is worn out. Worn girder rail is a major problem as it places car weight on the flanges, rather than tread. If electrolytic corrosion has removed much rail web or base, expect early rail failure regardless of railhead condition. MATA has used "T" rail to replace failed girder rail. Girder rail is difficult to bend and must be laid to close tolerances, especially on curves and in special work. References published as early as 1905 recommend against the use of girder rail where possible. Where guard rails are required, Bethlehem Steel's Strap Guard is an excellent replacement.

What to Look for When Building New Track

Utility relocation can be a major cost of new, as well as revived, track if insulated rail is not used. Aerial cables that cross the route may also need relocation, as the nominal height of trolley wire is 18 or 19 ft above the railhead. In some cases it will require 22 ft. City ordinances generally require that an uninsulated metallic conductor (pipe or structural reinforcement) be no closer than 5 ft below the base of a noninsulated rail. This separation is to prevent stray currents from causing electrolytic corrosion. Utilities placed when the old track was in service should conform to this standard; new placements will probably need relocation. Utility plats may not be accurate references.

Street railway trackwork requires techniques not normally demanded of a conventional railroad contractor. Sharp curves and special work need to be designed carefully and manufactured with precision. Curves of less than 50-ft radii should be bent to jigs and fitted on an erection floor before installation. Plan for proper drainage of turnout points and throw boxes. Turnout points should be located opposite car weight when operating. All curves should be spiraled. Inside the carbarn, avoid any curves or special work. Guard rails on tight curves may cause tracking problems, even if the track is in gauge. Before curves and special work are spiked down, any car with a long wheelbase (such as a single-truck Birney) should be test run over such sections. Gauge bars should be installed at frequent intervals.

Some Rules for VT Overhead Wire

The best source of basic overhead design will come from the domestic supplier of the components. Available contractors may have never seen trolley overhead and must be willing to work with component suppliers in execution of the job. The operational quality of the overhead depends almost entirely upon the quality of the installation, whatever the quality of the components. Special attention is needed on curves and special work, as well as proper wire tensioning along the entire route. After the wire has been in service for some months, expect it to undergo an initial stretch. The expense of initial retensioning should be included as part of the original construction cost.

Judging VT Personnel Matters

If the VT is an adjunct within city transit, volunteer, or part-time, workers may not be an option. If the VT is organized along MATA's profile, however, consideration of volunteer employees will be a likely event. It should be expected that properly selected volunteers will behave, usually, with high motivation and as independent agents. If they come from a trolley museum background, it may take some managerial expertise to convert their attitudes from those that involve casual operation to those that fit with serious, regular service demands.

SUMMARY

A properly planned and executed VT, that is promoted vigorously, can both benefit the locality of its route and generate external benefits that will augment city development in general. In the best case, VT will require subsidy at some level. As a result VT must be recognized as both a political and managerial activity that transcends running obsolete trolleys along restored trackage through interesting locations.

Vintage Trolleys in Portland

SCOTT R. FARNSWORTH AND JOHN W. SCHUMANN

As plans for a regional light rail transit (LRT) system began to gel in 1978, the local business community developed an interest in resurrecting vintage trolley service in downtown Portland, Oregon. Entrepreneurs envisioned streetcars shuttling between the older, established central downtown area and the Lloyd District, a "second downtown" office and shopping area across the Willamette River. This dream became a reality in late 1991 with a gala opening ceremony for the new/old trolley system. Four replica streetcars operate from the shared downtown terminal over 2 mi of line used jointly with LRT service. Facilities added to the basic system include a separate carbarn and a trolley station at Lloyd Center. Vintage trolley service currently is provided only on weekends and holidays; but the Portland region has plans for expansion that will use streetcars as an easily identifiable, understandable, and entertaining downtown distribution system, complementing line-haul LRT and bus services.

The Metropolitan Area Express (MAX), a modern light rail transit (LRT) system, has operated successfully since 1986 from downtown Portland, Oregon, to Gresham. The 15.1-mi route is served by 26 six-axle articulated light rail vehicles (LRVs). Service operates at 15-min intervals from early morning to midevening with 30-min headways continuing until about 1 a.m. every day of the week. Trains run more frequently during weekday morning and evening peaks. Average weekday ridership has grown from 19,000 initially to nearly 25,000 in 1992. Weekend riding is so strong, more riders are carried on some Saturdays than on weekdays.

PORTLAND VINTAGE TROLLEY PROJECT

The Banfield LRT project includes a vintage trolley (VT) element sharing the 2 mi of line from downtown to the Lloyd Center, effectively an east-of-the-Willamette River extension of downtown Portland incorporating a newly renovated and enclosed regional shopping center, the Oregon Convention Center (completed in 1990), several hotels, and a complex of office buildings. Though included as a component within the overall Banfield LRT project scope and budget, the running of replica streetcars trailed the start-up of the MAX trunk LRT service by 5 years.

A separate, nonprofit corporation, Vintage Trolley, Inc. (VTI), provides policy direction and coordinates funding support for the streetcars. VTI provides an entity in which public officials, the business community, and private individuals can work together in a coordinated fashion with each group contributing the type of funding and expertise of which it is most capable or qualified. Private-sector involvement is crucial, because it was this part of the community that initiated the trolley idea. Public agency participation is equally crucial, because the public sector controls the right-of-way (city streets) and LRT/trolley infrastructure (i.e., the Tri-Met LRT system).

LTK Engineering Services, Skidmore Building, Suite 600, 28 S.W. First Avenue, Portland, Oreg. 97204.

VINTAGE TROLLEY FACILITIES AND EQUIPMENT

Limited facilities, over and above those required by the basic MAX system, support the VT project. The only track added was at the Coliseum trolley barn and the one-block branch to the new Lloyd Center trolley station.

Vintage Trolley Cars

Vehicles were manufactured by Gomaco Trolley Company of Ida Grove, Iowa. This firm previously built several replica vintage streetcars, including those used at the Lowell, Massachusetts, National Historic Park. The four cars procured for Portland are replicas of Council Crest streetcars operated in the city until 1950. Only 10 of these cars actually were used on the steeply graded route to Council Crest, a picturesque area in the west hills and, in fact, the highest prominence in Portland. Nonetheless, local people consider this the most memorable and nostalgic trolley line that operated in Portland.

The original Council Crest cars, numbered in the 500 series, were semiconvertible cars manufactured by J.G. Brill. The first such cars were built in 1903. They were capable of operation on grades up to 13 percent and around tight-radius horizontal curves. Traditional trolley poles were used for power collection; the trolleys ran on 600 volts direct current (dc).

The Replica Council Crest (RCC) cars were manufactured to operate on a maximum grade of 7 percent (steepest grade on the MAX system) and a minimum horizontal curve radius of 50 ft. Braking requirements for the RCC cars are 3.0 mphps for service brake and an average of 5.0 mphps for emergency brake (25 mph entry speed). Normal service braking is provided by air-actuated tread brakes. Magnetic track brakes are provided for emergency use. These requirements were met by using rebuilt trucks and propulsion gear from retired Chicago President's Conference Committee (PCC) rapid transit cars.

The RCCs accommodate 40 seated passengers and a standing load of 31 people (8 per m^2) for a total capacity of 71 passengers. "Walkover" type seats are used for 24 passengers, whereas the remaining 16 are side-facing design.

Because the VTs operate on the MAX system, intermixed with the modern Bombardier LRVs, full collision strength (two times the empty weight of the car) and LRV-compatible anticlimbers, as well as collision posts, were required. An interesting design of sacrificial cowling hides the anticlimbers and posts. It satisfies the somewhat conflicting requirements of structural strength, LRV collision compatibility, and vintage appearance. LAHT steel structure is used to further satisfy the structural requirements.

Wheel flange and tread design was required to interface with the combination of American Railway Engineering Association (AREA) and European trackwork that already exists on the LRT line. Unlike a typical streetcar profile, this required a minimum of 5-in. width tread design to ensure passage of the wheels through special trackwork without excessive pounding of the wheels and rails with its associated noise and wear.

The VT route also includes the section of the MAX system that crosses the Steel Bridge. This bridge, owned and operated by the Union Pacific Railroad (UP), is a double lift span design built in 1911. The lower deck serves railroad traffic. The upper deck carries automobile and LRT traffic. Tri-Met operates over the bridge by agreement with UP, which requires that an enforced signal system be used. This is provided through use of wayside-mounted electromagnetic devices and car-mounted antennae. VTs have automatic train stop (ATS) antennae integrated with the trolley controls that will place the trolley in a full service brake mode if a red wayside signal is passed.

A train-to-wayside communication (TWC) system has been installed to make more expedient moves of VTs on and off the MAX main line possible by controlling powered switch machines for route selection. In addition, the TWC system provides an effective way to preempt automobile traffic signals along most of the 2.1 mi of the system on which the vintage trolleys operate.

To present an image of authenticity, every reasonable step was taken to ensure that the appearance of the RCC cars was nearly identical to the original cars. Several original parts were removed from the two remaining Council Crest cars and loaned to Gomaco for replication. In addition, research at Portland area libraries, consultant libraries, and other resources across the United States was undertaken to provide photo and written documentation to the manufacturer.

Equipment and structure on RCC cars includes PCC trucks, GE-CP27 air compressors, new walkover seats with rattan cushions (an original was used as pattern), semiconvertible wall and window design, including carved wood moldings and K-controller housings (with new low-voltage relay controls). A modified trolley pole/pantograph design, similar to a bow collector (once common in Europe), is used for power collection. This arrangement avoided modifications to the overhead contact system that would have been required for traditional trolley poles.

Accessibility for elderly and disabled people is provided by a ramp at Lloyd Center and a mini-high platform at the downtown Yamhill District station. A wheelchair can be loaded in the rear vestibule of the trolley, and provisions are included to secure the chair with a belt. This concept was developed by Tri-Met prior to publication of Americans with Disabilities Act (ADA) regulations and represents a reasonable approach to accessibility for the time period in which it was designed.

Vintage Trolley Carbarn

A VT carbarn is located at First Avenue and Holladay Street, adjacent to the MAX main line. The carbarn is only 10 city blocks from the vintage trolley terminus at Lloyd Center, which minimizes deadhead operation when trolleys go in or out of service. The carbarn is near the new convention center (diagonally across Holladay Street) and the Memorial Coliseum (two blocks away), the home of the Portland Trail Blazers. A bus transfer center is on the west side of the site.

Joint development of the carbarn, Coliseum Transit Center, and adjacent Oregon Convention Center, as well as reorientation of automobile traffic, has created a focus for tourism and special events. In keeping with this focus, Tri-Met and VTI stressed the importance of building a people-oriented area around the carbarn.

The shop accommodates maintenance activities and provides secure, inside storage for all four cars. The design includes brickwork that ties in some features of the MAX system's architectural elements, some features of the nearby convention center, and some features that give it an old-time identity. Large windows are provided on the south wall for viewing the vintage cars when they are stored at night and to accommodate "sidewalk supervisors" when maintenance is being performed.

The building is simple in design for maintenance features and capabilities. Daily routine maintenance and minor repairs are performed at this location. All heavy repairs are done at the MAX light rail maintenance and operations facility at Ruby Junction in Gresham. Major components will be trucked to and from Ruby Junction so MAX operations will not be interrupted by movements of vintage trolleys over the 11 mi of main line from Lloyd Center to Ruby Junction. When a vintage trolley deadheads to Ruby Junction, the movement is ordinarily made during night hours when MAX is not operating. With their "peppy" PCC running gear, the RCC cars can achieve speeds over 45 mph. This has prompted Tri-Met to allow deadheading and vintage trolley operator training between LRT trains during all periods of the day except commuting peaks.

Lloyd Center Station

Vintage trolleys now operate on 2.1 mi of the existing MAX system between downtown Portland and Lloyd Center, a major shopping mall near, but separate from, the downtown area. All trolley stops but one are shared with the MAX system. A single new stop is provided at Lloyd Center and serves as the trolley terminus.

Four hundred feet of new in-street exclusive trolley track is provided, and a new station platform and shelter were constructed. The station, adjacent to Holladay Park, includes a "vintage design" wood-framed shelter with ramps and a bridge plate for trolley access.

VINTAGE TROLLEY OPERATIONS ON EXISTING MAX EASTSIDE LINE

A gala event welcomed the "return" of Council Crest cars to Portland on the evening of November 23, 1991. Participants purchasing a $100 ticket enjoyed an evening of riding on the first two trolleys, hors d'oeuvres, entertainment, art gallery hopping, wine tasting, and dancing along the route. Patrons who purchased a $250 ticket rode the first trolley and were given commemorative models of the Council Crest car. All proceeds from the gala were used for initial operating expenses of the system.

Streetcars are operated by Tri-Met under contract to Vintage Trolley, Inc. During the first month of trolley service, two vintage cars were used and ridership exceeded 25,000. The cars ran from 10 a.m. to 3 p.m. daily and until 6 p.m. on Saturdays and Sundays. Trolley frequency was approximately every half hour, intermixed with regular MAX service.

The initial 1-month period featured free rides for all, sponsored by a local department store. Since that time, operation is limited to holidays and weekends. The third car in the VT fleet will be placed into service by April with the fourth and final car arriving in summer 1992.

Trolley operations are supported by fare donations, sponsors, and volunteers. The fare donation is $1 for a round trip. Fares are collected by a volunteer host/hostess. When riders pay their fares, they are asked by the host if they will be taking a return trip on the trolley, or will reboard later in the day. A return ticket is issued by the host for use as proof-of-payment when reboarding. Courtesy tickets are provided by some merchants and vendors along the line for use by their patrons. The tickets are provided to the vendors and merchants by Vintage Trolley, Inc., in exchange for advertising at the merchants' places of business and in their publications. Courtesy tickets also are part of the sponsorship relationship discussed below.

COSTS OF THE INITIAL PORTLAND VINTAGE TROLLEY PROJECT

Capital cost of the initial downtown-Lloyd Center VT project was $2.55 million, including two of the four RCC cars, the carbarn, Lloyd Center trolley station, 11th Avenue track and overhead wire extension, signaling and TWC, and other costs as displayed in Table 1. These costs are covered by $500,000 from the proceeds of a local improvement district (LID), encompassing properties fronting on the MAX/VT route, and $2.05 million in federal mass transportation funds. Total cost of the VT component is less than 1 percent of the overall $321 million Banfield LRT implementation and Interstate 84 freeway reconstruction project budget.

VTI raised an additional $825,000 in private donations to pay for the two RCC cars not covered by federal mass transportation funds.

Part of the cost for the RCC cars was donated by car sponsors. In exchange for 5 years' exclusive use of the interior advertising panels and for placement of the sponsor's logo on the exterior of the trolley, VTI received $100,000 from each car sponsor.

TABLE 1 Capital Budget for VT Portion of Tri-Met's Banfield Corridor LRT Project

Cost Category	Estimated Cost
Construction	$ 682,500
Procurements	$ 243,300
Replica Vintage Trolleys (Two Cars)	$1,008,400
11th Av. Station (Lloyd Ctr.)	$ 16,500
Tri-Met Staff and Consultants	$ 451,800
Miscellaneous & Contingencies	$ 147,500
Total Estimated Cost	$2,550.000

Part of the cost of the stations was donated by station sponsors. VTI received $30,000 from each sponsor in exchange for a 5-year agreement to name that station after the sponsoring company, placement of a bronze plaque on the platform, and signs along the route.

VINTAGE TROLLEY EXPANSION PLANS

VTI, the public-private, nonprofit corporation, is sponsoring studies by local consultants to plan an expanded VT network. Streetcars are seen as a more appropriate-size vehicle for the likely passenger loads and short-headway operation that will characterize downtown shuttle service. It is thought that VTs, with their fixed tracks, wires, and other facilities always visible, are more intelligible to casual users than buses, and that a system of VT circulators can meet several objectives:

- Improve accessibility to the regional transit system;
- Reduce congestion and air pollution created by short automobile trips;
- Link key destinations and attractions;
- Improve the mobility of shoppers, workers, tourists, and residents;
- Attract new visitors; and
- Support historical preservation.

A draft plan, Central City Trolley Alignment Analysis (1990), was prepared by consultants directed by the public-private Central City Trolley Advisory Committee (CCTAC).

First Priority: Extend VT Hours Downtown to Lloyd Center

To improve the effectiveness of LRT/VT shuttle service for short trips, a first-priority recommendation is to add weekday downtown Portland-to-Lloyd Center VT service during midday hours as soon as possible after starting weekend and holiday streetcar operations. VTI, its business community supporters and responsible public agency officials (Tri-Met and the city of Portland) must identify sources and sums of additional operating funding to implement this recommendation and negotiate a solution to the disparate VT and Tri-Met fare structures. Fare policy is particularly important as it relates to Fareless Square, Tri-Met's free-ride zone essentially encompassing all of downtown, but not Lloyd Center.

Expansion Plan for Three Lines Developed Incrementally

The alignment analysis recommends three additional vintage trolley lines of 1 to 5 mi each to be developed incrementally. As central area circulators, VTs would complement existing Tri-Met line-haul bus and MAX services. Streetcars would function initially as a distributor or "people mover" within the central business district (CBD) and later between the CBD and close-in activity nodes: Union Station, Riverplace, John's Landing, the Oregon Museum of Science and Industry, Nob Hill (the Northwest 21st/23rd Avenues commercial district), the Pearl District (the lofts and recycled warehouses at Northwest 13th Avenue), Portland State University, Central Eastside Historic District, and so forth.

The CCTAC recommended that, as a short-term action, VTI and the city should immediately begin implementation planning on an initial segment of the central city trolley system connecting John's Landing and Riverplace through the downtown core and Northwest Triangle (Pearl District) areas with the Northwest 21st/23rd Avenue district. The goal is to build the first segment and begin operations in mid-1994. This would produce a one-way route of about 4.3 mi, crossing the MAX light rail alignment on Morrison and Yamhill Streets but otherwise completely separate from it.

Further evaluations after this finding was published in October 1990 have led to shortening the proposed initial VT line to the 1.7 mi between Riverplace and the north edge of the CBD at Stark Street. This line is expected to require five replica cars, four to provide a 15-min headway service plus a spare.

A small trolley storage barn is proposed for the southeast end of the line beneath the Marquam Bridge carrying the Interstate 5 freeway over the Willamette River, moving trolleys to the Coliseum VT shop for routine inspection and repairs and to the Ruby Junction LRT shop for heavy overhauls.

Design Standards, Estimated Costs, and Potential Funding for VT Extensions

Wherever VT alignments do not coincide with any future downtown LRT route, they can be built to less stringent designs than LRT lines. Standard tie and ballast track construction is envisaged throughout, paved with black-top where VT tracks are in street lanes on Columbia, Park, and Ninth. Stray currents are expected to be lower for trolleys than LRVs, allowing more expensive embedded in-street track construction techniques for LRT to be avoided. Acceptance of this approach by local utilities has not yet been confirmed.

This approach provides the basis for the modest estimated capital cost of $21.5 million (1990 dollars) shown in Table 2.

Project capital and operating funding remains under development. Funding options being evaluated include a variety of user charge, fee, and tax-based alternatives:

- Farebox, advertising, and promotional revenues (estimated to cover less than 50 percent of operating and maintenance costs),
- Local improvement district (incremental property tax),

TABLE 2 Estimated Capital Costs for First Dedicated Central City VT Line from Riverplace to Park and Stark

Cost Category	Estimated Cost
Track and Civil	$ 8.9 million
Power and Signals	$ 4.4 million
Carbarn	$ 0.6 million
Replica Vintage Trolleys	$ 1.7 million
Engineering, Admin., Mobilization	$ 2.3 million
Contingencies	$ 3.6 million
Total Estimated Cost	$21.5 million

- City transportation funds,
- Urban renewal tax increment funds,
- State transportation and economic development funds,
- Parking or other automobile-related surcharges,
- Development or other value capture mechanisms, and
- Federal energy conservation, environmental, or other grants.

It is anticipated that federal funds will not be available for more than 50 percent of project capital costs. Expansion of vintage trolley service beyond the initial downtown-Lloyd Center operation is not a regional transportation priority. Therefore one activity of VTI and its backers must be to build the public consensus needed to include vintage trolleys in the official transportation improvement program (TIP) as a precondition to qualifying projects for public funding.

WILLAMETTE SHORE TROLLEY

Limited excursion-type trolley service was begun in 1990 from Portland to Lake Oswego. The scenic 13-mi route follows the former Southern Pacific (SP) Jefferson Street Branch. The line, abandoned in 1982 upon the cessation of sporadic local freight switching service, was purchased by the city of Portland in the late 1980s. Built as a narrow-gauge steam road in the 1870s, this branch was one of the lines SP electrified just prior to World War I as part of its "Red Electric" interurban service linking Portland, its nascent western suburbs, and Corvallis. At its peak in the 1920s, the line to Lake Oswego saw the passage of 64 electric trains per day.

Today's Willamette Shore operation is much less intense and entirely leisure-oriented. Tuesdays through Saturdays from late spring through autumn, two antique trolley cars from Gales Creek Enterprises share a total of four round trips. Speeds do not exceed 15 mph in deference to track conditions and the limitations of a power-generator towed along on a four-wheel cart.

Interestingly, this operation's northern terminus is under the Marquam Bridge, exactly at the south terminus now proposed for the first dedicated line of the planned downtown vintage trolley system. More evaluation and negotiation will no doubt be necessary to determine if Willamette Shore cars will be allowed to run over the city system's tracks, or if they will be cut back if and when city trolleys are extended to John's Landing.

In the meantime, this low-intensity operation effectively serves as a kind of place holder that keeps the line minimally active and preserved for some still-to-be-defined future VT or LRT role in the regional transportation system.

CONCLUSION

The new downtown-Lloyd Center vintage trolley and Willamette Shore trolley give Portland two "flavors" of heritage trolley operation:

- New replica trolleys built to be compatible with modern LRVs, and
- True heritage trolleys operating only on their own tracks.

Vintage trolleys on the MAX line are the result of initiatives by downtown business leaders, negotiated, developed, and funded in cooperation with public agencies: the city of Portland and Tri-Met. Similarly, the Willamette Shore trolley operates as a cooperative public-private venture, staffed by volunteers and sponsored by the city of Lake Oswego on a right-of-way owned by the public.

Will VTs become better coordinated and eventually integrated with other Tri-Met rail and bus services and fares? Will further central city vintage trolley circulator lines be built? And will any or all of these lines eventually be connected into a network? Only time, funding, and public advocacy will tell.