Special Report 221

LIGHT RAIL TRANSIT

New System Successes at Affordable Prices

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LIGHT RAIL TRANSIT

New System Successes at Affordable Prices

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San Jose, California

Conducted by the

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Foreword

Light rail transit (LRT) is alive and well in North America. Since the last National LRT Conference in Pittsburgh in 1985, five new light rail systems have begun operation—in Buffalo, Pittsburgh, Portland, Sacramento, and San Jose. Three light rail systems have been extended—in Calgary, Edmonton, and San Diego. Four more light rail systems are now being designed or are under construction—in Los Angeles, St. Louis, Dallas, and most recently, Houston. It was fitting, then, that this fifth National LRT Conference focus on the theme "New System Successes at Affordable Prices." The conference featured nine technical sessions in which more than 40 authors presented papers reporting on the lessons learned—both successes and difficulties—from these and other recent light rail systems around the world.

More than 450 participants attended the conference, the largest number since the first such conference was held in Philadelphia in 1975. Some 24 states and 10 countries were represented, which served to illustrate the widespread interest in this transportation mode in 1988, exactly 100 years after the first successful streetcar system was put into service in Richmond, Virginia. The conference was held in San Jose, California, the latest city in North America to open a new light rail system. The Santa Clara County Transit District's sparkling new Guadalupe Corridor light rail line and downtown transit mall offered conference-goers a chance to see and ride on a system that epitomizes much of the best state-of-the-art design in light rail transit.

The conference opened with two key presentations on recent worldwide light rail developments. John Schumann's extensive research produced the most up-to-date compendium of vital statistics on North America's many and varied light rail systems. David Bayliss reported on the latest light rail developments in Europe, Africa, Asia, and South America.

James Mills, Chairman of the San Diego Metropolitan Transit Development Board, delivered a very interesting and encouraging keynote address. Mills, who also spoke at the Philadelphia conference in 1975, offered a perspective on how much has been achieved in North American LRT development in the past 13 years. He quoted from then-UMTA Administrator Robert Patricelli's 1975 speech in which he stated, "Light rail should certainly not be treated as a panacea for urban mobility problems, but it should be considered as one of the various transit options available to cities." Mills went on to say,

> Light rail is, without doubt, the right technology for some corridors. But heavy rail is the right technology for others, and buses are right for many more. . . . Every decision about which transit technology should be used on any route must be based on the peculiarities of that route and must never be based on somebody's fondness for one type of hardware or another. Existing and future demands for service are the factors that are most likely to define the best transit mode in any corridor.

Mills also reported on San Diego's light rail ridership experience, pointing to an important phenomenon that should provide encouragement to all of the fixed-guideway transit systems that have opened recently or are about to open. Since 1981 ridership on the initial light rail line has doubled from 11,000 per day to 22,000 per day. The average annual ridership growth increase has been over 12 percent in an urban area dominated by high automobile ownership and plenty of freeways. Mills also stated that San Diego had recently conducted some attitudinal surveys that indicated that although many of those interviewed would never consider riding a bus, they would use light rail if it were built to serve their travel needs.

Mills' address set the stage for the first technical session, "The Great Debate," a spirited exchange among several advocates of different transit modes. This reinforces the theme that, although light rail offers many advantages to a city contemplating medium-capacity, fixed-guideway transit improvements, it is not the only choice. In certain instances, a busway may prove to be the better choice. For other corridors, a fully automated guideway system may prove to be a cost-effective solution. Each modal champion was asked to prepare a paper discussing the best attributes of his mode. These advocacy position papers were reviewed and changes were made based on the comments received. Nevertheless, some modal bias and hyperbole necessarily remain. Advocacy, after all, was inherent in their assignments.

Part 2 of this report contains six papers on planning and policy considerations, including two on what real estate developers are looking for in light rail systems to serve their new development projects.

Part 3 contains nine papers on the status of new LRT systems and the lessons learned from several recent LRT start-ups.

In Part 4, ten papers are presented on the technical issues of systems design and new light rail vehicle performance.

As a transition from planning and design to revenue operations, Part 5 offers 14 papers in the areas of operations and maintenance.

To sum up, the fifth National LRT Conference showed that much has been learned in the past decade from planning, designing, building, and operating several modern LRT systems in North America. It also proved that interest in LRT systems is at an all-time high and has not yet crested. There are more cities in North America either contemplating or actually implementing new light rail systems than ever before. Light rail systems are being implemented in both older, highly urbanized eastern cities and in newer, suburban sun-belt cities. 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 abandoned railroads to freeway medians, from surface streets to underground subways.

This report contains the papers presented at the conference as well as six additional papers submitted to the Transportation Research Board. Together with the proceedings of previous conferences, this report documents the development of North America's LRT systems and serves as a reference text for technical questions.

R. David Minister
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San Jose, California

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PART 1

Overview

Keynote Address

James R. Mills

IN JUNE 1975 THE first national conference on light rail transit was held in Philadelphia under the auspices of the Transportation Research Board of the National Research Council. Twelve years later it is interesting to look back on that meeting, to reflect on some of the statements that were made, and to consider what has transpired since then in the field.

Let me refer first to the printed record of the speeches made at those proceedings (*1*). The foreword was written by Robert E. Patricelli, who was then the administrator of the Urban Mass Transit Administration. He wrote:

> There is increasing doubt that a single transport system of any technology can effectively serve the broad range of travel patterns and services that prevail in a large city. There is also no compelling reason why a single type of transportation system must dominate an entire metropolitan area. This trend to move away from a unimodal solution to a system that blends a number of discrete transit elements, each of which is tailored to demands and local conditions, should make light rail transit a particularly strong contender for attention by cities that desire some form of a fixed guideway system. Light rail should certainly not be treated as a panacea for urban mobility problems, but it should be considered as one of the various transit options available to cities.

I find that statement so valid that I'd like to see it printed, framed, and hung on the wall of every transit agency in the United States. We who are involved in the development and the operation of light rail systems should give special emphasis in our own thinking to Bob Patricelli's point that travel patterns are so diverse in large cities that a diversity of technologies may best serve the many demands put on transit systems.

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The fact that a city has a heavy rail system to serve the busiest transit corridors is generally taken to mean that there are no parts of that city that can be better served by some other guideway technology. Yet some of the best systems in the world—Toronto, San Francisco, Boston, and Moscow, for example—owe a part of their excellence to a recognition on the part of their managers that a diversity of modes can be the best response to a variety of demands for service.

Commonly transit officials have striven to junk light rail and streetcar systems when they succeed in the great accomplishment of putting a heavy rail line in place. In fact, that has become a general rule on this side of the Iron Curtain. A great many very good light rail lines have been discontinued unnecessarily—to the disadvantage of the public.

Bob Patricelli's point that light rail should not be considered a panacea for urban mobility problems should be underlined in the frames on our walls. Light rail is, without doubt, the right technology for some corridors. But heavy rail is the right technology for others, and buses are right for many more. And paratransit is the right way to provide mobility in many areas. Every decision about which transit technology should be used on any route must be based on the peculiarities of that route and must never be based on somebody's fondness for one type of hardware or another. Existing and future demands for service are the factors that are most likely to define the best transit mode in any corridor.

Bob Patricelli was offering us a warning that light rail can be the wrong system to build if it is put in the wrong place. That must be balanced against his assurance that it is the right system when put in the right place.

I want to talk about how well light rail works when in the right place, and I hope that none of you will mind if I use the light rail system in San Diego as an example. However, before I begin telling you that success story, I would like to refer back to some of the remarks made by Vukan Vuchic at the meeting in Philadelphia 12 years ago. Vuchic said (*1*, p. 74):

> Some lay observers have posed this question: Why are we returning to LRT after abandoning streetcars as inefficient? The fact is that, if the LRT concept is understood properly, it is clear that introduction of this mode is not a step backward but a major step forward in upgrading existing surface transit systems. The potential for introduction of LRT into our cities lies in the fact that LRT is better adapted to separation and preferential treatment than are streetcars and buses, that it offers a higher service quality and that it has a better image. Most important, LRT can, because of these features, attract passengers that other surface transit cannot.

That statement is one that has gathered meaning in the last 12 years, particularly in San Diego. When our line from downtown to the Mexican border was opened in 1981, the daily patronage was well above the expectations of management, which were for 9,800 riders a day. Right at the start we had 11,000. That figure was proof that Vukan Vuchic was right, and that LRT can attract passengers that other surface transit cannot.

Since that time, ridership has grown steadily. The number of people taking our trains has been higher for each of the last 61 months than it was during the same month of the previous year. The daily figure for the South Line is now well over 22,000 a day—more than twice as many as seven years ago. The growth has not only been steady, it has been steadily increasing both in absolute numbers and as percentages.

The average annual patronage increase for the entire light rail system since January 1983 is 12.2 percent. In March 1988 our patronage was 20.8 percent higher than it was in March 1987. The only difference in our service was an increased frequency of trains, which apparently contributed a great deal to our increase in the number of riders served. That, I hope, is a point everyone here will note.

All categories of ridership are increasing, but the one that is growing fastest is commuter traffic. These are people who, we were warned, would never get out of their cars to ride transit. Californians, we heard, are in love with their cars and driving to work is a precious right as far as most of them are concerned.

It turns out that is not so. If San Diegans are given a pleasant alternative to their cars, a large number of them will take advantage of it to get to work. Our surveys show that one-third of the people who ride our system each day come to it in their cars and park at the lots at our stations. Our surveys further show that most of those people, when asked how they would get to work if the light rail line did not exist, say they would drive the rest of the way.

We have, you see, proved Vukan Vuchic right. Our system has also demonstrated a number of other truths about light rail transit. It can be cheap to build, compared with other fixed-guideway systems. Our South Line, complete with cars, shops, and every other appurtenance, cost us $117 million for 16 mi of a double-track railway. At less than $7.5 million/mi, including rolling stock, it is by far the cheapest urban passenger railway built during the lifetimes of most of us in this room.

It was cheap to build because management decided that it should be. Everything about the system is simple and practical. As a result it is also very cheap to operate. The last report on the operating costs of the urban rail systems of America showed that our line costs less to run per passenger mile than any other. That fact carries with it an important lesson. Complexity not only costs more to build into a system, it also costs more to maintain and operate.

Our high level of patronage and our low level of operating costs have produced a farebox revenue ratio of 85 percent on a year-round basis. During summer months, it has often risen to over 100 percent. Another lesson we have learned is that we have not reduced that figure by increasing our levels of service. When we have extended our schedules later into the evening, and when we have increased frequencies in midday, we have found that the increases in farebox revenues have been more than enough to pay for the costs of the new service.

As we look to the future, we anticipate keeping ourselves in good shape financially by adding further improvements in the quality of our service. Naturally we will be very careful about what we do in that regard. Making mistakes would be expensive. However, we are convinced that Vukan Vuchic was right in 1975 when he said that light rail transit can best attract new riders by offering higher service quality.

I should like to conclude by repeating a few of the remarks I made in my speech to the Philadelphia conference in 1975 (*1*, p. 5).

> The rediscovery of light rail was not motivated by sentimentality and nostalgia for a bygone era. It was the result of judgment founded on a realistic assessment of growing transit needs and diminishing financial resources. The reason for the rebirth of light rail transit is the inherent advantages of the technology. Light rail transit offers public officials the opportunity to initiate rail transit developments at a modest cost. . . . The flexibility of the technology allows transit service, system capacity, and available resources to be traded off in a variety of ways so that the best transit system for a community can evolve over time.

To repeat the words of Bob Patricelli, light rail should not be considered a panacea for the growing woes created by our increasing urban congestion. But, in the right corridors, it can be the right answer to the needs of a lot of Americans. It can make their lives more pleasant. It can make the cities where they live more vital and interesting places. And it can contribute to the quality of the air they breathe. Finally, it can help to assure them of a more prosperous America by diminishing, along with all other improvements in our public transportation systems, our dependence on foreign oil and the adverse balance of trade that dependence has helped to impose on us.

Like all of the speakers in 1975, I want to urge the careful consideration of light rail as the right technology in the right places. We owe it to the people we serve, we owe it to communities, and we owe it to the nation we so often pledge our allegiance to. Even though the contributions we might make to the solutions of very great problems may be modest ones, we should make them. The greatest of problems are only solved if a lot of people undertake to do whatever is within their power to do. Our responsibilities, though modest, are clear enough: to make correct decisions as to the modes of public transit we operate and as to how we operate them.

Let us reflect on the fact that the passing of time has borne out the truths of what was said at the first conference of this group, and let us go forward with the assurance that we are on the right track.

REFERENCE

1. *Special Report 161: Light Rail Transit.* TRB, National Research Council, Washington, D.C., 1975.

What's New in North American Light Rail Transit Projects?

JOHN W. SCHUMANN

This paper summarizes North American light rail transit (LRT) progress during recent years. Existing system rehabilitation and new project planning, design, construction, and start-up activities are discussed. To depict the significant effects of recent changes in the North American LRT situation, the text and data update the author's paper Evaluations of Operating Light Rail Transit and Streetcar Systems in the United States, published in TRB Special Report 182 (1978). Since then, U.S. LRT/streetcar cities (Boston, Newark, Philadelphia, Pittsburgh, Cleveland, New Orleans, Fort Worth, and San Francisco) have replaced old cars or rebuilt fixed facilities or both. Similar changes have occurred in Toronto and Mexico City. Seven cities have opened new LRT systems since 1977: Edmonton (1978), Calgary and San Diego (1981), Buffalo (1985), Portland (1986), and Sacramento and San Jose (1987). All these projects have been positive and productive additions to the transit networks in their respective areas. LRT is under construction in Los Angeles and in an advanced state of planning or design in more than a dozen other places. These projects encompass urban areas where LRT may be a natural "step up" from an all-bus transit system, as well as cities that have discarded proposals for other guideway technologies. With old system reconstruction and a flurry of new starts, LRT has become the guideway mode of choice for an increasing number of cities. LRT provides adequate levels of service, speed, and comfort for realistically projected passenger flows; it is affordable to build and run; it enhances urban development without "Manhattanization"; and it is a sensitive, environmentally compatible neighbor to the communities it serves.

FROM A TURN-OF-THE-CENTURY position of dominance among urban transport modes, surface electric railways—i.e., city streetcar systems plus suburban and intercity "interurbans"—dwindled nearly to the point of extinction. Although new rapid transit systems were begun, only three

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significant trolley projects were undertaken from the end of World War II through the late 1960s:

- 1955: Extension of Philadelphia's surface car subway from 23rd and Market streets to the University of Pennsylvania;
- 1959: Conversion of Boston's Riverside line from diesel-powered commuter rail to light rail; and
- 1963: Opening of Leonard's M&O (now Tandy) subway in Fort Worth.

By this time, the streetcars-to-buses changeover had largely run its course. Except in Philadelphia and Toronto, most of the remaining trolley lines had substantial portions of their routes on a right-of-way (ROW) separated from rubber-tired traffic; and in all cases, political pressure was growing to prevent their closure. During the latter 1960s and through the 1970s, it became increasingly clear that operators faced a choice of either refurbishing and modernizing their systems or weathering a public outcry if electric rail operations ceased.

THE LRT CONCEPT EMERGES

The light rail transit (LRT) concept emerged during this same period. It was applied with great success by European authorities to upgrade aging streetcar systems to modern, efficient transit services. By 1976, enough thought had been given to the subject in North America that the TRB Committee on Light Rail Transit adopted a concise definition for this new mode of urban transportation based on thoroughly proven electric railway technology (*1*, p. 1):

> 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.

Not all of the remaining North American trolley systems fit the new definition. Lines in North Philadelphia, San Francisco, and Toronto retained the look and performance of streetcars (little track reservation, frequent stops, slow running, and/or old cars). New Orleans continued to run streetcars dating from 1924 on a right-of-way that, though separated from parallel traffic, resulted in slow service speeds due to very frequent stops and minimally protected grade crossings. Other systems, though benefiting from substantial sections of reserved ROW, all used aging fleets of President's Conference Committee (PCC) or similar cars.

WHAT MAKES LRT UNIQUE?

As with any definition, TRB's is subject to interpretation. It has been, and no doubt will continue to be, the topic of spirited debate among experts. As used here, the definition is taken to mean that to qualify as LRT, a system: (1) must run on track mostly separated from vehicular traffic, (2) be capable of operating through grade crossings, and (3) use "straight electric" duo-rail vehicles. Table 1 compares some of the key aspects of LRT with other types of transit and indicates LRT's position as a medium-cost, medium-capacity mode. The range of new projects demonstrates the broad variations in service and costs that may be achieved with LRT and, more importantly, that adequate-to-superior performance and appropriate capacity can be provided on available or newly created ROW without breaking the bank.

TABLE 1 KEY CHARACTERISTICS DIFFERENTIATING LRT FROM OTHER TRANSIT MODES

Characteristic	Light Rail	Bus	Commuter Rail	Automatd Guideway	Rapid Rail*
System Costs:					
Initial	Moderate	Low/Moderate(a)	Low-to-High	High	Very High
Operating & Maintenance, per Passenger Mile(b)	---	Higher	Higher	Similar	Lower(c)
Attributes:					
Schedule Reliability	Excellent	Fair	Good	Superior	Excellent
Grade Separation	Varies	Less	More	100%	100%
Automatic Operation	No(d)	No	No(d)	Yes	Maybe(d)
Entrained Vehicles	Yes	No	Yes	Maybe	Yes
Public Perception:					
Comfort, Ride Quality	Good	Fair	Good	Good	Good
Route Comprehension(e)	Easy	Hard	Easy	Easy	Easy/Hard
Social Acceptability	High	Low	High	High	(f)
Railroad Involvement:					
Operating Labor	No	No	Yes	No	No
Freight Coordination	Maybe(g)	No	Maybe(g)	No	No

* Also called "Heavy Rail" and/or "Metro"
(a) But, busway/HOV lane cost per mile can equal or exceed LRT construction cost/mile.
(b) Other modes in comparison to LRT
(c) Not always; San Diego Trolley (which is LRT) has lowest O&M $/Passenger Mile of any transit system in U.S.
(d) May have automatic train stop (ATS), without full automation
(e) Generally, a surface or aerial guideway is visible and therefore easier to comprehend than a bus route on public streets or guideway in tunnel.
(f) Higher for new systems, but lower for old systems operating in depressed or deteriorating urban areas
(g) Yes, if joint track use or grade crossings with freight railroads

WHAT TRANSIT SERVICES CAN LRT PROVIDE?

Depending on local needs, city size, ROW availability, and financing capability, LRT systems can be developed to serve three principal classes of urban travel:

- Line haul transit from city or suburban residential areas to central business districts (CBDs) and other employment zones;
- Feeder service to rapid transit or commuter rail; and
- Local area transit within a portion of an urbanized area or activity center, including CBD distribution.

As indicated in Table 2, the North American systems all perform one or more of these functions. The ability to perform multiple transit functions is an advantage of LRT, which combines some operational characteristics of both bus and rapid transit modes. LRT can approach rapid transit commercial speeds to attract line haul traffic; but ease of access to simple at-grade stations and typically shorter station spacings also allow LRT to attract local ridership.

In Portland, for example, the Metropolitan Area Express (MAX) was conceived as an arterial trunk commuter line to downtown. But it also carries local passengers between suburban origins and destinations: along East Burnside Street and in Gresham, between downtown and Lloyd Center (downtown's extension on the east bank of the Willamette River), and on short hops within downtown Portland. In suburban Philadelphia, the lines to

TABLE 2 PRINCIPAL FUNCTIONS OF NORTH AMERICAN LRT AND STREETCAR SYSTEMS

<u>Line haul/express/commuter service</u> between employment zones (particularly central business districts) and residential areas, including coordination with feeder buses, auto passenger drop-offs, and/or park-&-ride:

> Boston (Green Line), Calgary, Cleveland, Edmonton, Newark, Philadelphia (Subway-Surface), Pittsburgh, Portland, Sacramento, San Diego, San Francisco, San Jose

<u>Feeder service</u> to rapid transit and/or commuter rail:

> Boston (Mattapan-Ashmont), Philadelphia (Media-Sharon Hill); secondary function for Boston (Green Line), Cleveland, Newark, Philadelphia (Subway-Surface and Streetcars), San Francisco, San Jose, Toronto

<u>Local area circulation</u> within a portion of an urbanized area or activity center, and/or CBD distribution:

> Fort Worth, Philadelphia (Streetcars), Toronto, and "Vintage Trolleys" in Detroit, Lowell, New Orleans, Seattle; secondary function for all other systems listed above

Media and Sharon Hill primarily feed the Market-Frankford rapid transit line at 69th Street Terminal. But they also carry students, shoppers, and others to destinations along the two routes.

LRT IN THE LATE 1970s

Ten years ago, there were 11 definable LRT and streetcar systems in eight U.S. cities, plus the streetcar systems in Toronto and Mexico City. The author's research (*2*, pp. 94–103) classified the U.S. properties according to system average operating speeds (V_{avg}):

- Light Rail Transit—Group I, $V_{avg} \geq 24$ km/hr (≥ 15 mi/hr): Cleveland, Newark, Philadelphia (Media-Sharon Hill), and Fort Worth;
- Light Rail Transit—Group II, $V_{avg} \geq 16$ to <24 km/hr (≥ 10 to <15 mi/hr): Pittsburgh, Boston (Green Line and Mattapan-Ashmont), and Philadelphia (subway-surface); and
- Streetcars, $V_{avg} <16$ km/hr (<10 mi/hr): San Francisco, New Orleans, and Philadelphia (streetcars); and Toronto's streetcar system.

By 1977, several cities had taken initial steps toward upgrading their LRT systems, a new 7.2-km (4.5-mi) LRT line was being built in Edmonton, and other North American cities were in various stages of LRT planning and design.

NORTH AMERICAN LRT SYSTEMS TODAY

Virtually all the systems running in 1977 have since been modernized or refurbished to some degree, and seven new projects have begun revenue service. Today, 19 definable systems serve 16 U.S. and Canadian cities.

Lines operated have grown in 10 years from 368 km (229 mi) to 541 km (336 mi), a 47 percent increase. Though impressive against the LRT mode's previous decline, average kilometers (miles) built per year have remained small (see Table 3).

Characteristics of Present U.S. and Canadian Systems

Table 4 lists the existing, physically separable LRT and streetcar systems operating in North America. Line lengths, number of revenue cars, rides per weekday, and two productivity indicators are shown.

TABLE 3 TEN-YEAR GROWTH IN NORTH AMERICAN LRT SYSTEMS

	United States	Canada	North America
LRT km (mi) in 1977	295 (183)	73 (46)	368 (229)
LRT km (mi) in 1987	430 (267)	111 (69)	541 (336)
Percent increase	46	50	47
Average km (mi)/year	13.5 (8.4)	3.8 (2.3)	17.3 (10.7)

Systems included meet TRB's definition of LRT or are streetcars providing all-year service as part of a larger, integrated transit system. Omitted are lines using vintage trolleys as local distributors (Detroit, Seattle) and seasonal tourist services (Lowell, San Francisco's Trolley Festival), as well as systems requiring 100 percent grade separation [the Southeastern Pennsylvania Transportation Authority (SEPTA) Norristown High Speed Line] and automatic operation (Vancouver's SkyTrain).

Based on system average operating speeds (V_{avg}), the distribution of North American LRT and streetcar systems is as follows (italics indicate new starts):

- Light Rail Transit—Group I, $V_{avg} \geq 24$ km/hr ($\geq$15 mi/hr): *Calgary*, Cleveland, *Edmonton*, Newark, Philadelphia (Media-Sharon Hill), *Portland*, *Sacramento*, *San Diego*, and *San Jose*;
- Light Rail Transit—Group II, $V_{avg} \geq$16 to <24 km/hr ($\geq$10 to <15 mi/hr): Boston (Green Line and Mattapan-Ashmont), *Buffalo*, Fort Worth, Philadelphia (subway-surface), Pittsburgh, and San Francisco; and
- Streetcars, V_{avg} <16 km/hr (< mi/hr): New Orleans, Philadelphia (streetcars), and Toronto.

Kilometers and miles of line, size of car fleets, and weekday rides (boardings) are distributed among the three categories of systems as shown in Table 5.

Group I headways tend to be longer and speeds faster; therefore, fewer cars per kilometer of line are required as compared with the more urban Group II and streetcar systems:

	LRT		
	Group I	*Group II*	*Streetcars*
Revenue Service Cars/km (mi)	1.7 (2.8)	3.9 (6.3)	2.6 (4.2)

TABLE 4 LINE LENGTHS, CAR FLEETS, AND PRODUCTIVITY

City/System	Parameters: km(mi) of Line	Parameters: Cars	Parameters: Rides/ Weekday	Statistics: Cars/ km(mi)	Statistics: Weekday Rides/ km(mi)	Statistics: Weekday Rides/ Car
LRT-Group I:						
Calgary, C-Train(a)	27.5(17.1)	83	83000	3.0(4.9)	3018(4854)	1000
Cleveland, Shaker Rapid(b)	21.1(13.1)	48	17500	2.3(3.7)	829(1336)	365
Edmonton, Northeast LRT(a)	10.5(6.5)	37	25000	3.5(5.7)	2381(3846)	676
Newark, City Subway(b)	6.9(4.3)	24	14100	3.5(5.6)	2043(3279)	588
Philadelphia: Media-Sharon Hill(b)	19.2(11.9)	29	9600	1.5(2.4)	500(807)	331
Portland, MAX(a)	24.3(15.1)	26	20000	1.1(1.7)	823(1325)	769
Sacramento, RT Metro(a)	29.4(18.3)	26	13200	0.9(1.4)	449(721)	508
San Diego Trolley(a)	32.8(20.4)	30	27000	0.9(1.5)	720(1157)	787
San Jose, Guadalupe(a,e)	32.8(20.4)	50	12000	1.5(2.5)	366(588)	240
Subtotals	204.5(127.1)	353	221400	1.7(2.8)	1083(1742)	627
LRT-Group II:						
Boston: Green Line(b)	40.1(24.9)	235	210000	5.9(9.4)	5237(8434)	894
Mattapan-Ashmont(b)	4.3(2.7)	12	7000	2.8(4.4)	1628(2593)	583
Buffalo, MetroRail(a)	10.3(6.4)	27	29000	2.6(4.2)	2816(4531)	1074
Ft Worth, Tandy	1.6(1.0)	8	5900	5.0(8.0)	3688(5900)	738
Philadelphia: Subway-Surface(b)	35.9(22.3)	112	49700	3.1(5.0)	1384(2229)	444
Pittsburgh, South Hills(b)	36.2(22.5)	102	27300	2.6(4.2)	754(1213)	268
San Francisco, Muni Metro(c)	32.2(20.1)	130	130000	4.0(6.5)	4037(6468)	1000
Subtotals	160.6(99.9)	626	458900	3.9(6.3)	2857(4594)	733
Streetcars:						
New Orleans, St Charles	10.5(6.5)	35	21000	3.3(5.4)	2000(3231)	600
Philadelphia, Streetcars	92.4(57.4)	110	51300	1.2(1.9)	555(894)	466
Toronto, Streetcars	73.4(45.6)	318	298300	4.3(7.0)	4064(6542)	938
Subtotals	176.3(109.5)	463	370600	2.6(4.2)	2102(3384)	800
Totals	541.4(336.5)	1442	1050900	2.7(4.3)	1941(3123)	729

(a) New start opened since 1977; (b) Major reconstruction/rehabilitation since 1977; current peak requirement is 60 cars, 33 LRV + 27 PCC; (c) Upgrade from Streetcar system since 1977; (d) East Line has no bus feeders; will update figures after 1/88 bus cut-over; (e) 10.5 km (6.5 mi) to be in service 12/87; Rides/Weekday - current projection for 1991 opening of full line

TABLE 5 NORTH AMERICAN LRT SYSTEM STATISTICS BY CATEGORY

	Extent of Line			Cars		Weekday Boardings	
	Kilometers	Miles	Percent	No.	Percent	No.	Percent
LRT—Group I	204.5	127.1	38	353	24	221,400	21
LRT—Group II	160.6	99.9	30	626	43	458,900	44
Streetcars	176.3	109.5	32	463	32	370,600	35
Total	541.4	336.5		1,442		1,050,900	

For the most part, LRT systems in Group I tend to link downtown employment with relatively distant, lower density residential neighborhoods 8 to 24 km (5 to 15 mi) away, while Group II LRTs and streetcars tend to serve neighborhoods closer to the core, 8 to 10 km (5 to 6 mi) or less away. Obvious exceptions are Newark (Group I), and Boston and Pittsburgh (Group II).

In keeping with divergent functions, the more suburban Group I systems tend to have stations spaced farther apart:

	No. of Stations	*Avg Spacing, km (mi)*
LRT—Group I	234	0.9 (0.5)
LRT—Group II	469	0.3 (0.2)
Streetcars	1,233	0.1 (0.1)

To serve their longer routes, the faster Group I systems run about as many car kilometers per year as each of the other two categories, but work their fleets harder:

	Car-km (Car-mi)/Year (millions)	*Annual km (mi)/Car (thousands)*
LRT—Group I	20.8 (13.0)	59 (37)
LRT—Group II	22.6 (14.1)	36 (23)
Streetcars	19.1 (11.9)	41 (26)
Total	62.5 (39.0)	43 (27)

Group I systems tend to be more commuter-oriented; therefore, as a group, they attract fewer rides per kilometer of line than the typically shorter, more urban lines of the Group II and streetcar systems (see Table 6).

By careful design, most of the new-start systems fall into Group I. Within the multiroute systems included in Group II, some individual lines meet the >15 mi/hr criterion and, if considered separately, would be in Group I (e.g., Boston's Riverside Line). Especially noteworthy is the upgrading of San

TABLE 6 WEEKDAY BOARDINGS PER KILOMETER, PER MILE, AND PER CAR

	Per Kilometer		Per Mile		Per Car	
	Range	Avg	Range	Avg	Range	Avg
LRT—Group I	366–3,018	1,083	588–4,854	1,742	240–1,000	627
LRT—Group II	754–5,237	2,357	1,213–8,434	4,594	268–1,074	733
Streetcars	555–4,064	2,102	894–3,384	3,384	466–938	800

Francisco from Streetcar to LRT—Group II in light of the system's metamorphosis as the Muni Metro with new light rail vehicles (LRVs) and the tunnel beneath Market Street, an important increase in reserved trackage (37 percent in 1977 to 44 percent now).

To achieve competitive average operating speeds at moderate costs, the new systems all are built on primarily reserved but not necessarily grade-separated ROW:

	Percent of Line-km (Line-mi)	
	Reserved	*Mixed Traffic*
LRT—Group I	97	3
LRT—Group II	67	33
Streetcars	10	90

In most cases, downtown construction in reserved lanes or transit malls has avoided costly subways, while making the new LRT systems in Group I at once more easily understandable and hospitable to riders. They employ one-person operation of multicar trains and self-service proof-of-payment (POP) fare collection to minimize operating labor requirements. As a result, the new all-surface or mostly surface LRT lines are able to provide rapid transit or commuter rail types of services at levels of investment and operating support appropriate for and affordable by the medium-sized cities they serve. Spacing of surface stops makes these new LRTs more accessible, though typically somewhat slower than grade-separated rapid transit systems. Each of the new LRT lines provides the backbone of a multimodal bus and rail transit system.

By and large, the new and rebuilt LRT systems have proven their worth in the marketplace. They attract substantially more riders than the previous all-bus systems they have replaced (or streetcar system in the case of San Francisco); and, where operating jurisdictions have allowed, the ability to run LRT with a small staff has resulted in economical operation.

Comparing Different Groups of LRT Systems

Table 7 displays some key statistics of the LRT and streetcar systems currently carrying passengers in North America. Compared with urban LRTs (Group II) and streetcars, the Group I—LRT systems extending furthest from downtown provide trunk line "arterial route" service and generally exhibit

TABLE 7 KEY DESCRIPTIVE STATISTICS

City/System	% R/W Reserved	Avg Sta Spacing km(mi)	% Dbl Track	# Thru Routes	# Cars: 4-Axl (a)	# Cars: 6-Axl (b)	System Av Speed km(mi)/h
LRT-Group I:							
Calgary, C-Train	100%	0.9(0.6)	100%	3	0	83	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)
Newark, City Subway	100%	0.6(0.4)	100%	1	24	0	34(21)
Philadelphia:							
Media-Sharon Hill	87%	0.4(0.2)	71%	2	29	0	26(16)
Portland, MAX	99%	1.0(0.6)	89%	1	0	26	30(19)
Sacramento, RT Metro	90%	1.0(0.7)	40%	1	0	26	34(21)
San Diego Trolley	100%	1.5(0.9)	99%	2	0	30	29(18)
San Jose, Guadalupe	100%	1.0(0.6)	95%	2	6(c)	50	32(20)
Subtotals/Averages	97%	0.9(0.5)	86%	15	53	300	
LRT-Group II:							
Boston:							
Green Line	89%	0.5(0.3)	100%	4	0	235	16(10)
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%	0.4(0.3)	100%	1	8	0	17(11)
Philadelphia:							
Subway-Surface	16%	0.2(0.1)	100%	5	112	0	18(11)
Pittsburgh, South Hills	97%	0.4(0.3)	90%	4	47	55	22(14)
San Francisco, Muni Metro	44%	0.3(0.2)	100%	5	0	130	18(11)
Subtotals/Averages	67%	0.3(0.2)	<100%	21	206	420	
Streetcars:							
New Orleans, St. Charles	88%	0.2(0.1)	100%	1	35	0	15(9)
Philadelphia, Streetcars	5%	0.2(0.1)	100%	7	110	0	14(9)
Toronto, Streetcars	4%	0.1(0.1)	100%	9	318	0	15(9)
Subtotals/Averages	10%	0.1(0.1)	100%	17	463	0	
Totals	60%	0.3(0.2)		53	722	720	

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

- More reserved ROW, to achieve higher speeds and schedule reliability;
- Longer distances between stations to increase schedule speeds;
- Less double track where longer trains provide sufficient peak capacity at longer headways;
- Fewer through service routes, relying on bus feeders and automobile park-and-ride for suburban distribution;
- Propensity to use large six-axle articulated cars to gain more carrying capacity while retaining the capability to negotiate sharp turns; and
- Higher system average speeds.

More detailed information on these and other LRT and streetcar system characteristics may be found in Tables 8 through 12 covering ROW location; station and grade crossing frequency; track traffic patterns, signal systems, and electrification; revenue service vehicles; and operating statistics.

LRT Progress in the 1980s

North America's LRT progress has been hard won and has been achieved in the face of severe obstacles:

- Continuing preference for automobile travel, seemingly at any cost, and corresponding antipathy to group transportation (reinforced by government funding allocations to the various transport modes);
- The present federal tilt against new rail transit systems; and
- The challenge of financing the capital costs of fixed-guideway transit, whether heavy rail, automated-guideway, or even some LRT systems.

These obstacles notwithstanding, new system construction during the 1980s has demonstrated that LRT can indeed provide "a wide range of passenger capacities and performance characteristics at moderate costs" (*1*, p. 1). Table 13 lists the recent North American projects, their initial cost, and total cost per kilometer of line constructed. Cost ranges for recent LRT capital projects are:

- New starts, \$5.4 million/mi (San Diego-South Bay) to \$82.8 million/mi (Buffalo);
- Extensions, \$7.6 million/mi (San Diego-Euclid) to \$42.5 × 0.75 ± ~\$31.9 million (Canadian)/mi (Toronto-Harbourfront); and
- Reconstructions, \$1.0 million/mi (Fort Worth) to \$51.6 million/mi (Pittsburgh—Stage I).

These expenditures have been for systems with a wide range of physical, operational, and service characteristics, as shown in the tables.

TABLE 8 RIGHT-OF-WAY LOCATIONS

City/System	km(mi) of Line Subway/Tnl	Exclusive (a)	Pvt R/W (b)	Median (c)	Lanes/Mall (d)
LRT-Group I:					
Calgary, C-Train	1.9(1.2)	1.3(0.8)	13.2(8.2)	8.7(5.4)	2.4(1.5)
Cleveland, Shaker Rapid	---	11.3(7.0)	---	9.8(6.1)	---
Edmonton, Northeast LRT	2.3(1.4)	---	8.2(5.1)	---	---
Newark, City Subway	2.1(1.3)	4.8(3.0)	---	---	---
Philadelphia:					
Media-Sharon Hill	---	---	16.3(10.1)	---	0.3(0.2)
Portland, MAX	---	8.7(5.4)	3.7(2.3)	8.4(5.2)	3.4(2.1)
Sacramento, RT Metro	---	9.5(5.9)	12.4(7.7)	1.0(0.6)	3.7(2.3)
San Diego Trolley	---	---	30.1(18.7)	1.6(1.0)	1.1(0.7)
San Jose, Guadalupe	---	15.8(9.8)	1.8(1.1)	14.1(8.8)	1.1(0.7)
Subtotals	6.3(3.9)	51.4(31.9)	85.7(53.2)	43.6(27.1)	12.0(7.5)
LRT-Group II:					
Boston:					
Green Line	7.2(4.5)	17.1(10.6)	---	11.4(7.1)	---
Mattapan-Ashmont	---	4.3(2.7)	---	---	---
Buffalo, MetroRail	8.4(5.2)	---	---	---	1.9(1.2)
Fort Worth, Tandy	0.6(0.4)	---	1.0(0.6)	---	---
Philadelphia:					
Subway-Surface	4.0(2.5)	---	---	1.6(1.0)	---
Pittsburgh, South Hills	3.8(2.4)	9.7(6.0)	20.9(13.0)	0.8(0.5)	---
San Francisco, Muni Metro	10.2(6.4)	---	1.2(0.8)	2.6(1.6)	---
Subtotals	34.2(21.4)	31.1(19.3)	23.1(14.4)	16.4(10.2)	1.9(1.2)
Streetcars:					
New Orleans, St. Charles	---	---	---	9.0(5.6)	0.2(0.1)
Philadelphia, Streetcars	---	---	---	---	4.2(2.6)
Toronto, Streetcars	0.3(0.2)	---	---	2.6(1.6)	---
Subtotals	0.3(0.2)	---	---	11.6(7.2)	4.4(2.7)
Totals: km/ (mi)	40.8/ (25.5)	82.5/ (51.2)	108.8/ (67.6)	71.6/ (44.5)	18.3/ (11.4)

(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

Table 14 summarizes changes in the North American LRT scene since 1977. Developments from 1977 through 1985 were reviewed at TRB LRT conferences in 1982 and 1985. The remainder of this paper discusses the specific progress made by North American LRT systems, new starts, and would-be new starts since TRB's last conference in May 1985. Much has happened in this short time.

TABLE 8 *continued*

City/System	km(mi) of Line: Mixed Tfc (a)	km(mi) of Line: Total	% of Line: Grade Sep	% of Line: Surf-Rsrvd	% of Line: Mixed Tfc
LRT-Group I:					
Calgary, C-Train	---	27.5(17.1)	12%	88%	---
Cleveland, Shaker Rapid	---	21.1(13.1)	53%	47%	---
Edmonton, Northeast LRT	---	10.5(6.5)	22%	78%	---
Newark, City Subway	---	6.9(4.3)	>99%	<1%	---
Philadelphia:					
Media-Sharon Hill	2.6(1.6)	19.2(11.9)	---	87%	13%
Portland, MAX	0.1(0.1)	24.3(15.1)	36%	>63%	<1%
Sacramento, RT Metro	2.8(1.8)	29.4(18.3)	32%	58%	10%
San Diego Trolley	---	32.8(20.4)	---	100%	---
San Jose, Guadalupe	---	32.8(20.4)	48%	52%	---
Subtotals: km/ (mi)	5.5/ (3.5)	204.5/ (127.1)	28%	69%	3%
LRT-Group II:					
Boston:					
Green Line	4.4(2.7)	40.1(24.9)	61%	28%	11%
Mattapan-Ashmont	---	4.3(2.7)	>99%	<1%	---
Buffalo, MetroRail	---	10.3(6.4)	81%	19%	---
Fort Worth, Tandy	---	1.6(1.0)	40%	60%	---
Philadelphia:					
Subway-Surface	30.3(18.8)	35.9(22.3)	11%	5%	84%
Pittsburgh, South Hills	1.0(0.6)	36.2(22.5)	37%	60%	3%
San Francisco, Muni Metro	18.2(11.3)	32.2(20.1)	32%	12%	56%
Subtotals: km/ (mi)	53.9/ (33.4)	160.6/ (99.9)	41%	26%	33%
Streetcars:					
New Orleans, St. Charles	1.3(0.8)	10.5(6.5)	---	88%	12%
Philadelphia, Streetcars	88.2(54.8)	92.4(57.4)	---	5%	95%
Toronto, Streetcars	70.5(43.8)	73.4(45.6)	<1%	>3%	96%
Subtotals: km/ (mi)	160.0/ (99.4)	176.3/ (109.5)	<1%	9%	>90%
Totals: km/ (mi)	219.4/ (136.3)	541.4/ (336.5)	23%	36%	41%

(a) Street lanes shared by LRT and other traffic; "streetcar" operation

TABLE 9 STATION AND GRADE CROSSING FREQUENCIES

City/System	Psgr. Stops (a)	Grd Xngs/ Intrsctns (b)	Spacing km(mi)	No. With Priority (c)	Grade Separations
LRT-Group I:					
Calgary, C-Train	30	43	0.6(0.4)	40	15
Cleveland, Shaker Rapid	28	24	1.1(0.7)	0	26
Edmonton, Northeast LRT	8	9	1.2(0.7)	9	3
Newark, City Subway	11	1	3.4(2.2)	1	8
Philadelphia:					
Media-Sharon Hill	50	4	0.4(0.2)	25	2
Portland, MAX	25	52	0.5(0.3)	52	20
Sacramento, RT Metro	27	72	0.4(0.2)	70	15
San Diego Trolley	22	77	0.4(0.3)	57	5
San Jose, Guadalupe	33	51	0.6(0.4)	51	21
Subtotals	234	333		332	115
LRT-Group II:					
Boston:					
Green Line	84	52	0.8(0.5)	0	28
Mattapan-Ashmont	8	2	2.2(1.4)	0	5
Buffalo, MetroRail	14	7	1.5(0.9)	7	N/A
Fort Worth, Tandy	4	3(d)	0.5(0.3)	0	2
Philadelphia:					
Subway-Surface	167	4	1.4(0.9)	1	0
Pittsburgh, South Hills	82	43	0.8(0.5)	30	18
San Francisco,					
Muni Metro	110	39	0.1(0.1)	0	2
Subtotals	469	150		38	55
Streetcars:					
New Orleans, St. Charles	50	98	0.1(0.1)	0	1
Philadelphia, Streetcars	573	14	0.3(0.2)	0	0
Toronto, Streetcars	610	3	0.9(0.5)	0	1
Subtotals	1233	115		0	2
Totals	1936	598		370	172

(a) Stations and Car Stops
(b) Line segments except Street-Mixed Traffic
(c) Railroad-type gates &/or flashers, plus traffic lights w/LRT pre-empts, priority, green wave, etc.
(d) 1-vehicular & 2-pedestrian crossings

TABLE 10 TRACK TRAFFIC PATTERNS, ELECTRIFICATION, AND SIGNALING

City/System	Double Track km(mi) (a)	Double Track %	Trctn Power (VDC)	Substatns No.	Substatns Rating (mW)	Type of Overhead (b)	Signals Blk (c)	Signals Tfc (c)
LRT-Group I:								
Calgary, C-Train	27.5(17.1)	100%	600	17	≤2	Both	91%	9%
Cleveland, Shaker Rapid	21.1(13.1)	100%	600	6	(d)	Catenary	85%	47%
Edmonton, Northeast LRT	10.5(6.5)	100%	600	6	(d)	Catenary	100%	--
Newark, City Subway	6.9(4.3)	100%	600	4	0.75	Trolley	100%	<1%
Philadelphia:								
Media-Sharon Hill	13.7(8.5)	71%	635	4	(h)	Trolley	50%	25%
Portland, MAX	21.6(13.4)	89%	750	14	0.75	Both	52%	49%
Sacramento, RT Metro	11.7(7.3)	40%	750	14	1	Both	70%	32%
San Diego Trolley	32.7(20.4)	99%	600	20	1	Both	91%	9%
San Jose, Guadalupe	30.9(19.2)	95%	750	15	1.5	Both	58%	42%
Subtotals	176.6(109.8)							
LRT-Group II:								
Boston:								
Green Line(f)	40.1(24.9)	100%	600	11	3-6	Trolley	61%	39%
Mattapan-Ashmont(g)	4.3(2.7)	100%	600	1	6	Trolley	100%	--
Buffalo, MetroRail	10.3(6.4)	100%	650	5	2	Catenary	81%	19%
Fort Worth, Tandy	1.6(1.0)	100%	600	1	(h)	Trolley	--	--
Philadelphia:								
Subway-Surface	35.9(22.3)	100%	600	(e)	--	Trolley	11%	89%
Pittsburgh, South Hills	32.6(20.3)	90%	650	6	6	Both	90%	10%
San Francisco,								
Muni Metro	32.2(20.1)	100%	600	12	2-8	Trolley	19%	81%
Subtotals	157.0(97.7)							
Streetcars:								
New Orleans, St. Charles	10.5(6.5)	100%	600	(h)	(h)	Trolley	--	100%
Philadelphia, Streetcars	92.3(57.4)	100%	600	(e)	--	Trolley	--	100%
Toronto, Streetcars	73.4(45.6)	100%	600	(h)	(h)	Trolley	--	100%
Subtotals	176.2(109.5)							
Total	509.8(317.0)							

(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

TABLE 11 REVENUE SERVICE VEHICLES

City/System	Car Types (a)	Builder	Fleet	Accelrtn (b)	Max Spd (c)	Length (d)	Weight (e)
		Characteristics of Car Equipment:					
LRT-Group I:							
Calgary, C-Train	LRV-6-A	Siemens	83	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)	31(34)
Newark, City Subway	PCC-4-R	St Louis	24	1.8(4.0)	72(45)	14(46)	17(19)
Philadelphia:							
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	26	1.1(2.5)	80(50)	24(80)	36(40)
San Diego Trolley	LRV-6-A	Siemens	30	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			353				
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	135	1.3(3.0)	88(55)	22(72)	30(33)
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)
Philadelphia:							
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	47	1.8(4.0)	72(45)	14(46)	17(19)
San Francisco, Muni Metro	LRV-6-A	Boeing	130	1.3(3.0)	88(55)	22(72)	30(33)
Subtotals			626				
Streetcars:							
New Orleans, St. Charles	VTL-4-R	Perley-Thos '24	35	0.8(1.7)	43(27)	14(48)	19(21)
Philadelphia, Streetcars	PCC-4-R	St Louis	110	1.8(4.0)	72(45)	14(46)	17(19)
Toronto, Streetcars	LRV-4-R	UTDC	196	1.5(3.2)	85(53)	16(53)	23(26)
(Also In Service)	PCC-4-R	Various	122	1.8(4.0)	72(45)	14(46)	17(19)
Subtotals			463				
Total			1442				

(a) See Note (a) on next page. (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).

TABLE 11 *continued*

City/System	Car Types (a)	Endedness	Train (b)	Seats	Capacity (c)	AC? (d)	ATS/ATO
		Characteristics of Latest Car Equipment:					
LRT-Group I:							
Calgary, C-Train	LRV-6-A	Double	3	64	144	No	ATS
Cleveland, Shaker Rapid	LRV-6-A	Double	2	84	144	Yes	ATS
Edmonton, Northeast LRT	LRV-6-A	Double	3	64	144	No	ATS
Newark, City Subway	PCC-4-R	Single	1	54	83	No	No
Philadelphia:							
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	64	144	Yes	No
San Diego Trolley	LRV-6-A	Double	4	64	144	(e)	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
Mattapan-Ashmont	PCC-4-R	Single	1	52	83	No	No
Buffalo, MetroRail	LRV-4-R	Double	3(f)	51	121	Yes	ATS
Fort Worth, Tandy	PCC-4-R	Double	1	60	83	Yes	No
Philadelphia:							
Subway-Surface	LRV-4-R	Single	1	51	90	Yes	No
Pittsburgh, South Hills	LRV-6-A	Double	2	62	151	Yes	ATS
San Francisco, Muni Metro	LRV-6-A	Double	3	68	130	No	No
Streetcars:							
New Orleans, St. Charles	VTL-4-R	Double	1	52	68	No	No
Philadelphia, Streetcars	PCC-4-R	Single	1	50	83	No	No
Toronto, Streetcars	LRV-4-R	Single	1	46	95	No	No

(a) LRV-Light Rail Vehicle, PCC-Presidents' Conference Committee, VTL-Pre-PCC Vintage Trolley; # Axles, 4 or 6; R-Rigid, Non-Articualted, A-Articulated
(b) Maximum Cars/Train in Regular Operation
(c) Car Length (Feet) * 1.8 - comfortable load of seats + standees at $\pm 4/m^2$
(d) Air Conditioning
(e) 6-Yes, 24-No
(f) 4-Car Trains for Special Events

EXISTING SYSTEMS UPGRADED

The process of renewing and upgrading older LRT systems is largely complete. Since 1985, nine cities have made major accomplishments.

Boston

Most visible has been delivery of 100 new LRVs from Kinki-Sharyo. Similar in size and configuration to the Boeing-Vertol cars delivered in the late 1970s, but specified to prevent a repeat of their reliability problems, these LRVs will

TABLE 12 OPERATING STATISTICS

City/System	Anl Car km (mi) (mil)	Annual Train Hours(a) (000s)	Anl km (mi)/Car (000s)
LRT-Group I:			
Calgary, C-Train	4.3(2.7)	79	52(33)
Cleveland, Shaker Rapid	3.1(1.9)	66	65(40)
Edmonton, Northeast LRT	2.1(1.3)	29	57(35)
Newark, City Subway	0.9(0.6)	39	38(25)
Philadelphia:			
Media-Sharon Hill	1.0(0.6)	52	34(21)
Portland, MAX	1.6(1.0)	36	62(38)
Sacramento, RT Metro	1.6(1.0)	36	62(38)
San Diego, Trolley	3.3(2.1)	56	110(70)
San Jose, Guadalupe	4.5(2.8)	140	90(56)
Subtotal/Averages	20.8(13.0)	533	59(37)
LRT-Group II:			
Boston:			
Green Line	7.6(4.7)	384	32(20)
Mattapan-Ashmont	0.5(0.3)	23	42(25)
Buffalo, MetroRail	1.5(1.0)	35	56(37)
Ft Worth, Tandy	0.2(0.1)	9	20(13)
Philadelphia:			
Subway-Surface	4.5(2.8)	297	40(25)
Pittsburgh, South Hills	3.5(2.2)	183	34(22)
San Francisco, Muni Metro	6.5(4.1)	400	50(32)
Subtotals/Averages	22.6(14.1)	1331	36(23)
Streetcars:			
New Orleans, St Charles	1.1(0.7)	83	31(20)
Philadelphia, Streetcars	3.5(2.2)	274	32(20)
Toronto, Streetcars	14.5(9.0)	968	46(28)
Subtotals/Averages	19.1(11.9)	1325	41(26)
Total/Averages	62.5(39.0)	3189	43(27)

(a) Train km(mi) and Train Hours essentially the same as Operator Platform km(mi) Hours for systems with one-person train operation.

supplement the existing fleet and ultimately replace a majority of the remaining PCC cars on the Green Line. However, rebuilt PCC cars will continue to serve the Mattapan-Ashmont route feeding the Red Line.

LRT facility improvements continue to be made. Reconstruction of Central Subway tracks and signaling began in 1985 and will continue through 1989. Surface line rehabilitation also has continued in several locations. Particularly intriguing was a 1987 agreement with a private developer to reconstruct the Riverside Line's Newton Center station as retail shops, a fine reuse for this structure dating from the line's steam engine commuter train days.

TABLE 13 COSTS OF NEW LRT PROJECTS AND MAJOR LRT RECONSTRUCTION

City/System	Line km(mi)	Project	Year Open	Capital Cost Initial ($Mil)	Capital Cost Per km(mi) ($Mil)
LRT-Group I:					
Calgary, C-Train					
South Line	12.7(7.9)	New Start	1981	$C174	$C13.7($C22.0)
Additional LRVs	N/A	---	1982	$C53	N/A
Northeast Line	9.3(5.8)	Extension	1985	$C169	$C18.2($C29.1)
Northwest Line	5.5(3.4)	Extension	1987	$C104	$C18.9($C30.6)
Cleveland, Shaker Rapid	21.1(13.1)	Reconstrctn	1981	$150	$7.1($11.5)
Edmonton, Northeast					
Northeast Line	7.2(4.5)	New Start	1978	$C65	$C9.0($C14.4)
Clareview Extnsn	1.7(1.0)	Extension	1981	$C10.5	$C6.2($C10.5)
Corona Extension	1.6(1.0)	Extension	1983	$C110	$C68.8($C110.0)
Newark, City Subway	6.8(4.2)	Reconstrctn	1985	$20	$2.9($4.8)
Philadelphia:					
Media-Sharon Hill	19.2(11.9)	Reconstrctn	N/A	Unknown, work ongoing	
Portland, MAX	24.3(15.1)	New Start	1986	$213	$8.8($14.1)
Sacramento, RT Metro	29.4(18.3)	New Start	1987	$176	$6.0($ 9.6)
San Diego Trolley					
South Bay-Phase I	25.6(15.9)	New Start	1981	$86	$3.4($ 5.4)
South Bay-Phase II	N/A	Add Dbl Trk	1983	$31	$1.2($ 1.9)
East Line-Euclid	7.2(4.5)	Extension	1986	$34	$4.7($ 7.6)
East Line-El Cajon	18.5(11.5)	Extension	1989	$101	$5.5($ 8.8)
Bayside	2.1(1.3)	Extension	1990	$40	$19.0($30.8)
San Jose, Guadalupe	32.7(20.3)	New Start	1991	$500	$15.3($24.6)
LRT-Group II:					
Boston					
Green Line					
Riverside Carhse	N/A	New Facil	1975	$37	N/A
Commonwealth Av	~6.8(~4.2)	Reconstrctn	1982	$5	$0.7($1.2)
Reservoir Carhse	N/A	Reconstrctn	1984	$37	N/A
100 Kinki LRVs	N/A	New Cars	1988	$112	N/A
Central Subway	~7.2(~4.5)	Track Rcnstrctn	1989	$26	$3.6($5.8)
Traction Power	N/A	Improvements	1991	$37	N/A
Mattapan-Ashmont	4.2(2.6)	Reconstrctn	1981	$8	$1.9($3.1)

TABLE 13 *continued*

City/System	Line km(mi)	Project	Year Open	Capital Cost Initial ($Mil)	Per km(mi) ($Mil)
Buffalo, MetroRail	10.3(6.4)	New Start	1985	$530	$51.5($82.8)
Ft Worth, Tandy Subway	1.6(1.0)	Reconstrctn	1978	~$1	$0.6($1.0)
Philadelphia Subway-Surface	35.9(22.3)	Reconstrctn	1983	Data unavailable	
	N/A	New Cars	1983	$589	~$0.5 mil/car
Pittsburgh, South Hills	36.2(22.5)				
Stage I	16.9(10.5)	Reconstrctn	1987	$542	$32.1($51.6)
Stage II	19.3(12.0)	Reconstrctn	F	~$300	12.0($19.4)
San Francisco, Muni Metro	33.3(20.7)	Reconstrctn	1981	$330	$9.9($15.9)
Streetcars:					
New Orleans, St Charles	10.5(6.5)	Reconstrctn	1991	$43	$4.1($6.6)
Philadelphia, Streetcars	110 PCCs	Rehab Cars	198?	$16	~$0.1 mil/car
Toronto, Streetcars					
4-Axle LRVs	N/A	New Cars	1981	$C98	~$C0.5 mil/car
Articulated LRVs	N/A	New Cars	1988	$C82	~$C1.6 mil/car
Harbourfront LRT	2.1(1.2)	Extension	1989	$C51	$C25.5($C42.5)

$ - U.S. dollars in expenditure year
$C - Canadian dollars in expenditure year
F - Future project, no firm timetable established

Relocation of North Station area trackage and the Lechmere terminus are in final design. Construction of a new LRT maintenance facility at the latter location is in the planning stage. In conjunction with its automatic vehicle identification (AVI) system, to be installed over the next 18 months, the Massachusetts Bay Transportation Authority (MBTA) is working with Boston on providing LRT prioritization at some intersections along surface lines.

Newark

Rehabilitation of the tunnels, tracks, subway and surface stations, and PCC cars was completed in 1985. With bus services reconfigured to feed LRT, the system now carries 14,100 per weekday. Several extensions continue to be evaluated; and in 1987, a feasibility study was initiated for a new station at Summit Street in conjunction with a major redevelopment project. LRT as an extension to the city subway is one of several alternatives being considered to link Newark with its airport and the adjacent city of Elizabeth.

TABLE 14 CHANGES IN NORTH AMERICAN LRT AND STREETCAR SYSTEMS, 1977–1987

City/System	Code (a)	Changes Since 1977
LRT-Group I:		
Calgary, C-Train	NVX	Opened South Line 1981, Northeast Line 1985, Northwest Line 1987; total system is 27.5 km (17.1 mi)
Cleveland, Shaker Rapid	RV	48 new LRVs, new shop, completely rebuilt facilities; currently planned: Van Aken Project (twin office towers above station)
Edmonton, Northeast	NVX	Opened 1978, and since extended to 10.5 km (6.5 mi)
Newark, City Subway	R	Rebuilt PCCs and facilities
Philadelphia, Media-Sharon Hill	VR	29 new LRVs and rebuilt facilities
Portland, MAX	NV	Opened 1986, 24.3 km (15.1 mi)
Sacramento, RT Metro	NV	Opened 1987, 29.4 km (18.3 mi)
San Diego Trolley	NVX	Opened South Bay Line 1981, Euclid line 1986; total system is 32.8 km (20.4 mi)
San Jose, Guadalupe	NV	Partially open December 1987, 10.8 km (6.7 mi). Extension to downtown scheduled June 1988; full line in operation mid-1991
LRT-Group II:		
Boston		
Green Line	RV	235 new LRVs, new shops, rebuilt PCCs and facilities
Mattapan-Ashmont	R	Rebuilt PCCs and facilities
Buffalo, MetroRail	NV	Opened 1985 and 1986, 10.3 km (6.4 mi)
Fort Worth, Tandy	R	Rebuilt PCCs (second time) and refurbished facilities
Philadelphia: Subway-Surface	VR	112 new LRVs, new shop and refurbished facilities
Pittsburgh, South Hills	VRX	55 new LRVs, new shop, 40 rebuilt PCCs and rebuilt 16.9 km (10.5 mi) line including two new subways
San Francisco, Muni Metro	VRX	140 new LRVs, new shop, new Market Street subway, line extension and rebuilt facilities
Streetcars:		
New Orleans, St. Charles	R	Designated National Historic Landmark
Philadelphia, Streetcars	R	110 rebuilt PCCs; some track reconstruction
Toronto, Streetcars	VRX	196 new CLRVs, first of 52 ALRVs under test, Harbourfront LRT begun Sep '87, 2.1 km (1.2 mi); ongoing track renewal, 19.8 km (12.3 mi) in last two years

(a) N–New Start, R–Rebuild/Rehab Facilities, V–New Vehicles, X–Extension

Philadelphia

The Media-Sharon Hill lines were served by buses during summer 1987 so that the 69th Street terminal loop facilities and tracks in Terminal Square could be rebuilt. Much of the surface track was renewed in 1984–1986. This work follows acquisition of 29 Kawasaki LRVs and rehabilitation of track, the traction power system, and the line's attractive stone waiting shelters.

The five subway-surface lines have enjoyed a ridership increase of about 42 percent since being reequipped with Kawasaki LRVs in 1983. These cars are serviced in the new Elmwood Depot completed in the same year.

The North Philadelphia streetcar system is in a period of retrenchment, primarily because the useful life of the fixed plant has been completely consumed, and capital resources are lacking for either renewal or upgrading to LRT standards. Because there is little reserved trackage, except on Route 15-Girard Avenue, service speeds are low. Buses have replaced PCC streetcars on several routes, some permanently and others on a sporadic basis in response to car availability problems, deteriorated track, and street and sewer reconstruction projects. In 1987, the City of Philadelphia initiated a congressionally mandated review to see if certain lines previously converted to bus would have the potential for reintroduction of rail service. Special focus was placed on creation of a reserved ROW LRT line on Allegheny Avenue that would feed both the Broad and Market-Frankford rapid transit lines. City and SEPTA officials are weighing future options for these services.

Pittsburgh

An ambitious reconstruction of about half this system was completed in mid-1987. The 10.5-mi Phase I South Hills LRT line includes new tracks, electrification, and signaling over its entire length, 13 high-and-low platform stations, 23 low-level car stops, 1,600 park-and-ride spaces spread among five stations, 55 new Siemens LRVs, and 2 new subways—1.1 mi under downtown Pittsburgh and 0.2 mi under suburban Mount Lebanon. Both replace former mixed-traffic street operations in areas subject to severe congestion. As a result, average speed between the Mount Lebanon station and downtown Pittsburgh has increased 22 percent, from 17.1 to 20.9 mi/hr. Weekday ridership averaged 27,300 from June 1987 through February 1988.

Up to 45 PCC cars are under consideration for rehabilitation. Eight have been rebuilt to date. Future plans include possible reconstruction of the South Hills Junction-Castle Shannon trunk line via Overbrook, and the branches to Library and Drake.

In addition, an alternatives analysis is in progress to evaluate various LRT options in the "Spine Line" corridor linking downtown with the Northside, Oakland, and Squirrel Hill.

Cleveland

The 48 Breda LRVs delivered in the early 1980s continue to serve the reconstructed Blue/Green (former Shaker Rapid) LRT system and are maintained with the Red Line rapid transit cars in the opulent new Central Rail Maintenance Facility. An award-winning renovation of Shaker Square station, at the junction of the Shaker and Van Aken branches, was completed in 1986.

Current work focuses on key stations. The Van Aken Project, a cooperative effort with the City of Shaker Heights using an UMTA grant, will relocate the Warrensville Road LRT platforms to permit construction of twin office towers and a parking garage.

Renovation of the downtown Tower City LRT and rapid transit stations will include across-the-platform transfers. Rail transit patronage in Cleveland is inhibited because Tower City, the only downtown stop, is not centrally located. The Dual Hub Corridor alternatives analysis currently in progress is addressing the problem of transit distribution through the Cleveland CBD to the city's Cultural Center at University Circle. LRT is emerging as a prime candidate.

New Orleans

The St. Charles streetcar line was designated a National Historic Landmark in 1973. System rehabilitation is in progress, including the tracks, maintenance facility, and the fleet of 35 vintage streetcars built in 1924.

New Orleans also is studying the feasibility of introducing modern LRT, with interest currently focused on a reincarnation of the Canal Street line. Work also is progressing on a 2-mi Waterfront Vintage Trolley.

Fort Worth

The Tandy Subway has not changed since 1985 but continues to function as an efficient connector between peripheral parking and the Fort Worth CBD.

San Francisco

Of all the system renewals, San Francisco's best exemplifies the upgrading of an old streetcar system using modern LRT service standards. Located in a densely developed urban core city, this achievement required substantial capital expenditure, though much less than other rail options.

During Bay Area Rapid Transit (BART) planning in the mid-1950s, a two-level rail tunnel under Market Street was adopted, with Muni trains running above BART's. Consultants proposed a Muni heavy rail system, all in-tunnel, consisting of the new Market Street tunnel plus Muni's existing Twin Peaks and Sunset tunnels, and a new subway under Geary Street, all to be fed by buses.

By the late 1960s, this costly proposal had foundered, and the Muni Metro concept emerged: use subway-surface rail cars (the term LRV was not yet invented) to provide no-transfer service directly to the CBD on the existing five streetcar lines and through the new subway. This system was implemented by the early 1980s. The public response has been a 32 percent increase in rides to about 130,000 per day.

Current projects include extending the J Line 2.2 mi to the Muni Metro Center to expand LRT service and avoid a long, circuitous deadhead route. Construction is to begin in October 1988. An Environmental Impact Statement is being prepared for a new Embarcadero ramp and surface turn-around loop at the Ferry Terminal. Further in the future is an extension from the Ferry Terminal to the area south of Market, where several major land development projects are under construction or planned.

An environmental assessment is being prepared for the F Line. This service will run from Market and Castro via the now-to-be-retained Market Street surface trackage to the Ferry Terminal, then continue on a former freight line to the Fisherman's Wharf area. The project includes rehabilitation of 20 PCC cars.

Toronto

Toronto's large streetcar network was upgraded in the early 1980s with 196 4-axle UTDC LRVs. Track reconstruction usually is in progress along one or more line segments, with 19.8 km (12.3 mi) renewed in the last 2 years.

Since 1985, the system has tested a prototype articulated LRV from UTDC based on the Canadian Light Rail Vehicle (CLRV) design and has ordered 52 production cars. Work on a 2-km (1.2-mi) Harbourfront LRT line began in September 1987. Expected to cost $51 million (U.S. $38 million), the line includes a short tunnel and segregated surface street lanes linking Union Station and a redevelopment zone to the south and west.

NEW STARTS OPENED

Most exciting to LRT advocates has been the opening of several new systems. From 1977 to 1985, four all-new LRT projects were opened for revenue service: Edmonton (1978), Calgary and San Diego (1981), and Buffalo (1985). Since then, three more systems have opened: Portland (1986), and Sacramento and San Jose (both 1987).

Four of these projects—Edmonton, Calgary, San Diego, and Sacramento—all use variants of the Siemens/Duewag U2 LRV. Since the joint Boston-San Francisco order with Boeing, this is about as much "standardization" as the

North American LRT scene has been able to achieve. Of these four projects, only Sacramento used U.S. federal funding.

Edmonton

Edmonton opened its initial 4.5-mi line in 1978. Since then, LRT has been extended on both ends, to the new town development of Clareview in 1981, and further through the CBD (in subway) in 1983. A new shop opened in 1984.

Currently, a 2.4-km (1.5-mi) extension to the University of Alberta is under construction, including a new bridge over the North Saskatchewan River and tunnels on both the CBD and University sides of the river. This short but expensive segment is consuming Edmonton's present LRT financing capabilities, but it is a necessary prelude to one or more longer, lower-cost per kilometer surface extensions to the southern suburbs planned for construction after 1990.

Calgary

By avoiding subway construction through its downtown, Calgary has been able financially to expand its LRT system coverage at a faster rate than its sister city to the north. After the 1981 opening of the South Line, which is mostly in a jointly used railroad ROW, Calgary turned to its Northeast Line. This required a new bridge across the Bow River and, north of that point, tracks laid primarily in the median strips of Memorial Drive and 36th Street NE. The Northeast Line opened in 1985.

September 1987 saw the start of revenue service on Phase I of the Northwest Line, three months ahead of schedule and $3 million (U.S. $2.24 million) under budget. This latest line extends 5.5 km (3.4 mi) to the University of Calgary. It was a key element in Calgary's transport strategy for the 1988 Winter Olympics in which transit played a major role. On the heaviest single day, the LRT system alone carried 262,000 rides, more than three times its normal weekday load.

Further plans call for extending the Northwest Line another 8.5 km (5.1 mi) along Crowchild Trail. The next kilometer (0.6 mi) is in final design, with construction expected to start in summer 1988.

Long-term plans call for building lines to the west and, eventually, the north. When completed, the South/Northwest and Northeast/West lines will operate as two through-routed services.

San Diego

As the first new U.S. LRT system to open since Fort Worth's subway, the start of revenue service on the 25.6-km (15.9-mi) San Diego Trolley in 1981 was a landmark event. San Diego opted for a "no-frills, low-budget, reuse what you have" approach. The payoff has been a system relatively inexpensive to build and operate, popular with riders, and readily expandable. Since opening the initial line, San Diego, like Calgary, has demonstrated how LRT can be expanded in affordable increments.

The first improvement was full double tracking of the initial South Line, begun in late 1981 and finished in 1983. Then work began on the East Line in two phases. Phase I extends 7.2 km (4.5 mi) to Euclid Avenue and was opened in March 1986. A few months later, the South Line's new Bayfront/E Street station in Chula Vista was opened, providing access in what had been a gap of about 3 km (1.8 mi).

As a result of these improvements, patronage has grown from 11,000 per weekday in 1981 to about 27,000 in 1988. Only about 16 percent of total riders are tourists.

Now work is proceeding on the nearly 18 km (11 mi) of Phase II to El Cajón, scheduled for a 1989 opening. A 2.1-km (1.3-mi) "Bayside" line from the Santa Fe Depot to the Imperial & 12th Transfer Station is in final design and should open in 1990. At the latter location, major reconstruction is in progress, including a 10-story MTS Tower office building set to open in January 1989.

The Metropolitan Transit Development Board (MTDB) also is purchasing another 41 Siemens LRVs, which will bring the total fleet to 71.

Future extensions include El Cajón-Santee and Santa Fe Depot-Old Town, each about 5 km (3 mi) long and in preliminary engineering, and lines from Old Town to the north and into the Mission Valley, both in the planning stages.

Buffalo

After years of planning, Buffalo's MetroRail finally started running in spring 1985, not as the heavy rail subway-elevated line originally planned, but as a light rail rapid transit system. Alone among the new North American LRT projects, Buffalo opted for four-axle nonarticulated cars (from Tokyu Car).

Buffalo's 1985 opening was partial. Finish work continued around trains along the 1.2-mi Main Street Mall and service stopped short of the two outer end stations. Nonetheless, antirail critics were quick to pounce and loudly proclaimed Buffalo "another rail transit failure." They were a little too fast off the mark.

At the end of November 1986, all the work was completed, and the system fully opened from end to end. Patronage, which has been growing, now has settled in at 29,000 on weekdays. Productivity in passengers per kilometer of line and per LRV is quite high (Table 4).

Buffalo, too, has plans for extensions: completion of the initial line to Amherst and a branch to the Tonawandas. But funding is difficult, and the timing for these improvements remains indefinite.

Portland

The genesis of Portland's successful MAX LRT project was a local decision in the late 1970s to drop a planned segment of Interstate highway, the so-called Mount Hood Freeway. The 24.3-km (15.1-mi) MAX line represents $212.7 million of a $319 million project, the $107 million difference representing reconstruction of 7.2 km (4.5 mi) of Interstate 84, the Banfield Freeway. Even the LRT cost includes substantial road works: building-to-building reconstruction of streets and sidewalks along 3.5 km (2.2 mi) in downtown Portland and Lloyd Center, and complete reconstruction of suburban East Burnside Street for 8.5 km (5.3 mi). Opened to revenue service in September 1986, MAX was an instant hit, for these reasons:

- LRVs are perceived as fast, quiet, reliable, and comfortable.
- Bus connections are crisp and comprehensive; because MAX is integrated with the rest of the transit system, all-day use is assured.
- Park-and-ride lots are adequately sized (but not overbuilt).
- MAX is one link in a 20-year chain of public and private investments made to keep downtown Portland vital; these efforts continue.

In September 1987, Portland completed its new three-theater Performing Arts Center only three blocks from MAX. Engineering for a Vintage Trolley service to complement MAX downtown is under way. Now the region is beginning preliminary engineering for a Westside MAX line to Beaverton; and ROW is reserved for extensions from the midpoint of the Gresham Line north to the airport and south to a major regional shopping and suburban office complex.

Sacramento

Like Portland, Sacramento turned in an unwanted segment of Interstate freeway, some of which had been built but never opened, and parlayed the substitution funding from 8.5 km (4.5 mi) of highway to 28.4 km (18.3 mi) of

LRT. Included in the $176 million project were conversion of downtown's unsuccessful K Street pedestrian mall to a transit mall, creation of a second mall on O Street, three major arterial street/freight railroad grade separations, and numerous smaller street improvements and repavings. Nonetheless, by such stratagems as using the built but unused freeway for a park-and-ride and existing bridges to avoid having to construct several major new structures, Sacramento achieved the lowest initial cost to date for a rail project using federal funds—under $10 million/mi.

As noted above, Sacramento uses the latest modified version of the Siemens/Duewag U2. From the passengers' perspective, the major addition is air conditioning, but there also have been changes in the braking system and in the car body end construction (steel instead of fiberglass).

As of April 1988, the fourth month of full LRT and feeder bus operation, Regional Transit's RT Metro averaged 13,200 boarding rides per weekday. This LRT ridership reflects overall transit use less than forecast during LRT planning due to the drastic drop in oil prices since 1981, shorter operating hours, and less feeder bus service because of RT budget constraints, and downtown parking that is cheaper and more abundant than forecast. As Sacramento's rapid growth continues and traffic congestion worsens, this LRT system built for the future may be expected to become more productive.

San Jose

In common with the preceding federally funded U.S. projects, San Jose's Guadalupe Corridor is the survivor of a long planning process. Conceived in 1973, the system began revenue service on the north end of its line in late 1987 to ensure eligibility for a sale/lease-back deal on some of the 50 UTDC LRVs. Construction on the south end will continue until the full system is completed in mid-1991. This $750-million (*3*) project includes:

- LRT system—33 km (20 mi) long at a cost of $500 million or $15.2 million/km ($25.0 million/mi),
- Freeway—14 km (9 mi) long at a cost of $200 million or $14.3 million/km ($22.2 million/mi), and
- Downtown Mall—0.7 km (0.4 mi) long at a cost of $50 million or $71 million/km ($125 million/mi).

The new downtown transit mall will be shared with buses, automobiles, and pedestrians. Vintage trolleys will supplement LRT service.

Supplemental environmental reviews and project redesign work associated with the decision to build a freeway instead of a surface "expressway" south of downtown San Jose caused the project's extended completion date. This change also is a major contributor to increased LRT costs, because freeway median stations now must be grade-separated and equipped with stairs, escalators, and elevators instead of being constructed as simple surface facilities.

Planning is under way for two extensions. A Phase 2 alternatives analysis (AA) is evaluating LRT and other options in the Fremont-South Bay Corridor. Milpitas-Sunnyvale subcorridor LRT options would use the existing Guadalupe LRT trackage along Tasman Drive from North First to Old Ironsides. Simultaneously, a Phase 1 AA is being conducted on the Vasona/Highway 17 Corridor extending southwest from downtown San Jose. This study will lead to selection of a small set of alternatives, of which LRT is likely to be one, for further evaluation in a Phase 2 AA.

NEW STARTS—CONSTRUCTION IN PROGRESS

Construction on a new-start LRT project is under way in only one city: Los Angeles. On the Long Beach-Los Angeles (LB-LA) line, ROW structures and the central maintenance facility are taking shape; track laying has begun; and 54 six-axle LRVs have been ordered from Nippon Sharyo. These cars will provide initial service on the LB-LA line and, perhaps, the Norwalk-El Segundo line.

The latter line also is under construction. Grading and structures for a transit line in the Century Freeway median are being built by Caltrans as part of freeway construction. Guideway facilities will be placed in this prepared ROW as in Portland's earlier construction and following the example of San Jose's current work. The El Segundo segment of the route is in final design, including 5.6 km (3.5 mi) of elevated line, and a satellite light maintenance and storage facility. The Los Angeles County Transportation Commission's (LACTC's) latest thinking is that this line will be automated, in which case it will no longer meet TRB's criteria for LRT since full grade separation will be mandatory and operation of the vehicles through grade crossings will not be possible.

LB-LA is expected to open in 1990, Norwalk-El Segundo in 1993. The scheduling of future lines is less certain; but plans call for LRT to Pasadena, Marina del Rey, and the San Fernando Valley.

PLANNING AND DESIGN UNDER WAY

Numerous cities have been considering LRT in planning studies; and several have progressed into system design. Indeed, during the 1980s, both LRT construction and interest in further new starts have increased, fueled by growing urban transportation problems, the clear successes of the new LRT systems opened so far, and shrinking budgets that rule out higher-cost solutions such as rapid rail and automated guideways.

This section describes projects well along the planning and design path. It is organized to show new-start LRT projects in—or ready to enter—the following categories: final design, preliminary engineering, and planning.

Final Design

In Dallas, planning and preliminary engineering have been completed for a 150-km (93-mi) system. If or when a public consensus is reached, construction can start on 23.3 km (14.5 mi), linking Oak Cliff and Park Lane via downtown Dallas. A further 23.2 km (14.4 mi) would open in increments thereafter to serve Parkland Hospital, Oak Cliff, West Oak Cliff, and Park Lane to Texas Instruments. Completion of the full system would not occur until 2010 or later.

St. Louis anticipates signing a full-funding agreement with UMTA later this year. This step will signal the start of final design on Metro Link, a 28.2-km (17.5-mi) LRT line using mostly railroad, freeway, and airport ROW to connect East St. Louis and downtown St. Louis with the Central Midtown and its hospitals, Forest Park, the University of Missouri, Lambert International Airport, and McDonnell-Douglas world headquarters.

Preliminary Engineering

In Baltimore, the Maryland Mass Transit Administration recently selected consultants to oversee design and construction of a South Line to Anne Arundel County and Baltimore-Washington International Airport, and a North Line to Hunt Valley. The 43.5-km (27.0-mi) system includes a 2.0-km (1.2-mi) downtown transit mall on Howard Street. State funds were approved this spring. The full system is expected to be in operation by the early 1990s.

The Hennepin County Regional Railroad Authority has completed a 20-year LRT development plan for Minneapolis. Preliminary engineering for Stage I is expected to begin in 1988. The initial system is likely to include four lines totaling about 40 km (25 mi) and radiating from downtown to the northwest, southwest, southeast, and University of Minnesota. ROW combines railroad lines, land acquired for a now-defunct freeway, and exclusive street lanes.

Planning

Planning, including UMTA-sponsored alternatives analyses (AAs) as well as locally funded feasibility studies, is in progress for at least 19 other LRT proposals. Potential projects include all types of LRT service capabilities (line-haul transit, feeder service, and local area circulation) in a variety of settings and route lengths.

Austin

An AA is ongoing in the Northwest Corridor; the city and transit agency have purchased a railroad ROW extending both northwest and east from downtown.

Brooklyn Waterfront

A local circulation system has been proposed as part of a major redevelopment planned for this formerly active, but now largely disused, docks area.

Charlotte

LRT is one option in an AA study to evaluate how this fast-growing sunbelt city can cope with worsening traffic congestion.

Chicago

An AA is starting to plan a Downtown Connector. The central core is separated from the two major commuter rail stations and a major redevelopment area west and north, respectively, of the Chicago River.

Denver

Planning continues on a regional guideway system. LRT is a strong contender for the initial Southeast Line, to be developed with substantial private participation, but support for automated-guideway transit (AGT) also is strong.

Detroit

Interest in LRT has been renewed. Woodward (priority corridor) and Gratiot avenues are being considered in the context of a regional bus and rail plan, which may lead to a referendum on dedicated funding.

Houston

Guideway plans were boosted by voters' January 1988 approval of the $2.6-billion Phase 2 Mobility Plan. A key element is a 32-km (20-mi) guideway system, perhaps LRT, linking four major employment centers.

Kansas City

Planning for LRT continues. An initial downtown distributor line of about 5 km (3 mi) is being considered as a first phase that will fit available resources.

Manhattan West Side

Alignments being considered include a rail freight line stretching from northern to downtown Manhattan, as well as adjacent streets, 11th and 12th avenues, and easterly extensions across 42nd Street and to Penn Station. Preliminary indications are that initial development efforts may focus on the midtown segments.

Memphis

A 26.2-km (16.3-mi) LRT line has been planned in the Poplar Corridor, about 56 percent in public thoroughfares and 44 percent along an existing rail alignment. A local decision-making process is under way to choose among LRT and various non-rail system improvement alternatives.

Miami

An AA is nearing completion on ways to connect the Metro with Miami Beach. A 10-km (6-mi) surface LRT option would use an existing causeway to bridge the channel separating Miami from Miami Beach.

Milwaukee

An AA completed in 1987 identified a North/Northwest LRT line 16 to 29 km (10 to 18 mi) long. Interim express bus improvements are proceeding, because LRT capital is not likely to be available in the near future.

Norfolk/Virginia Beach

A 31-km (19-mi) LRT line has been proposed using railroad ROW, with about 1.6 km (1.0 mi) of street operation at each end. City councils are expected to consider local funding options this summer.

North Jersey Waterfront

Plans for renewing this former shipping hub include a 24-km (15-mi) LRT/bus north-south transitway. The system would link new office and residential developments with other transportation: trans-Hudson links, commuter trains, and the New Jersey Turnpike.

Phoenix

A plan for a regional guideway system has been developed for consideration by voters in this fast-growing area. Modal options included LRT, aerial AGT, and commuter rail, with the latter two being recommended. Public review meetings on the draft plan are scheduled this year, with a sales tax referendum in early 1989 seeking to raise nearly $5 billion over 20 years.

St. Paul

Ramsey County's railroad authority has reviewed alignment options to extend Hennepin County's University Connector to downtown St. Paul. Further activity awaits local and state funding decisions.

Salt Lake City

An AA nearing completion includes an LRT option extending 26 km (16 mi) south from downtown. Decisions on a preferred alternative and funding plan may be adopted in late summer or early fall 1988.

Silver Spring, Maryland

Montgomery County is studying transit options, including LRT, to connect and feed two Washington Metro lines using 6.6 km (4.1 mi) of the former B&O Railroad's Georgetown Branch.

Tampa

A three-line fixed-guideway system up to 65 km (40 mi) long using either LRT or AGT is being evaluated in a technology assessment. In addition, local business interests have proposed a vintage streetcar system as a downtown distributor.

DEVELOPMENTS IN MEXICO

Work continues in Mexico City to modernize the remaining two streetcar lines to Xochimilco and Tlalpan. These lines are mostly on reserved ROW, and feed the Metro at Tasqueña. Facility improvements include high-platform stations, renewed track, and overhead lines. A fleet of 30 eight-axle, double-articulated LRVs is being rebuilt from PCC cars. The system ultimately is expected to serve over 30,000 riders daily.

In Guadalajara, a turnkey contractor is building a new 16-km (10-mi) LRT system on a route previously worked by trolley buses. The first 10 km (6 mi) are to open in November 1988. The work includes provision of 16 six-axle, articulated LRVs (with local assembly in Mexico), as well as installation of track, power, signals and maintenance equipment, and staff training.

Finally, the northeastern city of Monterrey is evaluating proposals for an 8-km (5-mi) LRT route. The mostly elevated alignment would serve 12 stations.

CONCLUSIONS

With old systems largely rebuilt and a flurry of new-start successes, LRT has become the guideway mode of choice for an increasing number of cities. The operating systems frequently host groups of would-be emulators gathering ideas for LRT projects being planned at home.

LRT provides adequate levels of service, speed, and comfort to accommodate realistically projected passenger flows. It is affordable to build, operate, and maintain. It can enhance urban development without "Manhattanization" and is a sensitive neighbor to communities served. Light rail should continue to enjoy a bright future.

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What's New in European and Other International Light Rail Transit Projects?

DAVID BAYLISS

The paper takes a broad look at the pattern and nature of recent developments in light rail transit outside North America. In so doing, it uses a liberal definition of "light rail" to include both conventional street tramways and unconventional automated systems. It looks first at the distribution of the light rail operations and describes the recent revival of interest in light rail in the United Kingdom, including recent developments in London's Docklands. The broad pattern of recent innovation in Western Europe is described with fuller accounts given of developments in Hanover and Grenoble. The paper goes on to review the status of light rail in the Eastern Bloc countries, Japan, and the Pacific Rim. As an example of good state-of-the-art development, the new Tuen Mun line in Hong Kong is described. Brief reference is also made to examples of other forms of innovative low- and intermediate-capacity guided passenger transport, and their attributes are contrasted with modern light rail. It is concluded that the flexibility and performance of modern light rail make it a suitable and affordable technology for improving public transport in a wide range of cities.

OUTSIDE NORTH AMERICA MORE than 300 light rail transit (LRT) systems of varying age and size are in service in 33 countries. As Table 1 shows, this total is heavily dominated by the fairly conventional streetcar systems of the Eastern Bloc countries. All but six systems are in the northern hemisphere, yet one of the largest (Melbourne) is the most southerly of all. Outside the Eastern Bloc, systems are concentrated in western Europe and

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TABLE 1 COUNTRIES OUTSIDE NORTH AMERICA WITH LIGHT RAIL SYSTEMS

Country	Number of Systems	Country	Number of Systems
Argentina	1	Italy	5
Australia	2	Japan	20
Austria	5	Mexico	1
Belgium	5	Netherlands	4
Brazil	2	Norway	2
Bulgaria	1	Paraguay	1
China	7	Philippines	1
Czechoslovakia	10	Poland	14
Egypt	4	Portugal	2
Finland	1	Romania	9
France	6	Spain	3
East Germany	26	Sweden	4
West Germany	31	Switzerland	5
Great Britain	3	USSR	118
Hong Kong	2	Vietnam	1
Hungary	4	Yugoslavia	4
India	1	Total	305

NOTE: Includes systems nearing completion.

Japan. Within Western Europe light rail is used more intensely in the north (especially in the Federal Republic of Germany) than in the south.

Most systems use single-deck rigid or articulated vehicles with overhead power collection (Blackpool and Hong Kong are exceptions with their double-deck vehicles), but track gauges vary considerably. In Western Europe the normal gauge is 4 ft 8 in., whereas in the Soviet Union the standard is 5 ft and in Japan, 3 ft 6 in. The 1-m (39.4 in.) gauge is common in central Europe, but there are a dozen or so others, ranging from 35 in. in Lisbon to 5 ft 3 in. in Rio de Janiero.

Few developing countries have LRT systems, presumably because, during the heyday of light rail construction, the necessary paved streets and electricity supplies were not generally available.

Manufacturers of light rail vehicles (LRVs) are also distributed unevenly around the world, but in rather different ways than the systems. Western Europe unquestionably dominates state-of-the-art light rail systems, with over 20 manufacturers. The Eastern Bloc is the biggest manufacturer of light rail equipment, with Tatra's (Czechoslovakia) production dwarfing that of any western supplier. Japan's limited production reflects its small domestic market. The "higher tech" manufacturers outside these areas (e.g., Comeng of Australia) generally use Western European-derived technology. It is to be expected therefore that in looking into light rail technological innovation outside North America, Western Europe is the principal focus of attention.

LIGHT RAIL IN THE UNITED KINGDOM

The first trams appeared in the United Kingdom at Birkenhead in 1860; however, the number of these horse-drawn systems grew slowly. Around the turn of the century electrification changed this, and the number of tramways grew rapidly up to the outbreak of World War I. During the 1920s trams were at their peak with over 200 systems carrying 15 million journeys in British towns and cities on an average working day. During the 1930s the motorbus started to replace the tram and by the outbreak of World War II the number of systems had halved. Growth in automobile ownership and the consequent traffic congestion this created in the 1950s accelerated the process of closure until the penultimate system closed in Glasgow in 1962 (London having lost its trams 10 years earlier), leaving the sole surviving system at Blackpool. Blackpool is a seaside holiday resort on the northwest coast of England, and its tramway system contained a long coastal line largely segregated from highway traffic and virtually free from traffic intersections. Although the system survived, and still does today, mixed traffic operations were progressively reduced and the system has shrunk to the coastal line.

During the 1960s and 1970s most British cities conducted land use transportation studies, usually along lines developed in North America, and these resulted in transport plans heavily biased towards the needs of road traffic. However as the 1970s dawned and the first oil crisis left its mark, it became clear that plans strongly oriented towards the motorcar were less appropriate and this was clearly reflected in those drawn up for the Tyne and Wear (Newcastle upon Tyne) metropolitan area.

Tyne and Wear

In Tyne and Wear transport plans featured a new LRT system as well as a substantial program of highway improvements. The choice of LRT rather than an alternative bus system reflected the extensive, underused rail rights-of-way that could be adapted by the proposed system to feed into the new tunnel under the city center and bridge across the River Tyne. The system comprises four lines with a combined route length of 35 mi. There is no mixed running and the 39-ton, 91-ft cars operate singly or in pairs with an overhead 1500-volt power supply. With a maximum gradient and minimum curvature of 3.3 percent and 690-ft radius respectively, this system is at the heavier end of the light rail performance spectrum.

After 8 years of operation the LRT system has become the backbone of the transit system in Tyne and Wear and, prior to bus deregulation, ticketing and services were fully integrated with the bus and ferry services in the region. The Tyne and Wear "Metro" carries about a million journeys a week and yields an 8 percent first-year rate of return on the £284 million historic capital costs (about U.S. $501 million at the present exchange rates of $1.7645 per £1). A number of extensions are being studied, including one to the airport, and it may be necessary to use lighter technology on the extensions to avoid prohibitive land and property take.

The other post-war LRT system to be built in the United Kingdom is in London's Docklands and is described below. The success of these two systems, the need to improve the quality of public transport in Britain's metropolitan areas, and the prohibitively high cost of heavy rail systems initiated and reinforced interest in light rail in about a dozen British towns and cities. This interest has been further excited by the potential role of LRT in stimulating urban renewal, which is a major policy issue in Britain's older cities. Systems at the study and planning stage in the United Kingdom are listed in Table 2. Of these, two raise particularly interesting issues.

TABLE 2 LIGHT RAIL SYSTEMS IN THE PLANNING AND EVALUATION STAGE IN THE UNITED KINGDOM

System	Length (mi)
London (Docklands)	4.5 (Beckton)
London (Croydon)	14.5 (1st phase)
Manchester	19 (1st phase)
South Yorkshire	14 (1st phase)
West Midlands	12 (1st phase)
West Yorkshire	14 (1st phase)
Avon	37 (1st phase)
Strathclyde	Unspecified
Lothian (Edinburgh)	Unspecified
Southampton	3
Gloucester	Unspecified

Greater Manchester

Greater Manchester has been considering a variety of rapid transit schemes since the early 1960s and has looked at systems ranging from monorail to conventional heavy rail, but the government funding on which such schemes traditionally rely has not been forthcoming. As the current national administration's transport policies have clarified, it became obvious that any new rail transit scheme would only proceed if substantial private sector participation could be secured. This presented the promoters of Manchester's scheme with a dilemma because, if all the costs and risks of the project were set against the forecast operating surpluses, the balance was not attractive to private funding; yet the project was worthwhile in overall cost-benefit terms.

This project was at the public tender stage in the first half of 1988. The bids were being invited to design, build, operate, and maintain the initial 19-mi phase, which involves 1.7 mi of street running through Manchester City Centre. The successful contractor will be granted an operating concession for a fixed period under which he will be responsible for maintaining the operating assets owned by the client (the Passenger Transport Executive) and operating the railway and will receive the commercial revenues. Work for the initial phase was expected to start on site by September 1989, to be followed shortly by a second phase.

Avon

The Avon transit scheme is being promoted by a private consortium (Advanced Transport for Avon), which already has a parliamentary bill (the process for promoting new railways in the United Kingdom) for the first stage of the system before Parliament. The system would operate for most of its length over disused and lightly used British Rail rights-of-way, but would also penetrate the center of Bristol, the largest city in the area. Long sections of the proposed route run through areas with considerable potential for development and redevelopment and it is intended that the enhanced land values that the new light railway would bring could be captured to help provide the capital needed to build the system. Loans, to be repaid by future operating surpluses, would also be a major source of construction funding.

London Docklands

The most remarkable light rail development in the United Kingdom in recent years is the Docklands Light Railway (DLR). The Docklands area covers about 5,000 acres of land and water and was the site of the historic Port of London. During the 1960s and 1970s port activities declined and moved downstream to Tilbury, which is closer to the main shipping lanes and has the backlands and road access needed for a modern container port. The area opened up a huge urban redevelopment challenge, because it is cut up by the serpentine path of the River Thames and the massive enclosed docks, which make it very inaccessible even though the western parts are within sight of the Tower of London and St. Paul's Cathedral.

To improve accessibility, particularly to central London and the Underground network, a new subway line (the Jubilee Line) stretching from the West End through the City of London and out into Docklands was proposed in the 1970s. Being in a deep tube the line could cross and recross the river, thereby stitching together the main dock areas as well as connecting them to central London. However the high costs [about £800 million at today's price levels] at a time of tightening public expenditure restrictions precluded building this line.

Following the change of government in 1979 a series of new initiatives to promote the redevelopment of Docklands (and a number of other decayed inner city areas) was introduced. The theme was that the public sector would provide the basic infrastructure and, assisted by tax concessions and a loosening up of planning controls, the private sector would handle the main redevelopment task. To carry these ideas through, special development corporations were established; in the case of London this was the London Docklands Development Corporation (LDDC). In 1980 the LDDC, the Greater London Council (which was abolished in 1986), London Transport (the LRT's predecessor), and the government agreed that a package of road and public transport proposals should be progressed as a matter of high priority. Out of this the Docklands Light Railway was born.

The DLR was conceived initially as a manually operated LRT with some street running; careful design and routing allowed a segregated right-of-way to be determined and consequently automatic operation was a possibility. Although the cash limit for the railway of £77 million at outturn prices was set while it was still thought of as being a manual system, with the assistance of a keen design-and-build contract the fully automated segregated railway has been built within budget and program. It is now operating successfully with ridership slightly higher than expected.

The costs of the initial railway were shared equally among the government departments responsible for transport (the Department of Transport) and urban renewal (the Department of the Environment). It presently comprises two lines, one connecting the Isle of Dogs development area to the edge of the City of London and the other connecting it to Stratford, which is both a major interchange with the regional and Underground rail systems and a town center in its own right. It is well on its way to achieving a trading surplus (i.e., covering operating and depreciation and renewal costs out of commercial revenue). Initial teething problems have now largely been overcome and, despite some localized noise problems, operation is generally quiet.

A major objective of the Docklands Light Railway was to stimulate the redevelopment of Docklands and this it has done with a vengeance. Present plans for the area envisage about 100,000 jobs on the Isle of Dogs by the mid-1990s compared with only 10,000 in 1980 when the scheme was conceived. A major element in this redevelopment is Canary Wharf, which is to be a new financial complex with an ultimate size of 12.2 million ft^2, making it larger than the World Trade Center in lower Manhattan. To carry the heavy loadings this development will generate and to provide the direct connection into the heart of the City of London required to make Canary Wharf attractive to firms there, the initial railway is being extended and upgraded.

The extension under the city will connect the DLR into Bank Station, providing direct access to the heart of London's financial district and connections with the District, Circle, Central, and Northern lines on the Underground, and to British Rail's Waterloo and City tube line. The upgrading will increase the capacity from 16 single trains per hour to 30 double trains per hour and ultimately the system will be able to take three-vehicle trains over its most densely trafficked sections. Each articulated car can carry up to 260 passengers. Because the upgraded and extended railway is critical to the viability of the Canary Wharf development, the developers (Olympia and York) have agreed to pay £68 million towards the cost of approximately £156 million. Work is already under way on the Tunnel and Bank Station (TABS) contract and on the upgrading of the existing system. An order has been placed for an additional 10 cars.

Because the present system does not serve the other major development area of Docklands, the Royals area, a further 4-mi easterly extension is being planned. The necessary bill is going through the parliamentary procedures and funding for this £150 million scheme is to be provided entirely from increases in the value of land in the corridor it serves via the LDDC. Although the nature of the development in this area is not as intensive as on the Isle of Dogs, it does include proposals for several million square feet of offices, hotels, a business park, a STOLPORT (already operating), a 26,000 seat Londondome, and a 1-million ft^2 shopping mall. It is intended that construction begin in the first half of 1989 with the opening in 1992. With this extension the DLR is forecast to carry over 80 million passenger journeys per year by 1996—i.e., more than the San Francisco Bay Area system (although journey lengths will be much shorter). A particular feature of this scheme is its integration with both a new highway in the corridor and major developments around the stations.

The possibility of further extensions is now being studied. The most obvious candidate is extending the service down the Isle of Dogs and under the river to the densely populated areas of Greenwich and Lewisham to the south and connecting with the commuter rail network serving the southwest sector of the metropolitan area. This extension also offers the possibility of a better balance of traffic on the several arms of the DLR, thereby relieving the heavy loadings between Canary Wharf and the city. However the committed expansion of the £77-million light railway, in a period of 4 years, to a £400-million network capable of carrying a quarter of a million trips a day means that further early expansion is being treated with some caution.

Studies have been made of other opportunities for light rail in London and several promising possibilities have emerged. An important general conclusion was that there is little benefit to be obtained in a simple one-for-one replacement of conventional rail services with light rail. The operational savings that light rail can bring are also largely available by using new low-cost, lightweight, high-performance stock, with lower manning levels on trains and at stations. The main scope for worthwhile light rail applications lies where its particular attributes of very low-cost stops, improved performance, greater flexibility, and street running capability can be used to advantage.

This conclusion is reinforced by the Railbus experience in the United Kingdom. This used a bus body to form a light (nonbogied), diesel-engined rail vehicle. These vehicles did not perform well or achieve any great cost savings although a similar vehicle is currently being marketed by a Hungarian manufacturer.

LIGHT RAIL IN CONTINENTAL WESTERN EUROPE

Unlike the United Kingdom, many continental countries retained their tramway systems in the face of rising post-war traffic congestion. Undoubtedly a major factor in this was the extensive creation of central areas, usually circumvented by a new high-capacity road within which vehicular traffic was restricted. This often allowed the street tramways to operate in relatively congestion-free conditions in the urban core and gave them a penetration advantage over the private car. As a result there are over 70 light rail systems operating in continental Western Europe. These systems vary greatly in age and extent, ranging at one extreme from the Lisbon tramways with their tiny two-axled cars negotiating 35-ft curves and 14 percent gradients to the driverless, rubber-tired system in Lille.

Naturally the balance of development of light rail in Western Europe is more heavily weighted towards modernization, upgrading, and extension of existing systems than is to be found in the United Kingdom and North America. The main exception to this rule is France, where trams did not survive well and several new light rail systems have been built recently or are under construction. Herbert Felz, Director of Planning and Development of USTRA Hannoversche Verkehrbetriebe, has classified European light rail developments into three main groups:

Group I—Upgrading of existing streetcar systems that involves more exclusive and protected rights-of-way with preferential treatment for public transport at traffic lights (e.g., Basle, Zurich, Karlsruhe, Stuttgart, Cologne, and Hanover). This upgrading often involves renewal of the equipment itself with new modern cars and improved trackwork that is easy to maintain.

Group II—New systems involving running in mixed traffic as well as on exclusive rights-of-way (e.g., Nantes, Grenoble, Utrecht, and Valencia) and new systems on exclusive rights-of-way (e.g., Lille and Toulouse).

Group III—Extension and conversion of existing metro and suburban rail to light rail operation. This will often involve right-of-way features such as steep gradients, tight curves, and street running that can only be negotiated by light rail (e.g., Rotterdam, Stockholm, and Paris).

All of the Group I systems have seen recent modernization and extension. Before describing one of these, Hanover, it is worth identifying the main features of a typical Group I system. The route will be partly segregated, but with significant street operation usually running through pedestrian areas in the city center. It will occasionally have grade separation, usually in tunnel rather than on viaduct. Stations are predominantly low-platform but the cars typically have a high floor, thus making access for disabled people inconvenient. The vehicles are most often six-axle triple-bogied cars between 80 and 90 ft long and weighing 35 to 40 tons each (6 to 7 tons per axle). They will usually operate singly but are sometimes coupled in high-demand corridors.

Improvements to these systems include replacement of rolling stock with more modern designs (often with lower floor heights), line extensions and additional grade separation to reduce the effects of congestion, at-grade priorities (e.g., exclusive lanes and traffic signal priorities), improved trackwork including resilient mountings to reduce noise, and better integration with bus services and surrounding developments.

Hanover

Hanover, West Germany, retained its conventional tramway network, but during the late 1960s and early 1970s ridership began to fall and authorities decided to upgrade the system. The first route was converted from tramway to light rail in 1976 and today 43 of the 60 mi of route have been converted to full light rail. All tramways are to be converted to light rail eventually and the length of the system is to be expanded to 67 mi.

This conversion has involved building tunnels and segregated rights-of-way so that 70 percent of the light rail operation is protected from the problems of running in mixed traffic. Service reliability is improved by the use of green waves in the traffic signal patterns that reduce LRV delays where there are traffic conflicts. Also the use of vehicle location and status monitoring and radio allows centralized service control, which, as well as improving reliability, assists the full utilization of the capacity of the central area tunnels that are shared by several services and can carry 35 to 45 trains per hour during peak periods.

Bus and LRT services are fully integrated with purpose-designed transfer stations with real-time LRT service information. Above-ground stops have a low, raised platform and, at 195 ft long, can accommodate two-vehicle trains. (Platforms on the route serving the fair site are 295 ft long.) In tunnel the stations are 335 ft long with high-level platforms. The 93-ft cars are double articulated and can carry 150 passengers each. They have both high and low steps for above-ground and tunnel operation and are chopper-controlled for smooth acceleration. The light rail system carries about 60 percent of all the public transport journeys in the area and the cost recovery ratio for the public transport in the region is about $^2/_3$ to 1. Public transport ridership rates are approximately 150 trips per capita per annum—a high level of public transport orientation for a city with a population of just over 1 million and high car ownership.

Of the new light rail systems built in Western Europe over the past few years, the most advanced is the Lille system in France. This is a rubber-tired fully automated system that necessarily uses completely segregated guideways. Service headways of as low as 60 sec can be operated reliably and the 8-mi system has been a notable success. However there have been a number of more conventional, but equally important, systems in other French cities, including Nantes and Grenoble.

Grenoble

Grenoble lost its old trams in 1952 and started planning its new system in 1979 and 1980. The objectives were mainly to achieve an efficient and balanced transport regime for the area and also to assist economic development. The Grenoble system, which opened in autumn 1987, represents high-quality, state-of-the-art LRT technology for an onstreet system. The single main line extends for 5 mi and serves 21 stations. The level of sophistication and quality is reflected in the cost of $30 million (U.S.) per route mile (i.e., three times the Sacramento LRT rate). The track is at-grade yet segregated by barriers or by raising it above the level of the adjacent highway. When the line was opened both the other public transport services and the general traffic arrangements were substantially reorganized to help establish the LRT line's role as the spinal transport facility for the city and to facilitate its efficient operation. In fact the route directly serves 40 percent of residents and 35 percent of jobs.

The cars are 95 ft long and high capacity, carrying about 250 passengers (54 seated). They are triple-bogied, six-axle vehicles, but with two-thirds of the floor area only 14 in. above rail height they are easy for disabled passengers to board, allowing unassisted wheelchair access from the low platforms. To achieve this low-floor design, most of the electrics have been installed above the saloon roof. Traction current is controlled by choppers and braking effort is electrohydraulic, making for a very smooth drive. Also, wheel slip is automatically controlled. Similar attention has been paid to wheels and track. The wheels are formed largely of resilient material and have automatic flange lubrication. The track is carefully designed with extensive use of resilient and elastic materials to inhibit structural transmission of noise. On steep curves the rails are lined with antisqueal strips. The combined effect is a smooth and quiet ride.

Services operate at 4-min intervals in the peak hours and service speeds average 12 mph. Service control is centralized using real-time communication and located jointly with the city's road traffic control center. It is forecast that the line will attract 20 million journeys a year, which, if achieved, will make it one of the busiest light rail lines in Western Europe.

The sustained demand over many years for LRVs in Western Europe has resulted in an evolutionary design process that has incorporated general innovations, such as solid-state electronics, as well as technology-specific innovations. The resultant vehicles can have capacities of up to 300 passengers, a top speed of over 60 mph and service acceleration and deceleration rates of 4 ft/sec. Moreover the ride quality and the environmental impact of LRVs have improved greatly over the last two decades. The great strength of this line of technological development is its evolutionary nature in sophisticated operating environments stretching back over many decades.

LIGHT RAIL OUTSIDE WESTERN EUROPE AND NORTH AMERICA

Although the Eastern Bloc with its 180 or so systems has by far the most extensive array of light rail systems, it has not been a major source of innovation for a number of reasons. Low automobile ownership rates and associated centralized policies that favor public transport (witness the opulence and low fares of the metros in Moscow, Leningrad, and Tashkent) have not served to stimulate innovation. Indeed there is a strong orientation towards heavy rail in the Eastern Bloc, and in the USSR transport policy envisages that all cities will have metro systems once their populations exceed 1 million. Light rail vehicle replacement generally uses fairly conventional technology as do the few new lines, such as that recently opened at Volgograd. There are however moves to improve system performance by increasing the acceleration, braking, and cruising speeds of vehicles, but the time it will take to replace the larger fleets (e.g., Leningrad with 2,000 vehicles operating over 350 mi of route) means that the effects on service will be very gradual.

Although Japan has 19 conventional light rail systems, these are fairly traditional and involve extensive mixed running. Typically they are 10 mi or less in route length and services are provided by twin-bogied rigid vehicles driven by 600-volt dc current collected from overhead wires. The longest system is in Kyoto (16 mi) and total length of systems is about 140 mi including the 10-mi high-speed line in Kitakyushu, which is operated by three-section articulated vehicles. Although new vehicles being introduced on a number of systems are good quality state-of-the-art (chopper-controlled, etc.) technology, probably because of the limitations of extensive street running and the smallness of the systems, recent developments have been towards contraction and closure rather than the upgrading and expansion seen in Western European cities. In Kobe, for example, the rubber-tired Portliner has resulted in the closure of the old parallel street tramway, and the same fate awaits that part of the Kyoto system that parallels the new Metro.

Innovation in Japan has frequently been in the form of new systems. The rubber-tired, automatically controlled Portliner in Kobe is being followed by a second line. Similar intermediate-capacity transit systems (ICTSs) have been built on a small scale in Tokyo and Osaka; the Newtram system in Osaka is a derivative of the Airtrans system installed at Dallas-Fort Worth airport. An oriental equivalent, VONA (Vehicle of New Age), is operating at Yukarigaoka near Tokyo. Monorails have also gained a popularity in Japan not found elsewhere, the most recent being the Town Liner at Chiba, which is a suspended system.

An important attraction of light rail is the relatively low civil engineering costs when compared with heavy rail. However the lower-capacity light rail cannot carry the intensity of loadings experienced in many heavy rail corridors. (The peak capacity of 40,000 passengers/hour claimed by the Budapest LRT system is achieved by a continuous stream of slow-moving vehicles.) In Tokyo the loadings forecast for the new Line 12 of the Metro are substantially less than the Tokyo average, yet rather high for light rail (a little under 25,000 passengers/hour in the peak). This has led the designer to opt for small profile stock. This is formed of motorcars 54 ft long, 8.2 ft wide, and 10 ft high, weighing 27 tons each, and with an 88-passenger capacity. This has enabled tunnel diameters to be kept down to 14 ft (compared with the previous standard of 20 ft), which will lead to considerable savings in tunnelling costs. It is worth noting that the London tube tunnels have an internal diameter of less than 13 ft.

There is a growing interest in new light rail systems in Pacific Rim cities such as Manila, Jakarta, and Bangkok. A new system is nearing completion in the New Territories of Hong Kong. In Melbourne two former heavy rail lines have been converted to light rail and linked together to provide through-running across the city center and a new direct rail connection between a low-income suburb and the beach. Other light rail expansion proposals being developed include an LRT route down the center of an expressway.

Hong Kong

The rapid population growth in the constrained geography of Hong Kong and the New Territories over the last two decades has made improved public transport essential. Street congestion is such that urban rail on its own right-of-way has been the main focus of public transport development in the last decade. As a result the electrified Kowloon-Canton Railway (KCR) and Mass Transit Railway (MTR) have been added to the long-established Island Tramway. Currently a new modern light rail system is being built between Tuen Mun and Yuen Long and is to open in 1988.

Tuen Mun is a new town with a population of 270,000 in the Hong Kong Northwest Territories. It is situated on the coast. Inland to the northwest two new towns of Yuen Long and Tin Shui Wai are being built. Yuen Long already has a population of 65,000 and the first phase of Tin Shui Wai, to house 40,000, is under construction. Tuen Mun will be the main employment and service center for these new communities and thus good accessibility along this corridor is very important. The railway will be operated by the KCR company. Its first phase will comprise a fleet of 70 cars running over a 14¼-mi network and is expected to carry over 250,000 passengers per day. If these loadings are achieved, this will be one of the most intensively used light rail systems anywhere in the world, with route traffic densities of 18,000 passengers/route mile/day, higher than those achieved on many heavy rail systems.

The cars are stainless steel, rigid, 66 ft long, and weigh 27 tons each. They have 60 seats and a nominal capacity of 190 passengers, but up to 275 can get in under crush loading conditions. They can operate singly or in pairs and have a maximum speed of 50 mph and minimum service acceleration and braking of 4¼ ft/sec. Power is collected via a pantograph from overhead wires at 750 volts dc. The traction current is chopper controlled with regenerative braking. The vehicles are air conditioned with rubber and air bag suspension, and particular care has been taken to produce overheads and supports that are both unobtrusive and robust against high winds.

The 41 stations have raised platforms with ramps to assist access by the physically handicapped. Ticket issuing is by automatic machines that are centrally monitored. The vehicle drivers have direct radio communication with central control and the movement of vehicles across at-grade intersections is automatically monitored. Of the Phase 1 route one-fifth involves street running. Over the remaining four-fifths there are many at-grade intersections with local streets and arterial roads. The route runs through some high-density areas; indeed the plans for the area locate accommodation for 25,000 people above the depot and terminals. Great care is therefore being taken to minimize the structure-borne sound. Along critical sections the running rails are embedded in flexible grout that both reduces vibration in the vehicle trucks and suppresses ground-borne transmissions.

Perhaps the most interesting features of the Tuen Mun light rail system are the traffic priority arrangements. Although most of the route has a segregated right-of-way there are numerous street crossings at grade—37 minor and 19 major. The number of crossings has been kept down by collecting local access roads along a parallel service road that then has a single link across the LRT route. Clearly if the LRT is to give reasonable service, the delays from traffic conflicts at this large number of intersections have to be strictly limited. The idea of "green wave" priorities (as used in Hanover) was considered but rejected as being infeasible in that the required strict adherence to schedules that this would require is unlikely to be achieved with the passenger loading densities anticipated.

In the system adopted each LRV is equipped with an electronic label that identifies it and that can be read by trackside detectors. This technology is borrowed from an earlier electronic road pricing (ERP) experiment carried out in Kowloon. As an LRV comes up to an intersection its approach is detected and a request for a green signal initiated. This request is sustained until the LRV exits the intersection zone. This means that normally LRVs are confronted with a green aspect at most intersections, although, if an LRV comes up to an intersection just after the phase for the LRV has concluded, a few seconds' delay may be encountered. Time "borrowed" by the LRV priorities is repaid to other traffic during the subsequent cycle when it is of no value to LRV operations.

At the great majority of intersections this regime gives a high degree of priority to LRVs. However at a few busy, complex intersections the delays to other traffic caused by giving full LRV priority would be unacceptably high. A reduced level of priority is therefore being accorded and fine tuning will optimize this in practical operation. Overall it will be possible to complete the end-to-end run, which is about 10 mi, in under 30 min even in peak road traffic hours.

NEOLIGHT RAIL SYSTEMS

Over the years many "cousins" to the light railway family have appeared. The majority of those that have survived have carried out tasks that were in some respect beyond light rail. Thus the aerial tramways of Switzerland and Japan, the ropeways of Burma, and the funiculars in places such as Georgetown (Penang) in Malaysia and Hong Kong are not just different technologies but truly different modes of transport. Other novel systems have been tried from time to time but relatively few have survived. An exception to that rule is the suspended monorail at Wuppertal, West Germany.

Since the late 1960s, when urban transit became a potential area of diversification for the aerospace industries of a number of technically advanced nations, there has been a steady stream of new technologies that, in their transportation function, overlap the applications traditionally covered by light rail. Some recent and current examples are listed in Table 3. These only include systems that have reached the stage of successful trials or beyond. There are many other systems that have not gotten that far.

Given the very large amount of effort put into LRT innovation, the results are really rather disappointing. The systems offer little by way of improvements in acceleration, braking, or speed, and those that offer some exceptional capability (e.g., SK's maneuverability) usually sacrifice general performance to this end. Perhaps the only real exception to this is the O-Bahn, which combines the advantages of tracked systems for line haul with the flexibility of the bus for collection and distribution.

The main innovations lie in the areas of traction, suspension, vehicle control, and vehicle size. Linear induction motors are now established as an alternative to rotary motors where dedicated and protected rights-of-way are available but have not yet demonstrated much advantage under normal operating conditions. Rubber tires and magnetic levitation can produce a ride significantly better than steel wheels on steel rails, but only with cost and lateral control penalties. Automated vehicle control is a feature of almost all the new systems (O-Bahn being a notable exception) and, provided a protected operating environment is available, this of course can be used by light rail systems (e.g., Docklands Light Railway). The ability to reduce vehicle size offered by many of these systems can be an advantage in low-demand applications, and light rail is probably not as flexible as some other systems in this respect, although the Belgian TAU system, with its meter-gauge track, 40-ft-radius curves, and 28-ft-long vehicles (6 ft 8 in. wide), shows that miniaturization of modern light rail is feasible and can lead to substantial savings in civil engineering costs.

The general lesson from recent attempts to innovate in this area is that there are no systems offering major advantages over conventional light rail. Features such as automatic vehicle operation can be applied to light rail in the right environment. Rubber wheels can have ride and noise advantages over steel wheels on steel rails, but these have to be weighed against the complex and bulky guideways needed by rubber-tired vehicles unless they are steered. Probably the most interesting recent development is the O-Bahn, which combines the flexibility of the bus with guided transit. However the inability

TABLE 3 INNOVATIVE LIGHT RAIL TRANSIT SYSTEMS OUTSIDE NORTH AMERICA

System Name	Manufacturer	Type	Development/Application
Aeromovel	Coester Air Train	Conventional steel wheel and rails driven by compressed air	A 0.5-mi test track is in passenger operation in Porto Alegre, Brazil
Aramis	Matra Transport	Small rubber-tired vehicles, electric propulsion and electronic coupling	Demonstrated at Orly Airport in the mid-1970s; new trial track being built at Boulevard Victor (Paris)
C-Bahn	Messerschmitt-Bölkow Blohm	Linear induction motor (LIM), small/medium vehicle sizes	Prototype tested during 1970s
Habeggar Monorail	Habeggar Von Rol	Supported lightweight monorail	Demonstrated at several recreational sites (e.g., Expo '86); system being built in Sydney (Australia)
H-Bahn	Siemens/Düwag	Suspended people mover with LIM or rotary motors	0.7-mi system operational in Dortmund (West Germany)
Maglev	GEC Transportation Projects	Small LIM and magnetically levitated vehicles on elevated guideway	0.5-mi system system operational at Birmingham Airport (England)
M-Bahn	Magnetbahn	Medium LIM, magnetically levitated vehicles on concrete guideway	1-mi system operating in Berlin (West Germany)
Mini Metro	Otis	Medium LIM, air-cushioned vehicles on concrete guideway	1-mi system operating in Serfaus (Austria)
Newtram	Niigata Engineering	Rubber-tired vehicles (75 passengers) driven by rotary motors on concrete guideway	4-mi system operating in Osaka and Tokyo (Japan); system is derived from LRV (Airtrans) technology
O-Bahn	Mercedes Benz	Mechanically guided bus	92-vehicle system operating successfully in Adelaide (Australia)
SK	Soulé Fer et Froid	Small cable tracked cars on narrow-gauge track	Prototype operated at Saint-Denis (France)
TAU	ACEC SA	Small-profile light rail, rotary electric motors	Trial operation at Jumet; system being built in Liège (Belgium)
VAL	Matra Transport	Rubber-tired automated medium-size vehicles on concrete guideway	Now operating in Lille (France); systems being planned in Strasbourg and Toulouse (also in Jacksonville and at O'Hare Airport, U.S.)
VONA-One	Nippon Sharyo Seizo Kaisha	Rubber-tired automated medium-size vehicles on concrete guideway	2-mi system operating in Yukarigaoka near Tokyo (Japan)
Westinghouse Metro Mover	Westinghouse Electric Corporation	Rubber-tired people mover on concrete guideway	Operating at Gatwick Airport in London (England); also several U.S. applications

to entrain vehicles limits the scope for increasing labor productivity with rising ridership.

CONCLUSIONS

Light rail outside North America has not seen the dramatic resurgence that has been seen in the United States and Canada. This is simply because, apart from the United Kingdom and France, LRT's fortunes had not sunk so low. This generalization however covers a wide range of situations. In the Eastern Bloc countries, where most of the traditional systems are to be found, the slow growth of automobile ownership and urban population growth have ensured a continued role for light rail systems. This security, along with a slower pace of general technological development, has meant that innovation has been relatively limited; by and large Eastern Bloc LRTs are conventional street tramways using rather traditional technology.

In the United Kingdom light rail had all but disappeared by the 1970s but the pathfinder Tyne and Wear project marked the end of this decline. More recently the London Docklands Light Railway has demonstrated spectacularly how light rail can play a crucial role in the renewal of the inner areas of older cities—a major problem in many developed countries. Light rail schemes are being promoted for most of the other large U.K. cities and the next in line in Greater Manchester, on former railway rights-of-way plus a section of street running, uses modern tram technology and construction and is due to start in 1989. Continental Western Europe has about a quarter of the world's LRT systems. The majority of these has been steadily improved over the last 10 years. Innovations have been comprehensive, covering vehicles, tracks and trackside equipment, system control, and integration with the rest of the urban transport system. Systems in this area include both revolutionary new systems and high-quality, state-of-the-art "traditional" systems.

Outside Europe and the Eastern Bloc there are about 30 systems, mostly in Japan. Innovation in LRT systems here has been fairly limited so far, with the trend in Japan being oriented toward the creation of new unconventional high-technology systems rather than development of existing formats, although there have been improvements to these. However interest in LRT is growing, particularly in the Far East, and the new system in Hong Kong is an impressive example of how to establish a high-capacity, high-quality LRT system in a difficult mixed traffic environment.

The list of contemporary innovations is rather impressive. Modern vehicles are attractive, relatively quiet, and can have low floors to facilitate access by handicapped passengers. Modern electronics make for smooth acceleration and braking, environmental control, and regenerative braking, which can save energy. It is increasingly common for "voice and data-to-control" communications and vehicles to register their presence frequently with track-side equipment to obtain priorities in mixed traffic. Electronic passenger information systems are now being provided on the more modern systems. A still small but growing number of light rail systems are automatically controlled.

Off the vehicle, significant improvements have been made in track design and maintenance that contribute to ride comfort and help keep down noise intrusion. Particular progress has been made in reducing structurally transmitted noise and vibration that can be a serious problem in dense urban areas, especially when new routes are introduced. Progress has also been made in the design of overhead power supply equipment, which is now significantly less bulky and intrusive than that associated with the traditional streetcar systems. Recent projects have seen changes in the relationship between light rail systems and their environment on even wider scales. The provision of priorities for LRVs by local traffic and environmental management now can include selective vehicle detection. In some cities transport has been more widely adapted to make the most effective use of new light rail lines with road traffic circulation modified to reduce mixed running and traffic conflicts and with bus services reorganized to act as feeders to LRT. This invariably has been accompanied by full integration of fares and ticketing to reduce the inconvenience of interchange between bus and LRT.

The most fundamental examples of powerful relationships between LRT and its environment are where LRT has been used to stimulate or complement large-scale development and renewal. Perhaps the most impressive example of this is in London's Docklands where light rail has played a catalytic role in Europe's largest urban redevelopment scheme. This required a modern up-market image that is also to be found in the new systems at Lille and Osaka (where again there is a strong urban renewal dimension). In these cases the systems have employed exclusive rights-of-way that have undoubtedly allowed a more reliable service to be run and contributed markedly to the systems' image. The associated automation has also reduced staffing requirements and costs.

In an era when concerns about the costs of major public projects are growing, one of the major achievements of recent light rail developments is to provide high-capacity, quality public transport at a cost that is only a fraction of full metro costs. This does not, of course, mean that LRT can always do a full metro's job; but its low initial cost has meant that quality tracked public transport has been provided in cities and corridors where, despite civic ambition, metros were simply not viable. In a few instances light rail schemes have brought with them innovative funding that has further reduced the burden on the public purse. The opportunities for this seem to lie mostly in inner city renewal projects where traffic densities are well suited to light rail and its capacity to thread through the urban environment and piece together former rights-of-way comes into its own.

The most striking feature of innovation in light rail transit outside North America is its great variety. There are still many humble streetcar systems in developing and Eastern Bloc countries where innovation is limited to replacing assets with conventional modern equivalents. At the other extreme the new automated high-tech systems are establishing LRT as a transport mode for the cities of the future. This range of innovation reflects the inherent versatility and adaptability of light rail, which should secure its future in an increasingly urbanized world where the economic and environmental cost of automobile use is driving the search for other, more cost-effective means of handling passenger movements in busy corridors.

The Great Debate

Potential Roles of Different Transit Modes

VUKAN R. VUCHIC

Although selecting a transit mode for a city is perhaps the most important step in system development, the decision process is too often plagued by biased or faulty arguments for or against particular modes. Transit "fashions" have swept the world decade after decade. People movers, automated-guideway transit (AGT), light rail transit (LRT), exclusive busways, and paratransit have all had their day. Although not all succeeded in North America, some have succeeded elsewhere. In this decade, important innovations and maturing concepts have included the guided bus or O-Bahn, further development of LRT designs, and diversification and implementation of AGT systems. As a result, a continuum of transit modes exists. Making reason-based choices, however, remains problematic.

SELECTION OF TRANSIT MODES for a city or a corridor is usually the most important technical step in transit system development. This is particularly the case in selecting modes with extensive infrastructure, such as rail transit. Moreover, since transit mode influences the role of transit in a city, this selection may strongly influence the form and character of the entire urban area or region in its future development.

Analyses, debates, and, often, controversies about transit mode selection have occurred in many cities. In addition to the comparisons and selections of modes for specific cities, there have been those who have tried to compare modes on the basis of hypothetical cities and theoretical models. The results of these studies varied widely. Due to the complexity of transit mode comparison and selection, and to the confusion introduced by various advocacies, opinions

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and arguments for and against individual modes tend to vary considerably. It is the purpose of the following four papers and our debate at the Light Rail Transit Conference to narrow down this wide range of opinions and arguments about several frequently used modes of urban transit.

To illustrate various aspects and forms of this long-lasting "Great Debate" about transit modes, let us briefly review the developments and "fashion waves" in this field over the last quarter of a century, pointing out the realistic and useful promotions as well as the slanted arguments against different modes.

The 1950s and 1960s saw a major polarization of transit systems to modes that are, in many respects, on opposite sides of the family of transit modes: rail rapid transit and buses on streets. The large difference in characteristics and performance between these two modes did not prevent various planners and researchers from analyzing and comparing them in very simplistic ways. Thus, a major theoretical study was written during the 1960s that used a very narrow definition of urban transportation modes: private automobile, bus, and rail rapid transit treated as exclusive solutions, i.e., as if the question was which one should best be used as the single mode of urban transportation. The fundamental differences among these modes in the types of services they can offer were ignored. The comparison was made in the simplest possible way—on the basis of their hypothetical average costs only.

The traces of the "fashion" in which theoretical researchers demonstrate their academic credentials by taking extreme stands against transit (particularly against rail transit) have endured until the present time. At times extreme positions are taken with respect to transit, public investments, and established cities in general.

The 1970s saw the arrival of people movers in various forms, culminating in personal rapid transit (PRT). These modes were strongly promoted, not only by a number of industrial developers, but also by the government through funding in several countries. The PRT fringe of these modes, in spite of three international symposia on the topic, never came close to realization in any actual application because of the deep flaws in the basic concept: the paradox between the investment-heavy infrastructure and small vehicles involving high operating costs and low capacity. The people mover branch of the concept, however, eventually evolved into more realistic forms, using considerably larger units than initially proposed, and has contributed to the adoption of fully automated operation of transit lines in several cities. Therefore people movers, or, as transportation professionals have called them in recent years, automated-guideway transit (AGT) systems, today represent a very competitive and attractive mode of urban transportation.

During the early 1970s finally came the recognition of light rail transit (LRT) as a new transit mode that has a major role in providing services between the two extremes: high-performance, high-investment rapid transit and low-performance, low-investment buses on streets. Although systems resembling LRT did exist many decades ago and although this mode was developed very extensively during the 1950s and 1960s in several European countries, its acceptance in the United States and Canada took place only during the 1970s. This was followed by acceptances in many other countries around the world, developed as well as developing ones.

The 1970s also saw the maturing of the concept of preferential treatments for buses, culminating in construction of several exclusive busways. It may seem amazing that nobody thought about it before. It had always been obvious to us in the transportation profession that buses, similar to light rail vehicles, can be given separated rights-of-way to make them independent from other traffic. But the attitude toward this concept, combined with some technological, design, and operational inventions, matured only during the 1970s.

It should be mentioned that while busways have had success in several cities around the world (e.g., Ottawa, Lima, Adelaide) and are continuing to spread, the concept has been severely and permanently damaged in the United States by the massive conversion of the original busways (i.e., Shirley Highway, El Monte, and several others) into high-occupancy-vehicle (HOV) roadways and lanes. Not only has this conversion reduced the full benefits of an exclusive bus facility, but it also has greatly diminished the image of this transit mode in general. Fortunately, in most other countries bus lanes and busways are being kept in their exclusive form.

A major push for paratransit modes also occurred during the 1970s. On the basis of the claims of some promoters, outsiders could have formed the impression that paratransit modes were the only public transport modes of the future. While the inherent limitations of paratransit modes—their unavailability to the public at large, high labor costs, etc.—limit their role in the family of urban public transportation modes, the intensive campaign for development of these modes during the 1970s did result in a number of operational and organizational innovations and an improved image. Benefits from introduction of various paratransit modes in our major cities did increase appreciably, but probably the most significant is their greater role in small towns and in suburban and rural areas.

The 1980s witnessed further inventions and innovations, as well as conceptual maturing of many modes, such as:

- Further improvements and inventions in bus vehicle technologies, including the guided bus.
- Further developments of LRT designs, ranging from introduction of rail systems not only on partially separated rights-of-way (category B), but also on some lines with street running (category C), as well as operations on exclusive rights-of-way (category A).

• AGT systems also diversified and began to operate on regular transit lines.

As a result of these developments, we now have virtually a continuum of transit modes: buses and trolleybuses, dual-mode vehicles, streetcars, light rail, AGT (including systems on rails and on rubber tires), rapid transit (again including systems on rails and rubber tires), and regional rail, which is becoming increasingly similar to rapid transit in its technology and type of service.

It is obvious from this review of conceptual developments, promotions, limitations, and implementations of different modes that evaluations and opinions about different modes consist partly of realistic, factual, quantitative, and qualitative arguments and partly of subjective, sometimes exaggerated ones. Some of the claims that have been proved incorrect, unfortunately, continue to be quoted, even in professional circles. For example, it is still often claimed that rubber-tired AGT systems are so light that their aerial structures can be much lighter than aerials for rail systems. Actually, rubber-tired guided vehicles are not lighter than rail vehicles measured either per square meter of floor area or per axle. Further, "flexibility" is frequently quoted as a major advantage of buses as compared with guided modes and even more so as an advantage of paratransit. Actually flexibility is not always a desirable feature of transit systems; permanence, predictability, and reliability of service are major positive characteristics of transit systems.

Due to the character of the problem of mode selection, affecting many parties and involving different values, it will probably never be completely devoid of emotion. However, the extensive experiences in real-world, applied theories and other developments should reinforce the rational portion of the evaluation at the expense of the emotional one. Our debate at this LRT conference comes at the right time: the diversity of modes is greater than ever, and a more rational method of selecting the mode is needed in many cities. Our debate should therefore represent an important step in the right direction.

The debate focused on the major transit modes of intermediate capacity presently being discussed and planned in many cities: buses on busway, LRT, and AGT. The debaters were instructed to take advocacy stands for their respective modes and yet to remain factually correct. Also, each mode should, as much as possible, be considered in the realm of realistic assumptions and conditions. Consequently, although each of the subsequent papers prepared for the debate places a distinct emphasis on the advantages of one mode, it is expected that all four papers together will contribute to the clarification of the relationships among these transit modes on a factual basis.

Advocacy for Conventional Light Rail

TOM PARKINSON

Although no one mode of transit can serve as the best alternative for every corridor, light rail has significant advantages in many applications. Usually, light rail can be planned and built in less time, with lower costs, and with less environmental impact or construction disruption than other types of rapid transit. It also fosters investment and redevelopment in the areas that it serves and stimulates tourism as well, while drawing additional revenue from off-peak tourist passengers who favor light rail over other transit modes. Most urban corridors in North America with transit demand in the mid- to high-intermediate capacity range already have automated rapid transit, heavy rapid transit, or light rail. With the exception of some new growth corridors and the expansion of existing systems, most new opportunities for intermediate-capacity transit modes will be on the lower end of the scale. At lower passenger volumes, light rail can compete effectively against bus alternatives when it is built with economy in mind. Existing rights-of-way, surface alignment, barrier-free self-service fare systems, practical station design, and light overhead all play a part in making light rail the transit mode of choice in a number of cities.

URBAN CORRIDORS COME IN many shapes, sizes, and passenger levels. One mode cannot be right for all. Good transit is integrated transit with each mode effectively and economically used and effectively coordinated and with fares and schedules that maximize convenience to the people transit is built and run for—the passengers. Buses will remain the most important and dominant transit mode in North America, and the possibility of a fixed-guideway system is little excuse for not planning, maintaining, and operating them well, whether they are feeders to that system, on truck routes, or providing the line haul over busways, high-occupancy-vehicle (HOV) lanes, or dedicated traffic lanes.

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Light rail can be defined too narrowly. Light rail now has fully grade-separated systems (Manila), automated driverless operation (London Docklands), and hybrid automated operation (Düsseldorf). Several lines operate three- to five-car trains on close headways, offering capacities to and beyond those of any rapid transit line in North America outside Toronto and New York. Yet it is still light rail. The vehicles possess typical characteristics, including geometric flexibility, even when the power collection is by the third rail.

Automated light rail can match all the advantages of automated-guideway transit (AGT) at lower cost with less risk. Further, hybrid light rail can run automated on segregated right-of-way, then take on a driver to operate over less expensive alignments. This provides more miles of service per dollar and also gives more passengers a one-vehicle ride.

In making a case for light rail, tabulated cost comparisons are unnecessary. Rather this paper presents the advantages of light rail, many miles of which have been built in the $10 million/mi to $20 million/mi range. Certainly some lines have cost a great deal more. Many of these higher costs were unavoidable; some were not. This paper points out how to avoid unnecessary costs. There are few urban corridors left in North America where fixed-guideway transit can be supported. These corridors generally have modest transit demand. For light rail to continue to proliferate, it must be built leanly and cost-effectively.

CONVENTIONAL LIGHT RAIL ADVANTAGES

Light rail transit (LRT) spans a wide range of technical and application options. One of light rail's major attributes is its street running capability. Light rail cars are designed with the ability to accelerate and brake rapidly and to traverse sharp curves and steep grades. Cars are narrower than those in heavy rapid transit and fit within the maximum allowable highway width. This enables tunnel or underpass sections, where unavoidable, to be correspondingly narrower and less expensive than with most other fixed-guideway modes. Single-track sections are possible where space is tight and the ensuing capacity limitations are acceptable.

Light rail can usually be planned and built in less time and with lower costs and fewer environmental impacts or construction disruptions than other types of rapid transit. For example, where no exclusive right-of-way is available, light rail can run on a street or make a sharp curve around a historic or expensive building, avoiding property take and destruction.

Even when segregated on-street trackage cannot be provided and the light rail vehicle (LRV) must run in mixed traffic, there are advantages. The LRV does not have to pull to the side of the road at stops. The wide multiple doors provide faster loading and unloading. Both of these features result in higher schedule speeds that attract patronage, reduce operating costs, and reduce interference with other road traffic. In this mode LRVs are streetcars whose clearly visible tracks discourage motorists more than an unmarked bus route. Track paving can be raised or use a rough surface, discouraging automobiles although not impeding use by emergency vehicles. These conventional streetcar advantages are often played down, but a look at Toronto shows how streetcars can dominate certain streets that local drivers then avoid. When buses temporarily replaced streetcars on a major Toronto street, both transit and traffic speeds decreased. The streetcar can, in fact, act like an enforcer, keeping traffic in lanes and setting a travel speed.

Other light rail advantages are less tangible and more difficult to deal with. The fixed tracks of streetcars or light rail provide an indication of support, commitment, and continuity to the community and neighborhoods served. This is a catalyst that can trigger renovation, redevelopment, investment, employment, and even recovery for economically depressed areas. Light rail also has tourist potential. This provides extra revenue and good publicity, and encourages tourism and tourist-oriented development and jobs, as San Diego so ably demonstrates.

Light rail's contribution to reducing air pollution in most metropolitan areas is modest, although there can be significant localized improvements where a downtown street is converted from congested traffic to a transit-pedestrian mall. But it is not always that the amount of pollutants is reduced; rather it is that an agency demonstrates its intent on using the least polluting mode, and sets a positive example for others.

Similarly the use of nonpetroleum fuels is of minor concern now, particularly given that electricity in many areas is partially generated from oil. It was very different following the oil shortage of 1973 when many transit projects that reduced oil dependence were favored. The fact that the current Middle East problems could bring another oil crisis tomorrow is worth taking into consideration when evaluating light rail over a diesel bus alternative.

In addition to the low or zero use of petroleum resources and the freedom from any local pollution, light rail has the inherent environmental advantage of low impact, plus the ability to fit gracefully into the urban structure. Light rail can have very low noise levels with resiliently mounted track and resilient (elastomer-cushioned) wheels. However, for a variety of reasons recent light rail street track has not been resilient and in-street noise on most new systems is higher than need be. Calgary and Portland are exceptions. The flexibility in selecting alignments and the subsequent lower capital cost is the "light" in light rail. There is nothing light about the cars, which can weigh and cost as much or more per passenger space than a heavy rapid transit car. Stations can be also be very modest and unobtrusive.

This "lightness" of light rail—a combination of flexibility, low impact, modest cost, and environmental softness—is ephemeral. It must be carefully guarded. Ignorance or ineptitude during the planning, design, specification writing, engineering, or construction phases of a project can lose the "lightness." Light rail's advantages can be diminished or even destroyed with overdesigned overhead; ugly, noisy, or difficult-to-maintain cars; poorly conceived alignments; or simply uneconomic applications. This is why certain systems provide better examples of light rail's "lightness." Calgary, Portland, and San Diego in North America and Nantes and Grenoble, France, in Europe are exceptional among many fine, recently built systems.

APPLICATION AND ALIGNMENTS

Light rail systems can be built to handle from 15,000 to 200,000 passengers per day, equivalent to 3,000 to 20,000 passengers per peak hour direction. This range is often termed "intermediate capacity." The lower end of this range is well within the economic capability of a bus route, particularly if articulated buses with traffic management measures such as reserved lanes and traffic signal preference are used. To be competitive light rail must be built at low cost and may have to incorporate many design compromises. The San Diego, Calgary, and Sacramento light rail lines are good examples—all built within the range of $10 million/mi, inclusive of vehicles, yards, and project overhead.

San Diego bought an operating freight line, retained long single-track sections, reused much of the existing rail and ties, and retained rail freight operation on a time-separated basis. Sacramento made several cost-saving compromises with much single track, carving out rights-of-way at the side of highways, and squeezing the line onto existing underpasses and overpasses.

The upper capacity range of light rail requires long trains of LRVs at close headways that preclude some of the light rail advantages. Single-track sections, downtown surface operation, and grade crossings of any streets with significant traffic flows become difficult or even impractical. It is at these volumes, where light rail requires advanced signaling and a wholly or predominantly grade-separated right-of-way, that a case can be made for automation, and where light rail overlaps and competes with heavy rapid transit and the AGT systems.

When there is a case for automation there is every likelihood that it can be provided with conventional light rail cars equipped for automatic or driverless operation at less cost than the proprietary intermediate capacity rapid transit systems referred to as AGT. An example of driverless light rail is the Docklands Light Railway in London. The 10-km line was built inexpensively and equipped with classic light rail vehicles without a driving cab that uses third-rail power collection. Problems with the automatic train control relate to the all too common error of designing a new system rather than using or adapting an existing, proven system. The "not invented here" complex continues to bedevil various transit modes in many countries. It is unfortunate that it has now migrated to the light rail mode.

A hybrid of light rail also has potential that cannot be matched by the proprietary AGT systems. Light rail can run on totally segregated track in automatic mode, then proceed onto in-street or partially segregated right-of-way under driver control. If needed, the power collection can also be hybrid, third rail on the segregated section, overhead elsewhere. Düsseldorf will shortly be opening a section of its light rail system with automatic driving, using the same SEL technology as the Vancouver proprietary AGT system.

Most urban corridors in North America with potential transit patronage at the middle to high end of this intermediate capacity range already have automated rapid transit, heavy rapid transit, or light rail. With the exception of some new growth corridors, predominantly in the Southwest sunbelt and expansions of existing rail systems, the great predominance of opportunities for new intermediate-capacity transit modes will be in the lower patronage range. It is in this range that light rail and prioritized buses, with or without busways, compete. Light rail vehicles are three to four times the first cost of the equivalent capacity of diesel buses. Although this cost premium usually can be recovered from longer vehicle life and lower operating costs, particularly operating labor, the selection of light rail in many applications will depend on keeping infrastructure costs down. This means going back to basics, making compromises, and persuading authorities to give up street space or adjust standards. It means avoiding monumental stations and other gold-plating and staying on the surface whenever possible.

DOWNTOWN AREAS

Much of the economy of LRT comes from its ability to use existing rights-of-way, including those of railroads, power lines, and the medians of streets and freeways. When no such rights-of-way exist, particularly in the city center, a dilemma is presented: to run on the surface, mixed or partially mixed with traffic at lower speeds; to build a transit mall; to build an elevated (aerial) guideway at typically three to five times the cost of a surface alignment; or to go underground, typically an order of magnitude more expensive.

Elevated sections sound attractive, but unless the street is very wide (in which case a surface right-of-way should be used) or the adjacent land use is industrial, public concerns are hard to overcome. Even the most carefully designed elevated structure is large and intrusive and the relatively quiet LRVs can add noise to a community when the cars are raised in the air. Many proposals for elevated light rail sections have failed to get approval, particularly in downtown areas. This leaves a seemingly obvious choice between surface and subway alignments. With slow speeds on congested streets at the highest patronage section of the light rail, surely the costs to go underground, possibly for a relatively short distance, can be justified.

The cost of a short underground section may be justified relative to the overall economies of light rail, but a downtown surface alignment, even at slow speeds, and especially if traffic signal preemption or a light rail mall can be built, can be advantageous, and can in fact provide faster overall travel times provided passenger volumes are at or below the medium level of LRT capability.

Underground sections require longer station spacing with longer walks and access time. This access time will often fully offset the slower travel times of LRVs on the street. In addition to easier access, the light rail is highly visible and can share a street with buses, minimizing the impedance of a bus/rail transfer. This light rail presence should not be underestimated. It is a major marketing tool for the light rail, for retailing, and for other existing and future developments along the line. It enhances the tourist ridership, and adds to light rail's already good record of attracting more ridership than comparable non-rail-based transit improvements, particularly at off-peak times.

The then-general manager of the San Diego light rail system put it succinctly during the planning stages 10 years ago. He said that the city did not deserve light rail if the planners and council were unwilling to forgo a very small amount of traffic capacity in the city center! After a lengthy battle San Diego got its surface running downtown and went on to build what is still the most inexpensive LRT line in North America—with high presence and high visibility.

It is not always necessary to forgo street capacity. Light rail vehicles use less green time at an intersection than the equivalent capacity of buses, typically carrying a given number of passengers through the intersection in less than half the time. Providing preemption for light rail and coordinating or sequencing traffic signals for several intersections either side of the light rail can actually increase traffic flows both across and parallel to the light rail.

FARE COLLECTION

All new North American light rail systems except that in Pittsburgh have adopted the barrier-free self-service fare system (proof-of-payment). In Edmonton this was introduced after an expensive period when a manned-barrier fare system was used. The self-service system is sometimes disparagingly referred to as an honor system, but it is far from this. The thorough percentage checks of passengers have resulted in accurate evasion statistics, which range from below 1 percent to less than 3 percent in the nine North American applications. This is lower than typical evasion levels with conventional bus driver or turnstile fare collection. Although self-service failed in Portland when it was introduced systemwide on the buses, it is successful on the light rail line. Pittsburgh and San Francisco are now examining conversion to self-service.

The ticket inspectors or checkers play a much wider role than their title suggests. They are front-line information officers. They handle lost children, ill and confused passengers, and normal operational problems. But above all they provide a high level of security, appropriate for most North American cities. Perceived passenger safety on all new light rail lines is exceptionally high.

At typical light rail volumes, a self-service fare system has capital costs as low as one-tenth those of a barrier system. Operating costs, after taking security into account, are comparable to or lower than those for conventional systems. If these advantages are not enough, self-service provides the greatest flexibility in station and vehicle design, minimizes station stop time through use of all doors, and avoids the impedance turnstiles present to handicapped passengers.

The misgivings associated with the self-service system have almost disappeared thanks to the pioneering efforts in Vancouver and San Diego. Hybrid self-service fare collection with barriers only at central area stations is being introduced on Toronto's GO Transit, on the London Underground, and in the New York and Philadelphia areas. Fear of self-service is no longer an excuse to lose the light rail advantages of low station capital and operating costs, fast multiple-door loading and only a single "driver" per train.

THE STATIONS

Light rail provides astounding flexibility in station location and design. Stations can be as short as one car (80 ft or 25 m). With care they can be located on curves. They can be as minimal as a transit stop sign on a light rail mall or a full-featured, multilevel underground station with escalators, elevators, retailing, and direct connections into adjacent buildings.

The basic station needs only a simple shelter with room for a bench, ticket vending machines, pay telephone, newspaper boxes, and information signs. With a self-service fare system, access can be multidirectional, but care is required to ensure that passengers cross the tracks at safe, marked locations. This simplicity aids the provision of a low-cost, low-maintenance, vandal-proof facility. It can help to think of a basic station as just a large bus shelter. It is possible, as with many bus shelters, to pay in whole or in part for the station and its maintenance through advertising contracts. Alternatively, a local developer, retailer, or major employer may contribute to or even provide and maintain a station, whether minimal or more elaborate.

One difficult decision is whether to provide high or intermediate-height platforms. High-platform and street-level loading can be mixed by using vehicles with moving (high-low) steps or by designating specific vehicle doors for high loading, others for low loading. San Francisco is an example of the former, Pittsburgh the latter. Both add costs and complexity.

High platforms speed loading and provide optimal arrangements for handicapped passengers, including those with wheelchairs. Where high platforms cannot be economically provided, wheelchairs can be accommodated three ways: lifts on the cars (San Diego), lifts at stations (Portland), or station ramps (Sacramento). Wheelchair users prefer high platforms. The station ramps are the next best alternative, as they avoid mechanisms on the car or on the street that require maintenance and whose failure precludes wheelchair access. But ramps at stations are not elegant and can be difficult to fit into the available space. Sacramento has some commendable designs that are worth examining.

On the horizon is the possibility of a light rail car with a low floor in all or part of the car. Alternative designs are now entering service in Geneva and Grenoble. Other car manufacturers have designs on the drawing board. A very low floor design (12 to 16 in. or 300 to 400 mm) brings high-platform advantages to street-level loading, particularly with an intermediate-height platform. Intermediate-height platforms are used in Europe, but somewhat inexplicably, have not made it to North America except in Portland. They are no higher than a street curb, avoiding the first step into the vehicle, just as a bus does when it pulls to the side of the road. Combined with the low-floor cars now becoming available, they provide the same speedy, wheelchair-accessible loading as high platforms, at lower cost.

Although light rail stations can be simple and inexpensive, they also can be more substantial when appropriate, for example as part of a new development. Stations reflect the flexibility and low-cost potential of basic light rail.

LIGHT RAIL VEHICLES

LRVs are relatively heavy and expensive, all the more so with the recent fall of the dollar against the mark, yen, lira, and franc. This problem is accentuated by the small quantities in typical procurements. The West German VoV is sponsoring research into lighter designs with single-axle trucks. A new generation of cars could be available in 5 years. Currently there are several other designs of lower-floor cars under trial or in production. There are no manufacturers in the United States, although facilities to build in the required

U.S. content have almost created several U.S. light rail car builders. Bombardier's Vermont plant is an example.

In the mid-1970s the UMTA-sponsored U.S. Standard Light Rail Vehicle was intended to obtain the benefits of President's Conference Committee (PCC) car-style universality and continuity of batch, if not mass, production. These aims were thwarted by the relatively poor performance and high maintenance of the Boeing-Vertol car. Designing a car from the tracks up obviously presents some risks, making the common practice of developing an extensive and expensive customized specification questionable.

The alternatives are negotiated procurement, adding on to an existing order, or restricting selection to a car that has been or is expected to be in production for some time. These present institutional difficulties but are both possible and practical. San Diego and Calgary have negotiated additional orders with prices comparable to current competitive bids.

Operating two different vehicle designs is practical in large fleets, particularly if the couplers and multiple-unit controls are compatible. In small fleets this is undesirable. Here custom designs can be a liability, operators of "orphan" LRVs can rarely add to someone else's order, and negotiated procurement, the second time around, may be the only option.

OVERHEAD AND POWER SUPPLY

There have been many comments made about the extreme variation in overhead design on new light rail lines, both in North America and Europe. Certain systems have complex, heavy, and expensive designs. The visual pollution can be an appreciable obstacle to local and political acceptance of light rail. Given that there are several thousand miles of simple suspended trolley wire over light rail, streetcar, and trolleybus routes, the need for counterweighted (tensioned) catenary or compound catenary designs with structural supports that resemble the framework of a building merits examination.

Catenary designs have advantages at high speeds, in areas with extreme temperature variations, and where the added conductivity of the messenger wire can avoid or reduce feeder cables. Such designs are generally unnecessary on North American light rail, where speeds rarely exceed 50 mph (80 kph). They are often a result of overspecification or lack of knowledge of the simpler alternatives.

A system starting out operating single articulated cars may specify overhead for long trains and require the capability for a dead train to be pushed by an equivalent-length operating train. Similarly, requirements that the overhead remain intact through earthquake, flood, and 100-year winds is admirable but questionable. Overhead that survives an earthquake is of little advantage when it is unlikely that the roadbed can be cleared of debris for several days. Even on the lightest systems fallen overhead is rare and injuries are even rarer. Power is automatically disconnected when faults occur or can be turned off remotely.

The best examples of simple, unobtrusive overhead are on existing light rail, streetcar, and trolleybus systems. The two new French systems, in Nantes and Grenoble, have light, elegant designs. The latter is of particular interest as it uses Kevlar plastic span wire, avoiding the need for any insulators. In city centers, span wires can be attached to buildings, although it takes some effort for the transit agency to get legal approval. Support poles can be integrated with those for lighting, whether modern or ornamental antiques.

The basic, simple light rail line deserves basic, simple, and inexpensive overhead. Designers, engineers, and specifiers should be pointed toward the best appropriate examples elsewhere and asked to copy them.

LIGHT RAIL APPLICATIONS

The best way to determine the design of a new basic light rail line is to look elsewhere and see the cost-saving features, light elegant overhead, traffic management measures, station architecture, and other careful design features that many existing systems demonstrate.

In Europe, light rail has evolved predominantly from the post-World War II modernization and upgrading of streetcar systems, particularly in West Germany. Quite recently several all-new systems have been built. Notable for good "light" design are France's new systems in Nantes and Grenoble; the latter also has exceptionally low floors on its articulated cars.

Other good examples of light rail are in Gothenburg, Sweden; all large cities in the Netherlands, including a new system in Utrecht; Hannover, the Rhine-Ruhr district, Bonn, Frankfurt, Stuttgart, and many other locations in West Germany; Kiev, Volgograd, Lvov, Minsk, Riga, Tallinn, and elsewhere in the Soviet Union; numerous places in Switzerland; and in Italy at Milan, Turin, and Genoa (under construction). Light rail is also being planned in three British cities, with projected low costs per mile achieved by using railway and street rights-of-way.

Elsewhere in the world, the Manila system is notable for very high ridership on totally grade-separated aerial structures and for farebox recovery of all direct operating costs and most of the capital amortization. In Tuen Mun, Hong Kong, an extensive new system will soon open that is also projected to cover more than direct operating costs.

The new systems in Britain and France are of special interest, as these countries had all but given up on the streetcar and there was considerable antagonism to the reintroduction of this mode. In France "high-tech" systems have been heavily promoted and have competed technically, economically, and politically with light rail.

Table 1 summarizes both old and new light rail systems and streetcar operations in North America. It is based on data compiled by Ed Tennyson and provided by the American Public Transit Association's Light Rail Transit Committee.

TABLE 1 NORTH AMERICAN LIGHT RAIL SYSTEMS

City	Year Opened	Kilo-meters	Passengers per Day	No. of Cars	City Center Operation
Boston	1897	52	70,000	230	Old subway
Buffalo	1985	10	21,000	27	Mall
Calgary	1981	22	36,000	78	Mall
Cleveland	1920	22	17,500	48	Underground
Edmonton	1978	10	25,000	37	Underground
Fort Worth	1962	3	6,500	8	Underground
Los Angeles (est.)	1989	64	100,000	54	Underground
Mexico City	1900	34	47,000	50	Not central
Newark	1935	7	12,000	26	Underground
New Orleans	1893	11	21,000	35	Street
Philadelphia	1892	160	127,000	236	Old subway
Pittsburgh	1891	36	20,000	90	Underground
Portland	1986	24	21,000	26	Mall
Sacramento (est.)	1986+	29	21,000	26	Mall-street
San Diego	1981	33	23,000	30	Mall-street
San Francisco	1897	39	133,000	141	Underground
San Jose	1987	32	40,000	50	Mall-street
Toronto	1892	73	334,000	284	All street
Vancouver	1985	22	80,000	114	Old tunnel

NOTE: New Orleans has a historic streetcar line in street median. Toronto has a classic streetcar system, not typical light rail. Part of the Philadelphia system is also classic streetcar. Fort Worth has a short, private parking lot shuttle. Vancouver has a fully automated and driverless system that is often not classed as light rail. Tourist lines also run in Seattle and Detroit.

CONCLUDING COMMENTS

The remaining North American corridors with potential for capital-intensive transit improvements generally will have patronage in the low to middle-intermediate capacity range, that is, 15,000 to 50,000 passengers per day. To be competitive and cost-effective with buses in this range, light rail must be designed to be inexpensive. Attention is needed to retain the basics and avoid gold-plating. AGT is entirely uncompetitive in this range, and where passenger volume can justify higher expenditures, automated or hybrid light rail can do everything AGT can do with less technical risk and lower costs.

The case for busways is very corridor-specific. They have an unhappy history, with the few guided busways costing as much per mile as basic light rail. Where underground running is needed, the ventilation duo-mode bus costs are unfavorable. Busways and bus lanes have the habit of being usurped by general traffic or HOV lanes, and buses cannot compete with light rail in ride quality at the best of times. The comparison is also colored by the unfortunate trend when budget cuts must be made of reducing bus maintenance and cleaning while delaying vehicle replacement. The results can be seen on busways and bus lanes from time to time: aging buses with malfunctioning air conditioning, hazed-over windows, and smoking engines, fumes from which often infiltrate into the passenger compartment.

Much is made of the busway's advantage in avoiding transfers. Buses on the main busway can branch off and serve a suburban or downtown distribution role. This is indeed an advantage, but it is also a disadvantage that often results in long headways to specific destinations rather than frequent trunk headways with connections to less frequent feeder buses. Transfer can be regarded as an opportunity rather than an inconvenience—an opportunity to drop off dry cleaning, pick up groceries, or do the banking. Where park-and-ride is available, the advantage of avoiding any transfer is moot.

Light rail offers a quality of ride, a presence, and an influence on development that buses cannot approach. However, to compete with buses at the lower passenger volumes, light rail must be built economically. The most important phase in light rail development is the early alignment planning. Perceptive planning maximizes the use of existing rights-of-way, retaining a surface alignment wherever possible and making compromises with sections of single-track operation or on-street operation as necessary. This exploits light rail's flexibility and, with light overhead, the environmental advantages, while holding costs to a minimum.

All rail modes have a proven record of attracting more development and urban renewal than other transit improvements. Light rail also has a good record of attracting more ridership, including tourists, than comparable non-rail-based transit improvements, particularly at off-peak times. This increases revenue to the transit agency and the development adds to the municipal tax base. Light rail's positive image and extra revenue together with the environmental benefits can be the edge that puts light rail ahead of other comparably priced transit alternatives.

The final and in many regards most revealing, satisfactory, and cogent case for light rail is its widespread use. In North America during in the last decade, a majority of the new fixed-guideway transit systems built (excluding airport or distributor systems) have been light rail. These cover a wide range of applications, designs, and costs. They are popular, they work well, and they are being extended. Although every urban corridor has specific wants that may, at times and in places, justify other modes, it is clear that in a time of stretching every transit dollar light rail will continue to be the dominant intermediate-capacity, fixed-guideway mode. We can look forward to many new light rail systems built perceptively and economically and equipped in due course with new-generation vehicles—vehicles that are more cost-effective and have the low floors that provide more dignified accessibility for the handicapped.

The Case for Automated-Guideway Transit

GEORGE J. PASTOR

Automated-guideway transit (AGT) is a class of transit systems characterized by fleets of driverless transit vehicles operating under computer control on exclusive rights-of-way above, at, or below ground level. AGT systems, in general, can perform all of the operating functions of conventional, fixed-guideway transit systems, ranging from simple shuttles through collection and distribution to urban and commuter line-haul systems, including complex networks. AGT transit systems represent a fundamental change in the operational capabilities of transit systems, resulting in significantly improved service levels with simultaneous improvements in productivity when compared with conventional transit. Two of the most significant urban deployments of AGT are in North America and Europe: the SkyTrain system in Vancouver, British Columbia, Canada, and the VAL system in Lille, France. Their first years of operating performance are compared with those of other contemporary but conventional fixed-guideway systems. The conclusions drawn are that, in certain applications, AGT is more than competitive with conventional transit, and that, under certain conditions, AGT systems can return sufficient revenues to match and even exceed their total operating and maintenance costs at acceptable fare levels.

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A variety of AGT systems have been developed and deployed during the past 20 years, with most applications located at airports and activity centers built during the 1970s. But it was the 1980s that produced several successful installations of AGT systems in urban transit applications in Japan, France, Canada, Germany, and the United States. Today AGT systems increasingly are recognized and accepted as a proven, workable alternative within the repertoire of transit modes.

This increasing acceptance is justifiable, because AGT systems are a fundamental improvement to urban transit system design and technology and the major innovation for transit during the 20th century. What is less well understood and accepted is, indeed, the fundamental and profound improvement that AGT provides to transit, namely, a quantum jump in improved service levels at affordable low costs, or, put in another way, cost-effectiveness and productivity surpassing conventional transit. It is full automation of transit system operations and the impact of automation on the entire AGT system design that give AGT systems this unique capability. This is revealed by an examination of the needs of the passenger, the needs of the system owner and operator, and the needs of the communities in which transit operates.

NEEDS OF THE PASSENGER

For acceptable mobility, the urban transit passenger needs a high level of safety, an acceptable level of comfort, and, most important, good service. Good service means ready access, high frequency, and a high level of certainty that the time it takes to get from origin to destination will be short. The total travel time includes access time, waiting time, and trip time.

Considering trip time first, it has been well known for many decades that, in congested urban areas, acceptably short trip times can be achieved only by fixed-guideway transit with reserved rights-of-way. [Even busway and light rail transit (LRT) systems today are trying to minimize the shared, or nonexclusive, portions of their routes.]

It is in waiting time that conventional, fixed-guideway transit has a severe limitation, which, through the uncertainty of waiting time for the next train, discourages many potential patrons. Yet the economics of conventional fixed-guideway transit are such that only in the most highly traveled corridors and during peak rush hours can a few large metropolitan transit systems afford headways on the order of 1.5 to 3 min and off-peak headways of 5 to 15 min. In most other transit systems, typical peak-period headways are 5 to 6 min and off-peak headways range from 10 to 30 min.

AGT systems, in general, can provide access times that are as convenient and short as those of any conventional fixed-guideway systems, or better. In addition, stations for AGT systems are smaller and less costly than those for conventional systems, as will be discussed later. Thus, more stations and more frequent stops to accommodate this convenient access are not a penalty. Nevertheless, LRT systems at grade and in mixed traffic can provide easier access with simple stops at the cost of lower overall speed and interference with vehicular traffic.

Today's AGT systems are the only ones that have demonstrated reliable and safe peak-period operations at 40 sec and, in general, 1- to 3-min rush-hour headways, and off-peak operations at 3- to 5-min headways. It is only in AGT systems, which provide economies of operation through automation, that the owners can afford this level of service. It is this unparalleled service level that captures the added ridership and creates the 3- to 4-hr noon rush by ensuring the AGT patron of negligible waiting time and a predictably fast trip time throughout the day and the night. This quantum jump in service level is one reason two automated line-haul AGT systems turned an operating profit over and above operation and maintenance costs during 1986 in Lille, France, and Vancouver, Canada—an unparalleled achievement in recent transit history. The other reason for such achievement by the early urban AGT operations is their affordably low costs.

NEEDS OF THE OWNER-OPERATOR

Essentially all fixed-guideway transit agencies in North America (and most around the world) operate at a deficit and therefore depend on subsidies from local, state, and federal sources. This fact "politicizes" the transit business. Nevertheless, each agency wants to provide the best possible service that it can afford, which, of course, depends on the following:

- The capital cost of a (new) transit system, and
- The operating and maintenance (O&M) costs.

The above two costs are frequently combined and expressed as the life-cycle cost (LCC) of a transit system. In the politically dominated transit business, the changing availability of capital and O&M cost subsidies frequently distorts the cost-effectiveness analyses among competing modes. Thus, for a politician with a 2- or 4-year horizon in office, the "cheapest" is often confused with the most cost-effective. AGT system design was undertaken to minimize all three costs—capital, O&M, and life-cycle costs—taking full advantage of automation in service to provide cost-effectiveness and productivity through careful system design.

In the following, the UTDC design of AGT is used for illustrative purposes, but the analysis holds true for most AGT systems. It will be shown that

AGT systems design is far more complicated than snapping an automatic train control (ATC) package on an existing conventional vehicle or pulling the operator off an existing subway train running under ATC.

Capital Cost Reductions

The characteristics of AGT systems permit capital costs to be trimmed as the following suggest:

- The passengers' need for frequent service could be easily satisfied by newly developed automation, proven initially abroad, not using the old block system, and providing safe headway control down to 40 sec (or even less).
- The short headways permit considerable, and respectably high, line-haul capacities (over 30,000 passengers per hour per day) with smaller and lighter vehicles than conventional heavy and light rail vehicles (750 versus 1,000 lb/ft).
- Smaller and lighter vehicles provide for significant cost reductions in elevated guideway construction (two-thirds of the width of a guideway required by most heavy or light rail cars and less depth) or significant diameter reduction in tunnel construction, if required.
- To achieve a given line-haul capacity, short trains are used at short headways, which allows the train station and platform lengths to be reduced to up to one-half of that required by conventional rail vehicles.
- Trains formed from small vehicles with improved turning ability permit tight turning radii in urban applications, thereby reducing right-of-way costs.

It is clear from the above that a very significant cost reduction in guideway and station (or tunnel and station) construction costs can be achieved through the interaction of automation and vehicle and train sizing. Obviously, the trade-off here is between guideway costs and more vehicle miles to satisfy a given capacity and frequent service. Thus, O&M costs must also be significantly reduced to balance the increased vehicle miles.

O&M Cost Reductions

The lighter weight of AGT vehicles in general reduces both the power requirements and the wear and tear of both vehicles and running surfaces in the wayside. In addition, the following system features were incorporated into the UTDC AGT design (others use different innovative features):

- Steerable trucks that provide tight turning radii and eliminate squeal in turns and that also reduce wheel flange and track wear, thus reducing maintenance costs. (Initial operational problems with the steerable trucks have since been corrected.)

- Linear induction motors (LIMs) provide propulsion power without depending on traction between wheels and rail. This feature provides all-weather capability without heating the guideway, improved gradability, and an almost complete elimination of moving parts. The only moving parts are the cooling fans for the LIM, and the passive rolling axles and wheels in the trucks and the doors. There are no costly motor overhauls; no significant brake wear, because the LIMs act as electromagnetic brakes; and no gearboxes to maintain. Most mechanical complexity is replaced by solid-state electronics, which is virtually maintenance free.
- The hierarchical structure of automation provides ample diagnostics and fault identification at a continually shrinking cost typical of the computer and semiconductor industries.
- Judicious use of redundancies provides both for high operational availability and minimized maintenance costs at predictable intervals.

Operational Flexibility

Another important feature for the owner-operator is operational flexibility to meet service demands. Essentially all AGT systems provide the ease of adding or withdrawing consists from operations by pushbutton control at a central control console without any other manual operations.

A particularly noteworthy example of operational flexibility occurred in Vancouver throughout Expo '86. Less than half a year after opening a new system, and throughout the six months of Expo '86, BC Transit operated 18 to 22 four-car consists in fully automated mode over the 13.5-mi line-haul route of SkyTrain, carrying up to 120,000 passengers daily at 2- to 4-min headways. Simultaneously, and superimposed on the downtown portion of the route, two dedicated four-car consists shuttled up to 40,000 Expo visitors between two shared, but secured, Expo stations separated by about 1.5 mi and three stations. The jam-packed shuttles essentially operated in a demand-responsive mode, interwoven with the regular line-haul trains, frequently operating at 40-sec headways. Each shuttle made the switchover for its short turnaround without any noticeable interference with the line-haul service, fully automatically—a magnificent example of operational flexibility through automation.

Cost-Effectiveness and Productivity

Capital costs of transit systems are perhaps the least meaningful measure for comparison because they vary so drastically based on location (by country, geography, and geometry), time of construction, currency rates, system complexity, capacity, and service levels.

Nevertheless, capital cost is important to decision makers and politicians, so it must be identified. Vancouver's SkyTrain cost approximately $615 million (1986 U.S. dollars) or approximately $46 million/mi. Lille's VAL cost approximately $328 million (early 1980 U.S. dollars) or approximately $38 million/mi.

These capital costs per mile for AGT systems are generally higher than recently constructed LRT lines, which tend to range under $20 million/mi (although the Long Beach-Los Angeles line currently under construction will exceed $32 million/mi), but far lower than most heavy rail transit (HRT) lines, which range from $58 million to well over $100 million/mi. Yet, from a passenger-capacity point of view, these AGT lines are performing more like HRT than LRT.

Costs are, however, just one part of cost-effectiveness. Vancouver's SkyTrain carried 34 million passengers during 1986, its first year of operation. Lille's VAL carried 28 million passengers each during 1985 and 1986, its third and fourth years of operation. Hardly any North American LRT line approaches these ridership figures.

To provide a reasonable comparison among the capital costs of nine new-start rapid transit or light rail transit systems opened in North America during the last 10 years, the number of passengers carried (which is at least partially indicative of the quality of service) must be considered. Thus, the measure of capital cost per mile per weekday passenger is used in Table 1. All of the information in this table has been obtained by B.C. Transit, the Vancouver authority, from published documents or directly from the transit authority concerned. In addition, the data for the first VAL line in Lille, France, were provided by Matra Transport (*1*). All actual costs have been meticulously indexed to a common time period ending in 1986.

Thus, it is seen from Table 1 that the two AGT systems in Vancouver and Lille, together with the LRT systems in San Diego, Calgary, and Portland, are among the least expensive systems based on cost per mile per weekday passenger and, therefore, among the most cost-effective new-start systems. Both Vancouver and Lille produced an operating profit during the above-quoted years based on their total operating and maintenance costs. No other North American LRT or HRT line can make this claim.

An excellent performance measure for transit system operations is productivity, simply defined as annual passengers carried per operating and maintenance employee. Vancouver's productivity figure during Expo '86 ranged between 120,000 to 130,000 passengers per operating and maintenance employee. Lille's productivity figure is reported to exceed 140,000 passengers per employee. Among the LRT systems, Calgary, in its fifth year of

TABLE 1 CAPITAL COST PER MILE PER WEEKDAY PASSENGER

System	Length (mi)	Capital Cost [U.S. $ millions (1986 equivalent)]	Year Opened	Weekday Passengers[a]	Capital Cost (U.S. $) per Mile per Weekday Passenger
Vancouver, B.C.	13.4	615	1986	80,000	573
San Diego	15.9	149	1981	16,000	585
Calgary	7.8	196	1981	40,000	628
Portland	16.1	243	1986	22,000	686
Pittsburgh	10.6	529	1985–1986	35,000	1,425
Edmonton	6.4	215	1979–1982	20,000	1,679
Baltimore	8.1	833	1984	38,000	2,706
Miami	21.6	1,250	1984	20,000	2,893
Buffalo	6.4	516	1985–1986	18,000	4,479
Lille, France	8.2	387	1984–1985	58,000/ 78,000	813/ 605

[a]Now or estimated for initial year.

operation, carried just under 100,000 passengers per employee; Edmonton, inits fourth year of operation, carried about 70,000 passengers per employee; and San Diego serves about 45,000 passengers per employee. It is premature to report on Portland. All of the data for the figures in this paragraph were obtained by the author during 1987 directly from the authorities mentioned.

The above information is illustrated in Figure 1. The data for the selected European systems are from Matra Transport (*1*), the data for Vancouver from that transit company (*2*), and, for the balance of North American systems, from unpublished data.

Another, perhaps more widely used, measure for operating productivity is the operating cost per passenger carried. Biehler, in a paper in this report, gives the following figures for recent LRT systems:

City	*Operating Cost per Passenger ($)*
Buffalo	1.17
Pittsburgh	1.50
Portland	0.95
Sacramento	1.55
San Diego	0.89

The average is $1.21 per weekday passenger. In contrast, the total operating costs per passenger for the AGT systems are as follows:

Lille (1985 data @ 5FF = U.S. $1): $0.53,
Vancouver (1987 data @ C$1.28 = U.S. $1): $0.94.

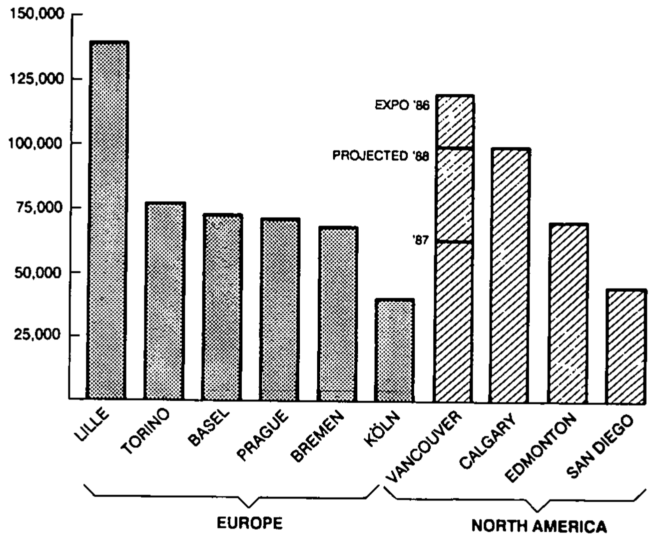

FIGURE 1 Productivity: annual passengers carried per operating company employee.

By both measures, the two AGT systems perform at higher productivities than the comparable conventional systems.

To preserve the accuracy of reporting, the Vancouver ridership figures must be clarified. Figure 2 gives the total monthly ridership history of the SkyTrain operations in 1986, 1987, and the first half of 1988 (2). While 1986,

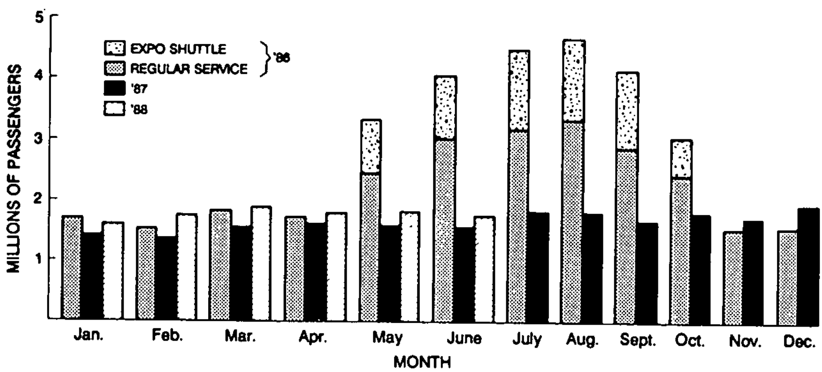

FIGURE 2 Vancouver ridership.

the opening year, was an extraordinary success with 34 million passengers carried during the year thanks to Expo '86, the weekday ridership was conservatively scaled back to 80,000 by B.C. Transit for the purposes of performance comparisons. The post-Expo '86 economic slowdown in Vancouver, however, reduced the SkyTrain weekday ridership to 60,000 or slightly below. Thus, an operating subsidy was required during 1987. Starting with November 1987, ridership began increasing again and this trend has been maintained throughout 1988, resulting in a current rate of 75,000 weekday passengers, which restores the credibility and significance of the above comparisons.

Simultaneously, the more mature Lille AGT system has shown an increasing weekday ridership from 58,000 in 1984 to 78,000 in 1986 and 1987, further reinforcing the validity of these comparisons. Thus, Vancouver's SkyTrain and Lille's VAL appear to be the least-cost, highest-productivity lines among the new-start transit systems surveyed.

THE NEEDS OF THE COMMUNITY

All fixed-guideway transit systems are designed to be "neighbor-friendly." So are AGT systems, with a few pluses, as follows:

- Reserved rights-of-way provide no street interference and no grade crossings;
- Smaller, lighter structures and stations provide a clean modern look, drawing no aesthetic objections;
- Noise levels are equal to or better than those of other transit modes, frequently less than the urban ambient;
- No pollutants are used;
- Safety (unsurpassed records over millions of passenger and train miles);
- Image (modern, high-tech, progressive); and
- Good developmental impact (captures the imagination of the private sector, stimulating mixed and joint development).

CONCLUSIONS

The advocates and developers of AGT technology have been promising a potential to recover operating and maintenance costs from farebox revenues. This promise has been fulfilled in Vancouver and in Lille with even a small operating profit. AGT systems' ability to reduce operating deficits has been proven. The ability of AGT systems to attract extraordinary, induced ridership, especially in off-peak hours through improved service, also has been proven. Public acceptance of fully automated (driverless) trains is complete and highly enthusiastic. Thus, AGT systems are here to stay and the mode has become a prime candidate for implementation in new public transit initiatives.

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Exclusive Busways Versus Light Rail Transit

A Comparison of New Fixed-Guideway Systems

Allen D. Biehler

Busways can offer clear advantages over light rail in many transit corridors. By comparing Pittsburgh's exclusive busways with light rail there and in four other cities—Buffalo, Portland, Sacramento, and San Diego—these advantages can be demonstrated. Light rail transit (LRT) theoretically offers greater capacity. But experience has shown that not only can busways carry just as many passengers, they actually can carry more riders per mile of guideway because busways can be shorter in length and still provide a good level of service. Busways cost less than half as much per passenger to operate than LRT and, in terms of capital cost, busways can be built for about one-fourth of an LRT of equal capacity. Busways can handle the passenger volumes expected in the great majority of urban corridors and, given their expected level of ridership, should prove to be as attractive to development interests as LRT. Simpler to operate and maintain than LRT, busways also provide greater operational flexibility.

IN THE LAST 10 YEARS, transit agencies in a number of U.S. cities have been busy building new fixed-guideway facilities. For Portland, San Diego, Buffalo, and Sacramento, the mode chosen was light rail. Most of these cities have opened their new light rail transit (LRT) systems within the last $2^1/_2$ years and are still fine tuning their operations.

A different mode was chosen in Pittsburgh—busways. Two new exclusive busways were built and opened in the last 10 years—the South Busway and

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the Martin Luther King, Jr. East Busway. A light rail line was also opened in Pittsburgh recently, but not a new one. Port Authority of Allegheny County (PAT) recently rebuilt about half of its old streetcar system to light rail standards.

PAT's favorable experience with operating its two busways is the impetus for this paper, which compares four new light rail systems and one rebuilt light rail system with PAT's exclusive busways. Operating experience on the light rail systems is still somewhat limited, but the author believes that sufficient evidence exists to conclude that busways offer an advantage over light rail for many applications due to their attractiveness to riders, cost-effectiveness, and flexibility.

There are many types of busways, including high-occupancy-vehicle (HOV) and busway lanes, contraflow lanes, and concurrent flow lanes. However, PAT's exclusive busways were chosen to provide a conservative standard for comparison with light rail facilities.

DESCRIPTION OF SYSTEMS

The five cities discussed in this paper are all medium-sized, medium-density cities. Two are older northeastern cities with long-established transit systems and declining populations. The other three are western cities with increasing populations and newer transit systems. Light rail and busway facilities were opened in each city within the last 10 years.

Buffalo has a 6.4-mi light rail line that has both at-grade and subway sections. Buffalo's downtown distribution system operates at-grade on city streets. The initial system was opened in 1985, the last section in 1986. There are 14 stops and stations along the line.

Portland's Banfield light rail line is 15.1 mi long with 27 stops and stations. This at-grade facility was opened in late 1986 and operates on city streets in the downtown area.

Sacramento completed its two light rail lines, which total 18.1 mi in length, in 1987. This at-grade system with its 28 stations and stops is operated in through-routed fashion. An unusual feature of the Sacramento system is the preponderance of single-track line sections. To minimize capital costs, the system was built with seven single-track sections totaling 11 mi. Vehicle headways are limited to a minimum of about 15 min as a result. Downtown distribution is handled on city streets.

San Diego has operated its light rail system longer than the other four cities discussed here. Two lines totaling 20.4 mi, built entirely at-grade, have 22 stops and stations. The South line was opened in 1981, the East Urban line in 1986. Downtown distribution is handled by light rail vehicles (LRVs) operating on city streets.

Pittsburgh has two busways and a rail system. Both busways are two-lane roadways built exclusively for mass transit and are located on separate rights-of-way owned by PAT. The 4-mi South Busway was opened in 1977. It is primarily at-grade with one section in tunnel. Two sections of the South Busway operate in combination with Pittsburgh's light rail/streetcar system. There are five locations where buses can enter and exit the South Busway.

The 6.8-mi Martin Luther King, Jr. East Busway is entirely at-grade except for a 0.25-mi elevated section. The East Busway has six bus access points and was opened in 1983. Both of Pittsburgh's busways utilize downtown streets for distribution.

Pittsburgh's 22.5-mi rail system is composed of two interwoven lines in one corridor, 10.5 mi of which have been rebuilt to LRT standards. The light rail line is primarily at-grade. It has a downtown subway section and two additional tunnel sections necessitated by Pittsburgh's hilly terrain. Old streetcars, which operate on the remaining 12 mi of streetcar line, also operate in the downtown subway and short outer sections of the rebuilt LRT line. The light rail line was opened in sections between 1984 and mid-1987. Two unique features of Pittsburgh's light rail system are its unusually large number of stops and stations—35 within 10.5 mi—and its incorporation of both high and low platforms at major stations to accommodate both LRVs and streetcars. Only the 10.5-mi light rail portion of Pittsburgh's rail system is used in making comparisons in this paper.

Operation of these new light rail systems should still be considered as being in a "break in" period. All five cities are making adjustments to maximize system performance. For example, some cities are fine tuning headway spacing and the number of LRVs that are being entrained. Others, like Sacramento, San Diego, and Pittsburgh, will be phasing in more feeder bus service, which will change the character of their systems.

Operation of Pittsburgh's two exclusive busways has generally stabilized. Nevertheless, over the next few years it is expected that efficiency will be increased through the use of additional articulated buses.

CAPITAL COSTS

Examining capital costs, ridership, and guideway length helps illustrate the differences between the five light rail and two busway systems. As shown in Table 1, the light rail line segments range in length from 6.4 to 15.9 mi, whereas the two busways are 4 and 6.8 mi long. Weekday ridership for the seven systems ranges from 14,000 to 30,000. The range in daily riders per mile is 800 to 4,700.

TABLE 1 CAPITAL COSTS OF RECENT LIGHT RAIL AND BUSWAY SYSTEMS

	System Length (mi)	Weekday Ridership	Ridership per Mile	Capital Cost ($ millions)	Capital Cost per Mile ($ millions)
Light rail					
Buffalo	6.4	30,000	4,700	540	84
Pittsburgh	10.5	18,000[a]	1,700	500[a]	48
Portland	15.1	19,000	1,300	223	15
Sacramento	18.1[b]	14,000	800	176	10
San Diego	20.4[c]	27,000	1,300	175	9
Average	14.1[d]	21,600	1,500	313	23
Busway					
Pittsburgh East	6.8	29,000	4,300	132	19
Pittsburgh South	4.0	18,000	4,500	36	9
Average	5.4	23,500	4,400	84	16

NOTE: Costs updated to 1987 dollars.
[a]Ridership and cost are shown for the rehabilitated portion of the system only. Excludes ridership on the older portion of the line and capital costs that could be attributed to the older system.
[b]Includes two lines 8.6 and 9.5 miles in length.
[c]Includes two lines 15.9 and 4.5 miles in length.
[d]The average length of each line *segment* equals 10.1 mi.

Capital cost ranges from $36 million for the shortest busway to $540 million for one of the light rail lines. Capital cost per mile varies between $9 million and $19 million for the two busways and three of the light rail systems. The other two rail lines range from $48 million/mi to over $80 million/mi. The higher cost of these two systems results from the use of expensive subway construction.

Hence, the busways are shorter in length than the light rail lines, carry about the same number of passengers per day (although at higher rates of ridership per mile because of their shorter length), and cost about the same per mile to construct as lower-cost light rail lines.

The average length of the two busways is 5.4 mi versus an average of 10.1 mi for the light rail line segments. One advantage of busways emerges: they can be shorter than light rail lines, and therefore cost less to construct, yet still carry as many riders. Busways can be shorter because the routes that use them can fan out into residential areas for passenger collection and distribution. Of course, light rail lines typically have feeder bus routes that serve the same purpose. But the time delay and associated rider frustration involved in transferring from feeder bus to an LRV mean that the light rail line probably has to extend further to provide a travel time benefit, hence the length of the LRT systems in Table 1.

Another reason that light rail lines need to extend further is to gain locations for vehicle maintenance shops and park-and-ride lots. Land close to downtown areas is generally not available for these purposes. In contrast, bus maintenance facilities can be located at any suitable site in the service corridor because they do not have to be located adjacent to the busway.

OPERATING COSTS

Past attempts to standardize transit industry operating cost data have been difficult at best. UMTA's Section 15 data are probably the closest thing there is to an industrywide standard. Unfortunately, Section 15 data were not available at the time of this writing due to the newness of the systems being discussed.

Operating cost data gathered for this paper were obtained directly from transit agencies in the topic cities. Care was taken to request the same data from each agency. The operating cost data presented here include the full cost of transportation, vehicle and facility maintenance, fuel and utilities, and administrative overhead in the transportation and maintenance areas. Purposely excluded were agencywide support costs for other functional areas such as administrative overhead, scheduling, accounting, service planning, and so forth.

Feeder bus data were not included in the costs of either mode. This resulted in excluding the cost of operating feeder bus to rail and the cost of that portion of busway routes that lay beyond the busway limits. The operating cost of the downtown distribution portion of the busway routes, however, was included.

The operating cost data collected are shown in Table 2. Annual operating cost for the light rail systems ranged from $5.4 million to $10.5 million versus $3 million to $3.7 million for the busways. Operating cost per passenger ranged from 89 cents to $1.55 for light rail, and from 43 cents to 56 cents for busway. Average cost per passenger for the five light rail systems was $1.21 compared with 50 cents for the busways.

It can be seen from Table 2 that the most cost-effective light rail system was still 60 to 80 percent more costly than the average busway. And on the average, light rail operating costs were 200 percent greater than busway operating costs.

The operating cost and ridership figures shown in Table 2 will change, because the systems are still undergoing operational changes. Probably the best way to standardize an analysis of operating costs would be a systemwide approach similar to that employed in many corridor alternative analyses.

TABLE 2 OPERATING COSTS OF RECENT LIGHT RAIL AND BUSWAY SYSTEMS

	Annual Operating Cost ($ millions)	Operating Cost per Passenger[a] ($)
Light rail		
Buffalo	10.5	1.17
Pittsburgh	8.1	1.50
Portland	5.4	0.95
Sacramento	6.5	1.55
San Diego	7.2[b]	0.89
Average	7.5	1.21
Busway		
Pittsburgh East	3.7	0.43
Pittsburgh South	3.0	0.56
Average	3.4	0.50

NOTE: Operating costs are for calendar year or fiscal year 1988.
[a]A ridership annualization factor of 300 was used in the calculation of operating cost per passenger.
[b]Includes operating cost data obtained from the property minus a portion attributed to nonoperational overhead that was estimated from the American Public Transit Association 1986 Operating Report.

Nevertheless, it is the author's opinion that the basic differences in operating cost per passenger favoring busways will remain.

OTHER FACTORS

To make a clear distinction between the two transit modes, busways and light rail can be compared in several ways: planning, design and construction, operation and maintenance, capacity, passenger satisfaction and image, capital and operating requirements, and development potential.

No significant difference exists in the manner in which planning for these transit systems is conducted. Indeed, both types of fixed-guideway systems fall under the same federal Alternatives Analysis/Environmental Impact Statement process. The following factors are considered in this process regardless of mode: cost, level of service, ridership, and environmental impacts. However, estimation of capital and operating cost for busways should be simpler and more accurate than for light rail because of the greater prevalence of the bus mode, and because of the similarity of busways to highways in terms of construction and design characteristics.

In terms of design and construction, light rail systems present more difficulties for three reasons:

• Light rail has some complicated design characteristics, including electrification, train control, computerization, rail alignment requirements, weight, and specifications of LRVs.

• Light rail lines are more likely to have sections in subway, leading to special design and construction requirements.

• Busways are essentially simple highways and can be designed and constructed as such. Significantly more design and construction firms are experienced in highway design than light rail design.

Busways are also simpler to operate and maintain than light rail systems. The need for operations control centers is unique to rail. Even the vehicle maintenance facilities are more complicated to operate and maintain. The requirement for separate but interrelated communication, signal, power, and propulsion systems for LRT also contributes to complexity for training, operating, and maintenance.

Busways permit far more flexible operation than light rail. With busways, the same vehicle that performs the feeder system function also performs the line-haul function. Further, buses going in the same direction can pass each other more easily than light rail cars, particularly when off-line busway stations are used. Broken-down light rail cars are much more likely to tie up the system.

Light rail operates at a greater theoretical capacity than busways, but this advantage does not necessarily hold up under closer examination. The capacity of light rail is about 200 passengers per vehicle times 40 vehicles/hr (90-sec headway) or 8,000 passengers/hr. Articulated buses operating at 60-sec headway yield 6,000 passengers/hr, assuming 100 passengers per bus.

Of course, light rail vehicles can be entrained, thus providing two, three, or more multiples of this 8,000/hr capacity. However, three factors can greatly increase busway capacity as well. First, it is relatively easy for two buses to use a single off-line station at the same time, thereby doubling capacity. Second, through buses that pass buses stopped at a station increase capacity even more. Third, busways can serve as a "shunt facility" on which buses that have performed passenger pick-up on local residential streets can bypass traffic congestion and travel nonstop to downtown areas at a high rate of speed. These nonstop buses can then provide passenger distribution on any number of downtown streets.

For these reasons, busway capacity can be 10,000 riders/hr or greater. Expanding the capacity of 10,000/hr to a daily ridership average yields 67,000 riders/day, assuming that 15 percent of daily riders are riding in the peak hour in the peak direction. This is more than twice as high as the ridership of any of the new light rail systems. Therefore, although light rail has a greater theoretical capacity, busways can easily carry the expected ridership in the great majority of urban corridors.

In terms of passenger satisfaction and image, neither transit mode can claim a clear advantage. Although busways and light rail provide equivalent levels of service in terms of travel time and vehicle comfort, busways have an edge in that transfers to and from feeder bus are less likely to be required. However, due to the prevalence of light rail systems as opposed to busways, light rail is considered to have an image advantage that belies the comparability of customer service for the two modes.

Capital costs per mile are similar for some of the light rail and busway systems shown in Table 1. However, light rail's longer length and more frequent use of subway clearly leads to higher total capital cost.

Given the significantly lower busway operating costs shown in Table 2, why is it commonly stated that rail is less labor-intensive than bus? It is true that light rail requires fewer operators for a given level of ridership based upon the ability of each LRV to carry about twice as many passengers. This ratio of 2 to 1 holds only during peak periods, however. During other time periods the number of operators for the two modes is closer to being equal because policy headways, rather than capacity, play a greater role in scheduling service. However, light rail requires personnel in other job categories such as track crew, structures crew, switch maintainers, overhead lines crew, signals and communications crew, and substation maintainers. This increases the personnel requirements for light rail, thereby contributing to higher operating costs.

In terms of development potential, rail advocates claim that their mode spurs development. It seems clear that the ability of fixed-facility transit systems to move large numbers of people would be attractive to those developments that are located at or near stations. However, there is no reason to think that attractiveness to development is inherent in a specific mode. As long as the number of riders is equal, there should be equivalent development potential; as shown in Table 2, the newer busways and light rail systems typically carry the same range of riders.

SUMMARY AND CONCLUSIONS

The recent investments and operating experience of San Diego, Pittsburgh, Portland, Buffalo, and Sacramento provide the transit industry with new information about fixed-guideway systems. In nearly all areas of comparison, busways appear to offer advantages over light rail systems.

Experience of the past few years has shown that busways carry as many riders as light rail systems do. Because busways can be shorter in length and still provide a good level of service, they carry more riders per mile of guideway.

The operating cost advantage is such that busways cost less than half as much per passenger to operate than light rail. On the capital side, the averages presented in this paper show that an $80-million busway carries as many riders as a $310-million light rail system.

The capacity of busways is sufficiently large to carry the expected ridership in the great majority of urban corridors. And, on the basis of their expected level of ridership, busways are as attractive to potential development as light rail.

In addition, busways and bus systems are simpler to operate and maintain, and training requirements are less in comparison to light rail. Finally, busways provide greater operational flexibility than light rail, particularly in the ability to skip stops or to not stop at any stations along the busway if passenger demand warrants. Express and local services can be better tailored to suit patron requirements.

Those planning new fixed-guideway facilities are encouraged to consider busways. The advantages are simply too great to ignore.

A Comparison of Some New Light Rail and Automated-Guideway Systems

GERALD D. FOX

The past decade has seen dramatic developments in urban rail transit, particularly in the field of light rail transit (LRT). At the same time, several proprietary automated systems have been developed and deployed, often claiming superior levels of service and cost-effectiveness. Data are now becoming available that make it possible to check, for the first time, how well the new automated-guideway transit (AGT) systems are meeting their promoters' claims, and to compare such systems with the new conventional LRT systems. Methodologies are presented to collect and screen performance data from different systems in a uniform manner, and examples are developed to show how these data can be used to compare modes using actual operating information to the maximum extent. When new AGT systems are compared with new LRT systems, or when AGT and LRT are compared on identical alignments, it appears that the cost of additional maintenance and supervising staff and additional "non-staff" budget may exceed the savings that AGT systems achieve by eliminating operators. Although the new AGT systems represent a further advance in the development of urban transit technological capabilities, and reflect great credit on those who have built and financed them, they may also contain the seeds of future problems. Having a significantly higher construction cost per mile than LRT, urban areas with AGT will tend to have smaller rail networks than equivalent areas selecting LRT. Being proprietary systems in limited use, they may experience future procurement problems, particularly if the promoter goes out of business. Being a contemporary, high-technology product, there is also a high risk of obsolescence in future years.

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THE PAST DECADE HAS seen dramatic developments in urban transit, particularly in the field of light rail transit (LRT). Several proprietary automated-guideway transit (AGT) systems have been developed and deployed, often claiming superior service and reduced operating costs, mainly through the elimination of the need for train operators.

Until recently, the manufacturers were the primary source of information on the new AGT systems. Data are now becoming available from other sources, making it possible to check, for the first time, how well the AGT systems are meeting their promoters' claims in actual transit service, and to compare the results with those of some new LRT systems.

This paper offers a compilation and interpretation of data from some of the new LRT and AGT systems, and a methodology to measure how well the claims of the proponents are being realized. For the purposes of this paper, only transit systems that are in revenue service are considered, and minor special purpose lines, such as downtown or airport people movers, are not included.

Characteristics of LRT usually include the following:

- Manual operation, with one operator per train;
- Large, articulated cars, typically 80 to 90 ft long, able to run in trains of up to four cars;
- Operation on a variety of rights-of-way, from city streets to fully grade-separated tracks; and
- Use of a long-established "generic" technology, with many supply sources available for every component.

Characteristics of AGT usually include the following:

- Automatic operation, not requiring an operator for each train;
- Medium-sized cars, typically about 40 ft long, and often operated as married pairs, and in trains of up to two pairs (four cars);
- Requirement for full grade separation, often with elaborate anti-intrusion devices at stations and on the right-of-way; and
- A number of competing proprietary technologies, mutually incompatible, and in some cases, aggressively marketed.

Examples of AGT systems include these seven:

System	*Country*
Skybus	United States
VAL	France
SkyTrain	Canada
Docklands	England
TAU	Belgium
Portliner	Japan
M-Bahn	West Germany

INFORMATION SOURCES AND INTERPRETATION

Information on the operation of various LRT and AGT systems was derived from a variety of sources. These included reference material, promotional material, industry publications, budgets, correspondence, and field visits. Whenever possible, data were cross-checked between sources, and major inconsistencies explored. Sources are referenced as they are used throughout the body of this paper.

As information was collected and cross-checked, the need for careful screening became more apparent. Reporting methodology differed between systems, and information was sometimes published in a format intended to show the operation concerned in the best light. Such partial or incomplete data can be said to suffer from the "iceberg effect"—only part of it is visible.

This "iceberg effect" is commonly caused by at least one of several factors. On new systems, the suppliers are sometimes required to provide maintenance or spare parts for a period of time. Such costs may not be reported as operating costs. The published budget or staffing on a system may not be complete. In Portland, for instance, fare inspection and security personnel are budgeted in the finance department, and therefore do not appear in the rail department budget. In addition, many systems contract out for some maintenance functions. Consequently fewer operating staff are needed by the agency. For instance on the Docklands system, station maintenance is performed by outside contractors, and some of the vehicle maintenance is carried by the supplier. Contract personnel may not be considered as an operating cost. And finally, direct operating cost may or may not include all maintenance, clearly a pivotal issue when such indicators as farebox recovery ratio are being compared between systems.

Another problem is the need to screen special events from transit statistics. For instance, during Expo '86, SkyTrain carried almost twice as many passengers as it did in 1987, many of them on a short shuttle. This Expo '86 ridership is still sometimes quoted as system ridership, despite its irrelevance to the corridor or regular daily operation. Similar ridership surges are experienced on most other transit systems, for instance in Calgary during the Winter Olympics or in Portland during annual Rose Festival week, and have been screened out of this analysis.

On some systems operating surpluses have been claimed without explanation of what was included as operating cost. Such claims cannot always be substantiated when system budget is considered.

To minimize such problems, this paper draws mainly from basic unprocessed data, and on budgets, where available.

SOME STATISTICS

Some 20 new LRT systems have opened during the past decade, as well as several AGT systems. Eight of these systems were selected for more detailed study, three AGT systems and five of the more numerous LRT systems.

The LRT systems were selected to present a range from the low-cost "no frills" systems adopted for some of the low-density North American cities to the high-capacity, grade-separated Manila system.

The Nantes system was the first new LRT in France, and, together with the new LRT in Grenoble, offers an interesting contrast to the Lille VAL. It exhibits the low-cost, simple design approach to LRT carried out with great elegance. The policy background, design, construction, and first year of operation of this system are described in detail in *Le Tramway Nantais* (*1*). In the first year of operation, this system recovered its direct operating cost plus amortization and tax charges. Operating improvements and line extensions are planned.

The San Diego LRT was the first of the new low-cost LRT systems in the United States and has been cited as a prototype by several more recent systems. The San Diego system offers an excellent example of how rail transit can be built in corridors requiring only medium capacity for the least cost. Several new lines are being planned and constructed.

The Portland LRT drew heavily on the San Diego system for its design and operating philosophy. It includes a wide spectrum of right-of-way design, from full grade separation to a short section in mixed traffic, with some elegant downtown street improvements. An expanded LRT system forms the core of the region's long-term transportation plan, which will be implemented over the next 20 years as funding becomes available.

The Calgary LRT system was included because it has the highest ridership of any of the new LRT or AGT systems in North America. A somewhat "heavier" application of LRT than those in Portland or San Diego, it has operated very successfully in the demanding climate of Alberta. Two major extensions have been built since the first line opened in 1981.

The Manila LRT is an example of a fully grade-separated LRT operating in a corridor requiring high capacity. LRT was selected for this system to make possible low-cost at-grade extensions and branches wherever right-of-way permitted. In 1986, Manila LRT recovered 98 percent of its direct operations cost, as well as interest and depreciation, from fares (*2*).

A similar high-capacity LRT opened in Hong Kong (Tuen Mun) in August 1988. However this system is entirely at grade.

Three AGT systems were selected, representing major applications of three different AGT technologies in urban transit service.

The Docklands Light Railway in London is actually an AGT system. It uses large, LRT-type vehicles on standard gauge track, but with automated operation. Each car is staffed by a "train captain" who checks fares, monitors operation, and can operate the train when necessary. Efficiency is constrained by operation of single-car trains only. Two-car trains will eventually be operated when the stations have been expanded and more cars purchased. Staffing levels cover only the operating agency staff. Much of the vehicle maintenance is done by the supplier, and station maintenance is also contracted out. Full operating costs are not available.

The VAL AGT in Lille, France, is the first, and most successfully marketed, of the AGT systems in transit service. Operating in a heavy corridor through central Lille, it uses relatively small cars on a rubber tire/concrete guideway system. The full operating cost of this system has not been published and staffing levels reported by independent sources differ. Recently CFDT, the French Transit Union, published a comparison between VAL and the Nantes LRT containing current information on the performance of both systems. This information is generally consistent with material from other sources, where available, and has been used as a resource in this paper (*3*). The VAL system is being expanded in Lille, and new systems are under construction in Strasbourg, Toulouse, and at Chicago's O'Hare Airport. The Lille VAL recovers its full operating cost from the farebox.

SkyTrain, in Vancouver, British Columbia, is North America's first major AGT in transit revenue service, and its construction and performance have been extensively documented. Using relatively small vehicles on standard gauge track, it was conspicuously successful at moving large crowds at Expo '86 only a few months after start of revenue service. Under normal ridership since Expo, the system appears to require a rather large operating staff, but continues to perform satisfactorily (*4*). An extension is under construction. Other SkyTrain-type systems are operating in Detroit and Toronto (Scarborough).

Table 1 presents the information collected from the above eight systems, listing primary sources.

TABLE 1 COMPARATIVE STATISTICS

	LRT Systems					AGT Systems		
	Nantes	San Diego	Portland	Calgary	Manila	Docklands	VAL	SkyTrain
Line length (km)	10.6	32.8	24.3	27.7	15.0	12.1	13.5	21.4
Cost (incl. cars) ($ millions)	115.0	150.2	212.0	358.9	157.0	139.0	328.0	615.0
Cost/km ($ millions)	10.8	4.6	8.7	13.0	11.0	11.5	24.3	28.7
Year opened	1985	1981–1986	1986	1981–1987	1985	1987	1983	1986
No. of stations	22	22	28	30	18	15	18	15
No. of cars	20	30	26	83	64	11	76	114
Car size, w × l, m	2.3×28.5	2.65×24.3	2.65×26.8	2.65×24.3		2.65×28	2.06×12.7	2.4×12.7
Max cars/train	1	4	2	3	2	1	4	4
Capacity, seats	58	64	76	64		84	34	40
Standees 4/m^2	112	86	90	86		130	43	35
Total	170	150	166	150		214	77	75
Annual car-km (millions)	0.9	3.3	2.4	5.1			5.9	20.0
Annual board. pass. (millions)	12.0	8.4	7.0	24.3	100±	6.8	27.0	18.0
Annual pass.-km (millions)		105.2						
Max trains scheduled	15	10	11	23	27	9	18	21
Operating staff—total	51	54	48	81		55	103	132
Administration	4	2	4	6[a]		incl.	29	6
Control/supervisors	5	11	11	6		12	28	28
Train operators	42	41	33	69		–	–	–
Other	–	–	–	6		43	46	98
Maintenance staff—total	27	51	55	90		35	87	144
Administration	4	incl.	6	8		3	11	incl.
Vehicles	10	incl.	22	30		32	31	75
Way, power, signals, storage	7	incl.	27	52		incl.	45	69
Fare inspection/security	4	contract	12	30		incl.	incl.	incl.
Other	2	20	–	–		20		42
Total rail staff	78	125	115	207		110[b]	190[c]	318
Rail staff budget ($ millions)	2.1	4.2	4.7	5.7			–	13.2
Materials/service budget ($ millions)	1.5	3.8	1.8	2.0			–	5.9
Total rail budget ($ millions)	3.6	8.0	6.5	7.7			21.9	19.1

NOTE: Data are generally current year, except where stated otherwise.
[a]Calgary does not segregate bus/rail administration. This number is estimated from the other LRT operations.
[b]Docklands staffing is budgeted to increase from 110 to 140 in 1988.
[c]According to *Railway Gazette International* and CFDT (the French transit union) the VAL system also requires 47 "vigiles" for right-of-way security.
SOURCES: Nantes data from Semitan and CFDT. San Diego data from MTDB. Portland data from Tri-Met 1987–1988 budget. Calgary data from Calgary Transit. Manila data from *Modern Tramway*. Docklands data from Docklands Light Railway. VAL data from Matra Transport, CFDT, and Semitan. SkyTrain data from I. Graham and S. Hall, SkyTrain Operating Experience—January 3, 1986 to April 30, 1987, presented at APTA Rapid Transit Conference, 1987.

COMPARISON BETWEEN MODES

The comparison between modes based on real operating statistics is fraught with the potential for confusion, and it is here that the identification of relevant comparative measures is most important. Once relevant comparative measures have been established, then data based on real operating statistics are far more valid than the theoretical projections that must usually suffice in transit planning projects.

A common cause of confusion is the oft-made claim that ridership on a given line is a mode-related attribute rather than a corridor characteristic. Proponents will imply that the SkyTrain or VAL ridership is a consequence of mode choice (*5*). Thus it is interesting to note that the VAL line, serving Lille, a city of 1.06 million, carried 28 million passengers in 1985, while the Lyon Metro, serving a city of 1.1 million with about the same length of line, carried some 62 million (*6*). The Manila LRT, also about the same length, now carries some 100 million passengers a year (*2*).

Nor is the ability to attract off-peak ridership necessarily a modal characteristic, at least when comparing tracked modes. In Portland, the LRT has attracted a midday ridership not experienced on the bus system, and the daily ridership is usually heaviest on Saturdays.

Other factors influencing ridership in a given corridor, such as speed, headway, access time, security, comfort, and system integration, are not necessarily related to mode, except for perhaps headway. One advantage of automatic operation is that the cost to run two one-car trains is much the same as one two-car train (unless on-board attendants are required). It is thus possible to offer reduced headways when to do so with LRT would be considered uneconomical. It should also be noted that several AGT systems operate with a train attendant, thereby losing this potential benefit.

The impact of headway on ridership has been extensively documented elsewhere. Total travel time for a trip plays a significant part in choice of travel mode. Total travel time includes access time, wait time (half the headway), in-vehicle time, and time to exit the system and travel to a destination. Typically, LRT will have reduced access time compared with AGT, but longer wait time, particularly in the off-peak hours. METRO, the Portland metropolitan planning organization, projects a 2 percent change in ridership on the LRT for every 10 percent change in headway. As headway gets smaller, the impact on ridership diminishes.

It should also be noted that in major corridors such as those in which AGT systems are operated, LRT headways would need to be relatively close (4 min or so). At this frequency further headway reduction would produce little additional ridership, the rail transit potential of the corridor having been fully developed. Thus, for purposes of comparison between tracked modes, potential ridership is primarily a corridor characteristic.

Length of line, or more properly, average trip length, is often ignored when comparing productivity between systems. Yet a passenger traveling 10 mi clearly "consumes" more transit in terms of vehicle miles and associated operating and maintenance costs than one who travels half the distance or uses a shuttle. Consideration of passenger totals alone is meaningless when comparing lines of significantly different length.

Another area of potential confusion is in the presentation of capacity. There can't be much confusion about the number of seats in a car, but the number of standee spaces is a function of standee density. Design capacity is usually presented with 4 standees/m^2, but sometimes other units are used without acknowledgment. If this is done, comparative capacity calculations are meaningless (*5*).

It is also important to compare systems representing the most recent and effective applications of the mode on the assumption that those interested in such comparisons are attempting to reach a valid conclusion for their own situation and certainly intend to make effective application of the mode selected. A recently published comparison between VAL and the Lille LRT (*5*) omitted to mention that the Lille LRT was a remnant of an 80-year-old narrow-gauge streetcar system, operated with 28-year-old second-hand cars.

COST OF SERVICE COMPARISON

There is considerable interest in France in the comparative merits of LRT and AGT systems. Several new systems of each type are planned. This topic was the subject of a recent study by the French Transit Union (*3*).

Besides the ancient Lille LRT, with which VAL is often compared by its promoters, there are also in France two new LRT systems, in Nantes and Grenoble. The Nantes system, opened in 1985, operates largely on street right-of-way with few grade separations or preempts, using only single-car trains. Improvements are currently in progress in Nantes to expand the use of preempts at traffic signals and to introduce two-car trains. Current statistics do not reflect these future improvements. Not surprisingly, the Nantes LRT recovers 117 percent of its operating cost from fare revenue (see Table 2).

It should also be noted that VAL's estimated total rail budget cost is very high in proportion to the reported operating staff, which would distort the comparative productivity of the two systems had staffing been used as the sole measure of cost effectiveness. Nor does this comparison screen out the corridor effect. Lille is twice the size of Nantes and would therefore be expected to contain stronger transit corridors.

Although some earlier work (*1*, *7*) had alluded to this situation, the numbers are so clearly at odds with conventional opinion in the transit industry that independent corroboration was sought. The French government

TABLE 2 COMPARISON BETWEEN LILLE VAL AND NANTES LRT

	VAL (AGT)	Nantes (LRT)
Capital cost ($ millions)	328	115
Operating employees	190	78
Length (km)	13.5	10.6
Ridership (millions/year)	27	12
Annual passenger-km (millions)[a]	182	64
Projected budget ($ millions)[b]	21.9	3.6
Capital cost/km ($ millions)	24.3	10.8
Passenger-km/employee (millions)	0.96	0.82
Operating cost per passenger-km (¢)	12.0	5.6

NOTE: Derived from Table 1.
[a]Both systems run suburb to suburb, across the city center, and are likely therefore to have similar trip length characteristics. Because average trip length data are not yet available, this analysis treats each line equally, and assumes average trip length is half the line length.
[b]$1 = 5.71 francs.

TABLE 3 1980 TO 1986 TRANSIT SYSTEM TRENDS IN LILLE AND NANTES (*8*)

	Lille[a]			Nantes[b]		
	1980	1986	Percent	1980	1986	Percent
Total system operating cost (FF million)[c]	188	471	151	116	239	106
Subsidy (FF million)[c]	97	210	116	62	112	81
No. of buses operated	365	402	10	334	365	9
Total system ridership (millions)	51	75	47	44	65	48
Ridership/capita	48	72	50	103	140	36

[a]Opened in 1983.
[b]Opened in 1985.
[c]$1 = FF 5.71.

publishes statistics for the transit industry annually and comparison was made, using these data (*8*), of key indicators for the Lille and Nantes transit systems. These are summarized in Table 3, for the years 1980 and 1986, which bracket the opening of the VAL line and LRT line, respectively.

From Table 3 it can be seen that during the period in which both cities opened rail lines, both experienced similar gains in ridership, but the system operating cost and subsidy grew at a much faster rate in the Lille system. This would support the conclusions from Table 2. All of which begs the question: If Lille had used LRT on the alignment of the VAL system, how cost-effective might it have been?

DIRECT COMPARISON TECHNIQUE

The literature of AGT is sprinkled with assertions that automated operation eliminates operators and therefore reduces operating costs (*9*) and, if a line is largely grade separated, then it "might as well" be automated. The direct comparison technique models AGT and LRT on the identical line, and with identical ridership to test these assertions, using data from actual operating conditions.

The strength of such an analysis technique, when applied to existing systems, is that it uses the maximum of hard data. Each element of the comparison, from system to system, is tied to known conversion factors. Thus the number of cars required to carry a given ridership is known, and hence the number of train operators or car maintenance personnel can be estimated with a high degree of certainty. The direct comparison technique can also screen out the "corridor effect" that hinders the comparison of AGT and LRT on different corridors with different ridership potential.

Two systems for which much information is available, and that are similar in size, are the Vancouver SkyTrain and the Portland LRT. About a third of the Portland system actually operates on a grade-separated right-of-way similar to SkyTrain's at similar speeds. On several occasions, the Portland ridership has reached or exceeded the average daily ridership of SkyTrain. Portland has a centrally located business district. Vancouver is a larger city with its business district on the waterfront and all the suburbs to one side. For this and other primarily nonmodal reasons, the Portland LRT corridor produces less than half the SkyTrain corridor ridership.

Several assumptions are required to simulate LRT operation on the SkyTrain line:

- Peak-hour capacity must be maintained;
- LRT and AGT operate on the same minimum headway of 5 min during the base period;
- Both AGT and LRT operate on the fully grade-separated SkyTrain alignment.

Table 4 develops the Table 1 data to simulate how a grade-separated LRT might perform on the SkyTrain alignment.

While it is possible to debate the minutiae of such calculations, the general conclusion is very clear and makes obvious sense. If you take a line like the Portland LRT, remove all the grade crossings so that it goes faster, and more than double its ridership, it is highly likely to become more productive. In fact, the numbers suggest that, in this corridor at least, LRT would have been

TABLE 4 COMPARISON BETWEEN SKYTRAIN AND LRT OPERATING ON SKYTRAIN CORRIDOR

Line	Existing AGT SkyTrain	Existing LRT in Portland	Conversion Factor	Simulated LRT on SkyTrain
Length (km)	21.4	24.3		21.4
Stations	15	28		15
P.H. trains	20 × 4 cars	11 × 2 cars		14 × 3 cars[a]
P.H. headway	3 min	7 min		5 min
P.H. capacity	5,700	2,656		5,976
Base trains	13 × 4 cars	8 × 2 cars		14 × 2 cars[a]
Base headway	5 min	15 min		5 min
Cars required	100± AGT	26 (LRV)		48 (LRV)
Boarding passengers (millions/year)	18	7		18
Passengers/km (millions/year)	193	85		193
Staff				
Operations				
Administration	6	4		6
Control/supervisors	28	11	P.H. trains	15
Operators	–	33	P.H. trains	43
Field operations	98	–		18[b]
Maintenance				
Administration/finance	42	6.5	cars	12
Vehicles	75	21.5	cars	40
Power	incl.	3.5	length	3
Signals	incl.	2	signaled length	4
Trackway	69	9.5	length × trains	11
Stations	incl.	5.5	pass. × stations	8
Lifts/fare machines	incl.	6.5	passengers	17
Fare inspection	incl.	9	passengers	23
Security	?	3	passengers × 2	15
Contingency[c]	N/A	N/A		22 (10%)
Total staff	318	115		237
1987 budget in $ millions	19.1	6.5		13.4
Passenger-km/employee	0.60	0.74		0.81
Cost/passenger-km	10.0¢	7.6¢		6.9¢

NOTE: Assumes average trip length is half the line length.
[a]LRT includes extra train to allow operator layover time.
[b]Assumes six key stations have an attendant part-time.
[c]Contingency provides additional staff to cover extra off-peak service, and supervision, maintenance, etc., thereof.

a lot more productive than an AGT operation when compared under identical conditions. It is also interesting to note the similarity between this comparison and that between the two French systems in Table 2.

Other measures and comparisons can be developed from the Table 1 data for capital or operating costs measured against various performance indicators. For instance, "break-even" fare, the average fare at which the total rail budget would be met from fares, is shown in Table 5.

TABLE 5 BREAK-EVEN FARES

System	Nantes	San Diego	Portland	Calgary	VAL	SkyTrain
Annual boarding passengers (millions)	12.0	8.4	7.0	24.3	27.0	18.0
Total rail budget ($ millions)	3.6	8.0	6.5	7.7	21.9	19.1
Break-even fare ($)	0.30	0.95	0.93	0.32	0.81	1.06

AN INTERPRETATION

The installation of a simple LRT system in a transit corridor can lead to major gains in productivity compared with bus operations. This is achieved basically because the gain from the six- to eightfold increase in operator productivity is much greater than the added maintenance-of-way and equipment costs, particularly if the LRT system is of simple "no frills" design.

Compared with the productivity gain from the bus/LRT substitution, the potential for further productivity increase by eliminating the operator entirely is much less. In fact there will be no productivity gain if the added costs of supervising the line, trains, and stations, and maintaining the more numerous (small) cars, signals, and safety devices, etc., exceed the cost of the operators displaced on the alternate LRT system. This seems to have occurred on the AGT systems built so far.

Although the technical problems that have attended the first AGTs will probably be solved with time, the factors that hold down productivity are not of a predominantly technical nature. Simple everyday events, such as tripping the car door emergency switch, an almost daily occurrence on the Portland LRT, become a significant operating problem in the absence of on-board personnel. Even a minor delay on a close headway system can quickly become a major problem. Policing the line, supervising grade-separated stations, and maintaining the extra control and safety devices needed for automatic operation are a permanent requirement.

The oft-quoted AGT advantages, such as the ability to add service at short notice or the added ridership attainable with very close headways, may not be worth as much as the higher operating costs required to achieve them. Moreover, these same attributes can probably be attained on an LRT system at less cost (see Table 4).

CONCLUSIONS

Unlike LRT technology, in which no party holds a proprietary interest, AGT systems have been enthusiastically marketed by their developers with glowing claims of efficiency and even profitability. The AGT systems now operating are indeed triumphs of transit technology and reflect great credit on those who brought them into service. However, it appears that requiring fully grade-separated right-of-way and stations, and with higher car and systems costs, total AGT construction cost is invariably higher than that for LRT. As a result, the potential for future extensions is weaker, and a city selecting AGT will tend to have a smaller rapid transit network than a city with LRT. Nor do existing AGT systems operate any more efficiently than conventional, simple LRT systems, particularly if compared on the same quality of alignment.

In addition, being the product of contemporary technology, AGT systems carry with them the probability of obsolescence as technology changes, and the future problem of matching different generations of technology. And finally, being proprietary systems, the AGT owners' future procurement options are more limited, particularly if the manufacturer ceases production.

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PART 2

Policy and Planning Considerations

Issues and Requirements of Real Estate Developers

CHARLES P. ELMS

Real estate developers can virtually make or break mass transit projects. Understanding their perspective, therefore, is critical to any project's success. Experts on real estate development and its relationship to mass transit in Pittsburgh, the District of Columbia, New Jersey, Las Colinas, and San Francisco point to many of the same issues. First and foremost, it must be understood that developers work under considerably greater time pressures than do the public bodies that approve and construct mass transit systems. Second, the uncertainties that have plagued mass transit projects weigh heavily on the thinking of developers, who cannot gamble on a system's being built on an optimistic time schedule or even on a system's working properly once built. Developers are also concerned about funding and financing; a need exists for better working relationships in which public and private entities share the profit and loss of a project. Other developer concerns include coping with the necessary dialogue with public bodies and citizen groups, determining feasibility, competitiveness, access criticality, internal circulation, rights-of-way, aesthetics, costs, and the balance of risks.

IT IS RECOGNIZED THAT transportation and good access are the most important aspects of urban infrastructure on which stable and growing economies depend. Public transit systems play a key role in transportation and access by allowing major activity centers to be less dependent on only one mode of transportation. Moreover, transit conserves the use of prime real estate for greater commercial and economic activity, rather than for storage of automobiles. Early in the 1800s real estate developers used public transit as a means to open up prime lands for development, essentially creating the first suburbs.

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Today the real estate developer continues to be a central player in planning, designing, and funding transit systems. Transit projects that adhere to the needs and interests of the real estate development community will have a better chance of being funded and built. Without the support of this community, a project is almost certainly doomed to failure. Therefore, what leading real estate developers identify as the critical issues they consider when determining to either support or reject a proposed transit project can be vital information. And, given these issues, what are the requirements of real estate developers? It is believed that transit planners and engineers must fully understand the decision processes and vernacular of the real estate industry to plan and design successful projects.

The viewpoints presented in this paper are those of experts (see Acknowledgments) who are leaders in large-scale real estate development throughout the nation or are directly involved in planning or building a transit system in which the real estate interest is highly visible. Each expert outlines key issues and requirements brought to light during the project with which he has had experience in coordinating public transit with real estate development. Then the experts reexamine and rank the key issues and requirements according to importance.

THE VIEW FROM PITTSBURGH AND WASHINGTON, D.C.

By making key locations more accessible, transit increases land values and rents. By mitigating traffic impacts and allowing development to occur, transit can unlock development potential. But transit cannot turn a sow's ear into a silk purse. Transit can influence location decisions within a market, but it cannot generate a market where none exists. This is the essence of the competitiveness issue.

A 1 million-ft^2 office development has been proposed at Three Rivers Stadium in Pittsburgh. Two plans have been offered to the city—one involving a Westinghouse people mover that would connect the stadium to downtown and one without a people mover. Adjustments for phased integration of a people mover were also proposed. Calculating the impact on the project raised the per-square-foot land value more than 50 percent when a people mover was included, as well as proffers for fixed-price construction, provision of a station and guideway within the project, and willingness to participate in a special district that would make annual cash payments to defray operating costs.

The difference in the values offered constituted the value of the transit connection. The site would be developed without the people mover and there is a market without the people mover. The site has tremendous views, plenty of parking, a waterfront park, amazing highway access, and striking visibility, even if it does not have a fixed-guideway link to downtown. But are developers prepared to pay more for the people mover? Yes, and the extra value can be quantified. That value—or increment, the delta—is where the public/private partnership begins.

The impact of transit improvements on land values and development potential will vary depending on the nature of the prior land uses. For example, in Washington, D.C., Metrorail raised downtown land prices near stations about 10 percent. In suburban and secondary market areas, property values have doubled or tripled within just a few years. Don't let the percentages mislead in figuring dollar impacts—$500/ft^2$ land values jumped 10 percent, while $5/ft^2$ land values tripled. The delta in this case is $50 downtown and $10 outside, even though the percentage changes are different.

In order to derive these increments, another factor must be present—project credibility. Few Washington developers were influenced by Metrorail until the system actually began operation. Given all the years most transit projects are talked about and given all the false starts, few developers can place themselves at risk until they see the system built and, in not a few cases, see it working properly. Washington is the hottest real estate market in the country and Metro stops are the hottest locations. However, Metrorail is not creating that market; it is only influencing location decisions within it.

Recently, the Washington Metropolitan Area Transit Authority put out a major joint development site for bid in Prince George's County, Maryland, a growing bedroom community. Although many bids were received, all but one of the five short-listed contenders have withdrawn because they do not believe the market can support Metro's expectations for the site. The message is that even in the hottest market in the United States and with a world-class transportation system, it is possible for planners to exaggerate the benefits of transit on development potential.

Recently, more than 1,300 acres of property were placed under contract in two sites in Virginia, south of Fredericksburg. The hope is to develop the land in a responsible fashion that does not add to the traffic woes of this rapidly growing exurban area on the bow wave of development pushing out from Washington, D.C.

Driving this market is economics—relatively low-priced land and low taxes. If these properties are developed with extensive infrastructure and fixed-guideway transit services to mitigate traffic, there is absolutely no way they can compete against neighboring sites. Although development of these 1,300 acres is planned to address the quality end of the market and utilize new concepts for mixed use communities, the end product must meet the requirements of the marketplace or fail.

The dried bones of visionaries whose projects were ahead of their times—the new towns and the like—are a painful reminder that solutions to difficult transportation problems must still allow competitive developments.

Government, through proper planning, can form a true partnership with developers to prevent the mess often referred to as "suburban mobility problems." One developer with vision and creativity will not be able to reverse the effects of poorly planned, cheap, destructive development fostered by a "y'all come down" attitude toward growth that suddenly reverses 180 degrees when traffic and public service impacts become intolerable.

In order to allow quality development that is supportive of transit and meets the needs of the market, government must have professional and competent land use planning and be willing to invest in the infrastructure required to support desired levels of growth.

In the next sections, views of the Las Colinas, Texas, and New Jersey waterfront developers are aired. These are both prime examples of how this aim can be accomplished. Although Dallas is severely overbuilt, Las Colinas began in a hot market, just as the Jersey waterfront is now. Both areas—New Jersey through public processes and Las Colinas through the vision of private individuals—recognized the need for fixed-guideway transportation to accommodate a projected level of development and incorporated it into comprehensive land use and financing plans. This is the kind of support that responsible developers need to build to the quality end of the market.

THE VIEW FROM THE JERSEY WATERFRONT

The process used by New Jersey Transit and the New Jersey Department of Transportation in negotiations with real estate developers to provide transit for the rapidly developing Hudson River waterfront is described in the next paper in this report, Integrating Light Rail Transit into Development Projects on the Hudson River Waterfront, by Martin E. Robins, Jerome M. Lutin, Alfred H. Harf, Clifford A. Ellis, and Viktoras A. Kirkyla.

From the real estate developer's point of view, the key issues are (1) feasibility and decision making; (2) finance, particularly the public side; (3) schedules and delays; and (4) the degree of certainty.

The real estate developer, from experience, looks at mass transit projects with skepticism. By the time anything happens with the transit system, it may be too late for current real estate plans. Therefore, things must happen more quickly. Perhaps projects should be planned on a more limited scale. For example, the developer cannot build the building before tenant leases are signed. Because tenants are concerned about losing employees when relocating, transportation becomes an important factor. This means that the developer may need to develop interim plans that can fit into the overall longer-term transit project, hence the need for phased development. Actual improvements must occur while future improvements are being planned and implemented.

Vacancy along the Hudson River waterfront is 8 percent, whereas the New Jersey statewide average is 22 percent. While a real estate developer is privately providing additional transportation access, this only underscores the point that public transit does not make the real estate market. There must already be a good market, which transit only enhances.

THE VIEW FROM LAS COLINAS

Las Colinas is a 12,000-acre master-planned development near Dallas. It includes single-family and multifamily residences, four golf courses, recreation facilities, an equestrian center, industrial and commercial business parks, a telecommunication center, film and recording studios, hotels, public schools, a college, and the Las Colinas Urban Center. The Urban Center is a 960-acre central business district of high-rise office buildings and multifamily residence buildings and hotels surrounding a 125-acre artificial lake.

Access to the Urban Center is provided on three levels:

- Lowest—water taxis and a water bus operating on the lake and canals;
- Ground—pedestrian ways and streets; and
- Upper—a fixed-guideway automated transit system called the Area Personal Transit (APT).

The APT was a key element of the Las Colinas master plan as originally conceived in 1967. Access and internal circulation were and are central requirements for the real estate development project. Residents of the Las Colinas Urban Center are provided with a choice of transportation access.

The APT is being planned and built in phases over a 10- to 15-year period. When completed it will include about 25 stations, more than 5 miles of dual-lane elevated guideway, and a fleet of 50 vehicles.

Stations and guideways through each individual site are typically funded by that site developer. Certain stations, guideway across property owned by Dallas County Utility and Reclamation District, public rights-of-way, and the APT operating system itself are funded by the district. The access right-of-way for the system is planned well in advance of land sales and development to ensure proper alignment and station locations. The early commitment is important and reserving the space for the right-of-way is critical or the site developer will be enticed to put something else in the APT's place.

The initial phase, presently under construction and implementation, is a double-lane shuttle over 1½ miles long with four stations. One two-car train will shuttle back and forth on the outside lane while a single car will shuttle on the inside lane. Aesthetics has been a critical issue. The guideways have been designed to present a slender appearance, which blends nicely with a variety of other types of architecture.

Because early commitment is considered the key to success, the maintenance facility was designed and built for future expansion. Also, the central control facility and its consoles include all the provisions for easy expansion. Hence, it is possible to show prospective property owners how the system will accommodate future stations and guideways serving their property.

No local, state, or federal funds are involved in the development and implementation of the Las Colinas APT system. All funding is being provided by the district from tax-exempt bonds repaid through ad valorem taxes from property owners within it.

On its completion and commencement of passenger service, the APT system is expected to become an important catalyst for further development within the Las Colinas Urban Center. While it is difficult to estimate the direct value that the APT system will have to the development, it is believed that the implementation of the system will make the important difference to potential site developers between choosing a site in Las Colinas over those available in other areas of metropolitan Dallas. With each land sale and subsequent construction of improvements comes increased value to the City of Irving and the district. Increased value means increased tax base, which in turn allows both the city and the district to support additional expansion of infrastructure and services to serve the public.

THE VIEW FROM SAN FRANCISCO

When a transportation link is involved in the design of a new building, the architect often serves as the liaison between the developer and the public agency. From an architect's viewpoint, the process between private developers and public agencies takes longer and costs more than anyone would expect. A developer must begin conversations early in the process to avoid cost and schedule overruns. Inherent differences exist between the goals, objectives, resources, needs, and constraints of real estate developers and public bodies, which lead to some fundamental conflicts.

The developer has limited time in which to complete a project or fail to fulfill lease contracts with tenants. Therefore, the developer wants to move fast, whereas the public body traditionally moves more slowly. Limited resources and shorter-term lease contracts also create differences in the quality of design and construction. The developer designs and builds for lifetimes that are consistent with reasonable periods to recoup investments and make a reasonable profit. These lifetimes are short term. In contrast, the public body designs and builds transit systems to last forever.

The developer is usually under serious time constraints. More time spent on delays translates into more interest (or least payments) paid out. As public agencies run out of money, they look to the developer for more and different kinds of fees. However, it is not only the fees that cost money. Public agencies usually require developers to maintain a dialogue with technical, financial, and community relations departments. Coordinating with the various departments can be frustrating and time consuming if it is not done carefully. For example, developers frequently work with few data and make decisions without the benefit of detailed studies. Public agencies usually require too much detailed information, much of which is less than relevant to the project. Citizen groups are also an important third force that must be brought to the table. The architect can help to mediate disputes between this diverse set of public groups and the developer.

In summary, there is need for realism in determining time schedules and budgets. The developer is working within a very specific time frame and budget. Therefore, in the beginning the worst-case schedule and budget should be identified. Feasibility in the eyes of the real estate developer must be decided on this worst case.

IDENTIFICATION AND RANKING OF KEY ISSUES

When the real estate development experts were asked to identify important issues, they ranked them as follows:

- Schedules and delays—Differences exist in the time frames of projects. Developers work in the short term; public bodies work in the long term.
- Certainties and uncertainties
- Funding and finance—The need exists for a mechanism to form better working relationships in which the public and private bodies share in the profit and loss of a project.
- Dialogue
- Determining feasibility and making decisions
- The public need to be evenhanded
- Project competitiveness
- Access criticality by mode (automobile, transit, pedestrian)
- Internal circulation
- Access rights-of-way and alignments
- Aesthetics and image

- Costs and fees
- Balance of risks

ACKNOWLEDGMENTS

This paper was developed from presentations by, and a panel discussion among, Morton Goldfein, Secaucus, N.J. ("The View from the Jersey Waterfront"); Stanford W. Lynch, Irving, Tex. ("The View from Las Colinas"); and Piero Patri, San Francisco, Calif. ("The View from San Francisco"). Jeffrey A. Parker, Washington, D.C. ("The View from Pittsburgh and Washington"), was unable to attend the conference but submitted his views in writing. Joseph Martin and Jerome M. Lutin, both from Hoboken, N.J., however, were on hand to present papers and participate in the discussion. Their views are presented elsewhere in this report.

Integrating Light Rail Transit into Development Projects on the Hudson River Waterfront

MARTIN E. ROBINS, JEROME M. LUTIN, ALFRED H. HARF, CLIFFORD A. ELLIS, AND VIKTORAS A. KIRKYLA

The New Jersey Department of Transportation (NJDOT), in cooperation with NJ Transit, recently completed a conceptual engineering study for a combined bus/light rail transit (LRT) system on the Hudson River waterfront in Hudson and Bergen counties. The project is unique in that the area is undergoing rapid redevelopment. The pace of development is so fast that NJ Transit was faced with the possible loss of desperately needed transportation rights-of-way if quick action was not taken. In addition, the environmental permit review process required for waterfront development in New Jersey offered the opportunity for the state to dedicate transit easements and require developers to provide these easements as a mitigation measure for the heavy traffic congestion that development is expected to cause. To take advantage of this opportunity, NJDOT entered into negotiations with developers. Because this process began before completion of an UMTA alternatives analysis and draft environmental impact statement, several bus and LRT modes had to be considered in formulating easement agreements so as not to preclude future federal funding. Because developers retained air rights above the easements, NJDOT and NJ Transit had to provide information to developers and approve air rights construction without a final transitway design in place. The process used to define the appropriate easement envelopes and negotiate transit easements with developers is described.

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REAL ESTATE DEVELOPERS OPERATE in a risky, highly competitive world where fortunes can be made or lost in an instant. To be successful they must quickly find and seize development opportunities; acquire parcels and assemble sites; deal with architects, engineers, and municipal officials; locate prospective tenants; market their projects; and raise capital to make development a reality. They must alternate between total secrecy, to prevent a competitor from getting an edge, and total hype, to convince prospective financiers and tenants that today's barren, rubble-strewn site will be tomorrow's shining waterfront. To real estate developers, time is always of the essence. Delays can mean lost tenants, heavy finance costs, lost profit, and forfeited opportunities.

When a transportation agency proposes a new transportation system directly through a developer's property, extreme reactions seem to occur. If a developer has a serious access problem and site development plans are not too far along, he or she may welcome the proposal. No one is asking for money yet and the site, on which the developer may hold only an option, is not a major liability or negative cash-flow generator. The developer may see the transportation system as a boon to the project. Perhaps it is the solution to access problems, a possible source of government funds for the project, or a good source of publicity. Most often, the transportation agency receives a different kind of reaction, a negative one.

On learning of the proposal, the developer may object, protesting that transit is something not necessary or desirable or worthy of discussion. The developer may view transit as a design constraint, a consumer of valuable land, out of keeping with the aesthetics of the project, or, most important, something that will cost money and keep the project from moving forward. The further along the developer's plans are, the stronger is the objection. Many decisions have been made, space requirements have been calculated, and much has been spent on architect and engineer design fees. Redoing plans to accommodate transit is an expense that the developer had not anticipated.

Thus, it is often an inhospitable environment in which the transportation planner begins negotiations with developers. The process may be long and fraught with difficulties, but offers much to transit system designers to justify the time and the effort.

WATERFRONT DEVELOPMENT ENVIRONMENT

New Jersey's Hudson River waterfront spans eight municipalities and 17 mi along the Hudson River across from Manhattan. Until the late 1950s, it was the site of major maritime commerce and housed large freight and passenger railroad terminals and yards for as many as nine major competing railroads. Over the last 30 years, much of the rail freight traffic has been diverted to trucks and other modes, driving most of the railroads into bankruptcy and leaving the rail yards and warehouses abandoned and deteriorating on the waterfront.

In recent years, booming growth in the financial and service industries in the metropolitan New York/New Jersey area led to major building expansions and a demand for more office space and housing units. Developers began to acquire and assemble large tracts of former railroad land on the waterfront with magnificent views of the Manhattan skyline. Development was aided by local municipalities eager to replace jobs and residents lost to the decline in manufacturing, maritime, and railroad activities. Developers received municipal tax abatements and, in some cases, grants to promote redevelopment. In all, about 35 million ft^2 of new office space, 36,000 new dwelling units, and 3.2 million ft^2 of retail space as well as marinas, hotels, restaurants, and major tourist attractions are being promoted for the New Jersey waterfront.

Recently, the Newport Development Company in Jersey City opened a 1 million-ft^2 shopping mall and four high-rise apartment buildings. Owned by two of the largest developers in the country, Newport will eventually build 4.3 million ft^2 of office space, 9,000 dwelling units, 1.5 million ft^2 of retail space, a hotel, a marina, and possibly an aquarium. The 400-acre site, formerly an Erie Railroad (later Erie Lackawanna, then Conrail) yard, is located astride the Holland Tunnel, one of three vehicular crossings between Manhattan and New Jersey. Development of Newport was aided by a federal Housing and Urban Development (HUD) block grant, and other considerations from state and local governments. The multiuse Newport project, in the heart of the waterfront project area, is typical of the developments through which the state is seeking to preserve a transit corridor.

WATERFRONT TRANSPORTATION PLAN

Planning for the Hudson River waterfront transportation needs began in 1984 and culminated in the preparation of a draft transportation plan. Released by the governor of New Jersey in 1985, the plan identified a need for a north-south transportation corridor to support the economic revitalization of Hudson County. Because developers were proposing to consume most of the developable land and seeking site plan approvals, the New Jersey Department of Transportation (NJDOT) and NJ Transit recognized the need to act quickly to preserve right-of-way for a transit corridor.

A conceptual engineering study was commissioned in 1985 to define alternative alignments and physical layout concepts for the corridor. These alignments and design concepts were to serve as the basis for:

- Determining right-of-way requirements,
- Discussing easements with developers,
- Defining the scope of the system as a basis for budgeting, and
- Providing input for environmental studies.

The conceptual engineering study developed plans, profiles, and typical sections for the transportation system. Working papers were produced documenting alternative alignments, design criteria, and cost estimates.

The overall transportation plan for the Hudson River waterfront is shown in Figure 1. Included in the plan are an 11-mi Waterfront Boulevard (a four-lane arterial roadway) and 9 mi of exclusive busway (including a connection to the Lincoln Tunnel and the Port Authority Bus Terminal in Manhattan to serve trans-Hudson commuters). Also included is a waterfront transit spine, currently conceived as a 13-mi light rail transit (LRT) line, collocated with the busway for 6 mi north of Hoboken Terminal. The portions of the system jointly used by bus and LRT are termed "transitway" in Figure 1.

North of Hoboken, the system would be located largely on or adjacent to an existing railroad right-of-way slated for acquisition by the state. South of Hoboken, the transit spine system would be located largely on land owned by developers. Figure 2 shows the extent of system right-of-way on or adjacent to major development projects.

PRESERVATION OF OPTIONS

The waterfront transportation plan examined a number of modes for the waterfront transitway spine and settled on LRT as a logical candidate to serve as a benchmark for concept development. However, it was recognized that the transit mode would be selected on the basis of cost-effectiveness and other criteria. For example, if development buildouts fall short of forecasts and travel demand is reduced, buses may be more cost-effective than LRT.

For this reason, design criteria were drawn up that would permit deployment of bus and/or LRT. Figures 3 through 7 show typical sections for the LRT and busway technologies that are being considered. The typical sections and the corresponding space requirement for the transit elements were developed on the basis of vehicle characteristics and operating conditions that established the preliminary design criteria for the system. The criteria are quite general at this time in order to encompass a broad range of options for vehicles and operating conditions. The design elements used for the LRT and bus technologies are shown in Tables 1 through 3. These criteria were developed by the consultant as part of the conceptual engineering study.

In general the criteria for LRT govern such items as curvature, grades, and station lengths (based on providing for a three-car LRT consist). The width of

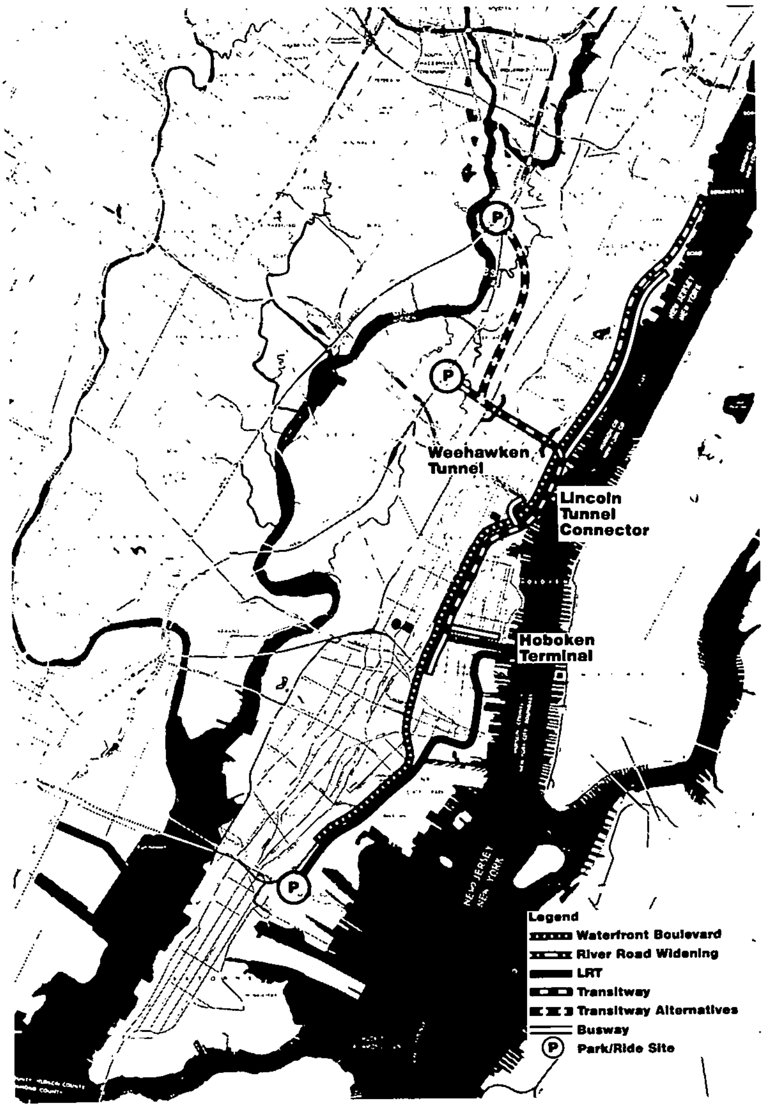

FIGURE 1 Transportation plan for Hudson River waterfront.

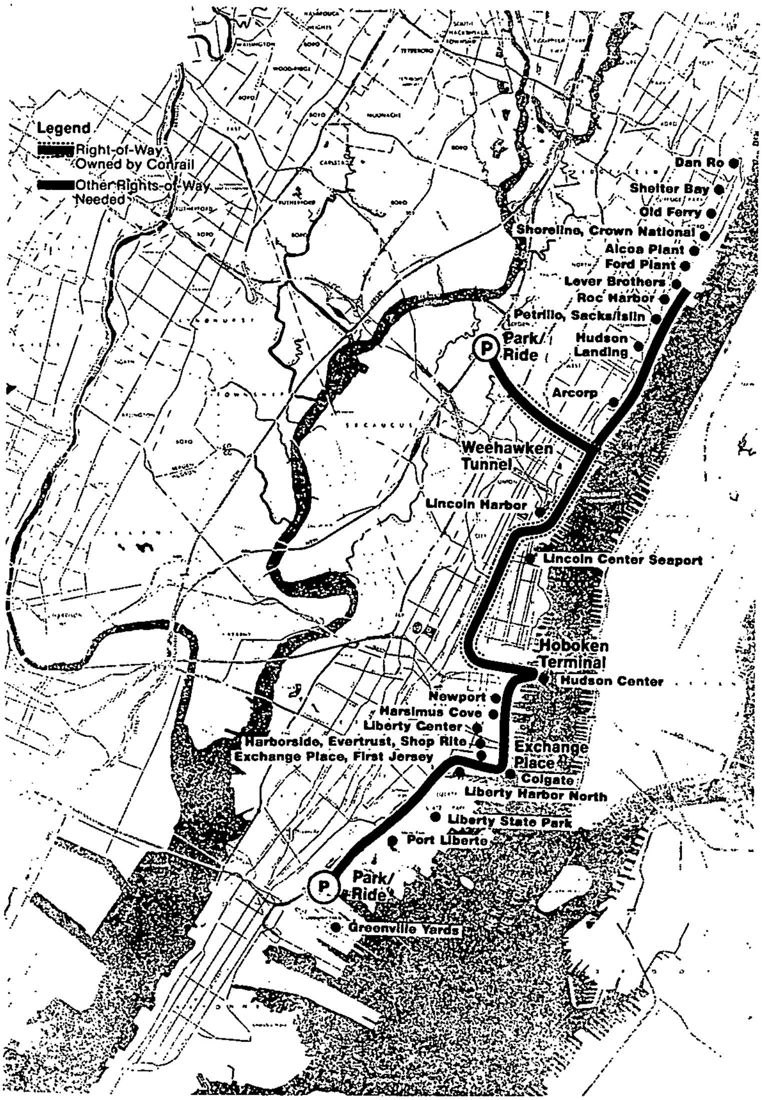

FIGURE 2 Waterfront transitway system.

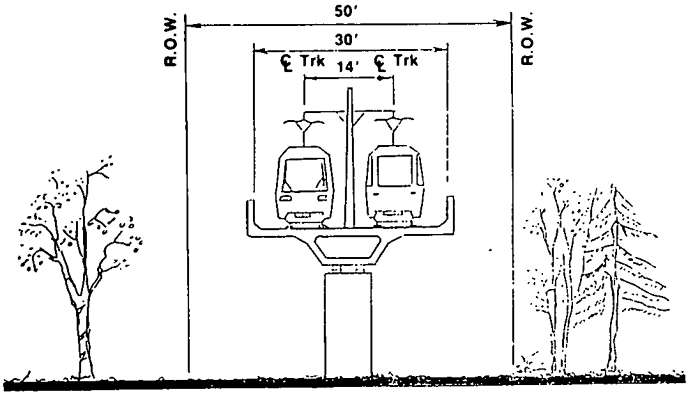

FIGURE 3 Typical section for LRT on structure.

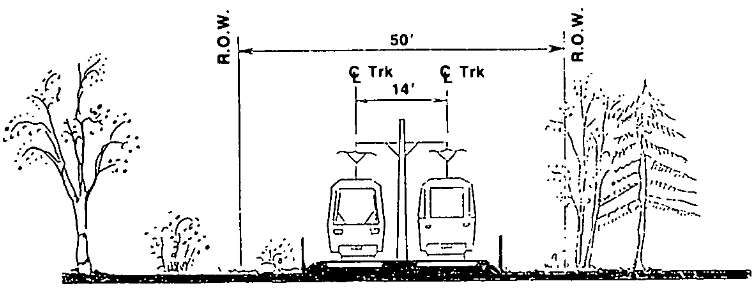

FIGURE 4 Typical section for LRT in separate right-of-way.

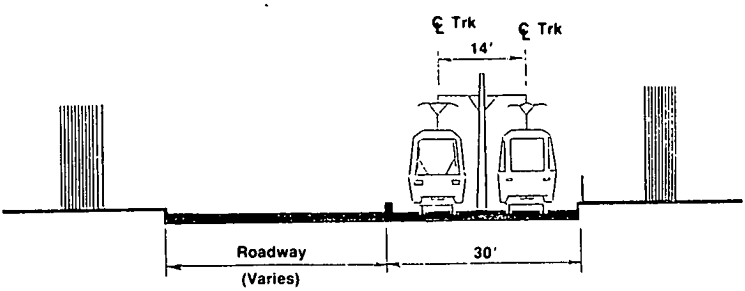

FIGURE 5 Typical section for in-street, two-direction LRT.

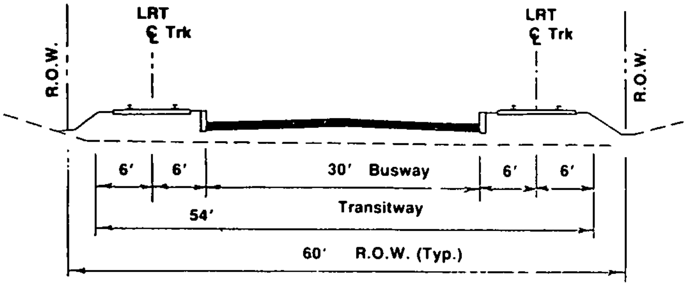

FIGURE 6 Typical section for transitway.

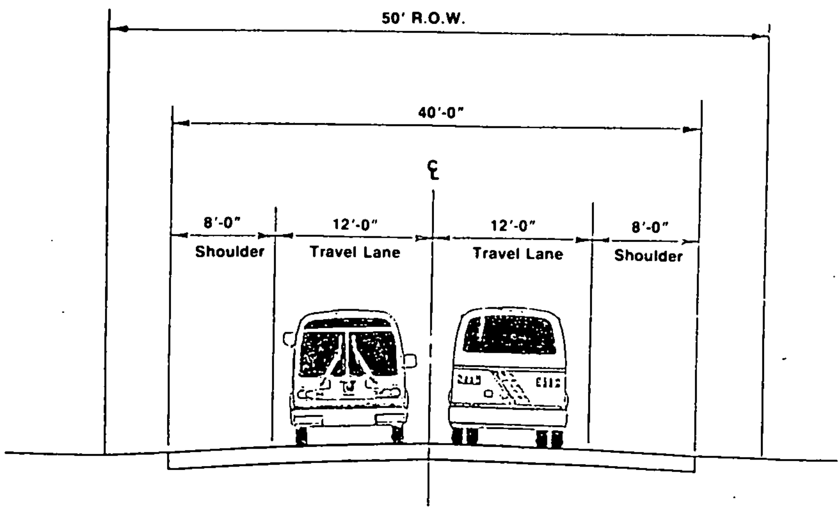

FIGURE 7 Typical section for at-grade busway.

some stations, however, is governed by bus operating requirements since bypass lanes may be needed for express buses.

TRANSIT EASEMENTS

Based on the needs for operating, maintaining, and constructing the transit system, rights-of-way and easements were defined in terms of horizontal and vertical space requirements. The easements include the following:

- The permanent operating easement will provide for the necessary clearances, drainage, and utilities. It will be 50 ft wide and 18 ft high in the areas

TABLE 1 LIGHT RAIL DESIGN ELEMENTS

Criterion	Description
Vehicles	
Dimensions	
Length (ft)	89 (max.)
Width (ft)	8–10
Height (with pantograph at lowest operating height) (ft)	13
Operating speed[a] (mph)	15–35
Passenger capacity	
Seated	73
Standing (normal/crush)	115/144
Doors (double) (no. and location on vehicle)	Four on each side
Fare collection[b]	
Major station	Off vehicle
Minor station	On vehicle
Guideways	
Operating speed (mph)	15–35
Horizontal clearance (from track centerline)	
From obstructions (ft)	7.5 (min.)
Between tracks (at-grade) (ft)	13.0 (min.)
Vertical clearance (from top of rail)	
Mixed traffic (ft)	18.0 (min.)
Exclusive right-of-way (ft)	18.0 (min.)
Alignment (mainline track)	
Horizontal radius (ft)	400 (min. desirable)[c]
Vertical grade (%)	4 (max. desirable)
Stations	
Platform length (ft)	300
Side platform width (ft)	10 (min.)

[a]Vehicles capable of 55 mph maximum under appropriate operating conditions.
[b]A "proof of payment" system is also being considered to allow patrons to purchase tickets at stations and present them on demand to roving inspectors.
[c]Minimum allowable radius of 100 ft in yards and under extreme conditions.

where the transitway is at ground level. To the extent that the easement is elevated, it will not be more than 38 ft from the ground, nor more than 18 ft above the running surface of the transitway.

• The permanent maintenance easement will be 10 ft wide and located on the same side of the permanent operating easement from street intersection to street intersection. A developer may locate a service road on the permanent maintenance easement, which will not exceed the height of the adjacent permanent operating easement.

• The temporary construction easement will be located parallel and adjacent to the permanent operating easement on the side that the developer designates, as long as all portions of the easement are located in a manner that is reasonably usable. In those areas where the transitway is to be elevated, the

TABLE 2 BUS DESIGN ELEMENT: VEHICLES

Criterion	Description Transit	MCI Commuter	Articulated
Dimension			
Length (ft)	40	40	60
Width (in.)	96 or 102	96	96 or 102
Height (in.)	120	144	129
Turning radius			
Outside (ft/in.)	43 10	50 7	39 6[a]
Inside (ft/in.)	37 3	27 9	21 4
Top speed (mph)	60	70	70
Passenger capacity			
Seated	47	47	67 or 64
Standing	23	19	32
Axles	Two	Three	Three
Doors	Two	One	Two or three
Fare collection	On board	On board	On board

[a]Can sweep an additional 11 ft 4 in.

TABLE 3 BUS DESIGN ELEMENTS: GUIDEWAYS

Criterion	Description
Maximum speed (mph)	55
Operating speed (mph)	15–45
Horizontal clearance (ft)	
Travel lane	12
Shoulder lane	3.75
Vertical clearance (ft)	15.5
Maximum vertical grade (%)	
Travel lane	6
Ramp	8

temporary construction easement will be 40 ft wide (measured from the adjacent edge of the permanent operating easement). In those areas where the transitway is to be at grade, the temporary construction easement will be 30 ft wide. The temporary construction easement will not exceed the height of the adjacent permanent operating and permanent maintenance easements.

Based on the established design criteria and the requirements imposed by the uses of the easements described above, a set of review guidelines was prepared. The objective of the review guidelines was to provide a mechanism for a mutual understanding with the developers of the potential impacts of the transit system on the planned development and of the development on the transit system. Because in most instances the development will be completed before the transit system is constructed, negotiations with the developers must be held to accommodate the needs of the transit system, including such items as:

- Provisions for stations,
- Pedestrian access and circulation,
- Foundations for transit structures,
- Utilities, and
- Power substations, signals, and communications.

The review guidelines covered a number of items, including access, clearances, sight lines, structures, buildings, utilities, mechanical systems, fire protection, traction power, communications, and ventilation.

DEVELOPER NEGOTIATIONS

Land use decisions in New Jersey lie mainly with municipal governments. With eight municipalities on the Hudson River waterfront, development approvals were based primarily on the expected benefits and impacts on the host community with little consideration for effects on the region. In the absence of an adopted regional transportation plan, site plan reviews considered only local roadway improvements and parking/floorspace ratios. In some cases, developers proposed improvements to existing transit—such as station and pedestrian facility enhancements—and, in one case, even a new bus garage to justify reductions in expected automobile traffic.

Until the state-sponsored waterfront transportation study, no one had collectively assessed the traffic impacts of all waterfront development on the regional highway system. Once that traffic assessment was made, it became apparent that the already congested waterfront roadways would be gridlocked by development-generated traffic by the year 2000. Additional transportation capacity would be needed.

The waterfront transportation draft plan was released in November 1985. That plan stressed mass transit as the main element in the solution to the waterfront traffic problem. By distributing the plan the NJDOT brought a regional perspective to solving traffic problems created by development of the waterfront.

In recent years New Jersey has become increasingly involved in regulating waterfront development. Under state statutes, the Department of Environmental Protection (NJDEP), Division of Coastal Resources, is empowered to review and approve permit applications for major waterfront developments.

As part of that review, NJDEP studies the environmental impact of proposed development, including new traffic generation. NJDEP is aided in the traffic review by the NJDOT. It was NJDOT's involvement that led to the requirement that waterfront developers provide easements for the LRT spine through their properties as a means of mitigating traffic impacts.

In some waterfront locales, municipal and county planning and engineering staffs have also begun to require provision of the LRT easements as a condition for site plan approval. Thus, it is the regulatory powers of state and local governments that are being used to gain developer participation in the transit project.

Developers of large projects who had already retained traffic consultants also began to understand the benefits that transit could bring to their projects. First, the provision of an LRT system gave them an opportunity to reduce parking requirements. In most instances, developers proposed a parking ratio of 1 space/1,000 ft^2 of commercial development, far less than the 4 spaces typically required by local zoning. By arguing that LRT would carry a large share of their traffic, developers were able to convince local zoning and planning boards that parking could be reduced at considerable savings to their projects.

Second, developers were able to use the projected diversion of automobile trips to LRT as a means to lessen the expected traffic impact on local streets. This also led to cost savings in both on-site and off-site roadway improvements that otherwise might have been mandated by local officials. Third, it was recognized that air rights development was possible above the easements granted for the LRT line and stations. Thus, the actual loss in developable land was reduced. When coupled with the reduction in parking, this gave developers more buildable space.

NEGOTIATION PROCESS

An initial meeting was held with developers to brief them on the LRT project and obtain site plans for the proposed development project. These initial meetings produced the kind of mixed reactions mentioned earlier. Because of the regulatory process, however, developers were willing to continue negotiations to expedite approval of their waterfront permits.

A series of meetings was necessary to define the alignments needed for an ultimate agreement. It was useful to work from an array of alternatives towards a consensus on a preferred alignment. Frequently there were several alignment options that worked reasonably well from a transit perspective. Rarely was there only one alignment alternative available. Alignment negotiations were conducted primarily with the architectural consultants for the developers, but developers often brought their attorneys as well.

Once an understanding was reached on the physical alignment for the LRT, it was necessary to formalize the agreement. This, in its ultimate form, would constitute a deed of easement for the transit right-of-way. In the time available, however, neither the LRT system planners nor the developers had enough data to define the easement with the precision needed for a metes and bounds description. The LRT planners needed to keep open technology options and grade separation options, whereas developers were often redesigning their plans to reflect changes in the market. Both sides felt the need to reach an agreement quickly, but still retain some flexibility.

Consequently, an agreement for grant of easements was used as the instrument to preserve the right-of-way prior to the actual grant of easement. This document established a preliminary LRT easement shown on a 1 in.:100 ft scale development site plan. The preliminary easement was shown to scale in the approximate location without benefit of a survey, but within the accuracy available at that scale.

The developers wished to continue with development in the vicinity of the preliminary LRT alignment, so a review zone was established to provide NJ Transit the right to review and approve any development plans within a specific distance from the centerline of the preliminary easement path. This distance varied depending on the level of accuracy of the developer's plans available at the time the agreement was signed. A multiyear period was established for finalizing the actual easement so the plan could be developed in segments. Currently, work is progressing on 30 scale drawings to develop the easement. Several proposed building plans are under review by the state.

KEY ISSUES

Some decided developer preferences were observed in the negotiations process. They were far more supportive of LRT than of bus technology. They preferred midblock or roadway median alignments to roadside alignments. Midblock alignments seemed to be preferred by developers who did not view the system as aesthetically pleasing. Mostly, they preferred LRT alignments that traversed the commercial, rather than residential, portions of their sites. They worried about the aesthetics of the system and its impact on marketability of residential units. Their desire for rectangular building parcels led to pressure for sharper turns than denoted in the design guidelines.

Traffic and building access proved to be an important consideration. In one instance, the alignment preferred by the developer required crossing a busy street. Analysis by his traffic engineer indicated the probable need for a grade separation. The issue was settled when the developer agreed to share the additional costs of the grade separation structure.

CONCLUSION

Dealing with developers requires a combination of firmness and flexibility. In New Jersey, the power of the state to regulate waterfront development got the developers to the negotiating table and paved the way for the granting of no-cost easements for LRT. At the same time, it was necessary to create a "win-win" atmosphere for negotiations. The developers needed to see that good transit benefited them in a way that affected their bottom line positively. Through the use of the preliminary easement path, it was possible to reach agreement quickly on locating LRT on development sites, deferring the expensive and time-consuming surveys and engineering. The process of defining the easements for the Hudson River waterfront transit system continues, but it is believed that the methods discussed herein will continue to be successful in obtaining a transitway alignment at relatively little or no cost to the state.

Development and Implementation of Greater Manchester's Light Rail Transit

A. P. YOUNG

Greater Manchester will soon be constructing the first new-generation light rail transit (LRT) line to involve street operation in Great Britain. The 31-km first-phase system makes extensive use of existing suburban railway infrastructure, and provides new highway-based links across the city center. This paper describes the background of the project, the options considered, and the development of the present scheme through a period of major administrative and regulatory change. A 3-week demonstration of a light rail vehicle, sponsored by manufacturers, strengthened support for LRT, and government approval has now been obtained to proceed to tender stage. Private sector involvement in funding and operation is to be sought. Conclusions are drawn on the approach needed to advance a cost-effective LRT project.

COMPARED WITH OTHER EUROPEAN countries, the United Kingdom has until recently neglected light rail transit (LRT) as an urban transit mode. Now the scene is changing rapidly. In 1980 Tyne and Wear Metro in Newcastle upon Tyne brought light rail technology to Britain, and the automated London Docklands Light Railway took developments a step further in 1987. Both are fully segregated high-platform systems.

The next system will almost certainly be in Manchester, and will exploit fully the flexibility of LRT, including on-street operation. The Greater Manchester project developed in a potentially hostile environment—the Metropolitan County Council had been abolished and bus services had been deregulated. By mid-1988, however, it is anticipated that the pre-tender stage will be under way.

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BACKGROUND

Greater Manchester is a conurbation of 2.6 million people in the industrial Northwest of England (Figure 1). It boasts the world's first passenger railway station (Liverpool Road in Manchester), opened in 1830 on the Liverpool and Manchester Railway and now surrounded by a thriving museum complex. Manchester's railway industries once exported locomotives and components to many parts of the world. The historic major industries of coal, cotton, and heavy engineering have declined and been replaced by new, higher-technology industries. But local companies still make a significant contribution to railways, with GEC supplying electric traction equipment; Whipp & Bourne, dc switchgear; and Davies & Metcalfe, brake equipment.

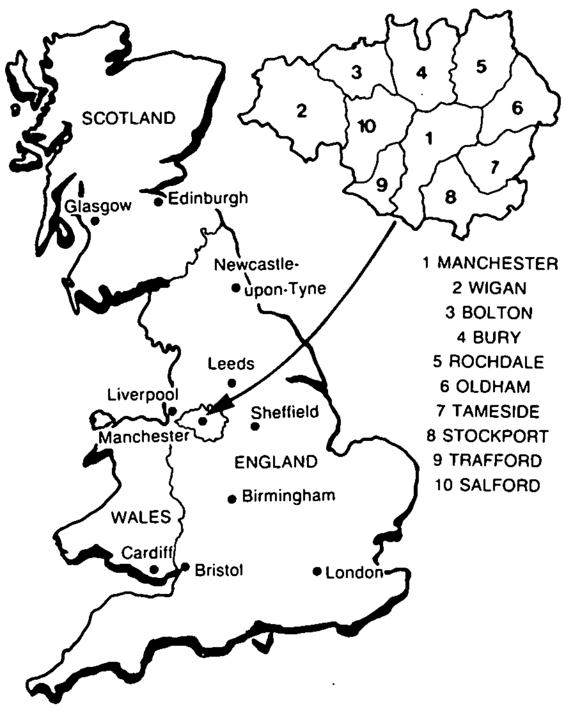

FIGURE 1 Greater Manchester location plan.

About 350 million passenger-journeys per annum are made on public transport, all but 25 million on the extensive bus network. The rest are rail journeys on the 16 radial commuter lines operated by British Rail (BR) under an agency agreement with the Passenger Transport Executive (PTE). The

PTE was set up in 1969 to plan, operate, and coordinate all transit services in the metropolitan county, but since deregulation in October 1986 it has ceased to operate buses and become primarily a planning and financing body.

The rail network suffered from lack of investment in rolling stock and infrastructure, and from having four different traction systems (25 kv ac, 1,500 dc OH, 1,200 dc third rail, and diesel). But the major problems were poor accessibility to the central business district (CBD) and the lack of any north-south cross-city rail link. The rail network was in two virtually separate halves, one north and one south. Five stations, including two intercity terminals, serve the CBD but all are on the periphery (see Figure 2).

The first proposal to build a cross-city rail tunnel between Piccadilly and Victoria was made in 1839. An amazing array of alternative solutions was proposed over the next century, including underground railways, streetcar

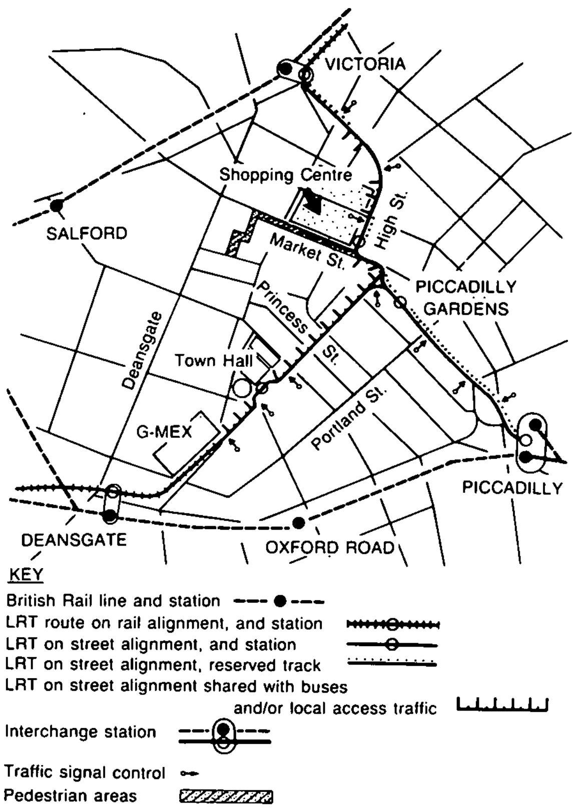

FIGURE 2 Manchester City Centre—existing British Rail lines and proposed LRT lines.

tunnels, monorails, and busways. None was ever built. In the 1970s the "Picc-Vic" tunnel was designed to link suburban lines north and south, similar to Philadelphia's Center City Commuter Tunnel. But even though it obtained parliamentary approval, funding was denied and the tunnel plans were scrapped in 1977.

Then in 1982 the Greater Manchester Metropolitan County Council (GMC), which was responsible for all strategic highways, planning, and transportation policies, decided to set up a joint study team with the PTE and BR. The main objective was to find a sensible and practicable solution to the rail network problems, bearing in mind the likely shortage of capital funds, and the £18 million (U.S. $31 million) annual operating subsidy being paid to BR.

OPTIONS CONSIDERED

The study brief was wide. Any reasonable solution was to be examined, including those previously discarded. Two categories were considered, namely "conventional" solutions based on the existing commuter rail technology and "unconventional" solutions embracing everything else, including light rail transit (LRT) and busway. In addition two base cases were defined, against which any option could be tested. The first base was the existing rail system and the second was a no-rail base, or all-bus solution. The latter was required by the government's Department of Transport (DTp), which insisted that each existing rail line be justified, let alone any investment in new lines. Each investment option entailed the use of existing BR suburban alignments and the creation of new cross-city center links. Existing track and signaling would be used if appropriate, and some traction power supply equipment could be reused, but not rolling stock.

The "conventional" rail options included the Picc-Vic tunnel and some lower-cost commuter rail tunnel alignments through the city center. These had been well studied and documented previously. To operate any unconventional system, it would be necessary to segregate movements from any BR operation, whether intercity, provincial passenger, or freight. Therefore the first exercise was to examine each local rail service to see if it could be segregated from the BR network. It was found that five existing local passenger lines could be segregated, including two of the busiest, together with a former passenger line that closed in the 1960s but that passes through a dense residential area. This made six lines that conveniently approached the city center at three key locations, Victoria Station in the north, Piccadilly Station in the southeast, and the former Central Station in the southwest. Various routes linking these three points were considered in tunnel or on the surface, depending on the mode. LRT was the only mode that could operate at either level because other rail modes cannot operate on-street and buses in tunnel were not considered acceptable.

At the first assessment, all system options that were not fully developed and proven in urban transit service were eliminated, together with all fully automated driverless systems. The latter were not deemed appropriate for the types of existing rights-of-way, or for an area with very high unemployment. Thus all forms of monorail, and the VAL, Transit Expressway, and UTDC/ICTS systems were discounted.

The short list of potential unconventional systems then consisted of LRT with tunnel links, LRT with surface links, busway, and guided busway. These were the subject of feasibility studies carried out by consultant engineers Mott, Hay, and Anderson to assess their technical advantages and disadvantages and their capital costs (*1*). In parallel, transportation study modeling was undertaken to assess their effects on patronage and passenger benefits.

Table 1 gives some of the initial findings. It was apparent that all the options would attract similar levels of patronage, although the figure for LRT with tunnel links was slightly higher. Capital costs varied much more widely, however, with LRT with surface links having the lowest cost. It seemed likely, therefore, that LRT would offer the best value for the money.

TABLE 1 RESULTS OF FEASIBILITY STUDY AND INITIAL SCHEME TESTS

	Capital Costs (£ millions Nov. 1982)			
Option	Fixed Facilities	Rolling Stock	Total	Forecast Peak Period Patronage
Conventional rail in tunnel	136.4	19.5	155.9	11,350
LRT with surface links	47.9	37.6	85.5	11,450
LRT with tunnel links	65.9	37.6	103.5	12,050
Busway	92.0	16.0	108.0	11,350
Guided busway	110.5	17.0	127.5	11,350

This conclusion was confirmed by further economic appraisal. The detailed cost/benefit evaluation then concentrated on comparing LRT with the existing rail base and also with the no-rail base. This showed a very strong case for retaining rail services. The benefit of LRT over existing rail, i.e., its marginal benefit, was less strong but still significant. Based on the results of these studies, the GMC unanimously agreed to proceed with the LRT option, to seek parliamentary powers for the key city center links, and to seek government grant aid for construction.

SYSTEMS PLANNING

The proposed LRT network was not developed in isolation, but in close cooperation with BR, taking account of their plans to develop their intercity and provincial passenger services. BR had already decided to develop Manchester's Piccadilly Station as their intercity hub and remove the remaining intercity trains from Victoria. Thus the overall rail strategy for the county included some short new BR rail links and a spur line to serve Manchester's rapidly expanding international airport (2). The airport link still awaits government approval, but the other new links are already in service.

The LRT feasibility studies identified a 100-km six-line network (see Figure 3) comprising three cross-city routes. Although the total estimated cost of this network was extremely modest by American standards, less than £100 million (U.S. $175 million) at 1982 prices, it was clear that the government would not entertain a grant application for the whole network as had been the case with the Tyne and Wear Metro. Despite its obvious success, the Metro was still regarded in official financial circles as extravagant and not to be repeated. Tyne and Wear Metro cost £248 million for a 55-km network, but this included some major civil engineering construction, including bridges, tunnels, and viaducts.

A first-phase system was therefore defined, taking in the two most promising commuter lines, those from Manchester to Altrincham and to Bury, and

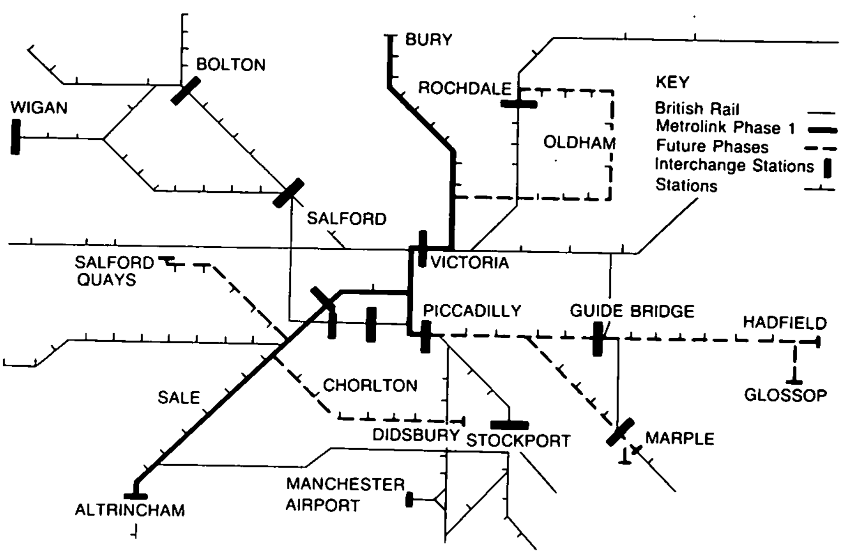

FIGURE 3 Greater Manchester's British Rail and LRT lines circa 2000.

the 3-km section of new surface tracks across the city center, mainly on-street but with some private right-of-way. Some sections will be shared with buses and others with mixed traffic. This phase 1 system totals 31 km and is estimated to cost £43 million at 1986 prices, including rolling stock (35 cars), power supply, signaling, and control. Existing BR track (25 km) and stations can be used, with minor modifications. At present the Altrincham and Bury lines carry 6 million passengers per annum. It is estimated that this will increase to 10 million on conversion to LRT. For the past 3 years the main effort has gone into advancing phase 1.

For any new section of railway in Britain, parliamentary powers are required. A first parliamentary bill was deposited in November 1984 seeking powers to construct the city center sections. Legislation referring to street tramways had not been seen in Parliament for some 40 years, and one aim of this bill was to test the waters in Parliament as well as in Manchester. A second bill was deposited in November 1985 seeking the remaining powers needed to complete the phase 1 system, including various works on the Altrincham and Bury lines (*3*).

These two bills created remarkably little opposition and achieved almost unanimous political support across party lines. Extensive public consultation during the options study proved worthwhile. The bills passed through the House of Lords and House of Commons committee stages unopposed, but progress was still rather slow. By late 1987 they were in the final stages.

Obtaining parliamentary powers is relatively simple compared with obtaining grant approval. This is because parliamentary procedures are clearly documented in standing orders, but there are no comparable rules for government grants. An application to the Department of Transport was made in July 1985 for a 50 percent capital grant for phase 1 construction, together with the necessary borrowing powers to enable the GMC in its role as Passenger Transport Authority to fund the remaining 50 percent (*4*). This started a long and thorough scrutiny of all the assumptions and estimates made in the economic and financial evaluations.

ABOLITION AND DEREGULATION

By then two major changes had appeared on the horizon, neither of which could have been foreseen at the time of the initial studies. First, the metropolitan county councils were to be abolished nationwide by the government. Second, bus services were to be deregulated and privatized and the PTE was to be reduced to the role of a planning and financing agency, losing its fleet of 2,500 buses. The PTE did, however, retain its powers over local rail operations.

The GMC was abolished in March 1986 and its functions, including that of Passenger Transport Authority (PTA), passed to a bewildering array of joint boards and committees, controlled mainly by the 10 metropolitan district councils. Control of the PTE passed to the new PTA, which was composed of 30 elected members from the 10 district councils. The PTA very quickly affirmed its unanimous support for LRT. Thus abolition did not have a major impact, except that some impetus was lost during the transition period.

Deregulation was potentially rather more significant. It meant the end of integrated transport planning. Bus services would be determined by bus operators on purely commercial criteria and the PTE would only let contracts by tender for services that were judged socially necessary but that were not being provided commercially. The DTp asked what effect bus deregulation would have on the case for LRT. In truth, nobody knew.

Instead of just waiting to see what happened, the PTE commissioned some market research to examine in more detail the factors affecting submodal split between bus and rail using the stated preference technique. From this a model was developed for detailed testing of options. In addition the actual changes and trends were monitored closely.

The market research suggested that existing rail passengers would be fairly resilient to bus competition, except where a through bus could offer a reduced total journey time compared with feeder bus and rail. Even then the relatively low frequency of many bus routes and their peak period journey times meant that transfer from rail to bus would not be automatic.

Bus deregulation took place in October 1986. While the situation has been somewhat fluid, practical experience has tended to support the conclusions of the market research. There has been comparatively little competition between bus and rail services and none that has posed any serious threat to rail traffic. In fact, after deregulation rail traffic increased, in some cases by significant percentages. This was due partly to an overall reduction of some 20 percent in bus mileage, and partly to the reliability and consistency of rail services in a sea of changing bus services.

The results of the market research were incorporated in a revised submission to the DTp (5). To cut a long and fairly complex story short, agreement was finally reached with the DTp in July 1987 that the case for LRT was robust. The Secretary of State for Transport then indicated that the scheme looked promising but that the government wished to examine options for private funding. The PTE had already retained merchant bankers as financial advisers but the DTp decided to appoint their own advisers.

Funding is also being sought from the European Economic Community. Preliminary discussions have suggested that a grant under the European Regional Development Fund, possibly amounting to 30 percent of the capital cost, may be obtained. However, under current rules, this reduces the DTp contribution and still leaves the PTA to raise its 50 percent, either from the Public Works Loans Board or other sources such as the European Investment Bank.

PROJECT LIGHT RAIL DEMONSTRATION

In March 1987 LRT was given a major boost, not just in Manchester but throughout the United Kingdom, by a unique demonstration of the rail industry's faith in British LRT proposals. A group of manufacturers, including GEC Transportation Projects, Balfour Beatty Power Construction, Fairclough Civil Engineering Limited, and British Rail Engineering Limited, set up a 3-week demonstration of a light rail vehicle (LRV) in Manchester with the support of the PTE and BR (*6*).

A 2-km section of lightly used freight line in east Manchester was made available by BR, which also provided power at 750 v dc overhead using a static electric multiple unit to step down from the main line 25 kv ac feeder supply. A temporary timber station, part of a new low-cost station in the PTE's ongoing program, was erected by Fairclough. New overhead was provided by Balfour Beatty, including examples of overhead equipment currently being supplied to the Tuen Mun LRT system in Hong Kong. The LRV was Docklands Light Railway car number 11, provided by GEC with assistance from Linke Hoffman Busch. Static exhibits included typical sleeper and grooved rail track and modern shelters.

Over 10,000 people traveled on the car, including members of the public, over two weekends. Professionals and politicians from every conurbation in Britain visited the demonstration. The Minister of State at the Department of Transport, David Mitchell, formally opened the proceedings accompanied by the chairmen of British Rail and the other sponsoring bodies.

There can be little doubt that Project Light Rail had a significant effect on raising awareness of the Manchester scheme with extensive media coverage, including television. It also encouraged a number of other cities to consider LRT more seriously.

TOWARD IMPLEMENTATION

In January 1988 the Secretary of State for Transport made a statement in the House of Commons that effectively authorized the PTE to proceed to invite tenders for phase 1, but on the basis of a concession to design, construct, operate, and maintain the system. All the assets, including rolling stock, will remain in the ownership of the PTE. The government believes that this approach will encourage the greatest contribution to the project from the private sector. If satisfactory bids are obtained, the government will provide a 50 percent grant. In February 1988, the two parliamentary bills received royal assent, becoming Acts of Parliament. They give the PTE the legal powers necessary to construct and operate the LRT system.

Steps had already been taken to initiate a number of pre-tender activities, including the appointment by the PTE of a project manager. Activities now under way include detailed site surveys, establishing statutory undertakers service diversion requirements, developing rolling stock specifications, and developing central area design parameters, particularly in regard to stations and pedestrian areas.

Particular attention has been given to the needs of disabled or mobility-impaired passengers. After study of a range of solutions including those used in Calgary, Buffalo, Portland, Sacramento, and the various European low-floor car designs, a decision was made to develop a high-platform, high-floor car design. A single sliding step will give access from the few medium-height platform stations in the city center, and these will incorporate a shallow ramp access to a short high-platform at the first door, similar to Buffalo's.

Consideration has also been given to the form of contract to be adopted. After review of all options and the experiences of broadly comparable projects, it was decided to seek a single contractor for the entire project under a two-stage design and build tender. The government's January announcement means extending the scope of this tender to include operation. It is expected that the first-stage tenders will be solicited in autumn 1988, with the second-stage tender (on which the contract will be awarded) being solicited in early 1989. Construction could then commence in mid-1989 and operation in 1991. The response to the initial advertisement inviting contractors to register their interest has been encouraging, and strong competition is likely for first-stage tenders. In June 1988, the project was relaunched under the name Metrolink (Figure 4).

FUTURE PLANS

Even before the phase 1 system had been approved, pressures were growing for extensions to the phase 1 network. Most notable is a proposed extension to Salford Quays, the former Manchester docks area that is now being extensively redeveloped in a manner not unlike the London Docklands (7). A good mix of land uses, including residential, commercial, retail, and leisure, should ensure good traffic levels for an LRT line. A feasible alignment has already been defined with close cooperation from Salford City Council. A parliamentary bill was deposited in November 1987. Adjacent to Salford Quays is Trafford Park, once one of the largest industrial estates in Europe

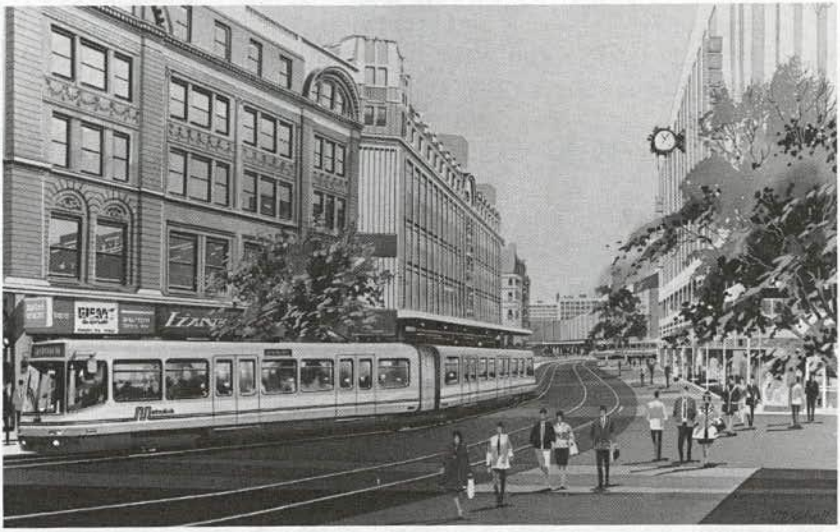

FIGURE 4 Metrolink LRT train in Market Street, City Centre, Manchester—artist's impression.

and now under the control of a new Urban Development Corporation, which is keen to explore the role of LRT to encourage potential developers.

Elsewhere in the conurbation, extensions are being considered in discussion with the appropriate district councils, again making use primarily of existing rail alignments but with short extensions to exploit LRT's capability of gaining good access to town centers.

The remarkably low cost of the scheme has been achieved by making maximum use of existing rights-of-way, both rail and road, and by avoiding costly civil engineering works such as tunnels or viaducts. The existing rolling stock is life-expired and needs replacing anyway.

In developing the Manchester scheme, visits have been made to a large number of existing systems in Europe and North America. Lessons have been learned, both from good practice and bad. It is hoped that Manchester will be able to demonstrate the best practices in a number of aspects and will indeed prove to be a new system success at an affordable price.

CONCLUSION

Greater Manchester will soon have its cross-city rail links after 150 years of trying. But why have so many previous attempts failed? What lessons can be

To succeed, any scheme must be technically sound, financially viable, administratively feasible, and politically acceptable. Too often in the past, Manchester sought the best solution but could not fund it, or politicial differences could not be resolved. The present LRT scheme has evolved from careful analysis of the problems and possible solutions, drawing extensively on market research and on relevant current experience in other cities. Great importance was given to public consultation, both to inform and to obtain comments from a wide range of local groups including users, traders, businessmen, and politicians. For example this indicated at an early stage that considerable support existed for LRT, but very little for busways.

It is essential to involve all the professional groups concerned, including highway and planning authorities, bus and rail operating agencies, and central and local government departments. The joint study team of GMC, BR, and the PTE brought together a wide range of expertise and resources.

Perhaps most important of all is to find the technology appropriate to the task, and to local circumstances. If Manchester had sought a solution involving expensive tunnels or high-technology automation, it could well have had to wait another 150 years.

ACKNOWLEDGMENT

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Elderly and Handicapped Accessibility

The California Ways

ROBERT E. KERSHAW AND JOHN A. BODA

Making light rail transit accessible to the disabled is done in ways as varied as the number of systems in existence. The interpretation and implementation of "full accessibility" is just as varied. Full accessibility must include provisions not only for the wheelchair-bound, but also for the deaf, hard of hearing, blind, partially sighted, elderly, and developmentally handicapped. These provisions include wheelchair ramps or lifts, wheelchair spaces in the vehicles with tie-downs, safety tile, Braille, audio devices, station space planning, and signage of proper size and contrast. Early planning and design decisions must include input from disabled groups and adequate funds in the project budget. Prerevenue service training for disabled access should also be considered as part of the project. This is usually a shared effort with the various disabled groups and the system operator. It has proven to be a good public relations tool, also.

PLANNERS AND DESIGNERS OF light rail transit systems must provide full accessibility to the system for the general public. This includes meeting the unique needs of the disabled community. The interpretation and implementation of "full accessibility" and the provisions for disabled access to light rail transit (LRT) are as varied as the number of systems in existence.

Full accessibility must include provisions not only for the wheelchair-bound, but also for the deaf, hard of hearing, blind, partially sighted, elderly, and developmentally handicapped. These provisions include wheelchair

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ramps or lifts, wheelchair spaces in the vehicles with tie-downs, safety tile, Braille, audio devices, station space planning, and signage of proper size and contrast.

Early planning and design decisions must include input from the disabled groups. The impact of accessibility alternatives must be weighed against their associated costs and these costs included in the development of the project budget. Once the accessibility choices are approved, preoperational training must then be considered. This training process should be a shared effort by the various disabled groups and the system operator. It has proven to be a good public relations tool, also.

How new California LRT systems have chosen to provide accessibility gives insight into the planning and design process and into the results yielded by operational experience. It is not the intent to pass judgment on the selected methods of disabled accessibility that were deemed appropriate for each unique system. The purpose is to provide accessibility choices to any agency considering a transit system and to encourage them to select and agree to these choices early to reduce conflict, budget repercussions, and possible construction delays.

The following systems will be reviewed for early planning and accessibility criteria, methods for dealing with the special interest groups, and the various techniques implemented to meet the full accessibility requirements for transit projects:

- San Diego (Trolley),
- San Jose (Guadalupe Corridor),
- Los Angeles/Long Beach (Willowbrook Line), and
- Sacramento (RT Metro).

SAN DIEGO

San Diego's 16-mi LRT starter line was completed in 1981 without federal funds. This was the first of the new LRT systems to be constructed on the West Coast and was the model for others soon to follow. A 5-mi extension was recently opened for revenue service and another extension is under construction. The Metropolitan Transit Development Board (MTDB) has a very aggressive extension plan under development.

Planning for elderly and handicapped (E&H) accessibility was not an afterthought on this project. MTDB, as the agency responsible for the planning and design of the LRT project, worked closely with the Ad Hoc Committee for Elderly and Handicapped Access. This committee issued a 1978 draft E&H accessibility study that was ultimately adopted by MTDB in

1984 after countless meetings and compromises over detail and the objective meaning of "full accessibility."

The adopted "Elderly and Handicapped Access: Design Handbook for Stations" condenses current California regulation (State Building Code - Part 2, Title 24, C.A.C.) and incorporates additional recommended standards and design criteria as defined by the MTDB's E&H ad hoc committee. The final system design incorporated the criteria, leaving very little to chance or to change on the sensitive issue of disabled accessibility.

The handbook primarily addresses three major categories of disability that will be affected by environmental factors. These are visual impairment or blindness, mobility impairment, and hearing impairment or deafness.

Visual Impairment

Station Access

Drop-off areas are conveniently located immediately adjacent to the loading area. Walkways are delineated and are wide and free from potential hazards to the visually impaired.

Safety Stripe

An 18-in. safety stripe runs along the entire length of the station. Initially it was contrasting brick pavers but was later modified to a slightly raised yellow surface of epoxy and sand grit. The yellow is for the partially sighted and the tactile surface for the blind cane user. Also, contrasting mats are placed opposite the doors to allow for ease in locating the doors.

Signage and Identification

MTDB complied with all adopted standards and requirements for signage, opting for large light-colored lettering with contrasting dark background. No signs are backlighted; consequently glare is precluded. Signage is uniform throughout the system in location, quantity, and quality.

International symbols are used wherever possible. The use of Braille was considered but has not been implemented to date.

Station Platform

Platform design provides orientation and uniformity in the location of fare vending machines, telephones, benches, signage, and other elements of potential hazard for the blind and partially sighted. Textured and contrasting paving colors assist the patron from the bus to the trolley boarding area in a relatively straight and unimpaired path. The stations are all well lighted for safety and security. High-pressure sodium lighting is used because it reduces glare for the partially sighted.

Vehicle

The button to operate the trolley door is raised, located on the side of the car, and outlined with contrasting color. Grab bars and stanchions are provided for the safety of those standing. The operator calls out station stops and emergency or important announcements.

Mobility Impairment

Station Access

Drop-off areas and parking for the disabled are conveniently located immediately adjacent to the loading area. Size, detail, and number of spaces comply with local standards and the E&H handbook.

Ramps and Walkways

Ramps and curb cuts are provided at convenient locations and comply with all rules and regulations as far as slope and width are concerned. Walkways are wide and free of obstacles to the mobility impaired.

Fare Vending Machines

Fare vending machines and phones are all located for convenient access. The height of the machine mechanisms is located for wheelchair-bound patron use.

Vehicle

E&H access to the light rail vehicle (LRV) is available only at the front right door of a lift-equipped train consist. The lift is an electromechanical device placed in a dedicated doorway. Because each train loads on the right side, only one doorway is blocked from general use. There are no tie-downs in the vehicle but steel clips serve as wheel stops for a maximum of two wheelchair users.

The mainline train consists are all E&H lift-equipped, but the Euclid extension has accessibility only between 30- and 60-min intervals because of the single-car consist. The train schedule is marked to indicate which trains are accessible. A rubber mat is placed at the head of each station platform and is marked with an international wheelchair symbol. The wheelchair lift controls are in the operator's cab with a clear line of sight to the lift. The average cycle time per user is approximately 2 min. This delay has not caused a significant problem in the scheduled operations.

After several experiments with other lifts, the Ricon lift was chosen for its reliability and adaptability within the vehicle. This system has drawbacks. There are no hand rails for the user; instead curbs on the lift keep wheels from rolling off. Mechanical systems are labor-intensive and subject to breakdown. The 2-min cycle could disrupt schedules and upset rush hour passengers. And the lift user has to rely on the vehicle operator, which reduces the user's independence. Also, a two-car train is needed to provide accessibility in both directions. This requirement could cause operational problems in changing vehicle consists from one- to three-car trains, hence increasing operation costs.

Hearing Impairment

No provisions for the hearing impaired were made on the platform or within the vehicle other than some preoperational training. Because hearing-impaired people require visual warnings for any emergency alarm, a visual display of any audio message provided to the public and telephones with amplification are minimal conveniences available to accommodate their disabilities. The E&H handbook states that telephones must generate a magnetic field to allow hearing-aid devices to pick up the voice signal. In addition, at least one telephone must be equipped with a volume control, according to the handbook. These improvements have yet to be implemented.

SAN JOSE

The recently operational San Jose Light Rail System involved the disabled community from the beginning in planning, design, and construction processes. A technical memorandum, "Access for Elderly and Handicapped Patrons," was developed by a consultant suggesting alternatives and recommendations for use during preliminary engineering. Later, two committees were established.

An ad hoc committee, made up of several active proponents of E&H accessibility, works on accessibility problems related to the county areas. The second committee, called the Disabled Advisory Committee, works on accessibility problems in the City of San Jose. Both committees meet once a month to resolve problems, make recommendations, or vote on staff proposals. Presently, they are working with the LRT marketing group to educate and train disabled patrons. In addition, the San Jose system benefited from having the LRVs manufactured before the final guideway design. Hence, the designers had more flexibility in providing E&H access to the vehicles.

Visual Impairment

Station Access

Drop-off areas are conveniently located adjacent to the loading areas. Walkways are wide, well lighted and defined, with obstacles located to the sides.

Safety Stripe

Safety tile 18 in. wide is located along the entire edge of the station boarding area. The tile is a contrasting beige color with longitudinal grooves for detection. Stairways leading to the platform have a contrasting color band at the edge of each stair tread. In the pedestrian mall area, a safety stripe 11 in. wide runs the full length of the 4-in. curb parallel to the tracks. The safety stripe is also continuous along the nonplatform side of the tracks.

Signage and Identification

Surburban station signs have gray aluminum backgrounds with black, Helvetica-style letters. All other station signage is white lettering on tile. Station signage is distributed throughout the platform. At the park-and-ride walkways to the station platforms, the signs are grouped in central locations. Downtown signage is done on the stainless steel shelters and on bus stop signage poles.

International symbols are used wherever possible. Signs are not illuminated, but area lighting is placed to highlight all station signage. Braille operating instructions and system information are proposed for the fare vending machines. The Braille should be in place prior to complete system operation.

Station Platform

Major access to the platforms is from one or both ends where fare vending machines and telephones are located.

Uniformity of other elements, such as shelters, benches, light poles and planters, was a consideration in design for safety and security. Illuminated handrails are placed on the suburban station access stairways.

Vehicle

The button to open the LRV door protrudes from the side of the car next to the doors and is lighted in the center with a contrasting color. A public address system allows the operator to call out the station stops. Grab bars and stanchions are provided for those standing. The stairwells have a contrasting color band at the edge of each stair tread.

Mobility Impairment

Station Access

Drop-off areas and parking for the disabled are conveniently located adjacent to the loading area. Size, detail, and number of spaces comply with local standards. Curb cuts, ramps, walkways, and elevators, where needed, are provided for the elderly and wheelchair-bound in compliance with local requirements.

Station Platforms

Platform design includes lighted and unobstructed space for wheelchair access and waiting. Fare vending machines and phones are located for convenient access. The height of the mechanisms is located to accommodate the wheelchair-bound patron.

Vehicle

Access to the LRV is through the front right door of each train. Two wheelchairs are permitted per train in an area near the operator at the front of the vehicle where the chairs can be secured. The wheelchair spaces are equipped with tie-downs. An intercom is placed within reach of the disabled so they can contact the driver for information or emergencies. The electro-mechanical lift is located at the head of each station. After general loading, the operator pulls forward to the lift, gets out of the cab and operates the lift, placing the disabled person into the vehicle. It takes approximately 3 min to load or unload the disabled patron.

After two unsuccessful attempts to obtain bids on the Portland-type wayside lift and a feasibility study of wheelchair ramps, a platform-mounted lift, similar to the concept of the San Diego MTDB on-board lift, was chosen. Platforms and ramps were judged aesthetically unacceptable in downtown areas, and vehicle-mounted lifts were considered less reliable than platform-mounted lifts. If a platform lift breaks down, train operations will not be affected. Drawbacks to this lift include the 6-min loading/unloading cycle, which will disrupt peak hour travel; the possibility that vandalism could occur on platform lifts; the E&H patron's reliance on the vehicle operator for access; and the high maintenance and operational costs that will continue throughout the life of the system.

Hearing Impairment

Phones with volume adjustment are not presently in place. Signage and maps are located so they can be seen from the vehicle and the platform. The vehicles operate with their lights on and are equipped with a bell for intercity warnings and a loud horn for suburban area warnings. Beyond that, little else has been provided for the hearing impaired other than preoperational training, printed schedules, maps, and a TDD (telecommunications device for the deaf) machine to call for other assistance.

LOS ANGELES/LONG BEACH

The 20-mi Los Angeles/Long Beach system is in final design stages and construction is well on the way for summer 1990 operation. An E&H Committee was set up about 3 years ago at the beginning of preliminary engineering to develop accessibility design criteria for the project. Because these criteria are specific, it is anticipated that few problems will develop. The committee continues to meet to review and approve all station designs for compliance with the approved design criteria. The system is funded by local sales tax monies; no federal dollars are presently involved.

Visual Impairment

Station Access

Well-lighted drop-off areas free from obstacles are conveniently located for the disabled. A portion of this line is in the subway and interfaces with the L.A. Metro Rail. It also interfaces with the Century Freeway Transitway. Both of these lines have high platforms. This was the major factor in the decision to use a high platform on the Los Angeles/Long Beach line, along with the fact that high platforms reduce boarding times. Because the station platforms are all high (at car, not track, level), access is by walkways with a 1:20 slope. This design enhances accessibility for all users. All stairs have a contrasting edge strip and slip-resistant surface.

Safety Stripe

An 18-in. safety stripe of light colored, contrasting, textured material will be placed on all high-level boarding areas. All pavement and ramped walkways have a textured, non-slip surface. The 18-in. width is required because the platform height is 39 in. above the track—adequate warning is very important given the severe consequences of falling.

Signage and Identification

A consultant will be selected to develop the scope and details of system signage and identification. The consultant will have a general set of guidelines to follow and will submit the design for approval. Braille is being considered for the fare vending machines and certain phone instruments. Since the blind are not charged a fee to ride, the Braille will be used for informational purposes. Braille will be placed at all elevator locations according to state requirements in Title 24.

Station Platforms

Platforms are raised to the height of the LRV floor, so all doors of all cars will be accessible for all patrons. All platforms will be lighted for safety and security. Emergency phones will be located on the platform. Because all platforms are elevated, warning curbs, guard rails, and handrails will be used at all nonboarding edges. A public address (PA) system and closed-circuit TV system will be installed at each station. The PA system will be used to assist patrons with schedules or problems as they arise. The platforms will have minimal obstacles and those that exist will be set back from the platform edge.

Vehicle

The operator will control opening and closing of all doors. An emergency switch will be available to open doors if necessary. The LRV is equipped with an audible whistle and bells that can be heard from 500 ft. Floor coverings at all door openings will be marked by a 2-in. strip of contrasting color and differing texture.

Mobility Impairment

Station Access

Curb cuts, sloped ramps, and elevators will be provided for platform access. Parking for the disabled will be provided immediately adjacent to the platform area and will comply with local codes for size, identification, and number of spaces required.

Signage and Identification

The consultant will propose all signage and will maximize use of international symbols for the handicapped.

Station Platform

The raised platform will have curbs and handrailings for safety. Wide walkways and loading areas will allow for ease in wheelchair use. The platforms will be well lighted for safety and security. A raised safety stripe at the boarding edge will warn wheelchair-bound patrons. All telephones and vending machines will be accessible to wheelchair-bound patrons.

Vehicle

The continuous raised platform will provide wheelchair-bound patrons easy access to doors at the end of the vehicles. This allows for more wheelchairs per train and also provides quicker access and egress. The trade-off for the raised platform is considerably higher capital cost and a physical barrier that could be a conflict for circulation.

The maximum gap between the platform and vehicle will be 3 in. horizontally and ½ in. vertically. The vehicle has air shocks to adjust the car floor to the platform level. However, the gap may present a hazard, especially to small wheelchair wheels. The door opening is 32 in. wide, which allows passage for a single wheelchair. A priority area next to the door is set aside at each end of the vehicle for wheelchair tie-downs. The criteria indicate 1 percent of seating space must be available for wheelchair-bound patrons.

Hearing Impairment

Visual warnings have been proposed for all emergency alarms. Telephones will have volume controls. Vehicle flashing lights will have a minimum oscillation of 60 flashes/min. Training and other assistance for the hearing impaired will be considered during final design and before scheduled opening.

SACRAMENTO

The Sacramento Regional Transit (RT Metro) design criteria established only general guidelines for providing full accessibility. The following excerpt is from the design criteria:

> 1. Accessibility to Vehicles
> Access shall be provided by a short high platform ramp meeting grade, width, and other criteria noted elsewhere. The ramp shall be located to access the front door of the first car of a maximum length train at all station sites practical. Details for access will be determined by the end of preliminary design. Some sites may be physically constrained to preclude the E&H ramp; however, all efforts will be made to remedy this situation. Final decision on elimination will be made by RT.
> 2. Platform Accessibility
> Platforms shall be designed to meet accessibility requirements for the E&H.
> 3. Parking
> E&H parking shall be located as close to the platform as possible. Parking space number and size shall comply with Caltrans standards and the California Vehicle Code.

This excerpt exemplifies the very general and unspecific criteria for disabled access to RT Metro. The design criteria were prepared before the environmental document or preliminary engineering was completed and before the total scope or cost of the project was known in detail. The requirements for full accessibility are all well known and have been published in many documents.

How these requirements are to be satisfied, however, is not specified. Early in the planning phase of this project the various disabled groups showed little interest. However, after the preliminary engineering and the environmental work were completed and approved and funding was ensured, disabled access became a very critical issue in the final design phase.

After many attempts by the numerous disabled groups to become the spokesperson for all, it became apparent that no one group could speak in the best interest of all. After numerous meetings with the disabled groups and concerned individuals, an agreement was reached to work with the Sacramento County Advisory Committee for the Handicapped. This committee served as the forum for all meetings with staff and ultimately proposed recommendations for the RT Board's final implementation.

Visual Impairment

Station Access

Convenient drop-off areas and access for disabled patrons were provided contiguous to the platform to preclude vehicle/pedestrian conflict.

Safety Stripe

The issue of the safety stripe on the RT Metro project was a classic example of misunderstanding and miscommunication. The safety stripe ceramic tile material was described by staff and conditionally approved by the committee for the handicapped pending receipt of an actual tile. Similar tiles were provided to the disabled community for review. After the tile had been delivered and installation begun, actual samples were provided for further review and were rejected by the committee because they lacked detectability and contrasting color. After numerous meetings, discussions, debates, delayed contracts, and board action, the decision was made to reject the ceramic tile and replace it with rubberized safety tile. This occurred just prior to start-up and drew much negative attention to the project. It also required an additional construction contract to remove the portions of ceramic tile in place and install the rubberized safety tile at a cost of approximately $500,000.

A slight depression and a painted yellow line were placed as a temporary solution prior to contracting for the rubberized safety tile. Several other related safety stripe issues surfaced, such as limits of tile, width of tile, definition of a platform, and the need for additional safety tiles to direct disabled patrons to fare vending machines and vehicle doors, and to provide detection for raised or recessed elements that could be dangerous to the blind. These issues were all resolved with few, if any, additional changes. The rubberized safety tile is now in place and is meeting with approval from the disabled. But a concern remains about the durability of the material in a changing external environment. The additional placement of directional tile is being considered.

Signage and Identification

As RT Metro had no specific guidelines for signage, the disabled community became actively involved in review of colors, lettering types, size, and configuration. The basic color scheme was accepted with modifications and the contrast and lettering size and type were agreed upon. Full-size, color prototype signs were presented to the committee for approval prior to final fabrication. The basic colors were beige, accented with either dark burgundy or dark green for contrast.

Few additional issues on signage or identification surfaced after this approval. However, the use of Braille became an issue. The staff's position was that no other operating system uses Braille, no funds were budgeted for Braille, and Braille was not required as a specific element for full accessibility. This issue came to the board with a staff recommendation that the use of Braille be rejected. After much arguing, debate, and "good old-fashioned politicking," it was decided by a 3-to-2 vote that Braille would be placed throughout the system. This decision was made even after a national group, representing a faction of the blind community, stated that Braille was not desired by their members because fewer and fewer blind individuals read Braille. The group suggested that training and audio devices could serve the same purpose at much less cost.

Braille now in place on the fare vending machines includes station name and all operating instructions. The disabled ticket selection button on the machines was raised to allow for ease in location. The change machines also have limited instructions in Braille. The use of additional Braille is under consideration.

Station Platform

The design staff made a concerted effort to design each platform with uniformity and common elements. Open and clear paths are provided to the shelter area. Phones are located at one end of the shelter, fare vending and change machines at the other end. The station platform is well lighted for safety and security. The light poles double as support for the signage. This reduces the number of potential hazards for the blind.

Vehicle

Raised buttons with a yellow background are located on either side of the vehicle doors. Homing devices were proposed to make it easy for the blind to locate the buttons. No proven technology was found for this, and the fact that all blind patrons would have to carry the devices precluded their use. It was decided that the safety stripe and directional tile on the platform at the door location would provide sufficient identity.

In- and out-of-vehicle public address systems are provided in each vehicle so that station names can be called out and emergency messages announced. There are no intercom systems on the trains. There is no striping or other means of warning blind riders of their proximity to the stairwells. Many visually impaired users with canes and dogs prefer the handicap ramps for boarding.

Mobility Impairment

Station Access

Drop-off areas and parking for the disabled are conveniently located immediately adjacent to the loading area. Size, detail, and number of spaces comply with local standards.

Station Platform

Ramps and curb cuts are provided at convenient locations at most stations and comply with local rules and regulations regarding slope, width, and texture. The platform loading area is wide and uncluttered and allows for ease of wheelchair movement. The platforms and walkways are well lighted for safety and security. The fare vending machines and phones are all located for convenient access with the height of the mechanism located for wheelchair-bound patron use.

Vehicle

Vehicle access was one of the very few accessibility elements determined early on. Staff had viewed the on-vehicle lifts in San Diego and the wayside lifts in Portland and were concerned with safety, reliability, operational time, and maintenance cost of the lifts. Early meetings with the wheelchair-bound community indicated their acceptance of a staff-proposed short ramp to access the vehicles through the front doors. A mockup was built to show how it would function. A demonstration ramp built on the San Francisco Muni system that would provide similar access was also examined.

The short E&H ramps were provided at 22 of the 27 stations where space was adequate. Four locations where it was physically impossible to provide the ramp required lifts to a wayside platform for vehicle access. After an in-depth review of this deviation, the E&H committee approved the patron-operated lifts. The lifts were initially designed with no gate between the lift floor and the elevated platform and without a safety device to prevent operating the lift with the lower gate open. It was later decided that an upper gate should be included and that both gates should be equipped with an interlock switch to prevent operation of the lift if either gate were left open. One on-street station could not be made fully accessible because of a shared lane with vehicular traffic. This was acceptable to the E&H committee because the next station is only three blocks away.

Because the Sacramento system is not fully double-tracked and the train can load from either side depending on the station, lifts on the vehicle were precluded. A lift on the platform was also precluded because of the 20-sec station dwell times necessary to maintain schedule. A 2- to 3-min delay cannot be made up on a single-track system schedule. Sacramento did not consider high-platform stations because of the high cost and the narrow sidewalks downtown. The ramp concept was the better solution for this system configuration. But there are drawbacks.

At some downtown stations, a ramp would partially block building doorways, so the lift/platform was used. The sidewalk width also was reduced in the area of the ramps and the ramps are visible at each station.

The space between the edge of the vehicle floor and the ramp is approximately 13 in. wide due to the out-folding doors and clearance requirements. Consequently, the vehicle specification required the car manufacturer to provide a mechanical, nonelectrical or nonhydraulic folding plate that would cover the stairwell and bridge the gap between the vehicle and the platform. Final review and approval came after many proposal iterations, shop plan submittals, and review by staff and the E&H committee. The folding plate is placed in the down position on both front doors when an inbound run begins and remains down until the end of the run. When a wheelchair-bound patron desires access, the door opens automatically and the operator moves out of the cab to press a handle that places the bridge plate across to the ramp platform. It takes approximately 30 sec to load or unload a wheelchair patron; patrons with walkers take slightly longer.

Space for up to two wheelchairs is available in the covered stairwell areas near the operator's cab. Plans are being implemented to retrofit the cars to provide jump seats in lieu of two fixed seats near the front doors. This would provide convenient space for an additional wheelchair. Chair tie-downs were deferred because no one type or model was acceptable to the majority. Tests and evaluations are being conducted by others that may lead to acceptance of one specific type suitable for all users. Grab bars and vertical stanchions are provided for additional stability.

Before revenue service began, training sessions were provided to the disabled community to familiarize them with the system and to acquaint operators with the concerns and needs of the disabled.

Hearing Impairment

To accommodate hearing impaired people, one telephone at most—but not all—stations is equipped with a volume control. Vehicle lights are on during operation.

CONCLUSION

As can be seen, there are numerous ways to meet elderly and handicapped accessibility requirements dictated by state and federal laws. What is most interesting, however, is the dissimilarity in a few critical methods used to provide accessibility, such as lifts, ramps, Braille, safety stripes, and signage. In choosing methods, reliability, maintenance and operation costs, aesthetics, and, most of all, local preference of both the operator and users must be considered. Other considerations must include physical constraints, such as shared right-of-way, narrow streets and sidewalks, urban and suburban station differences, availability of right-of-way, and utilities.

Once these options and considerations are understood, quantified, and approved, staff assumes the responsibility for developing these further so a total understanding by management, the governing board, and the disabled community is reached. Early involvement of an E&H advisory committee (preferably at the beginning of preliminary engineering) is a must in order to make accessibility choices and mitigate the accessibility problems inherent with these types of transit projects. It should be noted that the California Administration Code (C.A.C.) Title 24 and its interpretation are more specific and restrictive than the federal regulations governing handicapped accessibility to transportation systems. However, this may not be true in other states.

The four systems discussed are representative of the problems and varied solutions that will most probably be encountered with any LRT system considered in North America.

Ridership Forecasting Considerations in Comparisons of Light Rail and Motor Bus Modes

LYNDON HENRY

From the standpoint of ridership forecasting, light rail transit (LRT) and motor bus modes vary in their attributes. Specific modal attributes (stations, passenger space and seating, ride quality, air pollution, noise, schedule reliability and safety, system identity and public orientation, familiarity) can be rated for LRT, busway, and street bus systems and analyzed. While LRT is rated highest in this comparison, the implications for mode choice behavior require more intensive research. Another factor in mode choice is the hypothesis that LRT and other rail transit modes have stronger potential to induce adjacent real estate development in contrast to busway operations. The results of a survey of perceptions of real estate decision-makers in eight U.S. cities operating either LRT lines or busways indicate that decision-makers tend to perceive LRT stations as significantly more desirable than busway stations for commercial real estate development. Respondents' perceptions regarding public orientation to LRT versus busway routes and service levels also score LRT higher, but analysis did not determine this difference to be statistically significant. Improvements in the acccuracy of ridership forecasting are essential, particularly in terms of differences between LRT and motor bus as alternative transit modes, and some approaches for further investigation can be defined.

FOR MANY COMMUNITIES CONSIDERING the installation of new fixed-guideway rapid transit systems an analysis of alternative transit modes frequently leads to an evaluation of conceptual light rail transit (LRT) counterposed to motor bus configurations for a given application. One of the

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major focuses for most analyses is the ridership attracted to the proposed alternatives.

Taking a specified pattern of land use and other data as input, conventional ridership forecasting methodology typically calculates time and out-of-pocket cost "disutilities" or "impedances" to project ridership on each modal configuration for a selected design year. The result—commonly expressed as a discrete patronage volume—plays a critical role in the decision-makers' process of evaluating the alternative systems.

However, many professionals point to weaknesses in current ridership forecasting methodology. Some analysts refer to deficiencies in the mode choice component of forecasting, while others cite land-use impacts on potential ridership that may be neglected. Inaccuracies in accounting for different characteristics in ridership generation between transit modes (e.g., LRT versus bus) could lead to unwise investment decisions.

Over 20 years ago, Hille and Martin observed that "modal split models have been only moderately successful." While commenting that "modal choice decisions appear to be more complex than generally thought," they noted that "as few as two variables have been used (travel time and cost) to predict modal choice." They concluded that "the development of valid prediction models for modal choice seems to rest on incorporating several factors into the prediction milieu" and improving model sensitivity to "the complex interrelationships" among such factors (*1*).

Some 10 years later, Spear observed that "a major problem confronting both transportation planners and researchers in travel behavior is how to build travel demand models that are sensitive to transportation system attributes other than time and cost" (*2*). Similar observations were made by Algers et al., who noted (*3*):

> Research on travel choice has for the past 10 years been concerned with the value of time savings and estimates of time and cost elasticities. The role of comfort and convenience was always referred to as important but rarely was incorporated explicitly as a policy-oriented variable in econometric models.

These researchers developed a model incorporating transit seat availability as an indicator of comfort and convenience factors, such as the need for automobile availability during working hours, and applied the model to work travel in metropolitan Stockholm. Their studies determined that, in addition to other influences such as waiting time, "the level of the travel-time value also depends to a large extent on the in-vehicle comfort in terms of seating opportunities. The overall travel-time value decreases substantially when commuters can enjoy a seat as compared to when they cannot." The only modal difference analyzed was in terms of transfers; here it was found that rail-to-rail and bus-to-rail transfers were significantly less onerous than bus-to-bus. The researchers concluded that this was due to the greater comfort of rail stations, the lower schedule reliability of street buses, and the difficulty of synchronizing interconnecting bus routes (*3*).

In a paper on ridership attraction to LRT, Jessiman and Kocur pointed out that, at least for some riders, schedule reliability might be a more important consideration than conventional time and cost factors. While presenting a modeling approach that based impedance solely on travel time and cost, they suggested that other factors such as a transit mode's level of passenger comfort could play a significant (though currently unquantified) role in ridership attraction (*4*). Despite such concerns, travel cost- and time-related factors continue to be virtually the sole attributes considered in most current forecasting models. Capital Metro's rapid transit sketch planning model in Austin, Tex., did incorporate a "convenience" variable representing number of transfers, but this could also be interpreted as a time-related convenience attribute (*5*).

Differences in passenger attraction to alternative modes independent of the usual time and cost impedance characteristics have been found in some studies. Finding that some travelers surveyed indicated a preference for the slower mode, Spear suggested that "attributes are not perceived in terms of absolute differences but rather in terms of some difference in satisfaction for the alternatives" (*2*). Some conventional forecasting procedures have also been criticized for deficiencies in accounting for mode-specific attributes, a circumstance that could more directly affect LRT versus bus evaluations. Referring to "sketch-planning projections of questionable veracity, "Tennyson has suggested that ridership forecasting should take into account the "inherent passenger appeal" of LRT, citing attributes such as "the wider aisles, smoother movement, absence of odor and engine noise, all-weather reliability . . ., and obvious fixed route to which people can relate." Tennyson concludes by observing that "the estimating process may be reasonably good, but the pressure on the estimators to produce a 'winning' estimate may be unprofessional and irresistible" (*6*).

Similar concerns have been raised elsewhere. For example, in response to the solicitation of views regarding Capital Metro's demand estimation methodology, it was suggested that several passenger-attracting attributes of LRT should be considered for inclusion in the proposed model: (1) route understandability—the public's "enhanced sense of the permanence and presence of the system and where it goes," (2) riding comfort, and (3) attraction of real estate development near LRT stations. However, it was acknowledged that "no reliable studies contrasting rail vs. busway systems up-and-down have been conducted which provide hard, empirical data on these phenomena" (*7*). Inclusion of such factors in Capital Metro's forecasting process was subsequently rejected on the grounds that "biases in mode choice models which are different between rail and bus modes" are unacceptable to UMTA, and that "we must use technical methods which are generally accepted within the profession and which are acceptable to UMTA" (*8*).

Nevertheless, the presence of qualitative differences between modes—even under conditions of time and cost equivalence—is propounded as a significant modal choice factor by numerous analysts. Suggesting that a variety of behavioral variables may be relevant to the modal choice process, Feldman has pointed out that "different modes, while performing the same essential functions in terms of origins and destinations apparently satisfy the needs of their users in different ways" (*9*).

Certainly, these are issues that could have implications not only for present and future fixed-guideway planning but also for the accuracy and validity of demand forecasting. Contrasting operational differences between LRT and motor bus configurations are readily modeled today in terms of different schedule speeds and running times, headways and waiting times, number of transfers, etc. But possibly different public behavior toward other modal attributes, and trip-generating differences in land-use impacts, is widely disregarded in both research and practice.

Does the public indeed perceive LRT as inherently more comfortable and reliable than motor bus transportation? Is LRT route structure more understandable? Does an LRT line tend to be more attractive to real estate development than a street bus route or a busway? How might researchers go about evaluating such factors? And if differences are validated in regard to certain modal attributes, how might these be quantified and incorporated as modifications of demand forecasting procedures?

PASSENGER MODE CHOICE FACTORS

The significance of passenger comfort and other perceptual characteristics in travelers' choices between mass transit modes is suggested by many analysts. Researchers developing a modal-split model for the Buffalo area, for example, recognized that factors such as comfort and crowding were important indexes of service quality, but "the difficulty with these factors was lack of evidence . . . . There was, therefore, no real choice open to our research workers, and these factors were excluded" (*10*). Feldman's marketing-oriented survey of travelers' attitudes in the Chicago area likewise found that modal dependability and comfort tended to rival speed and convenience in ranking by respondents—well above trip cost, in fact (*9*).

In assessing implications for LRT versus bus systems planning, three issues are involved: (1) whether there are qualitative (other than operational) differences between these modes, (2) to what extent these differences are perceived by the public and are significant in their modal choice behavior, and (3) how such differences might be quantified and incorporated in predictive models capable of generating numerical passenger forecasts.

Comfort and Convenience

Wide variances of opinion (and, in some cases, data) exist in regard to whether there are differences in comfort levels between rail and bus transit modes. In the development of modal-split models in the 1960s and 1970s, comfort differences between modes were deemed insignificant in many studies. Evaluating rail versus bus alternatives for Washington and suburban Chicago, for example, Pratt and Deen observed that "it seemed not unreasonable to assume that passenger loadings and transportation equipment conditions would in the aggregate not seriously affect sub-modal choice" (*11*). The consulting firm of Coverdale & Colpitts, Inc., has observed that "from the standpoint of riding comfort, there does not appear to be any great difference between buses and the types of vehicles employed in fixed guideway systems. Seat configuration, air conditioning, lighting and other features are quite comparable" (*12*).

The existence of distinct differences in comfort levels between LRT and bus, however, has been cited by others. In an article written when abandonment of streetcar lines was still widely favored, Ferreri noted that "transit riders who remember the spacious and comfortable PCC [President's Conference Committee] trolley cars may not agree that there has been any progress at all." Pointing out that "PCC trolley cars are rapidly disappearing from the urban scene, to be replaced by the diesel-powered transit bus," Ferreri observed that operational advantages, such as "increased flexibility in modifying routes," were being obtained "with passenger comfort as a secondary consideration; bus operations are accompanied by what some feel are offensive exhalations of smoke, noise and odor" (*13*). Calling for improvements in bus design, an industry magazine article noted that "present buses emit noise, noxious gases, and odors which are objectionable to individuals and contribute to the degradation of the urban environment" (*14*). Even an International Road Federation news article promoting bus-based rapid transit acknowledged that "the aesthetic and passenger comfort features of buses commonly used in U.S. local and commuter services certainly need improvement" (*15*).

Engineers reporting the results of an LRT versus busway feasibility study for Rochester concluded that "while individual preferences may vary, there is no doubt that the rail vehicle with wider seats, wider aisles, wider doorways and high level boarding provides a more pleasing environment for the traveler" (*16*). Citing evidence that LRT operations have tended to retain ridership substantially better than surface transit as a whole, Tennyson attributes this success, in part, to amenities such as absence of "on-board engine noise or smell," absence of "unexpected swerving or sudden stops," ability of passengers to read while commuting, smoothness of ride, and availability of double doors "to speed loading and unloading," among other factors (*17*).

A leading textbook on urban public transportation, while acknowledging that the riding comfort of buses "in straight running on well-maintained streets is excellent," observes that in conditions of heavy traffic and frequent maneuvering "vehicle sway and high jerk rates often make standing uncomfortable." In addition, buses' "noise and air pollution are often objectionable, particularly at terminals and stops due to engine idling and frequent accelerations." On the other hand, "rail transit provides better riding quality than any other mode." Furthermore, "the spaciousness of rail vehicles allows the use of a larger space per seat and design of wider aisles than in buses. Sitting is therefore generally more comfortable, and standing is more acceptable for short to medium travel than in buses" (*18*).

System Identity and Public Orientation

By its nature, LRT's trackage, electrical supply, and stations accord it a high profile. This highly visible route structure, some analysts contend, may enable the public to recognize and understand a line's location, connectivity, and service—giving potential riders an enhanced sense of the permanence and presence of the system—and may be simpler and easier to comprehend and retain than is the case with bus systems.

The simplicity, identity, and clearer image that may characterize what Tennyson has called LRT's "self-proclaiming route" (*17*) could foster an important "user-friendly" sense of orientation to the system among the public that could influence patterns of modal choice behavior distinct from those of bus alternatives. (Likewise a busway may exhibit similar influences to some extent in contrast to local street bus service.)

The implications for ridership forecasting could be quite significant. Not only might such popular awareness of and orientation to the system produce greater short-term public acceptance of a new installation, but, sustained over time, potentially greater cumulative ridership for the mature system.

Assessment of Specific Factors

To evaluate the issue of mode-specific attributes such as passenger comfort and schedule reliability in regard to LRT and bus facilities and vehicles, it is worthwhile to consider specific components of these attributes, especially as they have been examined in various research studies.

Stations

Transit stations or stops can vary drastically in amenities, from fully climate-controlled enclosures to a simple pole marker. While the quality of such facilities undoubtedly influences public perceptions, this has not been adequately measured in terms of mode choice behavior. Assessment of existing and proposed new systems indicates that, per length of route, LRT tends to have substantially more well-defined stations with amenities such as sun and rain shelters and route information. Busway systems tend to have some well-defined stations together with simple pole-marker stops off the guideway in suburban and downtown areas. Street bus systems rarely have shelters or stations, perhaps only at a major interchange or park-and-ride location. Based on research such as the previously cited Stockholm study (*3*), it is reasonable to assume that station facilities as a passenger-attracting feature are greater for LRT than bus modes, and greater for busway than street bus, but additional research is needed to quantify this attribute.

Passenger Space and Seating

Because dimensions of LRT and bus vehicles vary substantially, firm conclusions on this factor are elusive. Light rail vehicles (LRVs) tend to have one or two more doors per vehicle than buses, and doors tend to be 1.2 ft wider (*18, 19*); thus LRVs tend to provide greater boarding convenience than buses. Finn's comparative study of transit modes, however, based on observed peak operations, concluded that space on LRVs averaged 0.26 to 0.29 m^2 per passenger while on buses it averaged 0.32 to 0.59 m^2 (*20*). For non-crush-load and off-peak conditions, however, LRT may be more spacious. A vehicle comparison in Minneapolis indicates 265 ft^2 of aisle space for a typical LRV versus 73 to 100 ft^2 for a standard or articulated bus (*21*).

While LRVs tend to have greater passenger capacity, buses tend to offer approximately as many seats (*18*), with a higher proportion of seated passengers in service conditions (*19*). The importance of seat availability has been observed in the Stockholm study previously noted (*3*). Experience in some new West Coast LRT operations likewise indicates significant passenger resistance to standing; similar experience could be anticipated in new fixed-guideway services in the Southwest and South.

Implications for passenger-attractiveness would need further study. This should also consider trip distance as a factor—e.g., seat availability is possibly more important for longer trips, but these tend to originate closer to line end-points where more seats may be available. Because of all the trade-offs indicated, in this analysis LRT and bus must be considered approximately equal and moderately comfortable modes in regard to this factor.

Ride Quality

Jerk rate (rapid change in acceleration) is a common measure of ride comfort. While LRVs provide much higher acceleration than buses, the Finn study concludes that buses are highest in jerk "because their acceleration is incontinuous" (*20*). Ride quality at running speed is probably also superior for LRT due to the predominantly greater smoothness of steel rails versus asphalt or concrete and the suspension and weight qualities of modern LRVs. It is also likely that busway operations would yield superior ride quality, on average, than stop-and-go street bus service. The effect of these advantages on public perceptions, however, needs further research.

Air Pollution

While some air pollution is associated with both electric and internal-combustion transit modes, only with motor buses is the pollution produced directly by the vehicle. Except for conditions of poor maintenance, exhaust odor inside buses is no longer a problem. However, objectional levels of exhaust fumes could exist in roofed or enclosed waiting areas, during heavy accumulations of vehicles (e.g., bus "platoons"), during long idling, or under conditions of poor maintenance. While public perception may be worse than the actual problem, it could have a direct bearing on mode choice and should be researched.

Noise

Both exterior and interior noise levels are substantially higher for buses than LRVs by some 5 to 15 dbA (*19, 20*). Exterior noise could be a problem for passengers waiting in bus stations. Since, as Finn notes, vehicular frequency tends to be much higher for bus operations, noise exposure would be more frequent.

Schedule Reliability/Safety

Taken together, reliability and safety may contribute to passengers' sense of confidence in a given system. In regard to safety, an LRT promotional booklet produced by Rhein-Consult cites an LRT accident rate about half that of bus measured in hours of traffic participation (22). The DeLeuw, Cather state-of-the-art review, using subjective indicators, rates LRT and bus as roughly equal in accident potential (*19*). An LRT/bus versus all-bus comparison for Harrisburg calculated substantially lower annual accidents for the LRT/bus system (*23*). On the other hand, an analysis of U.S. data from the early 1970s indicated an accident rate, measured in passenger-miles, some 30 percent higher for LRT than bus (*24*).

In terms of schedule reliability, the DeLeuw, Cather review, based on Pittsburgh projections, indicated a 99.5 percent schedule reliability for LRT versus 99.6 percent for bus (*19*). Finn's more comprehensive study, however, reports LRT schedule reliability to be twice that of bus (*20*). Vuchic's study of the Washington, D.C., Shirley Busway in the early 1970s indicated that only 46 percent of buses using the facility arrived on time or no more than 6 min late (*25*).

Although there are some conflicts in the data analyzed, it is reasonable to rate LRT highest in this factor; likewise busway service could be expected to provide somewhat greater service reliability than local street bus operations.

System Identity/Public Orientation

Vuchic observes that "a strong image and identity of rail transit, caused by the simplicity of its services and permanence of its lines, represents a major element of passenger convenience. This strong recognition contributes greatly to the large passenger-attracting ability of rail transit" (*18*). Tennyson refers to LRT's "obvious fixed route to which people can relate" (*6*).

Although a busway's fixed facilities undoubtedly have similar effects, these may be diluted by the meandering, confusing patterns often followed by routes leaving the guideway in suburban and downtown areas. Vuchic's analysis of the Shirley Busway presents an example; he notes the "extreme complexity of the service" as a factor in the failure of the system to tap substantial latent demand. Vuchic cites one major route with 48 subroutings and another with 21 subroutings. In central Washington, the study found, each bus followed one of three routings to one of three different terminals. Even the management of the major transit system using the busway had "no clear idea of where all its stops are" at the time of Vuchic's study (*25*).

Regarding local bus routes, Vuchic has indicated elsewhere that "the identity of bus services is very poor because of lack of fixed facilities," although he notes that this drawback can be partially overcome by good public information services (*18*). Based on such observations, it is reasonable to conclude that LRT rates highest in this factor, while busways, with their guideways and occasional stations, tend to have greater system identity than street buses.

Familiarity

It must be acknowledged that for totally new systems, LRT may initially be a less familiar and more intimidating transit alternative than the bus, especially for current bus riders; likewise a busway would be rather less familiar than a local bus running on streets. (On the other hand, LRT may represent a more appealing mode for some individuals precisely because it is different.) While this unfamiliarity should disappear over time, it may affect mode choice.

Summation

Conclusions from this analysis of specific modal attributes are summarized in Table 1 for LRT, busway, and street bus. Each mode is rated on a scale of 1 (low) to 3 (high) for each attribute. While LRT clearly is rated highest in this comparison, the implications for mode choice behavior are a separate issue. (It should be noted that with electric trolley buses vehicular air pollution and noise are not problems. However, for reasons of cost, performance, and other considerations LRT versus trolley bus comparisons are extremely rare. In any case, the subject of public perception of trolley bus comfort versus that of LRT lies outside the scope of the present discussion.)

TABLE 1 RATING OF MODES BY SPECIFIC ATTRIBUTES AFFECTING RIDERSHIP

	LRT	Busway	Street Bus
Stations	3	2	1
Passenger space and seating	2	2	2
Ride quality	3	2	1
Air pollution	3	1	1
Noise	3	1	1
Schedule reliability/safety	3	2	1
System identity/public orientation	3	2	1
Familiarity	1	2	3
Total	21	14	11

Exploring Modal Choice Behavior

If there is a greater passenger-attractiveness of LRT, it is unlikely that it is individually measurable for each of the separate factors discussed; rather, it would more probably take the form of an aggregate enhanced "image" perception by the public. The need for research to examine public perceptions and to evaluate modal choice implications of these mode differences is definitely indicated—particularly so in the case of federal involvement. While UMTA allows the incorporation of a bias constant in mode choice models that reflect differences in comfort, convenience, and "other unincluded variables" between transit, single-driver automobiles, and carpools, the agency notes that "these biases are computed in the development of the model based on the observed behavior of a sample of travelers." However, UMTA emphasizes that incorporating similar biases between mass transit modes (e.g., LRT versus motor bus) must be based on acceptable research data (*26*).

Use of a sensitivity scale, perhaps as a means towards developing a generalized attribute variable such as Spear has described (*2*), might represent a productive approach. Cities currently operating both LRT and bus-based systems would undoubtedly be the most fruitful areas to conduct research, since public familiarity with both modes would be useful. If significant differences in public mode-choice behavior toward LRT and bus are ultimately quantified, alterations to modal choice models could take the form of incorporation or alteration of bias constants (per UMTA's example), modifications to coefficients of current impedance variables, or perhaps the development of new variables and coefficients using standard regression and curve-fitting techniques.

REAL ESTATE DEVELOPMENT AND RIDERSHIP

Another characteristic that may lead to significant differences in ridership between LRT and motor bus modes is land use impact. Substantial evidence exists that LRT stations can function as strong attractors of adjacent clusters of real estate development. Such effects, if they could be quantified and predicted with some accuracy, undoubtedly would have major implications for rider forecasting.

As Vuchic points out (*18*),

> The most significant single impact of rail transit is its strong influence on land use and the form of cities. The permanence of rail transit lines and stations generates the developments of land use which interact with and

> depend on the high-quality transit service. Therefore, in time, stations generate their own patronage and "anchor" themselves at their locations. With good planning and urban design, this interaction can be used for the creation of attractive urban environments.

This latent potential to function as a tool to attract development and to stimulate and guide urban growth has been emphasized by Priest of the Urban Land Institute (*27*):

> Urban rail transit can promote development and redevelopment in the major cities of the United States. It can do so not only in the older cities of the northeastern and north central regions, but also in the auto-oriented cities of the South and West.

Knight reports the results of a federally funded study of the effects of rapid transit on land use, conducted in 1977, which found that "recent major rapid transit improvements have been important inducements to intensified development near stations both in CBDs [central business districts] and in outlying areas . . . ." While other factors such as land availability, appropriate economic conditions, and supportive public land use policies were essential, Knight observes, "major transit improvements often act as catalysts in the process of land use change . . . ." [Regarding LRT, it should be noted that the study found that "evidence of early impact is inconclusive" since the systems were either uncompleted or only recently inaugurated (*28*).]

A later study by Cervero focused on LRT's land use impact and concluded that "the urban development possibilities of LRT appear substantial, though only if other pro-development forces exist." Land use incentives and supportive local policies were deemed essential adjuncts to foster desired development, Cervero emphasized (*29*).

Considerable circumstantial evidence exists that indicates that newly installed LRT lines do attract or reinforce significant adjacent real estate development. The following summary provides examples:

- San Diego Trolley: Important influence on suburban development near stations is reported; several transit center and joint development projects are noted; a \$120 million, 800,000-ft^2 mixed-use development is planned for downtown with an integral LRT station (*30–32*).
- Buffalo Metro Rail: LRT has been directly associated with downtown revitalization; over \$200 million in private downtown construction was committed during the first year of construction; adjacent downtown office space is expected to increase by one-third; over \$100 million in private development has occurred near one station alone; an extensive Theater District reconstruction boom is associated with the new LRT line (*29, 33*).

• Portland's Metropolitan Area Express (MAX): $214 million in adjacent private development was completed upon opening of the line; an additional $300 million is planned or under construction (*34*).

• Pittsburgh's LRT: The system has helped generate $1.5 billion in downtown construction; local developers are exploring the feasibility of commercial and office complexes at suburban stations (*35, 36*).

• Sacramento's LRT: RT Transit cites a list of developers who have invested in facilities to improve connection of their developments with LRT stations. Illustrative major impacts include a 465,000-ft^2 state office development with 3,000 employees and nearly 1 million ft^2 in adjacent office and retail development (*37*).

While the development-inducing effects of rail transit are generally perceived, professionally accepted ridership forecasting processes typically do not take them into account. The following are suggested as some of the most important reasons for this:

• Precise levels of development that could be attracted are extremely difficult to quantify.

• Real estate development tends to be unpredictable, with a staggering array of influential variables such as size and density of service area, economic conditions, length of line, character of immediate station sites, public attitude towards transit, local government policies, etc. Furthermore, land use regulation in U.S. cities is quite weak, leaving development significantly dependent on free-market forces.

• Researchers encounter great difficulty in distinguishing between transit-induced development and development that would occur otherwise.

• In alternatives analyses, typical procedures currently assume no differences in land use influences between different modes. In addition, inclusion of transit-induced traffic generation changes would likely increase the complexity and cost of modeling procedures.

These problems notwithstanding, it seems unrealistic for ridership forecasting efforts to assume, in effect, that a relatively massive investment in fixed-guideway transit stations, and its dramatic alteration of an urban landscape, will have no more effect on land use patterns, and experience no greater adjacent concentration of activity centers and other ridership generators, than ordinary local bus service.

Comparative Influences: LRT Versus Bus

It is generally recognized that all major public transport passenger facilities, from fixed-guideway stations to bus terminals and park-and-ride locations, can attract real estate development to some degree. However, fixed-guideway systems—particularly rail—are widely perceived to have especially strong influence both in the quantity of development attracted and in areawide impact. As a working paper prepared by the Austin (Texas) Planning and Growth Management Department observes (*38*):

> The influence of transit in stimulating development increases as the permanence and volume of the transit system increases. Bus systems which can be easily rerouted thus have less effect on development patterns than fixed guideway systems that represent a significant public commitment and generally carry a larger volume of passengers.

Directly discussing the relationship of LRT and development, Paaswell and Berechman have stressed a major difference between bus and rapid transit modes (*39*):

> Buses take people to where activities are and can follow the movement of activities over a wide geographic pattern. On a rapid transit line, there is a more active land use/transportation relationship. Large numbers of people are concentrated at specific spots, and activities become linked to the stops. Transit induces changes in station areas that often would not occur if no transit were there.

While the impact of most LRT facilities in terms of attracting or stimulating adjacent development seems evident, if not precisely quantifiable, the land use impact of busways is more debatable. Knight's 1977 study led him to conclude that "busway improvements have had no discernible impacts on land use to date" (*28*). In comparing exclusive busways versus LRT, Calgary's Transportation Department observed that "one of the advantages of a bus system is its flexibility. However, this characteristic reduces commitment to the facility. Therefore, busways do not influence land use to the extent that rail systems do" (*40*).

On the other hand, substantial real estate impacts are cited in connection with Ottawa's new busway system (*41*):

> The system operates just like any other rapid transit facility with vehicles, which in this case are buses, stopping at every station. In addition, ramp access is provided for express- and limited-stop routes so that a direct no-transfer service is provided between the residential street system and downtown and other major trip generators. . . .

> Much has been written about the development impacts of rapid rail transit. Preliminary indications in Ottawa-Carleton show that a similar relationship exists for busway systems. High-rise construction is already occurring at some stations and an integrated shopping centre/transitway station is nearing completion. In total, $600 million in new construction is already under way or in the final planning stages around Transitway stations.

It must be noted, however, that Ottawa planners possess some of the strongest land use regulatory powers existing in North America. Bonsall reports that a legislatively mandated land use and transportation plan was enforced to guide development in desirable patterns. Based on giving "precedence to public transit over all forms of road construction or road widenings" and implementing the bus-based rapid transit system, Ottawa's planning regulations require developers to concentrate developments near transit, orient buildings and private accesses to transit stops, provide walkways and transit-only roadways through developments, and enter into agreements with the municipality on matters such as staging construction to accommodate transit (*41*). While such formidable land use controls may be envied by many U.S. planners, it is most unlikely that the massive legal, political, and other obstacles to their implementation in U.S. cities could be overcome.

Despite the Ottawa busway's obvious success, many U.S. professionals and decision-makers continue to perceive a stronger potential for LRT in achieving land use objectives, all things being equal. Discussing LRT versus busway alternatives, San Jose-area planners concluded that "the light rail alternatives . . . generate the most opportunity for new development around major stations with a significant amount of developable land. The alternatives with a busway would provide slightly less opportunity. . . ." However, the planners noted that "light rail or a busway could be a catalyst to create the situation for this station area development to occur . . ." (*42*). Discussing the potential for transit-induced development in Seattle, Kask concluded that "high-capacity transit located in nonfreeway corridors would be more likely to generate significant transit-induced development; rail impacts would be the most significant" (*43*).

A likely factor in such conclusions is the smaller number of passenger stations associated with busway systems, due to reliance on collection and distribution activities off the busway. In addition, smaller congregations of passengers in each station could be expected for the same reason. Finally, mode-specific attributes such as air pollution and noise generated by motor buses may additionally act to suppress private developer interest in bus transit facilities in contrast to LRT, and thus may diminish the attraction of nearby real estate development and, ultimately, the ridership such development can generate.

Summation

Widespread circumstantial evidence of transit-induced development leads many planners to conclude that fixed transit facilities have the potential, in consort with other forces such as economic conditions, market demand, private developer cooperation, and public policies, to attract real estate development and thus create and expand their own traffic generators. Stations, serving as collectors of people, undoubtedly are the major influence in this phenomenon. LRT and other rail transit modes appear to have especially strong potential to attract such development; busway and other bus stations would seem to have significantly more land use effect than street bus operations.

Despite difficulties in predicting and quantifying these effects, research to enable their incorporation in ridership forecasting appears merited. For LRT, such adjacent development not only can produce short-term traffic generation to feed the LRT service, but may promise even more significant rewards in terms of securing steady, long-range ridership. To an undetermined extent, similar effects may occur in regard to busway stations. A major reexamination of rider-forecasting methodology would therefore warrant consideration. In the next section, research results touching upon this issue are discussed.

PERCEPTIONS OF DEVELOPMENT DECISION-MAKERS

The results of a recent study sponsored by Texas Association for Public Transportation (TAPT) provide some initial, tentative data related to certain ridership forecasting issues previously discussed.

Survey Description

In the fall/winter of 1987–1988 TAPT conducted a survey intended to elicit perceptions of individuals in a position to make decisions about real estate development at fixed-guideway stations in eight U.S. and three Canadian cities with relatively new LRT or busway facilities. It was expected that this research would begin to give some indication of the relative perceived attractiveness of each mode for real estate development. The target survey population was intended to consist primarily of organizations involved in real-estate development with emphasis on the private sector. A questionnaire addressing issues of real estate development and public orientation associated with LRT and busway systems was sent by mail to more than 200 organizations in the selected cities (copies of the questionnaire are contained in the project final report, which is available from the author).

It was hoped that such an assessment of relative perceived attractiveness would serve as a stimulus toward a more closely focused assessment of actual transit-induced development. However, the particular approach was undertaken because measurement of perceptions of real estate decision makers was comparatively less difficult to carry out. While a separate questionnaire was prepared for each individual system, customized to refer to that system by name to avoid misunderstanding, all survey questions were otherwise worded identically.

Survey Results

Because of the substantial differences between Canadian and U.S. cities in regard to land use regulation, transit policy, public acceptance of transit, and other characteristics, aggregation of Canadian data with that of U.S. systems has been deemed inappropriate; furthermore, the number of responses received to date from Canadian organizations pertaining to each of the two modes was regarded as insufficient to permit reliable statistical comparisons of new LRT and busway systems in Canada. For the remainder of this discussion, only data pertaining to new U.S. LRT and busway systems, for which sufficient responses for each mode were received, will be considered.

A listing of the nine systems surveyed in eight U.S. metropolitan areas, together with 1980 population and density data (taken from UMTA's Section 15 annual report), is provided in Table 2. As this exhibit indicates, 78 completed questionnaires have been returned from U.S. cities, yielding an aggregate response rate of 31 percent. About 64 percent of respondents represent organizations involved with real estate development (e.g., developers, construction firms, brokers, appraisers); the remainder are split about evenly between general businesses and public-sector planning and transit agencies that would also play a key role in real estate decision-making.

Statistical analysis of the questions dealing with the desirability of development near transit stations (questions A-1/B-1) and those concerning public understanding of system route structure and service (questions C-1/C-2) consisted of a one-tailed z-test. In this discussion of the survey, "LRT respondents" refers to those organization representatives responding to LRT system questionnaires; "busway respondents" refers to those answering busway system questionnaires. A tabulation of averaged responses for each of the U.S. systems surveyed is presented in Table 3.

TABLE 2 LRT/BUSWAY SURVEY INFORMATION: U.S. CITIES

Urban Area	1980 Population (Persons)	1980 Density (Pop./sq mi)	System ID	System Type	No. Orgs. Contacted	No. Orgs. Responding	Response Rate (%)
Buffalo	1,002,285	3,768	Metro Rail	LRT	23	9	39.1
Houston	2,412,664	2,300	Transitways	Busway	37	11	29.7
Los Angeles	9,479,436	5,189	El Monte Busway	Busway	22	4	18.2
Pittsburgh	1,810,038	2,539	The "T"	LRT	43	15	34.9
Pittsburgh	1,810,038	2,539	South/East Busways	Busway	43	14	32.6
Portland	1,026,144	2,940	MAX	LRT	17	10	58.8
Sacramento	796,266	2,864	RT Metro	LRT	16	4	25.0
San Diego	1,704,352	2,789	San Diego Trolley	LRT	27	6	22.2
Washington	2,763,105	3,424	Shirley Busway	Busway	24	5	20.8
TOTAL				LRT	126	44	34.9
TOTAL				Busway	126	34	27.0
TOTAL				ALL	252	78	31.0

TABLE 3 LRT/BUSWAY SURVEY INFORMATION: RATINGS

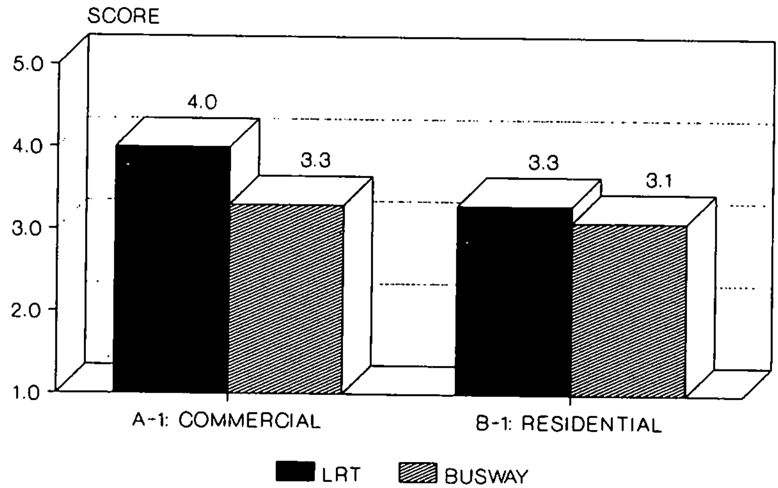
Urban Area	System ID	System Type	----Ratings---- A-1	B-1	C-1	C-2
Buffalo	Metro Rail	LRT	3.9	3.0	2.9	2.9
Houston	Transitways	Busway	3.4	3.3	2.2	2.4
Los Angeles	El Monte Busway	Busway	3.8	2.3	3.0	2.8
Pittsburgh	The "T"	LRT	3.8	3.7	3.9	3.8
Pittsburgh	South/East Busways	Busway	3.2	3.0	3.4	3.4
Portland	MAX	LRT	4.5	3.5	4.2	3.9
Sacramento	RT Metro	LRT	4.6	3.3	3.1	3.3
San Diego	San Diego Trolley	LRT	3.4	2.6	3.5	3.3
Washington	Shirley Busway	Busway	3.3	3.4	3.4	3.4
ALL		LRT	4.0	3.3	3.6	3.5
ALL		Busway	3.4	3.1	3.0	3.0

Real Estate Development

Results of the real estate decision-makers' survey are illustrated in Figures 1 through 5. Analysis of these survey results suggests that real estate decision-makers in the cities surveyed tend to perceive LRT stations as significantly more desirable than busway stations for commercial real estate development. Figure 1 illustrates the results of the question "Please rate the areas adjacent to the [system] stations as locations for commercial development" (question A-1), which yield a significantly higher mean "desirability" rating for LRT versus busway; statistical analysis indicates that this higher score is significant at the 99 percent confidence level.

Factors that these real estate decision-makers seem to perceive as particularly encouraging commercial development near LRT stations are the understandability of LRT's routes and service, its pleasant environment, and favorable land use regulations. Factors perceived as particularly discouraging development near busway stations would seem to include insufficient speed and service, poorly understood routes and service, and noise, pollution, or other environmental problems.

In regard to residential development, although the difference indicated was not determined to be significant at the 0.01 level used, a higher mean rating was registered for LRT. Factors perceived as particularly encouraging residential development near LRT stations would include, again, the understandability of LRT's routes and service and its pleasant environment. On the



KEY: A-1: Rating of areas adjacent to [system] stations as location for commercial development.
B-1: Rating of areas adjacent to [system] stations as location for residential development.

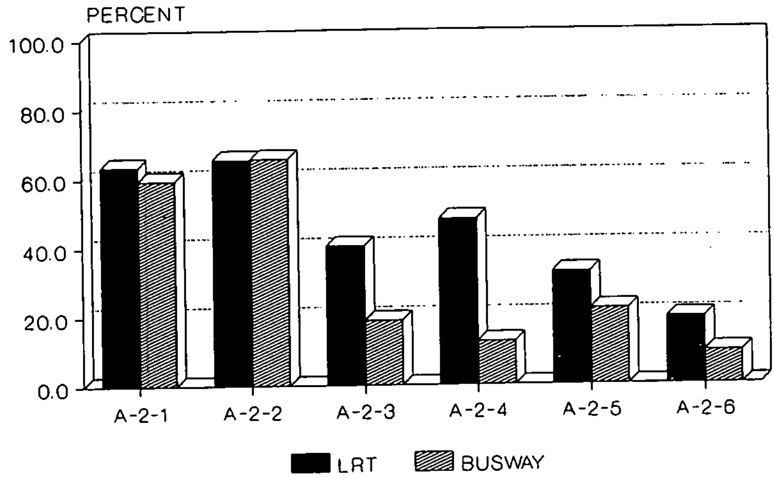
Scale: |---------|---------|---------|---------|
1 2 3 4 5
Undesirable Neutral Desirable

FIGURE 1 Development desirability scores: LRT and busway.

other hand, the availability of rapid transit appears to be perceived as an especially strong factor for busways in encouraging residential development adjacent to the system. Factors perceived as particularly discouraging development near busway stations would seem to be poorly understood routes and service, as well as noise, pollution, or other environmental problems.

Implications for Ridership Modeling

Results of the survey tend to suggest that there is some validity to the supposition that LRT is a stronger force than busway in commercial real estate development. If relevant decision-makers tend to regard LRT stations as significantly more desirable for development, it is reasonable to speculate that actual development might have a greater likelihood of materializing. Likewise, there are indications that fixed-guideway modes generally have more potential to attract development than street bus systems without stations and other fixed facilities. However, the quantification of such effects and differences is a subject for further research.



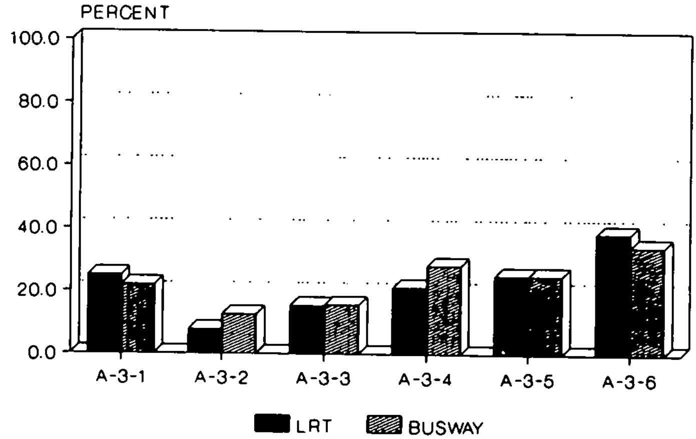
KEY: A-2: Factors strongly encouraging commercial development adjacent to [system] stations.
A-2-1 Lots of people gather there
A-2-2 Rapid mass transit is available
A-2-3 Route/service are well understood
A-2-4 [System] environment is pleasant
A-2-5 Favorable land-use regulations
A-2-6 Other

FIGURE 2 Commercial encouragement: percent respondents citing question A-2.

Nevertheless, while predictions of real estate development near transit stations are currently uncertain and unreliable, the potential for such effects could be approximated through the modeling of alternative land use/travel demand scenarios, with clustering of development near proposed stations being one scenario. An example of such a procedure is the Alternative Futures process initiated by the Austin Transportation Study in the 1970s, in which a redevelopment scenario assuming nodes of development at transit stations forecast ridership 7 to 8 percent higher than a base scenario without such land use effects (*44*). Such a process could be refined as more precise data regarding transit-induced impacts and modal differences are generated.

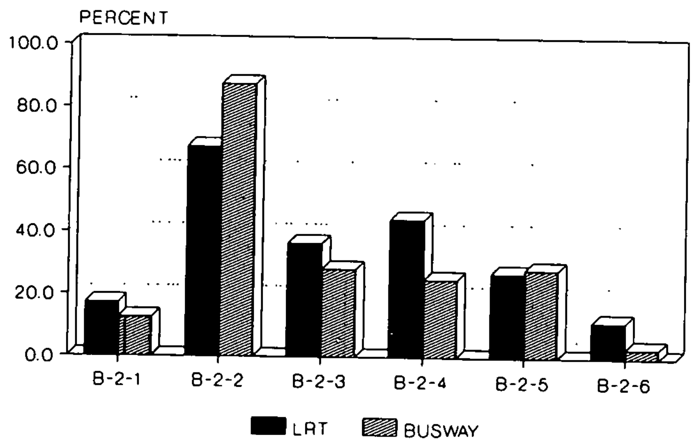
Public Orientation

While the survey results in regard to public orientation to a given system (see Figure 6) indicate higher average ratings for LRT, analysis at the .01 level did not find this difference to be significant. However, *z*-scores were sufficiently



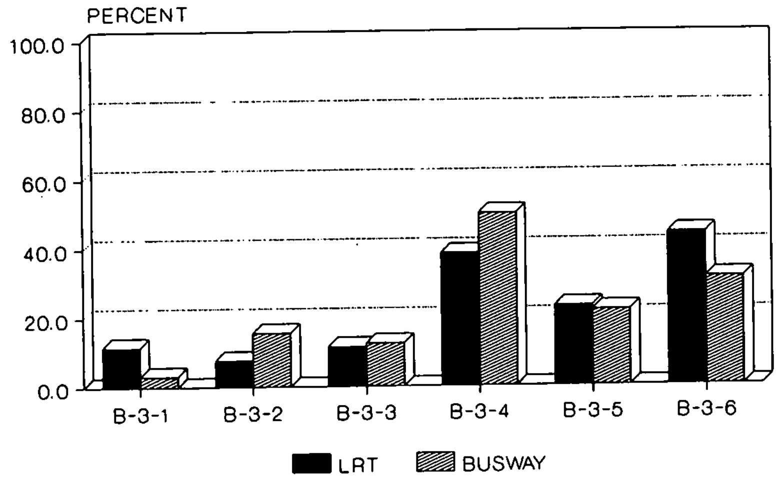
KEY: A-3: Factors strongly discouraging commercial development adjacent to [system] stations.
- A-3-1 Not used by enough people
- A-3-2 Speed/service not good enough
- A-3-3 Route/service are poorly understood
- A-3-4 Noise, pollution, or other environmental problems
- A-3-5 Unfavorable land-use regulations
- A-3-6 Other

FIGURE 3 Commercial discouragement: percent respondents citing question A-3.



KEY: B-2: Factors strongly encouraging residential development adjacent to [system] stations.
- B-2-1 Lots of people gather there
- B-2-2 Rapid mass transit is available
- B-2-3 Route/service are well understood
- B-2-4 [System] environment is pleasant
- B-2-5 Favorable land-use regulations
- B-2-6 Other

FIGURE 4 Residential discouragement: percent respondents citing question B-2.



KEY: B-3: Factors strongly discouraging residential development adjacent to [system] stations.
B-3-1 Not used by enough people
B-3-2 Speed/service not good enough
B-3-3 Route/service are poorly understood
B-3-4 Noise, pollution, or other environmental problems
B-3-5 Unfavorable land-use regulations
B-3-6 Other

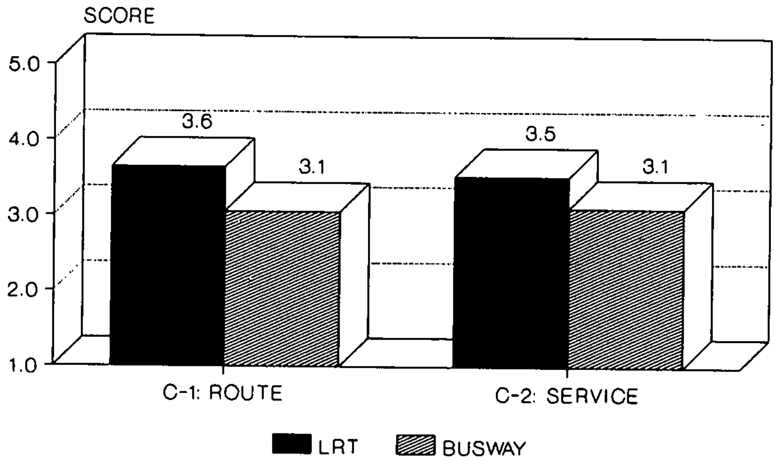
FIGURE 5 Residential discouragement: percent respondents citing question B-3.

high for both questions to provide strong justification for further research, e.g., to assess public attitudes directly.

CONCLUSIONS AND RECOMMENDATIONS

Improvements in the accuracy of transit ridership forecasting are essential. Significant underpredictions and overpredictions both can lead to costly errors in fixed-guideway implementation. However, gross ridership forecasting has not been the primary focus of this discussion, but instead the differences between LRT and motor bus as alternative transit modes. In this comparison, ridership projections represent one of the primary criteria on which most decisions are currently based, and for this reason must be made as realistic and accurate as possible; otherwise, poor investment decisions could be a consequence. Several considerations may be helpful toward this goal:

1. Problems of Current Methodology. While differences in LRT and busway operation (passenger access, headways, schedule speeds, etc.) are



KEY: C-1: Rating of how well, in respondent's opinion, [system] route structure is understood by the public.
C-2: Rating of how well, in respondent's opinion, [system] service characteristics (schedule, travel time, etc.) are understood by the public.

Scale: 1 — 2 — 3 — 4 — 5
Poorly Understood — **Neutral** — **Well Understood**

FIGURE 6 Public orientation scores: LRT and busway.

generally accounted for in current ridership forecasting methodology, important characteristics affecting ridership are omitted. These include differences in (a) passenger comfort and confidence and the level of public awareness and understanding of a given system, and (b) effects of possible real estate development in clustering traffic generators adjacent to transit stations. Preliminary evidence suggests that these factors are stronger for LRT than for busways; and while quantification is difficult, their exclusion from current modeling procedures may produce inaccurate results that underpredict potential LRT ridership vis-à-vis motor bus alternatives.

2. Need for Further Research. To further verify and resolve such possible deficiencies, investigative research appears essential, perhaps along the lines suggested earlier in the paper. Initially this could involve public surveys, particularly in urban areas where both LRT and bus modes are operated. Inclusion of other modes such as heavy rail rapid transit, commuter rail, and automated-guideway transit might also be considered.

3. Possible Alternatives to Procedures and Models. Current ridership forecasting procedures typically predict a single calculated passenger volume for each alternative mode for a targeted design year. This can tend to give an inappropriate illusion of certainty when such figures are considered in evaluation and decision-making. In view of the forecasting weaknesses discussed in

this paper, changes to prevailing forecasting procedures might be considered: (a) predictions could be presented in the form of ranges of potential ridership volumes reflecting various assumptions as to public attraction to alternative systems; and (b) alternative land use/travel demand scenarios, with clustering of real estate development near stations modeled, could be generated to reflect the potential impact of different modes and provide a richer information base for decision-making.

If research eventually validates and quantifies significant mode-specific differences in passenger attractiveness and real estate development, efforts should be made to translate such results into improvements in the accuracy of forecasting models and techniques.

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Streetcars for Toronto Committee

A Case Study of Citizen Advocacy in Transit Planning and Operations

Howard J. Levine

Determined to save Toronto's streetcars, a citizen advocacy group, the Streetcars for Toronto Committee, formed in 1972. By issuing an authoritative paper challenging the Toronto Transit Commission staff's plan to abandon streetcar operations and by dealing effectively with the media, the committee persuaded the transit commissioners to retain the metropolitan area's streetcars. Since then, the committee has gone on to fight other transit battles, representing transit users who favor more efficient and cost-effective transit alternatives. The committee has become a model for citizen action elsewhere and currently is promoting "realistic" light rail transit as a component of Toronto's long-range "Network 2011" plan, which calls for a conventional heavy rail subway.

ALTHOUGH THE AUTHOR WAS a founding member of the Streetcars for Toronto Committee and is still active in its pursuits, an attempt has been made to describe the committee's formation and development from as objective a viewpoint as possible. The paper should not be construed as a textbook primer on public participation; rather, it is an examination of the evolution of a group of concerned citizens that was created on reaction to political decisions that were being made on the basis of technical and professional analyses of a specific issue, in this case whether to commence abandonment of the streetcar network in Toronto in the early 1970s.

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By relating the steps that were undertaken by the committee in challenging that initial proposal for streetcar abandonment, the development of a citizen advocacy group specifically concerned with transit planning and operations can be described. Furthermore, it will be shown how this group became an effective and widely recognized political lobbying and pressure group.

Public involvement in the transit field has become an accepted concept reinforced by legislation in almost all jurisdictions across North America. Citizen reaction and involvement have had particular impact in the development of light rail operations in the U.S. and Canadian cities where this mode has been implemented over the past dozen years or so.

FORMULATION AND INITIAL AIMS

By autumn 1971 the Toronto Transit Commission (TTC) had decided in principle to begin phasing out its vast streetcar system (*1*). By 1980 there were to be no more streetcars operating on the streets of Toronto, the last city in Canada to have a streetcar network. As early as 1952, a report had been prepared by the TTC (2) that indicated a policy to eventually eliminate the streetcars although, by that time, the TTC had the largest operating President's Conference Committee (PCC) fleet in North America. In 1966 (*3*) an agenda had been developed for gradual elimination of the system. The first line to go was St. Clair. It was replaced by trolley buses made surplus by the conversion of the intensive Yonge Trolley Coach to diesel buses in conjunction with the extension of the Yonge Street subway. It was ironic that St. Clair was chosen as the first route to go, as the line was originally constructed on its own central right-of-way along one of the widest thoroughfares within the City of Toronto proper. This conversion was, interestingly, being planned at the same time that the light rail concept was beginning to gel and gain support on this side of the Atlantic (*4*).

In late summer 1972, two City of Toronto aldermen from the north wards, Paul Pickett and William Kilbourn, called a public meeting at City Hall. Over 100 citizens from all over the metropolitan area jammed a committee room, all expressing commitment for retaining the streetcar as an important aspect of Toronto's transit system. A call was made for those interested in working on a committee to meet the following week, at which time the Streetcars for Toronto Committee was formally initiated.

In all, about a dozen individuals came together to devise strategies to oppose the streetcar abandonment program. The chairman was a professor of child psychology from the University of Toronto, Andrew Biemiller. The vice-chairman was Steve Munro, a computer programmer. Other members included Mike Filey, a historian; Ross Bobak and Chris Prentice, then university students; Robert Wightman, a secondary school teacher with a background in electrical engineering; and the author of this report, an urban planner. Instead of devoting energy to organizing mass demonstrations, it was decided at the outset that all efforts would be pooled to produce a documented argument for retention. This argument was to be thoroughly researched, technically correct, and as emphatic as possible in putting forward sound and logical evidence in support of the streetcar.

In preparing the paper, a meeting was held to organize the content and to assign various sections to those with a particular interest or background in that subject. To begin, it was decided that a history of the TTC would preface the positions that were to be developed. This would be followed by a section dealing with the current status and operations of the TTC in general as they relate to metropolitan Toronto, the TTC's service area. Next would come a more technical section that would address the operational aspects of the proposed streetcar conversion program. Immediately thereafter, a critically important section would attempt to detail the financial aspects of the streetcar conversion program. Finally, a summary would repeat the most important points that the committee wanted to highlight.

It was agreed that the paper would be documented as much as possible, preferably by the TTC's own reports. Additionally, the format used by the TTC in relating details and operating statistics in its own reports would be copied. At all times the paper would be positive in its approach and would scrupulously avoid innuendo and any aspect of personal attack.

Thus, the format and the content were determined prior to the actual writing. Moreover, each writer agreed to compose that part of the paper that related to his own particular interest or expertise. It would truly be a committee effort, but would be honed, tailored, and rewritten at least twice by all those involved at a general meeting where all would be encouraged to criticize each other's contributions. The term "devil's advocate" took on real meaning at these sessions.

The critical importance of educating the public, the politicians, and, most important, the media, was recognized from the very beginning. Accordingly, it was agreed that as soon as the report, "A Brief for the Retention of Streetcar Service in Toronto," was completed, a one-page news release with two fact sheets would be produced to summarize it for widespread distribution throughout metropolitan Toronto.

The brief was a comprehensive 18-page document that put forward a succinct argument in favor of streetcar retention, based on widely accepted economic, engineering, and land use planning principles. In addition, an attempt was made to elucidate the subjective values of the streetcar system as an integral component of the city's history contributing to Toronto's unique character among the major urban centers of North America. Finally, the brief focused on the streetcar as an important social component of Toronto that greatly contributed to the city's claim as one of North America's most livable cities of its size.

The committee recognized the role that the media would have to play in presenting to the public the issues that were involved in either retaining or abandoning the streetcar system. It was agreed that there would have to be at least a 3-week period prior to the TTC meeting at which that decision would be made. Fortunately, one of the committee's members had had first-hand experience for some time in dealing with the press and with the television and radio stations in Toronto. As a popular historian, Mike Filey had written several books about Toronto and had dealt with the media in publicizing his works.

A formal press conference was held at City Hall on October 17, 1972, to unveil the brief. Six days later, the committee chairman presented the brief to the City of Toronto Council's public works committee so that the paper could be officially received and commented upon by the local politicians prior to its presentation to the TTC. All facets of the media picked up the story, and the airwaves and newspapers were filled with interviews, commentary, and editorials. In retrospect it was indeed a wise decision to allow a 3-week lead period for disseminating the brief. The issue was allowed to develop into one of high visibility and interest.

By the time of the November 7, 1972, TTC meeting, it seemed that everyone had become aware of the issue and had reached his or her conclusion. The committee had succeeded in making the issue one of significant public concern. The preparation of easy-to-read fact sheets and a one-page press release to summarize the salient points was a lesson in dealing with the media that the committee has retained to this day. Lengthy, convoluted arguments do not reach the public or the politicians, because the media generally refuse to even read such documents, let alone boil them down on their own. The committee foresaw this and devoted considerable energy to making readily digestible documents available.

Underlying all formulation of strategy and position was the concept of committee, each member contributing his expertise and everyone criticizing everyone else in a forum setting. The desire to second guess the decision-makers was a constant throughout all the steps leading to the release of the brief, be it preliminary discussion, individual preparation, or committee review. This process has also remained with the committee.

At its November 7, 1972, meeting the TTC, whose members are appointed by the Metropolitan Toronto Council as a mix of politicians and citizens, unanimously decided to retain the streetcar system although TTC staff had recommended that the St. Clair street line be abandoned as the first phase of total street railway elimination (*5, 6*). In retrospect, that decision has proven to be one of the most significant in the recent history of public transit in

Toronto, not only from the standpoint of the physical system, but from the effect that citizen advocacy and public pressure had on the TTC in a manner never before experienced.

MODIFIED GOALS

With a major victory in its favor (reconfirmed by the TTC in May 1973) (7), the Streetcars for Toronto Committee immediately reexamined its role and realized that an effective transit lobby group could have a beneficial impact on metropolitan Toronto in terms of better user-oriented public transit. Therefore, it was decided that the committee would, above all, represent those who actually used public transit and would attempt to focus political and media attention on more cost-effective transit development and operations than were being proposed.

At the same time that important transit decisions were being concluded at the local and regional levels in Toronto, even more significant events were occurring at the provincial level as the Province of Ontario began to assume an ever-increasing role in public transportation. The provincial Ministry of Transportation and Communications was commencing a major initiative in terms of financial assistance for both capital and operating costs of municipal transit throughout Ontario. The implications of vastly increased provincial involvement through extensive funding were quickly materializing. They were explicitly emphasized by the establishment of the Ontario Transportation Development Corporation, which would shortly transform itself into the Urban Transportation Development Corporation. The Streetcars for Toronto Committee soon had an entirely new area of concern as the province began to exert its influence in metropolitan Toronto.

CHANGING INTERESTS

Following the retention of the streetcar system in late 1972, the committee began work on a number of projects, all directed at initiating new concepts and improving current aspects of the transit system in Toronto. Among these was the proposal in 1973 to restore a 1920s Peter Witt car for a tourist sightseeing service. Now franchised to a private operator, the Witt tour has become an integral part of the downtown Toronto tourist scene. Another project was the proposal to convert the Bay Street diesel bus service to trolleybus for environmental and better fleet utilization purposes. In June 1973, the committee presented a "Brief for the Establishment of Light Rapid Transit on Spadina Avenue," the first instance in which any agency or group had proposed such a scheme. As an aside, it's interesting to note that when the Spadina LRT proposal was reintroduced by the TTC in this decade, no mention was made of the committee's early initiative, which, in retrospect, was far simpler and much more sympathetic to the complex urban framework than the current TTC scheme, which is still mired in community and political controversy.

In November 1973, a little over a year after its initial victory, the committee came face-to-face with provincial might, as the Ontario government's ill-fated GO-Urban project was thwarted by the committee's document that successfully challenged the unproven assumptions of that magnetically levitated automatic system. The committee's contention that GO-Urban's claims were "naive, inaccurate and misleading" was completely vindicated as the province pulled the plug on its grandiose visions of science-fiction transit encircling Toronto on 90 mi of guideway. As part of its efforts in this struggle, the committee prepared an overview of light rail as "A Viable Form of Intermediate Capacity Transit," which was presented before various committees and bodies in metropolitan Toronto. Accompanying this paper was a series of slides and a commentary that are still pertinent today, almost 15 years later.

THE COMMITTEE IN THE 1980s

Provincial influence in municipal transit became a fact of life as Ontario increased its financial contribution in the late 1970s. Obviously, while paying for more and more, the Ontario government wanted a bigger say in the planning and operations of public transit. The provincially owned Urban Transportation Development Corporation (UTDC) was a strong manifestation of the provincial interest in transit, but the UTDC itself was being used by the province as a means to implement transit developments. Even more significantly, transit developments themselves were being proposed as a means to generate business for the UTDC. It was this latter situation that stimulated the resuscitation of the Streetcars for Toronto Committee in the early 1980s.

The City of Toronto Council decided in early 1984 to challenge the agreement concluded by the TTC and by the Metropolitan Toronto Council to purchase 52 articulated light rail vehicles (ALRVs) from the UTDC. The city argued its case at the Ontario Municipal Board (OMB), a quasi-judicial body that oversees major municipal decisions and purchases. The city believed that the cost was too high and that the use of these high-capacity vehicles would be detrimental to the service levels on the streetcar routes in operation on city streets. The committee was asked to prepare a commentary and position paper by the two aldermen who presented the motion. In addition, the committee was asked to work with the city solicitor and to participate on the city's behalf at the OMB. Unfortunately, the OMB refused a full hearing and the UTDC was allowed to conclude the deal without a tendering of any kind. (It is interesting to note that almost 4 years later, in January 1988, the TTC accepted one of the ALRVs for revenue service on the Long Branch route, a route that would not normally see articulated operation.)

Provincial influence was also very much in evidence when the TTC decided to replace conventional light rail technology as the operating mode on the Scarborough extension to the Bloor-Danforth east-west subway line. Instead of conventional light rail, the line would now use the UTDC's automated intermediate-capacity system, which was developed after GO-Urban had been scrapped. The Province of Ontario agreed to pay for all additional costs that this new system would require over conventional light rail. Following this decision, the Streetcars for Toronto Committee utilized the media, not only to express its strong reservations about the change in technology, but also to expound on the virtues of conventional light rail.

On other matters, the committee has continued its activities in the struggle to retain the trolleybus system in Toronto. For almost 5 years, the committee has responded on at least three occasions to efforts by the TTC staff to convince the commissioners to eliminate the trolleybus completely from TTC operations. At this writing, management has been promoting TTC natural gas-powered buses as replacements for the trolleybus fleet.

Additional areas of concern for the committee have been the committee's own initiatives: daily passes, "short turning" of streetcar service, and rebuilding of PCC streetcars (besides the Spadina streetcar and the Bay trolleybus previously mentioned). In responding to issues such as night owl service and the long-range "Network 2011" transit plan for metropolitan Toronto, the committee followed a set pattern of participation, namely a response to the specific official document and the position(s) therein on the basis of step-by-step analysis utilizing the TTC data as much as possible. The committee's reports are written mostly as a group effort with participation from the members in critical self-examination prior to its final draft. Second guessing the decision-makers is still a strong practice and summaries are carefully prepared for the media.

CONCLUSIONS

In responding to what appeared to be a crisis situation, namely the imminent elimination of Toronto's streetcars, the Streetcars for Toronto Committee was formed as a means for citizens and transit users to express their opinions directly to the decision-makers. Circumstances brought together a group of articulate and dedicated individuals determined to have an influence on those who had been chosen to make critical decisions that would have immediate and, more important, long-range ramifications, not only on the transit system per se, but also on the character and direction of Toronto itself.

Examples in which the public has ignored similar situations regarding their transit systems and, particularly, regarding their streetcars were plentiful in North America. Viewpoints at odds with those being put forward by officials in positions that have the attention and trust of policy-makers more often than not fail to gain adequate exposure. It is all too common for those actually responsible for running a system, any system, both to ignore day-to-day problems and to view the overall operation with tunnel vision. The reaction to outside criticism, to suggestions, or to innovation often becomes an automatically negative one, initially defensive but often evolving into an offensive one in order to preclude anyone from commenting. This is hardly the way to be responsive to public input.

The Streetcars for Toronto Committee, after 15 years, remains a small group of concerned transit advocates who have had significant impact on public transit in metropolitan Toronto. Although adversarial in essence, often opposing positions being taken by technical staff, the committee has always avoided personal confrontation, although a recent statement by the TTC chief general manager at a public meeting called to hear citizen input accused the committee of attempting "to con the Commission and the public." Needless to say, the committee members were shocked and dismayed and vowed to continue their efforts as a citizen advocacy group in such a way that this accusation, although totally unwarranted, would continue to be without substance.

As discussed, the committee's methodology has been followed meticulously since the group's inception. By a rigid insistence on being as accurate and as responsible as possible, facts and figures that have been presented in the committee's documents have always been substantiated. The TTC commissioners have consistently respected the viewpoints of the committee and have always listened attentively to the committee's presentations. Moreover, planning and technical staff have, on numerous occasions, requested input and feedback from the committee, albeit on an informal basis.

Thus, responsible and informed public participation can have a positive contribution to both the planning and operating of public transit. Such input should be encouraged and ultimately made a mandatory component of a transit undertaking. Although experience in Toronto has been much more positive than negative, there are still many who view the committee strictly as an adversarial group. This is indeed unfortunate, to say the least, for a more receptive approach to public input can channel creative energy into positive solutions in the vast majority of situations.

Over the years, the committee's efforts have become known outside of Toronto. For example, citizen groups concerned with public transit projects in

Hamilton, Ottawa, Vancouver, and Victoria have contacted the committee for insight into how to operate as well as for technical information. Although efforts in those cities by these groups have been mixed in terms of affecting decisions relating to the various transit schemes, the experience of the Streetcars for Toronto Committee has proven to be useful. This is especially the case in terms of the methods of publicizing positions and getting the most out of the media. In all instances the need to be responsible and accurate has always been stressed for those on the citizen side, just as much as it is expected for those in an official capacity. Surely this advice is universally applicable.

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PART 3

New Light Rail Transit Systems and Lessons Learned from Start-Ups

Infrastructure Rehabilitation and Technology Sharing in Bringing LRT to St. Louis

DOUGLAS R. CAMPION AND OLIVER W. WISCHMEYER, JR.

Metropolitan St. Louis, after 19 years of planning, is developing a dual-mode, cost-effective public transportation system integrating light rail technology with a vastly improved regional bus network. The light rail transit component, known as Metro Link, is an 18-mi continuous fixed-guideway rail line connecting the St. Louis, Missouri, central business district with the Lambert International Airport and McDonnell-Douglas complex to the northwest and with East St. Louis, Illinois, to the east across the Mississippi River. Complementing Metro Link are shuttle bus operations to major employment centers, and realigned routes that form an extensive feeder bus network in the corridor. The initial rail line will directly connect the principal retail, office, recreational, educational, medical, and transportation activity centers with the densest urban population areas. Existing infrastructure is being used, including right-of-way, structures, and facilities to be acquired from two railroads. Nearly all the railroad property is abandoned, but will be revived for this light rail system. Additionally, street and highway right-of-way and other public lands will be made available for permanent Metro Link easements. The capital expense budget for building Metro Link is $287.7 million, covering design and engineering, construction and procurement, testing and start-up, and project management. As a federally funded project, this capital expense is matched with railroad property and facilities acquired separately by the City of St. Louis and donated to the project with a value in excess of $100 million.

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FOR NEARLY THREE DECADES most American cities have relied on the conventional urban bus as the primary form of public transportation. Whether riders are transit dependent or riders by choice, their alternative to the private automobile has been and still is, principally, a bus—a form of public transit that must ply the same congested highways, downtown streets, and intersections as the automobile. In larger cities, where population densities and ridership justified a significantly higher level of public transit service, rail rapid transit and commuter rail have continued to serve as major modes of travel in key corridors. Since the 1960s many cities—for example, San Francisco, Washington, Atlanta, Miami, and Baltimore—have developed new rail rapid transit systems.

St. Louis metropolitan-area decision-makers and planners have searched unceasingly since the late 1960s for an ideal solution to the public transit needs of their region. A chronology of events and activities over 17 years led to preliminary engineering for the current project. As the record reveals, St. Louis had its share of false starts and reconsiderations, and St. Louis officials found themselves caught in the ever-changing federal policy maze.

OVERVIEW OF ORGANIZATIONS INVOLVED

In the St. Louis (Missouri-Illinois) metropolitan area two primary organizations are involved in transit planning and programming: the regional council of governments, East-West Gateway Coordinating Council (EWGCC), and the regional transit operator, Bi-State Development Agency (BSDA). In addition, the City of St. Louis and the County of St. Louis (which are completely separate political jurisdictions) are active participants in all transit-related matters.

EWGCC was formed in 1965 as a metropolitan association of local governments. Its two-state jurisdiction includes the City of St. Louis, four counties (including St. Louis County) in Missouri, the City of East St. Louis (Illinois), and three Illinois counties. EWGCC serves as the metropolitan planning organization for the region. The council's board of directors is composed of 14 chief elected officials from local county and municipal jurisdictions; 6 citizens from the region, appointed by elected officials; and the board chairman of the regional transit operator, BSDA. EWGCC is financed by cash contributions (based on a per capita assessment) from member jurisdictions, state contributions, and federal grants.

BSDA owns and operates the regional mass transit system. It also owns and operates the general aviation Bi-State Parks Airport, operates the Gateway Arch tram system, and serves as the regional coordinator for the Port of Metropolitan St. Louis. BSDA was created in 1949 through a compact between Missouri and Illinois ratified by the U.S. Congress. It was given broad powers to plan, construct, maintain, own, and operate specific public works facilities and services. BSDA serves the City of St. Louis, three counties (including St. Louis County) in Missouri, and three counties in Illinois, an area that covers nearly 3,600 mi^2. BSDA is governed by a 10-member board of commissioners appointed by the governors of Missouri and Illinois (five members by each) to 5-year terms. BSDA has no taxing powers, but is a quasi-public agency authorized to issue tax-free industrial revenue bonds, collect fees, and receive funds from federal, state, and local governments.

In 1963, in an effort to stabilize mass transit service in the St. Louis metropolitan area, BSDA was empowered to take over and consolidate 15 separate transit providers. Subsequently, in 1973, a ½-cent sales tax for transit/transportation purposes was authorized by the Missouri General Assembly in the City of St. Louis and County of St. Louis. The city and county annually appropriate these funds in whole (for the city) or in part (for the county) to support BSDA transit operations. BSDA receives support for transit services in Illinois via a downstate transit tax allocation and ¼-cent sales tax in areas of two counties served; both sources of funds are tied to purchase of service agreements annually.

PROJECT HISTORY

In 1983, funding was approved for an alternatives analysis study for the central/airport corridor, which had been shown to be a prime target for major transit investment since 1971. This new alternatives analysis study encompassed five primary alternatives. In July 1984, culminating the alternatives analysis process, a public hearing was held on the draft Environmental Impact Statement (EIS). After receiving all public comments, the EWGCC board adopted a modified light rail transit (LRT) alternative for implementation.

This preferred alternative included LRT between East St. Louis and the University of Missouri's St. Louis (UMSL) campus, all via abandoned or underutilized railroad right-of-way and facilities. The lines then extended to Lambert International Airport and the McDonnell-Douglas headquarters and manufacturing complex at Berkeley (Missouri) via either mixed traffic operation along an existing collector street (Natural Bridge Road) or an exclusive light rail alignment using the Interstate 70 right-of-way. This preferred alternative included a conceptual set of bus service and realignment provisions to effect a feeder bus system to light rail stations and regionwide bus improvements. The estimated capital cost of the light rail component, including more than 18 mi of line, 24 or 25 stations, and 34 vehicles, was put at $250 million in escalated dollars.

The innovative financing developed for funding the preferred alternative was critical to the project's acceptance. The City of St. Louis explored with affected railroads their willingness to provide right-of-way at zero or minimal capital outlay by local government. Compensation for the railroads would entail a swap of the city-owned, and still very much operating, MacArthur railroad bridge across the Mississippi River, public assumption of maintenance responsibilities for railroad bridges in the alignment, and provision of operating rights for one of the railroads on a portion of the acquired line to allow limited freight switching to continue. With an agreement in principle from the railroads to consummate such a transaction, these potential assets were appraised and determined to have a value, if donated to the project, sufficient to cover the 25 percent local-share matching requirement for UMTA capital grant funds under the new start category of the discretionary capital program (Section 3, Urban Mass Transportation Act of 1964, as amended).

UMTA, meanwhile, was expressing considerable reservations about the local decision to pursue the preferred alternative, light rail, rather than the transportation system management (TSM) alternative. Further, although UMTA had provided guidance on the appraisal of railroad assets value, they were not prepared either to accept the appraisal results or to commit to ruling that such assets were indeed eligible to meet local-share matching requirements. But the project's logic, financial feasibility, and uncanny adaptation and reuse of existing infrastructure had now surfaced unmistakably at the local level and in Congress. Through earmarking, Congress designated $2 million in Section 3 funds for a preliminary engineering effort on light rail. Locally, another $1.5 million was allocated from the region's formula allocation of UMTA Section 9A funds, and local cash was raised to provide the match for both UMTA program monies. An application to UMTA for these grant funds was filed by EWGCC in August 1984.

What ensued thereafter was a fairly typical iterative process of application reviews and comments by UMTA. Evidenced in the application review cycle, however, was continued reluctance by UMTA to accept the local decision to pursue light rail. Fortunately, the new budgeting cycle at the federal level was advancing through Congress simultaneously. In anticipation that the St. Louis light rail project would continue to prove its merits through the preliminary engineering analyses and design, Congress acted to again earmark new-start monies for it. The fiscal year 1985 budget earmarked another $10 million for St. Louis; these funds were to be used to initiate final design and construction.

In February 1985 the EWGCC received approval of its grant application to proceed with preliminary engineering on the locally preferred alternative. UMTA, in approving the grant request, stipulated that St. Louis must also evaluate further the no-action and TSM alternatives at the same level of detail as light rail. The EWGCC also agreed to review its demand forecasting, assuring UMTA that the models would be validated (and recalibrated using 1984 on-board survey data from the transit operator) and entirely new travel projections used for preliminary engineering. A final EIS and the UMTA-required cost-effectiveness analysis would also be prepared. The stage and financing for advancing transit improvements were set.

On July 1, 1985, consultants were hired, an EWGCC light rail project office was established, and the preliminary engineering phase was begun—including the additional alternatives analysis and a third demand forecasting techniques assessment.

Demand forecasting techniques were assessed and found to be satisfactory, models were recalibrated and validated, networks for each alternative—including three subalternative lengths of the preferred LRT alternative—were prepared, and travel projections were made. In response to the direction given by the EWGCC board as a result of the draft EIS public comment, analysis of the alternative alignments to reach the airport and Berkeley concluded in the selection from six options of a route that would use Interstate and airport rights-of-way, avoiding any mixed traffic operations on existing thoroughfares and eliminating one or two passenger stations that optional alignments would have required. The initial design work also determined that a major improvement in the alignment in East St. Louis could be made, eliminating in-street trackage and one proposed passenger station. Initial operational analysis also led to a reduction in light rail vehicle (LRV) fleet requirements from 34 to 31 cars, and major changes in the preferred alternative in the downtown St. Louis portion of the line. Detailed modeling work on patron access and egress, and productions and attractions by traffic analysis zone, revealed little negative impact on ridership but substantial positive impact on travel times, and capital and operating costs from the elimination of two underground passenger stations downtown.

All of the preliminary engineering phase activities were augmented and enhanced by third-party oversight. In addition to locally staffed technical, policy, and design review advisory committees that met at least monthly to critique the work constructively, a peer review group and value engineering workshop were convened. The peer review group, composed of seven transit industry professionals from across North America, met at the end of January 1986 in St. Louis to consolidate and tender their critique after several weeks of individual reviews of technical documents. Similarly, a consultant team was given an independent contract to perform a value engineering assessment. This culminated in a week-long value engineering workshop on-site in April 1986.

After 12 months of analysis and design, the preliminary engineering phase was completed. The refined LRT alternative proved through environmental assessment and cost-effectiveness measurements to be the most feasible and prudent course to follow. Engineering and architectural plans were completed to an aggregate 30 percent of design level, with decisions solidified on station locations, track geometry, vehicle requirements and design, construction and procurement contracts and schedules, financing plan, and other deployment details. The initial system of integrated bus services and routes with LRT was defined, detailed, and costed. The time, the option, and the opportunity to deal effectively with travel needs in one key corridor in the region had arrived.

METRO LINK ROUTE

The St. Louis metropolitan area rail transit system, known as Metro Link, is an initial 18-mi continuous fixed guideway rail line from East St. Louis (Illinois) through the St. Louis (Missouri) central business district to the Lambert International Airport and McDonnell-Douglas complex at Berkeley (Missouri). Complementing Metro Link are shuttle bus operations to major employment centers and a realigned regional bus system. The initial line will directly connect the principal retail, office, recreational, educational, medical, and transportation activity centers (see Figure 1).

Metro Link will make maximum use of existing infrastructure. Adaptive reuse of infrastructure is, through rehabilitation of freight railroad rights-of-way and structures, the backbone of Metro Link's feasibility. Included are the historic 113-year-old Eads Bridge (which spans the Mississippi River), the Washington Avenue-Eighth Street railroad tunnel (which runs from the Eads Bridge under the St. Louis central business district), the historic St. Louis Union Station baggage tunnel, a former rail passenger car repair facility and yard, and nearly 14 mi of continuous railroad trackage and right-of-way. Additionally, street and highway right-of-way and other public lands will be made available for permanent, exclusive Metro Link easements. The initial Metro Link alignment will be on a reserved right-of-way, exclusive except for 16 to 18 low-volume street crossings that will be accommodated using common railroad at-grade crossing protection devices.

Because of the availability of existing railroad, highway, and other public rights-of-way, the Metro Link project requires very little real estate acquisition and associated relocation. Near the airport a total of nine single-family residences, all of them under the airport's principal flight path, will be acquired. Elsewhere, only four business properties, three of them at-grade parking lots, will be acquired.

Table 1 displays the Metro Link alignment type and route miles of right-of-way. The existing railroad rights-of-way are being donated by the City of St. Louis to the project after the city has innovatively acquired ownership from

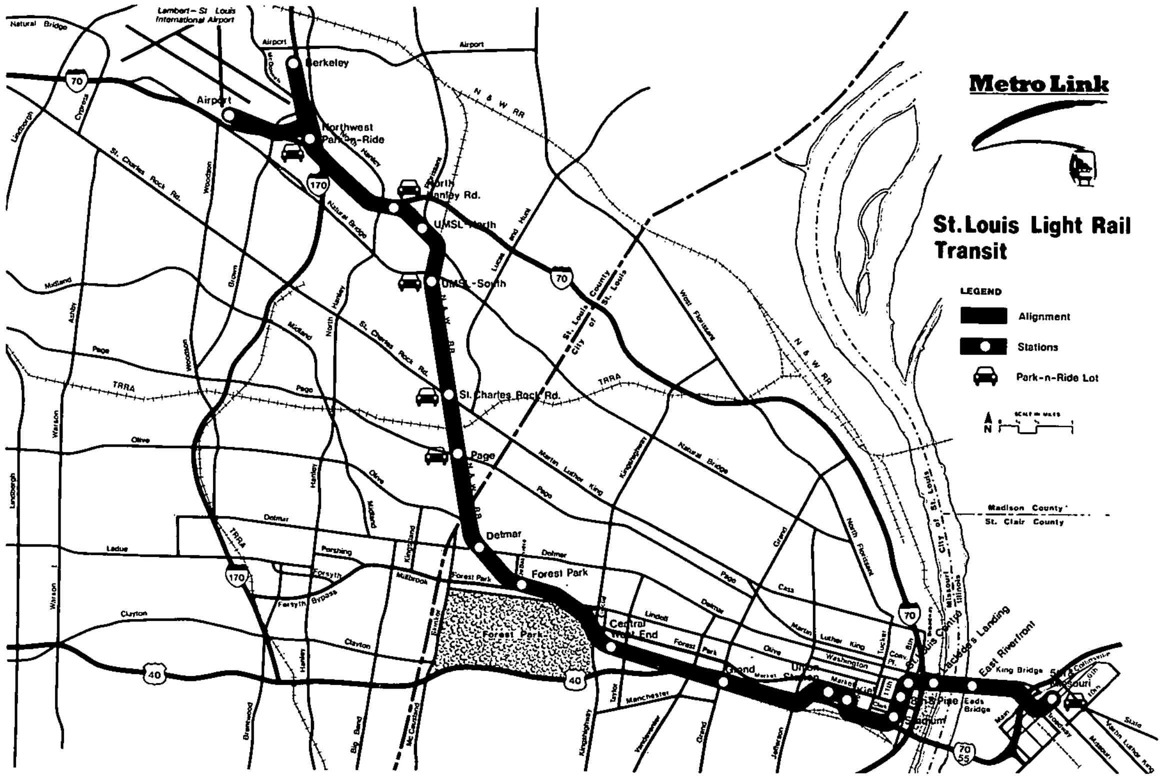

FIGURE 1 Metro Link route map.

TABLE 1 METRO LINK ALIGNMENT/RIGHT-OF-WAY

Alignment Type	Existing R.R. ROW (mi)	Other ROW (mi)	Total (mi)	Percent
At grade	11.8	3.4	15.2	84
Elevated	0.9	0.9	1.8	10
Subway	0.8	0.2	1.0	6
Total	13.5	4.5	18.0	100

the railroads. In the "other right-of-way" category, less than 1 route mile must be acquired from private landowners; the remaining mileage will be made available for exclusive Metro Link use by public entities through permanent, no-cost easements.

DESIGN PHILOSOPHY AND CRITERIA

Not unlike circumstances in the vast majority of its counterpart urban centers across the country, St. Louis had no existing LRT system of its own from which officials could garner practical, local design requirements. The last streetcars in St. Louis ceased operating in May 1966. Consequently, and for better or for worse, the Metro Link managers had to develop a design philosophy without current home-grown experience with light rail. Fortunately, St. Louis came to the preliminary engineering phase with reasonable and pragmatic plans, and at a time when other cities that had already completed a like journey could be tapped for guidance.

At the outset of preliminary engineering the governing charges to staff and consultants were made clear and definitive. Metro Link would be designed based on off-the-shelf equipment, proven technology and construction practices and techniques, strict adherence to budget and schedule, and conscious consideration of every opportunity to incorporate provisions for future system enhancements and extensions. Part and parcel of each of these charges were the overriding goals that the end product be safe, reliable, maintainable, effective, and efficient. Philosophically, then, the initial 18-mi Metro Link system would be capable of being implemented quickly and would provide at least basic rail service that constituents would find immediately successful.

From that rather fundamental and clear project genesis, preliminary engineering proceeded to meet its 1-year completion schedule within its $4.5-million engineering budget and to design a system that, with little risk of overrun, can be deployed for approximately $288 million (escalated dollars) in capital expenditures.

The design philosophy had to be translated into design criteria. To that end, criteria were liberally adopted or adapted from other systems. Because nearly 14 mi of the initial 18-mi alignment are railroad right-of-way with structures built for freight traffic, trackway and trackwork design criteria were fashioned along American Railway Engineering Association (AREA) standards without notable deviation or applicability issues. Systems engineering elements and operational principles were shaped using the San Diego Trolley as a model. Metro Link design criteria for the yard and shops were in large measure an adaptation of Portland's MAX criteria and physical plant.

If there are any elements of the Metro Link design that suggest variation from the U.S. norm for similar projects, they would most likely be station platforms and design implications for contract packaging. After considerable review of what other systems were doing to address the issue of accessibility, and weighing that issue with station dwell times, vehicle dynamics and track geometry, fare collection options, and accident liabilities, Metro Link's designers opted for high-level loading platforms at all stations. Regarding contract packaging, the decision was reached to limit construction and procurement contracts to the smallest number possible—18 contracts at most. Hence, design could proceed in terms of plans, specifications, and estimates in a manner that was conducive to placing the majority of coordinative responsibility on general contractors, not on the Metro Link staff and consultants. Further, the design work carefully disaggregated civil and systems elements so that contract units could be assembled that had the highest likelihood of achieving economies of scale, disadvantaged business enterprise (DBE) goals, optimum equipment, material and labor resource allocations for contractors, etc., within the context of the implementation critical path and right-of-way constraints.

METRO LINK SYSTEM

Stations

Twenty stations will be built along the initial 18-mi Metro Link route. Two will be in East St. Louis, 10 in St. Louis, and 8 in St. Louis County. (The City of St. Louis is a totally separate political jurisdiction from St. Louis County, a century-old circumstance that is not without its negative consequences on fiscal and areawide cohesiveness.)

With the alignment encompassing the reuse and rehabilitation of nearly 14 mi of excellently situated railroad right-of-way, including tunnels and a major bridge, the character of stations was uncontrollable in many respects.

Fifteen stations are at-grade, for the most part accessible without substantive vertical circulation features except for minimal stairs and ramping; one of these stations will be built at the airport to achieve platform interface with the airport terminal's planned people mover system. Three stations are in subway: two in the Washington Avenue-Eighth Street tunnel, and one in the Union Station baggage tunnel. The remaining two stations are on existing elevated bridge structure, one at each approach to the Eads Bridge, where they are enclosed by approach superstructure.

All station platforms are high-level loading to provide full accessibility and to minimize boarding time for all patrons. Platform lengths are typically 200 ft long to accommodate two-car trains. Depending upon the functional and physical location of each station, elevators and escalators will be provided (see Figure 2).

Metro Link stations will be built with materials and finishes chosen with several key criteria in mind. Materials are to be readily available, to have optimal life-cycle costs, and to require only common construction or installation techniques. Station finishes are designed to be resistant to vandalism and to mitigate weathering impacts. Platforms exposed to the elements will have space-frame steel pylon canopy structures with roofing material of copper and glass. Canopies are modular and sized to accommodate 100 percent of each exterior station's peak hour patronage per headway at a minimum of 5 net ft^2 per patron and to cover the complete platform width.

Only essential wall requirements to protect patrons, fare collection equipment, and other elements from crosswinds will be provided, using glass block, free-standing wall segments. The structural elements will be used to support and integrate canopy, lighting, graphics/signage, platform security and communication, and seating requirements. Landscaping will enhance appearance, control and passively direct the movement of patrons within station sites, and enhance or improve microclimates at the stations.

Patron access and egress at stations varies, of course, by location. Six stations will be built with integral park-and-ride lots, providing an initial capacity of nearly 2,000 parking spaces. Kiss-and-ride as well as bus drop-off provisions are incorporated at all station sites except those in downtown St. Louis, where existing thoroughfare provisions adequately perform these functions.

Access and egress treatments are hierarchical. First priority is given to bus patrons using the drop-off lanes, second priority to short- and long-term parking for handicapped patrons and kiss-and-ride patrons, and third priority to long-term commuter parking patrons. Patrons accessing or leaving stations on foot are provided the most direct circulation available to the adjacent land uses.

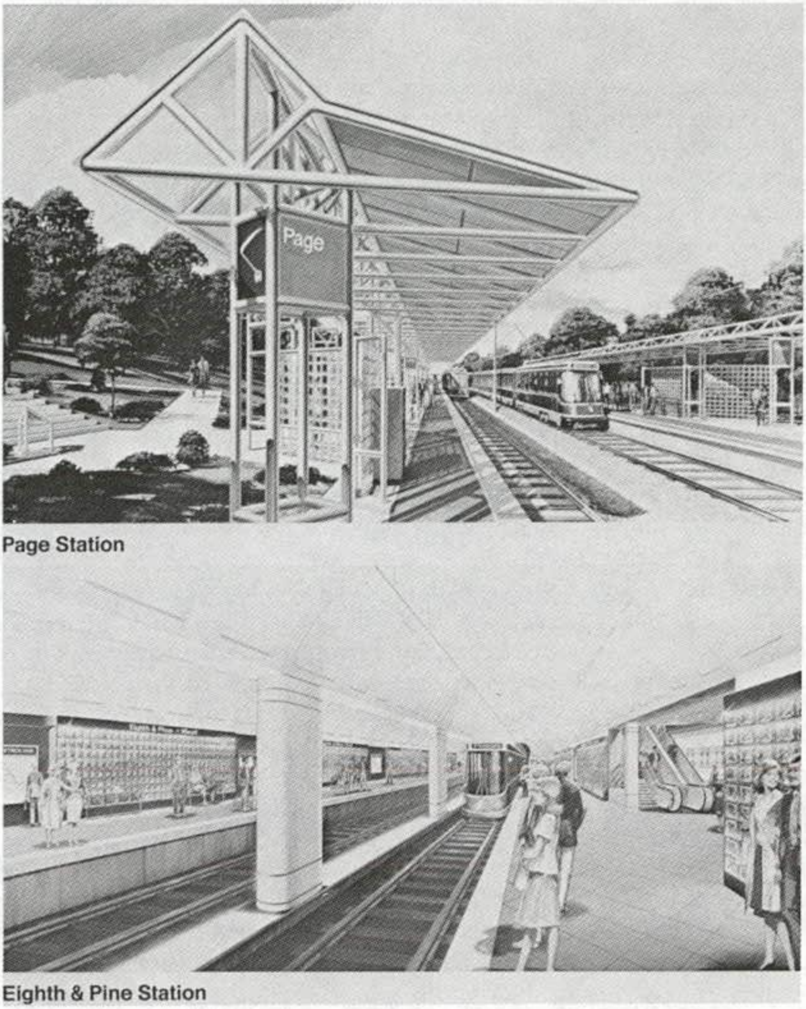

FIGURE 2 Metro Link renderings of outdoor and indoor station platforms.

Light Rail Vehicles

As with other federally funded projects, the engineering for Metro Link LRVs has proceeded using a generic car. Conforming to the overall design philosophy, the LRV design used in preliminary engineering was for off-the-shelf, service-proven technology and components.

In this section the generic LRV used in preliminary engineering is generally described. But from this point forward the LRV final engineering will proceed toward completion of a performance specification within a period of 6 to 8 months. That is to say, Metro Link staff and consultants will not design the LRV. Procurement will be based on general and technical conditions that can best ensure proven vehicle and vehicle subsystem performance, leaving detailed design to the manufacturers. Testing at the component level, integrated subsystem level, and, finally, the system level, coupled with pre-revenue and revenue performance criteria, will provide the primary means of product assurance. Also, an on-site maintenance component is planned for inclusion in the procurement to permit the supplier to use his own forces during the first years of revenue service to monitor actual conditions and correct problems that might otherwise cause deficiencies in contracted reliability, availability, maintainability, and other intrinsic threshold levels.

The LRV procurement will use a one-step competitive bid process or, pending further analysis of market conditions, competitive negotiation. In either case, the contract specifications will be aimed at sharing the procurement risks between owner and supplier. Performance criteria, payment provisions, incentives, and damage clauses will be structured to provide owner protection. Supplier control of maintenance for up to 5 years, supplier-detailed design of their off-the-shelf, proven LRV, and the payment and contract incentive provisions will be structured to provide bidder protection.

This procurement philosophy should save scarce resources and time. It will eliminate costly detailed engineering by the owner, whose generic vehicle design constraints under current procurement regulations tend to void much of the work anyway upon bid. Likewise, potential suppliers are given greater latitude in offering a design that they already have and are willing to bid to the performance criteria. They also can avoid costly negotiations over substitutions or equivalents. Being willing to admit that most owners and their engineering consultants are not skilled in manufacturing can pay dividends by reducing final design project costs while simultaneously freeing resources to concentrate on end-product assurance.

This is not to suggest that any and all LRV procurement problems will be avoided, let along mitigated by the Metro Link approach. There are no illusions, only proactive policies that have their roots in the design and procurement experiences of Metro Link project staff and the shared wisdom of colleagues in other transit agencies.

Patronage estimates and the service design require an initial fleet of 31 LRVs. Double-ended, six-axle articulated vehicles with passenger capacity for 64 to 76 seated and 160 to 200 standing at crush load conditions are planned. Dimensionally, the LRV will be between 8 ft 8 in. and 9 ft 3 in. wide, no more than 93 ft long (over couplers) or 12 ft 3 in. high, and equipped with four gangways per side for floor-level boarding.

LRV performance characteristics include maximum operating speed of 55 mph; random and synchronous spin/slide detection and correction control; negotiation of minimum flat horizontal curve radius of 82 ft and minimum vertical (crest or sag) curves of 1,640 ft; and maximum superelevation of 6 in.

Metro Link LRVs will be fully climate controlled, have a normal operating condition interior noise threshold for acceptance of 67 dBA, and general watertightness. Fully automatic, self-centering couplers will be provided for all mechanical, electrical, and pneumatic train connections.

The preceding data are included in preliminary engineering documents distributed in February 1987 to LRV suppliers for an industry review. Very informative and constructive comments were received from every supplier with an LRV currently in service at, or in production for, a U.S. transit agency. These review comments will be revealed at the outset of final engineering. Every performance-oriented criterion or contract condition will be given independent evaluation and reevaluation in the context of both the LRV product requirements and the requirements for interdependent Metro Link project elements. Among other early final engineering tasks, thorough and vigorous integrated value engineering, life-cycle cost, human factors, operations and maintenance cost, and implementation schedule analyses using the largest and longest lead-time contract unit (i.e., the Metro Link LRV) as the catalyst will provide an invaluable project focus.

Yard and Shops

In the planning of yard and shop layouts, thorough consideration was given to all aspects of LRV maintenance, car cleaning operations, operation of the shop with respect to mainline operations, internal operating characteristics, and all other facets of Metro Link-related operating activities. The importance of establishing a clear maintenance and repair philosophy provided the designers with general parameters for a functional, efficient design.

Basic system philosophy consideration and analysis were given to the following requirements to generate specific design solutions:

- Levels of maintenance and repair;
- Work activities;
- Shop loading;
- Contract maintenance;

- Inventory requirements;
- Work flow;
- Space requirements;
- Equipment requirements;
- Personnel requirements;
- Scheduling;
- Routine inspection and preventive maintenance;
- Records, procedures, and method;
- Cost restriction, budget limits;
- Future expansion; and
- Interaction with operations.

An abandoned passenger car maintenance facility and yard on a 10-acre site in the Mill Creek Valley railroad yards area just west of downtown St. Louis, together with two acres from an adjoining city-owned lot, will be Metro Link's yard, shops, and central control location. This site, at the intersection of Scott Avenue and 22nd Street, is approximately one-third of the distance along the initial 18-mi alignment. An existing metal car shed 160 ft long by 67 ft wide by 34 ft high with inspection pit will be rehabilitated and incorporated into the Metro Link shops.

The Metro Link yard and shops facilities will include a three-story maintenance and office building providing approximately 56,500 ft^2 of floor space; a materials storage yard; storage tracks and LRV movement trackage, including a run-around track with a loop; arterial service roads; and parking lots. The yard and shops will handle 24-hr operations.

Three fundamental levels of LRV maintenance, repair, and overhaul will be handled by the shops, i.e., routine maintenance, periodic maintenance, and major repair. Inbound trains from revenue service will be routed to a track or tracks where the following routine maintenance functions will be performed: visual inspections, maintenance technician sign-off, and interior and exterior cleaning. Outbound trains will be inspected by their operators prior to departure. Periodic maintenance will be performed in service and inspection areas, and will include scheduled inspections, correction of deficiencies, scheduled preventive maintenance, and lubrication and testing. Major repair will be done in the shop, including major scheduled maintenance, change-out or complete repair of major LRV components, wheel truing, and collision repair functions. An environmentally separated blowdown facility will be located on a track not normally used for daily inspections.

Space will be provided for the storage of the following types of equipment and structures: electrification poles, signal apparatus, lighting poles, rail, ties, special trackwork, other track materials, ballast, and reels of wire.

Storage tracks initially will provide for 31 LRVs; in the future space will be arranged to accommodate up to 50 LRVs. LRVs will be stored on level tangent track, with both longitudinal and lateral access aisles. Storage tracks will incorporate reused railroad rail salvaged from the existing trackage in the acquired rights-of-way.

Trackwork

The initial Metro Link alignment includes approximately 34 track miles of double-track mainline and one track mile for the airport branch single-track spur. All construction plans and specifications comply with the current edition of the AREA Manual for Railway Engineering and Portfolio of Trackwork Plans, modified as necessary to reflect the physical requirements and operating characteristics of the Metro Link system. Where the system operates across a public street, applicable design requirements of the American Association of State Highway and Transportation Officials (AASHTO), the Missouri Highway and Transportation Department (MHTD), the Missouri Division of Transportation (MDOT), the Illinois Department of Transportation (IDOT), the Illinois Commerce Commission (ICC), and the local counties and municipalities also are utilized.

The track meets or exceeds the minimum requirements of the Federal Railroad Administration (Title 49, Part 213: Track Safety Standards for Class 3 Track). Class 3 track limits freight trains to a maximum operating speed of 40 mph and passenger trains to 60 mph.

The standard gauge of Metro Link is 4 ft 8½ in. Wider gauge will be used in some curves, depending upon the degree of curvature, in accordance with the following: gauge of 4 ft 8¾ in. for curves with a degree of curvature greater than 160, but equal to or less than 240, and a gauge of 4 ft 9 in. for curves with a degree of curvature greater than 240.

Primarily ballasted track will be used, meeting the requirements of AREA's Specification for Prepared Stone Ballast. Mainline cross ties will be pressure-treated oak and mixed hardwood 8 ft 6 in. long, conforming to AREA specifications for 7-in. grade ties spaced 20 in. center-to-center on the joint trackage, 24 in. center-to-center in yard track. A ballastless track system will be utilized on the Eads Bridge approach and main river spans and on the floor of the maintenance building at the yard and shops.

All Metro Link mainline track, turnouts, and yard lead tracks will be constructed of continuous welded rail, welded into continuous strings by the electric flash-butt process. Field welds will use the approved preheat thermite process in accordance with AREA specifications.

New rail will be procured for all mainline track, turnouts, and yard lead tracks. Rail will be 115RE section new prime rail, while rail for paved track will be 128RE 7A new prime girder rail. Heat-treated or alloy rails will be used in all special trackwork (i.e., turnouts and crossings) and on all curves where the degree of curvature is greater than 40. The rail for the yard and storage tracks and exclusive freight tracks will be Number 1 relay 115RE rail.

All mainline track with a center line degree of curvature greater than 150 will have an inner restraining rail adjacent to the low rail; rail for this purpose will be Number 1 relay 115RE rail. Emergency guard rails will be installed on tracks on all bridges; for this purpose relay 115RE rail, extending 50 ft beyond each end of the bridge, will be used.

Special trackwork will be manufactured and installed in accordance with AREA specifications and plans. Single crossovers will be used in lieu of double crossovers unless space restrictions dictate otherwise. All special trackwork will be located only on vertical and horizontal tangents; it will not be superelevated. The minimum length between any facing switch points will be 45 ft. The minimum horizontal or vertical tangent distance preceding a point of switch will be 10 ft. Special trackwork is to be located as follows (and includes use of geotextile fabric): Number 10 and Number 8 turnouts with 19-ft 6-in. curved switch points as the standard mainline turnout; Number 6 and Number 4 turnouts with 11-ft straight switch points as the standard yard turnout.

Appropriate measures will be evaluated during the final design of trackwork to minimize stray currents to ground resulting from the use of rails as the negative return for the traction electrification system.

Operations

A track and signal schematic diagram of the mainline route for the St. Louis Metro Link system is shown in Figure 3. The schematic is a simplified representation of station locations, special trackwork junctions, emergency crossovers, pocket tracks, tail tracks, and other operationally important features such as yard locations and railroad junctions.

Trains on the Metro Link system will be operated manually. Signaling and control subsystems are basic and confined to those functions required for safety (i.e., train protection and at-grade street crossing protection) and for the oversight and management of operations at terminals, turnbacks, and transfer zones between yard and mainline areas (i.e., train supervision).

For mainline operations, train protection and supervision are accomplished by these means:

- Train movements will operate by line of sight on Fifth Street in East St. Louis;
- Wayside block signals providing automatic train protection (ATP) will be installed beginning at Fifth and Broadway in East St. Louis and continuing across the Eads Bridge, in the Washington Avenue-Eighth Street tunnel, on

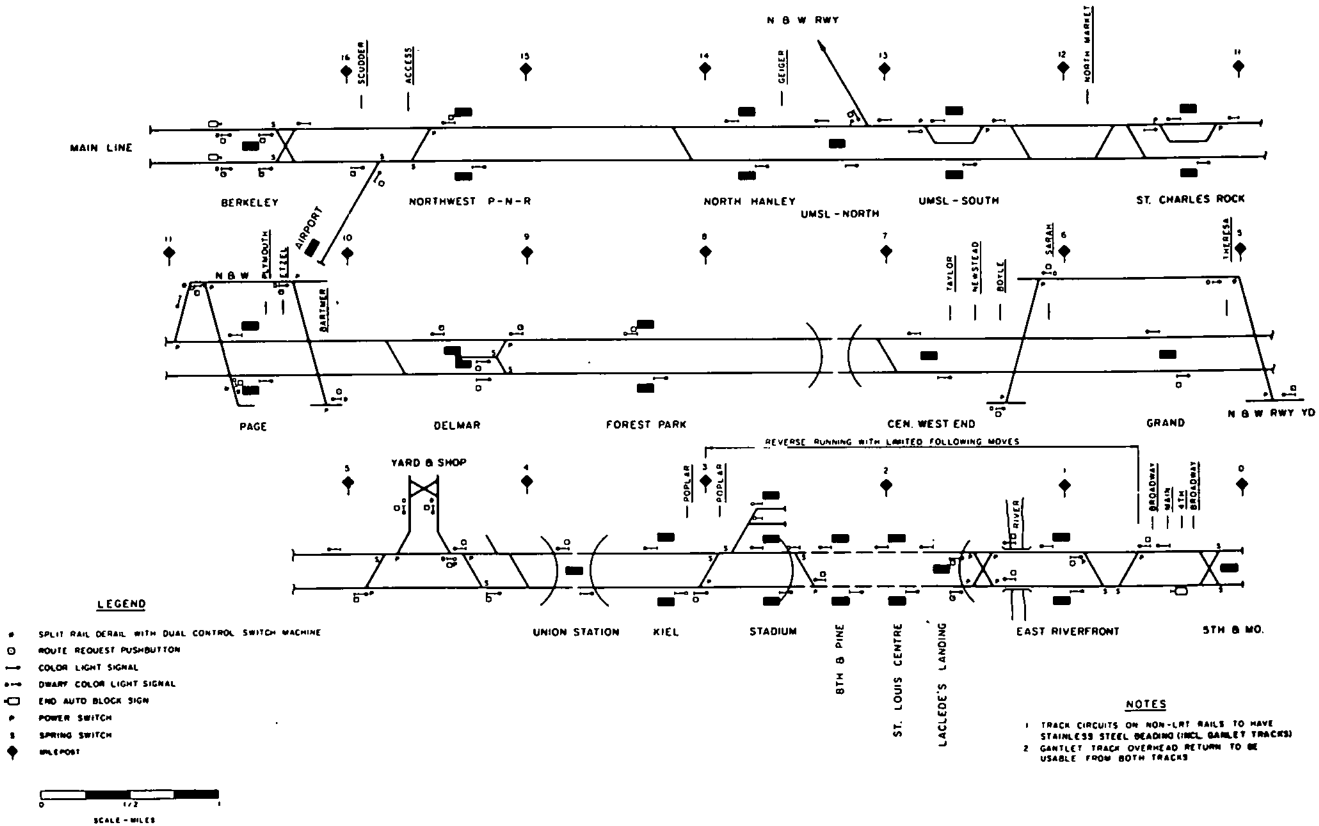

FIGURE 3 Single line diagram of the signal system.

the TRRA/new right-of-way/Norfolk & Western segments from Busch Stadium to UMSL, and on the new right-of-way from UMSL to Berkeley to protect following movements on these high-speed line sections; and

- Signals will be provided on the airport branch to control movements on the single-track section.

Track switches will be controlled in one of three ways. Switches located at junctions where frequent through and diverging facing train movements are made will be power operated, with routes requested by operator-controlled wayside pushbuttons. Switches located in low-speed territory and used primarily for through facing movements and trailing movements from the diverging route will be spring-operated. Infrequently used switches will be thrown by hand.

The 18 street grade crossings along the initial Metro Link line will be protected with railroad-style flashers and gates. Where necessary, crossing protection will be coordinated with adjacent street intersection traffic signals (e.g., at Scudder Road near the airport).

Operations (whether normal or abnormal) will be directed, controlled, and monitored by central control personnel operating out of the shops and office building at Scott Avenue and 22nd Street. Central control will supervise all mainline train operations, maintenance and storage activities, and traction power distribution in accordance with established operating schedules, rules, and procedures. It will implement any corrective actions required to maintain service schedules and to minimize adverse effects of equipment failures or emergency situations. Central control will also monitor station operations to provide for the safety and security of passengers, employees, and system facilities and equipment.

Central control will have several systems at its disposal. The route schematic display system will provide a complete visual indication of the mainline tracks, special trackwork layouts, signal block visual indication limits, and passenger station and substation locations. Radio communications with train operators will permit dispatchers to plot specific train locations manually. The radio communications system will provide channels for train operations, security supervisors, maintenance, and management. Two channels will provide two-way communications between central control and all trains and security personnel. Maintenance and management personnel will have exclusive channels. The telephone system will provide dedicated voice channels for use as telephone extensions from central control to selected sites along the right-of-way, primarily at passenger stations. Telephone service will be provided for passenger assistance and for administrative and maintenance purposes. Emergency telephones will be provided at each passenger station.

The closed-circuit television system will include cameras at selected points in stations and other facilities connected to monitors at central control. The public address (PA) system will be used to issue systemwide announcements (or selective announcements) in all stations. A PA system will also be provided on each LRV so that train operators can make announcements to riders and, via roof-mounted speakers, to people on the wayside. The tape recorder system will provide a record of all dispatcher radio transmissions and phone conversations.

The cable transmission system (CTS) will provide the backbone communication link between central control and various field locations. Terminals located at central control and at each major node of the LRT system will be interconnected by the CTS. The supervisory control and data acquisition (SCADA) system will operate over the CTS. Supervisory alarm and control circuits will connect each fare vendor and each electrical substation with central control. Electrical and support data related to intrusion and field equipment status alarms also will be transmitted on this system.

Trains will reverse direction at Fifth and Missouri in East St. Louis, at the western ends of the line (Berkeley and Airport), and at Delmar and Union Station (21st Street) for turnback service. Train operators will change ends and reset the vehicle destination signs. In addition, at both Delmar and 21st Street, it will be necessary to make diverging moves through the turnback tracks. Turnaround times have been allocated for these tasks.

Speed limits for the Metro Link line are shown in Table 2. These speeds generally reflect performance capabilities, station spacing, adjacent development, and traffic interference. In some locations, sharp radius curves further reduce speeds for relatively short distances.

Normal weekday service (see Figure 4) will begin at 5:30 a.m. and end at 1 a.m. (2 a.m. in East St. Louis to or from Union Station). Commuting peaks will occur from 6 to 9 a.m. and from 3 to 6 p.m.

The number of cars per train is a function of headways, platform lengths, vehicle limits, and street block lengths. The limiting factor for the line is the initial 200-ft platform length, which restricts train lengths to two cars. Two-car consists will be operated on several peak hour, peak direction trains, but

TABLE 2 METRO LINK SPEED LIMITS

Segment	Speed Limit (mph)
East St. Louis to Eads Bridge (East Approach)	20
Eads Bridge (East Approach) to 21st Street	20 to 55
21st Street to UMSL—South	55
UMSL—South to UMSL—North	40
UMSL—North to North Hanley	30
North Hanley to Berkeley	40 to 55
Airport Branch	40 to 55

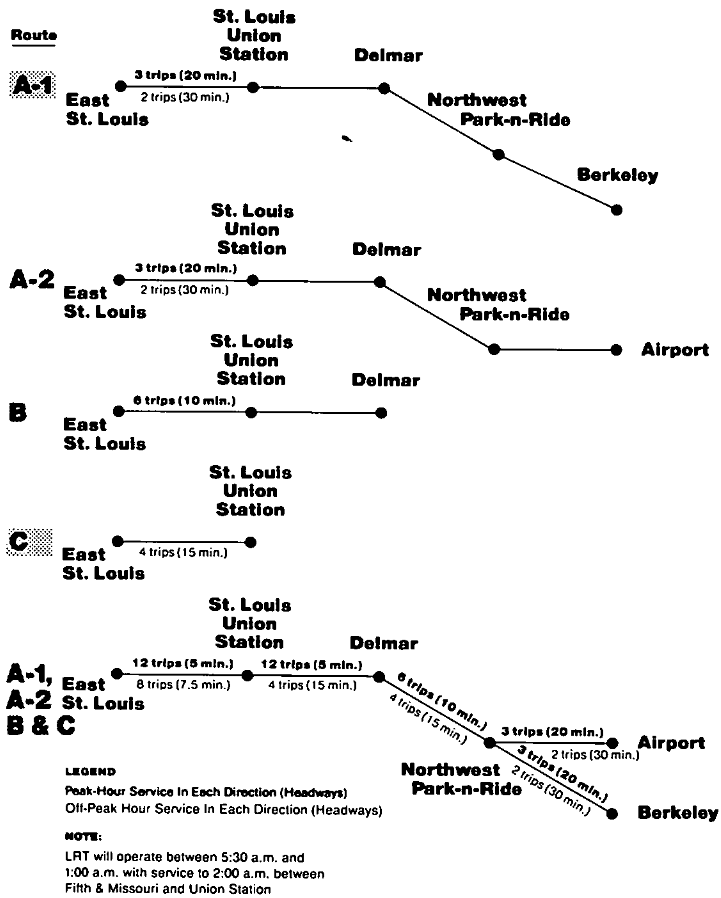

FIGURE 4 Metro Link year 2000 service and headways.

single-car consists will suffice for other peak and all or most off-peak services.

Based on the Metro Link operating plan, including a network of bus routes and services revised to interface with the LRT stations, ridership is projected at about 37,000 daily for the year 2000 (after some seven years of revenue service).

As with other new LRT systems in the United States, Metro Link will utilize a self-service proof-of-payment fare collection system. Fare inspectors will patrol the operation on board vehicles. The San Diego Trolley policy has been proposed in St. Louis as the model legal base for evader citation and enforcement (using the criminal versus civil code).

For system security, a metropolitan transit police force is under review. This police force could work directly for the bus and light rail operator, BSDA, and be augmented by local police departments through interagency agreements.

IMPLEMENTATION AND BUDGET

This section describes the schedule development for the Metro Link project for the final design, bidding, procurement, and construction of all elements of the project. Seven line section construction contracts provide for the basic construction of the 18-mi alignment, the structural elements of the 20 passenger stations, and 6 park-and-ride lots. One station-finish construction contract will provide for the architectural, mechanical, and electrical finish work for the 20 stations. The one yard and shops construction contract will provide for the vehicle maintenance, central control, and storage facility for the system. Four systemwide construction contracts will provide for the trackwork, signals and communications, traction power, and utility relocations. Three procurement contracts will provide for the LRVs, fare vending equipment, and service and maintenance equipment. Other contracts will provide for the consultant assistance for engineering, construction and procurement management, start-up, risk management, and legal counsel.

The schedule gives the sequence for construction and procurement efforts to complete the work, allows 6 months for vehicle and system testing and start-up, and targets revenue service for the end of 1992.

Acquisitions and easements of private properties, railroad properties, and other properties have been or are being finalized early to avoid delaying the construction efforts. Adequate time has been scheduled for long-lead procurements and for the coordination and work of contractors that must complete work within areas of other contracts.

UMTA funding to meet the cash-flow needs of the project to complete work and begin revenue service as scheduled is contractually delineated in a full funding grant agreement, subject only to congressional appropriations under the budget authority contained in the Federal Mass Transportation Act of 1987 (P.L. 100-17).

The final design effort has been organized, and will be completed, in accordance with milestone review and approval dates for 40, 60, 90, and 100 percent submittals for each individual construction contract. Preliminary engineering provided an aggregate 30 percent design level for all work. Therefore, the designated 40 percent review and approval milestone will serve as a midcourse correction checkpoint.

The bidding and award of construction contracts have been timed to provide sufficient time for necessary long-lead procurements and construction activities. The most critical are the design, manufacture, delivery, and acceptance of the LRVs. Other long-lead items have also been considered for their fit into the final design schedule planning. Detailed schedules for the various contracts will be completed early in the final design phase. The anticipated levels of other construction in the St. Louis metropolitan area during Metro Link project construction have been reviewed, revealing no problems in the construction labor market in terms of meeting the project's construction needs.

The systemwide contracts must be completed in partial segments that will coincide with the line segment contracts and their respective schedules, which have staggered starts and time periods. While it will not be possible to start systemwide contracts at one end and progress to the other within the time constraints necessary to meet the anticipated completion date of the project, the general availability of right-of-way will permit these contractors almost unrestrained intermediate scheduling.

The anticipated allocation of funds and the commitment of design and construction dollars based on the contract schedules have been evaluated. The awarded contracts require obligations slightly in advance, on average, of the UMTA grants. However, actual dollars paid out will be well within the UMTA grant cycles each fiscal year. Section 306 of the Federal Mass Transportation Act of 1987 specifically authorizes such advance obligations.

UMTA funds for federal fiscal years 1985, 1986, 1987, and 1988 have been appropriated. The funds for 1989 and beyond are delineated in the full funding grant agreement. This future funding provides a reasonable cushion for cash flow to continue construction to its scheduled completion. Obviously, if the anticipated funds for 1989 to 1991 are significantly varied or delayed, the completion date may be delayed and additional costs may be created for the total project due to continuing inflation additives and other delay costs. Figure 5 shows the capital cost to complete the Metro Link project, \$287,699,046. That plus noncash assets contributed at the minimum local-share matching requirement level of 25 percent, or \$95,899,682, brings the total to \$383,598,728. For comparison purposes, Figure 6 distributes the capital expenditures by common LRT cost elements.

CONCLUSION

St. Louis has attracted nationwide attention by imaginatively recapturing the past and recreating it in modern and exciting fashion. Along the restored riverfront and in the rehabilitated commercial districts and in-town residential neighborhoods, new growth and prosperity have been created by a partnership between public and private interests. A transportation system that sets high standards of quality is needed to continue this revitalization. An LRT system is seen as the cornerstone of this new transportation system.

METRO LINK CAPITAL EXPENDITURE BUDGET

	In Millions
General Construction, Systems and Rights-of-Way	$136.0
Stations and Parking Lots	28.7
Light Rail Vehicles	57.1
Design, Construction Management and Administration	40.7
Contingency	25.2
Total Escalated Costs	*$287.7*

Dec. 1987 estimate

FIGURE 5 Metro Link capital expenditure budget.

In step with cost-conscious times, designers of the LRT system have crafted a practical plan for building this line by maximizing the use of existing bridges, tunnels, and track. This approach on an initial 18-mi line will meet several goals:

- Reduce construction cost by at least two-thirds;
- Virtually eliminate the social, economic, and environmental disruption that typically accompanies large-scale construction;
- Allow for a grade-separated rail operation with higher speeds and fewer delays;
- Reduce or eliminate negative transportation-caused environmental impacts;
- Rehabilitate the historic Eads Bridge and an ideally located downtown tunnel and reuse abandoned and underutilized railroad lines; and
- Ensure an effective core alignment from which prudent extensions can be efficiently deployed to serve every major travel corridor.

The St. Louis LRT project, Metro Link, is on the verge of being built and put into the planned dual mode (bus/LRT), fully integrated mass transit system. Urban rail transit in the region has been a long time in coming back. By simply adopting and adapting proven technical and operational experiences of other LRT systems to the unique alignment opportunity in St. Louis,

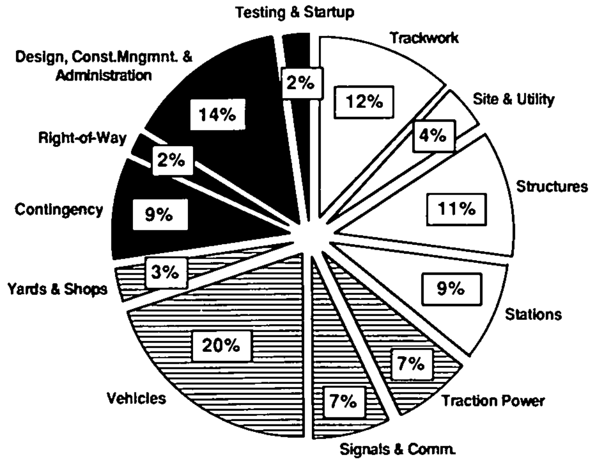

FIGURE 6 Metro Link capital cost breakdown.

Metro Link is feasible and cost-effective. In turn, LRT is the catalyst for a comprehensive restructuring of bus routes that produces a new start for improved public transportation service to the region.

ACKNOWLEDGMENTS

The planning studies for and preliminary engineering of the Metro Link project were conducted under sponsorship of EWGCC in cooperation with BSDA. The resources for undertaking the work on light rail were made available through grants from UMTA and the Missouri Department of Natural Resources/Division of Energy, and appropriations from EWGCC member jurisdictions. The authors would also like to thank the professional staff from the many firms making up the Sverdrup Corporation-led consulting teams, who performed the bulk of the design analyses, and Ellen Towe, whose work was essential in assembling this paper.

Hudson River Waterfront Transitway System

JOSEPH MARTIN, S. DAVID PHRANER, AND JOHN D. WILKINS

A unique transitway has been proposed for New Jersey's Hudson River waterfront. A narrow strip of land is being converted from railroad yards to large-scale mixed use development. At 35 million ft^2 of commercial floor space and 35,000 dwellings, this new development requires a high-capacity transitway. Add to the trips generated by the new development nearly 200,000 peak period trips (7 to 10 a.m.) passing through the waterfront to the Manhattan central business district. At least 75,000 trips made by bus ultimately will find their way onto the transitway. The core of the proposed transitway is the state-of-the-art light rail transit (LRT) facility to carry intrawaterfront trips. A busway component and land access roadway have been designated to integrate with the LRT. Transitway design variations include LRT exclusive, busway exclusive, transit in street, bus and LRT sharing right-of-way, and, in one location, bus and LRT sharing travel lanes.

"RECYCLING" IS A POPULAR buzzword in our environmentally aware society. Along the Hudson River waterfront, the term is being applied in two unique ways: recycling waterfront land and recycling the concept of light rail transit (LRT) in support of development. Imagine the opportunities in a strip of land 18 mi long and never more than a mile wide, largely vacant, and 1,000 yd from Manhattan's central business district (CBD). Five years ago, when commercial rentals approached $\$40/ft^2$ in Manhattan, one perceptive

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developer was purchasing 370 contiguous acres of vacant railroad yard at $21,000/acre less than a mile away in Hudson and Bergen counties, New Jersey, along the Hudson River's west bank.

Development of the Hudson River waterfront renewed interest in LRT in New Jersey. It evolved from a unique combination of changing economic conditions, unusual topography, and dynamic transportation needs. Palisades 150 ft high parallel the river along the northern portion of the waterfront. These cliffs isolate the riverbank from the development on the heights to the west. The narrow strip of land along the base of the palisades is a meager 300 ft wide in some locations.

The first cycle of development commenced in the mid-1800s on reclaimed landfill on the New Jersey side of the Hudson River. Nine railroads established beachheads on the narrow strip of waterfront at the base of the palisades. For these railroads and Public Service Railways (the regional streetcar operator), marine fleets, car floats, and passenger ferries completed the vital trans-Hudson River link. The first development cycle peaked around the 1920s when over 2,000 acres of waterfront were devoted to railroad use. Eight railroad tunnels or cuts penetrated the palisades ridge to serve the waterfront. Public Service streetcars scaled the palisades by various means at eight separate locations. These crossings over, through, and under the palisades were to become strong determinants in sketch-planning LRT transitway alignments.

The first cycle of waterfront development declined when the palisades and river obstacles were overcome by vehicular tunnels and bridges in the 1930s. By the 1960s, waterfront railroad properties lay idle as a result of declining railroad traffic, financial failures, mergers, and abandonments. Five of the largest (and bankrupt) waterfront railroad property owners merged into the Consolidated Rail Corporation (Conrail) in April 1976. Rationalization of Conrail's yards and rights-of-way combined with sale of surplus land by the trustees of bankrupt railroads resulted in hundreds of waterfront acres going on the market. This opened a second cycle filled with land development and transportation opportunities despite the topographical limitations that remained.

Today the challenge facing transportation agencies and land developers is to provide new waterfront transportation overlaid on existing trans-Hudson transportation volumes. Since trans-Hudson services are presently operating at capacity and utilize the same corridors required for waterfront access, staff have concluded that the two markets must be considered together. Officials endorse this dual function concept. A multiagency approach was formed with the New Jersey Department of Transportation (NJDOT), NJ Transit, the Port Authority of New York and New Jersey (PA), and other organizations working together. Partnership with the land developers became a key strategy for bringing transportation capability on line incrementally as development matures.

SOME UNIQUE OPPORTUNITIES

In 1984, a complex sketch-planning process revealed the grand scale of potential development. Even conservative estimates of commercial office space totaled over 30 million ft^2. Waterfront dwelling units at developer-planned build-out would hover near 35,000 units. Analysis confirmed that none of these plans and expectations are achievable absent a strong, visible, high-capacity transit presence.

If developers are to achieve their full build-out plans, the waterfront would have to host 64,000 parking spaces based solely on initial developer expectations. Even with restrained parking policies and high ratios of floor space to parking space (one space or less per 1,000 ft^2), total parking requirements would consume a huge amount of precious space. Nor is there enough roadway capacity to serve anticipated development. Compounding the problem are local land use regulations preserving, among other things, view corridors and view planes from the top of the palisades toward the Manhattan skyline. Placement of towers, size of development, and building height became critical calculations in developer return on investment. Infrastructure either did not exist or was in a state of overload and disrepair. With the exception of Port Authority Trans-Hudson Corporation (PATH), much of the total waterfront area is unserved, even by bus. Rush hour traffic is already congested at levels of service (LOS) D and E because of trans-Hudson and local growth.

The sketch-planning process concluded—and developers recognized—that growth could not be achieved nor could highest and best land uses be realized if automobiles were the primary means of waterfront access. Planning principles devised to guide policy included:

- Suppressed parking;
- Isolation of trans-Hudson and waterfront vehicular traffic flows as far inland as possible;
- Diversion of automobile users to transit in advance of congestion; and
- Trans-Hudson and local bus service and a waterfront transitway system on exclusive rights-of-way.

Fashioning an Alignment

Conrail currently operates its River Line, a freight trunk line, through the Weehawken Tunnel and along the waterfront. This line is of strategic importance to the light rail project because it is a waterfront access tunnel through the palisades and its right-of-way is strategically located at the base of the palisades. The line serves the waterfront from the Weehawken Tunnel south to its crossing of NJ Transit's commuter line into Hoboken. The total length of railroad that can be made available to the transitway system is 4.5 mi, or about 20 percent of the total right-of-way required (see Figures 1 and 2). Fortunately, physical and funding options are available to relocate Conrail to the parallel Northern Branch on the west side of the palisades.

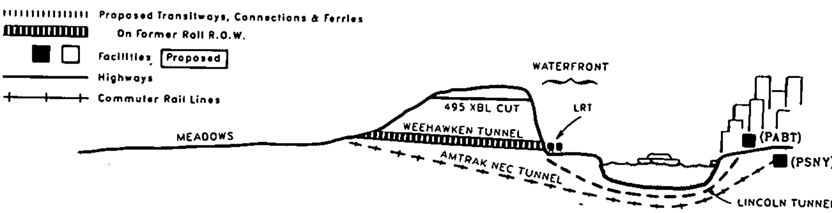

FIGURE 1 Hudson waterfront profile (scale exaggerated).

The state has entered into an agreement with Conrail that will yield benefits that include the relocation and betterment of Conrail's freight operations while vacating the existing River Line right-of-way for its use by the transitway system. The Port Authority's Bank for Regional Development is funding the Northern Branch upgrade and UMTA is funding the purchase of former Conrail waterfront tunnel and railroad alignment. Thus, NJ Transit falls heir to the vacated railroad line for its transitway and NJDOT for its Riverfront Boulevard.

The project has also been fortunate in obtaining a number of easements from private developers who will benefit from the transitway system. Although the construction of the system is some years away, staff approached developers early to ensure that the right-of-way will be available. The first transitway easements were obtained in 1984 from Arcorp. The easement covered nearly a mile of abandoned rail right-of-way north of the Weehawken Tunnel. The agreement was precedent setting, signaling developers' commitment to the transitway concept. Subsequent to that initial acquisition, negotiations with other developers have provided the project with significant amounts of right-of-way in areas where high-density development is taking place. The following rights-of-way have been, or are being, secured without cost to the project:

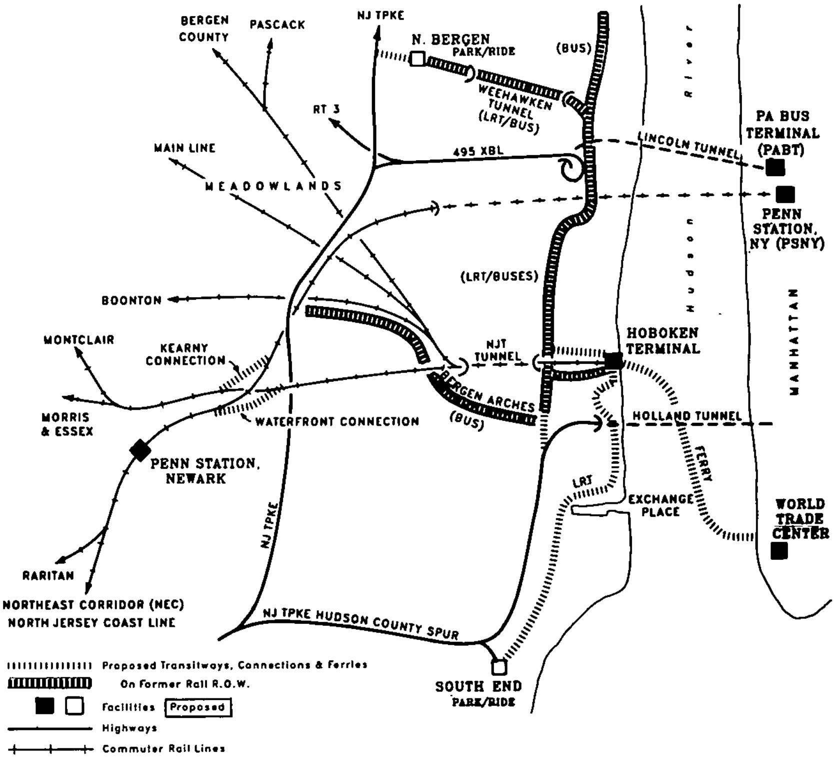

FIGURE 2 Hudson waterfront: existing and proposed transportation.

- Newport Centre—Direct negotiations with this developer yielded a right-of-way across the entire development for a distance of approximately 0.8 mi.
- Lincoln Harbor—Hartz Mountain has provided an additional 30-ft-wide corridor paralleling both its development and the Conrail right-of-way.
- Harborside/Liberty Center/Evertrust—It is anticipated that negotiations with these developers will result in securing a right-of-way in the area immediately north of Exchange Place in Jersey City.
- Lever Brothers Research Center—An agreement has been concluded substituting frontage for former railroad right-of-way as a transit easement.
- Harsimus Cove—Negotiations with this developer anticipate providing rights-of-way to connect the easements furnished by Harborside et al. and Newport Centre.

The combination of the Conrail acquisition with the developer-granted easements is expected to provide the exclusive right-of-way needed for the transitway system where development is densest. Securing transitway easements continues vigorously.

Development Initiative

Development of the Hudson west bank waterfront is on a particularly large scale, although it represents only a modest percentage of the total 775 mi of New York/New Jersey harbor shoreline:

- 18 mi of shoreline,
- 40-plus private and public developers participating,
- 34,900 new dwellings,
- 2,700 acres,
- 32.5 million ft^2 of commercial office space,
- 3.2 million ft^2 of retail commercial space,
- 3,200 hotel rooms, and
- 10-plus marinas.

Heightening the complexity of waterfront development are the institutional involvements. The Jersey waterfront spans two counties and eight separate municipalities, each with its own land use regulations and planning mechanisms. Local jurisdictions successfully defeated attempts to establish a waterfront regional planning institution. To promote development and liaison with developers, the Governor's Policy Office established a Hudson River Waterfront Office. Other state government participants include the Community Affairs, Environmental, and Transportation departments.

Complementary Programs

All transportation programs in the region aggregate to around $14 billion. Several projects are expected to alter dramatically travel patterns feeding to and crossing through the Hudson waterfront. The centerpieces of New Jersey's transportation capital program are two short inland rail connections to unify the two now separate operating segments of NJ Transit's commuter rail system. These connections act like a double slip switch at Kearny Meadows where the Northeast and Morris and Essex commuter rail corridors cross (see Figures 1 and 2). One of these, appropriately called "Waterfront Connection," enables the North Jersey Coast, Northeast Corridor, and Raritan Valley rail services to enter the waterfront directly at Hoboken. Existing and proposed rail services at Hoboken could thereby total 11 distinct rail lines. This, in combination with a Port Authority trans-Hudson ferry proposal, an upgrade of PATH, and the light rail transitway system, creates a waterfront transportation gateway through Hoboken. Prior to the Waterfront Connection, only former Erie-Lackawanna rail services in the northern third of New Jersey accessed Hoboken and the waterfront directly.

One of the major features of the waterfront LRT is the integration of its service with the high-capacity bus, rail, and, eventually, marine modes that surround it. Unlike most other new initiatives, where the LRT is the line-haul service exclusively, this light rail will be designed to perform feeding and distribution for the existing fixed-guideway modes as well as line-haul functions.

WATERFRONT TRANSITWAY SYSTEM CONCEPT

The concept of a joint transitway system that meets the waterfront's transportation needs with LRT and local bus, and trans-Hudson needs with express bus, was based on the planning principles detailed earlier. The transitway experiences in other cities demonstrated a number of options for consideration. Notable is Pittsburgh, where both busways and LRT operate jointly on open right-of-way and through a major tunnel facility. Busways as rapid transit/LRT substitutes in Ottawa service a high-density market, highlighting the capacity and flexibility of this particular mode. Visits to a number of the new LRT properties showed how this mode can be fitted compatibly into various environments.

Existing Highway Transportation

As the map and profile in Figures 1 and 2 indicate, there are exceedingly few access points to the Hudson River waterfront. The mature palisades communities, Hoboken and downtown Jersey City, create effective street barriers of urban density to the west. The principal access routes through the palisades and these communities include I-495, US-1, US-9, and the Hudson County spur of the New Jersey Turnpike. Unfortunately, these access roadways are also the same roadways that are heavily used by vehicles destined to cross the Hudson. These crossing approaches are operating at capacity during the peak hour period.

Local streets through the palisades are other alternatives for reaching waterfront destinations. These streets and boulevards are congested in developed areas. Further local roadway expansion and greater use would only degrade the quality of life in waterfront communities that are in the process of gentrification.

Existing Transit

NJ Transit operates rail commuter services to the Hoboken Terminal from seven rail lines now and may increase that number to 12 in the future. The local bus service operates in a radial fashion from two principal points on the waterfront, Hoboken and Exchange Place in downtown Jersey City. These routes bring riders from locations remote from the immediate waterfront area. With the exception of PATH between Hoboken and Jersey City, these transit services do not now distribute riders along the waterfront. Relying only on PATH raises concerns that it will not have the capacity to service the intrawaterfront market while absorbing more trans-Hudson growth.

Parking

Suburban developers traditionally provide four or five parking spaces per 1,000 ft^2 of office space. These parking ratios are not being incorporated in the waterfront developments. The initial developments along the waterfront have been located near established transportation linkages or planned linkages to New York City. Given this accessibility, the parking ratio at the initial developments has been held down to one or less per 1,000 ft^2 of office space.

Trans-Hudson Perspectives

The trans-Hudson bus system is operating over 700 buses during the peak hour through the contraflow I-495 express bus lane (XBL) and the Lincoln Tunnel to the Port Authority Bus Terminal in New York. This is beyond the practical capacity of the XBL. The ability to provide additional capacity in the I-495 corridor for bus operations is at best temporary. To improve the reliability of trans-Hudson bus service, to reduce total travel time, and to provide capacity for future growth, buses must access their own rights-of-way at some point in advance of the existing congestion. Additionally, the exclusive transitway must be two-way to recycle peak period bus runs, reduce deadhead hours, and handle an expected surge in reverse peak commuting to the new employment generators along the waterfront and other regional attractions.

Functional Requirements

Any waterfront transit plan fulfilling trans-Hudson and waterfront requirements must address four functional roles exemplified by the following trip-end pairs:

- Suburb-waterfront,
- Suburb-Manhattan CBD,
- Waterfront-Manhattan CBD, and
- Waterfront-waterfront.

The lack of good automobile access routes, the inability to make capacity improvements, limited parking, and capacity shortfall of the local street network create a need for fringe park-and-ride facilities. These parking facilities must be located where space, highway access, and direct transit links to the waterfront can be provided. The links to the waterfront also have to perform a distribution function so that persons using the fringe parking facilities have access to virtually all of the developing areas.

Early System Conclusions

A common solution for trans-Hudson problems and the developing waterfront areas was required. These dual needs dictate the nature of transit access to the conceptual Hudson River waterfront transportation system shown in Figure 3. The core right-of-way ingredients that fulfill these combined needs are Conrail's River Line, the associated Weehawken Tunnel, and a back-up penetration of the palisades further south called Bergen Arches (another former rail right-of-way). The Weehawken Tunnel links the waterfront to the Meadowlands, itself a major development area where sufficient land is available for a major park-and-ride facility. Because the Meadowlands area is bisected by both spurs of the New Jersey Turnpike and five state arterials, excellent automobile access will be provided to any park-and-ride facility.

Trans-Hudson bus routes utilizing the New Jersey Turnpike from Passaic, Bergen, and other counties will be afforded easy access to the transitway system by connecting the bus element of the transitway to the New Jersey Turnpike. The specific alignments to accomplish all this are detailed in a following section. A South End park-and-ride is fed off the Hudson County spur of the turnpike. The two park-and-ride lots at the outer extremities of the transitway are expected to provide a viable automobile intercept system. They also feed trips bidirectionally on the transitway.

Initial System Definition

The demand levels and trip concentrations associated with waterfront access needs and intrawaterfront and distribution functions led to the conclusion that a high-capacity LRT would be appropriate for certain portions of the transitway system. This conclusion was reinforced by the high person/trip turnover

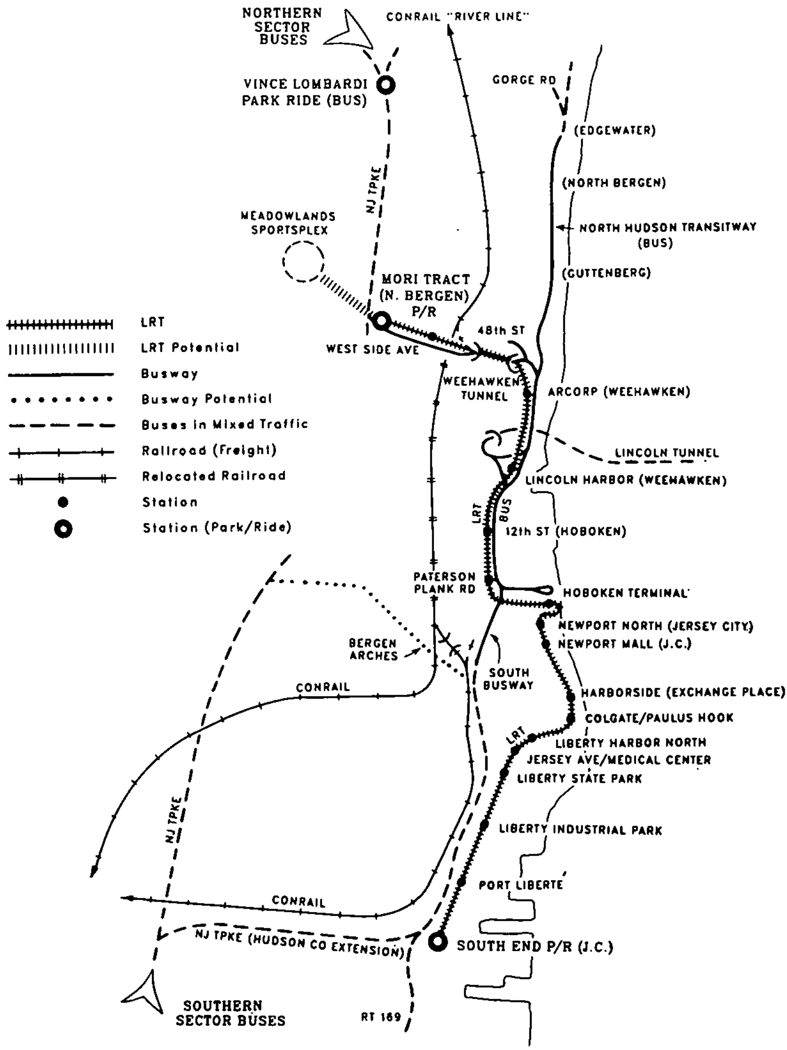

FIGURE 3 Hudson waterfront transitway services and stations.

rate expected at gateway points along a waterfront transit system. Developers were clamoring for a tangible commitment by the public sector to waterfront transportation. They wanted fixed-guideway, permanent, modern, high-capacity transit to complement their "world class" developments—and they appeared willing to help provide for transit that would be uniquely "waterfront."

Next came the determination of which segments would support LRT operations, which would justify busway operations, and which would require joint bus/rail operation. Where joint operations were to take place, staff considered European and North American experiences with various forms of transitways. Pittsburgh's transitway proved the viability of treatments where bus and LRT modes mingle on the same roadway, and where separated modes run parallel within the same right-of-way. But how to adapt joint operation through the Weehawken Tunnel on tight headways proved a challenging traffic management task.

The waterfront system also had to deal simultaneously with express and local service. Both the distributive and waterfront access services are predominantly local-stop in nature. The trans-Hudson services, on the other hand, would stop only at one major interface facility and then operate express to the Lincoln Tunnel portal. This type of operation dictated bypasses for the express trans-Hudson buses skirting station platforms for local transit vehicles.

Based on the vehicles and service types to be blended on the transitway, the following functions and mode pairings were devised:

- LRT Local Services—LRT waterfront services between northern park-and-ride and southern park-and-ride facilities providing local access to the waterfront and an intrawaterfront distributive function en route;
- Busway Express—Trans-Hudson, from northern turnpike connection to Lincoln Tunnel;
- Busway Express—Trans-Hudson, from southern turnpike connection to Lincoln Tunnel (South Transitway);
- Busway Semiexpress—Trans-Hudson, from entrances at Gorge Road and 48th Street to Lincoln Tunnel (North Hudson Transitway);
- Busway Local—from Gorge Road and 48th Street (bus lines servicing northern Hudson County and southern and eastern Bergen County) to Hoboken.

Plotting these functions and modes on a map (Figure 3) reveals a core transitway at the central portion of the waterfront containing joint LRT and bus and joint express and local service. Exclusive bus and exclusive LRT appendages diverge from the core to serve the rest of the waterfront and upland areas.

System Refinement

A conceptual engineering effort further refined a number of issues relating to this project. The major issues included:

• Alignment—What specific alignment should the transitway system follow and what should its specific terminal points be? Where are grade separations required? Are street operations warranted in certain areas?

• Joint Operation—If selected, should LRTs and buses operate in the same pavement area or should they be immediately parallel to one another? What volume and type of joint operation can the Weehawken Tunnel sustain?

• Technology Application—What state-of-the-art bus and LRT technology should be applied to this system?

DESCRIPTION OF THE TRANSITWAY SYSTEM

As presently envisioned, the transitway alignment totals 22 route mi. The total is composed of approximately 13 mi of LRT, 9 mi of busway, and approximately 4.5 mi of joint operation (only in the Weehawken Tunnel do bus and LRT share lanes). This system is depicted in Figure 3. The LRT service will originate at a major Meadowlands park-and-ride facility located on the turnpike either at the existing Vince Lombardi park-and-ride site or at a new site immediately north of Harmon Meadow at what is referred to locally as the Mori Tract. If the former site is chosen, alignment will be oriented north/south, paralleling the New York Susquehanna & Western Railroad. At the south end of Conrail's North Bergen Yard the transitway will turn east to the Weehawken Tunnel. The Mori Tract alignment would originate near the turnpike and proceed east over Westside Avenue to the Weehawken Tunnel. In this instance, provisions would be made for a future extension westward to the Meadowlands Sports Complex about a mile distant.

At the east portal of the tunnel, the alignment would turn south following Conrail's River Line right-of-way along the west side of Hoboken to the Hoboken/Jersey City boundary. At this point, it would turn east to parallel NJ Transit's existing commuter rail line to access Hoboken Terminal.

Leaving Hoboken, the alignment will turn west on an elevated structure for a short distance and then south to serve the Newport, Harsimus Cove, Liberty Center, and Evertrust developments. This will bring the LRT to the Exchange Place area on the surface where access will be afforded to the major Harborside and Colgate developments (12 million commercial ft^2). Continuing south, it will skirt the established Paulus Hook residential area (and historic district) with some street running and provide access to a number of new residential developments along the old Morris Canal basin. South of the west end of the basin, the alignment generally will follow one of several alternative routes parallel to the turnpike to a southern terminus in the Greenville section of Jersey City. En route, the LRT will provide access to a proposed technology center and museum, Liberty State Park, and several residential and industrial areas.

Trans-Hudson buses bound for New York from the northern sector of the commutershed will get new transitway access from the turnpike with an interchange to be built adjacent to the Mori Tract station. Buses would then share the transitway right-of-way with LRT (lanes shared only in the Weehawken Tunnel) to the vicinity of the Lincoln Tunnel. A bus-only link would then be provided for access to the Lincoln Tunnel. In a similar fashion, trans-Hudson buses originating from the southern sector would be diverted initially to the turnpike's Hudson County spur and then operate over the South Busway and shared transitway system to the Lincoln Tunnel. A somewhat longer-range proposal is to build a connection from the turnpike for buses to use the existing Boonton Line and Bergen Arches rights-of-way to connect with the transitway near the Hoboken/Jersey City line.

A busway branch will also be provided along the east palisades north of the Weehawken Tunnel. This North Hudson transitway facility will extend north to Gorge Road and will improve trans-Hudson services for communities in northern Hudson and southeastern Bergen counties. It will also provide a way for closer-in communities to access the waterfront area through the operation of direct local bus service on the transitway to the Hoboken area. The transitway system will provide direct busway access to a new Hoboken bus terminal separate from the LRT. Other local bus routes would utilize portions of the transitway to access the Hoboken Terminal.

System Costs

The conceptual engineering effort nearing completion has generated an estimate of system costs. As described above, the light rail system will cost approximately $638 million; the busway system, $265 million. Table 1 indicates a breakdown of these costs by some of their major components. These costs represent a per-mile cost of approximately $50 million for light

TABLE 1 PROJECT COSTS

Component	Cost ($ thousands)
LRT	410,162
Busway	38,165
LRT/busway	295,249
Roadway	225,948
Right-of-way	89,591
Engineering	154,299
Total	1,213,414

rail and $30 million for busway. A review is being made at this time of various design criteria and assumptions that have been made in order to highlight areas where project costs can be reduced.

Ridership

Table 2 indicates the p.m. peak hour ridership for each segment of the line. Maximum peak hour boardings are expected to be 16,379, with 4,163 passengers riding past the maximum load point between the Hoboken Terminal and Paterson Plank Road Station in the northbound direction. The intercept parking facilities accommodate 1,660 riders/hr at the northern facility and 2,847 riders/hr at the southern facility. This table also indicates that one of the prime functions of the LRT is as a distributor, particularly between the Liberty Harbor North station and the Arcorp south station. This table also indicates the major interfaces between the LRT system and the existing bus, PATH, and rail commuter systems.

Table 3 shows the heavy trans-Hudson busway volumes expected on the system in 1995. This level of patronage will compel peak hour bus headway of 9 sec on both the northern and southern approaches to the Lincoln Tunnel. (Present XBL bus headway is less than 5 sec.)

TABLE 2 LRT PASSENGER ESTIMATES: P.M. PEAK HOUR, MORI TRACT PARK-AND-RIDE TERMINAL

	Northbound			Southbound		
	On	Off	Thru	On	Off	Thru
Mori Tract	0	1,660	0	1,065	0	1,065
West Side Avenue	0	1,214	1,660	236	0	1,301
Arcorp	667	1,848	2,874	2,135	663	2,773
Lincoln Harbor	1,052	509	4,055	1,190	327	3,636
12th Street	263	562	3,512	449	277	3,808
Paterson Plank Road	237	589	3,811	255	293	3,770
Hoboken Terminal	2,238	266	4,163	325	1,496	2,599
Newport[a]	968	777	2,191	368	1,060	1,907
Harborside	794	104	2,000	1,315	502	2,720
Colgate/Paulus Hook[b]	864	120	1,310	1,327	656	3,391
Liberty Harbor North	111	24	566	18	234	3,175
Liberty State Park/Jersey Avenue	41	1	479	1	30	3,146
Liberty Industrial Park	40	7	439	3	68	3,081
Port Liberté	78	6	406	5	239	2,847
South End Park and Ride	334	0	334	0	2,847	0
Total	7,687	7,687	N/A	8,692	8,692	N/A

[a]Includes Newport North and Newport Mall.
[b]Includes added trips from Colgate redevelopment.

TABLE 3 PEAK HOUR BUS DEMAND—LINCOLN TUNNEL/XBL

	XBL Approaches					
	Tpke./17	Route 3	Tpke./16E	XBL Total	Local Approaches	Total Through Lincoln Tunnel[a]
1983	235	154	281	670	109	779
1986	266	174	317	757	123	880
1987	272	178	324	774	126	900
1988	278	182	331	791	129	920
1989	284	186	339	809	131	940
1990	290	190	346	826	134	960
1991	296	194	353	843	137	980
1992	302	197	360	859	140	999
1993	308	202	367	877	142	1,019
1994	314	206	374	894	145	1,039
1995	320	209	381	910	149	1,059
2005	368	241	439	1,048	170	1,218

[a]NJ Transit/PA joint venture forecast for bus ridership growth through the Lincoln Tunnel is 36 percent. PA estimate for total trans-Hudson growth from 1995 to 2005 is 10 percent. Anticipated growth for bus ridership is 15 percent owing to the inability of automobile crossing traffic to grow in the same time period.

Stations

As presently planned, there will be 17 or 18 stations on the light rail system. Figure 3 indicates their general locations.

The stations are intended to serve a number of users. Mori Tract and South End stations are primarily intended for park-and-ride patrons and possible transferees. Other stations, such as Arcorp, Lincoln Harbor, Newport North, Newport Mall, and Harborside, are in direct proximity to the residential and commercial developments currently being constructed or planned.

Hoboken Terminal will provide interchange with the commuter rail network, with the Port Authority's planned ferry, and with the existing PATH system. The Hoboken Terminal station hosts bus routes that originate in the palisades communities and can use the transitway. The station at Newport Mall will serve the large 1.5-million ft^2 retail development recently opened. The Harborside station will serve an area in common with PATH's Exchange Place station, a focal point for local bus routes serving the downtown and southern portions of Jersey City. Finally, West Side Avenue, 12th Street, Paulus Hook, Liberty Harbor North, and Port Liberté stations will provide access to both the established and the developing residential and recreation areas along the LRT line.

Three typical station types are being considered, although there will be variations on these schemes to adapt stations to their particular environments.

An LRT station at grade is shown in Figure 4. Platform lengths would initially be 200 ft with expansion capabilities up to 300 ft. Pedestrian crossing would be allowed at controlled points and a station track fence would be installed to prevent random intrusions into the track area. The architectural treatments will support full station accessibility for the disabled.

An elevated station is shown in Figure 5. Dimensions and amenities are similar to the at-grade station. Access to the platform is provided through four stairways located at both the fore and aft portions of the platform. Track fences are placed to discourage intrusions into the track area. The station is fully accessible to the handicapped and includes elevators on each platform.

Figure 6 shows a station designed to handle both bus and LRT vehicles. Light rail vehicles (LRVs) would service joint stations in a manner similar to the LRT-only station except for a merge point between buses and LRVs immediately outside of each station area. Buses would be required to move from the inside lane to access the LRT station platform lane. Express buses would use the inside lanes exclusively and avoid conflicts with LRVs making local stops. Due to the high volumes of buses expected during the peak hours, passenger access to the vehicle lanes is discouraged by design. A center pedestrian barrier stretches the full length of the station to discourage patrons from entering the vehicle lanes. Crossing between platforms will be accomplished by stairways, elevators for the handicapped, and an elevated walkway.

In those areas of the transitway system served solely by buses, station facilities will consist of 10-ft-wide platforms that will vary in length from 80 to 120 ft. Passenger circulation to and between station platforms will utilize at-grade pedestrian crossings as a result of the anticipated lower volume of buses and good sight lines in these areas.

Construction Types

The construction of the waterfront transitway system features several cross-section types to blend it with its environment and to accommodate joint bus/rail operation. In those areas where the LRT operates on its own separate right-of-way, a 50-ft right-of-way will be required as shown in Figure 7. The addition of a busway component requires a total of 60 ft of cross-section (Figure 8). As initially designed, both LRT and busway would share the same roadway in all instances of joint right-of-way use. Based on comments from a peer group review and an in-depth review of the dynamics of accommodating in excess of 400 buses and up to 30 light rail movements in a peak hour, it was decided to separate the bus and rail on a common right-of-way (Figure 9), with one exception.

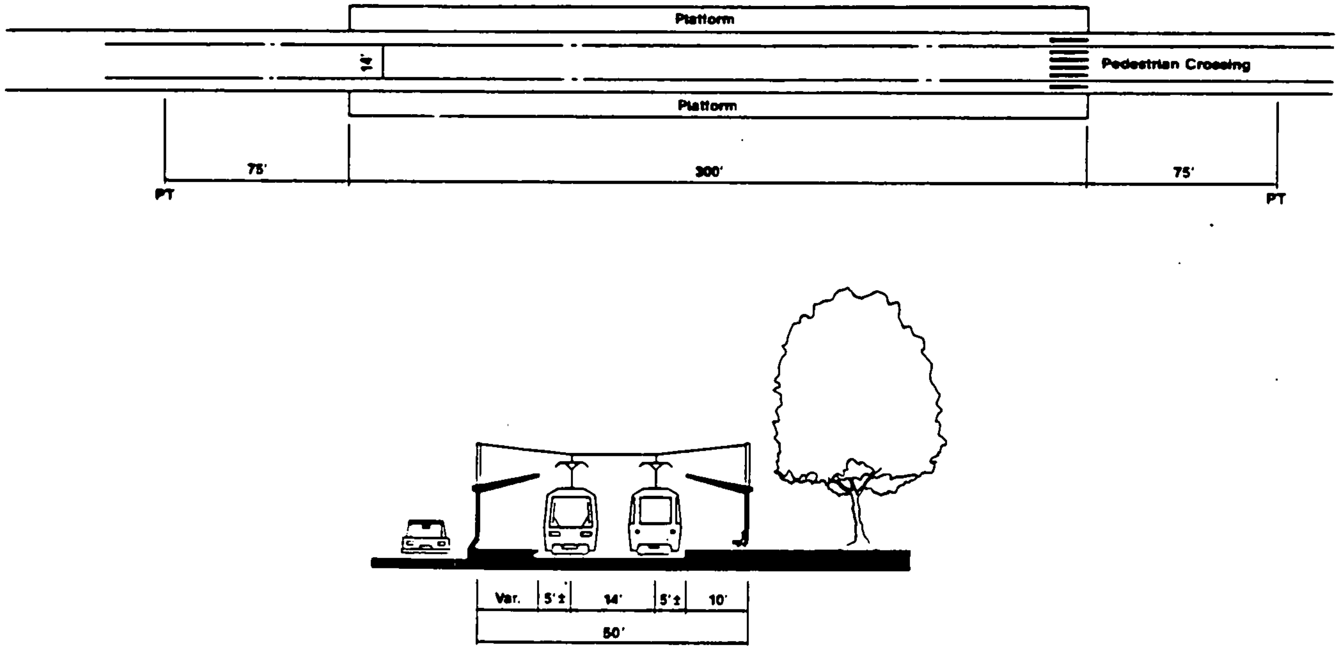

FIGURE 4 Typical station configuration: at grade.

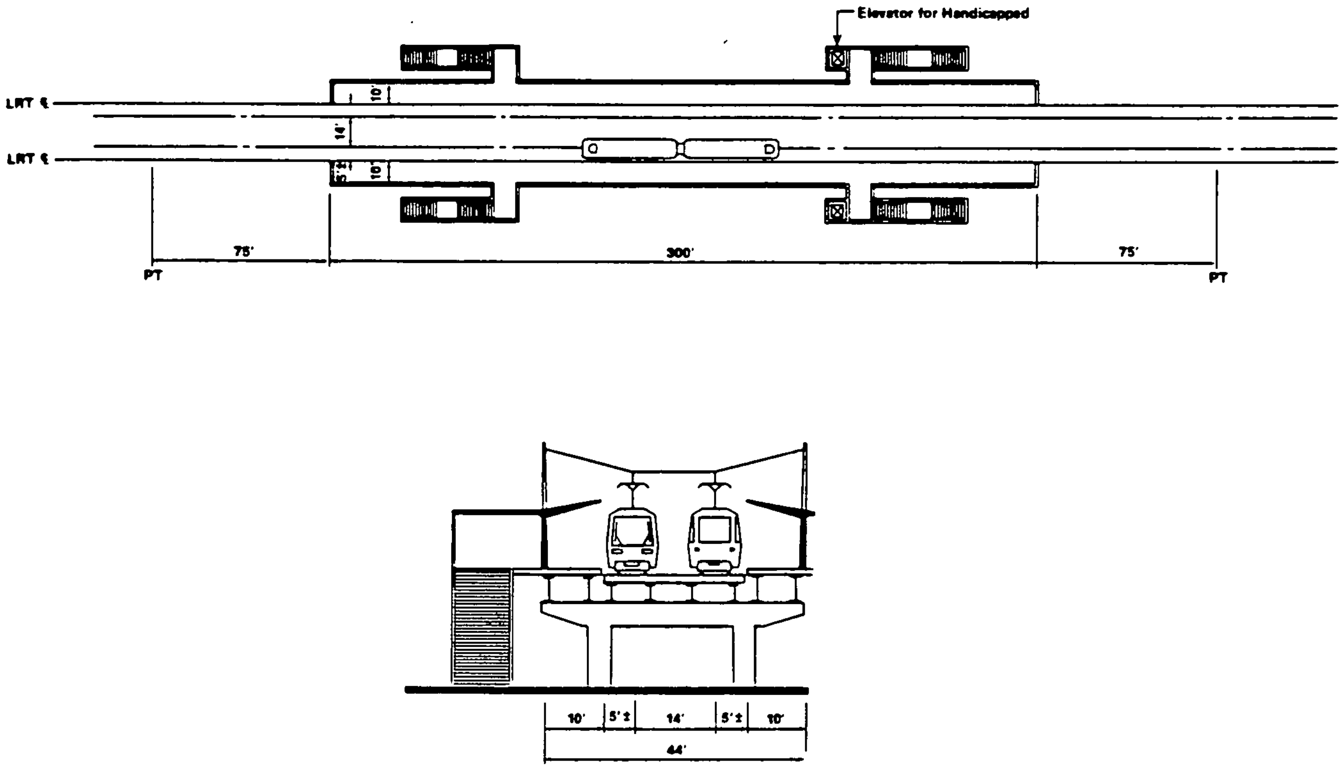

FIGURE 5 Typical station configuration: elevated.

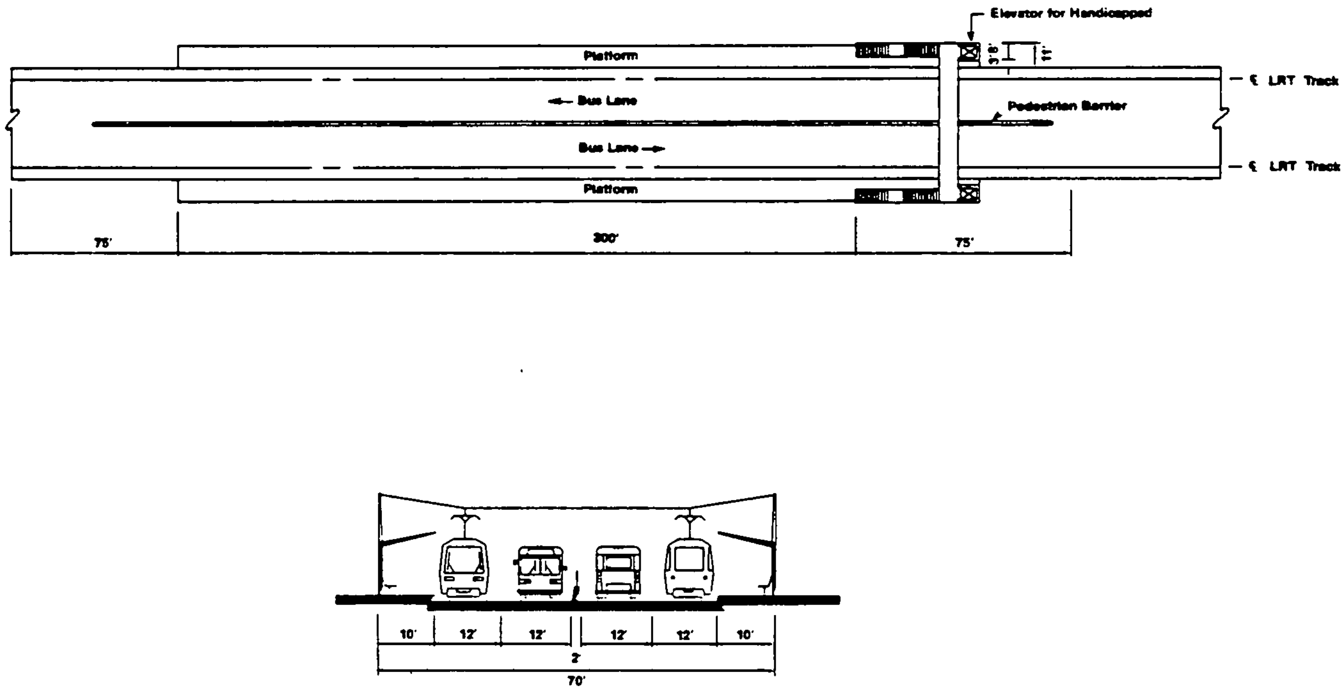

FIGURE 6 Typical station configuration: combined bus and LRT.

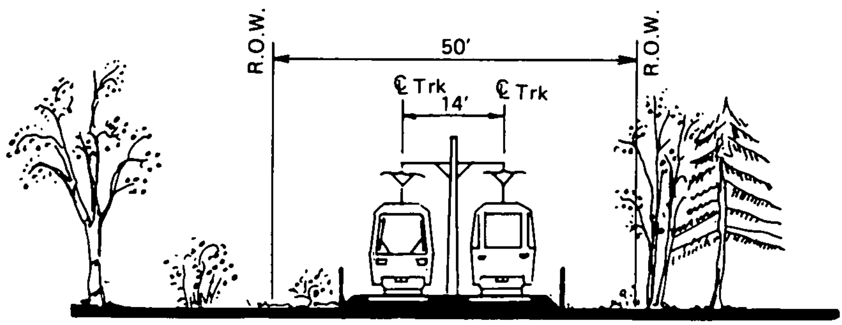

FIGURE 7 Typical cross section: LRT only.

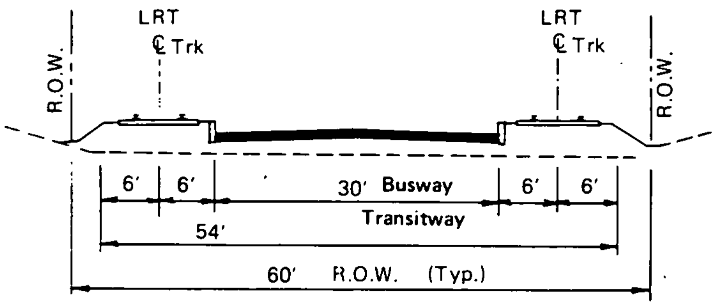

FIGURE 8 Typical cross section: LRT and busway.

Due to the limitation on right-of-way width available through the Weehawken Tunnel, which is only 27 ft wide, LRVs and buses will be mingled on the same roadway through the mile-long tunnel. The cross-section proposed in the Weehawken Tunnel is shown in Figure 10.

In those areas of busway-only operation, the typical cross-section consists of two 12-ft lanes provided together with 8-ft shoulders, and a 10-ft berm. This arrangement is adaptable, though, and could be reduced to 24 ft in areas of limited space.

To the greatest extent possible, the LRT/busway facility will be built at grade to reduce costs. However, there are certain locations along the line where conditions require elevated structures. Elevated locations are as follows:

- From the Mori Tract site to the east side of the Conrail right-of-way—Elevated structure in this area may be the most economical method of crossing the wetlands to avoid a costly earthen fill and accompanying mitigation requirements;

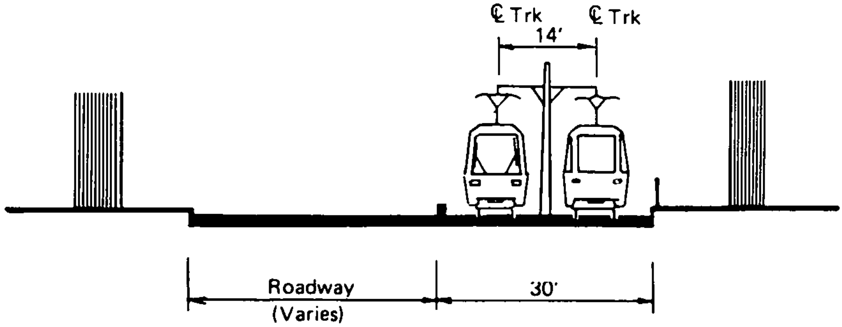

FIGURE 9 Typical cross section: LRT in street right-of-way.

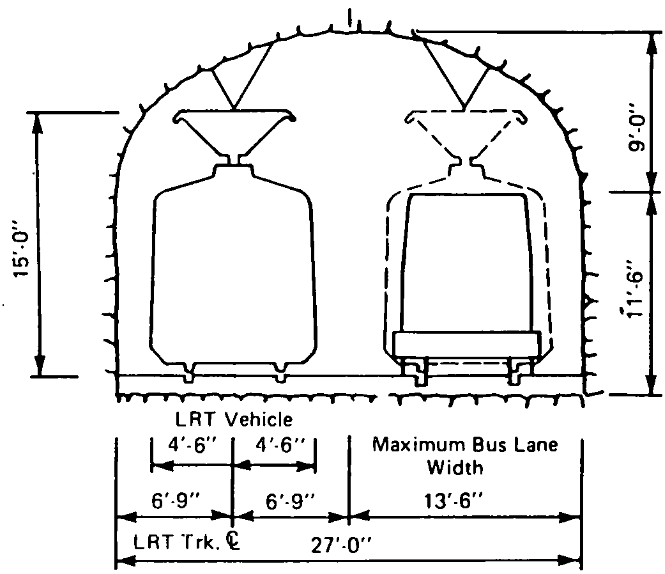

FIGURE 10 Typical cross section: Weehawken Tunnel.

• East of Weehawken Tunnel—An elevated transitway will be provided to grade separate the conflicting merging movements between the transitway routes and the busway from the north;

• Lincoln Tunnel Connector—The busways in this vicinity will be on a set of elevated ramps to sort trans-Hudson bus, local bus, rail, and vehicular movements;

• Crossing Paterson Plank Road and the Morris & Essex Rail Commuter Line;

• Newport—Current traffic projections indicate that grade separations may be required for crossing the major boulevards in the Newport area; and
• Additional elevated structures are being considered between Liberty State Park and the South End park-and-ride facility.

Each of these sections is being reviewed to minimize costs associated with special treatment.

Operating Parameters

Signals and Communications

The LRT system will use a conventional block signal system in those areas where it operates on its own exclusive right-of-way. Traffic signal preemption will be provided as necessary at major intersections. In those areas where both bus and light rail operate on the same roadway or where the light rail is operating within street rights-of-way, line-of-sight procedures will be practiced. The requirement for an on-line communication system will be met by piggybacking the transitway requirement onto the existing state-of-the-art bus radio system.

Transit Vehicles

At the present time the waterfront LRVs are planned to have the following features:

• Six-axle, articulated, double-end units with doors on both sides,
• Capacity for 73 people seated and about 120 standing, and
• 90-ft-long cars with the capability for coupling into two- or three-unit trains with a maximum speed of 45 to 50 mph.

Bus vehicles using the system will include conventional 40-ft transit buses, 60-ft articulated buses in both suburban and city configurations, and MCI commuter buses (intercity design).

Service Standards

During the peak hour, the LRT system will offer initial headways every 3 to 6 min depending upon the consists that are operated. Off-peak headways will be in the range of every 10 to 15 min. The span of service will be approximately between 5 a.m. and 1 a.m. initially, possibly expanded to 24 hours.

Maintenance Facilities

Because of limited available land in the heavily urbanized core of the system, the light rail maintenance center will be located near the northern or southern terminal. Investigations are under way to determine if storage facilities should be split between both ends of the line to minimize the amount of nonrevenue mileage required to set up the daily service pattern. The capabilities of the maintenance facility would be based on those activities already provided by other parts of the NJ Transit system. Integration of the light rail maintenance facility with existing NJ Transit maintenance functions will significantly reduce costs.

Weehawken Tunnel

The tunnel must accommodate both bus and light rail movements. Air circulation will be achieved through the installation of ceiling relay fans to avoid costly ceiling and floor plenums. The design volume for this facility will be approximately 300 buses in the peak hour.

The large peak hour volume of buses through the tunnel, coupled with the difference in braking characteristics between LRVs and buses, requires a unique operating scenario. In the normal operating mode, buses will have free-flow entry into the tunnel. Their bidirectional flow rate will be monitored to prevent more than 22 vehicles occupying the tunnel at any one time. When an LRV is to enter the tunnel, the control system will interrupt bus flow, admit the LRV, and control the time and distance interval between the last bus and any following LRV.

Park-and-Ride Facilities

The terminal park-and-ride facilities are major components of the light rail system. The Mori Tract park-and-ride is being considered in two alternate configurations. The first would feature a five-level parking garage holding 2,860 automobiles. The facility would also enable a transfer between buses and the LRT for those patrons desiring to use the trans-Hudson bus routes in Bergen and Passaic counties to access the waterfront. The conceptual layout of this facility is shown in Figure 11. Another option is to have surface-only parking at a similar capacity. Ordinarily, unstructured parking is cheaper, but the cost of filling wetland areas and mitigation requirements may make surface parking the more costly alternative.

Several options are being considered for park-and-ride facilities adjacent to the southern terminus. In all cases, access would be provided to the Hudson County extension of the New Jersey Turnpike and other arterials.

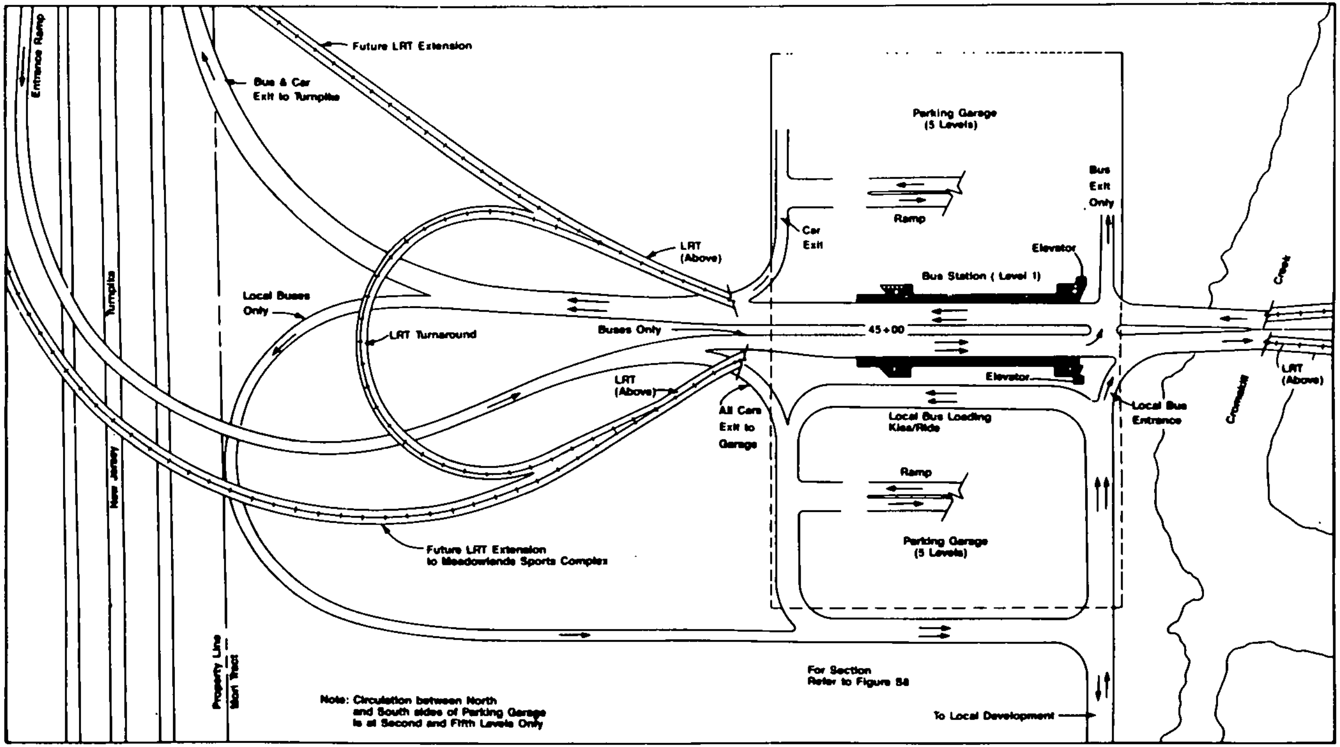

FIGURE 11 Mori Tract park-and-ride.

Funding and Institutional Roles

Funding initiatives and precedents are under way along several fronts. To meet its transportation capital needs, New Jersey has established a Transportation Trust Fund derived from gas tax revenues. This initiative, approved by the legislature in January 1988, is intended to address New Jersey's comprehensive travel needs, including the waterfront. Federal funds have already been applied to right-of-way acquisition along the waterfront. The Port Authority established two dedicated regional development funds from which New Jersey and New York each can draw at their discretion. New Jersey has already withdrawn funds for waterfront transit, highway, and pedestrian walkway projects. Finally, the developers have contributed rights-of-way and, in some cases, agreed to share the costs of transit improvements on the rights-of-way. The following institutions have already contributed to the study and design effort or supported right-of-way acquisition aggressively:

- NJ Transit Waterfront Office—Has been lead agency charged with overall responsibility for planning, design, and acquisition of the transitway system along with financial planning;
- New Jersey Department of Transportation—Provides engineering support for the planning and design effort; negotiates right-of-way acquisition with their consultant, Parsons, Brinckerhoff, Quade and Douglas; sponsors the initial study and design reports;
- Private Developers—Have granted dedicated right-of-way easements and other considerations through their properties and coordinated their designs;
- NJ Transit Bus Operations—Is proposed operator of the transitway property with major role in design standards and bus operations planning;
- Port Authority of New York and New Jersey—Has provided funding assistance for relocating Conrail off the waterfront, initiated consideration of several busway segments in sketch-planning phase, provided technical assistance on bus element of transitway and XBL bypass, and is providing funding assistance on South Busway segment of the transitway;
- Governor's Waterfront Office—Has played major institutional role in advancing the project and liaison with local jurisdictions, resolves land development and transportation issues, and participates in design;
- UMTA—Has provided funding for acquisition of Conrail's waterfront right-of-way to form the transitway core (further federal assistance is anticipated);

• Local Jurisdictions—Have adjusted plans and regulations and provided assistance through waterfront advisory body and directly on local problems; and

• Statewide Authorities and Private Institutions—Have provided other funds.

CONCLUSIONS

The last major addition to the North Jersey rail transit system occurred on May 26, 1935. On that date, Newark's City Subway opened as a light rail operation and closed an era of rail transit expansion. The City Subway, as a concept, an institution, and a light rail property, survived while other rail services in the New York/New Jersey region were discontinued. It is significant that this last new addition in 1935 and the anticipated future addition, the waterfront transitway of the 1990s, are both light rail.

Alternative Light Rail Transit Implementation Methods for Hennepin County, Minnesota

RICHARD WOLSFELD AND TONY VENTURATO

The Comprehensive Light Rail Transit (LRT) System Plan for Hennepin County, Minnesota, defines a Stage 1 system, a 20-year system, a financial plan, and an implementation plan. The purpose of the implementation plan is to define the contractual relationship between the Hennepin County Regional Railroad Authority (HCRRA) and the suppliers of the LRT system, to define the system operating and maintenance responsibility, and to define the relationship between associated land development and the LRT system. The reason for investigating alternative implementation methods is that much interest exists in involving the private sector to the maximum extent, consistent with the public interest. LRT system implementation will include not only the construction and procurement of system facilities and equipment, but also the financing of this work. In addition, options may be available to involve construction and procurement contractors in the operation and maintenance of the system after it is built. Recent years have also seen great interest in coordinating land development with rail transit construction. In some instances, developers of adjacent land have participated in the financing of transit stations. This report defines the LRT system components, identifies and evaluates alternative implementation methods, and outlines conclusions on an approach to LRT system implementation.

THE TWIN CITIES OF Minneapolis and Saint Paul have analyzed the feasibility of fixed-guideway transit systems since 1968 when the Metropolitan Transit Commission was formed. To date, no system has been implemented. The general history includes the following events:

R. Wolsfeld, Bennett, Ringrose, Wolsfeld, Jarvis, Gardner, Inc., 700 Third Street South, Minneapolis, Minn. 55415. T. Venturato, Bechtel Civil, Inc., 3505 Frontage Road, Suite 250, Tampa, Fla. 33617.

- Late 1960s and early 1970s—studies resulted in a regional, preferred fixed-guideway system that was automated and used a 40-passenger vehicle;
- Mid-1970s—significant study of personal rapid transit was undertaken and studies of busways were completed;
- Late 1970s and early 1980s—feasibility studies of LRT were completed;
- Early 1980s—Minnesota legislature enabled counties to establish regional railroad authorities to implement light rail transit (LRT) systems;
- Mid-1980s—implementation studies of LRT were completed; and
- 1985–1987—the legislature prohibited any public agency from spending public monies on the planning or design of LRT.

These studies were all undertaken by a metropolitan or state unit of government. This governmental focus changed in 1987, when the Minnesota Legislature reinstituted the authority of regional railroad authorities to implement LRT. Thus, after many years of discussion, a single agency has the authority to proceed with LRT implementation in Hennepin County. The legislation required that the railroad authority prepare a comprehensive LRT system plan. The plan is based upon previous work and answers the following questions:

- Where will LRT services be provided within 20 years?
- What will the Stage 1 system include?
- What method will be used to implement the LRT system?
- How will the LRT system be financed?
- Who will operate the system?

POTENTIAL LRT ROUTES

Five corridors considered to have high potential for successful LRT implementation are being analyzed in the LRT system plan (see Figure 1). The Northwest Corridor connects downtown Minneapolis with the northwestern suburbs. A 1981 study of LRT feasibility in the region identified this corridor as a high priority. The University Connector would link downtown Minneapolis and the Minneapolis campus of the University of Minnesota, the third largest generator of transit trips in the region. This link was a portion of the corridor including downtown Minneapolis to downtown Saint Paul, which was studied in a recently completed alternatives analysis.

The Hiawatha Corridor would connect the downtown area with the airport and the proposed 10 million ft^2 of development known as the Mall of America in Bloomington. LRT was identified as the preferred transit alternative in a corridor Environmental Impact Statement (EIS) completed in 1985.

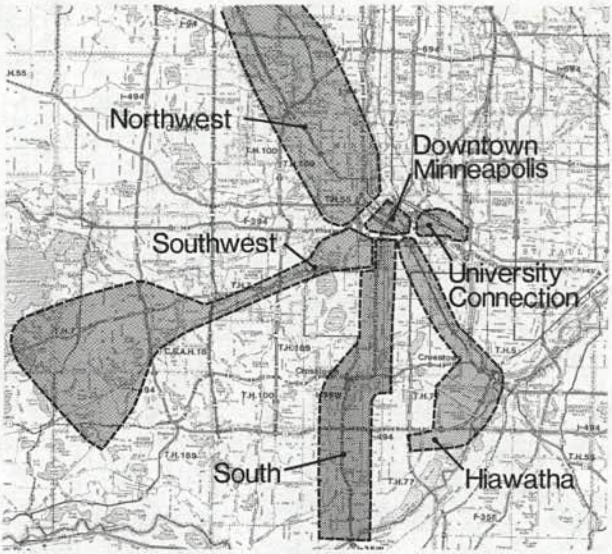

FIGURE 1 Study corridors.

The preferred roadway component of the corridor plan, a four-lane at-grade arterial, will go under construction in summer 1988. The South (I-35W) Corridor would connect south Minneapolis and the southern suburbs of Bloomington, Richfield, and Edina with downtown. Concurrent studies by the Minnesota Department of Transportation (MDOT) and the Metropolitan Council are assessing the need for I-35W highway and transit improvements in the corridor. The southwestern suburbs are connected to downtown via the abandoned Chicago and Northwestern Railroad right-of-way purchased by the Hennepin County Regional Railroad Authority in 1984. LRT was considered as an alternative during a draft and alternatives analysis of the University Avenue and Southwest Corridor.

In June 1988, the Hennepin County Regional Railroad Authority (HCRRA) adopted a Stage 1 system and a 20-year plan that are shown on Figures 2 and 3 and summarized in Table 1. The major conclusions of the plan are to proceed with implementation of an LRT service in the Twin Cities, to provide service in multiple corridors in Stage 1 versus service in a single corridor, and to construct a tunnel in the downtown area.

The financial plan for the Stage 1 system includes a countywide property tax, tax increment around stations, a portion of state sales tax on motor vehicles, and private sources. The county currently levies 0.75 mill, which raises $7 million per year. In April 1988 the Minnesota Legislature appropriated $4.17 million from the sales tax on motor vehicles for LRT "planning,

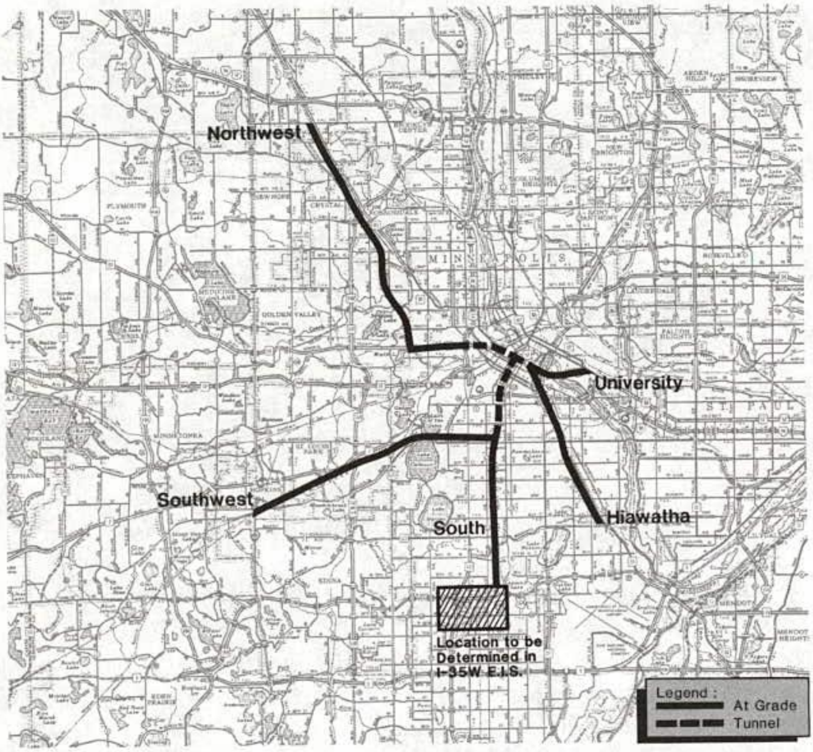

FIGURE 2 Stage 1 plan.

preliminary engineering, design, and construction" and also stated that the "funds appropriated for LRT should be considered as base level funding for presentation in the 1990–1991 biennial budget."

LRT PROJECT COMPONENTS

Figure 4 illustrates the major LRT system implementation components. LRT design and construction consists of the activities necessary to put the project's physical components in place: civil construction, procurement and installation of vehicles and their support systems, and construction of stations. The components include the following:

• Civil—the basic infrastructure of the system. For the purpose of simplification, this element involves preparation of the roadbed; all work below the subballast of the trackway, electrical subsystem foundations, underground conduit banks, drainage, subsurface treatment and grading; bridge structures;

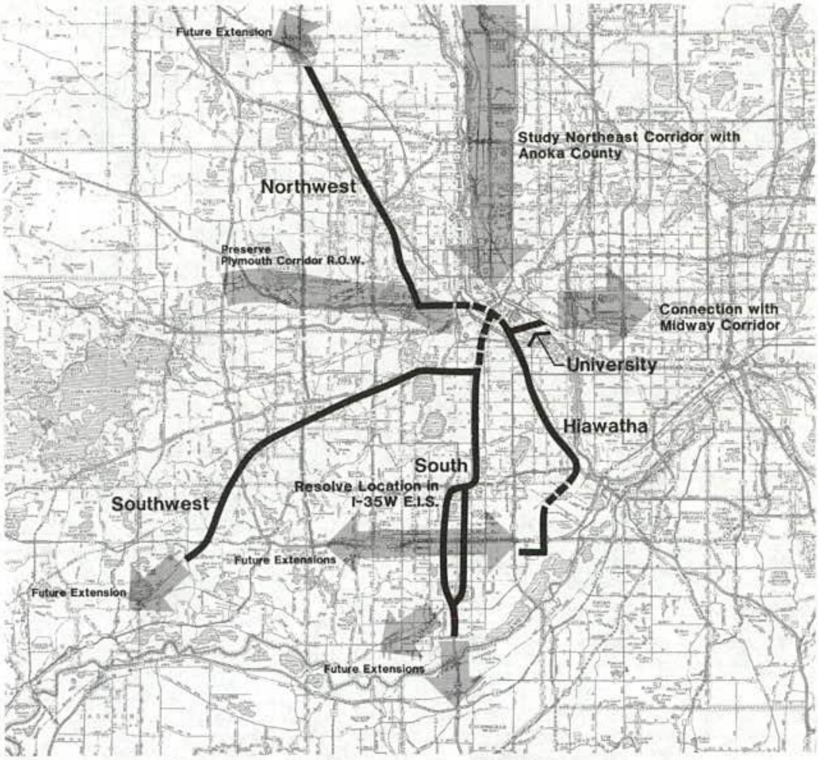

FIGURE 3 Twenty-year comprehensive LRT system plan.

street work; station footprints; and in the case of a subway section, tunnel construction.

- Systems—This element includes all facilities and equipment that are common throughout the system, i.e., light rail vehicles, track installation, electrification (power substations and overhead wires), signals, communication, fare collection, support equipment, and the central operations and maintenance facility.
- Stations—This involves station furnishings over and above the basic station footprint, including platforms and surface treatment finish work; lighting; furniture and amenities; electric power; shelters; heat; connections to roadways, public sidewalks and buildings; park-and-ride lots; elevators and escalators for any subway construction; and handicapped access.

Operations will commence upon the completion of design and construction. Public policy decisions (who will run the system and how) must be made prior to this event, an LRT operating structure defined and staff trained,

TABLE 1 CHARACTERISTICS OF RECOMMENDED 20-YEAR AND STAGE 1 PLANS

	TWENTY-YEAR PLAN			STAGE I PLAN		
SEGMENT	Length (Miles)	Capital Cost (1988 $ Million)	Daily Ridership Range Year 2010	Length (Miles)	Capital Cost (1988 $ Million)	Daily Ridership Range Year 2010
Downtown (Tunnel to 29th Street)	3.4	$138	–	3.4	$138	–
Northwest Corridor	12.0	139	19,600 - 25,500	9.0	114	18,000 - 23,500
Southwest Corridor	13.5	127	16,600 - 22,000	6.9	71	14,500 - 18,800
South Corridor	10.4	216	24,500 - 32,000	4.4	80	15,300 - 20,000
Hiawatha Corridor	10.0	145	17,300 - 22,500	3.9	34	13,000 - 17,000
University Connector	1.5	40	9,200 - 12,000	1.5	40	9,200 - 12,000
Yards and Shops	–	20	–	–	20	–
TOTAL	50.8	$825	87,200 - 114,000	29.1	$497	70,000 - 91,300

NOTE: The capital costs and patronage forecasts will be refined in Preliminary Engineering. The ridership forecasts are based on work reported in the Metropolitan Council report dated December 1986, "A Study of Potential Transit Capital Investments in Twin Cities Corridors" and the results of the Patronage Forecasting Peer Review Committee work.

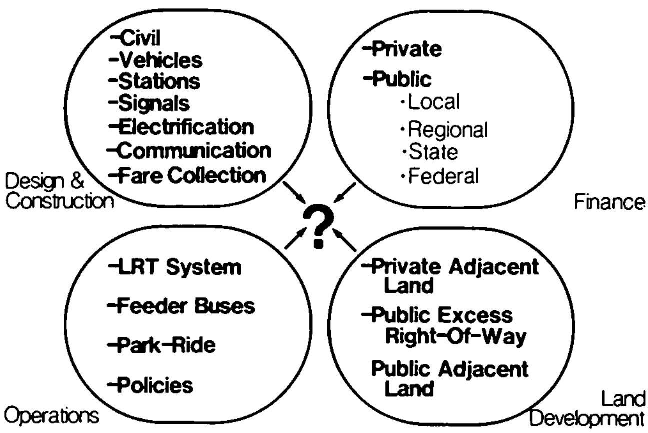

FIGURE 4 LRT project components.

and bus feeder services planned to coordinate service to the public. LRT will require that an organization be established, either within the structure of the existing transit agency or by a new operator, with rules and procedures appropriate to rail operations as distinct from the requirement of the present all-bus system. Personnel will be needed who possess specialized skills: transportation supervisory staff and train operators, security staff, vehicle maintenance personnel, and facilities maintainers.

Financing must be arranged from some combination of public and private sources to fund design and construction and ongoing operations. Related land development is likely to occur in the public right-of-way used by LRT as well as on adjacent private lands. Mechanisms can be implemented to capture for LRT system use a portion of the revenue that these new developments will create.

The issue addressed in this paper is how the above-defined LRT components should be related during system implementation and operation.

IMPLEMENTATION OPTIONS

LRT project implementation must efficiently coordinate the design, specification, procurement, and installation of equipment and construction of the LRT facilities. The objective of LRT project implementation is clear: on-time completion within budget with performance up to or exceeding the specification.

The major question is how to achieve this objective. To determine the best way to coordinate these facets of the implementation process, it is appropriate first to examine the various contracting methods as well as the roles and responsibilities of the implementers and then to match the contracting methods with the alternative implementation methods.

CONTRACTING METHODS

Several types of contracting methods may be used, each tailored to facilitate contractor performance of a particular set of construction, procurement, or furnishing and installation tasks. One-step competitive bidding (method A) is traditionally used when contract documents are clearly drawn and prospective contractors have a firm basis for their price proposals without significant latitude in interpretation. Advertisements solicit firm-price bids, after which award is made to the lowest responsive and responsible bidder.

Two-step competitive bidding (method B) is used when there is need to evaluate the bidders' approach to the project and their abilities to meet the stated objective. In these cases, the various prospective contractors have the latitude to approach the contract differently; and the owner reviews and selects the approach best suited to the original requirements before the contract award.

This process begins by advertising for technical proposals from potential contractors. Step 1 (which could be preceded by prequalifications, if desired) entails reviewing proposals (and possibly negotiating with the proposers separately to revise their technical proposals to meet the owner's needs). A limited number of responsive, responsible proposers judged to be capable of meeting the owner's needs are invited to submit prices. Step 2 makes the award to the lowest bidder.

Competitive negotiations (method C) are used when lowest price is not the only basis for award at the end of the evaluations. The process usually starts with an advertised request for letters of interest and qualifications. Proposals including technical approach and price are then requested from a screened list of qualified proposers. The main factors that are evaluated in the proposals are technical quality and price. Other factors, such as experience and performance history, may also be evaluated. Discussions and interviews are held separately with the proposers, as in method B, and continue until the proposers are asked to provide their best and final offers. Award is based on the highest-ranked proposals in terms of technical quality, price, and other prescribed factors.

ALTERNATIVE LRT IMPLEMENTATION METHODS

LRT system implementation will include not only the construction and procurement of system facilities and equipment, but also the financing of this work. In addition, options may be available to involve construction and procurement contractors in the operation and maintenance of the system after it is built. Recent years have also seen great interest in coordinating land development with rail transit construction. In some instances, developers of adjacent land have participated in the financing of transit stations.

The alternative methods of dividing the implementation work are discussed below. There are variations and hybrids of the methods shown, but those outlined constitute the basics for purposes of discussion.

Traditional

In the traditional method the project manager or engineer specifies the system elements (vehicles, electrification, signals, communications, fare collection, etc.) or components of the system elements (substation equipment, catenary network, track material, etc.) and issues separate detailed specifications for bid (see Figure 5). At the same time, the civil design is advanced to 100 percent drawings. Contracts are awarded for the system elements and components, and the contractors fabricate and furnish the equipment. The civil contract drawings are also issued for bid and awarded to low, responsible bidders; the contractors construct the LRT infrastructure. These construction contractors (or other contractors) could also install the electrification, signals, communication equipment, and fare collection. Upon completion, an operations contractor or a public agency operates the system.

Traditional contracting provides maximum control to the project owner, but limits the likelihood of obtaining contractor financial participation.

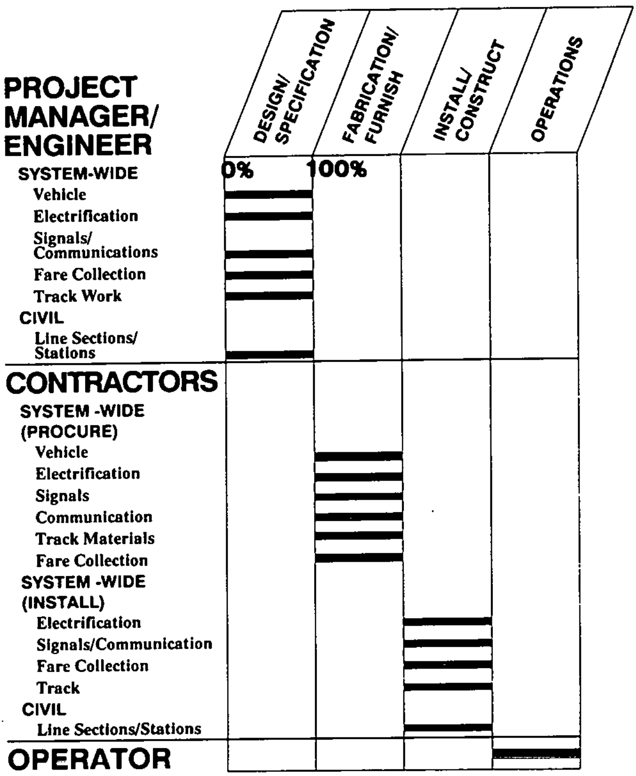

FIGURE 5 Traditional method.

Design/Build

In the design/build method, the project manager or engineer advances the design to the performance specification level in the case of the systems elements and to 30 percent in the case of the civil design (see Figure 6). The system elements each are awarded to contractors who design, furnish, and install the equipment. The 30 percent civil designs are issued for bid as design/build sections. Upon completion, an operations contractor or a public

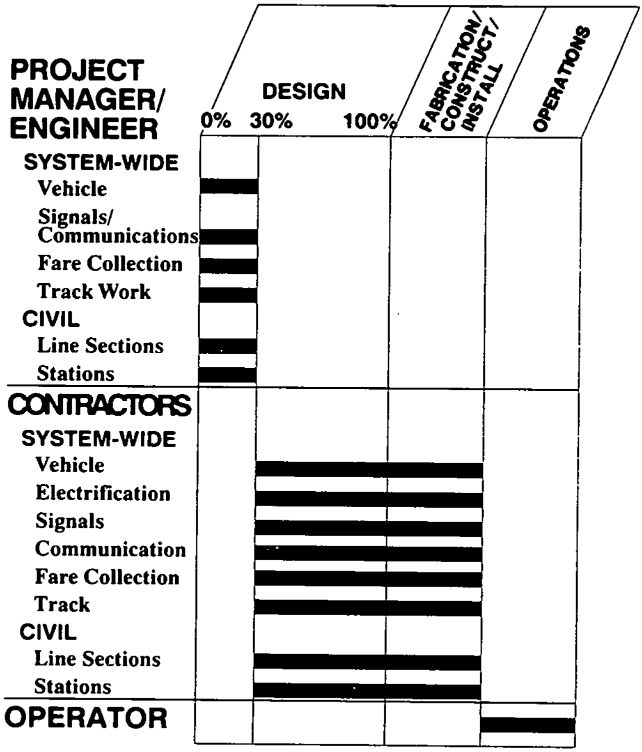

FIGURE 6 Design/build method.

agency operates the system; the operations decision is made independently of the design and construction.

The design/build method sacrifices a modest degree of owner control, but enables suppliers to tailor final design to their products rather than having to "reengineer" to the owner's exact specifications. Unless properly specified and managed, this approach can have the effect of limiting competition, thus affording an advantage in subsequent extensions to those firms successful in the initial stage.

Turnkey

In the turnkey method the project manager or engineer advances the design as would be done in the design/build method, but the performance specifications and 30 percent design are issued for competition as one package (see Figure 7). Having the project manager or engineer advance the design to 30 percent

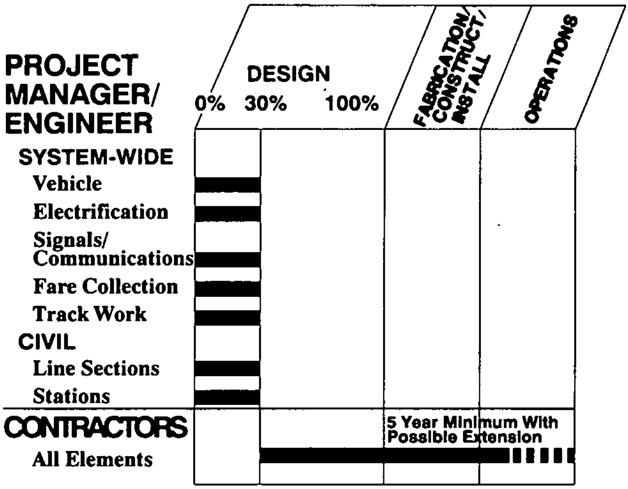

FIGURE 7 Turnkey method.

establishes the basic system parameters, allows for definitive cost estimation, and keeps the contingency margin reasonable.

The winning turnkey contractor completes the design in all areas and fabricates and furnishes the equipment at an agreed-upon price. The turnkey contractor also operates the system, at an agreed-upon price, for a prescribed period to ensure reliability. A minimum period of 5 years is usually suggested as a reasonable time period for problems to develop.

Turnkey further lessens owner control, but transfers responsibility for successful system operation to the turnkey contractor. Properly specified and managed, this approach focuses responsibility for cost and schedule performance, quality, and achievement of performance standards in a single entity. This removes many external interface-related claims.

Super Turnkey

The super turnkey method is the same as the turnkey approach except that the super turnkey contractor is also made responsible for partial or total system financing and is involved in the related land development. Financing might take the form of loans (e.g., vendor financing) or lease/buy-backs. There also could be a relationship of funding portions of the system, particularly at or around stations, through joint development.

The super turnkey approach makes the contractor responsible for financial and land development arrangements, but is likely to require that public agencies cede substantial control over the precise details of the technical and physical solution to the super turnkey contractor.

Contracting methods appropriate for each alternative implementation method are shown in Table 2.

TABLE 2 MATCHING ALTERNATIVE IMPLEMENTATION AND CONTRACTING METHODS

Alternative Implementation Method	Alternative Contracting Method
Traditional	One-step competitive bidding
Design/build	Two-step competitive bidding or competitive negotiations
Turnkey	Competitive negotiations
Super turnkey	Competitive negotiations

EVALUATION OF ALTERNATIVE IMPLEMENTATION METHODS

The evaluation of the applicability of the alternative implementation methods centers on the following criteria:

- Contractual, construction, and performance risk;
- Time schedule;
- Responsibility/accountability;
- Budget control/cost; and
- Quality.

Figure 8 presents a more detailed indication of how the various elements of LRT design and construction and operations fit together, and how they relate to options for public and private finance and development. Of 76 possible points of interaction, there are 32 "strong" and 25 "moderate" interrelationships.

These interrelations along with the above-defined criteria are used to reach conclusions. Although different metropolitan areas most likely will reach different answers about which implementation method to use, certain conclusions are reached on each of the implementation methods.

Civil

This element carries the greatest number of unknowns (e.g., soil condition variances), involves numerous third parties (utilities, railroads, and other

S Strong

M Moderate

N None

		LRT Design & Construction						Operations			Finance		Development	
		Vehicles	Civil	Stations	Communication	Signals	Electrification	LRT System	Feeder Bus	Public Policy	Public	Private	Public	Private
LRT Design & Construction	Vehicles													
	Civil	S												
	Stations	S	S											
	Communication	M	M	M										
	Signals	S	M	S	M									
	Electrification	S	M	M	M	S								
Operations	LRT System	S	S	S	M	S	M							
	Feeder Bus	N	M	S	N	N	N	S						
	Public Policy	S	S	S	N	M	M	S	S					
Finance	Public	M	M	S	M	M	M	S	M	S				
	Private	M	N	S	N	N	N	N	N	S	S			
Development	Public	N	M	S	N	N	N	S	M	S	S	M		
	Private	N	N	S	N	N	N	M	N	S	M	S	S	

FIGURE 8 Relationships among LRT system implementation components.

public jurisdictions), and also involves property acquisition. If a subway or tunnel is part of the LRT, the risks are even greater. With a 30 percent level of design completed by the owner, all potential contractors have to either complete a significant amount of additional engineering or include a significant contingency in any fixed-price bid.

The failure to make right-of-way available or to gain agreements with railroads has been a historic problem and a cause of many schedule delays on fixed-guideway projects.

The schedule delays have also resulted in increased costs caused by inflation. The owner will have to take this risk and establish a firm schedule for availability of right-of-way and clearance of all utilities with a turnkey or super turnkey approach. It does not appear feasible to use a turnkey or super turnkey approach for all portions of the civil component of an LRT system.

The traditional method affords the highest degree of control. Civil design can be paced and adjusted in accordance with systemwide design development, third party negotiations, and the overall project schedule. The owner or the owner's project manager or engineer can fast-track certain long-lead sections (e.g., bridges) and adjust implementation schedules on other sections as the need arises.

Systems

Systems procurement for furnish/install contracts for several North American LRT projects (e.g., Portland, Sacramento, San Jose) has successfully been implemented using the design/build approach. Some foreign projects (Istanbul, Tunis, Manila) are using the turnkey approach.

An important consideration is the integration of the various systems components with each other and with the civil components. Most integration problems encountered will fall into two categories: systems/civil coordination and the securing of approvals and permits from regulatory bodies. The owner's project manager or engineer must possess the requisite skills to ensure this coordination. The systems integration function is crucial to ensuring that an operable project is built. Under the design/build option, the owner, through the project manager or engineer, could perform the coordination between civil and systems and can perform the coordination among the systems components (vehicles, signals, etc.) as well. This will allow tighter control by the owner.

Regarding the turnkey approach, no single manufacturer can provide all of the systems components (see Table 3). Thus, a turnkey approach will require several companies to cooperate, organized either as a joint venture or as a prime contractor with subcontractors.

Some suppliers have expressed an interest in the turnkey approach based on experience with projects outside the United States. The "price" of some loss of control by the owner may be worth considering if the turnkey contractor is prepared to accept some of the cost and schedule risks, and if the contractor is made responsible for operations management of the system for an extended period of time beyond the normal 2-year warranty time (say at least 5 years overall).

There is some thought among transit engineers that the contractual link between the major components of building the system and operating it may bring additional benefits. By holding the contractor responsible for management of operations (local forces already in place will perform actual works under the turnkey contractor's management), there is a financial incentive not to allow operating costs to exceed initial projections. The contractor may be more careful to design equipment to reduce operating and maintenance costs, because equipment failures will reduce the contractor's profit. Conversely, reliable, maintainable equipment will reduce costs, hence increasing profit.

In conclusion, a design/build approach for systems components will apply contracting methods successfully used on other recent North American LRT

TABLE 3 REPRESENTATIVE LIST OF LRT SYSTEMS MANUFACTURERS BY AREA(S) OF SPECIALIZATION

		Light Rail Vehicles			Traction Power		Signals/Control		Communications			Maintenance		
Company	Home Country	Bodies	Mech/Elec	Track Matls	Substas	OH Equip	Rail	Traffic	Radios	Phones	CCTV	Tools	Vehicles	Access to Financing
Alsthom	France	X	X							X				Y
Siemens	Germany		Proplsn		X	X	X[a]		X	X	X			Y
BBC	Switzerland		Proplsn		X									N
ASEA	Sweden		Proplsn		X									Y
NYAB	U.S.		Brakes											N
Ohio Brass	U.S.				X	X								N
GRS	U.S.							X						Y
WABCO	U.S.		Brakes				X							?
Bombardier	Canada	X												Y
Duewag	Germany	X												?
UTDC	Canada	X												Y
WECO	U.S.		X											Y
Central Power	U.S.				X									N
Hegenscheidt	Germany											X		N
Stanray	U.S.											X		N
Motorola	U.S.								X					N
Bethlehem Steel	U.S.			Rail										N
L.B. Foster	U.S.			Ties										N
Niedermeyer-Martin	U.S.			Ties										N
Sumitomo	Japan	X		Rail										Y
Breda	Italy	X												Y

[a]Designs not compatible with U.S. practice.

projects and allow tighter owner control. A turnkey approach, however, may offer additional benefits regarding risk transfer and operating responsibility, albeit at the price of reduced county control.

Stations

The most appropriate implementation method for stations depends upon whether or not adjacent development opportunities exist. Traditional contracts are most appropriate to construct those stations where no developer involvement will occur. This will ensure maximum county control and coordination with other stations.

Super turnkey contracts are suggested where stations can be provided (i.e., built and paid for) by developers as part of adjacent building projects. Such contracts must be drawn to ensure compliance with LRT functional requirements (e.g., platform dimensions, weather protection for waiting passengers, station utilities, etc.); but some latitude may be given to allow developers to coordinate station architectural appearance with their projects.

Related Land Development

Counties in the State of Minnesota have no control over local land use decisions. They do not zone property and they do not approve building and site plans. Therefore, Hennepin County needs to establish interjurisdictional agreements with the various municipalities in which LRT service is proposed. With this completed, the county (as LRT developer) and municipalities can proceed together to solicit land developer or property owner interest and coordinate the development of stations integrated with adjacent real estate projects as discussed above and other developments on private land adjacent to the LRT right-of-way.

CONCLUSIONS

On the basis of the above discussion, two alternative approaches are suggested for metropolitan areas to pursue for the implementation of LRT systems.

Alternative A would use the traditional method for the civil component and the station/land development where no developer interest exists (see Figure 9). A design/build approach would be used for the system elements. Super turnkey would be used for station development where developer interest does exist. This approach retains significant control and responsibility with the owner, but allows the demonstrated advantages of design/build for the system

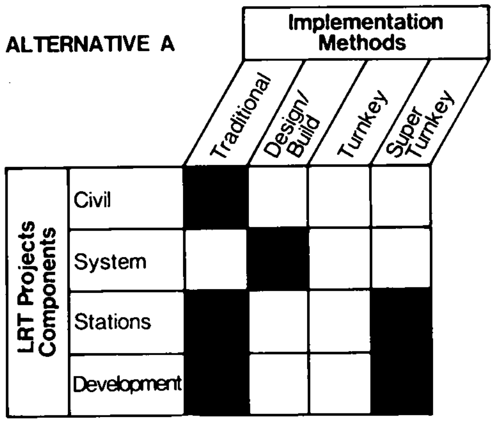

FIGURE 9 Alternative implementation methods for LRT project components (Alternative A).

elements. The role of the private sector relates to station construction and related land development. The objective would be to capture a portion of the increased value created by the presence of LRT.

Alternative B would result in maximum involvement of the private sector (see Figure 10). After the 30 percent design level the selected contractor would complete the design, build the system, operate the system, and be committed to capital contributions that relate to development around the stations or other innovative financing techniques. The contractor would be

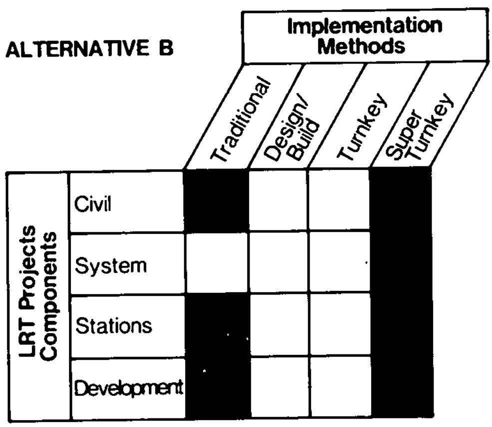

FIGURE 10 Alternative implementation methods for LRT project components (Alternative B).

selected on the following basis: financial capability, technical capability, management capability, and approach to "innovative" funding.

One of the problems with Alternative B is that no system has been completed using this approach. Many members of the private sector have recommended this approach, but to date it has not been used. One approach to giving Alternative B an opportunity without total commitment would be to follow the steps outlined below:

- Complete the preliminary engineering to the 30 percent level;
- While the engineering activities are being completed conduct the following tasks: prequalify super turnkey contractors and solicit technical approaches for innovative financing from the prequalified contractors; and
- If a proposal has substance, proceed with the super turnkey approach. If none of the prequalified proposers present "innovative" financing, continue with Alternative A.

West Side Manhattan Transitway Study

Gregory P. Benz, Wendy Leventer, Foster Nichols, and Benjamin D. Porter

In response to the current and anticipated changes in the type and intensity of land use activities on Manhattan's West Side, the New York City Department of City Planning is conducting the West Side Transitway Study to ensure that adequate transportation services are in place to serve the new workers, residents, and visitors. The study, funded by the UMTA, is a four-phase effort that is examining potential transportation problems created by the anticipated developments, defining the degree to which improvements are needed, and determining the feasibility of implementing and operating new transit services and facilities to solve the identified problems. Because current sources of funding for public transportation are fully committed to the operation, rehabilitation, and upgrading of New York City's existing systems, innovative methods for financing and implementing the recommended improvements are being explored. This paper summarizes the first three phases of the study's transportation component. The existing transportation conditions in the study area are explored along with the future problems and needs created by the new development. The type of transportation improvement alternatives developed, primarily light rail transit (LRT) options, and specific issues related to reinstituting LRT in a dense urban environment such as Manhattan are described. In addition, issues related to privatization of the project implementation and operation are reviewed.

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TO COPE WITH SIGNIFICANT changes in land use activities on Manhattan's West Side, the New York City Department of City Planning is conducting a major study to examine potential transportation problems and to seek solutions. Funded by UMTA, the West Side Transitway Study will develop land use strategies and a financial, legal, and institutional plan to support any transportation improvements. The first phase of the study's transportation component identified the transportation problems and needs within the study area, shown in Figure 1. (Note: The study area indicated in the figures in this paper is the original designation in which the east boundary in Midtown Manhattan was Lexington Avenue; the study area was later extended further east to the East River.)

In the second phase, the initial set of alternatives was refined and evaluated in the light of physical and operational constraints, costs, and ability to serve new travel patterns and demand levels. A reduced set of alternatives was carried into the third phase where more specific travel demand analyses, engineering, cost estimates, environmental evaluations, and public policy analyses are used to select a preferred alternative. The last phase of the study will package the proposed transportation improvements with the results of the land use and financial and institutional evaluations to form an integrated strategy for addressing the future transportation needs of the West Side. This paper summarizes the first three phases of the study, including issues related to privatization of the project implementation and operation.

EXISTING CONDITIONS

The primary transit service on the West Side of Manhattan is two subway (rapid rail transit) lines in the north-south direction—the Eighth Avenue IND (Figure 1, A, C) and the Broadway-Seventh Avenue IRT (1, 2)—and three in the east-west direction—the 53rd Street IND (E, F), 42nd Street Shuttle and Flushing IRT (7), and the 14th Street (Canarsie) (L) lines. The major crosstown streets have bus services that generally run river to river. The north-south avenues as far west as 10th Avenue also have bus services. The study area also contains several major commuter facilities, including the Port Authority Bus Terminal, Penn Station, Grand Central Terminal, the Port Authority Trans-Hudson Corporation's (PATH's) Uptown (33rd Street) and Downtown (World Trade Center) terminals, the Staten Island Ferry Terminal, and the George Washington Bridge Bus Terminal.

The travel demand for most of these services and facilities is approaching or exceeds the supply at present. During the morning peak period the express services of the Seventh Avenue IRT and Eighth Avenue IND subway lines are overcrowded where they enter the hub of Manhattan, specifically the southbound services at 60th Street. These lines are also congested during the

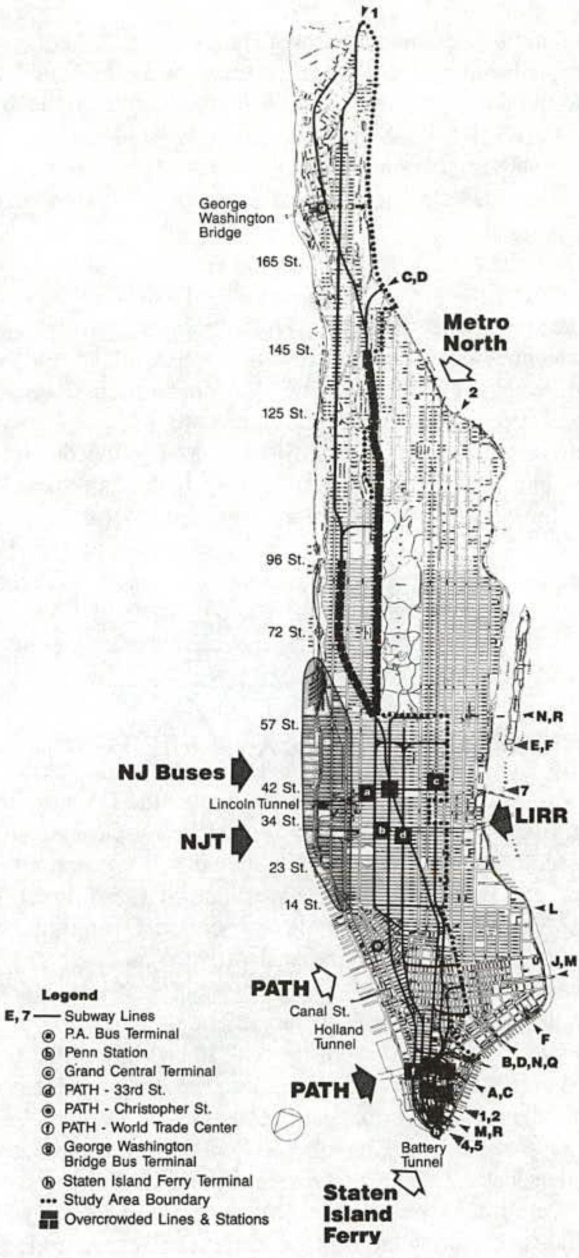

FIGURE 1 Existing conditions—transit.

evening peak, in the opposite direction. (The overcrowded conditions exist at current scheduled train service; however, the subway lines have the capacity to handle additional trains that could alleviate some of the overcrowded conditions.) Many of the subway stations in the study area are among the busiest in the subway system—Grand Central, Times Square, 34th Street (Penn Station), and Herald Square—and also experience significant crowding during peak periods.

Like much of the core of Manhattan, the West Side street network experiences increasing traffic congestion resulting from a growing reliance on travel by motor vehicles, particularly automobiles and taxis. Most of the north-south avenues and the major crosstown streets in the study area operate at congested levels—level of service D or worse on a scale of A (best) to F (worst). Travel speeds in the congested streets are as low as 2.5 mph, which is slower than average walking speed. Slow operating speeds and high traffic volumes combine to create concentrations (called "hot spots") of carbon monoxide pollution in excess of federally accepted air quality levels.

In addition to these problems, the area west of 9th and 10th avenues between 14th and 72nd streets has no subway service (see Figure 1). While this deficiency is not a major contributor to the problems with the transportation system today, the situation will change as this area is built up with new housing and offices.

FUTURE TRAVEL PATTERNS AND NEEDS

Recent and proposed development on the West Side is concentrated in four areas: Battery Park City/World Trade Center; Penn Station/Convention Center area; Lincoln Square West, which includes the proposed Trump City development; and Port Harlem at the west end of 125th Street. Most of this development is in the area with no subway service. Overall, the new residential development on the West Side will produce an estimated 22,000 new morning peak hour transit trips—a 10 percent increase over the number produced by today's residential inventory. The new office development will attract an additional 136,000 morning peak hour transit trips into the study area—a 14 percent increase. The evening peak hour will generate similar numbers, and the presence or expected construction of several major special trip generators—the Javits Convention Center, a new, relocated Madison Square Garden west of Penn Station, and a 1.5-million-ft^2 retail shopping mall in the Trump City proposal for the former rail freight yards between 60th and 72nd streets along the Hudson River—will create added loads on the transit system during the evening peak hour.

Most of the trips attracted by the new commercial development will originate in established residential areas of the outer boroughs and the surrounding suburbs. Many of these people will use the existing public transportation network to commute to midtown and downtown subway stations and commuter terminals. These transit patrons attracted by the new office space require connections between the existing transit system and the developing areas of the West Side not currently well served by the existing system. Specifically, the development concentrations in the area between 14th and 72nd streets west of 10th Avenue need to be tied into the stations of the Seventh Avenue and Eighth Avenue subway lines and possibly other lines farther east, as well as the Port Authority Bus Terminal, Penn Station, Grand Central Terminal, and PATH Terminals (see Figure 2). South of 14th Street and north of 72nd Street, existing subway lines are situated in proximity to the areas of proposed development and should be able to handle the anticipated transit trip levels.

Most of the trips from the new residential development will have destinations in the established employment centers in midtown and lower Manhattan, and will need direct transit links or connections to the existing transit system serving these established areas.

The majority of the trips generated by the new developments will end up on the existing transit lines and services. Although there is the potential that the 130,000 new peak hour transit trips—some 55,000 new trips in the peak hour on the Seventh Avenue IRT and Eighth Avenue IND subway lines alone—will increase crowding on the subway lines and stations, the capital programs of the New York Metropolitan Transportation Authority (MTA) and other transportation operating agencies in the region are designed to enable the existing system to handle these new trips.

The new West Side development will generate additional automobile and taxi trips on the already congested street network. In the absence of significant new transit connections in the area between 14th and 72nd streets west of 10th Avenue, 5,100 automobile and taxi trips in the morning rush hour and 7,500 afternoon peak hour vehicle trips will be generated. These numbers are up to twice the number of trips that would be generated if improved transit connections were provided. With a good transit connection available, this area would generate 3,400 fewer trips in the morning peak hour—a drop of 52 percent—and 2,800 fewer trips in the afternoon peak hour—a drop of nearly 30 percent. Given the problems of traffic congestion and air quality in the West Midtown area, it is essential that convenient, comfortable, and secure transit connections be provided to minimize the number of vehicle trips generated by the new developments.

The shift in the modal distribution of new trips away from automobiles and taxis to transit as a result of new transit connections will generate an estimated 7,300 additional transit trips in the morning peak hour for a total of 31,300 new transit trips in the peak hour (a 30 percent increase over existing

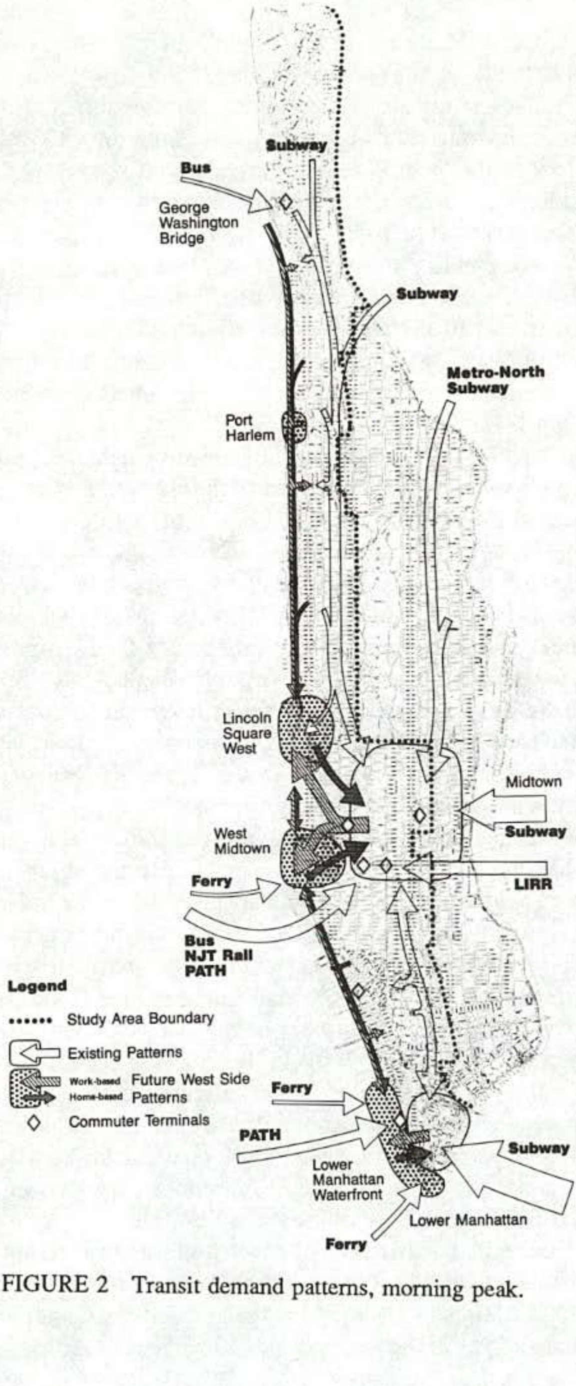

FIGURE 2 Transit demand patterns, morning peak.

transit volumes on the West Side). An additional 10,400 transit trips would be generated in the afternoon peak hour (a 28 percent increase) for a total of 47,000 new transit trips in the area between 14th and 72nd streets and west of 10th Avenue. The need to reduce traffic congestion and carbon monoxide produced by vehicles, as required by the policy of city, state, and federal governments, necessitates that good transit service connections be provided to the major development clusters on the West Side. This also will have the benefit of generating additional transit riders (and revenue) for the existing system.

In summary, the critical transportation needs identified in Phase I to be addressed by the West Side Transitway Study are twofold. First, to connect the developing areas of west Midtown between 14th and 72nd streets west of 10th Avenue with the Seventh Avenue IRT, Eighth Avenue IND, and other subway lines farther east; with the Port Authority Bus Terminal, Penn Station, PATH's 33rd Street Terminal and Grand Central Terminal; and to the midtown core. Second, to minimize automobile and taxi trips generated by the new development by attracting riders to transit through convenient, comfortable, and secure connections to the existing transportation system or to the midtown core.

In addition, the analysis of travel demand found that most of the trips from the new development were a combination of a north-south and an east-west trip and that a direct (no transfer) service was important in attracting riders to the transit service.

The West Side Transitway Study is focused on addressing the needs and problems of the developing area of the far West Side between 14th and 72nd streets, as well as considering the potential for improved transit services to the areas north and south. The problems of the existing public transportation systems and roadway network, such as crowding at stations and street congestion, are being addressed by the MTA, New York City and New York State departments of transportation, the Port Authority, and other state and local entities.

TRANSIT MODES

The most pressing transit need that emerged from the analysis of travel patterns was for a collector-distributor system that would connect the developing areas of the far West Side of Manhattan that are underserved by transit today with the existing commuter terminals and subway system in Midtown Manhattan. Extensions of the existing subway system, or new subway construction, are too expensive to be privately financed—the major thrust of this study. In addition, the spacing of the stations would not necessarily be compatible with the collector-distributor role of the proposed system.

Aerial structures across 42nd Street were determined to be unacceptable for environmental and aesthetic reasons. The lack of an affordable, completely exclusive right-of-way eliminated a fully automated guideway transit system.

Bus and light rail transit (LRT) emerged as the two modes of transportation that could work within the physical and operational constraints of the desired alignment. For many crosstown streets, improved bus service with some enhanced priority in the street to increase operating speeds meets the service needs. Along 42nd Street, however, the demand generated by either transit mode operating at the improved operating speeds offered by the transitway far exceeds the operational capabilities of bus technology. An unconstrained peak-hour, peak load point demand of 14,000 passengers is expected for a service operating at an average speed of about 9 mph at 3-min headways. As discussed later, LRT cannot handle the demand entirely.

PREFERRED ALTERNATIVES

In Phase III of the study, eight alternatives were analyzed, including no-build and transportation systems management alternatives. The six "build" alternatives were all LRT options that essentially addressed the problem to be solved in the area. The alternatives varied in the north-south direction using either a railroad right-of-way (ROW) (called the Amtrak Cut), 11th Avenue, or the West Side Highway-12th Avenue, or some combination. All the options included a 42nd Street crosstown segment, except one that went across 34th Street. All included a grade-separated transit link between Penn Station and the Long Island Railroad yard development site.

The primary difference among the alternatives was the capital cost and, to a lesser degree, the revenue generated. As a result of the financial analysis (discussed later), only one alternative emerged as being financially feasible under a viable privatization scenario. This alternative is a two-track LRT line across 42nd Street (river-to-river) in an at-grade transitway (Figure 3). On the east end is a loop track with an extra layover track. At the west end the line has two possible alignments: down 11th Avenue at grade to 30th Street, where it goes onto an aerial structure along 30th Street to Ninth Avenue and then eastward along 31st Street to Penn Station; or down the reconstructed West Side Highway (12th Avenue) in the median or along the western edge of the highway to 33rd Street, where it would go into the tunnel under 33rd Street to Penn Station at Eighth Avenue. In either case, the end of the line will be a two-track stub-end terminal. The resolution of the issues that will determine which of these alignments will be selected will not occur within

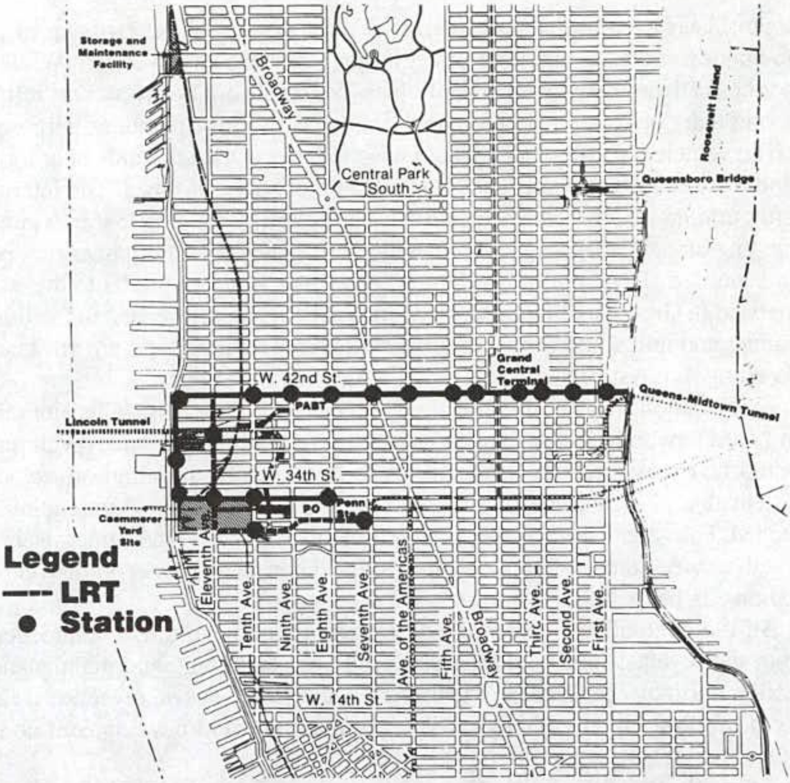

FIGURE 3 Preferred alternatives.

the time frame of the study, particularly the integration of the transitway with the highway reconstruction plans.

The peak-hour ridership for the system is forecast at 15,000 for the year 2005. The peak-load point demand of 14,000 (eastbound on 42nd Street in the area of Times Square) is constrained by the 10,000-passenger directional capacity of the system (two-car trains at 3-min headways). The total unconstrained peak hour demand for the system is estimated to be 19,000 riders. Even with the constraint, the daily ridership is expected to be 103,000 passengers. The annual ridership is forecast at 28.6 million, including over 3 million trips from the special trip generators such as Madison Square Garden and the Convention Center.

The operations are constrained by several factors. The block lengths in the north-south direction as well as some other factors limit the train length to under 200 ft. The study assumed two-car trains consisting of double-ended articulated vehicles of approximately 85 ft. The stub-end terminal at Penn

Station, heavy passenger boardings at several stops, and the crossing of all the major avenues along 42nd Street limited the headway to 3 min. While a shorter headway may be technically feasible, the 3-min headway was felt to be one that could be operated reliably and was used for planning purposes.

The vehicle for this service would have to have several features in order to handle the projected passenger loads and minimize dwell times. The internal configuration of the vehicle would have very few seats to allow maximum standing area. A total capacity (standing and seated) of 250 passengers per car is needed. To minimize dwell times, low-floor vehicles similar to the ones operated in Grenoble, France, or Geneva, Switzerland, are needed to facilitate loading and unloading from the curbside. High-level platforms are not feasible along 42nd Street.

An operational factor affecting dwell times is fare collection. Conventional on-board fare collection will not work at the high-volume stations; dwell time would be excessive. The issue still needs to be resolved, but an off-vehicle system that allows usage of all vehicle doors for loading and unloading is needed. Fare-controlled platforms are not feasible along 42nd Street. Hence, a self-service fare system, with inspection upon boarding at high-volume stations, is proposed.

All the alternatives, except the preferred option, have direct connections from the revenue tracks into the proposed vehicle storage and maintenance facility north of 72nd Street. The preferred alternative has no revenue service north of 42nd Street, although a future stage of system development could extend service farther north or south.

No viable sites for a full yard and shops exist adjacent to the revenue tracks south of 42nd Street. The 72nd Street site is the only location for the major maintenance and repair facility. The connection to the yards from the revenue tracks would be by way of the Amtrak Cut. The cut has sufficient width to have several lay-up tracks, but not a separate light transit connection to the yards. This connection would be over the proposed Amtrak tracks. Trains of light rail vehicles would be pulled over the Amtrak tracks by a diesel locomotive up to the yards. Overnight storage and major inspections and repairs would be done at the 72nd Street yards. Midday storage, running repairs, and daily inspections would be conducted south of the Amtrak connection in the railroad cut around 34th Street. While this arrangement is inefficient and imposes some potential operational constraints, it is the only means developed thus far to provide a yard and shop facility for the preferred alternative; without this, the alternative is infeasible.

The capital cost for the 3-mi line is $284 million. The factors contributing to the high capital cost include:

- Relocation of the maze of utilities under Manhattan streets;

- Maintenance of traffic for Manhattan's heavily traveled roadways;
- Large fleet requirements (35 vehicles) relative to the system length;
- Remote location of a maintenance facility; and
- Construction of the aerial structure or tunnel for the connection into Penn Station.

The annual operating and maintenance cost is estimated to be $7.5 million. This estimate includes costs for the fare collection system, the special operations for the connection to the remote yards, and extra service to handle the special events at Madison Square Garden and the Convention Center.

The ridership estimates are based on charging a separate $1 fare to use the system—distinct from any fare charged to use the existing transit system. A significant portion (two-thirds) of the expected morning peak riders are traveling along 42nd Street for the final portion of their journey from the commuter terminals or the subway system. In the absence of the transitway, these passengers would either use the crosstown bus (which will be replaced by the LRT line) or walk. The transitway offers a substantial increase in speed and capacity over the existing bus service. It is the combination of attracting both trips along 42nd Street and trips from the developing areas of the far West Side that provides the revenue that is the basis of the financing plan for the system.

FINANCIAL AND INSTITUTIONAL ISSUES

A major challenge in establishing the feasibility of the West Side Transitway was to determine whether the project could be constructed and operated without infringing on the region's ability to revitalize the existing public transportation system. This challenge posed two key questions. First, could the project succeed financially without relying on any of the revenue sources currently used to fund transit in the city? Second, under what type of institutional arrangements could these financial plans be implemented? An underlying theme to both of these questions, and an object of major interest to the study, was the extent to which private sector participation could expedite the project's implementation.

The financial and institutional analysis addressed these questions through the following steps. First, three financial plans were developed for each of the transitway alternatives. Each plan was intended to offer a different allocation of risk between the public and private sectors—100 percent private risk, shared public-private risk, and 100 percent public risk. Second, the feasibility of the plans was evaluated according to the internal rate of return to private investors in the project, and the amount of publicly derived revenues needed to make up the shortfall between operating revenues and the full cost of the project. This included a review of new revenue sources that could be implemented to support the project's cost. And finally, a review of the ability of potential public sponsors for the project was undertaken to determine the legal and legislative requirements to implement the project.

These analyses found that private sector financing of the project was more attractive than a traditional, tax-exempt financing approach. A special assessment was selected as the preferred revenue source. Further, the preferred alternative (described in the previous section) was the only transitway alternative that met the tests of feasibility, and the project could be implemented either by the city or by an existing or new state-created public authority. The key findings from each of these analyses are summarized below.

Financing Plans

The financing plans used in the analysis reflected a concept developed early in the study regarding possible approaches to the ownership of the transitway assets—a continuum ranging from complete private ownership to complete public ownership, with various options for shared ownership. The ownership of assets was stratified in this way because ownership dictates the types of financing mechanisms that can be used. The development of financing plans that reflected this distribution of ownership allowed the study to consider the merits of different financing mechanisms.

1. *Private Structure.* In the private structure approach, the transitway would be implemented via a franchise wherein a private company would assume all risks for the project. This approach relied on debt financing for construction and a combination of equity, senior lien debt, and subordinated debt for all permanent financing exclusive of vehicles. A leveraged lease was used for rolling stock procurement. Farebox revenues and advertising fees were the only sources of revenue for the project.

2. *Public-Private Structure.* In the public-private structure approach, the transitway would be implemented via a service contract between a sponsoring public agency and a private company or consortium. The private company would assume all risks for the cost of the project, while the public agency would assume all revenue risks. Thus, the public sponsor would agree to pay a negotiated annual service fee to the private company, irrespective of whether the operating revenues were sufficient to cover the fee. Revenue shortfalls would have to be made up from an alternate source. The financing structure used for the private company was similar to that used in the franchise approach above.

3. *Public Structure.* In the public structure approach, tax-exempt debt would be used to pay for construction and vehicle acquisition. Its chief

difference from the traditional approach to financing public transit capital projects is that no government grants were assumed to be available, and that the revenues (operating revenues and alternative revenue sources, such as special assessment) used to pay debt service cost would not be available until the transitway was operational. As a result, the capitalized interest costs would be substantial.

The results of this analysis contained some surprises. First, the public structure approach did not fare well because of the extent of capitalized interest costs. That is, the additional interest costs associated with 100 percent debt financing exceeded the benefits of the lower interest rate available through tax-exempt bonds. This finding is interesting in that it reveals the true cost of transit capital projects that is often masked when extensive federal financing is available. Second, the pretax rates of return for the private structure (i.e., the franchise approach) ranged from 4 to 12 percent—not high enough to attract investors. Given that the transitway alternatives are located in one of the most densely developed and transit-dependent areas of the country, these findings suggest that private sector ownership of capital-intensive transit systems is not viable without some public sector support. Finally, the annual shortfalls between full costs (operating and maintenance cost plus return on investment) and operating revenues for the public and public-private structures required that a strong and predictable alternative revenue source be available at least through the early years of the project.

Revenue Sources

Existing transit services in New York City are funded by a combination of operating revenues, bridge and tunnel toll revenues, general funds of the city, a mortgage tax, and grants from the State of New York and the federal government. All of these revenue sources were considered to be off limits to the project, given the intense and regionwide interest in revitalizing the existing transit infrastructure. Accordingly, the search for potential revenue sources focused on new mechanisms not needed to support the revitalization efforts.

The revenue sources considered in the analysis were all related in some fashion to the real estate development projected to occur in the study area. The rationale for the use of these revenue sources reflected two attributes of the transitway project: its ability to improve accessibility for travel to and within the service area, which should contribute to higher land values and rents; and its ability to mitigate the impacts to the existing transportation infrastructure associated with higher density development. It was generally agreed that existence of these benefits was essential to the acceptance and use of new, real estate-related revenue sources.

Six types of revenue sources were investigated:

- Special assessments—a fee (exclusive of property taxes) levied on property that is benefited by an adjacent or nearby public improvement. Special assessments have been used to support the financing of public transit improvements in Miami, Los Angeles, and Denver and were contemplated by the New York State legislature in the Rapid Transit Law of 1898.
- Tax-increment financing (TIF)—the dedication of incremental property taxes (above the current tax base) in a specified district to the financing of public improvements in that district. Although TIF is not commonly used to finance transit improvements, it was used to support the financing of the Embarcadero Station in San Francisco.
- Sale or lease of public property or air rights—the sale or lease of development rights above or adjacent to the station. It has been used as a source of revenue by the rapid transit systems in Washington, D.C., and Miami.
- Zoning incentives—incentives such as increases in the allowable floor-to-area ratio of a lot have been awarded by the city in return for the provision of certain public improvements (e.g., subway station improvements) by a developer, where these improvements are rationally related to the incentive being offered.
- Mitigation—actions taken by a person, or by a business entity, to minimize or avoid adverse environmental impacts associated with an action (e.g., a development) under consideration by a governmental agency. Developers have often provided public improvements as a component of the mitigative actions associated with new development (e.g., an esplanade along the East River was rebuilt by developers to mitigate an adverse environmental impact on open space).
- Impact fees—fees that are levied on new development and represent the new development's pro rata share of necessary public improvements that, but for the new development, would not be required to service existing residents. Although not commonly used for transit purposes, impact fees are levied on new office development in downtown San Francisco to support expansion of peak period transit services in connection with the increased transit demand generated by new office space.

Each of these potential revenue sources was evaluated with respect to five criteria: income generating ability (yield and profile), risk, legislative requirements, litigation risk, and administrative requirements. Special assessments were found to be the most logical choice. Although state enabling legislation would be required, this revenue source was preferred because: (1) it was established that the transitway alternatives enhanced accessibility (as measured by travel time savings) both to and within the study area; (2) these benefits would accrue to existing and to new development; (3) assessments could be collected concurrent with the city's collection of property taxes and be subject to the same system of remedies if collections were delinquent; (4) there exists legislative precedent within the state for its use; and (5) it could easily meet the revenue shortfalls projected in the financing plans.

Feasibility Analysis

Two criteria were used to evaluate the feasibility of the transitway alternatives. First, the pretax internal rate of return was used to evaluate the private structure finance plan. A minimum rate of 15 percent was believed to be necessary to attract investors to the project.

Second, the amount and duration of special assessments (based on the assessment per square foot of commercial property within walking distance of the transitway) was used to evaluate the public-private structure and the public structure finance plans. A rate of 30 cents/ft^2 was used as the threshold value. This rate was the approximate midpoint of the range of assessment rates in use in Miami and Los Angeles. These rates were adjusted to a comparable rate for New York City by normalizing for prevailing rents. This approach was used to ensure that the threshold rate was not so high as to deter new development.

The feasibility analysis found that only one of the transitway alternatives was financially viable and only under the public-private finance plan. This preferred alternative consists of an LRT line on 42nd Street between First and 12th avenues, on 11th or 12th Avenue between 42nd Street and the vicinity of the Jacob Javits Convention Center, and between the Convention Center and Penn Station. This alternative has a 15.4 percent internal rate of return and an assessment rate of 18 cents/ft^2 in 1994, declining to 3 cents/ft^2 in 1999 (the last year of the assessment).

It is notable that these results reflect relatively conservative assumptions on inflation rates [approximately 6.5 percent annually for construction and operating and maintenance (O&M) costs], financing charges, and ridership growth. Also, O&M and construction costs were modeled based on public sector experience. Nationally, private sector construction costs are approximately 15 percent lower. This would reduce the assessment rate by almost 50 percent and bring the private structure (i.e., franchise) approach to the threshold of feasibility.

Legal and Legislative Requirements

The financial analyses found that the preferred transitway alternative should be implemented through the use of a service contract between a sponsoring public entity and a private company or consortium. It is likely that the service fee to be paid to this company could not be borne by operating revenues alone, at least in the early years of the project—an alternate revenue source will be needed. A special assessment was found to be the most logical choice to provide these additional revenues.

The provision of transit services in the city via a service contract, and the use of a special assessment to support the funding requirements of these services, is a significant departure from the existing institutional environment. Currently, transit services are provided by the New York City Transit Authority (TA). The TA accordingly has all the powers necessary to operate transit service and to use city streets for this purpose. However, the TA does not purchase transit services via contract and its ability to do so on the scale envisioned for this project is open to question. Also, while the power to levy special assessments was apparently conferred on the TA in its enabling legislation (when it was conferred powers that were originally conferred on the city by the Rapid Transit Law of 1898), its ability to exercise this power has never been established.

Accordingly, an analysis of the legal and legislative requirements for implementing the project was conducted. This analysis consisted of a review of the requirements for establishing special assessment districts and a review of the powers of existing public institutions to implement the project using a service contract.

While the project's implementation by any public entity would require state legislation, the city may face the lowest hurdles. With the passage of a local law, the city could enter into contracts for the purchase of transit services. State enabling legislation would be required, however, to implement a special assessment district. There is no associated requirement for local approval of the special assessment.

A public authority, such as the TA or any other state-created public authority, could also implement the project, but not without additional state legislation and not without the city's involvement. For these authorities, state legislation would be required for at least the use of a service contract (for the TA), and possibly other mass transportation-related powers (if an authority other than the TA were to sponsor the project). State legislation would also be required for the special assessments, and this legislation would stipulate the city's involvement in the exercise of this power (e.g., in establishing the assessment rate).

CONCLUSION

This study generated several important findings that are relevant to consideration of LRT in comparable situations. The transportation need of new concentrations of dense development in urban centers is for a collector-distributor service connection to the existing transportation system. As such, frequent and easily accessible stations or stops are needed.

Placing a new LRT system into a very densely developed area that has limited feasible alignment options can introduce limitations on the operational potential (speeds, capacity) of the technology. The capital cost of constructing LRT is greatly affected by the environment into which it is placed. Relocation of dense old utilities, maintenance of traffic, and limited construction space can increase the cost significantly.

Given that the proposed transitway alternative is located in one of the most densely developed and transit-dependent areas of the country, this study indicates that private sector ownership of capital-intensive transit systems is not viable without some public sector segment.

Boston's Light Rail Transit Prepares for the Next Hundred Years

JAMES D. MCCARTHY

For over a century light rail transit (LRT) has played an important part in the development of the City of Boston and its suburbs by fulfilling its transportation needs. Today, LRT runs over many of the same routes it did a century ago. As we approach the century mark of Boston's first electric trolley, it is appropriate to review some of the accomplishments of light rail in Boston and to look at the future. The Massachusetts Bay Transportation Authority (MBTA) has two light rail projects currently in design. A third proposal would extend the light rail system in the future. At North Station, the Green Line (light rail) will be relocated to a new subway alignment that will create a new transportation center. At Lechmere Square in Cambridge, the existing Lechmere Station will be relocated across O'Brien Highway to a new site that will enable the MBTA to develop a new station and a light rail vehicle maintenance facility. The relocated Lechmere Station is the first phase of a plan to extend the Green Line beyond Lechmere into Somerville and Medford.

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) was created in 1964 as a political subdivision of the Commonwealth of Massachusetts to replace the Metropolitan Transit Authority. The MBTA has the responsibility of providing public transportation within the City of Boston as well as the surrounding 78 communities that make up the Regional Transportation District. The population of the 1,038-mi^2 district exceeds 2.6 million. The MBTA's net deficit after revenue and federal operating assistance comes from two sources: 50 percent from regional property tax assessments receipts and 50 percent from general state revenues.

Massachusetts Bay Transportation Authority, 10 Park Plaza, Boston, Mass. 02116.

The MBTA's system handles 600,000 passengers each weekday, employing 786 peak buses, operating over 150 routes covering 710 route mi; 4 light rail routes and 3 rapid transit routes operating on 183 mi of track; 4 trackless trolley routes covering 16 route mi; and a commuter rail system covering 357 route mi. The three rapid transit routes are distinguished as the Blue, Orange, and Red lines. The four-branch light rail system is known as the Green Line. The commuter rail system is the Purple Line (see Figure 1).

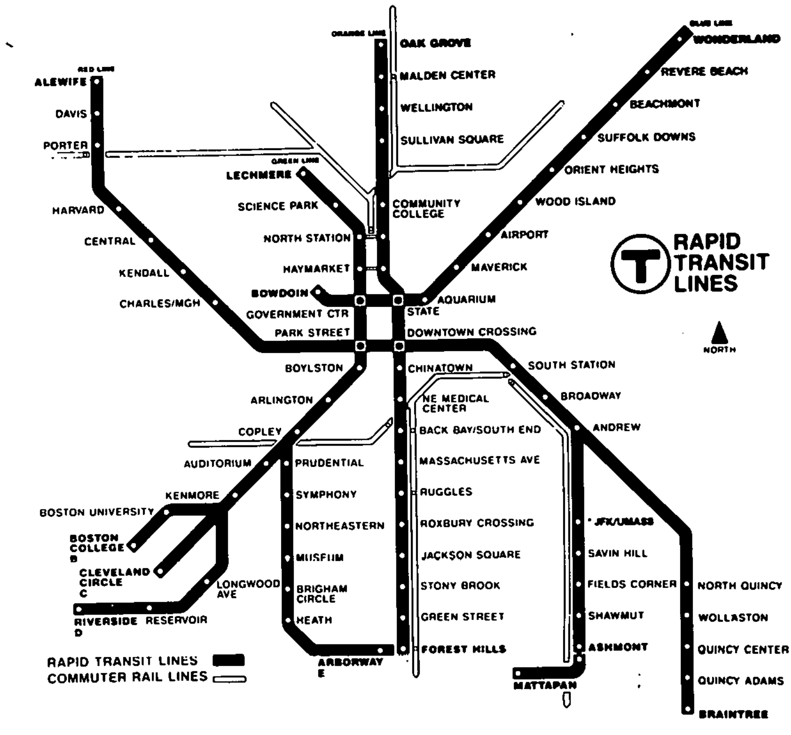

FIGURE 1 Boston transit system map.

HISTORICAL BACKGROUND

On January 1, 1889, the first electric trolley left the Allston Depot down Harvard Street to Beacon Street, traveling to its destination at Scollay Square in downtown Boston. As we approach the century mark of the first electric trolley to operate in Boston, it is appropriate to review the accomplishments of Boston's light rail system and look to its future.

This historic event had its origins in the first streetcar operation in the Boston region. On March 26, 1856, the Cambridge Horse Railroad, which had been organized in 1853 as the first street railway company in Massachusetts, inaugurated its first route, which ran from Harvard Square in Cambridge over Massachusetts Avenue, Main Street, and the West Boston Bridge to Bowdoin Square.

Not quite 33 years later, Boston's first electric car began operating from Allston to Scollay Square. The second electric line opened along Beacon Street less than two weeks later on January 12, 1889, running from what is now Reservoir Station at Cleveland Circle to Park Square. The third line opened the following day from Oak Square in Brighton to Park Square. By April 2, 1894, when the Boston Elevated Railway Company was chartered by the Massachusetts General Court, most of the streetcar lines were electrified and for the most part were still operating in the streets.

America's first subway was opened in Boston on September 1, 1897, when electric car No. 1752 from Allston entered the tunnel. Also in 1897, the Boston Elevated Railway Company took over the West End Street Railway. On September 3, 1898, the Tremont Street subway was extended from Park Street north to Causeway Street (North Station). There was a station at Scollay Square with the northbound side called Corn Hill and the southbound side, Tremont Row. The ensuing years saw the Boston Elevated Railway Company rapidly expand service, building the East Cambridge Viaduct to Lechmere that opened on June 1, 1912.

The Boston "El" was succeeded by the Metropolitan Transit Authority (MTA), and the MTA acquired the Boston & Albany Railroad from New York Central on June 24, 1958. On July 1, 1959, streetcar service was inaugurated on this new line into Brookline and Newton where the Riverside terminal is located.

Since August 4, 1964, when the MBTA succeeded the MTA, many improvements have been made to the Green Line. These include the modernization of Arlington, Government Center, Haymarket, Copley, Prudential, Kenmore, Auditorium (formerly Massachusetts Avenue), and Park Street stations; reconstruction of the Highland Branch (Riverside Line) by installing new roadbed and all-welded rail; and improving station platforms and lighting. In addition, new traction power and new signaling and communications equipment have been installed on the Riverside Line and in the Central Subway and a new track structure has been installed in the Central Subway.

TODAY'S LRT SYSTEM

The 27 mi of the Green Line (5 subway, 21 surface, and 1 mi elevated) and the 2.5 mi of the Mattapan-Ashmont branch of the Red Line are the last of the network of trolley tracks that once covered Boston and many of its suburbs. The Green Line runs on an elevated track from Lechmere Station in Cambridge to North Station in Boston, where it goes into the subway for Haymarket and Kenmore. The Central Subway provides connections to the three rapid transit lines—to the Red Line at Park Street Station, to the Blue Line at Government Center Station, and to the Orange Line at Haymarket Station (see Figure 2).

Kenmore Station in Boston's Back Bay is the last subway station before the line branches off for Commonwealth Avenue to Boston College in Newton; Beacon Street to Cleveland Circle through Brookline; and the Riverside rail right-of-way through Brookline and Newton to Riverside Station near Route 128 and the Weston line. The Arborway Line branches off at Copley Square, continues underground to Symphony, and then runs on the street to the Arborway in Jamaica Plain.

Operations

The President's Conference Committee (PCC) cars no longer run on the Green Line; they have given way to the new light rail vehicles (LRVs). The Beacon Street, Commonwealth Avenue, and Huntington Avenue lines still exist today almost as they did a century ago. The Central Subway is unchanged with the exception of station modernization and facility improvements. The Green Line carries approximately 220,000 daily riders and is the spinal cord of the MBTA's transportation system.

There are 56 colleges and universities in the Boston area and one out of every 40 college students in the United States attends classes here. The Green Line has direct service to several of these institutions: Boston College, Harvard Medical, Boston University, Northeastern University, Emerson College, Massachusetts College of Art, and Wentworth Institute of Technology. Also, Boston is blessed with some of the finest medical institutions in the world. Education and medicine provide one of every six jobs in Boston. The Green Line serves many of these hospitals.

Because the colleges and hospitals are located outside the central business district (CBD), they give the Green Line the unique quality of a two-way ridership demand during the peak and off peak hours.

Ridership

Over the past 20 years the MBTA has made major improvements to its rapid transit system. Major extensions and upgrades have occurred on the Red and Orange lines and the Blue Line has received new vehicles and track structure.

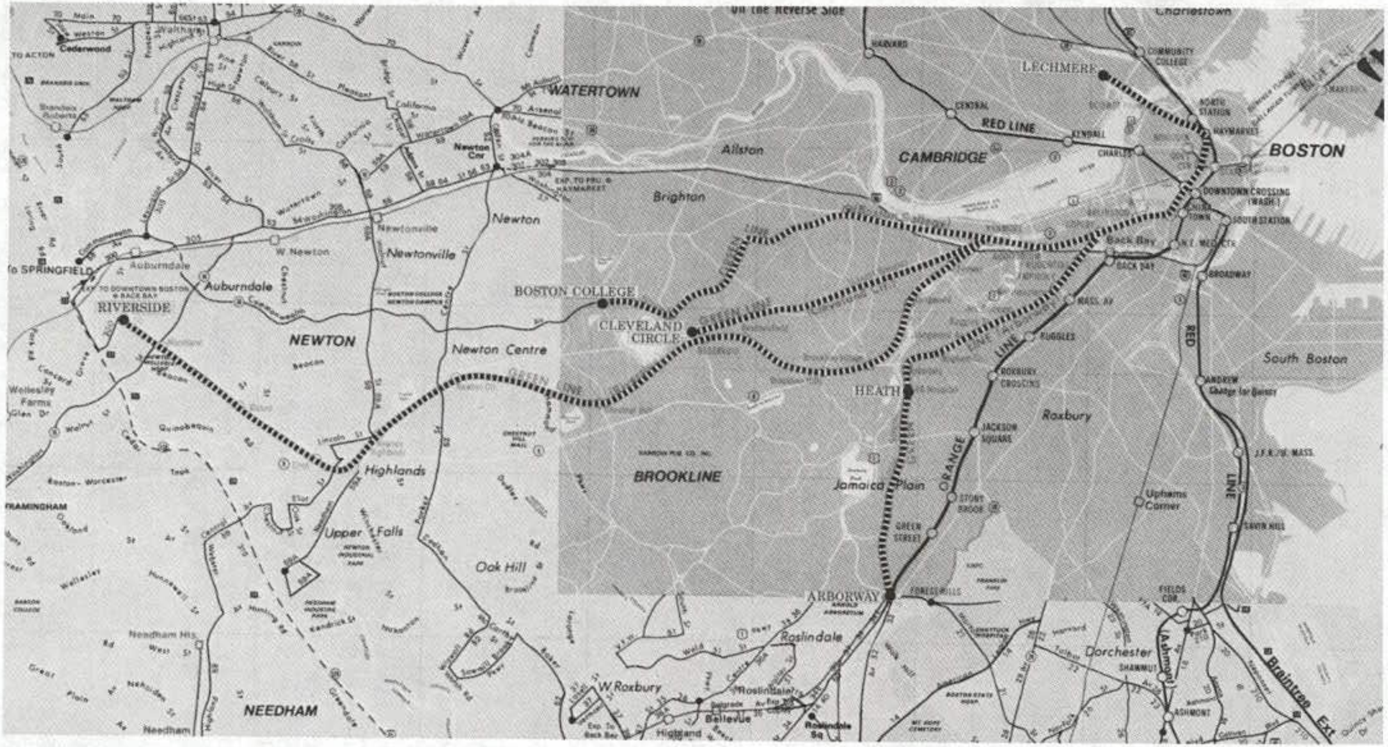

FIGURE 2 Green Line route map for Boston and its suburbs.

Demands for better transportation exist more today than ever. Ridership has increased on all lines, but the Green Line has experienced the most dramatic growth, with the usual consequences of operating at capacity. Although the other rapid transit lines have increased their capacity by adding cars to make longer train consists, the Green Line has been restricted by equipment problems, subway design, and a lack of LRVs to maintain an increased schedule.

Figure 3 shows the inbound surface ridership on the Green Line for all branches. Ridership has been on the increase for the past 10 years and indications are that it will soon pass the 25-year high. Of the 455,000 passengers/day that use the entire rapid transit and light rail system, approximately 220,000 include a Green Line segment. Of the total daily Green Line passengers, 39 percent make trips involving only the subway, and 17 percent make trips involving only surface segments. Table 1 breaks down the surface ridership of the Green Line. The figures for the Boston College line show that 35 percent of the total ridership is for surface only, indicating the strong student ridership for Boston University and Boston College.

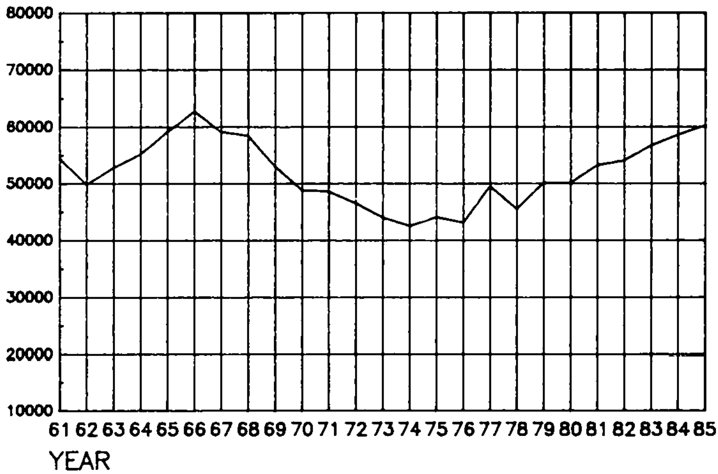

FIGURE 3 Light rail ridership, surface inbound.

Schedule

To meet the ever increasing demands on the Green Line, MBTA has developed two operating plans for future service levels—a 1990 service of 147 peak cars and a post-1990 service of 159 peak cars. Existing peak service is 125 cars.

TABLE 1 COMPARISONS OF GREEN LINE SURFACE TRIP GENERATION (7 a.m.–10 p.m.)

	Boston College (3.95 mi)[a]		Cleveland Circle (2.24 mi)		Riverside (9.25 mi)		Arborway Heath (3.6 mi)		All Branches	
	Total	Per Mile	Total	Per Mile	Total	Per Mile	Total	Per Mile	Total	Per Mile
In ons	15,837	4,009	9,310	4,159	13,729	1,484	16,153	4,487	55,029	2,888
Out offs	19,422	4,917	9,646	4,306	14,003	1,514	17,146	4,763	60,217	3,161
Two-way ridership	35,259	8,926	18,956	8,461	27,732	2,998	33,299	9,250	115,246	6,049
Inbound surface-subway	11,594	2,935	7,403	3,305	10,861	1,174	11,563	3,212	41,421	2,174
Inbound surface-only	4,243	1,074	1,907	850	2,868	310	4,590	1,275	13,608	714
Outbound subway-surface	11,196	2,834	6,624	2,957	9,442	1,021	10,793	2,998	38,055	1,998
Outbound surface-only	8,226	2,083	3,022	1,349	4,561	493	6,353	1,765	22,162	1,163
Two-way-surface-subway	22,790	5,770	14,027	6,263	20,303	2,195	22,356	6,210	79,476	4,172
Two-way-surface-only	12,469	3,157	4,926	2,199	7,429	803	10,493	2,915	35,770	1,878
Percent surface-only	35.4		26.0		26.7		31.5		31.0	

NOTE: 1985 counts.
[a]Surface length.

The post-1990 service will add cars to the 1990 schedule and possibly extend the Green Line beyond Lechmere. The impact of the proposed increased service levels will be discussed later in the context of the plans for the Lechmere Maintenance Facility and the extension beyond Lechmere. Table 2 shows the existing and projected Green Line service.

The following sections discuss how America's oldest subway system is preparing for the next hundred years.

PLANNED IMPROVEMENTS

In 1980 the MBTA undertook a study to examine the alternatives for making transportation improvements in the Green Line Northwest Corridor. The Green Line Northwest Corridor extends from Haymarket to Medford and lies between the Orange and Red lines. Three segments were identified for improvements in the corridor: North Station, Lechmere, and Beyond Lechmere.

The 1980 study was undertaken simultaneously with the City of Boston's unveiling of a plan to redevelop the North Station area. Two major components of the city's plans were the construction of a new federal office building and a new multipurpose arena. The Green Line presently rises from subway to elevated structure at North Station. The elevated structure, which is over 70 years old, has been a blight on the area and detrimental to the city's past revitalization efforts. North Station is a gateway to the city and the hub of the North Side's transportation network. The Orange Line serves the commuters to the north; the Green Line serves Cambridge and Somerville; and commuter rail serves the communities farther out to the north and northwest. In addition, many bus routes from the north now terminate nearby at Haymarket Station.

North Station

The City of Boston's redevelopment plans provided a unique opportunity for transportation improvements at North Station.

Initially, the MBTA identified eight alternatives to relocate the Green Line. An alternatives report and a draft Environmental Impact Statement were completed in 1982. Commuter rail improvements at North Station were expected to be a separate project but common to all Green Line alternatives. The following is a brief description of each alternative and the rationale for giving it or not giving it further consideration.

1. Alternative 1—No-Build: Alternative 1 would have maintained the existing Green Line rapid transit service and facilities in the North Station

TABLE 2 LIGHT RAIL OPERATIONS SCHEDULE: PEAK PERIOD

	1988				1990				Post-1990			
	Trips	Consist	Headway (min)	Total Cars	Trips	Consist	Headway (min)	Total Cars	Trips	Consist	Headway (min)	Total Cars
Boston College (via Commonwealth Ave.)	18	2	5	36	9	2	6	36	12	2	5	42
Cleveland Circle (via Beacon St.)	13	2	6/7	26	9	2	6	30	9	2	6	30
Riverside (via Highland Br.)	14 3	2 3	5	37	10	2	6	47	13	2	5	53
Arborway (PCC) (Forest Hills)	–	–	–	–	–	–	–	–	–	–	–	–
Arborway (Brigham/Heath)	6 5	1 2	6	16	10	2	5.6	20	10	2	5.6	20
Blandford Lechmere	–	–	–	–	6	2	10	12	6	2	10	12
Run as directed (RAD)	10	1	–	10	2	1	–	2	2	1	–	2
Totals				125				147				159
Average subway headway (sec)			75				75				62	

area. It would involve no physical modifications to either the elevated or the ground-level station facilities.

2. Alternative 2—At-Grade Relocation: Alternative 2 provided at-grade service between Canal Street and the elevated structure at Science Park Station following the existing alignment or two potential alternative at-grade alignments. This alternative was not carried forward because at-grade transit operations would disrupt vehicular and pedestrian circulation within the North Station district, an area already suffering from vehicular congestion and numerous vehicle-pedestrian conflicts.

3. Alternative 3—Elevated on New Alignment: Alternative 3 provided a new elevated structure between the existing transition section near Canal Street and Science Park Station by way of a new elevated alignment, which would pass between the Boston Garden and the Anelex Building and then run parallel to the elevated Central Artery/Leverett Circle connector ramps to Science Park Station. Alternative 3 was selected for further study because it featured a station location that would facilitate intermodal transfers to commuter rail services and would also serve proposed development in the North Station district. Its alignment was almost totally within public rights-of-way, and its estimated construction cost was about half that of several subway alternatives.

4. Alternative 4—Subway Under Existing Alignment: Alternative 4, which proposed a subway under the existing elevated alignment, was not carried forward for further study. Construction of a subway beneath the existing viaduct, while maintaining present Green Line service above, would present extreme problems related to underpinning and structure security. While technically possible, this construction process would be extremely costly and time consuming.

5. Alternative 5—Subway Under Boston Garden: Alternative 5 provided a below-grade alignment that extended from Haymarket Station, beneath the Boston Garden, and then climbed to meet the elevated Science Park Station. This alternative was further studied and became the preferred alternative.

6. Alternative 6—Subway to Cambridge: Alternative 6 was a subway alignment similar to Alternative 5. Instead of making the transition to the elevated Science Park Station, the alignment continued under the Charles River in a tunnel and ultimately transitioned to Lechmere Station in East Cambridge. This alternative was not studied further due to the dramatically increased investment requirements associated with building a new subsurface river crossing.

7. Alternative 7—Merrimac Street-Lomasney Way Subway: Alternative 7 provided a subway alignment from Haymarket Station via Merrimac Street and Lomasney Way before making its transition to Science Park Station. This alternative was evaluated further because the alignment was totally within

public rights-of-way and was convenient to the (then-proposed) General Services Administration office building. The relocation of the Science Park Station was required by this alternative.

8. Alternative 8—Replacement Bus Service: Alternative 8 eliminated all Green Line service between North Station and Lechmere Station, and made North Station the terminus for the Green Line. Bus service would have replaced the Green Line service to Cambridge. This alternative was rejected because replacement of light rail with bus did not conform to the stated goals of the MBTA or the Northwest Corridor communities of Boston, Cambridge, and Somerville.

Because of the complexities of the project, a preliminary engineering analysis was undertaken as the initial design step and proved to be invaluable. The alternatives were again examined and a detailed engineering analysis was undertaken on the two most promising alternatives: relocating the elevated alignment that ran beside and behind the Boston Garden (Alternative 3); and providing a subway alignment under the Boston Garden (Alternative 5).

An extensive geotechnical program that included a number of test pits was undertaken. A peer review group was formed and contractors were invited to participate in the engineering analysis. The most difficult part of the subway alternative was the tunnel under the Boston Garden, which has to be kept open during construction.

The engineering analysis showed that the supposedly cheaper option, Alternative 3—the relocated elevated structure—would have such impact on an adjacent building that it would cause its taking at a value of $25 million. Nor would the elevated structure afford the simple modal interchange provided by the subway alternative.

The relocation of the Green Line to a new subway alignment will enhance the change of mode at North Station and create a major transportation center. The North Station Transportation Center will serve the MBTA commuter rail, the Green and Orange lines, commuter buses, taxis, pedestrians, and attendees of Boston Garden events. The transportation center will be more than a location where many transportation modes converge; it is being designed to facilitate intermodal transfers, improve existing facilities and transportation services, and increase user comfort. It is being designed with full understanding of the existing surroundings as well as future plans in order to maximize coordination and thereby minimize conflicts among objectives and projects.

The subway alignment runs parallel to the Orange Line with track spacing of 18 ft as far as the north wall of the Boston Garden. There, it swings to the west, simultaneously increasing the track spacing to provide storage facilities under the MBTA commuter rail tracks. Continuing west, it swings to the north and emerges within the median of the proposed widened Lomasney Way to Science Park Station (see Figure 4).

Vertically, the alignment is governed by the existing profile at Haymarket and Science Park stations, the elevations of the Orange Line mezzanine and platform, and by the outfall sewer in Nashua Street. The profiles of inbound and outbound tracks are different within the station and beyond. The outbound track continues from Haymarket portal to Boston Garden nearly level and at the elevation of the mezzanine and then dips. The inbound track dips from the Haymarket portal to meet the elevation of the Orange Line platform. Beyond Boston Garden the profiles meet and continue nearly level to accommodate storage facilities. At Nashua Street, both profiles climb at constant 6.5 percent grade to Science Park Station.

The proposed Green Line station has been designed to serve existing and projected transit ridership. It will not only improve transit service but will also provide efficient connections with other transit modes, including the Orange Line, commuter rail, buses, taxis, and pedestrian routes. The station will have entrances at both ends of its platforms convenient to major pedestrian flow from the Government Center and financial districts to the south and the Boston Garden/commuter rail terminal to the north.

Entrances will be highly visible, clearly marked, and at ground level to promote security and street-level activity. Access to commuter rail will be provided through a pedestrian passageway under Causeway Street. A shared inbound ("super") platform will connect the Green Line directly with the Orange Line (see Figure 5). Direct connections will also be provided to the bus terminal above the Green Line station.

The station will be designed to provide the patron comfort and visual clarity to help them readily find their destinations. The spatial character of the station will accentuate major decision points such as collection areas, critical circulation elements, and the intersections of main paths.

There will be a four-track storage and turnback configuration behind the Boston Garden with storage space for 11 cars (see Figure 6). The turnback area will provide greater flexibility in handling extra or disabled cars. Also, it will serve as the turnback facility for the cars terminating at North Station. Extra cars will be stored in the area for the surge of patrons from Boston Garden events.

As a result of combining the Orange and Green line platforms, an opportunity exists to bring the existing Orange Line station up to current MBTA design criteria. New handicapped access will be provided with an elevator from the north mezzanine to the Orange Line outbound platform. New wall and ceiling finishes and accessories will be coordinated with the new Green Line portion of the station. The existing substandard portions of the platforms will be widened to a minimum of 8 ft and new access from the south end of

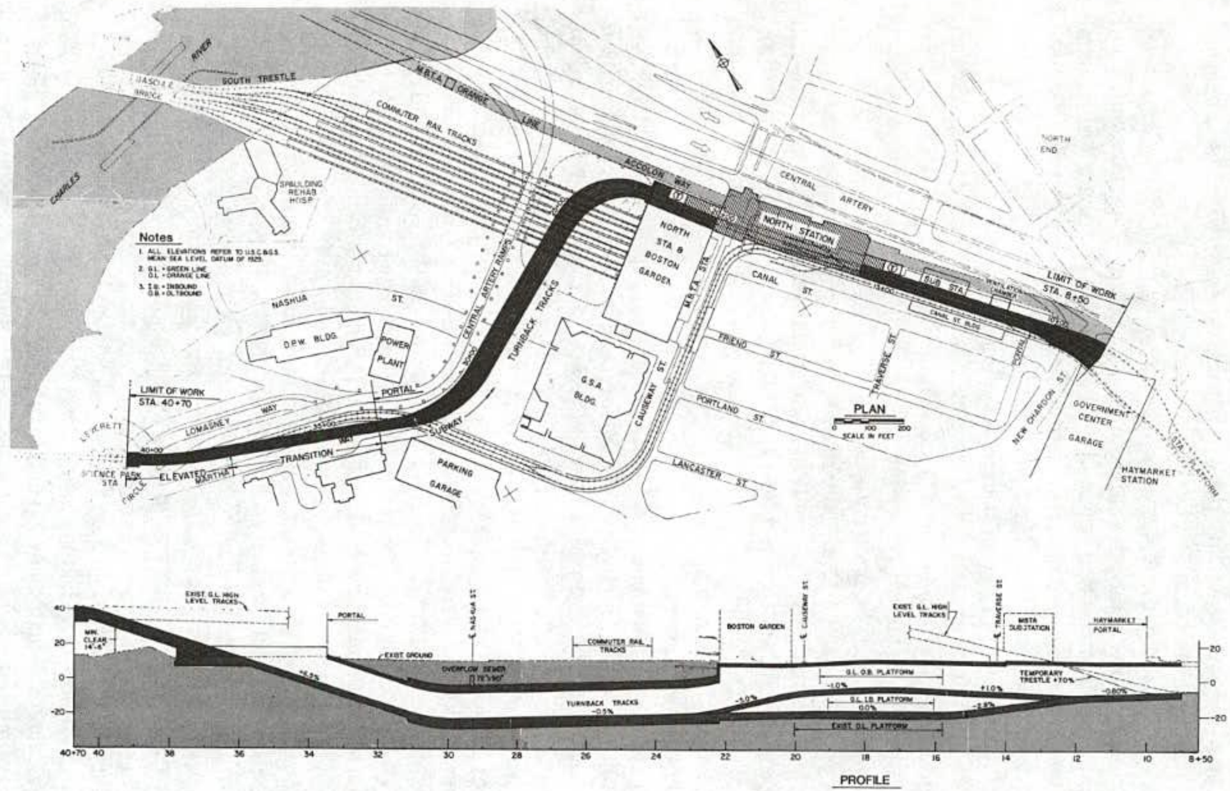

FIGURE 4 North Station plan and profile.

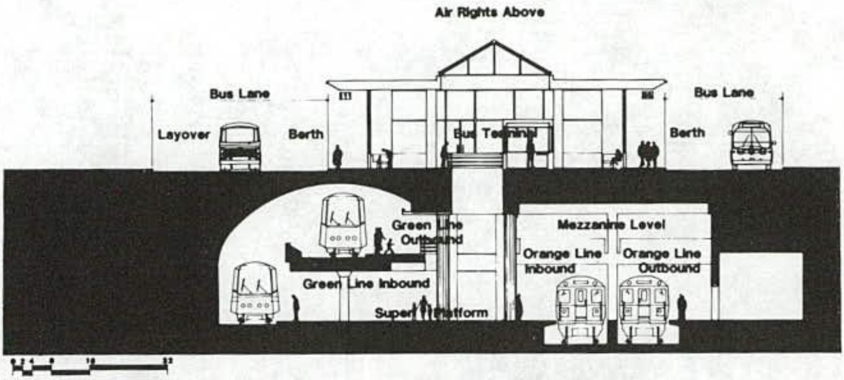

FIGURE 5 New North Station Transportation Center cross section.

the station will be provided via a stair/escalator unit from the new south mezzanine. The roof will be raised to a higher level, allowing natural light from skylights to reach both Orange Line platforms. In addition, all new artificial lighting and graphics will be coordinated with the Green Line portion of the station to provide a uniform, cohesive visual effect within the facility.

The depression of the Central Artery (the major north/south freeway), which presently runs through the city on an elevated structure, will have on and off ramps at Causeway Street across from the new station. The new ramps are ideal for the buses coming from the north and terminating at North Station. A new bus terminal will be constructed at grade above the Green/Orange station to serve bus routes from the north, making the station the best location for the transfer from bus to rail. As previously discussed, the Green/Orange station will have a combined platform for inbound riders and, because both lines provide service to some of the same areas, many transit riders will have the opportunity to take the first train to arrive, whatever color line it runs on.

The development of the station and the bus terminal will create the opportunity to develop the air rights above the transportation center as well. A feasibility study on the potential of air rights that will identify the highest and best use will soon be undertaken; however, preliminary indications are that an office use would be very marketable. The air rights development will provide additional funds for the transit project. In exchange for the air rights, a developer will make a contribution, such as a lease agreement, maintenance, or paying for a portion of the project.

Lechmere Station

Lechmere Station is the northern terminus of the Green Line and is connected to Science Park Station by an arched viaduct across the Charles River. The

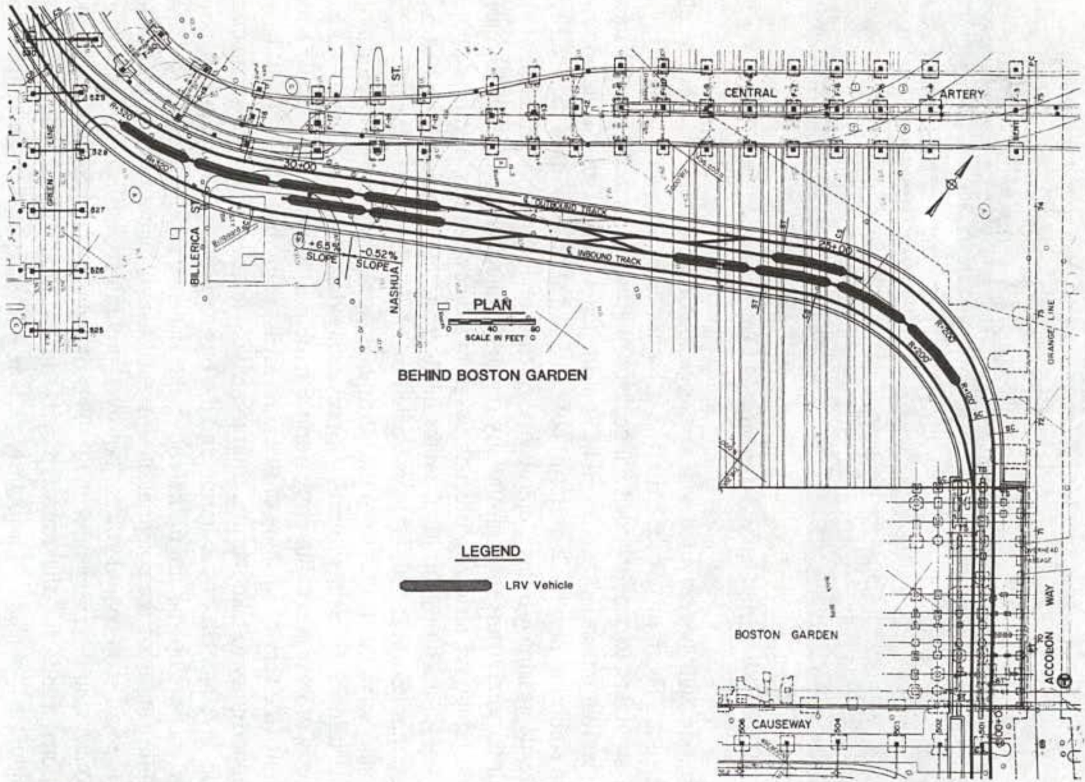

FIGURE 6 North State storage tracks.

arched viaduct was constructed in 1912 and is a historic landmark. The existing Lechmere Station was also constructed in 1912 and has operational deficiencies: lack of storage space, difficult bus movements, and a site that prohibits extension or expansion.

The Lechmere Canal area is undergoing a significant redevelopment. The City of Cambridge, as well as other public and private entities, has invested a great deal of effort and money in the revitalization of this area. The new Lechmere Station is a major component of this effort (see Figure 7). In addition to upgrading Green Line service, the new station will greatly improve the appearance of the area, while encouraging future developments such as the Canal Park project.

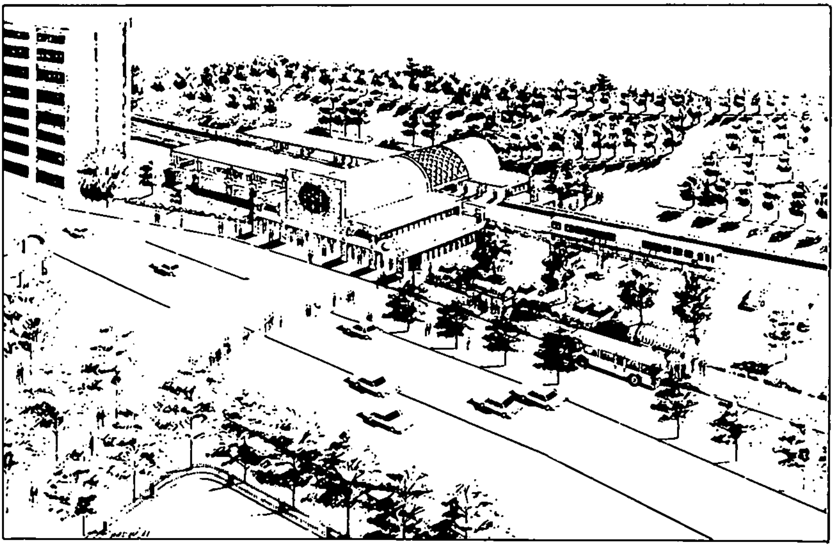

FIGURE 7 Lechmere Station rendering.

The site is primarily occupied now by MBTA parking north of Monsignor O'Brien Highway and across from the existing station. The relocated Green Line track will enter the station area on a viaduct from the east, gradually sloping down to grade level on the west side of the station. The station is located at this transition point on an embankment between elevated and at-grade track.

The relocated station will be highly visible from Monsignor O'Brien Highway and First Street, the major approach routes. The station will form one side of the new Lechmere Square, created by the Lechmere Canal buildings and the development of the existing station site. The eventual removal of the existing station will allow the center of this area to be redeveloped with a combination of open space and a new building.

A major roadway improvement project for Monsignor O'Brien Highway is under way. The relocation of the station will allow further improvements by removing the viaduct from the O'Brien-Cambridge Street intersection and by making other minor improvements possible, such as the upgrading of East Street. Access to the station site will be via East Street. The extension of First Street to O'Brien Highway, a project of interest to the City of Cambridge, would significantly ease traffic flow in the area and help bus and automobile movement to and from the new station.

Pedestrians will cross the highway at-grade at signaled crosswalks. The Cambridge Community Development Department and local East Cambridge groups are interested in a pedestrian bridge that would be fully accessible to handicapped and elderly patrons, and would be located to serve both the East Cambridge community and the Lechmere Canal area.

The station entrance is oriented toward the south and Monsignor O'Brien Highway, the primary approach for pedestrians and motorists. This area also will serve as the drop-off and pick-up area for bus passengers (see Figure 8). A covered platform for five buses will extend from the entrance, parallel to O'Brien Highway. A covered drop-off area will be provided for kiss-and-ride patrons; 300 parking spaces, controlled by one collection booth, also will be provided. A covered walkway will provide a path from the north side parking areas and the industrial development of the North Point area.

The entrance to the station will be through an enclosed brick structure that will contain the pay area, bus waiting, the concession, and vertical circulation. Within this space, access will be provided directly to the inbound rail platform and to a passage under the tracks to the outbound platform. Access to public toilets and the station service areas will be from the passageway under the tracks.

The rail platforms, located on an embankment one level above the entrance, will be reached by way of stairs, ramps, and possibly escalators. Both platforms are to be sheltered, with the track area open.

The building form and the materials to be used in the station are based on those commonly found in the older commercial and public buildings in East Cambridge. Brick columns, walls, and arches, in combination with the concrete viaduct and the glass enclosure and canopies, will emphasize this relationship between the station and the local context.

The construction sequence allows for continuous train service throughout construction. Both tracks can be maintained in operation, servicing the existing station and subsequently the new station, except for a period of 1 to 2 months during the phased rerouting when only one track will be in use.

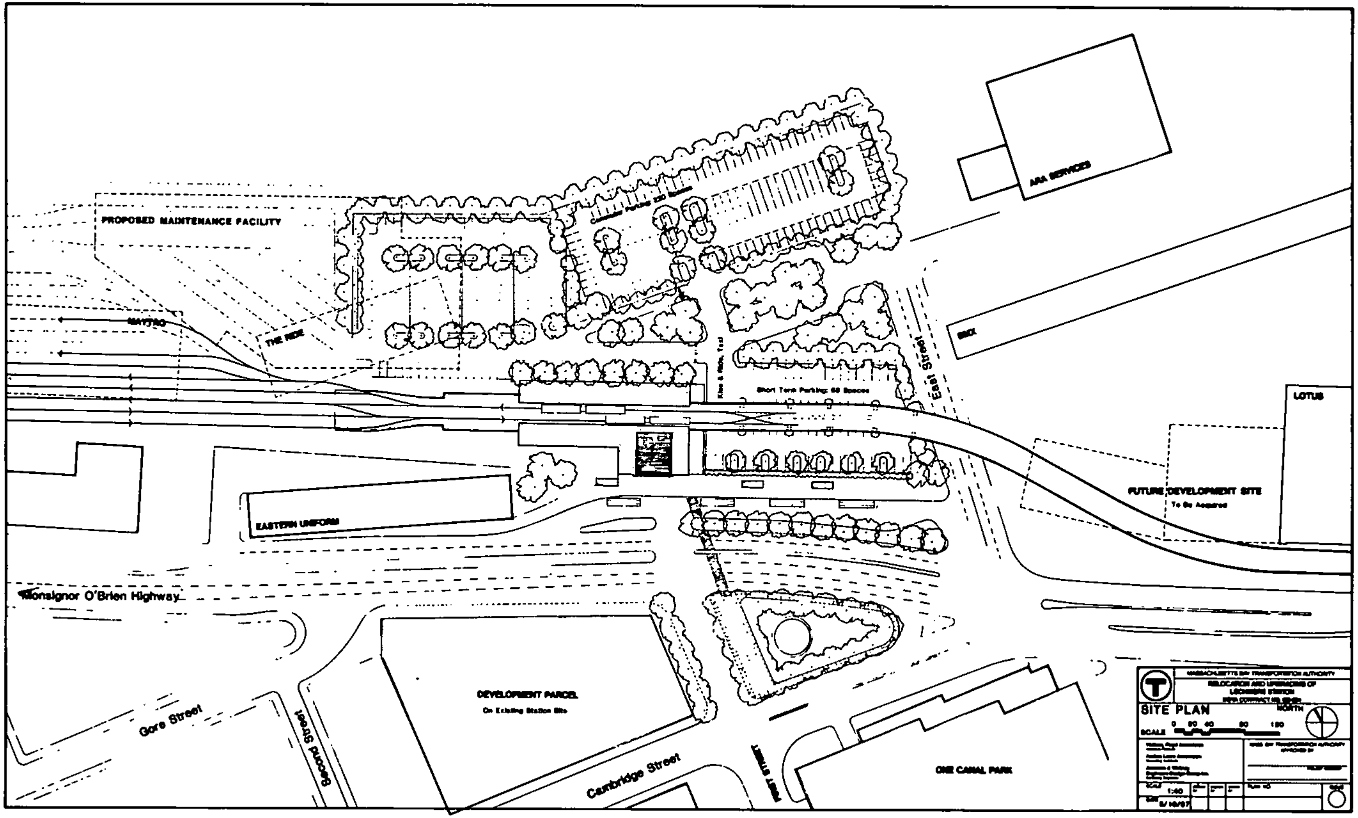

FIGURE 8 Lechmere Station site plan.

The new, relocated Lechmere Station will provide several operational benefits. The new site will be of sufficient size to provide train storage, operators lobby, bus area, maintenance facility, and work train area. In addition, the new station site will be next to the New Hampshire commuter rail right-of-way that may be used for an extension of Green Line service beyond Lechmere into Somerville and Medford.

Initially, a three-level station and LRV storage on a viaduct were studied, but emphasis on the related maintenance facility favored the current two-level embankment station. With the current station design, the related LRV storage can occur at grade rather than on viaduct, the connection between the rail line and buses is improved, the maintenance facility can be closer to the station, and the overall cost is significantly lower.

Lechmere Maintenance Facility

The Green Line is one of the largest light rail operations in North America, with four branches merging from the west into the Central Subway to downtown Boston and then north to a terminus at Lechmere. But vehicle maintenance deficiencies exist in the present system. All the LRV maintenance facilities are located at the western terminus points at Riverside and Reservoir with a running repair shop at Boston College. This arrangement requires all disabled cars running from the Central Subway to be moved a significant distance for repairs.

The existing Green Line facilities cannot provide the levels of maintenance and storage needed to support a larger fleet and expanded service. Nor can they be economically enlarged to satisfy increased requirements. A new LRV maintenance facility at Lechmere would be ideally located near downtown and the Central Subway. The Lechmere site is directly accessible to all branches and would produce a significant savings in car miles. It would also greatly improve the flow of disabled cars to be repaired, especially for failures occurring inbound in the Central Subway. In addition, the new Lechmere facility will provide a secondary benefit to Green Line operations by reducing the backlog of cars waiting to be repaired at the already over-taxed Riverside and Reservoir facilities.

Maintenance

Maintenance functions can generally be divided into the following areas:

- Running repairs,
- Periodic inspections (performed every 30 days),

- Annual inspections, and
- Heavy repairs (which include numerous categories and take more than one day to perform).

A recent review of shop records for two time periods showed an average of 50 cars out of service. Of this total, 32.5 or two-thirds were projected to be out of service 1 day or less, 20 percent for 2 to 5 days, and 14 percent for 6 or more days. It is estimated that there are approximately 40 maintenance actions per day, the bulk of which are running repairs.

A statistical summary of the three principal maintenance facilities on the Green Line—Riverside, Reservoir, and Boston College (Lake Street)—is shown in Table 3.

TABLE 3 GREEN LINE MAINTENANCE AND STORAGE FACILITIES

Carhouse	Running Repair Spots	Heavy Repair Spots	Yard Storage Capacity
Lechmere	–	–	18
Riverside	12	20	72
Reservoir	12	–	62
Boston College	2	–	21
Total	26	20	173

Storage

To determine the requirements for storage at Lechmere, several car-flow plans were developed. Essentially, it was determined that 40 to 44 cars were to be left at Lechmere during midday storage. The car-flow plans require that some trains be operated on different branches during a run. Although this is often done on an unscheduled basis, it is a change from current scheduling practice. This change will prevent any scheduled headway gaps or increases in car miles.

Lechmere Yard Storage Requirements

In addition to the midday storage, space has to be provided for storage of spare cars and for shop support. The 1990 service plan calls for the number of spare cars to be about a third of those operating. It would be operationally unwise to assume that all spare cars would be kept at Reservoir or Riverside. Therefore, some spare car space should be provided at Lechmere. The number of spaces required for shop support should permit resetting the shop on a given day.

The planned overnight storage at Lechmere, exclusive of the spare cars and the shop support, is as follows:

Storage	*No. of Cars*
Heath Street	20
Blandford Street	12
Run as directed (RAD)	2
Total	34

If one-third of these cars are designated as spares, about 10 spaces would be required to store them. Therefore, the estimated 1990 storage requirements for Lechmere is as follows:

Storage	*No. of Cars*
Midday	45
Spare	10
Shop support	15
Total	70

Because midday storage requirements exceed the overnight storage requirements, the space may be used to begin morning start-up service from Lechmere for other lines, too.

Shop Requirements

The ultimate shop requirements for the Green Line depend upon a number of factors. For example, by the year 2000, the Boeing LRVs will be over 25 years old and candidates for replacement. Thus, the composition of the fleet could be significantly different than it is today. Given this uncertainty, the analysis provides general guidelines for the shop requirements with post-1990 service levels.

Assumptions

The following assumptions were used for the analysis:

- The fleet will consist of 250 cars with 200 required for service. This results in an improved availability ratio of 80 percent.
- System car miles would increase in the same ratio as the increase in peak period car requirements. Thus post-1990 car miles will increase by a ratio of 1.33 to 8,342,666 mi.

- Mean distance between failures will approximately double to 3,000 mi.
- Approximately 50 percent of the failures will be sent to Lechmere compared with 40 percent in 1990. The increase is the result of new extensions for which Lechmere will be most accessible.

A summary of the storage and shop requirements at Lechmere based on a preliminary analysis is contained in Table 4.

TABLE 4 MAINTENANCE AND STORAGE REQUIREMENTS AT LECHMERE

Category	Existing	1990	Post-1990
Assumptions			
Active fleet	175	225	250
Peak cars required	105	150	200
Mean distance between failure (mi)	1,300	2,250	3,000
Car miles (thousands)	4,526	6,257	8,343
Maintenance incidents per day (system)	40	37	37
Maintenance incidents—Lechmere	0	15	19
Results			
Storage—Lechmere (cars)	18	70	100
Running repair spots—Lechmere	–	10	13–14
Heavy repair spots—Lechmere	–	15	15
Total repair spots—Lechmere	–	25	28–29

Beyond Lechmere

Travel in the corridor beyond Lechmere to Somerville is strongly oriented towards downtown Boston and neighboring urban centers. Analysis of origin-destination studies reveals that about a quarter of a million trips begin or end in the study area on a typical weekday. While 16 percent of these trips occur entirely within the study area, about 25 percent of the trips are oriented towards downtown Boston and Cambridge. In particular, journey-to-work trips show a strong orientation towards downtown Boston.

Transit accounts for 70 percent of the study area trips made to downtown Boston. An analysis of the demographic profile reveals some of the reasons for this high level of transit dependency and usage. The area has a high population density, a high percentage of elderly and low- to moderate-income residents, and a low level of automobile ownership—all indicators of transit dependency. Given such a high rate of public transit usage, transit system improvements (excluding new ridership from transit-induced new developments) are more likely to provide better service for existing riders than to attract new riders from an untapped transit market.

The corridor is served by an extensive system of buses, which primarily feed Lechmere Station. Ridership statistics indicate that a high proportion of trips originating in the corridor have destinations within it or in the North Station area of downtown Boston. These trips will not be well served by the Orange and Red lines because these heavy rail facilities are too distant and because of the inconvenience caused by the multiple intermodal transfers required to reach them via local bus.

An evaluation report on the alternatives beyond Lechmere was completed in 1984. The report evaluated a number of transit alternatives for the beyond-Lechmere corridor, including light rail, bus, busway, and combination light rail and busway. Most promising of the alternatives is an extension of the Green Line along the New Hampshire Main Line commuter rail route. The New Hampshire Main Line runs through the middle of the study corridor and is of sufficient width to accommodate both commuter rail and the Green Line.

The Green Line extension would be approximately 3.5 mi long and terminate in the vicinity of Tufts University. Although this alternative would not attract a large number of new riders because the area is already heavily dependent on transit, it would provide passengers with a one-seat ride to downtown Boston. One of the operational goals of an extension of the Green Line beyond Lechmere is the reduction of bus miles that would result.

An extension of Green Line service beyond Lechmere can be easily accomplished due to the availability of a portion of the New Hampshire Main Line right-of-way, which is depressed, and the flexibility that comes with light rail. The project can be constructed in segments to meet available funding. Simple platforms with crossovers can serve as temporary stations. No major parking structures or expensive stations will be required for the extension.

CONCLUSION

As we approach the 21st century, the need for mass transit becomes even more demanding. Although recent improvements to the heavy rail lines have increased their capacity and efficiency, Boston's oldest system, the Green Line, must also be improved. New, relocated facilities at the Lechmere and North stations are the first improvements. The new North Station will provide riders with improved transfer capabilities and operations with much needed storage and turnaround facilities for the LRVs. The relocated Lechmere Station will provide the opportunity to develop an LRV maintenance facility for the growing fleet and to extend service beyond Lechmere into Somerville. After a century of service, Boston's light rail is still looking to the future.

Rail Start-Ups

Having the Right People in the Right Place at the Right Time

PETER R. BISHOP

Staff plans and practices are vital to the success of any light rail operation. In Buffalo, the Niagara Frontier Transportation Authority's Metro Rail system began its efforts to get the right people in the right place at the right time in 1981 with a nationwide search for a rail operations leader with a background in research and development. With this superintendent aboard two years before the system began revenue service start-up tasks such as developing a rule book and standard operating procedures began. Management personnel were recruited next and sent to the Port Authority Transit Corporation's facilities in New Jersey to learn from an operating light rail system. Filling the rest of Metro Rail's positions then began. Screening for nonunion employees was extensive and systematic. Union employees recruited from Metro's bus operations, however, could only be ranked by seniority. Training became the next consideration and was at times complicated by the fact that, although equipment had been delivered, not all of it was operational when expected. The success of the recruitment and training process shows up in Metro Rail's low turnover rate.

THE NIAGARA FRONTIER TRANSPORTATION AUTHORITY (NFTA) was created by an act of the New York State Legislature in 1967. The NFTA, a public-benefit corporation owned by the citizens of New York, was assigned responsibility for developing air, water, and surface transportation in Erie and Niagara counties. The authority was given the further mission of formulating and putting into effect a unified mass transportation policy for the Niagara Frontier.

Niagara Frontier Transportation Authority, 93 Oak Street, Buffalo, N.Y. 14203.

Between 1967 and 1970 the NFTA conducted extensive planning studies leading to the production of the Transit Development Program. This program, which was officially approved by the legislature in 1971, encompassed three major elements: the establishment of a regional bus transit network, the construction of a Metropolitan Transportation Center in downtown Buffalo, and the design and construction of a rail transit system between Buffalo's waterfront and the suburban community of Amherst.

During the early 1970s the design of such a rail transit system was planned as a heavy rail line operating through the principal urban corridor, with both subway and aerial structures. After intense local review, the route ultimately evolved as a combination light and heavy rail system with mall operation through the central business district (CBD) and in tunnel elsewhere. The substitution of tunnel for aerial structures, occasioned by community opposition to the latter, substantially increased the cost of the project. As a result, to remain within fiscal limits the length of the line had to be reduced. Instead of a 10-mi heavy rail line, the project was scaled down to a shorter light rail route located completely within the city limits.

Construction of the Metro Rail line began in 1979. The project created many hundreds of badly needed jobs and much of the total cost of $530 million was spent in the western New York area. As a public works effort, Metro Rail surpassed in size even the famous hydropower installations at Niagara Falls.

Metro Rail opened in stages. Operation through the downtown mall, itself under construction, began on October 9, 1984. On May 18, 1985, trains began to operate underground as well for a total distance of 5 mi from the downtown terminal. On November 10, 1986, the entire route from Memorial Auditorium to the south campus of the State University of New York at Buffalo was opened to the public.

The current Metro Rail line consists of 6.2 dual-tracked route miles, 27 double-ended cars, 8 architecturally distinctive subway stations, and 6 stations located along the world's largest pedestrian mall, Buffalo Place. By early 1987 this modest-sized rail operation was carrying 30,000 daily riders. It currently operates weekdays and Saturdays until midnight with limited Sunday service. During peak periods the trains run every 6 min. Between the morning and afternoon peak periods, the trains operate on 10-min headways, while in the base periods the headway is lengthened to 20 min.

In 1981 Metro Rail was faced with its initial application of the "right people in the right place at the right time" rule. A company philosophy for preliminary staffing necessitated a nationwide personnel search for a rail operations leader with a background in research and development. Revenue service was still 3 years away but there was a pressing need to put in place as many operational facets as possible. The very heart of the rail transportation department began beating in 1982 when Anthony Schill came on board as superintendent. Through his efforts over the next 2 years, a rule book was developed, standard operating procedures were written, administrative and operational forms were designed, and a myriad of other start-up tasks were shouldered by the superintendent as the slow transition from construction to actual revenue operations got underway.

This transition developed its own set of prioritized problems. It also pointed up the importance of putting together a staff that could call on others in the industry to seek out knowledge and experience. Where possible, Metro Rail personnel wanted to avoid the problems cited by their contemporaries.

Supplemental staffing began in earnest in 1984 when employees from bus transportation, who would ultimately be responsible for various areas such as training, supervision, and operations, were reassigned to rail transportation. The superintendent's rail background was thus complemented by his staff's company background and experiences.

Metro decided that rail should be an entity separate from the established bus operations. This allowed the superintendent greater flexibility in performing his duties. However, it also developed a division within operations that is currently being evaluated. Initially such a division was appropriate, owing to the differences between the operating techniques of bus and rail. It also served as an enticement for recruitment within the rank and file. But now that a safe and efficient rail transportation has been operating for 4 years, the transportation division is taking steps to integrate rail with bus in all appropriate areas.

Once the initial candidates for transfer to rail management had been identified and approved, it was necessary to establish a training program. Rail familiarization and indoctrination for these management employees were accomplished during a 4-week tour of the Port Authority Transit Corporation (PATCO) facilities in Lindenwald, New Jersey. Basic concepts of training, operation of rail vehicles, record keeping, and ancillary functions such as maintenance, revenue, public relations, and control tower operations were viewed. More important, friendships were fostered that proved invaluable in the future. It was Buffalo's intention not to mirror PATCO's operation but to witness a successful operation and define those general concepts that could be applied to the new system.

Once back in Buffalo, management's attention was redirected to the immediate problems of accepting equipment and making it operational. Development of a training program dealing with the new equipment was an obvious requirement that resulted in its own unique set of problems. Personnel positions, both union and salaried, had to be structured. A system of recruitment for those positions from the rank and file was set up. All of this was accomplished against a timetable that kept slipping.

Operating personnel at Metro Rail are classified as either union hourly employees or nonunion salaried employees. The rail operations positions staffed by union employees are those of train operators, ticket inspectors, and station clerks. The rail operations positions staffed by salaried employees are those of train controllers and rail supervisors.

The train operator is responsible for proper and authorized operation of a rail vehicle in conformance with a published schedule of movements as well as other duties. The ticket inspector is responsible for passenger compliance with all published regulations regarding fare payment as well as other duties. The station clerk, an administrative position, is responsible for the distribution of work to train operators and all other clerical duties associated with the conduct of daily business at the station. The train operators and station clerks report to the district manager and are governed by a 3-year labor agreement between Metro Rail and the Amalgamated Transit Union Local #1342. (Union members are also covered by state legislation that prohibits public employees from engaging in labor strikes.)

The train controller is responsible for the operation of the sophisticated electronic and computer-based equipment that governs the movement of trains, controls traction power, and the ventilation in the tunnel. Rail supervisors are responsible for monitoring the train operators' proper attention to all rules, orders, and procedures that affect train movement. The train controllers and rail supervisors report to the operations control center manager (now retitled the assistant superintendent, rail transportation).

The balance of this presentation deals primarily with train controllers and train operators. The original operations equipment arrangements called for three train control consoles and four station control consoles. Based on this configuration, the initial manpower staffing levels would have required 10 controllers. The original hours of operations would have required four supervisors. Today's operations use fewer controllers, and more supervisors, and transit police personnel have been added.

During the early stages of the transition from construction to revenue service, a general mandate to cut costs triggered a review and subsequent reduction of staff and a shifting of responsibilities. The original complement of 10 controllers was cut to five. One console each was cut from the train control and the station control areas. The responsibilities for station operations were reassigned to the transit police, however, with the associated overhead costs retained by the rail transportation department.

The first two train controllers were recruited from outside the company. Individuals were solicited with previous rail operations experience, particularly those with control tower backgrounds. This was consistent with Metro Rail's philosophy of employing some "rail" people who could act as trainers. These two individuals, one from the Lehigh Railroad and the other from the Southeastern Pennsylvania Transit Authority (SEPTA), were joined by three trainees from within the ranks of Metro. The in-house people had a variety of backgrounds. They included a bus operator, a schedule department clerk, and a transportation assistant from the bus operations department. This original nucleus of five controllers has now been expanded to seven due to the additional responsibilities associated with increased hours of operation.

All in-house Metro candidates for controller positions responded to a job posting displayed throughout the company's premises. The response was overwhelming to the point that a screening process had to be developed that could reduce the number of applicants to a manageable level. It should be noted that this position was and remains a nonunion position. The basic qualification sought by the recruitment process was trainability. This was determined by weighing an applicant's company seniority, experience, and education. Work records of all applicants were reviewed for disciplinary actions. Interviews were conducted and innate mathematics, vocabulary, and comprehension testing was completed. Final recommendations were made to the internal personnel selection committee for approval. These steps led to the appointment of trainees who proved very trainable. During 4 years of operation, the turnover rate has been extremely low. Only one of the original outside controllers has left, returning to his former employer. This outstanding retention is directly attributable to the early screening efforts.

To refurbish a cliché, equipment waits for no trainee. Metro was optimistic to expect that, as personnel became available, the equipment they would work with would also become available. In reality, the equipment was shipped in time, but was not operational in time. The silver lining in this cloud was that the controllers not only had to learn how the systems were supposed to work, but also how they actually did work and what had to be done to make those two concepts compatible. This required considerable mental agility and the development of crisis management techniques. Such a grounding in basic operations is still bearing fruit today. On-time performance associated with terminal departures exceeds 99 percent efficiency.

The hardware and software necessary for our operation were termed "the leading edge of technology." At the time of installation that was probably true and as such the chief benefits Metro Rail derived from the original two controllers were not only having them act as trainers but also having them keep the system operational under very rudimentary conditions. While they were doing that, the balance of the controllers were learning basic railroad operations along with the new technologies.

Finally it all came together and regular routines were developed to cover Metro Rail's commitment to the riding public. During peak periods, which are from 7:00 a.m. to 8:30 a.m. and from 2:30 p.m. to 5:30 p.m., two controllers are working—one for the surface activity and the other for the subsurface activity. The balance of the day requires one controller to monitor the entire system. The controllers were given an opportunity to direct their own destiny when they offered suggestions on scheduling their work. Management listened, the controllers contributed, and thereby a measure of stress was removed from the control center. Currently 8-hour work assignments, which last 4 weeks, are selected by the controllers every 8 weeks. The order of selection is governed by a sliding seniority list. The only provision is that each controller must meet a quota of overnight assignments during a 6-month period.

All controllers are required to be certified every year, not only in their specific disciplines but also as train operators. Periodic train operation in revenue service is encouraged. This gives the controllers a better appreciation for the actual operating environment as seen through the eyes of a train operator. It also provided additional train operators when vacations, illness, and line practice training combined to produce a shortage of regular operators during summer 1987. No runs were cut.

Train controller recertification takes place annually. It is conducted by the assistant superintendent, who is responsible for the preparation of recertification criteria. Testing of rules, procedures, techniques, and experiences is required. This usually prompts the controllers to review annually those items that are a little vague before the testing begins.

Due to the expansion of operating hours Metro Rail has increased the original complement of five controllers. Using the established screening methods, we have added two more controllers. One was a bus operator and former yardmaster on the South Buffalo Railroad. The other was schedule designer from the service planning department. They have blended well with their coworkers. Their training was the responsibility of their fellow controllers, who developed an early relationship with them, nurtured through on-the-job training. The trainer-controllers were also able to relate real life experiences that helped to give a realistic perspective on the world of computers and electronics.

When a posting for 20 train operators was displayed, 134 employees responded and were placed on a trainee list. Their selection from the ranks of bus operators was less sophisticated because our attempts to use a screening method similar to that used for the train controllers were thwarted by the union. The only acceptable criterion was to rank the train operator applicants by seniority.

The train operator training program conducted by Metro's training department is 4 weeks long. The initial sessions deal with a concentrated review of the rule book, standard operating procedures, and all current orders and notices. This review features various written tests. Classroom sessions are supplemented with vehicle operation sessions. The second and third weeks primarily provide "seat time" for the trainee operators. They are accompanied by a line instructor on trains not in service. Not only do the trainees gain familiarity with the rail cars but also with distance perception for speed and braking purposes, station announcements, troubleshooting, and yard techniques. The last week of training consists of actual revenue operation with another regular operator present and the final comprehensive tests on signals and the rule book. The trainees are given only two opportunities to pass these final tests. If they don't succeed, they are washed out of training.

The collective bargaining agreement in place during the period in which Metro Rail was recruiting train operators made no provisions for rail transportation. A separate memorandum of agreement was required. One of the original stipulations was a commitment from the permanent train operators of at least 3 years of service. Now that we are approaching the end of that time limit for some operators, Metro Rail has had to reevaluate its personnel replenishment program. The original concept was to train as many permanent train operators for assignment as dictated by the scheduled service. However, service needs expanded faster than manpower levels. It was thought that temporary train operators could fill these short-term voids and also become a reservoir for future long-term needs. Therefore a request for temporary train operators was posted throughout the company. This resulted in a trainee list separate from the permanent operators' trainee list.

The agreement also stated that temporary train operators could only refuse a permanent train operator position twice before being banned from the rail operations. This created a problem for the company because the trainees apparently were interested only in an exposure to rail operations. They did not want to relinquish their seniority position at a bus station for lesser privileges, relative to run selection, at the rail station. This lack of commitment from the temporary train operator trainees meant more trainees had to be processed than there were open positions.

Many other items were spelled out in this memorandum of agreement but experience showed that its best feature was its expiration shortly after the commencement of full-scale operations. All segments of union activities that relate to rail transportation are now included in the current collective bargaining agreement. This made contract negotiations a little lengthier, but the result was well worth the effort. To this day Metro Rail is still finding nuisances that are not covered, but special provisions for these can be made. Actual operation is a wonderful test ground for such things as relief points, turn-in times, and report times.

Every train operator must be recertified annually by the training department. Such things as additions or deletions to the rule book, the standard operating procedures, and the operations orders are reviewed and tested. Actual train operation is monitored and bad habits that have crept into the train operators' techniques are corrected. System safety and emergency procedures are emphasized and troubleshooting methods are discussed. Retrofittings to the rail cars are explained and demonstrated. All questions are answered and test results are documented. With this program in place we have minimized our accident record and developed better harmony between operators and management.

Our work with the operators also includes informal "rap" sessions. These meetings between union members and management are usually held on a Sunday morning and attendance is voluntary and not compensated. Gripes are aired, suggestions for improvements are offered, and problems are resolved before they reach the grievance stage. These meetings definitely contribute to the sense of family at Metro Rail.

Everyone in Metro Rail understands that their efforts to make the system a success are well directed. Metro Rail is a tremendous catalyst in Buffalo. With the support this earns from the public, it is easy to understand our boasting that we have the right people in the right place at the right time.

Lessons Learned from New LRT Start-Ups

The Portland Experience

Richard L. Gerhart

The first light rail line in Portland, Oregon, began revenue service on September 5, 1986, after more than a decade of planning, engineering, and construction. The project was known as the Banfield Light Rail Project, recognizing the combined scope of Banfield Freeway (I-84) improvements and light rail construction. The combined $319-million project, jointly managed by the Oregon Department of Transportation and the Tri-County Metropolitan Transportation District of Oregon (Tri-Met), was the largest single public works project in the state's history. The overall project was delivered on schedule and within budget. The successful start-up of the 15.1-mi Portland-to-Gresham line was accomplished by stressing teamwork throughout all phases of the project. The transition from engineering staff to operating personnel was structured to maximize coordination. The establishment of an operations core start-up team provided the organizational framework necessary to develop a rail operations plan and complementary start-up activities schedule. First-year ridership exceeded prerevenue service estimates, and operating costs were below budget. This success reflects the importance Tri-Met assigned to learning as much as possible from properties with experience in light rail operations, and to including all areas of Tri-Met's organization in the development and activation of the start-up plan.

Tri-County Metropolitan Transportation District of Oregon, 4012 S.E. 17th Avenue, Portland, Oreg. 97202.

THE TRI-COUNTY METROPOLITAN TRANSPORTATION District of Oregon (Tri-Met) is the public transportation agency in the Portland region. Tri-Met serves a 725-mi^2 service area in three Oregon counties (Multnomah, Washington, and Clackamas). The service area population is slightly less than 1 million. Tri-Met has a fleet of 550 buses, of which 87 are articulated, and 26 articulated light rail vehicles (LRVs). The LRVs operate on a 15.1-mi rail line between downtown Portland and the City of Gresham, located in east Multnomah County.

Tri-Met was created by the Oregon legislature in 1969 to acquire the assets of the privately owned systems then providing transit service in Portland and its suburbs. It has a seven-member board of directors appointed by the governor. In addition to farebox revenues, Tri-Met is financially supported by a payroll tax levied at the rate of 0.6 percent on all employers' payrolls and self-employed persons in its service area. (There is no sales tax in Oregon.)

The Tri-Met system transports approximately 120,000 originating ("revenue" or "linked") passengers each weekday. About 60 percent of these trips are generated in the more densely populated area of the City of Portland; the remainder is almost all suburban ridership. During the peak hour 411 buses and 22 LRVs (11 two-car trains) are in service. More than 40 percent of the peak hour work trips to the Portland central business district (CBD) are made on Tri-Met.

Portland's light rail transit (LRT) system is the result of a freeway construction controversy that occurred in the mid-1970s. As part of the federal Interstate highway network, the Oregon Department of Transportation (ODOT) had proposed construction of the Mt. Hood Freeway. The name of the proposed freeway was somewhat misleading in that this was actually to be an urban freeway through southeast Portland. The political debate triggered by the freeway proposal resulted in a regional decision to withdraw the freeway proposal and to transfer the funding to a transit-oriented transportation solution. Eventually this produced a \$105-million upgrading of a segment of the existing Banfield Freeway (I-84), and the \$214-million 15.1-mi LRT system. The LRT system opened on September 5, 1986. It was named MAX, short for Metropolitan Area Express.

MAX has been recognized as a major success from opening day, with average weekday ridership at 20,000 boarding rides (versus a first-year projection of 17,000) and operating and maintenance costs 22 percent below budget for fiscal year 1986–1987. Much of the immediate success of MAX can be attributed to the positive momentum generated by delivering the largest public works project in Oregon's history (the \$319-million combined light rail and Banfield freeway widening project) on time and on budget, and by holding an opening weekend celebration, featuring free rides on MAX, that attracted over 150,000 people.

The successful start-up of MAX was really the culmination of more than a decade of planning and coordination. In retracing the history of the project, it becomes obvious that significant lessons were learned in all functional areas of the project (financing, preliminary engineering, construction, etc.). The primary focus of this paper is on the last 2 years before the start of revenue service in September 1986. This 2-year time frame provides an opportunity to critique the most intensive period of rail start-up activity.

PHYSICAL DESCRIPTION AND OPERATING CHARACTERISTICS

MAX extends 15.1 mi in a generally east-west direction between downtown Portland and Gresham. In the Portland city center the line terminates in a three-track offstreet loop just west of 11th Avenue between Morrison and Yamhill streets. Downtown operation on restricted lanes of city streets is on Morrison (westbound) and Yamhill (eastbound) between the 11th Avenue terminus and First Avenue, and on First Avenue between Yamhill and the approach to the Steel Bridge (*1*).

The line crosses the Willamette River on the Steel Bridge, a double-deck lift span, sharing roadway space with vehicular traffic. On the east side of the river the route stretches about 0.7 mi on a restricted portion of Holladay Street to the start of a completely grade-separated 4.9-mi section between the rights-of-way of the Banfield Freeway (I-84) and the Union Pacific Railroad. This section is between Lloyd Center and Gateway stations.

At Gateway the route crosses over the Banfield Freeway, running then in a north-south direction, adjacent to the I-205 connector freeway, for 0.6 mi between Gateway and Burnside Street. The line then resumes its generally east-west alignment in the median strip of East Burnside Street for 5.3 mi between I-205 and 199th Avenue. From this point to the eastern terminus at Cleveland and Eighth in Gresham, the line runs a distance of 2.1 mi on the former right-of-way of the Portland Traction Company.

Traction power at nominal 750 volts dc is transmitted to cars through simple trolley wire (in the downtown area) or catenary (in the outlying sections). Power is supplied by 14 mainline substations plus one at the Ruby Junction Operations Facility. These unmanned substations use transformer-rectifier units to convert 12,000-volt ac power, provided by Pacific Power and Light Company and Portland General Electric Company, to the 750 volts dc required for operation.

On most of the route the line is double-tracked, providing for one-way travel on each track under normal operating conditions. There are two major exceptions. The easternmost segment of the line, the 2.1 mi between Ruby Junction and Gresham Terminal, is a single-track section with a passing track at Gresham City Hall and a second track at the Gresham Terminus. The line also operates on a single track in the downtown area in a loop, using Morrison Street (westbound) and Yamhill Street (eastbound) between First and 11th avenues.

Track gauge is railroad standard, 4 ft 8½ in. (1435 mm). Between the Gresham Terminal and Lloyd Center, 115-lb heat-treated RE rail is laid on wood ties. Between Lloyd Center and the downtown terminus, girder rail is installed in a latex plastic material that holds rails in position, dampens vibration, and mitigates electrical current leakage.

Crossovers between inbound and outbound tracks are provided at intervals to permit operation in both directions on a single track during trackway repairs or service disruptions. Extra track space is available for emergency or special storage of cars at both terminals and at Coliseum, Hollywood, and Gateway stations.

Rail operation is protected by automatic block signal (ABS) systems in two high-speed sections, one between Lloyd Center and Gateway Station, alongside the Banfield Freeway, and the other between Ruby Junction and the Gresham terminus, the single-track section on the former Portland Traction Company right-of-way. In these sections trains are kept separated by operators' visual observations of wayside signals. Trains are stopped in the event of failure to observe signals, employing automatic train stop (ATS) protection. There is also a short signalized section governing the operation over the Steel Bridge with ATS protection.

In the sections of the route along East Burnside Street and Holladay Street, the line is not signalized per se, but operators are governed by street traffic signal indicators at the numerous intersections. LRVs preempt these signals as they approach, which halts cross traffic and permits the LRVs to proceed through the intersections without stopping. Special bar-type signals, located both in advance of and at each intersection, indicate to the operator whether street traffic signals have been preempted, providing sufficient time for stopping in the event of failure to preempt.

In the downtown area, LRVs are governed by traffic signal indicators, and there are no arrangements for preemptions. The only special rail signal is located at the entrance to the 11th Avenue loop; that signal indicates the status of the switches governing access to the three tracks within the terminus loop.

In downtown Portland, LRVs are scheduled to operate at low speeds (15 mph maximum), controlled by street traffic signals. The traffic signals compose the only crossing protection. On Holladay Street and on East Burnside Street, traffic signals control LRV, pedestrian, and automobile traffic flow at crossings. As noted previously, signals are preempted by approaching trains. In the section along the Banfield Freeway, there are no at-grade crossings. At

199th Avenue and at intersections east of it, grade crossings are protected by gates activated by the arrival and passage of trains. There are 10 locations at which gates are installed.

There are 22 station stops in each direction on the line, requiring 38 station platforms or sidewalk loading locations. (There are several island-style platforms that serve both directions of travel.) Stations are of simple design, generally consisting of concrete slab (or sidewalk in the city), a row of shelters, ticket vending and validating machines, information displays, and a hydraulic lift to raise wheelchair passengers from the platform to the level of the LRV floor. Four stations have park-and-ride facilities, providing a total capacity of about 1,600 parking spaces.

Fares are not collected on trains. Ticket vending machines at each station provide tickets for passengers without transfers or monthly passes. Discounted multiple-ride tickets are available in lots of 10; these tickets are individually validated by passengers on the platform before they board the train.

The fare structure is the same for both Tri-Met buses and MAX; fares are transferable between bus and MAX. Fare inspectors check payment receipts or passes to enforce correct fare payment, and issue citations with court authority to anyone without valid proof of fare payment.

The center of operations for MAX is the operations facility located in a four-story building close to the mainline at Ruby Junction (199th Avenue). The building houses the rail operating staff, the control center for rail, and the report facility for train operators. The facility is also the center of maintenance activities for right-of-way track, signals, and electrical systems, as well as for the LRVs.

Yard tracks surround the operating facility, providing storage space for cars not in service and permitting movement of LRVs to and from the mainline and through the shop and carwasher. The facility also has a storeroom for the spare parts and units required for the maintenance of facilities and equipment.

The LRV passenger fleet consists of 26 double-ended, six-axle articulated cars, with four double doors per side. The manufacturer is Bombardier, Inc., employing a design by BN of Belgium. Car specifications are as follows:

Length, 88 ft;
Width, 8 ft 8 in.;
Height, 12 ft 5 in.;
Floor height, 3 ft 2 in.;
Empty weight, 45 tons;
Seats, 76;
Capacity (seated plus standing passengers), 166 (design load);
Wheelchair spaces, 2;

Maximum speed, 55 mi/hr;
Minimum radius curve, 82 ft;
Brakes, dynamic, disc, and magnetic.

MAX is operated as a regional urban and suburban trunk route. Service is provided between approximately 5 a.m. and 1 a.m. 7 days a week. Service frequencies and train lengths (one- or two-car consists) are designed to provide seats for all passengers in any normal 30-min period in the off-peak period on weekdays and all day on Saturdays, Sundays, and holidays. During weekday peak periods, 7 a.m. to 9 a.m. and 4 p.m. to 6 p.m., service is designed for 30-min car loadings not to exceed 166 passengers per car.

On the basis of the above design standards, weekday MAX trains are scheduled every 7 min during peak periods, every 15 min during off-peak periods and until 10:30 p.m., and then every 30 min until 1 a.m. The peak vehicle requirement is 22 LRVs, deployed as 11 two-car consists. (Consists are limited to a maximum of two LRVs because downtown Portland city blocks are only 200 ft long.) On Saturdays, MAX trains run every 15 min until 10:30 p.m., and then half-hourly until 1 a.m. For Sunday or holiday service, MAX trains are scheduled every 15 min until 7:30 p.m., and then half-hourly until 1 a.m. Single-car trains are typically deployed during weekends, but second sections are added if warranted by passenger loads.

The opening of light rail service was accompanied by revised connecting bus services. Changes to the bus network were essential to provide access and connectivity to the rail service to fully realize the benefits of an integrated bus/rail service. Bus routes have been restructured so that buses connect with trains at 17 of the 25 light rail stations. Exclusive multimodal transit facilities (transit centers) have been constructed at Coliseum, Hollywood, Gateway, and Gresham Central stations. Bus/rail connections at other stations are made on the street.

Gateway Station is the most critical point of connection between buses and MAX. Timed-transfer operations occur there, with trains and buses pulsing every 15, 30, or 60 min. Inbound and outbound trains pass at Gateway during the timed-transfer "window" in order to make complete bus/rail meets. Timed-transfer operations are also scheduled at Gresham Central, 188th Avenue, 122nd Avenue, and Hollywood stations, particularly during periods of long headway operation. Trains are also scheduled for night and Sunday/holiday downtown meets.

RAIL OPERATIONS PLAN

One of Tri-Met's goals is to operate MAX safely, reliably, and efficiently and to integrate the rail line's operation with bus services for the greatest convenience to the public. The rail operations plan is designed to further this goal by providing information and by documenting procedures and policies necessary to activate and operate the light rail line in the safest, most reliable manner.

Formal development of the rail operations plan began in fall 1985, approximately 1 year prior to start-up. However, the first efforts directed towards conceptualization of the plan date back to 1980, when estimates for staffing plans, operating plans, and operating budgets were developed by a joint venture team of Parsons Brinckerhoff Quade & Douglas, Inc., and Louis T. Klauder & Associates (PB/LTK). Tri-Met began recruiting key rail operations staff then as well.

There was a transitional component to staffing and recruiting for the various phases of the overall light rail project. As the project shifted from planning to preliminary engineering, continuity was maintained by including some of the planners on the newly formed in-house engineering team. Specific technical expertise needs were addressed either by hiring outside talent or through consulting contracts. This strategy built a strongly qualified engineering team, yet maintained the needed links to both the history of the project and Tri-Met in general. Likewise, the same type of transitional staffing efforts followed as the project enlarged in scope to include final design, construction, and operational readiness elements.

In developing the rail start-up organization, Tri-Met's executive management placed top priority on defining the rail operations organizational structure. After various organizational structures from other transit systems with bus and rail modes had been reviewed and analyzed, separate departments for rail transportation and rail maintenance were created in Tri-Met's operations division. With this decision in place, executive management recruited the two key rail operations directors (one promoted internally and one hired from the outside, reflecting a balanced strategy) almost 5 years before actual start-up. Thus, the rail transportation and rail maintenance directors participated in the engineering team's planning and design efforts.

With the engineering project staff working closely with rail operations management, executive management addressed the issue of how to coordinate and prepare the entire agency for start-up. Again, various rail start-up organizational alternatives were reviewed and analyzed; ultimately it was decided to create an interdisciplinary rail operations start-up team. The core of this team was a small group of Tri-Met staff from planning and operations, plus two on-site consultants provided through a rail operations readiness contract with the firm of ATE, Inc. This start-up core team had three key aspects. First, the team members were fully reassigned to lead the start-up effort. Second, the two rail directors were not on the core team in recognition of the greater need for them to continue working closely with engineering.

Third, the core-team leader was formally recognized and authorized by executive management by creation of a director of rail start-up position.

The rail start-up core team was charged with developing the rail operations plan and a complementary start-up activities schedule. Addressing the need for thorough coordination throughout the entire agency, the core team identified 14 different functional areas related to start-up as shown below:

- Rail transportation;
- Rail maintenance;
- Safety;
- Security;
- Fare collection and structure;
- Hiring and staffing;
- Information systems;
- Financial forecasting;
- Rail budget development and cost control;
- Marketing and customer services;
- Press, political affairs, and community relations;
- Bus operations;
- Service design; and
- Handicapped access.

Each functional task area was assigned an appropriate task manager, who was responsible for developing the plan and schedule for that particular function. Through a series of weekly coordinating sessions, with all task managers present, the operations plan was refined and revised as necessary, until all task plans were consistent and coordinated.

The formation of a start-up team and the requirement to develop a detailed start-up plan not only provided a working structure for the large coordinating task, but also aided the transition of rail transportation and rail maintenance functions into operating departments. Staffing plans, operating plans, and operating budgets were all reviewed and updated from the preliminary estimates prepared in 1980 by PB/LTK (2). Tables 1 and 2 include PB/LTK's 1980 estimates of light rail operating statistics and costs.

Many of the important elements of the staffing and operating plans, such as the operator's rule book, maintenance rule book, standard operating procedures, training programs, and supplemental agreement to the existing labor contract, were being developed before the start-up plan was commissioned. However, with the additional resources dedicated in the form of a start-up team, it was possible to expedite individual efforts and place them into a cohesive framework. It was particularly advantageous to assign the experienced rail start-up professionals (the two ATE consultants) specifically to the rail transportation and rail maintenance directors.

TABLE 1 MAX LIGHT RAIL OPERATING STATISTICS COMPARISON

Operating Statistic	PB/LTK Estimate 1980	Tri-Met Estimate 1986	Tri-Met Actual 1987[a]
Annual boarding rides (millions)	9.2	4.1–4.9	7.2
Park-and-ride spaces	2,043	1,602	1,602
LRVs	26	26	26
Speed (mph)	19.6	17.1	15.5
Annual car miles (millions)	1.415	1.038	1.286
Annual car hours	72,000	60,000	89,000
Car hours/train hours	1.48	1.32	1.72
Staff			
LRV operators	32	34	34
Other transp/fare inspection	26	20.5	20.5
Vehicle maint/stores	28	26	26
ROW maintenance	23	25.5	25.5
Total staff	109	106	106

[a]September 1986 to August 1987.

TABLE 2 MAX LIGHT RAIL COST ESTIMATE COMPARISON

Annual Operating Costs	PB/LTK Estimate 1980	Tri-Met Estimate 1986	Tri-Met Actual 1987[a]
Rail transportation	3.002	2.085	1.894
Rail maintenance	3.626	3.144	2.558
Electrical power	1.331	0.840	0.567
Insurance & claims	0.167	0.168	0.092
General & administrative	0[b]	0.987	0.889
Estimated annual cost	8.126	7.224	–
Actual annual cost	–	–	6.000
Cost/car mile ($)	5.74	6.96	4.67

NOTE: All operating costs are in millions of 1987 dollars.
[a]September 1986 to August 1987.
[b]G&A costs included in rail transportation and maintenance figures.

In recognition of the importance of the peer review process, the rail operations plan called for continuing and intensifying the process initiated with the first peer review held in September 1984. Thus, additional peer reviews were held in February and August 1986 (1 month before start-up). Also, at Tri-Met's request, a system safety review was conducted by the American Public Transit Association's Rail Safety Review Board. All of the peer reviews provided excellent recommendations to improve Tri-Met's LRT system.

As it was being developed, the rail operations plan represented a vision of what the end product should be, namely a safe, reliable, efficient, and integrated light rail line. The companion volume to the rail operations plan, the start-up activities schedule, represented the process for achieving the goals enumerated in the plan.

START-UP ACTIVITIES SCHEDULE

The purpose of the start-up activities schedule was to summarize the sequence and timing of all activities required to establish revenue service on the target date, September 5, 1986. The schedule was actually a series of separate schedules that described the event sequence and deadline dates for each of the 14 task areas identified in the rail operations plan.

The first set of activity schedules was issued in December 1985, concurrent with the production of the second monthly progress report on the start-up effort. Each subsequent month, a new set of schedules, updated and reflecting progress made, was issued together with the monthly progress report up until the September 1986 start-up date.

In selecting a format and methodology for the activities schedule, various computerized and manual systems were analyzed. Ultimately, the start-up core team chose to use a simple manual tracking chart of a simple matrix design, with rows identifying tasks and subtasks, and columns denoting time in monthly gradations. This approach was selected because it maintained continuity and familiarity by replicating the engineering activities scheduling system, and maximized the simplicity and comprehensibility of the project scheduling system, particularly for nontechnical team members.

The core team was also concerned that team members might think that a detailed automated project scheduling system would obviate the need for oral project communication. Thus, the strategy was to foster open, face-to-face communication, in part, through the weekly coordinating meetings, and to position the easy-to-use activities schedules as supporting documents, useful for task monitoring and accountability purposes.

In many functional task areas the individual activities schedules were fairly straightforward and almost perfunctory in nature. However, there was one critically important start-up task that benefited from the development of activities schedules: the rail operations recruitment and training program. By graphically identifying subtask time requirements for recruiting, testing, training, and appointing different classifications of operating personnel, it was possible to develop a comprehensive, incremental schedule for staffing rail operations. The incremental schedule was then adjusted periodically to match the engineering staff's updated construction and equipment testing schedules, so that operating staff appointments coincided with the availability of equipment and facilities for training purposes.

Based upon the results of the supplemental working and wage agreement relating to light rail operation negotiated with union representatives, preference was given to qualified Tri-Met employees when filling positions for LRT operations and maintenance. The agreement also stipulated that all normal work would be performed by Tri-Met employees. Outside contractors could only be used for emergency repairs, unanticipated work overloads, and specialized heavy-duty maintenance for which Tri-Met does not have the necessary equipment.

For the rail transportation department, this meant that the rail controller and supervisor positions would be appointed according to seniority from the ranks of qualified bus supervisors. Similarly, light rail operators would be appointed according to seniority from the ranks of qualified bus operators.

The process for appointing rail controller/supervisors and operators was very thorough. It included personnel file reviews (with acceptable performance levels identified), written examinations of the rail operator's rulebook, medical examinations, and, after acceptance into the training program, daily written examinations and quizzes. Even with this relatively straightforward approach to staffing and training, various complexities surfaced, including coordinating replacement supervisors and operators for bus operations, separating total staffing complements into subgroups for effectively sized training classes, and rescheduling tasks based on replacement candidates' availability.

The rail maintenance department was organized into two sections: vehicle maintenance and right-of-way maintenance. For the vehicle maintenance section, foreman, LRV mechanic, and fare/lift equipment maintainer positions were appointed according to seniority from the ranks of qualified bus maintenance employees. The same agreement was in place for staffing the right-of-way section, which led to the appointment of rail right-of-way maintainers and cleaners from the bus maintenance building and grounds section. However, for the various skilled right-of-way labor positions (power maintainers, signal maintainers, etc.), in-house, qualified candidates were few. Thus external recruitment was required. Also, in some cases, qualified applicants were transferred from the Banfield Light Rail Project engineering department to the rail right-of-way maintenance section. The development and use of a simple, flexible activity schedule for coordinating and tracking the complexities of staffing the rail transportation and rail maintenance departments were quite helpful.

COST ESTIMATES AND RESULTS

Tri-Met's light rail operating cost estimates originated with the work performed in 1980 by the joint venture of Parsons Brinckerhoff Quade & Douglas, Inc., and Louis T. Klauder & Associates (PB/LTK). These cost estimates were documented in their Phase II report (2). The report was one of 11 technical reports that dealt with specific elements of the project.

Tables 1 and 2 compare 1980 estimates of operating statistics and costs with Tri-Met's 1986 estimates and actual results for 1987. PB/LTK's cost figures were originally calculated using 1978 dollars, then factored up to 1980 dollars using an 8 percent annual rate. For comparative purposes, these costs have been factored back to 1978 dollars and then multiplied by the actual annual change in the U.S. Consumer Price Index to determine equivalent costs in 1987 dollars.

PB/LTK's cost estimates were developed from an operating scenario that estimated first-year ridership of 9.2 million boarding rides. (This represented a level of service about one-third higher than the revised May 1986 Tri-Met estimate.) Based upon this service level, PB/LTK determined staffing and materials requirements.

Staffing estimates were based upon the organizational structures of other transit properties and Tri-Met's labor practices and productivity rates. Staffing assumptions were considered adequate for regular maintenance activities, with some contracting for specialized, heavy maintenance activities (track rebuilding, rail grinding, etc.). Power costs were based upon private utility company rate structures. PB/LTK estimated annual light rail operating and maintenance costs of approximately $8.2 million and assumed no increase in bus operations or administrative costs. A rail operations staff of 109 was estimated to be required to provide 1.415 million annual car miles of service.

Beginning in autumn 1985, Tri-Met tried to refine PB/LTK's original estimates and assumptions. Numerous iterations resulted in May 1986 estimates that included a staff of 106 providing 1.038 million car miles of service. The first-year ridership estimate was substantially reduced to a range of 4.1 million to 4.9 million boarding rides. The 1986 Tri-Met annual operating and maintenance cost estimate was 11 percent lower than the 1980 PB/LTK estimate. The estimated operations and maintenance cost per car mile is $6.96, compared with PB/LTK's estimate of $5.74, because Tri-Met reduced PB/LTK estimated operating speed by 2.5 mph (to 17.1 mph). The fairly sharp changes between the PB/LTK estimates and the Tri-Met figures are due primarily to the 6 years that elapsed between the two sets of assumptions underlying the estimates. Prior to 1986, Tri-Met developed several updates to PB/LTK's 1980 cost estimates; however, until the start-up coordination team was in place, in-house efforts to update operating assumptions and cost estimates were difficult.

First-year actual results (September 1986 to August 1987) reflect the higher-than-anticipated ridership level, as well as the additional car hours of service required to support this ridership level. The car-hour/train-hour ratio is higher than previous estimates, reflecting the need to operate more two-car consists as ridership levels warrant. The operating speed is considerably less than expected, due to slower-than-planned operating speeds along Holladay Street and the downtown Portland alignment.

First-year costs are $1.2 million below the Tri-Met 1986 estimate, because actual power and maintenance costs were significantly under budget. Power costs are expected to remain relatively stable at this favorable rate over the next few years. However, rail maintenance costs are expected to increase gradually in the next 2 years as the system ages and as warranty agreements expire, necessitating additional in-house labor resources. Beyond the 2-year mark, rail maintenance costs should remain stable.

SUMMARY

A successful light rail start-up project requires a strong commitment from executive management to create a start-up core team by contracting with experienced start-up consultants and fully reassigning key staff, and to support the leader of the team by conferring both the authority and resources required by the project.

A comprehensive rail operations plan and a complementary start-up activities schedule are essential project control documents. The primary purpose of producing and regularly revising these documents is to provide start-up team members with reference materials during weekly and daily communication and coordination meetings.

The large scope of a rail start-up project requires that considerable energies be focused towards resolving a myriad of detailed issues. To keep the overall project priorities in place and continuously synchronized, it may be useful to develop a start-up summary checklist. This checklist, or set of guidelines, can be drawn from lessons learned and experience gained by other properties' rail start-ups. An excellent method to assist in developing a property-specific set of guidelines is to conduct peer reviews at regular intervals.

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RT Metro

Trials and Tribulations of a Rail Start-Up

CAMERON BEACH

Putting Sacramento's RT Metro on the track took years of coordination and cooperation among government bodies, internal departments, contractors, and vendors. A core management staff was brought aboard early to plan the system's eventual operation. Governmental bodies other than the system operator itself, Sacramento Regional Transit (RT), eventually bowed out, giving RT full responsibility. City redevelopment funds were tapped to make up a shortfall in the original budget. Well in advance of the opening of the system's first leg in March 1987, RT managers negotiated with labor unions, assembled an Operations Coordination Committee as a liaison with law enforcement and fire department officials, and established a training program. As sections of track were turned over for testing, extensive walk-throughs were done, followed by further testing using a light rail vehicle (LRV). The LRVs themselves were tested extensively and a video camera mounted on top of one of them was used to check catenary construction and wire stagger. About 3 months before the system opened, simulated revenue service was begun to make sure the system would operate as expected.

AFTER 10 YEARS OF PLANNING and 5 years of construction, the Sacramento Regional Transit (RT) District opened the first 9.5-mi leg of RT Metro on March 12, 1987. The second leg, completing the 18.3-mi starter line, opened September 5, 1987.

Regional Transit was not initially responsible for construction of the line. A joint-powers agreement was signed with the City of Sacramento, the County of Sacramento, Caltrans, and Regional Transit to form the Sacramento

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

Transit Development Agency (STDA) in 1981. STDA's mission was to design, engineer, and construct a light rail system for Sacramento that would be turned over to Regional Transit for operation upon completion.

Early on, RT's senior management recognized the pitfalls of having a system designed and constructed without extensive input from the operator. With the line scheduled to open in spring 1985, RT General Manager David Boggs appointed a light rail manager in July 1983. This manager would be responsible for putting together a start-up plan, which would include the hiring and training of all employees. The manager was also responsible for coordinating design and construction activities with STDA.

By mid-1984, it became apparent that the spring 1985 opening date was not realistic. During this time, it also became apparent that the $131 million budget was not sufficient to construct the system as designed. Because RT had the financial responsibility for completing the project, it was decided that the construction responsibility should be RT's as well.

On August 15, 1985, the STDA was dissolved and responsibility for the light rail project fell solely on RT. At that time, a more realistic budget of $159 million was adopted utilizing city redevelopment funds to make up the difference.

During these times, RT's operations group put together a staffing plan that called for 68 employees to operate and maintain the light rail system. While staff felt that the number was low, budgetary considerations did not allow for higher staffing levels. In early 1985 the transportation superintendent and the maintenance superintendent came on board. The transportation superintendent authored the first draft of an operating rulebook. The maintenance superintendent was kept busy coordinating design reviews with the vehicle manufacturer, traction power installer, signal installer, and trackwork contractors.

The staffing plan was amended numerous times, primarily as the result of input from peer reviews conducted in 1985 and 1986. Primary increases in staffing occurred in wayside maintenance, fare inspection, and, to a lesser extent, in vehicle maintenance. The maintenance staff today is able to keep up with RT's requirements, but as the system gets older, additional personnel will be necessary.

During 1985 and 1986, negotiations were conducted with the Amalgamated Transit Union (ATU) and the International Brotherhood of Electrical Workers (IBEW) regarding wages and working conditions for the light rail operations employees who would be members of the respective bargaining units. The ATU represented the bus operators and office clerical staff, while the IBEW represented the maintenance employees. It is interesting to note that the IBEW representation came about because RT's predecessors operated the streetcar system in Sacramento until its abandonment in 1947.

Issues discussed with the unions included methods for selecting train operators and maintenance personnel, job descriptions, wages, and representation of new classifications. Visits were made to other rail operating properties represented by the ATU and IBEW to compare job duties and provide insight for union representatives who had previously only dealt with bus-related issues. Negotiations with the unions were concluded in late 1985 with the signing of side agreements to the existing contracts.

All work on the system is done by RT's own employees with the exceptions of station cleaning, landscape maintenance, security, and weed abatement, which are contracted out to local firms. When they become necessary, tasks such as traction motor rebuilding will also be contracted out.

Another area that required a great deal of attention was coordination with the police and fire departments. Because streetcars had been gone from Sacramento for over 40 years, the whole idea of overhead wires in the middle of a street was foreign to fire-fighting personnel. In addition, law enforcement officers needed additional training on how to deal with trains operating in traffic on the street.

To address this problem an Operations Coordination Committee was created. It consisted of police officers, deputy sheriffs, highway patrol officers, fire chiefs, and their respective training personnel as well as RT rail operations staff. This group met every other month for almost 2 years prior to the system's opening. Numerous questions and issues were raised during these meetings. There is no doubt that the current good working relationship with these groups is due to these efforts.

Operations staff moved into the Metro Division Operations and Maintenance Facility during early November 1986. The first light rail vehicle (LRV) was delivered 2 weeks later. To have properly trained personnel to operate the cars, the transportation superintendent, the two senior transportation supervisors, and the two most senior train operators were sent to Calgary, Alberta, for extensive training in LRV operation and train control. To this day, these individuals talk about their "vacation" in Calgary. All but one of them were native Californians who had a difficult time adjusting to the –15°F to –35°F temperatures that they encountered in Alberta in November.

It is important to note at this point that over 85 percent of RT Metro's employees were promoted from within the ranks. RT made a commitment early on that an expansion into light rail would mean new opportunities for existing staff. Only those positions that required specific technical expertise were filled from outside the agency. Prior to sending staff to Calgary, bus operators were asked to sign a list indicating their interest in light rail training. At that time, the level of interest that would be expressed was unknown. But after 1 week 175 of RT's 320 bus operators indicated they wanted to learn to run trains. The two operators selected to go to Calgary had almost 60 years of cumulative experience driving buses for RT and its predecessors.

The process in which the construction department turned over areas of track for testing and operation took a great deal of effort and patience on everyone's part. Sacramento was fortunate to have a high level of cooperation and camaraderie between construction and operations personnel throughout the project. Without this, it is questionable whether the system would ever have worked. Extensive walk-throughs were held on all phases of construction by operations personnel. Prior to any testing, every foot of track and overhead was inspected by operations staff. Following successful completion of this last walk-through, an LRV would be moved at no greater than walking speed through the affected territory. Speeds would be increased in 5- or 10-mph increments until track speed was reached. This process was slow and tedious, but in one case it prevented an LRV from hitting a curb that was too high and pointed out such problems as trees growing into the overhead.

Prior to train operations on the test track, procedures were developed for test track limits and "red tagging" of traction power so that both contractors and testing crews could work simultaneously. The buffer zones between construction and operations were established with track warrant and red tag procedures being rigidly enforced by operations personnel.

An extensive testing and burn-in program was developed for testing and accepting LRVs. Our first two operators made so many trips over the original 1.5-mi test track there were days they felt like they were operating a horizontal elevator.

As a part of their training, operators had been instructed that a dark (unlit) signal must be treated as a "red" signal. As signal equipment was installed by the contractor, burlap bags were used to cover the signal heads so that operators did not have to disobey operating rules.

As longer sections of the system were completed, a formal program was instituted that provided for extensive testing of the system and its components prior to unlimited use by operations. Once the walk-through and slow running tests were completed, a video camera was mounted on top of an LRV to check catenary construction and wire stagger. Following this, extensive system tests were conducted of each of the components, i.e., signals, switch machines, substations, traffic signals, and dynamic clearances. For example, each signal was checked for visibility from an operating cab. Each possible routing was checked to verify proper signal aspects and prevention of conflicting moves. Each substation was load tested by having two fully loaded four-car trains accelerate away from each other on a single feed.

Once this was accomplished, an extensive series of integrated tests was conducted to determine that all of the subsystems worked together properly. This included radio coverage tests, platform measurements with an LRV to verify clearances, and timing of traffic signal preemption devices to optimize train movements.

About 3 months prior to the opening of the system, an extensive program of operational testing was begun. Called simulated revenue service, this was the final test of whether the light rail system would operate as the planners and engineers intended. The system was designed for eight trains to operate on a 15-min headway. A computer simulation compiled by Foster Engineering of San Francisco showed that such an operation was possible, but that meets would be close on some stretches of single track. A plan to include additional sections of double track was deferred by the board until actual operation confirmed the need for the expenditure of additional (and very scarce) capital funds.

Included in simulated revenue service were the final aspects of operator training, for example, simulated and actual passenger boardings, elderly and handicapped access, schedule adherence, train meets, cuts and adds to train consists, and verification of running times previously plotted by computers. In addition, several incidents were staged to test the acuity of both the transportation and maintenance personnel as well as various public safety agencies. These incidents included derailments, collisions, signal failures, and other disruptive activities.

During the final 2 weeks prior to opening, a multialarm fire was to be simulated on the K Street Mall during the afternoon rush hour. The purpose of this test was to determine RT's ability to respond to such an incident and maintain an appropriate level of service. But 2 days before the test was to occur, there was an actual multialarm fire on the K Street Mall. The Sacramento Fire Department was able to utilize specifically created procedures for shut down of traction power and protection of fire fighters. RT personnel were able to test their ability to cope with a major disruption to service without actually affecting the riding public.

The simulated revenue service testing proved to be an unqualified success. Without this herculean effort, it is doubtful that the March 12, 1987, opening of Sacramento's light rail system would have come together so well.

Had we the opportunity to go back and do it again, relatively few things would have been done differently. Operations input into the signal system design would have been greater. Signal design was based on the Association of American Railroads standards. As an example, a green-over-red aspect would be displayed at a diverging route. This wasn't a problem for the system's ex-railroaders, but bus division employees had been taught never to go past a red signal. The green-over-red became an exception to the "never" rule. Therefore, in the interest of uniformity, the aspects and heads were reworked to provide that any red aspect would require permission from Metro Control before proceeding. In addition, we would have insisted on more comprehensive training from the signal and traction power contractors, similar to what was provided by the vehicle manufacturer.

During the construction and start-up process there were many occasions when operations staff, engineers, test crews, and contractors became frustrated with the whole process. But without the great deal of cooperation and attention put forth by these groups, Sacramento's system would not be where it is today.

Preparation for "Show Time"
The Los Angeles Story

NORMAN J. JESTER

The Los Angeles-Long Beach Light Rail Transit Project is scheduled to begin revenue operations in 1990. With the $700-million, 21-mi project already under construction, careful planning and coordination are being conducted to ensure that the system will give a stellar performance on the day of its debut. A test track will be constructed so that vehicle acceptance can proceed uninterrupted while construction of the system continues. Staffing is an area where early planning has already begun to pay off by providing an accurate picture of first-year operational expenses and by establishing an incremental plan to bring on staff just in time to meet the needs of each development phase. Planning for the training of operating and maintenance employees is also under way. And a detailed testing plan has been put together to verify the system equipment at every stage of development. Other considerations include labor agreements, logistics of spare parts and supplies, public relations and marketing, contingency plans, maintenance vehicles and shop facilities, and safety certification.

THE LOS ANGELES-LONG BEACH Light Rail Transit (LRT) Project is the forerunner of a projected multiline light rail network that will, it is hoped, someday encompass the entire Los Angeles basin. The initial line (see Figure 1), running some 21 mi from downtown Los Angeles to Long Beach and making 22 stops, is scheduled to open in July 1990.

Los Angeles County Transportation Commission, 403 W. Eighth Street, Suite 500, Los Angeles, Calif. 90014.

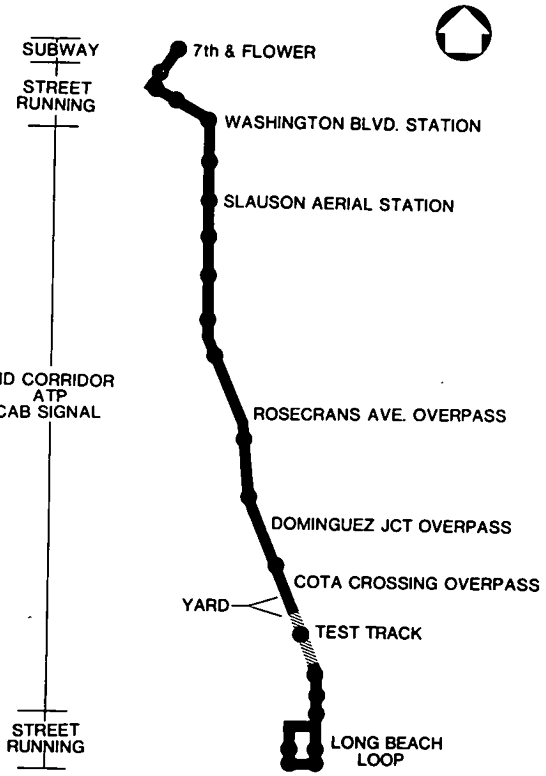


FIGURE 1 Los Angeles-Long Beach LRT schematic.

The Long Beach line will use conventional, state-of-the-art light rail technology: driver-operated articulated rail cars moving largely over surface tracks, interfacing with automobile traffic at numerous grade crossings, and including approximately 6 mi of street traffic operation. There will also be about 1 mi of subway operation in downtown Los Angeles, plus several short stretches of elevated structure serving as flyovers across congested areas.

Stations will be high-platform. Train-operator controlled track switches and a cab-signal system will govern train movements on areas of private right-of-way. A supervisory control and data acquisition system (SCADA) will allow central control dispatchers to monitor and control the traction power supply system, monitor train movement and ticket vending machines, and operate some interlockings during emergencies. Street-running and yard movements will be governed by an operations rule book.

The fare collection system will be the self-service system that has been successfully demonstrated in at least seven North American cities to date.

Two-car trains will predominate in the operation, running on 6- to 10-min headways in peak periods, 15- to 20-min headways off-peak. Initially, the light rail vehicle (LRV) fleet will number 54 and will be constructed by the Nippon-Sharyo works in Japan.

The cars will be delivered in "halves" and assembled in the newly constructed maintenance shop in Long Beach.

Funding for this $700-million project is entirely local, much of it coming from a 0.5 percent sales tax locally referred to as "Prop A" funds after the proposal was enacted in early 1981. Design of the system began in earnest in early 1985 and ground-breaking occurred October 31, 1985, at the Long Beach shop site. Much of the route alignment is shared with the Southern Pacific Railroad, which must maintain its freight service during the 4½-year construction period—not an easy task.

Although 4½ years may sound like a lot of time to spend building track on an existing right-of-way, when one takes a closer look at all of the individual pieces of the giant puzzle that must mesh together, time is of the essence if the trains are to roll on the scheduled opening day.

Few projects of this magnitude (aside from space exploration) involve more disciplines plus the public than a rail transit project. The Los Angeles project ranks among the biggest and is without question the largest single light rail project in this country. The list of players, all of whom have a role in opening the system, is awesome. Architects, planners, schedulers, engineers, draftsmen, politicians from many diverse constituencies, administrators, clerical workers, technicians, public relations persons, equal employment opportunity (EEO) officers, contractors, procurement specialists, insurance specialists, legal counsel, journeymen, utility companies, real estate agents, developers, parking authorities, traffic engineers, the state Public Utilities Commission, safety experts, police and fire jurisdictions, newspaper reporters, tax authorities, vending machine salesmen, the local bus operating agencies, test coordinators, operator training specialists, and on and on—all play active roles. Getting all of these people and organizations to work together towards the same goal is tantamount to getting a large army of fleas to march in step.

Yet by June 1990 the taxpayers of Los Angeles will have been paying sales taxes for 9 years and for 9 years they will have been reading about the promised beginning of the end of their gridlock nightmares. For over 4 years they will have been negotiating construction disruption in downtown LA and elsewhere. For as long as they can remember, they have been fed promises of this great new set of trains that will whisk them to their jobs conveniently. If the day arrives and the trains are not there, the taxpayers will vent their wrath in the press and at the polls. Our duty is not to let the public down when the big day arrives. That big day is what we are referring to as "Show Time."

To make all this happen, the planning must begin early in the design stage of the project. Actually it begins with the schedulers who determine which segment of the line has a possibility of being operable at the earliest date. Presently the Los Angeles County Transportation Commission (LACTC) is planning to start the system in two stages. The first stage, opening in July 1990, includes the entire system except the subway section, which is scheduled to open in December 1990.

Our story of getting ready for "Show Time" begins then in early 1985 when the final Environmental Impact Statement was approved, the route alignment was finally chosen, funding was in place, and a design engineering consulting team was brought on board to do the planning and design work.

TEST TRACK

From the very early days of the project, the need for a test track was recognized so that vehicle acceptance could proceed uninterrupted while construction of the system continued. The area selected for the test track is between the yard departure track and the Willow Station pocket track, a distance of approximately 10,300 ft. There are two grade crossings on the test track, but there is sufficient distance between the crossings for high-speed (55-mph) performance testing of the LRVs.

To ensure that at least the minimum requirements for a test track will be completed in time to support vehicle acceptance, schedule milestones were included in all the system contracts and some construction contracts. A special effort will be made by all our resident engineers to make sure that the test track work proceeds expeditiously so that vehicle acceptance will not be delayed. This includes the portions of the yard and shops required to support the vehicle deliveries.

STAFFING

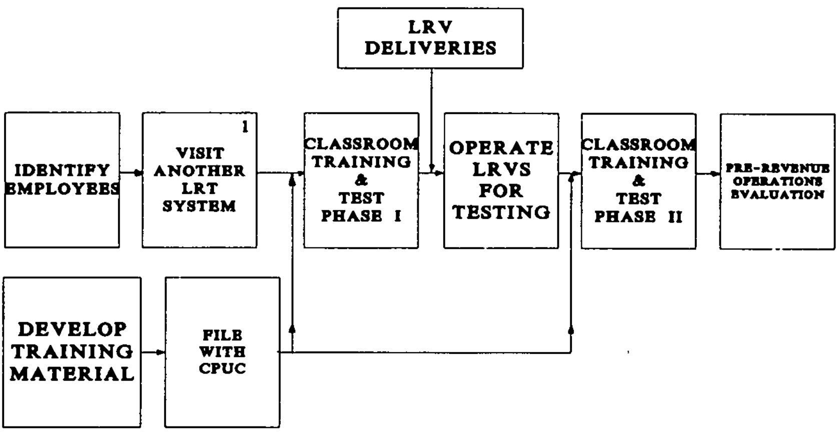
Another area where LACTC and its consultant staff initiated early planning was staffing. Besides giving us a very accurate picture of what operating expenses will be for the first revenue service year, this early planning will also allow smooth transitions from the testing phase through the prerevenue and revenue service phases of the project. The staffing plan for the system is incremental throughout the test and start-up phase, with personnel being brought on board only as needed to support testing, to ensure sufficient training time, and to provide preventive maintenance on equipment already accepted.

TRAINING OF PERSONNEL

A well-rounded training program is of key importance to the timely opening of the system and to ensure the safety of our passengers during the initial stages of revenue service. For the purposes of these discussions, our employees can be divided into two categories, operating employees and maintenance employees. We will not discuss the training of supervisory or specialized personnel, such as dispatchers, because these people will be hired as experienced personnel, and will only be required to familiarize themselves with the new environment and equipment.

Training of operating employees (see Figure 2) will consist primarily of two separate classroom sessions, with a lot of hands-on training in operating the vehicles before and after each session. The testing period will be an essentially hands-on training opportunity for the operators.

The operators will be given two written tests during their training period. The first will cover safety rules and those portions of the rules that pertain to test operations only. The second will involve the entire operating rules and procedures manual. This is done to avoid confusion, because operators must perform test operations with some rules and procedures that will not apply until prerevenue tests begin. The prerevenue test period is considered the final for operating personnel. During this period the operators' adherence rules and procedures, their reactions, and their responses to emergency and abnormal conditions will be evaluated and graded. Those requiring additional training, or those unsuitable for continued service, will be identified.

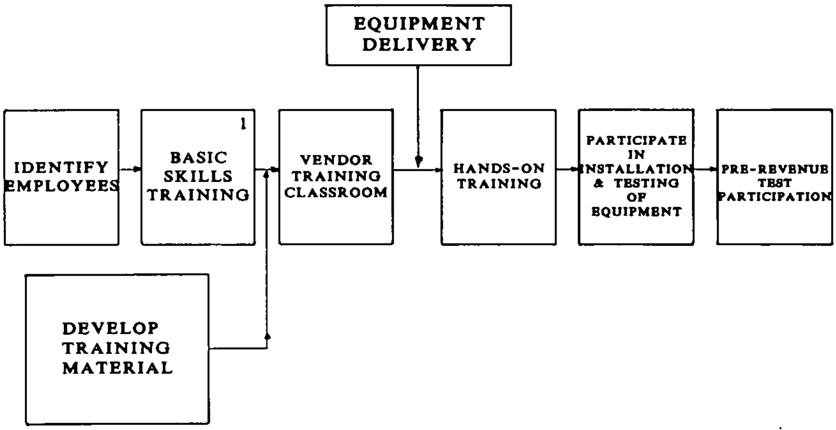


* Could be parts of the same document

1 Applies to initial group only

FIGURE 2 Training phases for operating employees.

The maintenance personnel (see Figure 3) hired for skilled positions will be required to possess at least basic skills. If the decision is reached to make the hiring of existing personnel a priority, some basic skills training may be required, particularly in electronics. This basic skills training will have to be coordinated with various technical schools in the area. All of the system's equipment specifications include requirements for vendors to provide classroom and hands-on maintenance training for our employees.



1 May be required if present RTD maintenance personnel are used for light rail system

FIGURE 3 Training phases for maintenance employees.

Maintenance personnel will also be used to monitor tests and will participate under the direction of the contractor in any retrofit or repair work on the equipment. This will provide our maintenance personnel the opportunity to gain further experience with the equipment.

TESTING OF THE SYSTEM

Test planning also started very early in the program and a very complete test program has been devised to accomplish four goals:

1. Demonstrate the safety and service characteristics of the system;
2. Validate and demonstrate system performance;
3. Verify contract compliance; and
4. Train personnel and integrate personnel, equipment, and procedures.

Test sections of the various contracts have been very carefully written to require the contractor to verify the equipment at every stage of development, starting with materials and manufacturing tests, the installation verification tests, and finally the integrated tests to verify that all systems work together as a fine-tuned light rail system.

Figure 4 is a flow chart of the field testing that will be taking place in a typical section of the midcorridor. Only tests that will be performed in Los Angeles are shown, but factory or qualification tests to be done at the factory are excluded. Numbers in parentheses in the following discussion correspond to the numbered tests in Figure 4. Starting from the left, the vehicle acceptance test (1) is performed at the test track on every vehicle received. After each LRV successfully completes this test, it will be used on integrated tests on other sections of the system. The vehicle test involves the verification of performance requirements in the specifications (such things as acceleration and deceleration rates, brake cylinder pressures, motor currents, etc.). The automatic train protection (ATP) and train-to-wayside control (TWC) vehicle equipment will also be tested to verify proper operation with the wayside installation.

After accepted vehicles are available, clearance tests (2) of the particular section under test will be performed. This test involves fitting a vehicle with a simulated dynamic profile to verify that proper clearances exist at all the physical facilities on the right-of-way, such as poles, switch machines, platforms, etc.

Overhead catenary system (OCS) mechanical and electrical tests (3) are the next step in the testing process. After mechanical checks have been done to each section of the OCS to verify the height and stagger of the contact wire, and after electrical installation verification tests (such as circuit continuity and loop resistance), hi pot insulation tests, and grounding resistance tests are complete, dead wire run tests (4) will be performed on the particular section. This test consists of using an LRV pulled by a rail-mounted vehicle to verify the pantograph sway and pantograph clearance envelope. This test is performed at several speeds in 5 mph speed increments.

Traction power supply system installation tests (5) are conducted at each traction power substation. These include insulation resistance tests, circuit continuity tests, and grounding system tests. The section will then be ready for the energization test (6) to verify proper voltage in the OCS.

Live wire tests (7) will then be performed to evaluate the collection performance between the LRV and the OCS. These tests will be done at various speeds (starting at 5 mph) in increments of 5 mph. Videotape recordings will be made of the interface between the pantograph and the OCS to verify behavior on various contact wire profiles and to show loss of contact, smooth transitions at overlaps, cross contacts, turn outs, and section insulators.

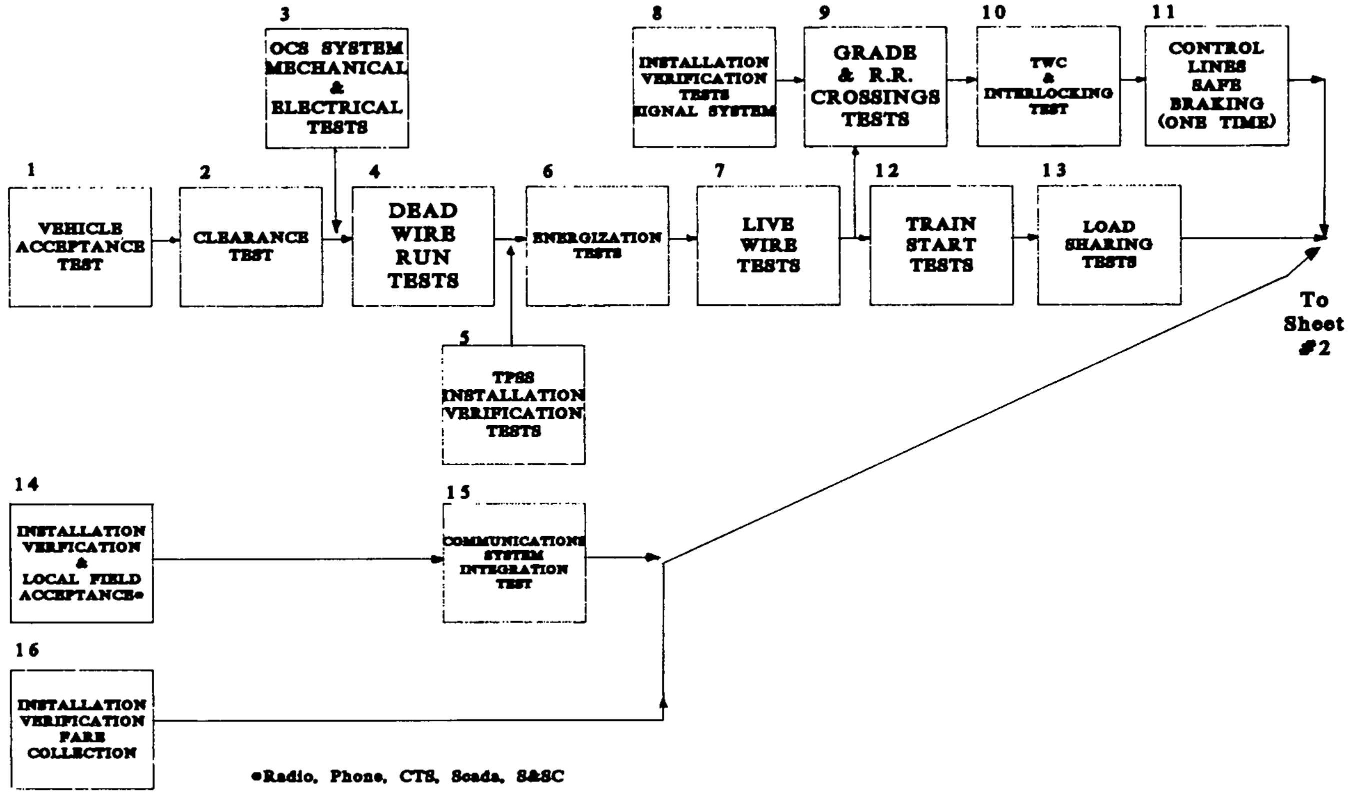


FIGURE 4 Testing phases for LRT components.

The signal system will be tested (8) after the proper installation verification tests of the signaling equipment are complete. These include tests of cable continuity and resistance, power bond resistance, insulated joints, switch machine installation, energy distribution, AFO and ac track circuit adjustment, signal adjustment, line circuits, traffic circuits, TWC, and interlocking verification.

Every grade crossing and railroad crossing will be thoroughly tested (9), first using shunts and then using actual LRVs. Grade crossing protection operation and timing will be verified for all speeds. Railroad crossings will be tested from both the LRT side and the Southern Pacific Railroad side. The TWC operation will be verified at all locations using actual LRVs and verifying every request at each location.

TWC and interlocking tests (10) follow. Each interlocking will be thoroughly tested to verify that the vital circuits, switch locking, detector locking, and signal locking operate as designed. All routes will be checked and route security proven using actual LRVs.

Next come the automatic train protection system tests and the safe braking test (11). Control lines will be tested with actual LRVs to verify that the correct speed command is received in each track circuit for every condition of track occupancy in the block preceding the track circuit under test. The test will be performed with one LRV incrementing from track circuit to track circuit. For one selected track circuit a safe braking distance test will be performed to verify that block design is sufficient to ensure safe train separation. An LRV with derated braking characteristics will be used for this test. These tests, of course, will not be performed in the downtown sections—Los Angeles and Long Beach—but traffic signal sighting tests will be performed there.

At each traction power substation one two-car train-start test (12) will be performed to verify the proper operation and coordination of the dc feeder breakers during the start. Also at each substation the proper load sharing of the two ac-to-dc conversion assemblies will be verified (13) during a three-car train start.

Local field acceptance tests (14) will be conducted on all the communications systems, namely the cable transmission system, SCADA, radio, telephone, public address, closed-circuit television, fire detection and suppression monitoring, and intrusion detection systems. When these are completed, an integrated test of the communications systems (15) will be conducted.

Installation verification tests will be conducted at each ticket vending machine (16). These will verify their proper operation and data reporting to the central data computer as well as the maintenance record-keeping computer.

After every section of the system has been tested as indicated in the preceding paragraphs, complete system tests will be run (see Figure 5).

The capability of the signal system to perform as designed will be verified by performing a system operations test (17). Three-minute headways and a three-hour-long rush hour simulation test (18) will be performed. Some failure modes for the signal system will be verified during this test.

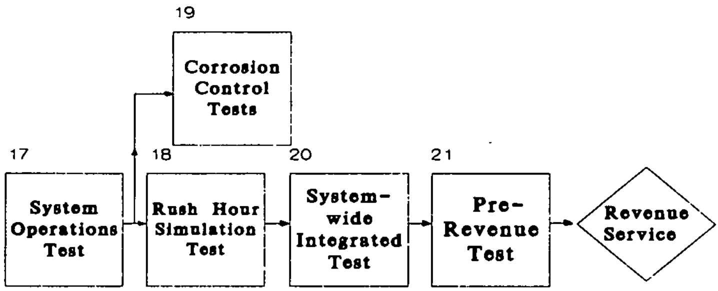


FIGURE 5 Testing phases for systemwide integrated tests.

Corrosion control tests (19) will be performed in conjunction with the simulated rush hour test to verify the effectiveness of the corrosion control measures installed within the transit system.

After all the above testing has been completed, a systemwide integrated test (20) will be performed by the LACTC and its consultant staff. This test will be attended by representatives of all the system contractors. Its purpose is to verify the complete integration of the SCADA, LRVs, signaling, traction electrification system, fare collection, and the various communications systems. The function of every annunciation and control circuit will be verified and all the operating features of the LRT system will be demonstrated.

After the systemwide integrated tests have been completed, the prerevenue operations phase will start. All testing up to this point is intended to verify equipment operation. The prerevenue operations tests (21) are intended instead to verify the knowledge and reactions of people.

There are three kinds of prerevenue operations tests, namely, those for normal revenue operations, abnormal operations, and emergency scenarios. All of the system equipment elements and operating employees will participate in these tests. The performance of employees will be observed and graded. Operating employees include the train operators, their supervisors, dispatchers, the maintainers, and their supervisors. The appropriate emergency response units for all of the areas over which the system operates will be called upon to participate in the emergency scenario portions. Employees who do not perform adequately will be scheduled for retraining or termination. Then, and only then, if all safety certification requirements have been satisfied, the system will be ready for revenue service.

OTHER CONSIDERATIONS

Several other considerations must also be dealt with: labor agreements, logistics, public relations and marketing, contingency plans, maintenance vehicles and shop facilities, and safety certification.

Labor Agreements

In the very near future some important policy decisions have to be made regarding the source of employees for the light rail system. If it is decided that the employees must come from within the ranks, negotiations must begin in the not too distant future. An agreement must be developed under which the operating employees can make the transition from the bus system to the rail system. Such issues as separate rosters for rail employees must be addressed by union and management alike. The trend towards privatization will also be considered. The cost and benefits of having any of the work performed by available private contractors must be known prior to any negotiations.

Logistics of Spare Parts and Supplies

All the systems contracts contain provisions for the equipment contractor to provide spare parts and special test equipment. They also must provide a suggested list of consumable and special tools. Decisions on the types and quantity of consumable supplies and tools need to be made in the near future. Work on the layout of the storeroom, presently under construction, also needs to be initiated.

Public Relations and Marketing

Some brochures have been prepared in English and Spanish to inform potential patrons and others about the LRT. An additional concentrated effort must be made through the media prior to revenue operations to ensure proper exposure to all our potential riders. Decisions must be made about whether demonstration rides will be given during the testing period (i.e., at the test track) or if a period of free rides will be instituted prior to revenue service.

Contingency Plans

During the entire process, contingency plans are constantly being formulated to cope with construction delays in certain line sections and facilities. Some contingency plans have also been made for opening smaller segments of the system, should it become necessary.

Maintenance Vehicles and Shop Facilities

Various high-rail maintenance vehicles must be purchased, tested, and their operators trained. Because these vehicles will not shunt the signal system and be detected, appropriate rules must be developed and incorporated in a rule book. Employees operating this equipment must be trained and tested.

Safety Certification

LACTC will be self-certifying the safety of the LRT. For this purpose a self-monitoring safety auditing program is being developed by our consultant staff to verify that all practical steps have been taken at every stage of the design and construction to maximize operational safety. Not until all the required steps identified in the testing section are fulfilled will revenue service start.

IT'S SHOWTIME

It's July 4, 1990. The largest metropolis in the world without a mass transit system is about to lose that dubious distinction. Standing in back of the big ribbon is simply "a train" that represents the fruits of at least 70 years of planning, proposals, propositions, referenda, lobbying, debate, schemes, dreams, and a lot of hard work on the part of the people who pulled together to make it all happen.

If the Long Beach line is typical of light rail lines in general, it will carry about 1,000 percent of typical daily patronage that first day, partly because the price is right on that day only (free), but mostly because curiosity is riding at an all-time high.

The success or failure of this "show time" is a direct result of how carefully thought out the practice sessions were. How many rehearsals were done? To what degree was the testing carried out? Were the test data properly analyzed? Were deviations from the norm detected? Were corrective actions identified? Was retesting carried out to determine if the corrective action fixed the problem? If the trains prove unreliable, the reason will undoubtedly be traceable to one or more of the equipment suppliers. However, it will be LACTC, RTD, and the designer that will suffer the black eye. The final report card will be handed out by the media. If the image is favorable and the patrons perceive the rail system as reliable, then they will ride it and ridership statistics will be favorable as well.

PART 4

System Design and Vehicle Performance

At-Grade or Not At-Grade

The Early Traffic Question in Light Rail Transit Route Planning

MICHAEL BATES AND LEO LEE

The planning, design, and construction of a light rail transit (LRT) line require that a wide range of complex issues be resolved. Understanding the degree to which individual issues can be addressed at each stage of the process can significantly reduce effort and time needed to gain community acceptance and to implement the LRT program. Important tools are effective methods for dealing with traffic issues in the feasibility and planning stages of LRT lines where early decisions need to be made between horizontal and vertical route alignment alternatives. Traffic issues play a critical part in making these decisions, and transit planners and traffic engineers need to know the potential magnitude of LRT impacts on traffic circulation, parking, and the degree of LRT priority or grade separation for which to plan. The grade separation issue is particularly critical, as it directly affects the operational, economic, and political viability of an LRT line. Traffic analysis and evaluation techniques can be used effectively to make early decisions on vertical and horizontal LRT alignments, to both guide LRT planning policy and focus subsequent LRT design efforts.

THE PLANNING, DESIGN, AND construction of a light rail transit (LRT) line involve several stages. The first stage is the identification of an LRT service area and corridor, usually in the context of a regional plan or sales tax proposition. The second stage is a route refinement study that identifies alternative alignments within the service corridor. These studies typically evaluate the feasibility and the pros and cons of the alternatives and estimated costs and recommend a preferred LRT alignment. The route refinement

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study, although including some concept or preliminary engineering, is largely focused at the planning level.

The third stage is usually preliminary engineering and environmental clearance. Based on a preferred alignment, specific alignment details are defined, more detailed engineering is conducted, LRT impacts are evaluated, and mitigation solutions are identified. Some of this work may be included in the route refinement studies. The fourth stage is final engineering, in which design details are resolved, the project is approved, and construction of the LRT line is accomplished.

ISSUES AND PERSPECTIVES

This paper focuses on the route refinement stage of LRT planning and design in which the objective is to define potential alignments, identify the impacts and feasibility of each, evaluate alternatives, and select a preferred route for more detailed study and engineering. The principal issues of concern regarding LRT impacts are usually community effects, traffic impacts, safety, land values, residential intrusion, cost, noise and vibration, adjacent land uses, and other environmental concerns.

The key issue transportation planners and traffic engineers have to face directly is traffic impacts (and their relationship to associated areas of concern). Traffic impacts are among the most prominent and controversial of issues, as they are highly visible and affect or are perceived to affect most people in the vicinity of the proposed routings. Key traffic issues include impact of at-grade or aerial LRT on traffic, traffic queues and delay due to LRT, safety of mixed operations, turn restrictions, access controls, on-street parking removal, traffic at stations, and parking at stations.

The numerous interest groups involved—including system planners and engineers, transit operators, government agencies, politicians, and local communities—bring many different perspectives to these issues.

Planners and engineers have a technical perspective. They are concerned with mitigating impacts and design solutions within the philosophy of LRT, which implies low-cost and at-grade operations wherever possible. System operators share this philosophy but are also concerned with system speed and performance, which implies that LRT takes priority over automobile traffic.

Government agencies sometimes differ and may be in conflict with these goals. Affected jurisdictions (usually cities and counties) are concerned with minimizing their costs and LRT impacts on the street system and traffic operations. Hence, they often favor minimal LRT priority over automobile traffic or grade separation of LRT.

Communities are understandably concerned with LRT's effect on their local environments. LRT is often perceived as a threat as well as a benefit.

Although this is often due to misconceptions or lack of knowledge about what LRT is and how it can operate, legitimate concerns exist regarding safety, traffic congestion, parking overflows at stations, and environmental intrusion.

The success of any LRT system requires consensus and support from all these groups, as well as from the political arena. It is therefore necessary to address issues early, share information, refine plans, and educate people about system performance and impacts.

The vertical alignment of a light rail line is perhaps the single most important issue in that it largely determines the cost of the project. An at-grade line is considerably less expensive to build, but may lower operational efficiency and increase impacts due to conflicts with automobile traffic. Although LRT is ideally suited for mixed traffic operations, in many western U.S. cities LRT operations over long route lengths with no priority over automobile traffic often result in slow run times, unreliable schedules, and consequently poor operational performance. Underground and elevated alignments, on the other hand, raise costs significantly and fail to capitalize on the flexibility of LRT technology. If the LRT line is all grade-separated, then it becomes a typical rapid transit heavy rail system and the cost may be prohibitive.

Grade separation is thus often an early and controversial issue in LRT route planning and is particularly critical because it directly affects the operational, economic, and political viability of a proposed LRT line.

The flexibility of LRT provides opportunities for compromise between system cost and operating speeds. The early identification of grade separation needs and of an LRT/automobile control strategy is important in the definition and evaluation of mitigation measures, and for the development of a realistic LRT operating plan and patronage forecasts. There is a wide range of traffic engineering strategies for LRT/traffic control. The key areas with respect to traffic decisions in LRT route planning are midblock alignment, alignment at intersections, and station locations.

At the planning stage, both qualitative and quantitative traffic evaluations can help assess the opportunities, constraints, and impacts of light rail operation. It is therefore important to understand what evaluation criteria are most appropriate and what analytical methods are best suited to the LRT route planning process.

TRAFFIC ISSUES IN MIDBLOCK ALIGNMENTS

Midblock sections between major roadways compose most of the length of LRT alignments. The principal traffic issues for midblock alignments thus primarily address the horizontal alignment. The key alignment options are in-street versus off-street. There are two in-street options, median running or side running, and two off-street options, adjacent to street or away from street.

For LRT to operate within the existing roadway right-of-way (either at grade or grade separated), roadway space available for automobile traffic is normally displaced. A number of opportunities usually exist for mitigation. If the reduced roadway space may be adequately absorbed through reduced lane widths, then the LRT will have no direct impact. Where this is not possible, additional roadway space may be obtained by either removing parking or widening minor roadways, which involves curb relocations. Alternatively, where traffic volumes permit, the dropping of a traffic lane or prohibition of turning movements at minor intersections and driveways may be viable.

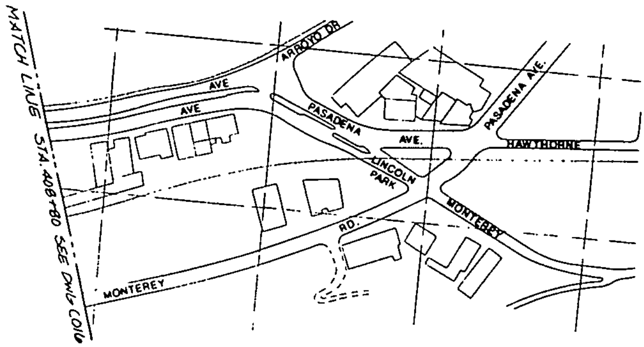
Criteria and Methodologies

LRT operations, particularly at grade, have the following potential impacts: reduced roadway space, reduced parking spaces, reduced accessibility to adjacent land uses, and increased automobile travel time and delays. With respect to midblock LRT impacts on traffic operations, the key criteria are available roadway and right-of-way widths, roadway geometrics, traffic volumes and operations, traffic controls, driveway locations and property access, on-street parking, and adjacent land uses.

The route planning process and the refinement process may involve many miles of potential LRT alignments, thereby precluding detailed quantitative analysis. A more prototypical approach can effectively address many midblock traffic issues, primarily by qualitative analysis. At the route refinement stage, the focus of traffic analysis is often more on the comparative impacts of various alignment alternatives than on the absolute impact. Geometric requirements for LRT, both at-grade and elevated LRT, and the need for lane modifications or eliminations are easily identified. Matrix evaluation techniques using the criteria listed above will often provide decision-makers with sufficient information to narrow down alternatives.

For example, in a route refinement study for the downtown Los Angeles-to-Pasadena corridor, a qualitative matrix format was utilized to evaluate impacts on roadway width, roadway geometry, traffic controls, parking, and adjacent land uses by LRT line segments. The matrix (see Figure 1) was presented adjacent to strip maps of LRT alignments for easy reference. This technique was used to make recommendations for median or side running and at-grade or elevated configurations for a preferred LRT alignment, as well as to focus on problem areas requiring subsequent quantitative analysis.

Graphical illustrations, particularly cross-sections, are also extremely effective in identifying the need for reduced lane widths, on-street parking



Segment	Santa Fe right-of-way	Lincoln Park	Monterey Place	Santa Fe right-of-way
ADT		14,000	14,000	
Roadway Width		60' with islands	60'	
Lanes		2 lanes each way with left-turn lane	2 lanes each way	
Traffic Controls		R.R. gates and signal	R.R. gates and signal. STOP signs on EB Pasadena. Hawthorne	
Land Use	Residential	Commercial	Commercial	Residential
Recommended LRT Alignment	Santa Fe right-of-way	At grade with gates.	At grade with gates.	At grade
Comments	No traffic impact	Existing geometry OK. Gated control with signal preemption. Detailed analysis required.	Existing geometry OK. Gated control with signal preemption. Detailed analysis required.	No traffic impact. provided that station does not reduce width of Hawthorne Street.

FIGURE 1 Example of qualitative matrix evaluation.

removal, left turn restrictions, shared through/right curb lanes, and lane removals. For example, the cross-sections in Figure 2 illustrate the comparative effects on lane widths, parking, turn lanes, and through lane capacity of at-grade versus aerial alignments. The cross-sections in Figure 3 were used in a route selection study in the San Fernando Valley to illustrate two options for accommodating an aerial LRT alignment along a major street through a regional activity center.

At midblock locations, LRT impacts are usually reflected through restrictions or loss of parking and loss of access to adjacent land uses. Simple

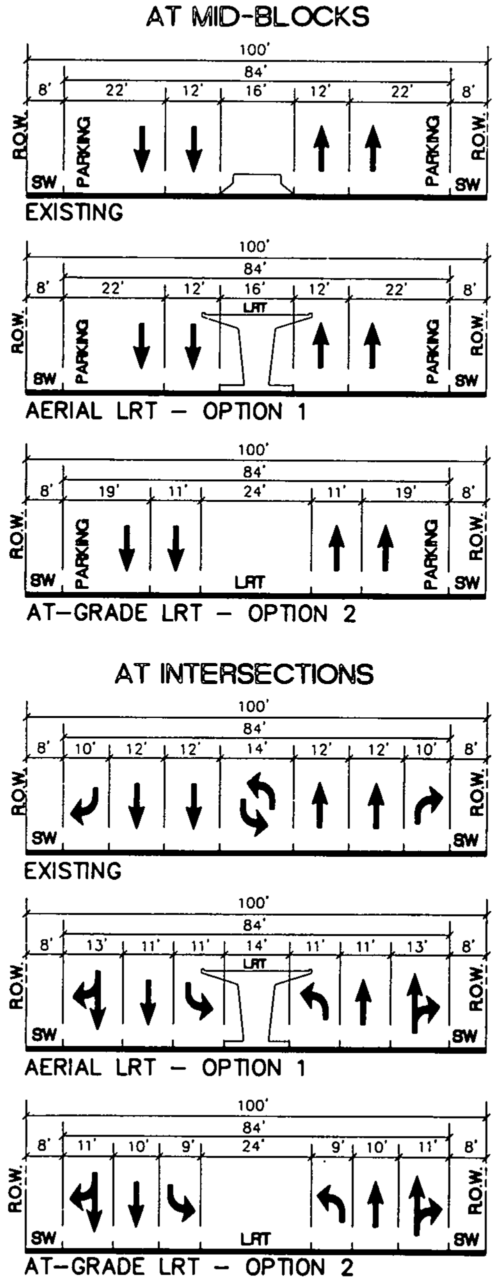


FIGURE 2 Prototypical highway: aerial versus at-grade LRT impacts.

quantification of the loss of parking will identify the need for mitigation measures such as on-street control and provision of off-street parking. Identification of critical access locations will also show the need for signals at certain minor intersections, for turn or access restrictions, or for improving geometric conditions at major intersections to compensate for access loss at the minor ones. The impacts of left-turn restrictions, modification to property access, closures of side streets, or diversion of traffic to parallel arterials can be further evaluated with conventional traffic impact techniques.

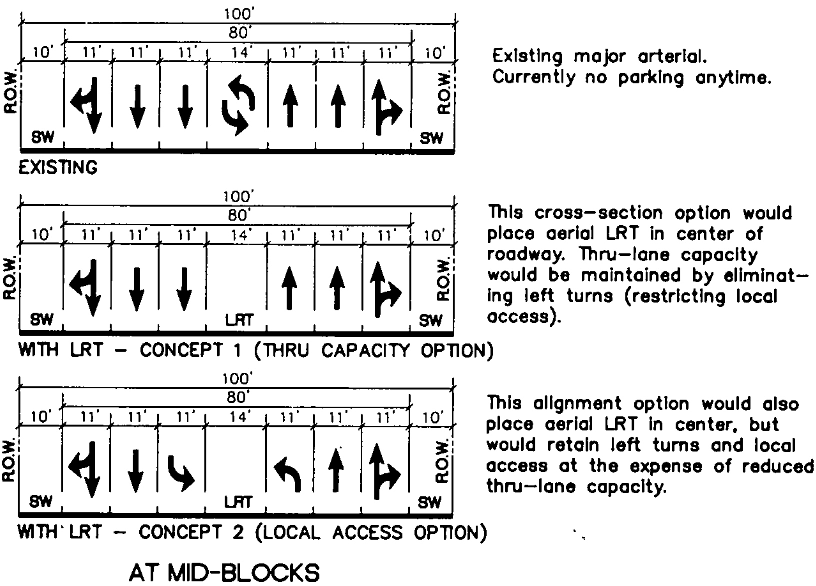


FIGURE 3 Examples of cross-section strategies for aerial LRT.

Analytical Approach

A qualitative approach is thus usually the most cost-effective way of dealing with midblock traffic issues early in the LRT route refinement process. Prototypical analyses can be used to illustrate likely LRT and traffic operating conditions under alternative scenarios (for example, at grade versus elevated, median versus side running). A qualitative overview, including matrix evaluations and illustrations, can rapidly identify general opportunities, constraints, and impacts of LRT operations, the appropriate type of mitigation strategies, and where they may need to be applied. This approach will also greatly assist in the educational process for decision-making, provide early input to civil engineers for alignment decisions, and provide the focus for more detailed analysis in the subsequent phases of the LRT planning and design process.

TRAFFIC ISSUES AT INTERSECTIONS

Traffic issues are often focused at intersections and where LRT crosses roadways, particularly with respect to the vertical LRT alignment. The key alignment choices to be made with respect to traffic are at-grade or grade separated. If at-grade alignment is chosen, the type and degree of LRT priority must then be decided. The traffic engineer has four strategies available to eliminate or reduce LRT impacts at intersections or midblock crossings:

- Separation of traffic flows in time (usually accomplished by traffic control signs or traffic signals that assign right-of-way to conflicting movements);
- Reduction in the number of traffic movements (converting one or both of the crossing streets to one-way operation or closing one or more of the approach legs);
- Separation of traffic flows in space at-grade (traffic and LRT can be separated at-grade by developing separate traffic lanes, by developing LRT medians, or by prohibiting or diverting certain movements); and
- Separation of traffic flows in space vertically (conflicts are totally eliminated by rail or highway grade separations).

Criteria and Methodologies

The evaluation of these traffic issues requires more quantitative analysis than do the midblock issues, as the traffic-LRT interface is more complex at intersections. LRT will generally have traffic operations impacts in both space and time, and the level of LRT impact will depend on the degree of priority that LRT receives over conflicting automobile traffic. The LRT may reduce roadway capacity (space impact) by taking roadway area previously used by automobiles, and may reduce signal capacity (time impact) by taking green time or adjusting the green splits due to preemption.

A considerable number of traffic engineering techniques can be used to mitigate the impacts of full LRT priority (preemption). If mitigation does not prove possible, then partial LRT priority is an option. Typically this involves the use of "window" techniques to obtain a more equitable balance of automobile and LRT performance and delay. LRT arrivals through linked signal systems may be timed to minimize disruption of automobile traffic. If partial priority does not work, then a decision must be made between no LRT priority at all or grade separation.

Thus one of the more important decisions in LRT planning is the degree of LRT priority and need for grade separation at intersections and roadway crossings. The principal criteria with respect to traffic issues at intersections are turn controls, intersection level of service, length of and dissipation of traffic queues, automobile delay, LRT delay, and impact on areawide signal systems.

A wide range of analytical tools is available to evaluate LRT priority and grade separation. Some are simple and easy to use; others are complex, sophisticated, and very time-consuming. At the planning level of route refinement, simple techniques allowing comparative and screening-level analysis are preferable. A number of alternative alignments are usually being considered, with many intersection locations. It is therefore not practical to conduct detailed or in-depth analysis at all locations, particularly when the majority will not be on the preferred alignment. (For example, a study in the San Fernando Valley had five alternative alignments and a total of over 80 major roadway crossings to be addressed.) The following techniques are available to address the key criteria listed above.

Level of Service

The impact of LRT at intersections may be quantified through level of service (LOS) analysis, which is a measure familiar to many people and is relatively easy to use. Changes in roadway geometrics and green time, as well as potential shifts in traffic volumes due to LRT, can be readily evaluated. LOS analyses have historically used a volume/capacity (V/C) ratio as a measure of the traffic conditions at an intersection.

More recently, the 1985 Highway Capacity Manual recommended average vehicular delay as the determinant of LOS. However, our experience has led us to conclude that delay is not a valid method of assessing LOS at intersections where LRT priority over automobile traffic occurs. First, there is no simple and accurate way of estimating average vehicular delay over the peak period while accounting for discrete light rail preemptions. Equations shown in the Highway Capacity Manual are developed empirically for steady state average vehicular delay where operations are similar from cycle to cycle. Transient occurrences, such as rail preemptions that may affect numerous signal cycles, are not accounted for. Second, the capacity of an intersection is a real measure with a definable threshold beyond which oversaturation will result, whereas average delay is a subjective measure, with no currently defined thresholds or standards of what is and is not acceptable. Third, drivers' perceptions of delay at an intersection due to automobile traffic are likely to be different from those due to rail, and there are currently no empirical data to quantify such a difference.

The V/C ratio is thus preferred over average vehicular delay for the definition of LOS. Intersection V/C calculations are conventionally based on assessing the V/C of the critical phase(s) assuming an optimal green time allocation. The primary impact of full priority LRT operation is the disruption of this optimal green split. This can be evaluated through the following equation:

$$V/C = [\text{Sum of critical } (V - V_p)/s] \times \frac{C}{C - L} \times \frac{3{,}600}{3{,}600 - P}$$

where

V = total traffic volume of a critical movement (vph),
V_p = traffic volume moving during preemption (vph),
s = saturation flow (vph),
C = signal cycle length (sec),
P = total preemption duration in an hour (sec), and
L = sum of critical loss time (sec).

This formula is a derivation of standard volume/capacity analysis that allows for the consideration of LRT preemptions in two key respects. The impact of preemption on capacity is accounted for by subtracting the total preemption time (P) in the LOS calculations. Traffic volumes are then adjusted to account for traffic movements that can occur concurrently with the LRT phase (V_p). Movements that are blocked during preemption receive no adjustment.

This general approach to LOS analysis has been successfully used to evaluate LRT impacts in numerous route refinement studies in Los Angeles and San Diego. It has enabled the identification of geometric improvements at intersections necessary to mitigate impacts of LRT preemption to acceptable standards and the subsequent evaluations of the feasibility and cost-effectiveness of such measures. Where mitigation measures were not considered feasible, the crossing was considered a candidate for either LRT control (no or partial LRT priority) or grade separation. Table 1 illustrates this approach for the midcorridor segment of a preliminary study in the San Fernando Valley area of Los Angeles. Mitigation measures were considered necessary, or feasible, at all crossings except Reseda and Balboa, which were identified as grade-separation candidates.

TABLE 1 EXAMPLE LEVEL OF SERVICE ANALYSIS

Crossing	Level of Service 1986	2010 No LRT[a]	2010 with LRT (A)[b]	2010 with LRT (B)[c]	Street Improvements Necessary by 2010 to Accommodate Traffic and LRT Full Preemption[d]	Street Restripe or Widening[e]
Tampa at Topham	0.75	0.66	0.73	0.73	(Add thru lane each direction on Tampa)	Restripe
					(Add thru lane each direction on Topham)	Widen
Reseda at Oxnard	0.65	0.90	0.99	0.82	Add thru lane each direction on Reseda	Restripe
Lindley at Oxnard	0.53	0.77	0.85	0.73	Add thru lane each direction on Lindley	Widen
White Oak at Oxnard	0.68	0.79	0.88	0.79	(Add thru lane each direction on White Oak)	Restripe
					Add thru lane each direction on Oxnard	Widen
Balboa at Victory	0.85	0.92	1.02	0.79	(Add right-turn lanes on Balboa)	Widen
					Add thru lane each direction on Victory	Widen
					Add thru lane each direction on Balboa	Widen

[a]Assumes street improvements where necessary to maintain Level of Service D (ICU 0.90 or lower).
[b]Assumes LRT preemption and no mitigating street improvements.
[c]Assumes street improvements detailed in remainder of table.
[d]Improvements necessary independent of LRT are shown in parentheses. Note that timing and phasing of and responsibility for street improvements will depend on when LRT line is constructed.
[e]Street improvements not requiring widening are restriping of existing roadway and removal of on-street parking.

Queue Length

Another useful parameter for the quantification of LRT impacts is queue length, particularly the maximum queue lengths under worst-case conditions. Whereas the LOS identifies the average operating condition over the peak period, the worst-case queue length indicates the impacts of a specific though-transient condition. The maximum vehicles in a queue may be estimated from the formula:

$$Q_m = q \times r$$

where

Q_m = maximum vehicles in queue,
q = vehicle arrival rate (sec), and
r = maximum red time (sec) due to preemption.

The key element of the analysis is the determination of r, red time due to preemption. The worse-case condition is typically two LRVs arriving back-to-back at the crossing. As the probability that such an event will occur is relatively slim, either the 85th percentile or an average of best case (single preemption) and worst case (back-to-back) can be used as a reasonably conservative measure of "worst case."

The maximum back of queue may be approximated and impacts may be categorized as minor (blocking driveways), moderate (blocking residential or minor roads), or major (blocking major streets). The need for and feasibility of mitigation measures to increase storage capacity can then be evaluated. Where such measures are not feasible, grade separation may need to be considered. Table 2 illustrates the application of such an analysis to the midcorridor segment of an alignment study in the San Fernando Valley in Los Angeles. The two crossings where queues could extend to adjacent major streets (Reseda Boulevard and Balboa Boulevard) were the two crossings targeted in Table 1 for potential grade separation.

Delay

More complex evaluations of queues (such as average queue length, dissipation times, and associated delays) are not recommended at the planning stage of route refinement, as they are significantly more complex, time consuming, and difficult to apply. Although the impacts of LRT on automobile delay are often of most interest to traffic engineers in affected jurisdictions, automobile delays are not considered a good general indicator of LRT impacts (as explained above). The preferred indicators of LOS and queue length are adequate for determining the effectiveness of mitigation measures, which, if feasible, make the further analysis of delay a moot point.

The real usefulness of delay calculations is thus at those locations where traffic engineering mitigations for full LRT priority are not considered feasible and the degree of LRT priority (none, partial, or full) is being considered. Both automobile delay and LRT delay can be computed and expressed as

TABLE 2 EXAMPLE QUEUE ANALYSIS

Crossing	Maximum Queue Length (ft)[a]	Queue Impacts		
		Driveway	Minor Street	Major Street
Tampa	400	Yes	Calvert	None
Reseda	380	Yes	Bessemer	Oxnard
Lindley	280	Yes	Topham	None
White Oak	400	Yes	Bullock Bessemer	None
Balboa	500	Yes	None	Victory

[a]Represents back of queue following LRT preemption. Average of best case (single LRT preemption) and worst case (back to back LRT preemption).

person hours of delay to assist in the determination of the optimal level of LRT priority and the overall minimization of delays in the transportation system. (A good example, comparing overall commuter delay for partial and full LRT priority at major crossings on the Long Beach-Los Angeles LRT line, is discussed by Taylor et al. in another paper in this report.)

However, the calculation of automobile delay is difficult and time consuming. A general formula for calculations of delay from discrete events such as LRT preemption is not available. Technical studies for the Long Beach-Los Angeles LRT line concluded that, where delay calculations were necessary, they were best obtained through simulation techniques. Unfortunately, traditional network models such as TRANSYT-7F and NETSIM do not provide the flexibility to accommodate LRT preemption sequences. For the Long Beach-Los Angeles LRT project, a microcomputer-based technique was developed based on a deterministic queueing model (similar to the description of deterministic queueing theory found in the ITE handbook, for example). The model evaluates successive signal cycles over a 10- or 15-min period, and was used to determine delays, queue lengths, and *V/C* ratios for various mitigating strategies.

While this approach yielded acceptable results, it was also extremely time consuming. It should also be noted that these studies were conducted during the design phase of the project to finalize design solutions for an already determined alignment. For the reasons outlined above, evaluations of delay are not recommended during the route refinement stage of LRT planning.

Analytical Approach

The emphasis in route refinement is on the evaluation of general feasibility, effectiveness, and costs of various LRT alignment alternatives. The traffic analysis should provide an indication of where at-grade crossings will work, what type of mitigations are appropriate, and what the relative levels of impact will be. It should also determine where grade separations may be necessary as inputs to cost estimating, fixing of vertical profiles, and preliminary physical (e.g., noise and visual) impact analysis.

A useful approach that has been adopted in studies in Los Angeles is to divide intersections and crossings into three categories during the early planning stages as follows:

- Category I: At-grade LRT priority should be feasible;
- Category II: Partial or no LRT priority, or grade separation, may be necessary; and
- Category III: Grade separation is probably necessary.

Although it should be clearly understood that every situation is different and that it is difficult to generalize, a number of sources do provide some general rules of thumb. These come from analytical work on LRT corridors in planning and design in Los Angeles County, from empirical data collected around the country, and from preliminary findings of ITE committee investigations. Generally these are as follows:

- For roadway crossings under 20,000 average daily traffic (ADT), at-grade crossings with LRT preemption should be workable.
- Between 20,000 and 30,000 ADT, at-grade may be workable, particularly if LRT is not accorded full priority. Depending on the operator's service needs, no or partial LRT priority or grade separation could be necessary.
- Over 30,000 ADT, grade separations should be seriously considered, although depending on site-specific circumstances, at-grade solutions may still be workable.

Clearly, factors such as roadway geometry, the number and configuration of traffic lanes, and peak hour traffic flows are important, and may cloud distinctions between these categories. Quantitative techniques such as LOS and queue analysis can be applied to validate and confirm such categorizations, and to further identify the level of mitigation required for at-grade solutions, particularly at Category II crossings. While "anything is possible" from the engineer's perspective in designing an at-grade solution, the "gray area" of 20,000 to 30,000 ADT crossings in Category II often becomes a matter of policy as well as technical feasibility.

It is in this category that the needs and resources of the operator, local jurisdiction, and community must be balanced. No LRT priority may produce no traffic impacts but may also be unacceptable from the operator or service point of view. Technical solutions may work for full LRT priority at-grade but may be too costly, unsafe, or politically unacceptable. Partial priority may thus be a satisfactory compromise between LRT operations and the affected jurisdiction.

Clearly all these trade-offs cannot be resolved at the planning stage because of the time and costs involved. The analytical strategy in route refinement should thus be to determine which intersections and crossings fall into Category I ("sure at-grade") and Category III ("probable grade separation") with a minimum of quantitative effort. The general level of mitigation required for Category II locations can be identified to assist decision-makers in evaluating the trade-offs between at-grade and grade separations. This approach allows the focusing of more detailed quantified analysis, particularly complex delay and queue evaluations on the much smaller number of Category II ("gray area") locations and on the subsequent design of mitigating strategies.

CONCLUSIONS

Early traffic analyses can be performed using both qualitative and quantitative techniques to assist in key decisions of LRT route planning. A generalized model for the types of traffic evaluation most appropriate to each stage of the LRT process is shown in Figure 4. In many cases qualitative evaluation can be used effectively to screen potential routes and alternatives, and is usually the most cost-effective way of dealing with midblock traffic issues early in the LRT route refinement process. A qualitative approach can rapidly identify opportunities, constraints, and likely impacts of LRT operations, and provide early input to civil engineers for alignment decisions.

Quantitative analysis is most useful for alignment issues at intersections to quantify LRT impacts, to identify the most feasible vertical LRT alignment in the traffic context, and to evaluate the degree of LRT priority necessary at particular roadway crossings. Quantitative methods are thus most effectively used after the initial screenings to determine impacts and, when applied to specific problem areas, to develop mitigation solutions.

Relatively straightforward criteria such as LOS and queue length will provide good early insights into the traffic issues of LRT route planning. Although these analyses will clearly not provide resolution of all the issues, they do provide a cost-effective way of focusing more complex subsequent evaluations. On the other hand, complex evaluation criteria involving automobile delay and impact on signal systems are not recommended at the LRT planning stage as they rarely need to be addressed to every location. Attention to these criteria can be focused on specific locations where decisions on the level of LRT priority must be made, and during the design phase when mitigating strategies are finalized.

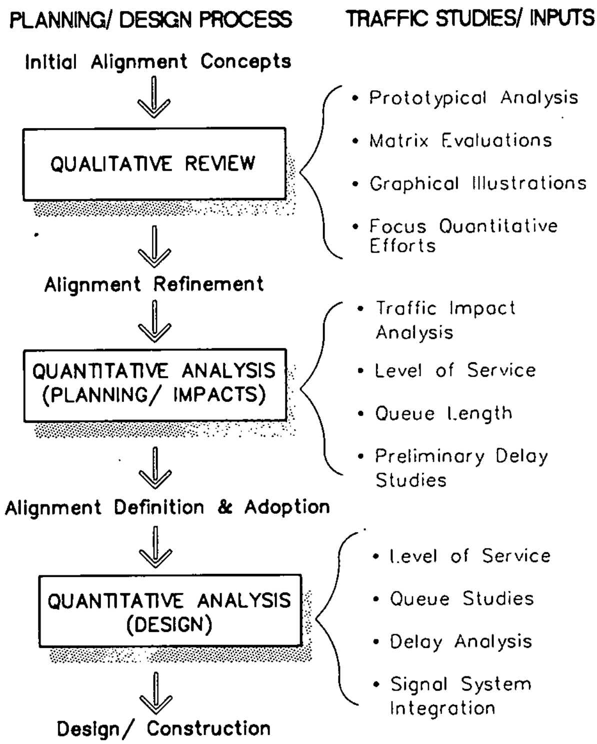


FIGURE 4 Generalized model for traffic study in LRT route planning.

In conclusion, the key decisions regarding traffic that can be made at the LRT route planning stage are as follows:

- Relative midblock impacts of horizontal alignment alternatives on traffic operations and on-street parking;
- Relative midblock impacts of at-grade versus elevated alignments on traffic operations and on-street parking;
- Potential grade separation needs;
- Potential for at-grade intersection solutions and likely techniques for LRT control and priority; and
- "Gray area" locations requiring trade-off decisions between level of LRT priority and grade separation.

Elements requiring more detailed analysis beyond the planning stage and throughout design of the LRT system are as follows:

- Impacts and delays associated with LRT priority, particularly at crossings requiring trade-off decisions between level of LRT priority and grade separation;
- Final grade separation decisions;
- Relative delays between automobile and LRT for at-grade strategies; and
- Final selection of preferred at-grade LRT control strategies and appropriate mitigating design solutions.

In the traffic context, many horizontal and vertical alignment and grade separation decisions can be made in the planning stages of the LRT route refinement process. The traffic evaluation techniques outlined in this paper will provide a good understanding of traffic issues at the early planning stages of LRT and focus subsequent LRT design efforts. Traffic studies are a key input to LRT alignment decisions, and the data provided on potential LRT control strategies, mitigations, grade separation needs, and impacts on costs can provide technicians, politicians, and communities with the traffic-related information necessary to make informed decisions between alternative alignments. Although significantly more complex levels of traffic analysis may often be necessary to determine final alignments and to finalize mitigating strategies for at-grade solutions during the design stage, the extent of such analyses can be effectively focused by application of appropriate traffic evaluation techniques in the early stages of LRT planning.

ACKNOWLEDGMENTS

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Preliminary Geometric Design Analysis for Light Rail Transit

GARY A. WEINSTEIN, RAYMOND C. WILLIAMSON, AND THOMAS M. WINTCH

During studies on the extension of the Guadalupe Corridor light rail transit (LRT) line, the City of Sunnyvale, California, was faced with the problem of entering an environmental review process with only one alignment option and very little information on LRT and city street geometrics or related potential impacts. City staff and consultants were able, within a very short time, to analyze, rank, and present to policy makers a large number of additional local LRT route options utilizing a technique of formalized design sketching. This paper describes preliminary geometric design for LRT, the design sketch formats that were used, and the two-step procedure in which they were applied. Observations and conclusions are also offered on the subject of conceptual geometrics and application of design sketching techniques to LRT planning and layout. Experience gained from the study demonstrates why all reasonable LRT route options should be considered in early planning and why the development of more detailed information on geometric design features is important in the early scoping stages of LRT projects. Quick and relatively inexpensive design sketch techniques make it possible to identify and evaluate alternatives and impacts earlier than otherwise would be possible, resulting in a better-understood project.

A RECENT PLANNING STUDY for light rail transit (LRT) in Sunnyvale, California, included the development and application of certain procedures for rapidly analyzing preliminary alignments and geometric design features

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of alternative LRT lines. Some of the procedures were found to be especially useful.

Sunnyvale is a city with a population of about 115,000. It is situated 44 mi south of San Francisco and 10 mi northwest of San Jose. The electronics and aerospace industries came to Sunnyvale in the 1950s and the city continues to be a major center for high-technology industries. Because of its success in attracting employers, Sunnyvale faces an imbalance of jobs and housing. The city is seriously concerned about traffic problems, and some hope for relief is seen in a proposed extension of the existing Guadalupe Corridor LRT line that begins in San Jose and now ends within 1,500 ft of the Sunnyvale city limit.

This possible LRT line extension was included among other options in an alternatives analysis by the San Francisco Bay Area Metropolitan Transportation Commission (MTC). The MTC study was made for the Fremont-South Bay Corridor and included only one route alternative for extension of the Guadalupe Corridor LRT line into Sunnyvale (see Figure 1). When it was first proposed, very little detailed information was available to the city about the line or its impacts, and the city was faced with the problem of entering into the alternatives analysis/draft environmental impact statement (AA/DEIS) process without sufficient information. At the time of scoping, the single LRT route defined by the MTC provided only limited information about such features as alignment specifics, impacts on city street traffic, right-of-way width, reduction of parking, and landscaping requirements.

SUNNYVALE LRT PLANNING STUDY

The City of Sunnyvale was greatly interested in the LRT mode, but was uncertain about whether the one route proposed by the MTC was the best available. Although a subsequent environmental analysis would provide more detail, it would come too late to influence the initial selection of alternatives.

Sunnyvale therefore undertook its own preliminary study of possible LRT alignments within the city limits to review the proposed route, anticipate its impacts, and identify any additional local route options that might prove attractive. The initial work was to be completed on a very short schedule of about 1 month so that it would not delay the MTC process. Within that schedule city staff and consultants were able to develop, analyze, rank, and present to policy-makers a range of new local LRT route options, utilizing a technique of formalized, freehand design sketching. Using this technique, several new alignment options were shown to be feasible that might better address city objectives. These options were then submitted to the MTC and were included in the main AA/DEIS process.

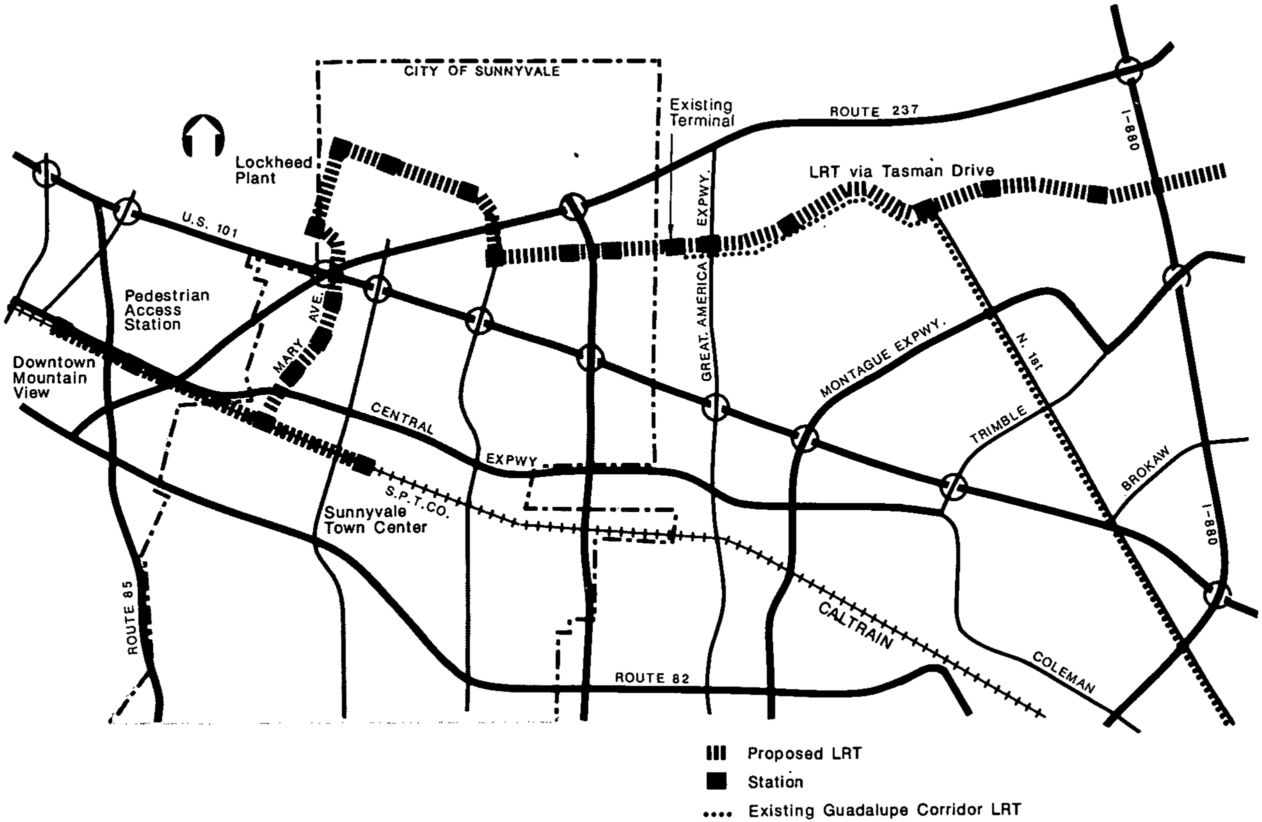

FIGURE 1 LRT routing through Sunnyvale as first proposed.

A major feature of the study was its early progress beyond a generalized concept of the route alignment, proceeding to develop a comprehensive preliminary geometric design for each alternative route. This proved important because the geometric configuration of the line is the key to defining environmental impacts such as right-of-way requirements, neighborhood noise and visual intrusion, traffic capacity, effect on landscaping and open space, extent of construction, etc. Furthermore, it was found that local impacts and costs could vary significantly with even minor route shifts.

The LRT route originally proposed by the MTC created two major concerns for the city. The first concern was the proposed use of Tasman Drive west from the end of the Santa Clara County Guadalupe Corridor line. The LRT route was then to cross the CA-237 Freeway and proceed to the vicinity of the Lockheed Company site. The industrial park sites associated with Lockheed were considered important destinations for LRT patronage. The Tasman route appeared to be the most direct way of extending the existing Guadalupe line, and offered a roadway width of about 60 ft in which a boulevard-type median could be constructed for the LRT line.

But the City of Sunnyvale was concerned that the roadway was barely wide enough for such a line, and that Tasman passed between three very large mobile home parks densely populated by elderly residents. The city was anxious to determine the exact space requirements and traffic impacts of the Tasman route, and to identify an alternative route to preclude a "take it or leave it" impasse with the local citizens.

The second major city concern involved the alignment south from Lockheed. The MTC proposed an alignment along Mary Avenue to the Southern Pacific (SP) Railroad right-of-way. Here would be located either an east or a west turn to follow the SP tracks to a terminal either at the Sunnyvale Town Center Caltrain commuter train station or to neighboring downtown Mountain View. The major advantage of the Mary route was its generous street width, within which LRT could easily be accommodated. The disadvantage of Mary Avenue was that it bisected a residential area and might bypass Sunnyvale Town Center on the way to Mountain View. A preliminary geometric analysis was needed to examine these problems.

The LRT route alternatives for Sunnyvale were developed in two stages, using design sketch techniques.

Step 1: Identify Alternatives

As the first step, city staff and consultants sought to identify new route alternatives, working with aerial photographs at a scale of 1 in.:200 ft. Scales of 1 in.:200 or 400 ft were preferred for initial sketching because they permitted an overview of the entire route, yet provided sufficient detail to identify all possible rights-of-way, such as local streets, contiguous parking lots, flood control channels, utility corridors, etc. Two large vellum overlays were used, each covering half of the route. On these overlays, a wide variety of possible LRT routes was sketched, using pencil lines to represent each trackway. At that stage of the analysis, all reasonable possibilities were sought, so that ultimately, the best one could be identified. Given the complex requirements of city planning goals, transit objectives, LRT operations requirements, environmental impact, and cost, the more obvious routes were not necessarily the best ones. Using single-line sketches, many alternatives were developed in a very short time. An example is shown in Figure 2.

In the Sunnyvale study, the design sketch method defined 12 new route alternative combinations in the Tasman-Lockheed area and 10 in the Lockheed-Town Center area. This work took about 1 week to accomplish. In the first area, one alternative, a route generally parallel to Tasman and consisting of Elko Street, a right-of-way along a flood control channel, and the CA-237 Freeway, was selected by the city for further review. The route was not as obvious as the Tasman alignment, had more curves and a longer freeway overpass, but was several hundred feet shorter than the Tasman route.

A similar sketch was used to define a preferred alternative to the Mary Avenue route in the Lockheed-Town Center segment. In that sketch, it was shown that the LRT line could follow a narrower local street, Pastoria Avenue, which serves a dense employment area of high-tech industrial parks. By passing through a number of existing parking lots, the Pastoria route could arrive more directly at the Sunnyvale Town Center.

Step 2: Define Impacts

In the second step, more detailed sketch plans were developed for the selected alternatives at a scale of 1 in.:100 ft. In locations where the geometry was difficult, the sketches proved that the LRT line could fit into the prescribed route, and made it possible to compare detailed impacts of the routes. Sketches developed over a 3-week period at the 100-ft-scale, prepared on a 3-by-10-ft sheet, were sufficient to illustrate fully 2 mi of line for two selected alternatives. All pertinent details could be shown, down to individual trees and parking places. It was possible at this early stage in the planning process to show the exact extent of trackway, individual traffic and turning lanes, prohibited turns, channelization and driveway geometry, curb cutbacks, station space requirements, potential landscape areas, and much more.

An important feature of the Elko route was the coordination of LRT geometrics with the redesign of the CA-237 Freeway interchange at Lawrence Expressway. To better accommodate LRT, the existing four-quadrant

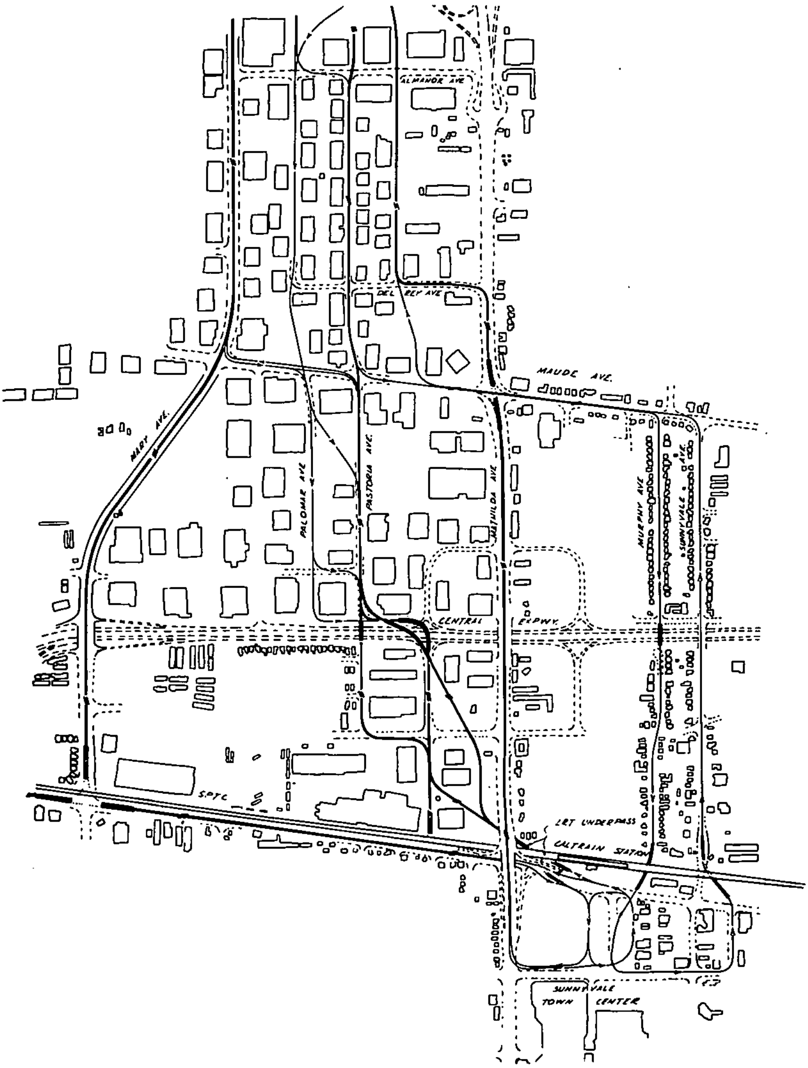

FIGURE 2 Single-line sketch illustrating numerous local route options for LRT from Lockheed area to Sunnyvale Town Center.

cloverleaf interchange was reconfigured into a more efficient partial cloverleaf (parclo), which demonstrated how improvements of road and rail systems could be coordinated and achieved simultaneously. The original sketch was later provided with a title block and colored for use in presentations to the city council and the public.

A large-scale design sketch was also prepared for the Pastoria route. This analysis identified the possibility of penetrating the Town Center by way of an underpass beneath the tracks and an existing overpass. Based on this possibility, the city intends to pursue a fully integrated plan for joint development of LRT and commercial expansion of the shopping center.

An example of the design sketch at 1 in.:100 ft is illustrated in Figure 3. It is compared with a more common format that uses tape on an aerial photograph and provides much less detail on the new facility.

DESIGN STUDY SKETCH FORMAT AND CONVENTIONS

For LRT, the important transition from planning to design occurs at the 1 in.:100 ft-scale sketch format, where, for the Sunnyvale study, the following project elements were physically defined for the first time:

- Right-of-way controls—Adjacent buildings are shown with heavy outlines. Other controls such as property lines, major tree lines, and structures are shown as necessary.
- Tracks—Each track (two rails) is shown as a single heavy line with an arrow indicating direction. Minimum distance between tracks is defined by the placement of the overhead system traction power poles between, or straddling, the tracks. Spirals are shown for curves, with track spacing on curves widened for carbody belly-in and superelevation.
- Stations—A rectangle is used to represent each station platform. Minimum length is defined by LRV length and maximum number of cars per train. At this stage, definition of center- or side-type platforms is made for the first time, based on availability of right-of-way, proximity of adjacent roadways, location of pedestrian crosswalks, and LRT operational requirements. In narrow rights-of-way, availability of width will, in many cases, define station locations and spacing.
- Roadways—For new road construction or modifications, each edge or curb of each traveled way is shown by a single line. Widths of roadways are based on local design standards. Existing curb lines are shown with lighter dashed lines. For a median LRT trackway, the left edge of pavement line also represents the center trackway boundary. Number of lanes is indicated by number of arrows, one per lane, in each segment of each roadway. Turning

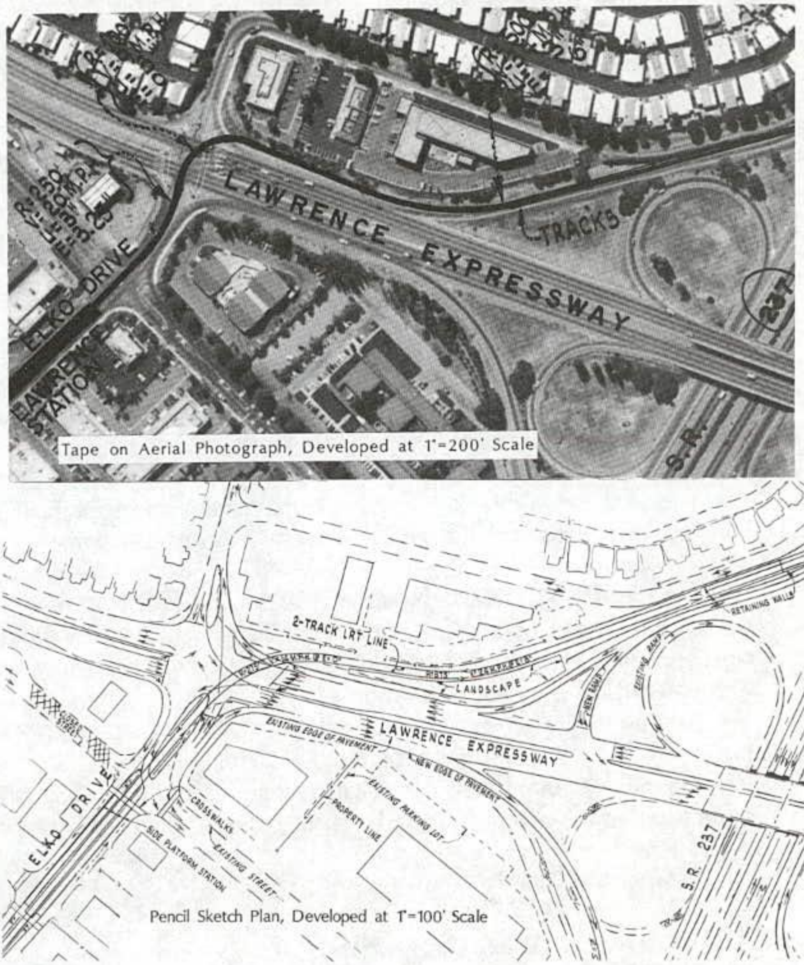

FIGURE 3 Comparison of geometric detail for preliminary planning on pencil sketch plan and tape-on-aerial photograph plan.

lanes are separated from through lanes by a fine line. Curb parking lanes are labeled.

- Channelization—All islands are shown, with adequate width and radius for turning vehicles. Arrows indicate permitted turns at intersections. All stop lines at intersections are shown.
- Crosswalks—Major crosswalks, such as those accessing station platforms, are shown. Crosswalk access is one of the factors defining feasible station locations.
- Traffic signal phasing—At each major intersection, a preliminary traffic signal phase chart can be shown, indicating the number of major phases. This may be required to define turning lane configuration.
- Grade separations—Parapet lines of bridge or underpass structures are shown as single or double lines. Extent of major retaining walls or pier locations, if significant, can also be shown. Width for emergency walkways should be provided. A profile sketch is needed to determine length of structures, fills, and retaining walls.
- Parking lots and driveways—If desired, the extent of any encroachment into adjacent existing parking lots can be clearly shown in the study sketch. Existing lot boundaries are shown with solid lines. Major driveways may require left turn access and should be shown, along with any relocated driveways.
- Landscaping—Potential new landscape areas can be outlined and labeled. Existing tree lines that are to be preserved constitute major geometric design controls.
- Dimensions—Critical or representative dimensions can be shown. Track curve radii should be shown, along with design speed based on assumed superelevation. (Track superelevation in paved roadway areas must be coordinated with roadway superelevation.)
- Profiles and cross-section—These can be sketched on the plan sheet or made separately. Profiles are important for defining grade separations.
- Options—If more than one local option is under consideration at the same location, an alternative can be sketched as an inset in a corner of the main plan.

ADDITIONAL USES OF DESIGN SKETCHING

In addition to their use in the preliminary analysis of alternative alignments and geometric design features, design sketch techniques can be applied readily to other aspects of LRT planning such as profiles, time-space graphs (train graphs) for operations planning, overhead system design, assistance in interdisciplinary coordination, identification of joint development opportunities, and as a basis for accurate early cost estimating.

Interdisciplinary Participation

Disciplines including trackwork engineering, LRT operations, traffic engineering, civil engineering and cost estimating, urban planning, structural engineering, landscape architecture, and traction power system design should be brought in early and integrated into the LRT alternatives analysis process. In particular, there is a compelling need to develop rail and roadway geometrics together to optimize use of the available space. This can best be accomplished in the early, flexible stages of project development.

An iterative process should be utilized to arrive at the best design for all purposes. This should include cooperative input from all appropriate disciplines early enough to affect the alternative selection process. Design sketching is an effective method of achieving interdisciplinary cooperation within the early planning stages.

Overhead Systems

The City of Sunnyvale has a very rigorous local policy encouraging landscaping of its thoroughfares. The preliminary geometric design prepared for Sunnyvale identified the need to preserve existing trees along the Tasman and Pastoria routes, and to use them to camouflage the trolley overhead. Side poles located in the tree lines were recommended. The more obvious alternative of center poles along Tasman was dismissed because a background of existing street trees favored the aesthetics of side poles.

Community concern frequently focuses on the visual impact of the overhead wires of a new LRT system. Examples of successful camouflage by buildings or trees along existing systems are frequently mentioned as a potential means of mitigation for a new system. To bring about such mitigations requires geometric design input at an early planning stage. Unsightly aspects of the overhead can be relocated, redesigned, hidden, or camouflaged. Major problem areas that need to be identified are special work at junctions and curves where numerous pull-offs, tension wires, and additional hardware are required. Trees can be used for either hiding wires or forming a softening background. The width required for a grove of major new trees needs to be considered early in geometric design, as does the coordination needed with the overhead layout. The ultimate result could be a true mitigation well worth the extra interdisciplinary effort, and the design sketch technique can effectively assist this effort.

Joint Development Opportunities

There are many examples of commercial and office joint development with rapid transit stations, but integration of development architecture with modern LRT has not been attempted often to date. Despite the few existing examples, LRT geometrics should be conducive to joint development. Quiet electric power and the physical flexibility of LRT can permit integration close to, and even within, the architecture of a major development. Accommodation of tramways within European historic plazas, through vintage archways, and even on top of multimodal terminals proves the physical feasibility of integrating LRT and architecture.

Geometric design options that bring the LRT line into available developable parcels, where more accessible and attractive passenger amenities can be encouraged, need to be sought out early. A local example of an earlier, innovative geometric solution that integrated a streetcar terminal into a building is the Transbay Terminal used by the San Francisco Municipal Railway. In San Diego, two joint development projects are being implemented that involve high-rise buildings constructed over LRT stations. Future joint development may lead to even more imaginative use of LRT geometric design flexibility.

Consideration should be given to locating LRT stations outside of street areas, closer to entrances of existing and new major buildings. For the Sunnyvale line, it would have been preferable to bring LRT to the door of one or more major Lockheed buildings. Unfortunately, in modern industrial parks buildings are usually surrounded with parking lots. Public rights-of-way are more easily obtainable for LRT use than private land. Thus, institutional disincentives may lead to LRT stations isolated in the street median, separated from the passenger destinations by streets and parking.

In contrast, as shown in Figure 4, LRT lines could be run behind the parking lots of the new industrial parks, directly linking the major building clusters. Each station then could become the center of a pedestrian-scale plaza, free of traffic conflicts. Creation of such a private right-of-way through existing industrial parks would involve more property acquisition and would be dependent on solving more challenging geometric problems. Advantages might include higher speeds due to separation of traffic conflicts, and avoiding utility relocations in city streets. Design sketching can help to bring out imaginative joint development options in the initial planning period.

Cost Estimating

The early availability of design sketches for cost estimating could be a vast advantage. More accurate estimates can be made in the early planning

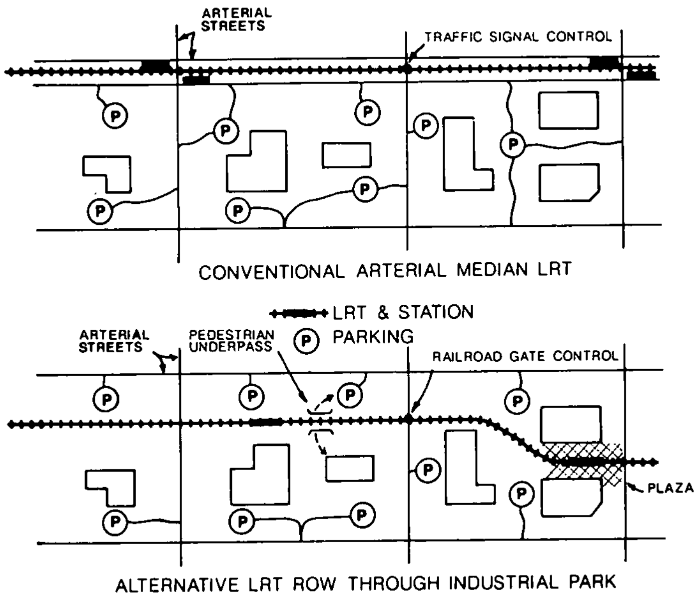

FIGURE 4 Routing concepts for LRT through an industrial park.

because the scope of the facility construction is available for quantity take-offs and measurements.

UMTA guidelines (*1*) suggest that preliminary cost estimates of rail systems may be based largely on cross-sections. This can be accurate for a heavy rail system, where most of the cost is confined to the guideway itself, and the guideway is mostly of uniform cross-section. For LRT in a city street, cost estimating by typical cross-section can be risky, because a significant percentage of the project cost may be due to geometric features outside the trackway. These may also be nonlinear, and vary in cross-section from segment to segment. Such features include street widening, intersection channelization, traffic signal installations, sidewalk and parking lot modifications, sound walls, landscaping, consolidation of driveways, and other such items where the new project must conform to existing conditions at the edges of construction. A detailed design sketch of geometrics that addresses these elements is a useful tool for more accurate early cost estimating.

HISTORY OF FORMALIZED SKETCH DESIGN

A formalized technique of freehand design sketching is not new. It was originally developed in the 1950s and 1960s for use in designing complex freeway interchanges and interchange systems. Formalized single-line sketch techniques for freeway alternatives were probably first developed by Jack E. Leisch, who later became the strongest and most effective advocate of the method. Leisch, who served in one period of his career as chief of design development of the Bureau of Public Roads, recalls that study sketches were first used in conjunction with an extensive study he prepared for an interchange complex in the Washington, D.C., area. This was accomplished in 1947–1948 at FHWA in Washington, D.C. It was during this study, as well as other projects involving interchange preliminary plans, that the study sketch technique for freeways evolved. The method was later formalized and officially reported for the first time in a 1948 paper (*2*).

The value of the procedure was well established in the ensuing years, and when the first "Blue Book" of the American Association of State Highway Officials (AASHO) (*3*) was released in 1954, it contained an appendix on "Intersection Design Procedure" that utilized much of the material from the 1948 publication. This served as a basis for developing and evaluating alternative plans and optimizing solutions for complex problems involving location, configuration, and traffic operation. In 1965, the design sketch technique was again published with minor changes in the second, revised version of the Blue Book (*3*).

During the 1960s Robert Conradt, working with Leisch, made a significant contribution in further formalizing the technique. His guidelines, as a chapter entitled "Notes on the Development of Single-Line Sketches," in a series of training course notebooks received wide circulation, and the studies he continued to perform enlarged upon the procedure. During the 1970s, Leisch, Conradt, and others continued to promote and refine these techniques. Sketching was also carried beyond the single-line format to include more detailed plans at larger scales. These larger scale formats are especially suited to LRT adaptations. The authors gratefully acknowledge Leisch's and Conradt's work on the concept of design sketching as well as a number of principles repeated in this paper.

The latest update by AASHTO in 1984, known as the "Green Book" (*4*), does not include the appendix of the previous AASHO publications. Perhaps implicit in the disappearance of the sketch technique from the AASHTO manual is the possibility that more glamorous computer-based design tools have overshadowed the simpler manual sketch techniques. Yet, even the most powerful computerized graphics now available have not obviated the practical need for initial conceptualizing using manual graphic methods. The sketch techniques may therefore be thought of as timeless in their import and value, and they remain available for use in LRT applications.

COMMENTS AND OBSERVATIONS

The Sunnyvale study brought some new insights on LRT planning to those who participated in the study, and it reconfirmed some other ideas that were held previously. The following observations relate to the study results and the study methods employed.

Alternatives Analysis Process

Geometric design of a transportation facility should begin in early planning. Planning for most fixed-guideway systems, including LRT, whether new starts or extensions, is now usually initiated in an UMTA-sponsored AA/DEIS process. By its nature, this process must deal with large-scale corridor alignment issues for numerous modes, of which LRT is usually only one. The flexibility of LRT can permit many local route options and geometric solutions, many of which may need to be addressed in the early scoping of alternatives.

The UMTA guidelines (*1*) recognize that supplementary analysis may be required in support of the scoping process to define which local alternatives are most attractive and need to be fully evaluated. The Sunnyvale study confirmed the need for this type of analysis and underlined the importance of defining more detailed geometrics in an early stage of project development.

The UMTA guidelines for the AA/DEIS process make a distinction between major alternatives that are to be included in the process, and minor variations that can be evaluated later in preliminary engineering. In a case where this distinction is not completely clear, as was true in Sunnyvale, a preliminary analysis of configuration and impacts can be useful. An early supplementary analysis can be helpful to a municipality in identifying environmental impacts that otherwise would not be addressed until later in the main environmental studies that follow alternative selection. Any new alternatives, if desired, can thus be identified during scoping as an informed decision. This also reduces the chances that major alternatives will need to be added later, possibly delaying the process.

Scope of Geometric Design

The question of what constitutes geometric design may require definition. System geometry includes the configuration and position of all visible aspects of the facility. The plan, profile, superelevation, and cross-section of the tracks and any adjacent roadways are elements of geometric design. Turnouts and special trackwork are geometric elements, as is station layout. Roadway elements of LRT geometry include traffic lane configuration, channelization, sidewalks, and crosswalks. Structures, such as bridges and subways, are special geometric elements. For LRT, the traction power overhead is also an important geometric design feature. Although the criteria of visibility may not include such features as underground utilities, ductwork, drainage, or structural systems, the implication of these may need to be taken into consideration in the geometric design.

Although geometric design is not limited to matters of appearance, it should address appearance, among other major issues. For example, public concern with the aesthetics of the overhead wire system is a recurring theme that requires special attention in LRT planning.

Geometric design is also directly related to transit operations. For example, the curvature and grade of the tracks can influence train speed. This affects travel time, scheduling, fleet size, and ultimately the quality of service and patronage. The geometric relationship of the LRT tracks and appurtenances to traffic lanes and pedestrian crossings is important in providing for operational safety. Potential conflicts need to be identified, and dealt with appropriately by such means as separation or controls.

Special Attributes of LRT

There are special attributes of light rail transit that have an influence on the planning procedures employed for this particular mode. LRT is extremely flexible in its geometry and therefore may have many route options. Light rail vehicles can negotiate much sharper curves and steeper grades than heavy rapid transit, and can utilize a wide variety of rights-of-way. LRT can fit into the cityscape in a multitude of patterns, not all of them immediately obvious. In contrast, heavy rapid transit routes may be limited to railroad rights-of-way, freeway medians, or costly subway. Light rail technology should allow, and even encourage, consideration of the richest possible variety of route applications. Identification, definition, and testing of all the many route options are required early enough in the planning process to permit selection of an optimum route. At the alternatives analysis stage it may be necessary to expand the number of alternatives as a prerequisite to later reducing them to ensure that the selected alternative is the best one available.

In some cases, the easiest LRT route—perhaps a railroad right-of-way or a wide street—is obvious from the start. The proposed route may, however, be circuitous or may not serve all the activity centers desired. In other cases, there may be no easily usable right-of-way, or the most obvious route may impose heavy operational disadvantages. Because of the flexibility of LRT, it is desirable in all these cases to carry out a preliminary geometric analysis early in the planning process to prove or disprove the functional viability of each route option, possibly including even the more obscure ones.

Formalized Design Sketching

No single prescribed format exists for working out preliminary geometric design of LRT or any other transportation facility. Although geometric criteria have been compiled into certain objective standards, the conceptualizing of geometrics is still a highly subjective process. The UMTA guidelines for the AA/DEIS process (*1*) refer to plan and profile drawings, and provide a sample of these. But the format does not emphasize the special needs of LRT, and may not illustrate the detail necessary or desirable for LRT segments in city streets. Although basic alignment can be shown as a simple line in plan and profile, the exact extent of street widening, layout of traffic lanes, new right-of-way, and the like require a more complex format. This is normally provided at the preliminary engineering stage, but it would be too late at that time to introduce major new alternatives. Preliminary geometric design needs to be developed through a rigorous study of alternatives. As previously described, the use of formalized design sketches was beneficial in quickly analyzing the large number of LRT route options through Sunnyvale.

The use of sketches may seem obvious, but formalized design sketching differs from the conventional diagrammatic sketches that most planners and engineers are accustomed to using:

Conventional Sketching

- Schematic—not to scale
- Usually conveys one or a few concepts
- No format—"off-the-cuff"
- Used to communicate to technical staff
- Little or no attention to graphic quality
- Usually small in size
- Short life—usually quickly discarded
- Redrawn by technician

Formal Design Sketching

- Accurate, to scale
- Integrates many ideas into one comprehensive analysis
- Carefully conceived graphic format and conventions
- May be used as a formal presentation medium to principals
- Graphic quality a major objective
- No size limitation—may be quite large
- Formal design product submittal
- Professional may produce final product

The development of small-scale sketches that subsequently graduate to larger scales of increasing complexity and detail can be one of the most important aspects of the planning and design process. In design sketch development the actual geometry of planning alternatives can be tested and matured into functional design. At this time, many of the features of the final design are first established and fixed. To be fully useful, design sketches must be developed with the fullest possible understanding and appreciation for the intent of project goals and objectives, as well as the practical limitations of the construction and operating environments. This is the only stage in which planning, design, and environmental mitigation can be given full and equal attention. The use of study sketch analysis can become the link between planning and design.

Sketches may be developed freehand with only limited use of drafting aids. Freehand pencil drawing allows ideas to be developed rapidly and permits fuller exploration of the design possibilities. It also develops a proper sense of perspective in executing the broader objectives of the plan by working with and visualizing larger areas of space. At the same time, the ability to deal expeditiously with long segments of alignment, no less rapidly than with fine details, is enhanced. The sketch method requires no costly equipment or special data base. The techniques can be easily learned or self-developed. The method is fast, and this has important relevance for the economy of the entire process in terms of both time and money.

Design sketches are not merely illustrations, but are simultaneously planning analyses and preliminary engineering designs. It should actually be possible to enlarge the sketches to the scale of the final design and to develop the final geometry from them directly with only moderate adjustments. Accuracy and attention to detail are therefore an important factor in the value of formal sketches. Unlike plans developed during later engineering, study sketches require no alignment calculation, all measurement being by graphic means. The fact that these have been developed largely freehand and may appear "sketchy" need not in the least detract from their accuracy if prepared with care.

The planner-engineer should endeavor to use study sketches to convey and test all appropriate ideas and all reasonable alternatives. Creativity and innovation are encouraged because of the speed of the method. Many geometric treatments can be shown, each identified as an option or variation. The process should stake out the extremes of the possible, in order—by contrast—to establish the practical optimum.

The method encourages the designer to tinker with, and constantly improve, the geometry. The freehand pencil line is easy to produce, to erase, and to redraw; the designer has little effort invested in each line, and should not hesitate to erase and modify it for improvement. Despite the detail that can be achieved, the design is free to evolve rather than being prematurely fixed.

Original sketches can become final presentation media. This can be easily accomplished by dressing up the sketch with labels and titles, and tracing major right-of-way controls from base maps. The finished print can also be colored using colored pencils. The possible objection to this product as "unfinished" or "sketchy" in comparison to such conventional media as sharp ink lines or tape on aerial map bases has little merit. The sketch should look tentative because the concept itself is still preliminary. The sketch medium encourages revision and participation in the evolving design. Popular ink and tape media have built-in disadvantages—they require the additional process of recopying the original design to appear more "finished," thereby cutting off the effort being devoted to conceptualizing. Ink and tape appear "sharp," but are not as specific and accurate as the pencil line. The freehand pencil sketch also encourages more direct participation by the professional-level engineer or planner.

The conventional use of aerial photographs as a base to enhance understanding of a preliminary plan may actually detract from the design by obscuring it with complex, irrelevant detail. Better to trace onto the plan only the limited number of most important right-of-way controls (e.g., adjacent buildings and streets) to emphasize the important, existing features that will be affected and their interrelationship to the LRT project. The use of large sheets is also to be encouraged to permit better perspective and understanding than a series of smaller discontinuous sheets.

The term "freehand" does not necessarily mean that drafting aids are not permissible. The exact technique employed can be altered to suit the individual practitioner. It is difficult to draw a long tangent line freehand, so most designers would prefer to use a straightedge even in "freehand" sketching. Naval architects' ships curves are excellent for track spirals. On the other hand, true freehand drawing is quicker, easier, and produces a better product for many curves, especially smaller radius curves and intersection channelization. The use of mechanical aids for these is actually a hindrance, and overdependence on instruments can result in a poor design.

Cost of Design Sketching

There could be some disadvantages in defining project geometry early in the planning process. Among the possible disadvantages are cost, requirements for staffing, and the danger of highlighting minor problems. The Sunnyvale experience indicates a cost for design sketch preparation of about $2,000 to $3,000 to detail a mile of LRT route alternative at the scale of 1 in.:100 ft. This is the cost of the engineering only, excluding data collection, meetings, and presentation time. If incorporated into the larger (and already costly) planning process, such additional cost should not be prohibitive, and could save later redesign costs. Alternatives that are identified earlier in the process are less costly to deal with than those that are discovered in later stages.

CONCLUSIONS

The LRT planning process should give ample attention to geometric design in the preliminary planning stage. An adequate number of different LRT alignments and geometric design alternatives should be developed and compared as a necessary preliminary step before a preferred route is selected.

The preliminary geometric design study should address rail and roadway features in a totally integrated fashion based on all of the appropriate interdisciplinary input. Formalized design sketching provides a valuable method for rapidly and accurately developing and testing LRT alternatives, and examining geometric design features. Design sketches are useful in detailing the specifics of the entire LRT route so that environmental impacts and costs can be clearly identified.

Design sketch methods have a long and successful history of use on transportation projects. The methods described can result in better design as well as better advance understanding of the potential impacts of a proposed LRT project.

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RT Metro

From Sacramento's Community Dream to Operating Reality

John W. Schumann

Sacramento's RT Metro was built for the lowest capital cost per route mile to date of any new, federally funded rail system—$9.6 million. This paper describes planning and design approaches leading to this achievement. Innovative elements, how all the pieces fit together, and how the system is functioning are discussed. Observations are made as to which aspects of the Sacramento experience merit imitation, and which might better be avoided. RT Metro is an 18.3-mi light rail transit (LRT) system extending about 14.5 km (9 mi) from downtown in each of two directions, northeast and east. A fleet of 26 light rail vehicles serves the system. Because the project budget was limited, development followed four key design principles, which could be emulated beneficially by other projects: use available rights-of-way (ROW), limit the investment to facilities for a "starter" LRT line, employ proven off-the-shelf equipment, and build to an efficient, no frills operating plan.

SACRAMENTO, CALIFORNIA'S CAPITAL, IS growing rapidly. Metropolitan population is approaching 1 million. In 1975, citizen transit advocates first suggested light rail as a potential key element in a program to accommodate growth while maintaining a livable city. Over the ensuing decade, a convergence of community support, right-of-way availability, and Interstate transfer funding enabled a light rail transit (LRT) project to be moved from planning and design into construction. Limited service began in March 1987. The full system became operational in September 1987.

LTK Engineering Services, 33 N.W. First Avenue, 1 Norton House, Portland, Oreg. 97209.

Project planning required the cooperation of the Sacramento Regional Transit District, the City of Sacramento, Sacramento County, the Sacramento Area Council of Governments, and the State of California through the California Department of Transportation (Caltrans). Policy approvals had to be secured from the California Transportation Commission and UMTA. Safety issues were negotiated and resolved with the California Public Utilities Commission. From conception to commitment to build, the project benefited from the support of local elected officials who, together, constituted a "reform era" in local politics. The coalition of pro-LRT transit advocates and environmentalists produced a force to which the elected leadership listened. When they were joined by business leaders at the crucial go/no-go decision time, LRT approval was ensured.

This project's odyssey illustrates that even cumbersome decision-making mechanisms can be made to work when a community's dream is strong enough.

THE PROJECT

RT Metro is an 18.3-mi LRT line extending about 9 mi in each of two directions from the central business district (CBD): to northeast Sacramento at Watt Avenue and Interstate 80, and to the eastern suburbs at Folsom Boulevard and Butterfield Way. The essential elements of the system are set forth in Table 1. A necessary response to the local political situation was that the initial line had to serve both the Northeast and Folsom Boulevard corridors.

The basis for LRT system development was an efficient, no-frills operating plan, which fostered the specification of a minimal "starter line" that would (1) accommodate the modest initial ridership forecast, (2) fit the sum of construction funds available (Interstate transfer plus state and local match), and (3) be operable, together with its associated feeder bus network, within the limits of the Sacramento Regional Transit (RT) District's existing operating budget.

LRT planning extended from 1975 to 1982 [a summary of the project's development in this period may be found elsewhere (*1*)]. Technical development followed four key design principles, which were set forth formally in design criteria (*2*) prepared at the start of preliminary engineering (PE):

- Use available rights-of-way (ROW),
- Limit the investment to facilities needed for a "starter" line,
- Employ proven off-the-shelf equipment, and
- Build for an efficient, no frills operation.

TABLE 1 SACRAMENTO LRT PROJECT: SUMMARY DESCRIPTION

Length:	27 Stations:	Light Rail Vehicles:
Main Line..... 18.3 miles	1-Watt/I-80	Articulated, Double-End
Double Track......... 40%	2-Watt/I-80 West	80 Ft Long, 8.7 Ft Wide
	3-Roseville Road	64 Seats, 80+ Standees
	4-Marconi/Arcade	Air Conditioned
Patronage (04/88):	5-Swanston	
	6-Royal Oaks	Security:
Total Weekday..... 13,200	7-Arden/Del Paso	
Northeast Line.... 6,700	8-Globe Avenue	Telephones at Stations
East Line......... 6,500	9-Alkali Flat	Mobile Security Patrols
	10-12th & I	Police Officers on
Operations:	11-Cathedral Square	Trains
	12-St. Rose of Lima	
50 MPH Top Speed	13-Capitol Mall	Fare Collection:
20 MPH Avg Speed, w/stops	14-7th & O	
2-4 Car Trains Peak Hours	15-Archives Plaza	Proof of Payment (POP)
1-2 Car Trains Base Hours	16-13th St.	Self Service Vendomats
Fleet: 26 LRVs (3 spares)	17-16th St.	Separate Bill Changers
81 LRT Staff	18-23rd St.	
	19-29th St.	Signals:
Service Frequency, Peak	20-59th St.	
& Base, Entire Line:	21-65th St.	Line of Sight Control w/
	22-Power Inn	Signs, Traffic Lights,
Weekday Peak...... 15 Min	23-College Green	Block Occupancy Indctrs,
Weekday Base...... 15 Min	24-Watt/Manlove	Automatic Block Signals,
Weekday Evening... 30 Min	25-Starfire	Crossing Gates/Flashers
Sat/Sun/Hol....... 30 Min	26-Tiber	
	27-Butterfield	Communications:
Implementation Schedule:		
	Station Facilities:	2-Way Radios
Plans Begun......... 1975		PA Systems on LRVs
Full Funding........ 1983	Low Level Platforms	
System Opened....... 1987	~350 Ft x 10 Ft	Traction Power:
	Shelters, Benches,	
Yard & Shop:	Info Aids, Telephones	750 Volt DC Overhead
	Access Ramps or Lifts	Catenary & Trolley Wire
Location: Academy Way	8 Park & Ride Lots w/	14 Substations, Each
26 LRVs-Clean, Service,	4,056 Total Spaces	Rated at 1 Megawatt
Repair; Way Maintenance &	LRT/Bus Transfers @ 6	
Operations HQs	Outlying Stations	

Based on "As Built" data and Regional Transit (RT) ride checks.

Because the project budget was limited, designers were "specifically cautioned to avoid costly features that may be construed as 'gold plating'" (2). This term was never specifically defined, but was understood to mean that project design should follow the then-recent model of the San Diego Trolley.

USING AVAILABLE RIGHTS-OF-WAY

Sacramento was blessed with existing ROWs that were available, in reasonable locations for a functional LRT system, and could mesh with and enhance the existing transit network. The key possibilities were identified in 1975 by the citizens' group that first advocated LRT, and were confirmed after 8 years of planning:

- Northeast: land for proposed I-80 bypass freeway (4.5 mi),
- East: underused railroad branch line (7.8 mi),
- South: abandoned railroad branch line (7.1 mi).

The northeast and east ROWs form the basis of the new RT Metro system. The south ROW has been purchased and preserved for a future extension.

Each of these ROWs ends short of downtown Sacramento. Therefore, LRT reaches the CBD via a variety of private ROWs and city street alignments: reserved medians, curb lanes, transit/pedestrian malls, and mixed traffic lanes.

Underused or abandoned railroads connected to the inner ends of major ROW opportunities. In the northeast, Sacramento Northern's abandoned interurban branch line paralleled Arden Way. In the east, a Union Pacific (UP) (former Western Pacific) branch extended west from the Southern Pacific at 19th and R streets. Both were incorporated into the LRT alignment.

City streets were used for downtown access, forming the route between the former Sacramento Northern branch at Arden/Del Paso and the former UP branch at 12th between Q and R streets. From Arden/Del Paso, RT Metro trains run in mixed traffic on Del Paso Boulevard (0.5 mi), then in an exclusive curb lane along CA-160 and North 12th Street to G. Double track begins between G and H, with the exclusive curb lane used by outbound (northbound) trains, and a track in mixed traffic provided for inbound trains. The K Street pedestrian mall between 12th and Seventh in Sacramento's retail district was converted to a double-track LRT/pedestrian mall; and a new mall was created serving the state office buildings on O Street from Seventh to 12th.

K and O are connected by tracks in curb lanes with trains running in the same direction as traffic: south on Seventh and north on Eighth. LRT planning anticipated that these lanes would be reserved for LRT (*3*, p. 2-27); however, they have been installed without curbs and are operating as mixed traffic lanes, apparently without serious impact on LRT service. From O Street to the UP ROW, trains run on center-of-street tracks in traffic on 12th for 2.5 blocks.

As pieced together (Table 2), the available ROWs form a continuous line that includes all three LRT alignment classifications: exclusive, semiexclusive, and mixed traffic. Because suitable surface alignments were located, subways were avoided. This was essential, because subsurface construction was beyond the reach of the project budget.

TABLE 2 RT METRO ROW SEGMENTS

Segment	Description	Km(Mi)
I-80 Median	Constructed but never used portion of I-80 Bypass in wide I-80 median	2.7 (1.7)
I-80 Bypass	Cleared R/W for unbuilt freeway	4.6 (2.8)
Evergreen Connector	Private land, purchased for LRT	0.5 (0.3)
Arden Way	Ex-Sac. No. interurban R/W	1.0 (0.6)
Del Paso Blvd. (a)	Center of street, LRT in mixed traffic	1.0 (0.6)
Route 160	Reserved curb lane w/Jersey barrier	1.3 (0.8)
North 12th	Reserved curb lane (b)	2.2 (1.4)
K Street	Transit/Pedestrian Mall-5 blocks	0.6 (0.4)
7th/8th Streets (a)	One mixed traffic curb lane in each of two streets (c)	0.6 (0.4)
O Street	Transit/Pedestrian Mall-5 blocks	0.6 (0.4)
12th Street (a)	Center of street, LRT in mixed traffic	0.3 (0.2)
Whitney Ave.	Ex-WPRR R/W (adjacent to alley)	0.7 (0.5)
Bee Bridge	New aerial structure	0.6 (0.4)
SPRR-R Street (a)	Center of street, LRT in mixed traffic (c)	1.0 (0.6)
SPRR R/W	Exclusive LRT occupancy of RR R/W	3.8 (2.3)
SPRR R/W	LRT & SPRR share R/W but use separate tracks	7.9 (4.9)
	Total System	29.4 (18.3)

(a) Mixed traffic segments: 2.9 km(1.8 mi), 10% of total line.
(b) From G to K Street, LRT is double tracked, with the southbound track in mixed traffic. Northbound curb lane track reserved for LRT.
(c) Planning anticipated reserved LRT lanes; city traffic and RT implemented as mixed traffic.

INVESTMENT IN FACILITIES

A major focus of planning and preliminary design was development of limited scope, low-cost facilities to provide a no-frills system (again, following the example of San Diego) that would be buildable and operable within the limits of funds then anticipated.

The Sacramento project emphasizes reuse of existing structures but includes six new bridges. These are the major structures on the line:

Structure	*Status*
I-80 Median (3 overheads)	Existing
Grand Avenue Bridge	Existing
Arcade Creek Bridge	New
Marconi, El Camino, Arden (3 overheads)	New
North Sacramento Undercrossing (CA-160)	Existing
North Sacramento Viaduct and American River Bridge	Existing
12th Street Undercrossing (Southern Pacific)	Existing
Union Pacific Overcrossing	New
Business 80 (2 overheads)	Existing
Brighton Overcrossing (Southern Pacific)	New
Route 50 Overhead at Folsom & La Riviera	Existing

The use of single track on certain structures, necessary for political or economic reasons, causes numerous operating constraints, because cars obviously cannot be allowed to meet in single-track territory.

The segment including the American River crossing follows CA-160, a six-lane highway. Outbound lanes are on a newer three-lane bridge. The three inbound lanes use the older, original four-lane structures, with LRT in the extra lane. For traffic engineering reasons, it was necessary to limit LRT to one track, separated from traffic by a concrete New Jersey barrier.

Similarly, only one track was placed through the 12th Street undercrossing and along adjacent sections of North 12th Street because of city traffic officials' concerns about LRT intrusions on vehicular traffic using this main arterial street.

Both the Union Pacific and Brighton overcrossings were built with just one track, to conserve funds.

Operations and Maintenance Facility

The operations and maintenance facility includes the light rail vehicle (LRV) storage yard and a shop building containing LRV maintenance facilities; way maintenance component work areas for track, power, signal, and fare collection equipment; parts stores; and RT Metro facilities (administrative offices, Metro Control, and operators' lockers and day room). The site in the abandoned freeway ROW was ideally shaped (+350 ft wide and as long as was needed) and located (between a Southern Pacific main line and an industrial park).

The LRV storage yard was laid out for the initial 26-car fleet. Space for additional tracks was left to accommodate fleet growth up to 50 cars. Tracks were built double-ended to provide operating flexibility.

The shop building is typical of current design: tracks long enough for two cars, and access from both ends so cars in the shop are not trapped. A turning loop was built into the shop access trackage at the end of the shop opposite from the storage yard. There are three tracks, giving a total capacity of six cars in the main bay. The design includes a future fourth track to provide a heavy body repair position and a paint booth.

During design, staff wrestled with the problem of matching perceived needs with available budget. Several suggestions were made to reduce costs, among them replacing the shop access loop track with a simple track fan, making the yard stub-ended to eliminate some special trackwork, reducing the number of way maintenance component work areas, and using a steel building instead of concrete. None of these options was adopted. However, the body repair and paint booth bay was not considered essential for system start-up, and was dropped from the initial project when bids came in high. Capital funding now is being sought to add this feature in the near future.

Maintenance and supervisory equipment consists of shop machinery, small tools, and vehicles. Major pieces of shop machinery include an LRV exterior washer and a milling machine-type wheel truing machine. Support vehicles are discussed in a separate section below.

Passenger Stations and Pedestrian Malls

Passenger stations and downtown pedestrian malls were designed to fulfill community desires for pleasing aesthetics. As compared with a minimal "bare bones" approach (e.g., using off-the-shelf bus shelters at stations), some design elaboration occurred with regard to platforms, sidewalks, shelters, and parking lots. Many more parking spaces were designed and built than the demand estimate indicated were needed for initial operation.

Platform and Shelter Designs

Platforms are constructed to accommodate four-car trains and are built to a uniform width (10 ft) and surface quality for their entire length, about 350 ft. Since trains are only one or two cars long at most times, some savings could have been realized without seriously impairing aesthetics by building full-width concrete platforms for two car lengths, but narrower (6 ft) black-top platforms for the areas used by third and fourth cars operating only in weekday peak periods. This would have saved about 5,700 ft^2 of paving per station.

As has been the case for most new-start LRT systems, the Sacramento project is graced with unique, architect-designed shelters. Some savings were made by not building shelters at locations where waiting passengers were expected to be few in number, e.g., certain outbound suburban platforms. Further savings could have been achieved by installing off-the-shelf manufactured transit shelters. This was unacceptable to project architects and public officials who made up the policy board. Even in Sacramento, there were limits on how far the "no-frills" approach could be pushed.

Parking Lot Design and Sizing

Parking lot design began by determining the maximum number of spaces that could be constructed at each site. This totaled approximately 5,000 spaces (*3*, p. 2-32). Unfortunately, designers were reluctant to reduce the lot sizes after the demand forecasts indicated a need for about 2,800 spaces systemwide (*3*, p. 2-33). The number of spaces built eventually was cut back to 4,056; but designs for such items as drainage were based on building whole lots at once instead of modularly, so savings have been minimal.

Actual usage in late January 1988 was running about 1,600 parked automobiles per day, leaving the project vulnerable to criticism of public funds "wasted" on unneeded parking. It would have been far better to preserve parking lot ROW, and build spaces at, or even a bit under, the demand estimate, then let the market (i.e., actual usage) dictate where future expansion should occur.

Transit/Pedestrian Mall Designs

PE budgeting provided only for modest improvements on K Street and tracks embedded in blacktop on O Street. More elaborate mall designs were developed for both streets, however, in the hope that city and state funding might become available. Since 1984, such funds have been secured; and the more aesthetic designs have been put in place. Even so, the designs are economical compared with malls in other cities.

K Street is 80 ft wide from building to building. Basement vaults extend from the buildings under the sidewalks. LRT construction avoided the vaults by incorporating the existing 14-ft exposed aggregate concrete sidewalks into the new mall design, thus limiting construction to the 52-ft cartway. This accommodates two LRT tracks, one on each side of the street centerline, and an 11-ft strip on either side used for LRT platforms, plantings, and pedestrian amenities (benches, trash receptacles, public telephones, etc.).

On O Street, two blocks have been turned over to exclusive LRT/pedestrian use. The remaining three blocks also provide a one-way travel lane and a pull-out lane for vehicular access to automobile passenger drop-off zones, building delivery entries, and parking facilities. The architectural elements (pavers, poles, benches, etc.) are the same as on K Street.

OFF-THE-SHELF EQUIPMENT

Wherever possible, proven designs were specified in procurement documents for LRVs, track materials, traction power equipment, signals, radios, fare vending machines, and maintenance equipment. This was necessary to meet the modest project budget, as well as to ensure high reliability and minimal phase-in and retrofit problems for RT, Sacramento's new-to-LRT system operator.

Light Rail Vehicles

Within the limitations of federal procurement regulations, Sacramento emphasized its desire to buy proven equipment. The rationale was that as a new-start project buying a small 26-LRV fleet, RT Metro would need every car (other than normal maintenance spares) available from Day 1. If LRT was to prove itself in this setting, there would be no room for a time-consuming program to debug and retrofit a new, unique-design car.

The LRVs purchased are yet another mutation of the Siemens-Duewag U2 car. As compared to modifications in the original Frankfurt design made successively for Edmonton, Calgary, and San Diego, the Sacramento version includes some relatively major changes, enough that the car is designated "U2-A" (advanced).

Changes include air conditioning (two roof-mounted units per LRV), a car body structure strengthened to support the air conditioning units, welded steel construction replacing the fiberglass end moldings, all steps built into the car body (as opposed to a retractable bottom step), and a modulating seven-step friction brake actuator replacing the former "on/off" arrangement.

Access for riders unable to use stairs is provided by placing fixed ramps and short car floor-level platforms at each station where the front door of the first car in each train stops. Trap doors, hinged and raised out of the way to allow steps to be used when doors are in trailing positions, are lowered to cover the front door step wells on both sides of the LRV in the lead position, thus providing a safe, flat space where wheelchairs can maneuver. Small, lever-controlled gangplanks are used to close the gap between the LRV and the platform. The matter of access is one area where an off-the-shelf solution was not available. Sacramento's response was to develop a simple system that avoids electrical, hydraulic, and mechanical gadgetry. It works.

The cars are "medium performance" LRVs, with maximum service speed of 80 km/h (50 mph) and initial acceleration of 1.1 m/s^2 (2.5 mi/h/s). Teething problems were relatively minor, and the cars have been performing reliably.

Lengthy negotiations were required to resolve issues related to federal "Buy American" regulations, to the point that despite delays on other contracts, the LRVs became the critical path for opening the Folsom portion of the system.

Track Materials

Standard North American track materials and construction methods were used to promote interest in bidding among domestic suppliers and to ensure that the track structure would be familiar to its maintainers, who were likely to have a U.S. railroad background.

Subgrade and ballast materials, depth, and cross-section are typical of North American practice, modified for local conditions and LRT loadings. American Railway Engineering Association (AREA) 115-lb/yd rail was specified, based on structural and electrical adequacy and availability. Rails were field-welded. Because wood ties were purchased when the lumber industry was depressed, concrete could not compete on price. Except for direct fixation on a few structures, track fasteners are standard cut spikes and tie plates, the latter purchased secondhand for economy.

Special trackwork also is to standard AREA designs. It was planned initially to limit frog angles to two, a small angle for yard and low-speed street trackage and a larger angle for use on private ROW. Also contemplated was location of double-to-single track transitions at stations, where slow-moving trains would require nothing bigger than a No. 10 turnout whose points could be spring-operated to avoid the capital and maintenance costs of a switch machine. Because fitting the track in the available ROW proved difficult in several instances, these goals were not achieved throughout the system, and turnout sizes range from No. 6 to No. 20.

Traction Electrification

The traction electrification system consists of three basic elements: substations converting high-voltage AC to traction-voltage dc current, a positive circuit (the overhead distribution system), and a negative return circuit (the tracks).

Electrical substations supplied by Controlled Power Corporation are rated at 1,000 kW and are virtually identical to units used in San Diego. These off-the-shelf units are factory-manufactured in halves and assembled on site, where they are mounted on poured slabs and ground mats custom-designed to local soil conditions.

Fittings for the catenary and direct suspension trolley-wire overhead systems are off-the-shelf designs from Ohio Brass, assembled to fit the requirements of the Sacramento alignment.

Signals

Two types of signaling are used. High-speed [57 to 80 km/h (36 to 50 mph)] sections of the line have railroad-type automatic block signals (ABS) using vital relays. In low-speed areas [56 km/h (35 mph) or less], trains are operated "on sight"; train operators obey street traffic signals at intersections; and nonvital block occupancy indicators (BOI) control access to single-track sections.

Two single-track sections of the Northeast line include both high- and low-speed segments. Unfortunately, system designers used both ABS and BOI in each segment, strictly following the design criteria. Now train operators face indicators for both types of signals at these block entry points. It would have been less confusing to use just one type of signaling—ABS—throughout such track sections.

Grade crossings on private ROW and along R Street from 23rd Street east are protected by railroad-type flashers and gates. Where LRT is in street ROW, intersection traffic lights include special indications for LRT movement, in most cases giving priority to LRT.

Two-Way Radio System and Train Control

A dispatcher at Metro Control (located at the maintenance facility) directs normal and abnormal train operations and coordinates maintenance crew occupancy of the ROW. Two-way radios in each LRV and support vehicle are the principal means of communication. The system operates as an expansion of RT's bus radio network, with one separate channel provided for LRT operations, maintenance, and security. A magnetized track schematic is provided at Metro Control but is used normally only during serious service disruptions; with just eight trains operating at one time, there is no need for a mimic board.

Ticket Vending Equipment

Self-service proof-of-payment (POP) fare collection is used on RT Metro to enable one-person operation of multicar trains, which was absolutely essential to the project's economic justification. Sacramento's approach follows what has become typical North American practice: ticket vendor/validators and changemakers on station platforms, no fare collection equipment on trains, "free" station platforms, "paid" train areas, and roving inspectors on trains to enforce the system. Fare evasion penalties, written into the criminal (not civil) code, range from $35 to $250.

POP works well. RT employs six inspectors to achieve an inspection rate of 25 percent. Fare evasion is low, according to SRTD officials, in the range of 1.5 percent, and consistent with the experience of other North American cities that have introduced POP.

Sacramento opted for vendor/validators and separate dollar bill changers to simplify the machinery. The Swiss supplier, Xamax, subcontracted with a U.S. firm for the bill changers to meet UMTA "Buy American" requirements. RT would like to have more than the single vendor/validator typically supplied at each station. A minimum of two vendor/validators per station would have been desirable had the project budget not been so tight.

Maintenance and Supervisory Equipment (Vehicles)

LRT operations and maintenance are supported by a service fleet of 11 automobiles and trucks. These range from sedans used by management and road supervisors, through pick-ups and vans for wayside cleaners and maintainers, to specialized trucks and other equipment, some with "hy-rail" road-rail capability. The more specialized vehicles are as follows:

- One Unimog (LRV mover, also carries rerailing equipment),
- One utility body line truck with lift (overhead maintenance), and
- Two electric utility carts (LRV cleaners).

Several of the sedans and pick-ups were purchased early in the project for use by construction management staff, then turned over to LRT operations. This saved the expense of renting vehicles for construction managers.

EFFICIENT OPERATING PLAN

The key to LRT capital and operating cost efficiency was found in the patronage forecast. Demand estimates indicated that peak passenger flows could be accommodated by lengthening one- or two-car off-peak trains to rush hour consists of up to four cars. Thus, peak operations continue at 15-min base service headways. As a result, only 40 percent of the Sacramento system has double track, and extra train operators are not required solely for peak traffic.

Peak hour, peak direction volumes at the peak load points were forecast to be about 1,600 on the Northeast branch and 800 on the East branch (*3*, p. 2-33). Based on loads of 144 (64 seats plus 80 standees) per 80-ft LRV and 15-min headways (four trains/hr), three-car peak direction trains would suffice on the Northeast line; and the peak hour policy consist of two-car trains would be more than adequate in the peak direction on the East line and in the off-peak direction on both branches.

With eight trains required to meet the round trip operating cycle time of 120 min, there would be a peak requirement of (4 trains × 3 cars) + (4 trains × 2 cars) = 20 cars in use, leaving a shop and spares margin of 6 cars (30 percent), which is more than adequate. To equalize peak hour loadings at about 100 to 110 per LRV on both branches, preliminary engineering assumed that a fourth car would be run on up to three of the four Northeast trains. This would require up to 23 cars, leaving as few as three spares, or 13 percent. Because "proven" cars were to be acquired, it was thought that this would be adequate, even though it was on the tight side of current rail transit practice.

Adequacy of 26-LRV Fleet

In actuality, RT feels pressed for equipment. Peak hour loadings are running as high as 120 standees per train (40 per LRV on a three-car train). Although this is less than the forecast, local bus riders have been used to sitting, so there are complaints about having to stand on the trains. In addition, Sacramento commuters are still learning how to adjust their commuting times to less crowded trains, and RT has not spread feeder buses among trains sufficiently.

Further, the split of demand between the two branches is almost even (51 percent Northeast, 49 percent East), whereas the Final Environmental Impact Statement (FEIS) forecast was heavily skewed (64 percent Northeast, 36 percent East). As a result, RT is running a.m. peak service as follows as of January 1988: (1 train × 4 cars) + (5 trains × 3 cars) + (2 trains × 2 cars) = 23 cars of 25 currently available (1 car undergoing wreck repairs). Having only two spares (9 percent) is really tight. Even with the wrecked car repaired, three spares (13 percent) is well under the 20 percent ratio more typical of rail transit.

It seems inevitable that system builders will continue to be frugal—even stingy—when buying initial fleets, effectively placing the requirement on their operating successors to be very sharp. But with every car such a big-ticket item, there is little option to do otherwise.

Adequacy of Single Track

A mostly (60 percent) single-track main line with six double-track segments was adopted based on PE train performance simulations and negotiations with city traffic authorities. Project staff at the time recognized that "tight" meet situations with some potential for delays existed at two double-to-single track transitions: 12th and G in downtown Sacramento and Arden/Del Paso in North Sacramento. LRT operating reliability would have been better had double track been extended north on 12th Street at least four more blocks to C Street, and around the corner from Del Paso Boulevard through the Arden/Del Paso station. Traffic engineers' concerns about arterial street operations scuttled both of these extra lengths of double track. The LRT operating plan had slack time added at these locations to compensate for the lack of a second main track.

As construction progressed, RT reconsideration of the LRT operating plan raised fears that 15-min headways might not be achievable, and that a 20-min interval service might be necessary until more double track could be installed. These fears proved to be overstated; and RT is operating 15-min LRT service, albeit with minor delays (typically 1 to 2 min, but occasionally up to 4 min) at the two points noted above.

When delays occur, recovery is more difficult than on a double-tracked line. A benefit of single track, however, is that it enforces the timetable. Trains simply cannot run ahead of schedule.

Single track limits the system to minimum headways of 15 min. This is adequate for initial demand, but restrains feasible expansion of peak capacity to four 4-car trains/hr. At 144 passengers per LRV, this is a total of 2,300 riders, the equivalent of over 30 similarly loaded buses (at 70 passengers per bus) or nearly 2,000 automobiles (at 1.2 persons per automobile)—well over a lane of freeway traffic.

Given Sacramento's limited funds, the choices were no system, a weak double-track system in the Northeast only, or a single-track system in two corridors. Sacramento selected the last, matching the investment to short-term peak demand to get as much system as possible for the money available.

Few single-track sections will have to be permanent. Only the American River crossing and the Arden/Del Paso intersection were not designed for future double-tracking. If the remainder of the system eventually is doubled, these segments will limit minimum headways to 5 to 7.5 min, twice or three times the existing service, and as much capacity as is ever likely to be needed.

PROJECT COSTS: ESTIMATED AND ACTUAL

As noted earlier, a major focus during PE was fitting the project scope to the available funds. Unfortunately, this goal was not achieved. When finally completed, the project capital investment exceeded the PE estimate by 34 percent, as shown in Table 3.

Except for the LRV procurement, which benefited from sharp car builder competition and a favorable exchange rate, increases were experienced in every major cost category. Fully 86 percent of the extra costs ($38.74 million of $44.97 million) were in two areas: ROW construction and management and engineering.

In the systems area, the procurement and furnish/install contract bids came in at or below budget. Increases were due to (1) significantly underestimating the traction power system installation cost ($3.96 million versus $840,000) and (2) supplemental contracts added late in the project to purchase additional signal equipment ($1.62 million), ticket vendors ($260,000), and copper wire ($40,000).

PE-level ROW construction estimates were tight and excluded items not directly part of the LRT system, but that were added later at the behest of agency staffs and citizen groups as the project progressed through final design, e.g., street repavings around suburban stations, reconstruction of a sewer under Seventh Street that project senior staff expected designers to avoid, K and O Street mall amenity improvements, etc. Regarding the improvements to mall aesthetics, it should be noted that some of these extra costs were covered by additional funds provided by the agencies benefiting: the local redevelopment agency (K Street) and the State of California (O Street).

Similarly, the stations budget had elements added during final design to satisfy various agencies and community groups. About 5 percent of the difference is the added-on art program (including art works and artistic tree grates). Parking lot design issues discussed above also increased station costs.

Like the stations, the shop suffered from architect's hubris. Designers were instructed to develop a modular facility to or from which functional areas could be added or deleted consistent with system maintenance needs and the budget. This was done to some extent; but when it came time to "value engineer" the building to the available budget, design staff resisted. The only substantive cut made was deferral of the fourth track (body repair spot and paint booth). Fortunately, procurements of shop equipment and maintenance vehicles came in below estimates to partially offset the building overrun.

In the ROW acquisition category, PE estimates tended to be less than the ultimate purchase prices. In addition, several more small parcels not

TABLE 3 INITIAL ESTIMATED AND ACTUAL SYSTEM COSTS

Cost Category	PE Estimate ($ mil)	As Built ($ mil)	Difference ($ mil)	% Diff
Light Rail Vehicles (26)	26.37	24.57	- 1.80	-7%
Power, Signals, Communication, Fare Collection	17.19	21.32	+ 4.13	+24%
Subtotal - Systems	43.56	45.89	+ 2.33	+5%
R/W Construction	34.42	54.15	+19.73	+57%
Stations and Parking	10.70	17.65	+ 6.95	+65%
Maintenance Facility & Equip	4.79	5.36	+ 0.57	+12%
Subtotal - Facilities	49.91	77.16	27.25	+55%
Right-of-Way Acquisition	12.36	16.92	+ 4.56	+37%
Management & Engineering	14.95	33.96	+19.01	+127%
Contingencies & Financing	10.25	2.07	- 8.18	-80%
Subtotal - Other Costs	37.56	52.95	+15.39	+41%
Total Project	131.03	176.00	+44.97	+34%

Sources:

PE Estimate: _______. Project Report. Sacramento Transit Development Agency, 1983, Table 3.

As Built: _______. Light Rail Monthly Progress Report. Sacramento Regional Transit District, November 1987, p. 12.

identified during PE were purchased at locations such as substation sites and sharp corners downtown (notably at 12th and the UP ROW).

Almost as large as the increase in ROW construction was the growth of management and engineering expenses. The primary cause appears to have been lengthening of the project schedule. Based on the timing of the physically similar LRT project in San Diego, Sacramento expected to open its system in late 1985 but experienced a delay of 15 months for the Northeast Line and 21 months for the Folsom Line. Major reasons for this included (1) an 11-month design concept resolution phase added to answer UMTA questions about patronage, costs, and traffic impacts in more detail than provided in the alternatives analysis; (2) the Sacramento Transit Development Agency (STDA) board's allowance of a bid protest that led to a second round of technical proposals and bids for the LRV procurement; (3) designer delays in completing civil plans, specifications, and estimates for construction packages; (4) negotiations between UMTA and the car builder (with RT in the middle) to settle disagreements over "Buy American" compliance; and (5) slower than forecast availability of Interstate transfer funds. Numerous other incidents had minor impacts that were mostly masked by the overriding concern with the timing of car deliveries due to the "Buy American" issue (*4*).

In trying to emulate San Diego's fast-tracked pace, Sacramento did not build into its schedule the time allowances required to appropriate and draw down federal funds, to confirm compliance with federal planning requirements and procurement regulations, or to accommodate the design of civil elements by a public agency with very limited prior LRT engineering experience. The failure of the political leadership drafting the original joint powers agreement to provide a strong local staff structure exacerbated the problem by severely limiting the STDA executive director's authority to run the project.

CONCLUDING REMARKS

Like any project, the Sacramento LRT system represents a mix of opportunities grasped and problems overcome with varying degrees of success.

Most notably, the LRT's construction was a victory for local citizen advocates determined to change the course of transportation system development in their community. Further, Sacramento achieved the lowest initial cost per mile of line of any federally funded rail system, yet has built a project adequate for present needs and capable of incremental expansion as demand requires and funds allow. Finding the funds for expansion, however, will be difficult under present federal, state, and local conditions.

It will be interesting to watch how local public agencies and developers react to the system—whether they take advantage of it or ignore it. On the positive side, for example, the California Franchise Tax Board (over 3,500 employees at a new location chosen because it is adjacent to the Butterfield Way transit center) encourages staff to commute by LRT or bus, and requires them to use LRT for business trips during the day to and from the State Capitol and other downtown destinations.

On the negative side, RT continues to limp along with a woefully tight operating budget: \$36.9 million in fiscal 1987–1988 for a service area of 929,000, compared with \$80.7 million for 1.1 million people in Portland, Oregon, another new LRT city. Sacramento's transit expenditures of \$39.72 per capita were little more than half Portland's rate of \$73.36. LRT is helping. Thanks to RT Metro's high ratio of passengers to operators, it is already RT's most productive service: 117 LRT rides per service hour compared with 60 for the best bus route and 27 for the overall bus system as of April 1988, according to SRTD. Further, the simple LRT hardware selected should help keep maintenance costs in check.

It can only be hoped that as Sacramento grows—and it is growing, rapidly—the electorate will see fit to provide the source of local operating and capital funds that RT desperately needs.

This background must be considered when evaluating the development of LRT and its initial performance in Sacramento.

Single Track—An Appropriate Solution

The system works as built, with 40 percent of the line double-tracked. Thanks to the diligence of the operating staff, 15-min headway service is being maintained reliably. It has developed that had some short additional lengths of double track on 12th Street and at Arden/Del Paso been built as noted above, a virtually trouble-free system could be running in Sacramento today. Instead, RT must wait to add these additional short lengths of second track until some future time when traffic authorities will agree and funding becomes available.

Sacramento's experience should encourage others to consider single-track operation where relatively long LRT headways will suffice to accommodate initial forecast demand, and where cost savings will help build political support to move ahead. However, adequate lengths of double track must be provided at all locations indicated by the system operating plan, and this must not be an area of compromise. As has been done in Sacramento, single-track section designs should enable eventual addition of the second track.

Ridership: Forecast and Actual

The FEIS was published in 1983, and included forecasts of demand made with the Urban Transportation Planning System (UTPS) battery of models, validated for metropolitan Sacramento. Initial LRT ridership was forecast at 20,500 per weekday. Actual patronage as of April 1988 is averaging 13,200, well below the FEIS estimate. Nonetheless, RT Metro carried 24 percent of all RT boardings on only 7 percent of the service hours.

Table 4, which makes several comparisons of the FEIS forecast versus actual ridership as of April 1988, may be summarized as follows (figures in Actual column obtained from SRTD, January 13 and April 29, 1988):

- Total weekday LRT boardings: actual is 64 percent of forecast, but
- Total RT system use is only 73 percent of forecast.

TABLE 4 FORECAST AND ACTUAL RT METRO RIDERSHIP

Item	FEIS	Actual	% FEIS
Total Weekday RT Unlinked Boardings (Bus & LRT)(a)	76,400	55,700	73%
Total Weekday LRT (Two-Way):			
Northeast	13,200	6,700	51%
Folsom	7,300	6,500	89
Total Weekday	20,500	13,200	64
% Northeast/Folsom	64/36	51/49	
Peak Hour/Direction (PHPD):			
Northeast	1,715	1,220	71%
Folsom	1,140	1,040	91
Combined	2,855	2,260	79
PHPD as % of Weekday:			
Northeast	13%	18%	
Folsom	16%	16%	
Both Lines	14%	17%	

(a) Forecast: FEIS, Ex. 2-20 fol p. 2-29, and p. 2-32.

The shortfall results from several differences between model input assumptions and present real-world conditions:

- Shorter hours of LRT operation due to RT budget constraints;
- Less feeder bus service, 29 percent fewer routes feeding the Northeast LRT, and 14 percent fewer feeding Folsom trains (*3, 5*), due to RT budget constraints;
- Cheaper downtown parking due to apparent city reluctance to raise rates as rapidly as anticipated and state construction of more new downtown parking spaces even as LRT was under construction; and
- Lower gasoline prices due to international market factors.

The split between lines is close to even (Northeast—51 percent:Folsom—49 percent), compared with the demand model's projection (64 percent:36 percent). On an all-day basis, Folsom line use is much closer to forecast (89 percent) than with the Northeast (51 percent). Finally, actual ridership to date is more skewed toward the peak hour and direction (18 percent) compared to the projection (13 percent).

LRT ridership seems likely to remain below FEIS estimates until local officials address the issues of improving LRT and feeder bus service and adjusting downtown parking rates and availability. Sacramento is one of the fastest growing areas in the United States, and no more freeways or other major road improvements to downtown are planned. LRT patronage may be expected to grow as ever-increasing traffic congestion on the area's existing freeways and streets makes LRT more and more attractive.

Summary: Sacramento Demonstrates LRT's Flexibility

Sacramento built for the future by taking advantage of one-time opportunities available in the early 1980s:

- Deletion of an unwanted freeway to create an Interstate transfer funding entitlement,
- State and local administrations sufficiently interested in rail transit to provide matching funds, and
- A variety of existing ROWs and structures that LRT could use, not all of which would have remained available had construction been delayed.

These opportunities, coupled with design criteria stressing proven technology, allowed Sacramento to build a system that works, at a price the community was willing to pay. On balance, Sacramento is pleased with the system. In fact, studies of extensions to the initial lines and new lines in other corridors were begun even before the first trains started running.

The principal lesson from the Sacramento system and other similar projects is that rail transit need not be limited only to the largest U.S. metropolitan areas. By using modern, yet technically simple and proven LRT, and by avoiding gold-plating, systems can be built to serve the arterial express routes in medium-to-large cities where the capacity of full rapid transit is not needed, but where LRT investment and operating costs will be affordable, and where LRT will increase transit productivity.

Short of massive, long-term oil shortages, North America's reluctance to fund opulent rapid transit systems is likely to continue. Only the largest metropolitan areas have any hope of finding the capital for these massive projects costing \$30 million to \$60 million/km (\$50 million to \$100 million/mi) or more. Local leaders seeking the benefits of guideway transit will best serve their constituents by emulating the practical and affordable solutions embodied in the new surface LRT systems in Calgary, Portland, San Diego, and, now, Sacramento.

ACKNOWLEDGMENT

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C. Beach and T. Matoff provided additional insights into LRT operations and the beneficial effects of prestart-up peer reviews.

While acknowledging this substantial assistance, the author retains responsibility for accuracy of the background data and analyses. The opinions contained herein are solely the author's, and do not necessarily reflect the sentiments of any other organization or individual.

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Design of Light Rail Transit Overhead Contact Systems at Complex Intersections

WILLARD D. WEISS AND JEAN-LUC DUPONT

Light rail transit (LRT) intersections and turning movements in downtown areas present some unique and complex problems in overhead contact system (OCS) design. However, OCS design procedures and principles can be applied at such locations to provide both economic construction and trouble-free vehicle operation. SPIDER has been developed as a software tool to facilitate OCS design at complex intersections. The program is interactive and permits efficient and accurate design of complicated overhead guying networks. It performs the following analyses: layout of overhead hardware, calculation of tensions in guying network, optimization of trolley wire profile, and determination of resultant pole loadings. Through the interactive process, the program allows the designer to optimize the overhead contact wire profile by adjusting guy wire tensions and attachment heights. Plan drawings can then be generated at any scale and transferred to a computer-assisted drafting (CAD) system for plotting final construction drawings. The SPIDER program, with its CAD interface, has been used extensively for OCS design on LRT projects including the Sacramento, Guadalupe, and Long Beach-Los Angeles LRTs, the Lowell Historic Trolley, and on several electric trolley coach projects in San Francisco and Seattle. The program has demonstrated economies in both the design and construction processes.

Morrison-Knudsen Engineers, Inc., 180 Howard Street, San Francisco, Calif. 94105.

ONE OF THE WELL-KNOWN advantages of light rail transit (LRT) is its ability to run on surface streets in downtown areas. Use of the street alignment, however, frequently necessitates sharp turns in the LRT tracks at existing intersections. For the overhead contact system (OCS) designer, these intersections can present some of the most challenging problems in the system. Because the complex wiring arrangements at intersections are more difficult to design for satisfactory current collection than on ordinary tangent trackage, and because construction costs are disproportionately higher, it is important that proven design principles and efficient analytical tools be applied.

Anyone who has attempted to develop an OCS guying network manually for even a simple LRT intersection will appreciate the complexities involved and will recognize the value of a computerized process for accomplishing this task in a practical and economic manner. Such a process can result in technical solutions that are not only safer and more reliable, but also more economical from the standpoint of both design and construction costs.

DESIGN APPROACH, PROCEDURES, AND PRINCIPLES

The primary concern that must be addressed by the OCS designer is that the overhead contact wire be supported in a position that will ensure smooth tracking of the vehicle pantograph under all operating conditions. Second, the arrangement of the overhead support system, besides being economic, should be as aesthetically pleasing as possible, considering the sensitivity of the typical urban environment. Finally, it is essential that the construction process be considered in design, as temporary imbalances in the guying network during construction must not overload a guy or support pole.

The design process itself is inherently complicated by several facts. The typical intersection guying network, containing both horizontal and vertical variables, presents an indeterminate loading problem. Guying tensions are often highly sensitive to small changes in network geometry. Wire tensions vary somewhat unpredictably with temperature variations. And, usually a wide variety of options exists for guying arrangements, but the most favorable may be restricted by available support pole locations.

The typical intersection OCS design starts with scale drawings of the existing intersection layout, including street widths, curb and property lines, locations of overhead and underground utilities, and other potential obstructions. Superimposed on this is the track layout, including both vertical and horizontal alignment geometry. Basic OCS criteria are then established, including contact wire size, tension, height above rail, vehicle and pantograph characteristics, electrical clearances, environmental conditions, etc.

Once the basic criteria have been established, intersection OCS design may proceed. In developing the optimum design, three objectives should be met. First, the contact wire must be supported horizontally (registered) so that it remains on the pantograph collector strip at all times; consideration should be given to factors such as pantograph width, vehicle sway, track alignment, pole deflection, wind blow-off, and temperature variation. Second, the contact wire must be supported vertically at a constant height above the track to offer a smooth profile to the pantograph. The "stiffness" of the contact wire (resistance to uplift due to pantograph pressure) along the track should also be as uniform as possible to achieve "sparkless" commutation between the pantograph and the contact wire. In addition, at turnouts any converging wire must remain sufficiently high above the horns of the pantograph to prevent hooking of the converging wire under the pantograph horn. Third, guying tensions and pole loadings should be kept to a minimum. The guying network should be kept as simple as possible, to minimize the structural support requirements and resulting costs, as well as visual obtrusion.

With these objectives in mind, the design process itself typically consists of the following steps:

1. Pole locations—Selection of locations of support poles at the sides of the streets;
2. Guying network—Development of a network of guy wires to register and support the contact wire;
3. Tension calculations—Calculation of guy wire tensions and attachment heights; and
4. Pole loadings—Calculation of loads in support poles.

Within the framework of this design process, the OCS designer should keep in mind a number of important principles to develop an overhead wiring installation that performs satisfactorily and is economical, safe, and aesthetically pleasing. Some of these principles are discussed below, along with descriptions of the individual steps involved. For further clarity, these steps are illustrated in Figures 1 through 3, using the example of a single track turning movement at a typical street intersection.

Step 1—Pole Locations

To the extent possible, the poles are located by the designer so as to best accommodate the planned guying network layout. The pole locations, however, are often restricted by the physical conditions encountered at the intersection and by architectural requirements, which are not usually under the control of the OCS designer. Restrictions that apply to pole locations at intersections are similar to those at any location in city streets: offset from pole to curb; clearance to driveways, trees, and fire hydrants; and requirements for joint-use with street lighting or traffic signal equipment.

Building eyebolts may also be available to support the OCS, but at intersections their use presents a minor drawback: their position is fixed, so once installed, there is no opportunity for vertical adjustment to improve the contact wire profile, as there is with a clamp on a pole.

The selected pole locations for the example intersection with the given track alignment are shown in Figure 1.

Step 2—Guying Network

In the next step, the designer examines the layout of the intersection and looks for direct pole-to-pole cross-spans that are as close as possible to perpendicular to the track alignment (say within ±5°). These cross-spans or "direct guys" form the starting point of the layout (see Figure 1). The designer then locates additional "semidirect" guys, which are perpendicular to the track but connected to only one pole. Next, the designer determines the position of the remaining registration points by dividing the spaces available between direct and semidirect registration points into equal segments that satisfy the maximum deviation criterion. The maximum deviation at each point is limited by the allowable radial load in the contact wire clamps used (see discussion on hardware below).

The layout of the guying network is completed with either "constant length pull-offs" or "variable length pull-offs." The constant length pull-off method uses identical steady arms at each registration point, and a "brail" wire, which parallels the contact wire throughout the curve, as shown in Figure 2. The variable length pull-offs are short cross-spans between bull rings, linked together and to the poles by a "backbone" wire (see Figure 3).

Several additional considerations must be taken into account when the guying network is laid out. Some of these are discussed below.

Hardware

Before establishing the guying network, the designer must have an understanding of the available support hardware. Overhead hardware varies from manufacturer to manufacturer; in addition, a given manufacturer may have several types of hardware available depending upon the guying concepts to be employed. Figure 4 shows several types of support and registration assemblies. These vary not only in loading capacities but also in weight and apparent "hardness," which is an important consideration in achieving good commutation of the pantograph on the contact wire.

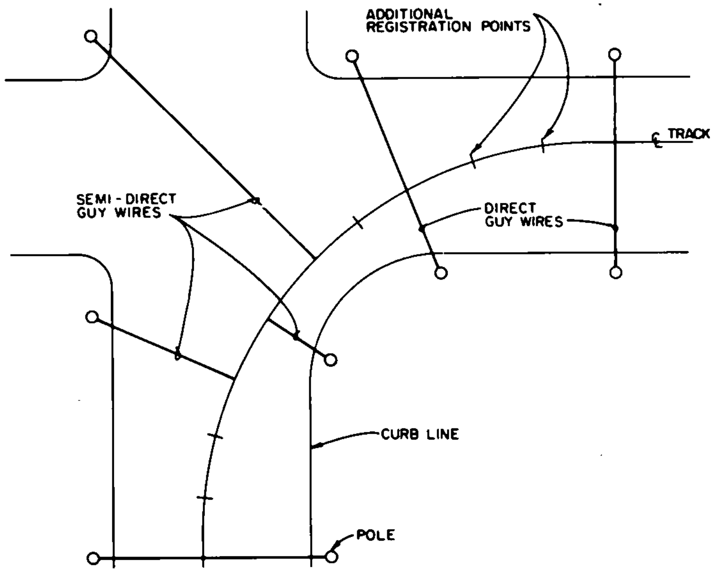

FIGURE 1 Intersection guying layout procedures, showing pole locations, direct and semidirect guy wires, and registration points.

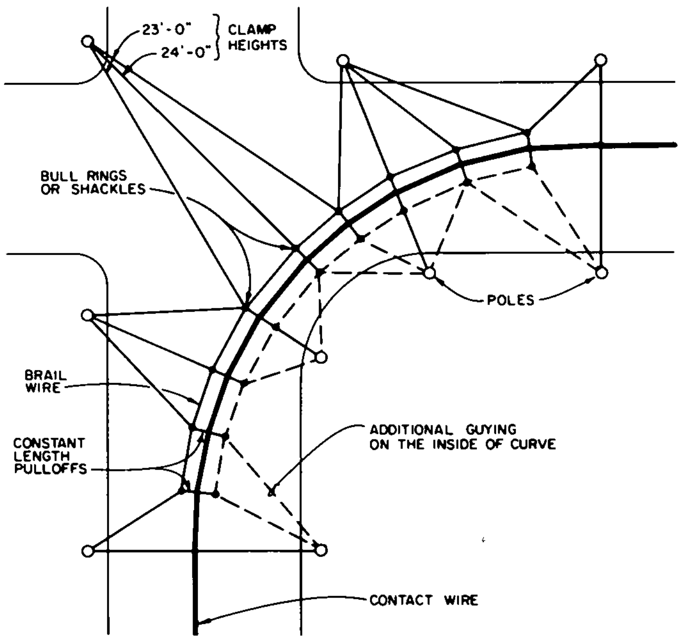

FIGURE 2 Typical guying network using constant length pull-offs.

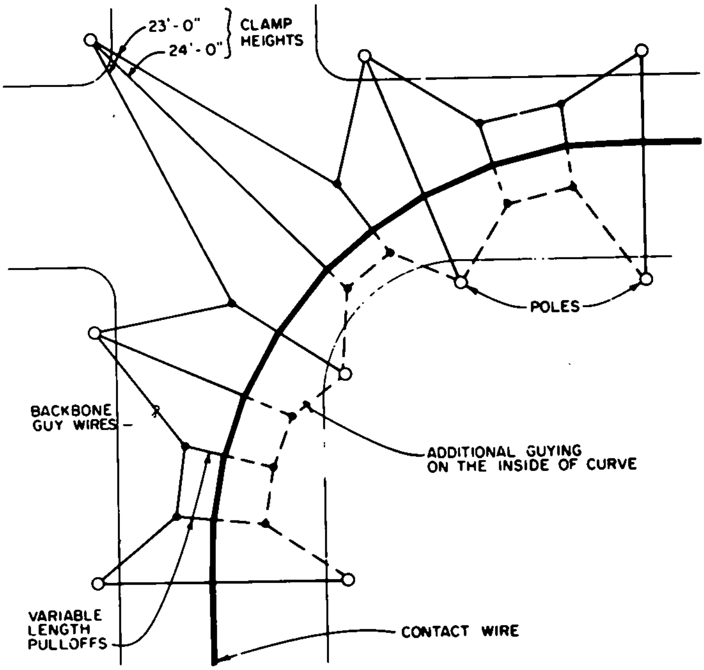

FIGURE 3 Typical guying network using variable length pull-offs.

Typically on new LRT projects, the hardware supplier is not known at the time that the design is prepared, and "generic" or "neutral" designs are required to permit competitive bidding. For extensions or rehabilitations of existing LRT systems, it may be possible to call out the hardware of the specific manufacturer that supplied the original equipment.

Generic designs may not fully utilize the capabilities of the hardware and may necessitate adjustments after the supplier is selected. For example, the designer may have assumed that the maximum allowable radial load in a pull-off is 500 lb. Thus, for a contact wire tension of 3,000 lb, 10 pull-offs would be required in a typical 90° turn. However, the actual hardware finally supplied may be able to sustain a 700-lb radial load; with such hardware, only 7 pull-offs would be needed on the 90° turn, resulting in a much simpler guying network.

This example highlights the importance of being familiar with the available hardware. Coordination between the designer and the various manufacturers before bidding is essential to ensure that the layout specified not only is feasible to all manufacturers, but also uses the available components as

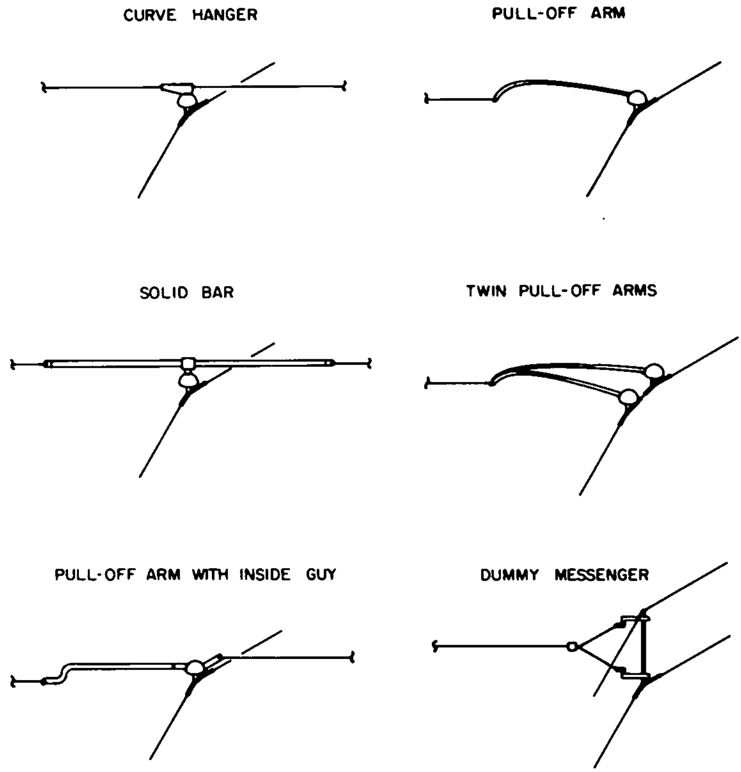

FIGURE 4 Typical contact wire support and registration hardware.

closely as possible to their rated limits. In addition, the design should be reviewed and finalized with the selected manufacturer after bidding.

Inside Guying

A second consideration concerns the proper use of inside guy wires. Using either the constant length or the variable length pull-off method, the guying network on the inside of the curve (dashed lines, Figures 2 and 3) is not needed for horizontal registration. However, inside guy wires are needed to assist in supporting the weight of the equipment. This is particularly important when more than one track is to be wired, or when additional hardware is to be supported (section insulators, contactors for traffic signal control, etc.). Furthermore, inside guy wires are needed so that most of the guying network can be installed prior to contact wire stringing.

Inside guy wires cause the inside and outside poles to pull against each other, thereby increasing pole loading; therefore the number of wires should be kept to a minimum. As a general rule, there should be at least one inside guy wire at every second or third registration point.

Reduced Contact Wire Tension

To limit the radial loads in pull-offs, it is sometimes desirable to reduce the normal contact wire tension in intersections, for example, from 2,500 lb to 1,500 lb. This permits a smaller number of pull-offs in the curve and therefore a simpler guying network and reduced pole loadings.

Tension reduction, however, should be applied selectively, for two reasons. First, the decreased tension in the contact wires makes it more difficult to develop a uniform profile, and the resulting decreased tension in outside guy wires diminishes their capability to provide vertical support to the equipment without raising the clamp heights. Second, the guys used as tension reducers themselves add to the complexity of the installation, both structurally and aesthetically, which may offset the positive effect obtained from the reduced number of pull-offs. Nevertheless, this technique can often result in an improved guying network, provided the reduction in tension is carefully selected.

Wire Crossings and Turnouts

At crossings and turnouts, the two joining contact wires should be installed so as to maintain essentially the same elevation to avoid hooking of the pantograph over the incoming wire. The wires must be held firmly in position by the guying network, despite the pantograph push-up force, which may be acting on only one of the two wires. To achieve this, a support point common to both contact wires should be located approximately 10 to 20 ft from each crossing point, the distance depending on the angle of the turnout used.

At contact wire crossings, special attention must be given to the selection of appropriate hardware. At angles below 30°, a contact wire bridge with common supports at approximately 4 ft on either side is satisfactory. For crossing angles between 30° and 90°, it is usually necessary to install supplemental parallel runners to make sure that the pantograph does not hook the crossing contact wire.

Step 3—Tension Calculations

Upon completion of the conceptual wiring layout, the designer determines the guy wire tensions. All guy wire tension calculations are performed for the conductor's reference temperature, usually 60°F. The tensions on inside guy wires are selected first; they are normally kept to a nominal value of a few hundred pounds. The tensions on the outside guy wires are then derived from the geometry of the network by summation of forces at each node point.

The attachment heights of the guy wires on the poles, or "clamp heights," are then calculated considering the vertical load-to-tension ratios and the distances to the poles. Some adjustments in previously determined tensions may be necessary at this time to stay within reasonable limits for pole attachment heights. Guy wires are grouped as much as is feasible to limit the number of pole bands.

The entire process of calculating tensions and clamp heights lends itself readily to an interactive computer process discussed in detail later.

Step 4—Pole Loadings

Resultant horizontal loads and bending moments on poles are calculated by vectorial summation of individual loads and moments. Poles can then be designed, or selected from a set of standard poles, for the resulting bending moments and deflecting loads. Pole selection must take into account not only provision of adequate bending moment capacity, but also restriction of lateral deflection to within allowable limits.

Unbalanced Pole Loading

Care must be exercised in the pole selection process for several reasons. First, in complex intersections, poles are often loaded from opposing directions and the recalculated resultant bending moment combining all guy wires can be, in some instances, less than the individual bending moments, or less than the partial geometric sum of individual bending moments. In selecting the pole size, any guy wire that "helps" the pole should be removed and the resulting bending moment calculated, to establish the potential worst-case loading condition.

Construction loads must also be considered. For example, poles at the entrance to an intersection are often selected to be temporary dead ends and may be subjected to additional loads during the construction period. One such condition occurs when prestressing is required to eliminate initial stretch and long-term creep.

Temperature Variations

As mentioned under Step 3, all guy wire tensions and attachment heights are calculated based on the "reference temperature." In an intersection wiring network, guy wire tensions and resultant pole loadings at other temperatures are very difficult to predict accurately. General purpose structural engineering computer programs, such as ANSYS or ABAQUS, have the required capability to model both cable and beam elements to simulate the overall intersection, including all wires and poles under temperature and/or ice or wind loading. However, such programs are relatively expensive to use, in terms of both labor to prepare the data and actual processing time.

An approximate approach to calculating the maximum loading on the pole is to assume that the bending moment on the pole varies in proportion to the contact wire tension. If the tension of the contact wires varies from, for example, 3,000 lb at 60°F to 4,000 lb at 25°F, the bending moment on the pole is assumed to increase by 4,000/3,000 = 1.33. For poles located on the outside of the curve, this assumption is usually conservative.

However, this approximation cannot necessarily be applied to poles on the inside of the curve. Because of the general elasticity of the guying network and of the differential stiffness between heavily loaded, strong outside poles and lightly loaded, weaker inside poles, the bending moment on the inside poles may actually be larger at high temperature (low contact wire tension) than at low temperature (high contact wire tension).

The amount by which the bending moment on the inside poles increases depends on many factors and is difficult to estimate. Calculations have shown that, in typical intersections, the maximum bending moment at high temperature can be anywhere from 1.2 to 2 times the bending moment at the reference temperature. One way to reduce the impact of the phenomenon is to increase the tension on the inside guy wires and to increase the stiffness of the inside poles. As a general rule, the strength (maximum allowable bending moment and resistance to deflection) of the poles selected for the inside of the curve should not be less than one-third to one-half of the strength of outside poles.

COMPUTERIZED DESIGN PROCESS

The OCS intersection design process described above was illustrated for a single-track turning movement. Intersections with multiple tracks, turnings, and crossings involve the same principles, but are more complicated, of course, because of the additional contact wires and guy wires in the network. Moreover, the design process nearly always requires a certain amount of iteration, as the initial layout concept may result in poorly balanced pole or guy loading, initial pole locations may not be suitable, or various other conflicts may develop. Because the tension and clamp height calculations are usually time-consuming, a computerized approach is of considerable benefit and can result in appreciable cost savings in performing the inevitable iterations required in the design process.

To facilitate the OCS design at intersections, Morrison Knudsen Engineers, Inc., developed a computer program called Special Intersection Design Program, or SPIDER. SPIDER is an interactive computer program that enables the designer to create a model of the intersection on a video graphic display, analyze the loading, and optimize the design in an efficient and accurate manner.

The Model

SPIDER represents the overhead contact system network by a model consisting of nodes and connections. Nodes are used to represent poles, bull rings, overhead hardware, and general purpose markers. A node is described by its coordinates (x,y,z), a type description (e.g., pole, bull ring, contact wire connection, etc.), and a mass. Connections are used to represent contact wires, guy wires, hardware elements, or boundary lines. A connection is described by its end-point nodes, a type description (e.g., 300 kcmil contact wire, $^3/_8$ in. guy wire, property line, etc.), its tension, and the clamp height for a wire attached to a pole.

The system developed to date accommodates up to 500 nodes and 600 connections. These numbers are sufficient even for the most complicated LRT intersections. Large yards may be separated into two or more independent networks, if necessary.

Operation of the SPIDER program generally proceeds in two phases: development of the horizontal layout, and establishment of the vertical profile.

Horizontal Layout

As the coordinates (x,y) of the nodes are entered by the designer, the data are continuously displayed graphically on the screen for easy checking and referencing. When a connection or wire is entered, the tension is specified by the designer for contact wires and redundant guy wires; the tension is left blank for other guy wires. The program then calculates the missing tensions, balancing the loads vectorially at each node.

The process of entering data and balancing nodes is continued until all nodes are satisfactorily balanced in the (x,y)-plane. An example of the completed plan view at this point is shown in Figure 5. The contact wire is now registered properly, and the design focuses on the second principal objective, which is to provide a smooth vertical profile.

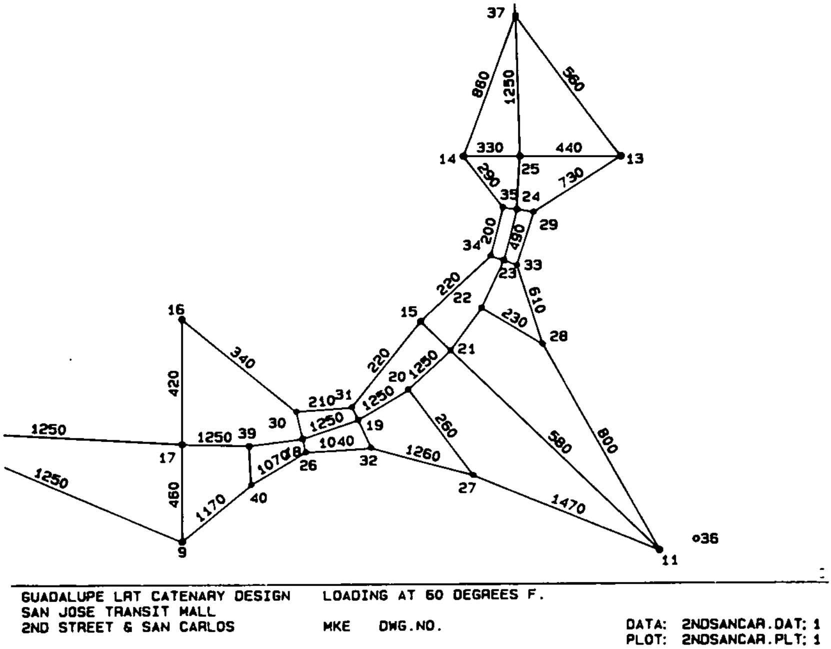

FIGURE 5 Example of SPIDER plot showing the plan view of an intersection guying network.

Vertical Profile

The next phase of the design process consists of selecting the clamp heights of the guy wires at their connections to the poles. The procedure is as follows:

1. The designer selects provisional clamp heights for all guy wires;
2. The program calculates the elevation of each node and the results are displayed on the screen;
3. The designer adjusts clamp heights as required, and the program recalculates the node elevations; this process is repeated until the contact wire profile is considered acceptable.

A typical acceptable design tolerance for contact wire elevations in intersections is ±3 in. However, considering the capabilities of SPIDER, the designer can easily select a more stringent design tolerance, such as ±1 in. This level of optimization will reduce significantly the amount of field adjustment ordinarily required during the construction process.

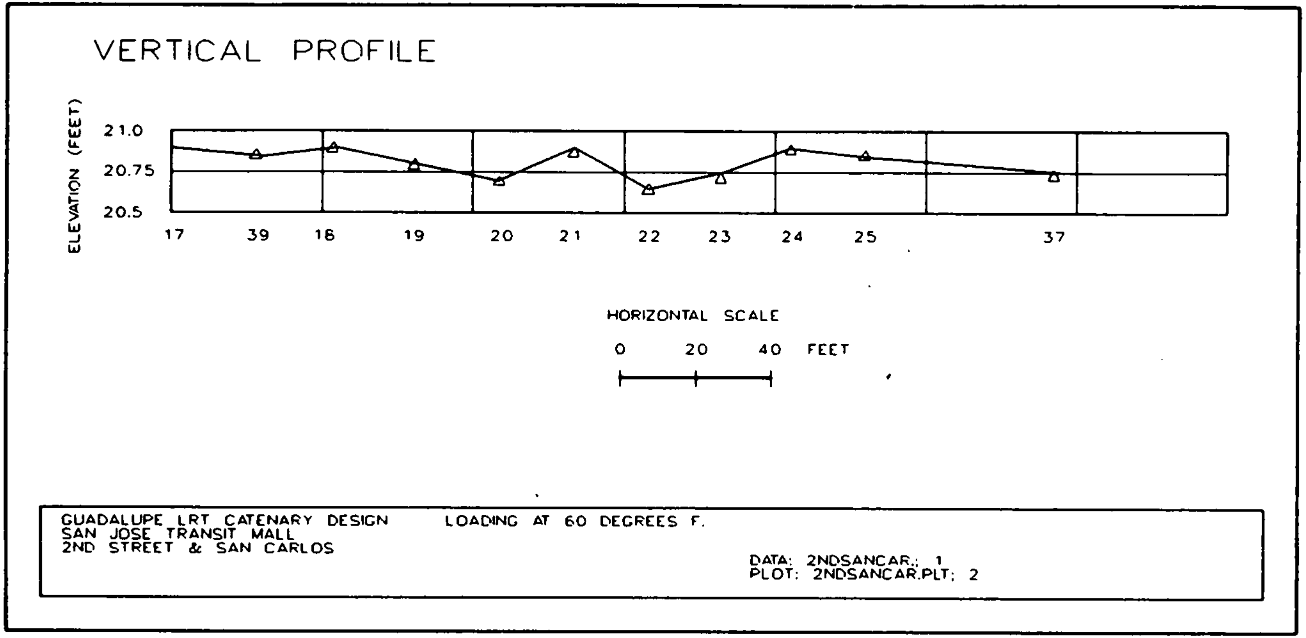

FIGURE 6 Example of SPIDER plot showing the plan view of an intersection guying network.

At this stage of the design, a plot of the contact wire profile can be produced, which will demonstrate the smoothness of the wire; any irregularities in the profile are highlighted and can be easily corrected by adjusting the appropriate clamp heights or guy wire tensions. Figure 6 shows an example of a contact wire profile plot.

In the above design process, the horizontal wiring layout and vertical profiling can be easily adjusted or modified through a simple iterative process to arrive at the most economical combination of guying, support poles, and hardware.

Design Documents

The various SPIDER outputs can be used as design records; they include:

- Electronic data file saved on disk or tape;
- Plots of plan view, showing node numbers, tensions and lengths of wires;
- Plots of contact wire profile; and
- Printouts, including node table (see Figure 7), wire table (see Figure 7), and pole table (see Figure 8).

In addition, the electronic file can be transferred to a computer-assisted drafting (CAD) system to prepare a formal drawing. In the CAD operation, street backgrounds, construction notes, title block, etc., are added and a final drawing is plotted with ink on Mylar.

A supplement to the SPIDER program permits the designer to plot a perspective view of the completed intersection OCS from any desired direction, above or below the contact wire level. These plots are useful in visualizing the aesthetics of a chosen layout. An example of a perspective plot produced on a recent project is shown in Figure 9.

EXAMPLES OF SPIDER DESIGNS

The SPIDER program, with its CAD interface, has been used successfully to design the OCS for several rail transit projects in recent years. Among these are the Sacramento, Guadalupe Corridor, and Long Beach-Los Angeles LRT schemes, and the Lowell historic trolley reconstruction project. Together these projects have involved over 30 intersection designs. Figure 10 shows one of the completed OCS installations on the Guadalupe Corridor Project, the First Street and Younger Avenue intersection in downtown San Jose.

In addition to LRT applications, the SPIDER program has been used extensively for design of two-wire trolley overhead for electric trolley

NODAL INFORMATION

----NODE----			BASELINE COORDINATES			LOCAL	
NUM	NTY	TYPE	--X--	--Y--	--Z--	ELEVATION	WEIGHT
1	800	END	-224.0	0.668	0.0	0.0	0.0
8	800	END	-13.382	262.515	0.0	0.0	0.0
9	700	POLST	-129.0	-40.0	0.0	0.0	0.0
11	700	POLST	42.0	-43.0	0.0	0.0	0.0
13	700	POLST	28.20	98.0	0.0	0.0	0.0
14	700	POLST	-28.20	98.0	0.0	0.0	0.0
15	700	POLST	-43.50	39.0	0.0	0.0	0.0
16	700	POLST	-129.0	40.0	0.0	0.0	0.0
17	20	SPAN	-129.0	-5.0	20.897	20.897	10.0
18	20	SPAN	-85.783	-3.032	20.926	20.926	10.0
19	20	SPAN	-65.884	3.820	20.794	20.794	10.0
20	20	SPAN	-47.845	14.659	20.683	20.683	10.0
21	20	SPAN	-32.742	28.682	20.942	20.942	10.0
22	20	SPAN	-21.780	43.811	20.667	20.667	10.0
23	20	SPAN	-13.772	60.790	20.742	20.742	10.0
24	20	SPAN	-9.049	79.007	20.938	20.938	10.0
25	20	SPAN	-8.0	98.0	20.921	20.921	10.0
26	10	RING	-84.638	-7.899	21.851	21.851	5.0
27	10	RING	-24.709	-16.114	23.492	23.492	5.0
28	10	RING	0.172	30.836	22.292	22.292	5.0

WIRE INFORMATION

ENDPOINT NODES		WIRE	X-Y	Z	WIRE	CLAMP	PLAN
N1-N2	TYP1-TYP2	TYPE	TENSION	TENSION	LENGTH	HEIGHT	ANGLE
1-9	END-POLST	CW300	1250	0.0	103.339	25.0	336.8250
1-17	END-SPAN	GUY3/8	1250	8.5	95.171	20.750	356.5856
8-37	END-SPAN	GUY3/8	2500	11.3	114.604	20.750	271.8736
9-17	POLST-SPAN	GUY3/8	462	-34.4	35.097	24.0	90.0000
9-40	POLST-RING	GUY3/8	1174	-78.1	32.204	25.0	39.5657
11-21	POLST-SPAN	GUY3/8	577	-25.4	103.660	26.0	136.1972
11-27	POLST-RING	GUY3/8	1469	-92.1	72.064	28.0	158.0485
11-28	POLST-RING	GUY3/8	804	-54.0	85.052	28.0	119.5315
13-25	POLST-SPAN	GUY3/8	443	-31.6	36.292	24.0	180.0000
13-29	POLST-RING	GUY3/8	730	-44.7	37.186	24.0	212.4515
13-37	POLST-SPAN	GUY3/8	561	-24.4	62.739	24.0	127.1297
14-25	POLST-SPAN	GUY3/8	333	-26.1	20.262	23.0	0.0000
14-35	POLST-RING	GUY3/8	286	-37.7	23.359	25.0	307.8209
14-37	POLST-SPAN	GUY3/8	855	-43.8	53.380	24.0	69.6199
15-21	POLST-SPAN	GUY3/8	333	-57.2	15.124	24.0	316.1960
15-31	POLST-RING	GUY3/8	218	-19.6	39.394	25.0	231.3647
15-34	POLST-RING	GUY3/8	224	-21.6	34.483	25.0	43.1881
16-17	POLST-SPAN	GUY3/8	417	-24.1	45.075	24.0	270.0000
16-30	POLST-RING	GUY3/8	337	-21.9	52.872	25.0	320.8685
17-39	SPAN-SPAN	CW300	1250	-1.3	24.025		358.6811
18-19	SPAN-SPAN	CW300	1250	-7.8	21.046		19.0006
18-26	SPAN-RING	GUY3/8	487	41.4	5.018		283.2424
18-30	SPAN-RING	GUY3/8	236	3.6	10.001		103.2397
18-39	SPAN-SPAN	CW300	1250	-3.5	19.363		187.4810

FIGURE 7 Portion of a node table printout (*top*) and wire table printout (*bottom*) from the SPIDER program.

WIRE N1-N2	CLAMP HEIGHT	X-Y TENSION	MOMENT FT-LBS	MOMENT DIRECTION
(14) TAPERED STEEL POLE				
14-25	23.0	333	7667	0.0000
14-35	25.0	286	7153	307.8209
14-37	24.0	855	20530	69.6199
			======	==========
			23528	35.2976
(15) TAPERED STEEL POLE				
15-21	24.0	333	8000	316.1960
15-31	25.0	218	5452	231.3647
15-34	25.0	224	5598	43.1881
			======	==========
			8786	317.2461
(16) TAPERED STEEL POLE				
16-17	24.0	417	10000	270.0000
16-30	25.0	337	8436	320.8685
			======	==========
			16663	293.1241

FIGURE 8 Portion of a pole table printout from SPIDER program.

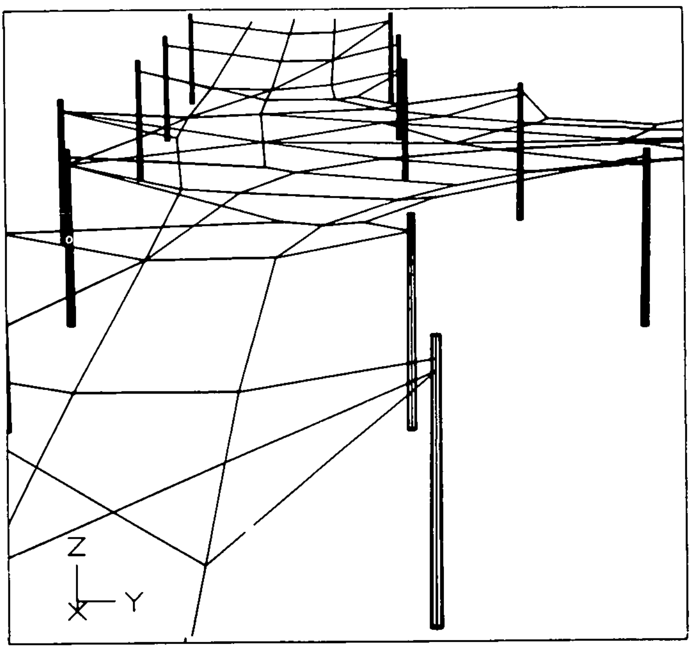

FIGURE 9 Perspective plot of completed intersection OCS design.

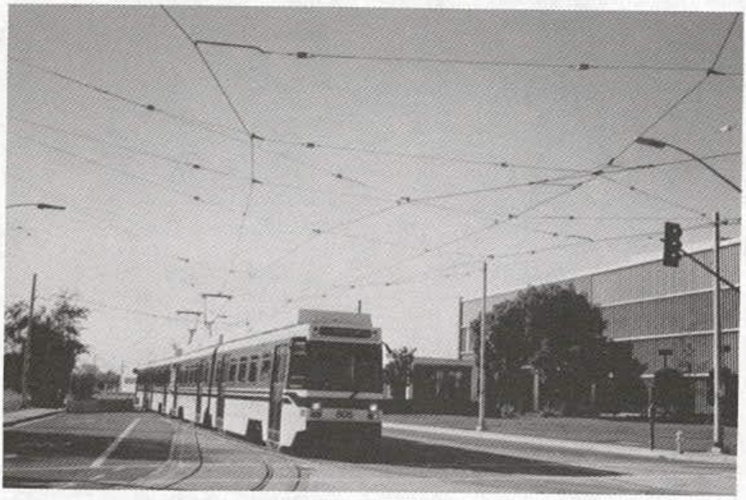

FIGURE 10 The completed intersection at First Street and Younger Avenue in San Jose, designed using the SPIDER program.

coaches in San Francisco and Seattle. In these two cities alone, the program has been used for the design of guying networks for more than 100 intersections. Similarly, it has been applied in the design of OCS in highly complex areas such as maintenance and storage yards, where multiple tracks intersect and numerous turning movements are required. In most of these applications, final construction drawings were produced directly from the SPIDER output using its CAD interface capability.

CONCLUSIONS

Because of the complexity of the typical intersection overhead contact wiring network, the design principles outlined in this paper should be carefully applied to produce an economical, aesthetically pleasing, and trouble-free facility. The SPIDER program greatly aids in the design process, and the versatility of this tool in the hands of experienced OCS designers has already proven its worth in numerous applications.

The design process itself, using the SPIDER program with its capability to examine numerous guying and support options, easily costs less than half that of the equivalent manual process. The real economies, however, lie in the resulting construction cost savings, through the ability to optimize the final configuration and minimize the number of poles, guys, and support hardware. Although it is difficult to quantify specific cost comparisons, considering that eliminating a single pole in a typical intersection can represent a 10 to 30 percent savings, the potential economies of the computerized approach are readily apparent.

Added to this, the inherent accuracy of the SPIDER design reduces the number of field adjustments that typically are needed when installing to a more approximate design. Finally, the efficient and clean design produced by SPIDER is less likely to get out of balance during operation and should therefore decrease overall maintenance requirements.

In summary, the use of the SPIDER program not only ensures maximum economy in OCS construction costs, but also permits a convenient appraisal of the aesthetic impacts of a proposed layout. The program now represents an economical and efficient resource for rapid design of any complex OCS guying network, from simple turning movements to complex intersections and multiple-track vehicle storage and service facilities.

Building Light Rail Transit in Existing Rail Corridors—Panacea or Nightmare?

The Los Angeles Experience

EDWARD MCSPEDON

The Los Angeles County Transportation Commission (LACTC) is constructing a 21-mi light rail transit (LRT) line between the cities of Long Beach and Los Angeles. Sixteen miles of the line are being constructed on right-of-way acquired from and shared with the Southern Pacific Transportation Company. The design and construction of this portion of the project have proven to be far more difficult and costly than was ever imagined initially. Among the more challenging aspects have been the need to maintain railroad operations while relocating the freight line and constructing LRT, undertaking an extraordinarily large utility relocation program, acquiring hundreds of real estate parcels in addition to the railroad right-of-way, and dealing with extensive institutional problems related to grade crossings, insurance, license agreements, franchises, and the permitting and approval processes of the political jurisdictions through which the railroad alignment passes. It is important that those planning similar projects gain a full appreciation of LACTC's experiences so that realistic cost estimates can be prepared for the purpose of making accurate comparisons of railroad right-of-way alignments with other alternatives.

THE FIRST SIGNIFICANT DECISION faced by any municipality or authority considering the construction of a new rail transit line (other than how to pay for it, of course) is simply where to put it. In most mature urban areas the available choices are relatively few and generally include the following:

Los Angeles County Transportation Commission, 403 W. Eighth Street, Suite 500, Los Angeles, Calif. 90014.

- On, over, or above existing streets;
- Within existing highway corridors;
- Within existing public or private rights-of-way (ROWs) (parallel to utility lines, rivers, drainage facilities, etc.), or
- Within existing railroad ROWs.

Problems with the first two choices are usually related to the facts that these facilities are already at or near capacity (thus the reason for considering a rail transit line) and that adjacent uses may tend to be environmentally sensitive (residential) and/or extremely expensive to acquire (thriving businesses).

Active power company ROWs with overhead electrical transmission lines will probably not have adequate space because of horizontal and vertical clearance problems, present difficult maintenance access problems, pose potential safety hazards, probably fail to serve major activity centers or bus routes, and probably suffer from adjacent environmental problems similar to those described for highway and street corridors.

Publicly owned waterways probably will pose substantial environmental problems, may not serve major activity centers or bus routes very well, and probably will not accommodate an operationally efficient light rail transit (LRT) track geometry.

Railroad ROWs, however, usually provide a much more favorable set of circumstances when these initial considerations are reviewed. First of all, freight railroad corridors are often underutilized. The freight railroads, which were so integral to the growth and development of our cities, have in a large number of cases lost substantial portions of their market shares to other transportation modes such as trucks. The railroads have often consolidated their services onto their most productive routes and have used techniques such as longer trains, double-stacked cars, and the like to improve their competitiveness. These factors, together with the deindustrialization of our economy, have caused many freight railroads to reduce or even discontinue service along corridors that access urban cores. The railroad ROWs themselves are often still intact, providing an assembly of land that is well suited for LRT operations because the standards for railroad design (loads, maximum grades, degrees of curvature) are much more restrictive than those required for light rail. Additionally, the types of land uses adjacent to existing railroad ROWs are often environmentally compatible with LRT construction and operations. Although these corridors may not be convenient to residential trip origins they often provide a very politically attractive "path of least resistance" to LRT implementation.

Such was the situation faced by Los Angeles County in the planning of the Long Beach-Los Angeles (LB-LA) Light Rail Project. Sixteen miles of the

21-mi route were planned to be constructed within the Southern Pacific Transportation Company (SPTC) Wilmington Branch ROW, from the southern fringe of the Los Angeles central business district (CBD) to the northern portion of the City of Long Beach (see Figure 1). Not only was this an underutilized freight corridor, but it also had served as the route of the last active Pacific Electric Red Car line, which was discontinued in 1961.

The corridor appeared ideally suited for the construction of a new double-track LRT line, and the Los Angeles County Transportation Commission (LACTC) decided to place the 16-mi midcorridor portion of the project there.

COEXISTING WITH RAIL OPERATIONS

Soon after the LB-LA line was authorized for final design and construction, the LACTC came face-to-face with consideration number 1: Someone else owned the ROW. In this case, the entity was the SPTC. To construct an LRT line within the SPTC corridor, LACTC had to purchase a portion of the SPTC ROW that was generally 16 mi long by 60 ft wide. LACTC did so in October 1985 at a cost of $26 million.

At the same time LACTC was also facing consideration number 2: Someone else may be operating in the ROW. In this case not only was SPTC operating freight service within the corridor, but to make room for construction of the two LRT tracks, the SPTC freight tracks would have to be literally picked up and moved over to one side of the ROW, while full freight operations were maintained (currently at a level of 12 freight trains per day). (See Figure 2.)

The framework for the LACTC's relationship with the railroad was established in June 1985 by a construction and maintenance agreement. The agreement, which was actually a condition of the sale of the ROW, places full responsibility on LACTC for performing the railroad relocation and LRT construction work at no cost to, and with minimal impact on, the operations of the SPTC.

The complications presented by the existence of an operating freight railroad within a very constricted ROW during LRT construction have been numerous and substantial. One of the elements of the construction and maintenance agreement that has had the greatest impact on LRT project cost is that the relocated SPTC is to be on a completely new track and substructure. Hence merely moving the existing track(s) is not sufficient. The design and track materials have to meet railroad standards and are subject to railroad inspection, acceptance, and approval. As might well be expected in a case where the owner (SPTC) does not bear the burden of the construction costs, the railroad has been extremely stringent in the application of its construction

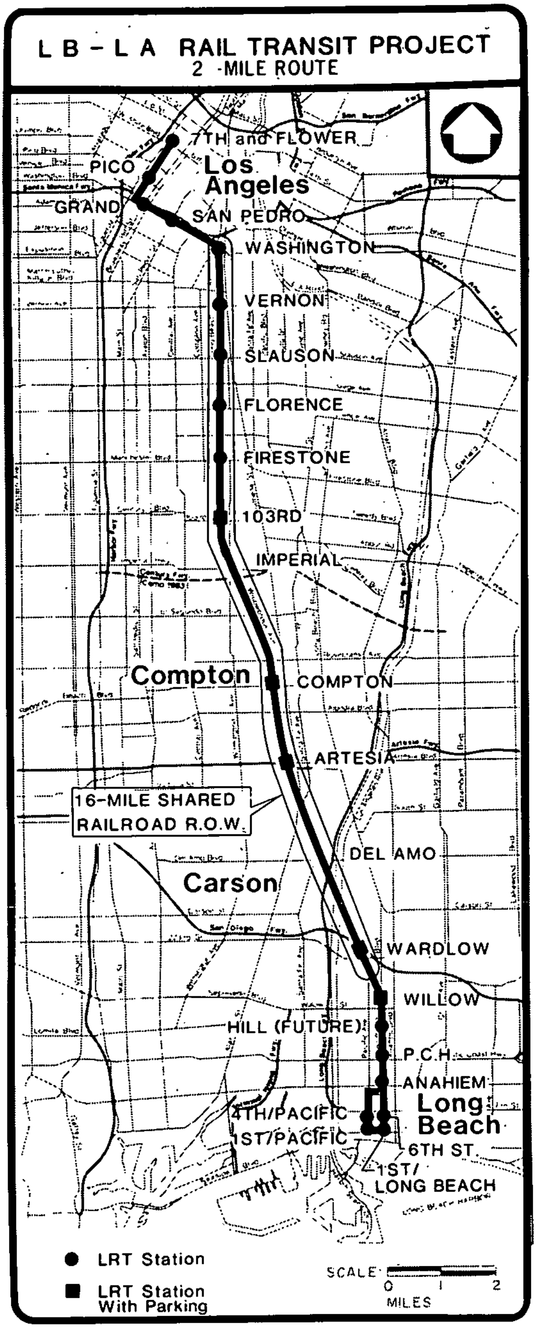

FIGURE 1 Long Beach-Los Angeles LRT route map.

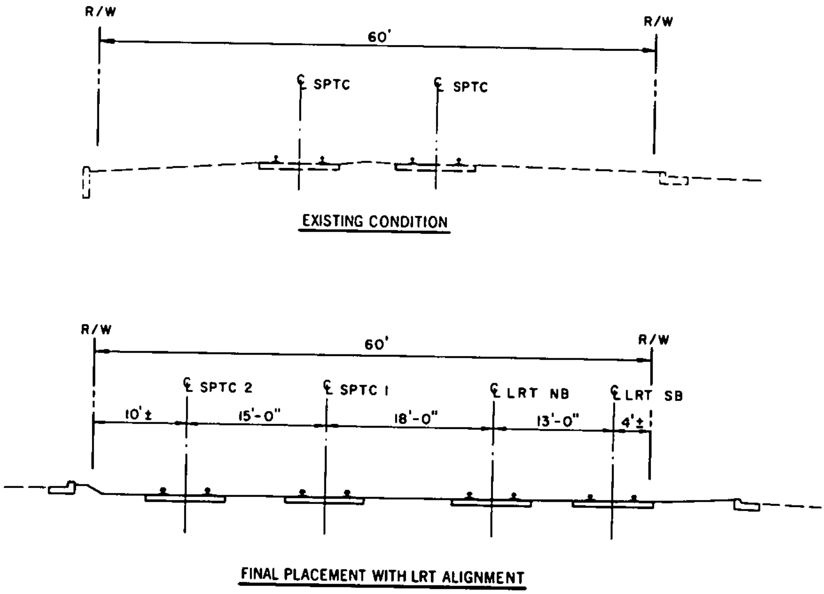

FIGURE 2 Cross section of SPTC right-of-way.

approval authority, resulting in change orders to contracts and pending contractor claims totaling hundreds of thousands of dollars.

In addition, although the current Wilmington Branch freight line is largely single tracked, the final design could not preclude the future installation of a second SPTC track, at minimal cost, wherever possible. This has resulted in several costly LRT design features, particularly related to column locations and bent configurations for LRT aerial structures.

Also, LACTC is required to indemnify the railroad against liabilities due to LRT construction, operations, repair, reconstruction, or physical presence by putting in place a $50 million railroad protective liability insurance policy. This policy must remain in effect so long as the two operations continue to share the corridor and must be increased in value to reflect cost of living index changes in future years. LACTC was unable to exert much leverage in the negotiation of these terms, which, unfortunately, are fairly typical of such arrangements in other U.S. cities.

The physical configuration of the SPTC trackage has also added to the cost of the LRT project. Although the Wilmington Branch predominantly parallels the LRT alignment, there are a number of locations where sidings and spurs depart in either direction to access freight customers along the line, and where branch lines cross or depart from the SPTC track. At heavy traffic locations it has been necessary to grade-separate the LRT to avoid crossing conflicts with the railroad. In total, 2 mi of the 16-mi midcorridor will be on aerial structure, of which 70 percent is due entirely to having to avoid railroad crossing conflicts. At two locations (Slauson Avenue and Cota Crossing) LRT aerial structures also serve to avoid crossing conflicts with other railroads (Santa Fe Railroad and Union Pacific, respectively). The additional design and construction cost of this work is estimated at $20 million.

Because the alignment of the railroad is being shifted, it has meant physical changes to each of the 37 railroad grade crossings in the midcorridor. No matter how minor the change, each requires the concurrence of the affected jurisdictions as well as the approval of the California Public Utilities Commission (CPUC). CPUC regulations require that the crossings be designed to stringent current safety standards and that a complex and lengthy formal application process be followed. The CPUC process often takes a year or longer for each crossing application. Compliance with the CPUC approval process has required that LACTC engage the full-time services of a former railroad official as well as specialized legal counsel, along with staff and engineering consultant resources.

In addition to the required approvals of regulatory agencies for each grade crossing, many of the existing railroad crossings on public streets were constructed and operated under franchise agreements obtained from the street owners. For each modification of these crossings an entire new franchise agreement has had to be drafted with revised legal descriptions and drawings. LACTC must research and prepare these agreements as well as schedule their preparation such that necessary approvals can be obtained consistent with LRT project construction needs.

Lastly, constructing the LRT project in an active rail corridor has imposed the normally anticipated problems and costs, such as contractor inefficiencies, construction site access constraints, railroad flagging requirements, construction of temporary railroad "shooflys," and the required use of railroad construction forces under force account agreements. All of these factors have contributed to increased LRT construction costs and project scheduling difficulties. The cost of relocating and replacing freight railroad facilities is estimated to exceed $40 million.

DEALING WITH OTHER ROW USERS

Perhaps the most greatly underestimated difficulty in the design and construction of the LRT line has come about from consideration number 3: Railroad ROWs are used by other parties as well. In the case of the LB-LA project it sometimes seems as if the LACTC was the last entity on earth to realize the usefulness of the Wilmington Branch corridor. The sheer density of Los Angeles County creates the paradoxical combination of great demand for utility services and lack of open spaces in which to install them economically. Add this to the fact that the railroad is a for-profit business anxious to maximize returns on its sunk ROW costs by leasing the unused spaces beneath and above it, and the result is an enormous number of utilities within railroad ROWs.

Consider the nature of Los Angeles County, with its vibrant economy, 8 million residents, defense industry (Northrop, Hughes, TRW, Lockheed, etc.), underground oil and natural gas deposits, and one can begin to imagine the number of oil lines, gas lines, cable television conduits, public and private communication lines, and other facilities that have been encountered within the Wilmington Branch ROW. All told, LRT construction has affected the facilities of 22 public utility agencies, 10 private utility companies, and 17 oil producers and refineries over the 16-mi shared railroad ROW. It also has required the relocation, replacement, removal, or protection of 2,300 individual utility lines.

LACTC has entered into 60 cooperative agreements with government jurisdictions, private and public utilities, and pipeline and railroad companies to define roles, responsibilities, and procedures for handling project impacts. Each utility within the ROW currently operates under terms of a license agreement with SPTC. These agreements generally indemnify the railroad against any possible detrimental effects from the existence or operation of each line and spell out terms of financial responsibilities of the utility companies to the railroad for the use of the ROW.

Each and every change in the location, configuration, or encasement of each and every utility affected by LACTC's construction has required preparation of a completely new license agreement for execution by the utility company and the railroad. Not only has this proved to be burdensome in and of itself, but the terms of these revised license agreements have often turned out to be contentious issues, particularly when increased lengths of encroachment have resulted in increased annual assessments by the railroad. In addition, LACTC has had to develop and negotiate similar indemnification agreements with each utility for easements beneath its own portion of the ROW.

Perhaps the most substantial difficulty related to utility relocations is that much of the design and construction work must, by regulation, be performed by the individual utility companies themselves. This has meant that the most complex and time-critical project coordination effort has been largely entrusted to dozens of third parties over whom LACTC has no direct control. Billing rates, man hours, and schedules are often a matter of faith considering the fact that many of the utilities are regulated monopolies. The identification of utility conflicts, the development of design solutions, and the safe and efficient relocation of the affected facilities have been combined to form one of the most challenging and frustrating aspects of the LRT construction project (see Figure 3).

COPING WITH RELATED IMPROVEMENT PROJECTS

Consideration number 4 is something that became more and more evident as the engineering and design efforts proceeded into the final phases. It can be summarily described as follows: "Lurking behind any neglected and underutilized railroad corridor are an infinite number of painstakingly conceived, but as yet unfunded, improvement projects." The 16-mi midcorridor passes through four cities and through unincorporated portions of Los Angeles County (see Figure 4). During design development necessary impacts to the facilities of each jurisdiction, as well as to the facilities of the SPTC and the Department of Transportation (Caltrans), were identified. In case after case the impacts of the project on these facilities have required substantial and extensive modifications that, at a minimum, require bringing the facilities up to modern-day design standards no matter how neglected or substandard they might have been. Some of the more significant examples of this phenomenon include railroad grade crossings, grade-separated crossings, and municipal improvements.

Railroad Grade Crossings

Each of the 37 SPTC grade crossings in the midcorridor has had to be modified to reflect changes in the track alignment and, in many cases, the addition of LRT tracks to the crossing. Through design reviews with the local jurisdictions it was found that many of these crossings had long been scheduled for widening. The municipalities dictated either that the widenings occur as part of the LRT project or, at minimum, that the reconstructed crossings be configured to facilitate future street widenings. This has meant longer gate arms, additional warning devices, and dedicated ROWs for future streets and sidewalks at additional project cost.

Another typical situation involves cross-street profile modifications at crossings. Throughout the midcorridor, SPTC's grade crossings often create severe "humps" in intersections. In many instances these crossing humps are 3 ft or more above adjacent street elevations with substandard vertical transitions. Naturally, with the extensive grade crossing reconstruction work involved in the LRT project, the local jurisdictions have required LACTC to eliminate these humps to improve sight distances and speeds for crossing traffic. The lowering of the railroad profile needed to accomplish this has

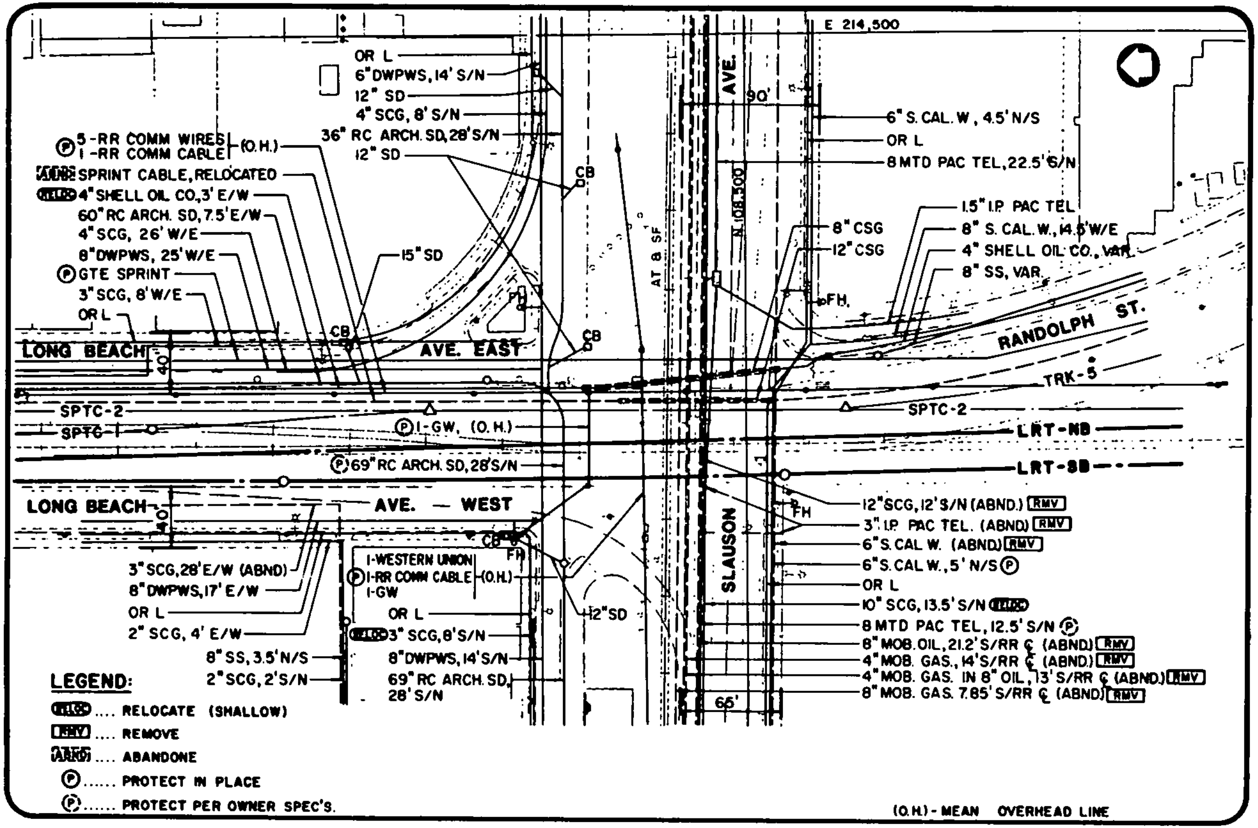

FIGURE 3 Cluttered utility relocation plan shows complexity of effort.

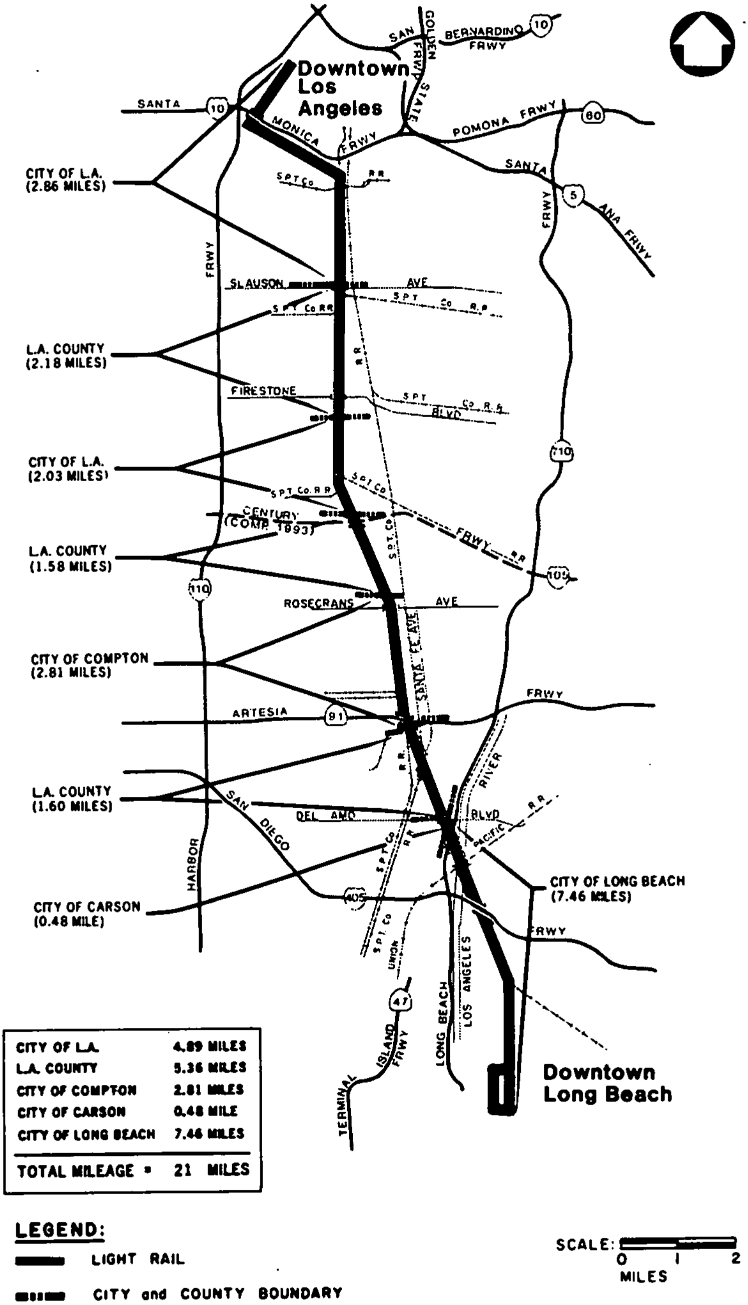

FIGURE 4 Route map showing multiple jurisdictions involved (with mileage per jurisdiction).

been accompanied by extensive related modifications and upgrades to streets, curbs, gutters, and sidewalks for hundreds of feet in either direction at each affected crossing.

Additionally, CPUC regulations require that each of these reconstructed crossings be designed and equipped with state-of-the-art railroad crossing protection. In many cases this has meant upgrading from as little as two wig-wag warning devices to full railroad gates, flashing pedestrian warning devices, and cantilever signal bridges in both crossing directions.

Grade-Separated Crossings

Even in situations where the railroad crossings are already grade separated, unanticipated and often costly problems have been encountered. A case in point is the Firestone Bridge, which is a four-bay SPTC structure crossing Firestone Boulevard (see Figure 5). LACTC's original plans were to utilize one of the four bridge bays for an LRT track and to build a single-track LRT structure adjacent to the railroad bridge. Two of the existing bays would carry the SPTC tracks, and the fourth bay would serve as a buffer between the two rail facilities. Detailed engineering, however, identified a number of problems with this approach and resulted in a costly sequence of events.

Because of the proximity of the center-platform LRT station to the bridge, the LRT track center had to be spread to approach the station. This made the use of the outboard (closest) SPTC track for LRT infeasible. Use of the next SPTC track over (the bay originally designated a buffer between LRT and SPTC) would violate CPUC regulations related to horizontal clearances between LRT and railroad. The only viable solution therefore would be to demolish half of the SPTC bridge and to construct a second single-track LRT structure, leaving one-half of the bridge intact for two operating SPTC tracks.

But the existing bridge does not meet current seismic design standards. Any significant modification to the facility (such as demolishing half of it) requires that it be brought up to standards. Nor is the bridge's design capacity adequate to carry the heavy freight loads that the railroad currently handles. SPTC has been restricted to operating only one train at a time across the bridge under a "slow order." The railroad, not surprisingly, requested that the portion of the bridge to remain intact be reinforced to increase its load-carrying capacity.

Further complicating the situation, the street over which the bridge passes, Firestone Boulevard, is a California state highway. At the point at which it crosses the highway the bridge creates a bottleneck because of its short center span length and the resultant column location on each side of the road. Caltrans therefore requested that the remaining SPTC half of the bridge be lengthened and that the column locations be moved to permit widening of

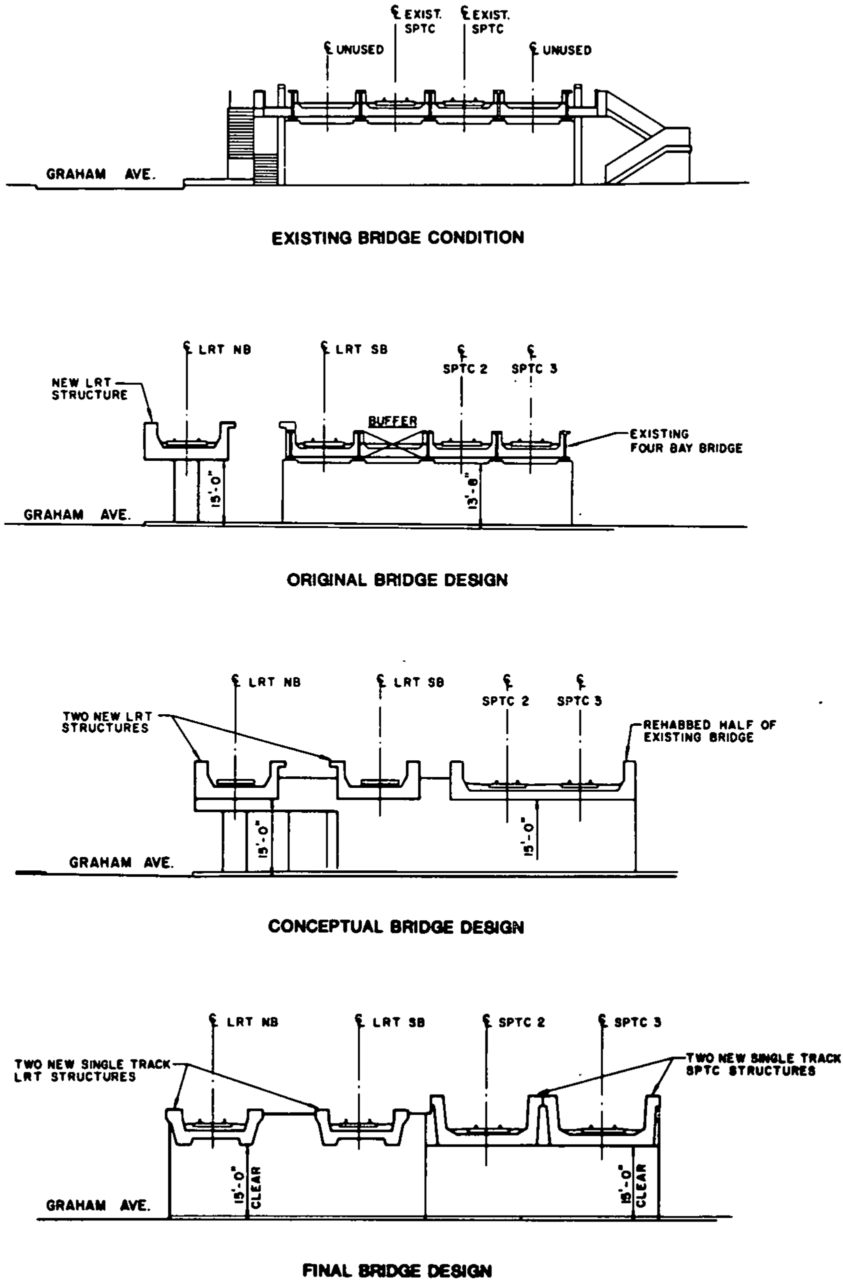

FIGURE 5 Firestone Bridge design and redesign stages.

Firestone Boulevard. The vertical clearance of the bridge over the highway is noncompliant with CPUC regulations and with current highway standards (13 ft 8 in. versus the 15 ft required) and needs to be increased. This can be done either by raising the bridge (a severe problem because it would change the SPTC track elevation and require extensive railroad alignment and grade changes for thousands of feet in either direction) or by lowering the street (also a severe problem because it would create a flood-prone area that would require extensive drainage improvements, including a pumping station).

The net result of all of these factors has been that what started out as an apparent opportunity to reduce project costs by utilizing an existing grade-separated crossing structure has led ultimately to a decision to demolish the entire four-track railroad bridge and to construct a new double-tracked SPTC structure as well as two new single-tracked LRT aerial structures—all to current design standards. This is the most cost-effective solution to all of the problems identified.

Although LACTC will obtain financial participation from SPTC for the increased capacity "betterment" and from Caltrans for the highway width improvement, LACTC will still realize on the order of $4 million to $5 million in additional project costs for this facility, nearly twice the initial estimate for the work.

Municipal Improvements

In terms of municipal improvements, the list is endless and, for the most part, not atypical of the kind of situation faced on all projects of this type. Included are such things as upgrades of adjacent streets and sidewalks, installation of new street lighting, computerized traffic signals and signage, addition of landscaping, construction of new fences and retaining walls, construction of new street crossings across the ROW, and closure of certain existing crossings, to name but a few.

One municipal improvement that is definitely not typical of the kinds of situations faced on projects of this type but that is an example of what can happen is known as MC-5. MC-5 (for midcorridor alignment alternative number 5) is a project element that involves the complete removal of the SPTC trackage from a 4-mi stretch of the Wilmington Branch in the City of Compton and the construction of replacement trackage in a parallel freight corridor (the San Pedro Branch) further to the east, together with connector tracks between the two corridors. The City of Compton was vehemently opposed to the LB-LA project largely because the Wilmington freight corridor cuts through the heart of the city, causing noise, vibration, and traffic congestion. Adding LRT trains to the same corridor was viewed by the city as a change that would exacerbate an already unacceptable situation.

The city decided to employ every available legal and political means to stop the LRT construction until and unless a solution could be found to the existing freight train problems. Although LACTC eventually prevailed on the legal front, the MC-5 project had gained enough political momentum during the several years that it was debated that LACTC ultimately agreed to implement it. This project element, which is not physically necessary for LRT construction or operations, will cost $67 million, of which LACTC will contribute $57 million and the City of Compton, $10 million. (A substantial portion of the city's $10 million consists of a long-term, zero-interest loan from LACTC.)

BUYING ADDITIONAL PROPERTY

The last major factor faced by LACTC is consideration number 5: No matter how perfect the ROW may look, it's probably not big enough. In this instance the project's statistics speak for themselves. In addition to purchasing the 16-mi SPTC ROW, LACTC has had to effect more than 250 other property acquisitions. Included are 43 additional parcels required for auxiliary LRT facilities outside the ROW, such as traction power substations, maintenance facilities, and park-and-ride lots.

Perhaps the most interesting and significant real estate statistic, however, is acquisitions that have had to be made for street modification purposes (typically widenings). An excellent example occurs at Vernon Street, which crosses the ROW at grade and which is the location of an LRT passenger station. Here, the track centers widen to facilitate access to the center-platform station (see Figure 6). The widened track centers result in an encroachment onto Long Beach Boulevard West, which parallels the LRT tracks. Traffic studies showed the need for additional queueing capacity on this street to handle pent-up turning movement demand across the tracks that will result from the increased gate-down time caused by the relatively short LRT headways.

The combination of increased LRT ROW needs, resultant street narrowing, and increased traffic queueing requirements has created the need to acquire portions of several real estate parcels for street improvements as well as the need to relocate three businesses and a church. In addition LACTC has had to acquire a parcel at this location for a traction power substation because there is no room for such a facility within the ROW.

CONCLUSION

Obviously, based on the LACTC's experiences to date on this particular project, the use of existing railroad ROW can hardly be considered a panacea.

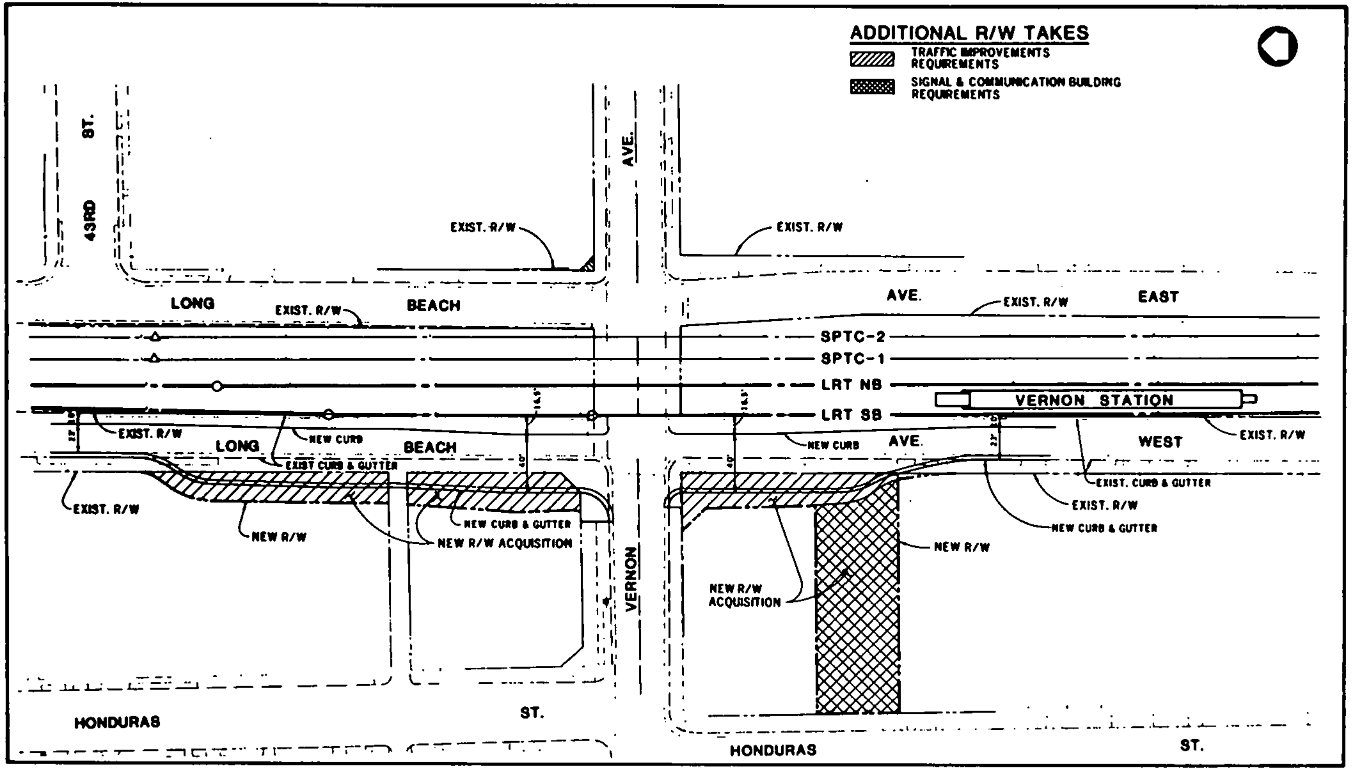

FIGURE 6 Vernon Station area plan.

Although probably not a nightmare either, it has certainly been more like the latter than the former. However, in a situation that requires the construction of a new rail transit facility in a mature, densely developed urban area with the objective of minimizing construction costs through maximum use of at-grade construction, the use of existing railroad corridors will always be high on the list of least-undesirable alternatives.

The important lesson to be learned is that the use of such corridors will probably be much more costly, time-consuming, and complex than might be presumed initially. Any railroad ROW alignment candidate should be closely examined, therefore, in the light of the five considerations presented herein:

1. Someone else owns the ROW;
2. Someone else may be operating in the ROW;
3. Railroad ROWs are used by other parties as well;
4. Lurking behind any neglected and underutilized railroad corridor are an infinite number of painstakingly conceived, but as yet unfunded, improvement projects; and
5. No matter how perfect the ROW may look, it's probably not big enough.

Only when these considerations have been carefully explored can realistic budgets and schedules be developed to facilitate an accurate comparison of railroad ROWs to other alignment alternatives.

Designing to Fit

The Boston Experience

RONALD J. MACKAY

The light rail vehicle (LRV) procurement process, easy to describe but difficult to effect, is intended to provide transit systems with LRVs that are both reliable and maintainable within given constraints. In Boston the process succeeded. The chosen vehicle has performed so well during the past 2 years that the original order has been doubled. Yet the process was complicated by the city's problematic operating environment—the new LRVs must operate on a subway system built at the turn of the century and in extreme weather and traffic conditions. The Massachusetts Bay Transportation Authority obtained the LRVs that suited their needs by assembling a capable internal staff with a balance of theoreticians and practitioners, carefully selecting an outside consultant, working closely with the consultant, and developing the specification by circulating drafts throughout the organization's various departments.

BOSTON, ALTHOUGH NOT UNIQUE, faces a variety of institutional constraints, both operational and social, that present a somewhat unusual environment in which to design and operate a light rail vehicle (LRV). The development of a state-of-the-art vehicle that will readily interface with a turn-of-the-century subway system is difficult in and of itself. Further exacerbating the situation are the legendary Boston automobile driver, traffic congestion, varied rights-of-way, extreme climatic conditions, track geometry, and a local populace with an advanced understanding of the political process—all of which tends to stretch the limits of technology. However, it appears that after almost 2 years of operation a large measure of success has been achieved with the introduction of the new Kinki Sharyo-built surface rail car.

Massachusetts Bay Transportation Authority, Light Rail Equipment Department, Reservoir Carhouse, 400 Chestnut Hill Avenue, Brookline, Mass. 02146.

THE NEW LRV

The Massachusetts Bay Transportation Authority (MBTA) car is a 72-ft, six-axle, articulated, bidirectional vehicle with air conditioning and straight air braking. A 55-kv-A motor alternator is employed to provide power for the various ac-driven auxiliary motors as well as for primary lighting, floor heat, and convenience outlets. Pantograph current collection provides power for the microprocessor-controlled dual dc chopper propulsion system driving bimotored, parallel-drive powered trucks. The vehicle is outfitted with outwardly folding bifold single engine doors for low-platform loading. The maximum width of 8 ft 10 in. and maximum height of 11 ft 10 in. are established by the constraints of the vintage subway system. The vehicle must be articulated to negotiate a minimum radius curve of 43 ft. Empty vehicle weight is 84,500 lb.

Chopper control was selected based upon Boston's previous experience with the Garrett system of the older Boeing Vertol LRV. Although some may argue that resistive controls are more desirable, Boston's experience has been to the contrary. After the technological gap had been overcome, the system proved very effective. A further benefit was derived from the selection of chopper control—the dual system approach. Basically, the Boston dual chopper system provides two separate and distinct propulsion systems whose only common elements are input power, load weighing, and train-line information. The advantage is significant—limp-home capability on incidents of on-line failure. Boston's decision has proven extremely beneficial on the rare occasion when such a failure occurs.

Although selecting the propulsion system is perhaps the single largest decision, a successful vehicle is dependent on overall design. In general Boston's philosophy was to insist on transit-proven technology. During the acceptance process, we also learned to be very wary of suggested "product improvements" or modifications to existing proven designs developed by other than actual operating experience.

Boston opted for bifold doors based solely on our own experience. Past excursions with other technology proved less than successful. Initially, we selected a dual-engine type for operational flexibility, but during design review yielded to the simplicity of a single engine. Both decisions have proven prudent in that on-line door system failure currently hovers around 90,000 mean miles between failures.

The decision to revert to straight air braking was similarly founded on past experience. The effort to maintain a hybrid system proved to be extremely labor-intensive, and the system was somewhat unreliable. Although some mechanical problems have surfaced within the new vehicles' braking systems, they generally fall into the category previously mentioned, product improvements. Modifications are currently under way to correct this situation and we remain convinced that straight air is more effective.

Air conditioning, in the eyes of the maintainer, should be avoided. The motivation to incorporate this system is driven more by the political perspective, "You can't take away what you have already given them." However, past experience also yielded significant benefit in this area. We have learned our lesson well: form follows function. System design is not the only criterion for successful operation. Placement, particularly on a trolley car, is crucial. Although it may spoil the sleek look of the vehicle, the system must be roof-mounted. Through one full summer of operation we have yet to suffer the first major subcomponent failure.

The decision to incorporate ac technology was twofold; the volume and weight of a continuous-duty three-phase ac motor are significantly less than its dc counterpart, and contact surfaces (brush/commutator) are eliminated, thus making the motor inherently more reliable and maintainable. Consequently preventive maintenance schedules are now established by internal bearing life rather than the more critical brush/commutator interface. A singular exception to the selection of ac motors was made. The new vehicle's air compressor utilizes the standard dc alternative. Similar to the selection of a dual chopper, this decision affords limp-home capability in the event of loss of auxiliary power.

It should be pointed out, given the recent advances within state-of-the-art gate turn-on (GTO) device technology, that if the decision were made today, we would most probably have opted for a static converter rather than the motor/alternator, again for reasons of reductions in size, weight, and number of contact surfaces. Further we would seriously investigate the use of ac traction drive. However, before such a large step could be taken, extensive study would be required.

As a final note, a specific advantage is offered the transit operator selecting microprocessor control—the availability of full diagnostics. Although there is some well-founded disagreement with the use of microprocessor control, there are some distinct advantages. Diagnostics most certainly enhance maintainability. They provide not only improved troubleshooting capability, but also systems self-test, preoperative checks, and fault logging. Among these diagnostics, fault logging appears to be the most significant. Logging also gives the maintainer the ability to reconstruct the actual circumstance leading to the fault, which is extremely beneficial in segregating cause and effect.

THE PHYSICAL ENVIRONMENT

Light rail service is provided in Boston on four distinct lines, all of which join in what is locally called the central subway. Unlike the situation in many areas where light rail service is just now being reintroduced, the MBTA has been providing light rail service continuously since 1897. The introduction of a new vehicle to an old system presents some interesting problems that must be dealt with at the outset. Issues such as power, tunnel dimensions, track geometry, and point loading must be considered. In rare instances modification is possible; in general, they simply must be dealt with as constraints.

In Boston, power upgrading was necessary (and is still under way), and all inclines leading from the subway portals had to be reinforced. All other aspects led to design compromise. At present, the MBTA provides two- and three-car consists on three of its four lines but is limited to single-car operation (with the new vehicles) on the remaining line until the power improvements can be made.

The vagaries of weather clearly have their impact in the Boston area as well. From the snow-filled days of winter to the humid days of summer, service is expected to be reliable and somewhat comfortable. Issues of maintenance simplicity tend to receive low priority when juxtaposed with the needs of freezing or sweltering passengers.

Finally, vehicle storage and maintenance facilities can present further constraints. If, as is the case in Boston, preexisting facilities are to be used for maintenance of the new vehicles, modifications may be required. Issues such as hoists, pits, and track loading must be examined and facilities modified or replaced.

PROCESS AND PHILOSOPHY

As is the case with many major decisions at the MBTA or in any public service organization, it is critical that all pertinent information be gathered and assembled by staff prior to final decision-making by top executives. Thus the steps to a successful procurement can be described quite simply:

- Assemble a capable internal staff,
- Engage a competent consultant,
- Develop a solid specification, and
- Select a reputable manufacturer.

Although simple in theory, this is extremely difficult in practice.

The initial step, the assembly of internal staff, is significant in that a proper balance of theoreticians and practitioners must be achieved. Intellect alone will not ensure success. A firm sense of reality must be maintained.

The way the MBTA handled this first step was through a staff in what was then the department of engineering and operations planning. At that time, the

MBTA was in the process of buying a new fleet of buses, the new light rail vehicles, and a fleet of heavy rail vehicles. Initially, this department took the lead role in all of the acquisitions and, fortunately, contained the proper blend of talent.

The staff established the basic concept of what was desired and assembled a draft specification for internal circulation. The interface with all operating departments was essential at this point. The MBTA's structure dictates an extremely close relationship between the equipment maintenance department (the maintainer), the transportation department (the eventual operator), and the engineering and maintenance department (the right-of-way, power, and facilities agent). All parties achieved a consensus as to what was required and provided the appropriate input for later incorporation into the formal specification. This step's importance cannot be overstated; consensus is not generally achieved easily, and patience is required.

Staff must also conduct a parallel effort—consultant selection. Again, this is a crucial step. The consultant must be selected on the basis of experience, talent, reputation, and cost-effectiveness. Larger, established properties may have significant advantage in this area given past experience with most prominent firms.

As is the case with most public agencies in a project of this scope, the MBTA used a competitive selection process. Proposals were submitted for evaluation by an independent review board, a short list was developed, and successful candidates were interviewed.

Upon ultimate selection, a team may be assembled on the basis of past experience with certain individuals within that consulting firm. Previous relationships may prove beneficial. Some have recommended that, once a consulting firm has been selected, the major responsibility be left to it. However, it is strongly urged that in-house personnel maintain their influence; nobody knows their railroad better. It is the opinion of the author that the property should drive the specification and that the consultant should form it to fit.

The relationship between internal staff and the consultant is, once again, critical. It is very important that the basic concept be conveyed clearly and distinctly, with all key elements specifically defined. The environment for consensus must be established. It is extremely difficult for staff to keep abreast of state-of-the-art technology; they are generally kept occupied running the railroad. The proper consultant not only provides this expertise but also brings along a wealth of experience, talent, and information not otherwise locally available.

The specification process, described in short form, is simply the establishment of the physical dimensions, the selection of a propulsion system type, and, thereafter—working through the vehicle—a series of trade-offs and a decision based on functionality, circumstance, cost, and desired result. This process, initiated at the conceptual stage, advances through design review and continues to actual procurement, all the while accompanied by a series of adjustments, which, it is hoped, produces a successful vehicle.

When a draft specification is complete, it is important that it be circulated in-house. This gives all concerned parties an opportunity to review all the changes submitted by various other departments as well as to note and provide exception to variations of their own. Thereafter it should be let for industry review. This will provide a forum to review the latest technology as well as to become acquainted with changes to or upgrades of existing equipment. Should industry review yield significant modification to the specification, it would be wise to recirculate it in-house.

THE CURRENT PICTURE

In retrospect, the Boston experience has been rewarding. The process defined above has yielded an overwhelmingly successful vehicle. With almost 2 years of operating experience on the initial vehicles, we remain confident that they will serve us well. Indicative of this confidence, the original order for 50 vehicles was expanded to 100, of which 25 have since been delivered and placed into revenue service. The remaining 25 are scheduled to be completed by September 1988.

ADDITIONAL COMMENTS

Some elements of the process not detailed herein but seen as noteworthy cannot be left without at least a brief comment. First, full-scale mock-ups should be requested in the specification and subjected to detailed review prior to final design. This is a good opportunity to see if the concept transfers to reality. The best human engineering can be carried out at this stage. Resident inspectors should be put in place at both the manufacturing facility and final assembly point. This can sometimes be difficult with off-shore procurement, but is crucial to success.

Design review is a continuous process throughout the procurement. The milestone chart may indicate otherwise, but the design review process extends beyond delivery. The temptation to overdesign the LRV must be resisted. Although safety cannot and should not be compromised, it is undesirable to remove all responsibility from the operating system, because this generally must be done at the expense of reliability.

And finally, a word on problem solving. A significant number of solutions are most apt to be developed by the project staff. Hands-on experience is invaluable, particularly when backed by direct knowledge of the operating environment.

CONCLUSION

The intent of the procurement process is to provide a vehicle that is both reliable and maintainable within given constraints. What is described herein is not meant to imply that this method or equipment would be totally suitable if applied by others, nor that it is the only approach. Given the variations within the industry, there is only one truly common thread—the success of any project is solely dependent on the people involved.

Buffalo's Light Rail Vehicle

BEN J. ANTONIO, JR.

Buffalo's 6.4-mi light rail transit line depends on a fleet of 27 four-axle, double-ended cars. The Niagara Frontier Transportation Authority (NFTA) uses a work order system to monitor failures in service, failures found during monthly preventive maintenance, and failures discovered during system checks. Now in the form of a computer data base, this system allows NFTA to keep a history of each vehicle and to estimate repairs, distances traveled between failures, and parts needed for repairs. After 2 million vehicle fleet miles logged since 1985, NFTA has been able to keep more than 95 percent of its fleet available for service at any given time. Aiding this effort is a maintenance strategy incorporating quick connectors, parts interchangeability, and an ample parts supply. Also important is the maintenance employees' familiarity with the light rail vehicles (LRVs). Because the Japanese-made LRVs had to have some U.S.-made parts to satisfy federal procurement regulations, buying replacement parts has been difficult and costly. And, since the warranty on the LRVs expired, resolving problems with the manufacturer has been very difficult. Recommended improvements in the procurement process include involving maintenance personnel in discussions about system requirements and including the spare parts needed to support the system in the overall LRV procurement.

BUFFALO'S LIGHT RAIL TRANSIT (LRT) line is 6.4 mi long, 1.2 mi of which is above ground (see Figure 1). The above-ground section of the rail line is a free-fare zone and runs from Auditorium Station to Theatre Station. It is considered one of the longest transit malls in the country. Except for emergency vehicles, only the light rail trains are allowed in the mall area.

Six passenger stations are incorporated in the mall area. They feature handicap loading ramps and low-level loading from 6-in. platforms. To accommodate the low-level loading, each car is equipped with folding steps that are deployed only at the above-ground stations.

Metro Rail, Niagara Frontier Transportation Authority, 164 Ohio Street, Buffalo, N.Y. 14203.

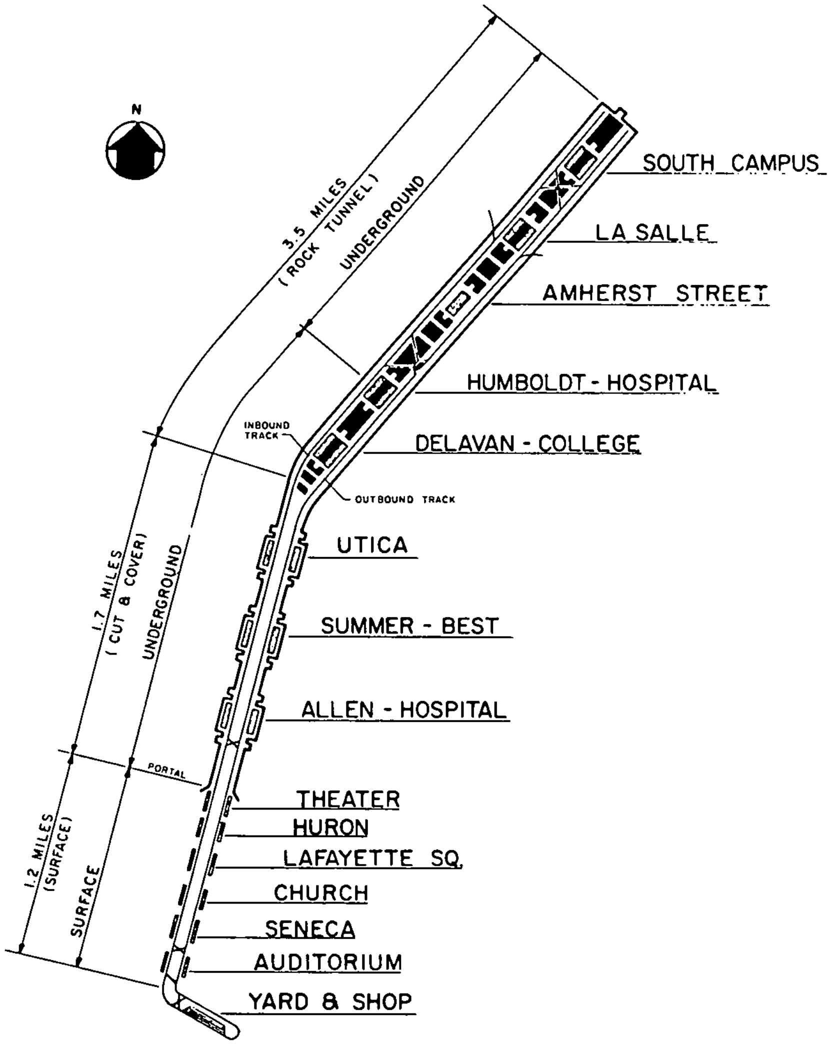

FIGURE 1 Buffalo system overview.

The line goes underground at Theatre Station and runs to South Campus Station. The first 1.7 mi of underground operations has been constructed by the cut-and-cover method. In this section the surface of Main Street was excavated and a concrete box built below through which the trains operate. The excavation was then filled and the street surface repaved. There are three passenger stations in the cut-and-cover section. The remaining 3.5 mi of the line was machine-bored into twin tunnels through solid rock. Five passenger stations are located in this section.

Loading underground is from 300-ft floor-level platforms (i.e., high-level loading). The system therefore requires a bilevel loading car. The folding steps are not utilized in the underground sections.

The Buffalo light rail vehicle (LRV) is a four-axle double-ended unit 66.8 ft long. Each car has 51 seats and can comfortably accommodate 140 passengers, standing and seated, during rush hour. The maximum crush load capacity is 210 passengers. Each car has three sliding doors and retractable steps for surface boarding on both sides of the car. Underground train speed varies up to a maximum of 50 mph. On the surface section train speed is restricted to a maximum of 28 mph due to pedestrian traffic.

Table 1 shows the carbody features of Buffalo's LRVs. The major LRV subsystems are detailed in the Appendix to this paper.

PROCUREMENT

In mid-1979, the Niagara Frontier Transportation Authority (NFTA) decided to use the two-step procurement process for purchasing their LRVs. The first step involved producing a request for technical proposals (RFTP). Nine car builders responded. In June 1980, five of the original nine respondents submitted technical proposals. Following NFTA's acceptance of the five final technical proposals, fixed-price bids were requested. NFTA allowed respondents to propose bids for both six-axle articulated cars and four-axle cars. Details on passenger capacity for the proposed cars and operational requirements were known. Thus, NFTA was able to specify a fleet size for each bidder. The bids are summarized in Table 2.

Tokyu Car Corporation (TCC) of Yokohama, Japan, was the low bidder. NFTA authorized the purchase of 27 vehicles under the two-step procurement method already discussed.

MAINTENANCE TRACKING SYSTEM

The car builder was required to catalog certain data so that the rail car could be evaluated with respect to maintainability and reliability requirements. A

TABLE 1 CARBODY FEATURES

Feature	Details
Manufacturer	Tokyu Car Corp.
Length over couplers	66 ft 10 in.
Width (across rubrails)	8 ft 7 in.
Roof height	11 ft 3 in.
Pantograph lockdown height	12 ft 3 in.
Underground contact wire height	12 ft 11 in.
Seats/seat width	51/19 in.
Door height/width (3 per side)	6 ft 3 in./45 in.
Floor	Stainless steel–clad plywood
Floor insulation	Ceramic fiber (Fiberfrax)
Emergency intercoms (to operator)	2
Wheelchair lockdowns	2
Floor height	
(AWO)	37.2 in.
(AW3)	36.8 in.
Headroom, center aisle	6 ft, 11 in.
Empty weight	70,000 lb
Usable standee space	237 ft
Door/step pushbuttons	2 per door
Fire extinguishers	2 per car
Air conditioning (safety electrical)	13.5 tons per car
Noise levels	
Inside	Spec.: 72 dBA @ 50 mph; test: 66 dBA
Outside	Spec.: 80 dBA @ 50 mph; test: 76 dBA (50 ft)

TABLE 2 NFTA LRV BID PRICE COMPARISON

Bidder	Fleet Size	Car Type	Deviation from Low Bid (%)
Tokyu (TCC)	33	4-axle	0
UTDC	33	4-axle	+14
Siemens	27	6-axle	+16
Bombardier	25	6-axle	+21
Hawks-Sido	25	6-axle	+38

work order system was developed to monitor failures in service, failures found during preventive maintenance checks, and failures discovered during system checks.

If an in-service failure occurs, the operator logs the symptom on a defect card. This card is then submitted to the maintenance department at the completion of the operator's run. The maintenance department then makes any necessary repairs and completes a work order.

The system check form, which is a daily check of the vehicle's operating system, is also used, but is completed prior to the vehicle's release for service. Any failures discovered during this check are a second source of information that is also entered into the work order system. A third source of information is the preventive maintenance check form.

The work order system provides a history of the vehicle categorized by subsystem. It estimates repairs, distances traveled between failures, and parts utilized to perform repairs. Each work order is numbered sequentially and logged with a brief description of the failure. This log is essential for traceability of the completed work order.

The work order system was developed further on the introduction of an IBM AT computer system. Using the dBASE III software package, an input form was designed that is similiar to the written work order form. Work orders now can be entered into a data base.

SUMMARY OF OPERATIONS

Full revenue service began November 1986. To accommodate passenger service, 23 cars are required daily during the peak rush hours. Figures 2 and 3 reflect the service requirements and fleet availability to meet those requirements during 1986 and 1987. Percent availability is computed by the number of vehicles that can be made ready for service. Percent service is based on maintaining car requirements to satisfy passenger loading. Both graphs were computed from monthly operating days using the following formulas:

$$\text{Percent service} = \frac{\text{No. of cars in service}}{\text{No. of cars required for service}} \times 100$$

$$\text{Percent availability} = \frac{\text{No. of cars available for service}}{\text{No. of cars in fleet}} \times 100$$

Out of the four cars not required for passenger service, three are required for preventive maintenance. The remaining car is used as a spare for revenue service. The preventive maintenance schedule is based on monthly checks of each car's subsystems. Discrepancies discovered during the preventive maintenance checks have reduced operating failures to a minimum, which is reflected in NFTA's ability to maintain service requirements.

One problem area during the first year of operation was the step assemblies. There were two to three step-related failures per day. NFTA worked

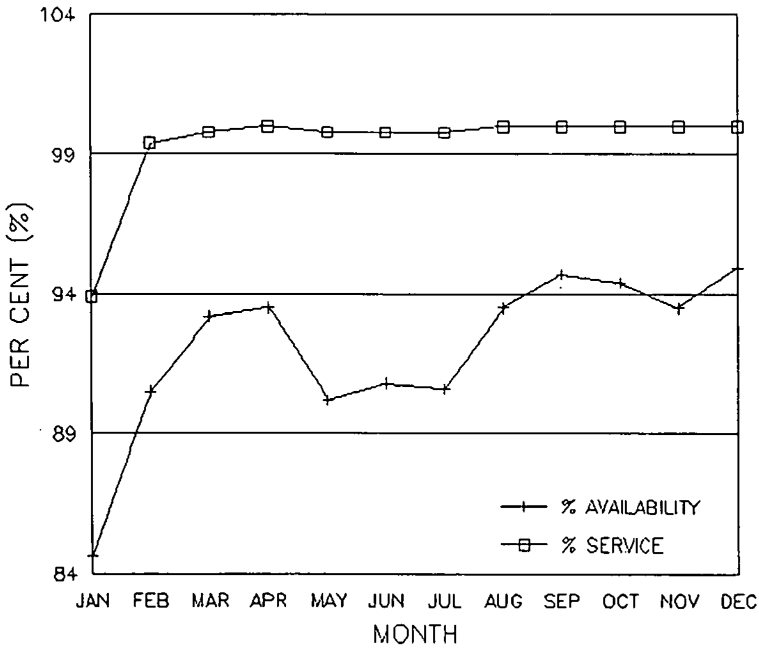

FIGURE 2 Service and fleet availability, 1986.

with the manufacturer to put the step assembly through a series of modifications that improved its performance. Internal bracing was required to prevent fatigue failure. Brass bushings and grease fittings replaced oil light steel bushings on hinge points to reduce binding. These two modifications improved step performance with a failure rate of less than two failures per week of operating time.

CONCLUSION

Since the line opened in May 1985, more than 2 million vehicle fleet miles have been accumulated. This equals approximately 75,000 mi per vehicle. In 1987, under full revenue service, 35,000 mi per vehicle was accumulated.

As Figure 3 shows, the service requirements for the 23 cars have been met over 99 percent of the time in 1987. This was accomplished by having over 95 percent of the total fleet (27 cars) available at any one given time.

Two factors have helped meet these requirements. The first is the vehicle system. Part replacement can be accomplished with minimum down time through the use of quick connectors, parts interchangeability, and an ample supply of spare parts.

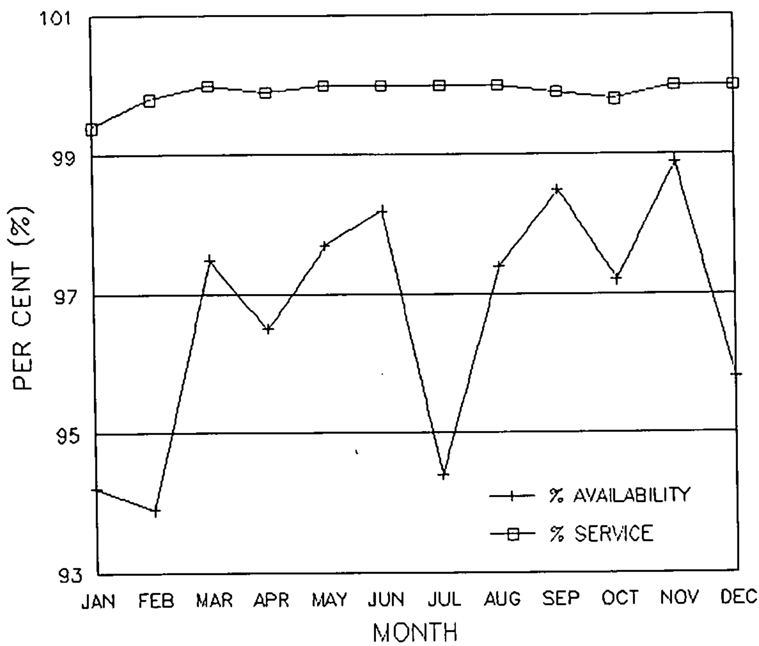

FIGURE 3 Service and fleet availability, 1987.

The second factor is the maintenance employees' familiarity with the vehicle. As the employees become familiar with the different LRV systems, they become more proficient in trouble-shooting defects. This has contributed to the reduction of down time due to failures.

It appears that Tokyu's cars have been a sound investment for NFTA. The vehicles are easily maintained and have been found to be mechanically sound. The preventive maintenance program as well as the maintenance employees' skill are also major factors in the system's reliability.

Two drawbacks of the vehicles can be attributed to funding and procurement regulations. The LRV has both foreign and American parts, which makes parts procurement both difficult and costly. Also, after the expiration of the warranty, communicating with the manufacturer became very difficult when it was necessary to discuss problems regarding the vehicles.

If NFTA were to purchase more cars under the same procurement process, two improvements could be made. First, maintenance personnel should be involved in the discussion of system requirements. Second, a close evaluation of the spare parts that may be required to support the system should be made. These parts should be ordered as part of the vehicle procurement process.

APPENDIX: BUFFALO RAILCAR SUBSYSTEMS

PROPULSION (Westinghouse)

* Four 1463D Motors/Car, Force Ventilated
* Nominal 650 Vdc Traction Power
* 310V, 343a, 2400 rpm, 135 hp (Cont. Rating)
* Chopper Control
  * Two Truck Motors in Series, Two Trucks in Parallel
* Max. Operating Speed: 50 mph (28 mph on Surface)
* Base Speed: = 21.5 mph
* 37.5Vdc Auxiliary Power
* Dynamic Braking
* Regeneration
* Spin/Slide Control
* Four WR-101-3 Gearboxes
  * Parallel Drive, Double Reduction, 7.130 Ratio
* Batteries (McGraw-Edison)
  * NiCad - MED 189
  * Twenty five 1.4V cells
  * 189 Amp/Hr.
* Acelleration (AW2 @ 650 V)

Spec.	Test
*Avg: 2.3 mphps (min.)	2.85
*Time to 50 mph: 37 sec.	35

TRUCKS (Tokyu Car Corp.)

* Primary Suspension: Chevron
* Secondary Suspension: Air Bag
* Track Gauge (Tangent Track): 4' 8-1/4"
* Truck Center Distance: 36' 2"
* Wheelbase: 6' 2"
* Wheels: AREA Plan 793-52, except for thickness, Ring damped
* Wheel Diameter: 26"
* Load Leveling
* Max. Axle Load: 29,300 lbs.

BRAKES (Knorr Brake)

* Disc: Spring Applied, Air Release
* Brake Blending: Dynamic to Friction = 10 mph (AW2)
* Anti-Rollback: Manual, 7% grade
* Track Brake: 37.5 Vdc/29.7a, 2000 lbs. @ 50 mph
* Full Service: Blended, Jerk Limited
* Emergency: Friction plus Track + Sand
* Deceleration (AW3 @ 650 V, 50 mph)

	Spec.	Test
*Friction:	3.0 mphps + 15%	2.55
*Service:	3.0 mphps + 10%	3.0
*Emergency:	V/T (gross) 4.0 mphps	4.35

COUPLER (Dellner-Schaku)

* Type 34
* Gathering Range: Hor. + 5.9", Ver. +3.2"
* Draft Gear: Elastic Range 46000#/in.
  Plastic Range 90000# (constant) over 12"

PANTOGRAPH (Stemmann)

* BS-80, Single Arm, Dual Brushes
* Spring Up, Power Down (Pneumatic)
* Contact Force, Static: 18 lb. + 5%
* Brush Width: 41.3"
* Bow Width: 66.9"

DOORS (Panel: Tokyu Car, Mechanism: Faiveley)

STEPS (Faiveley)

* Enable Mode: Manual, Passenger pushbuttons, all doors, inside and outside (Inoperative Underground)
* Normal Modes:
  * Open/Close: Left/Right
  * Open All Doors
  * Close All Doors
* Doors/Steps Air Actuated
* Door Open Indicator Lights
  * One each side - Outside
  * Three each Cabin
* Operating Times
  * Step Down/Door Open: 5 sec.
  * Door Close/Step Up: 6 sec.
* Sensitive Edges: On door edge
On edge of first step

WINDOWS (Ellcon National Inc.)

* Nine per side - Four with Transoms
* Tinted Safety Glass (Windshield is Clear)
* Transmissibility: 69%

Pittsburgh's Light Rail Vehicles

How Well Are They Performing?

ED TOTIN AND RICK HANNEGAN

The Port Authority of Allegheny County operates 55 double-ended light rail vehicles (LRVs) on a 10.5-mi segment of its 22.5-mi system in metropolitan Pittsburgh. The rest of the system relies on 45 President's Conference Committee (PCC) cars. Political and financial considerations dictated this mixed fleet. Introducing LRVs to a system served by PCC cars was not difficult because many of the operating techniques are the same. Port Authority Transit's experience with its LRVs began with a subway shuttle operation launched in 1985—nearly two years before the final segment of the light rail system opened to the public. In that time the authority and its car builder have tackled problems with the LRV braking system, doors, air conditioning, corrosion, and automatic trip stop system. Given the satisfactory solutions found for most of the problems, the authority is pleased with the performance of the LRVs.

THE DREAM OF A CENTURY came true on May 22, 1987, when the final segment of the Port Authority Transit's (PAT's) light rail transit (LRT) line opened to the public in Pittsburgh. The $542-million LRT improvement project, including the downtown subway, became the largest public works project ever undertaken in western Pennsylvania (Figure 1).

Because sufficient governmental funding was not available to rebuild the entire 22.5-mi rail system, PAT opted to build the downtown subway and to rebuild the Mt. Lebanon line, converting it from a turn-of-the-century trolley line to a state-of-the-art LRT line. The line to South Hills Village was also

Port Authority of Allegheny County, 2235 Beaver Avenue, Pittsburgh, Pa. 15233.

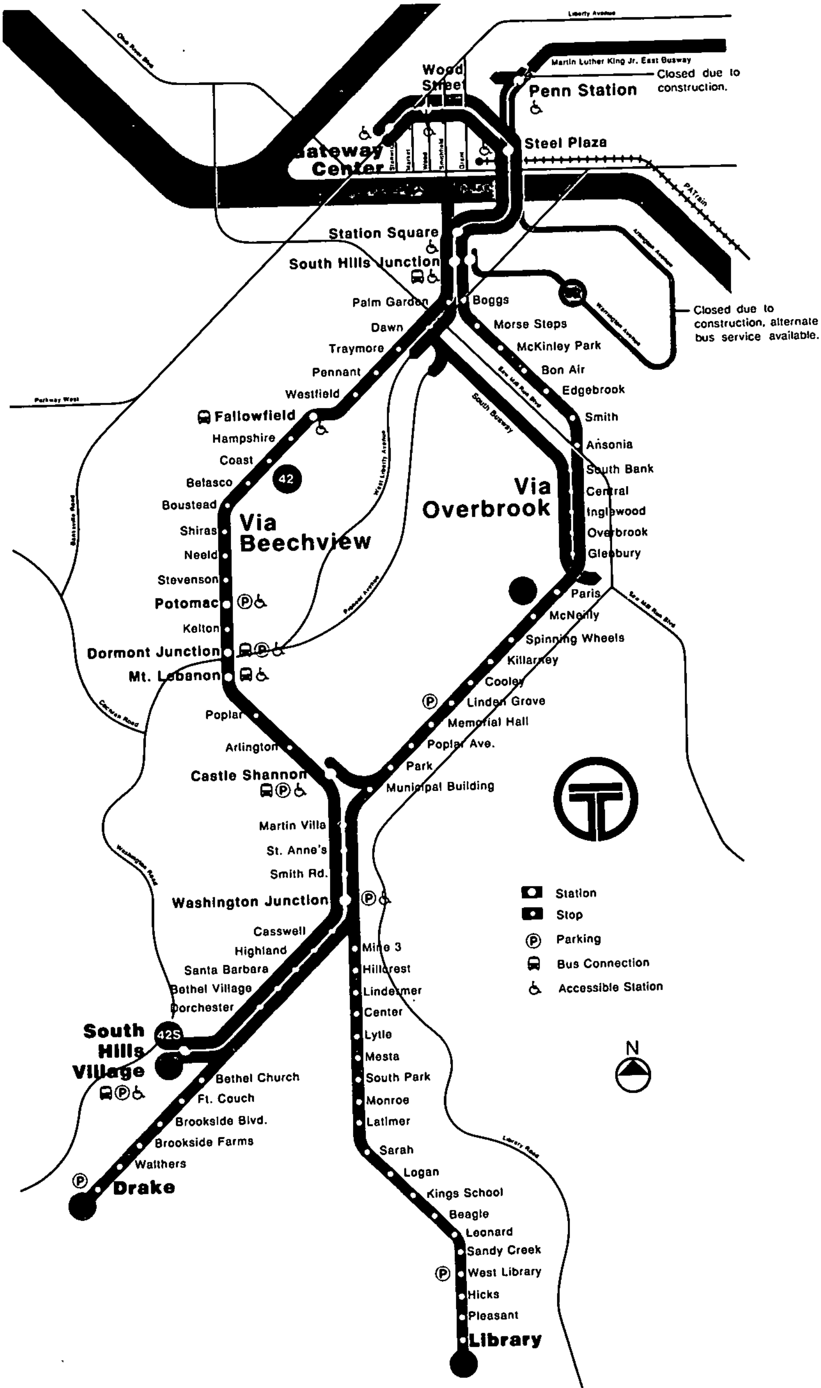

FIGURE 1 Pittsburgh's light rail transit system.

new construction—the first trolley line built in Pittsburgh in more than 50 years.

To maintain as much rail service as possible during the construction work, the lines were built, or rebuilt, incrementally. Construction on the downtown subway was accomplished with minimal interference while trolleys continued to operate on the streets. Reconstruction of the line outbound from Castle Shannon was performed simultaneously with construction of the new line to South Hills Village and construction of the 62-acre yard, shop building, and operations control center at the village. Once these contracts were completed, the base of operations was moved from the 1906 South Hills Junction Car House to the new facility. Work then progressed on rebuilding of the Mt. Lebanon line.

The downtown subway was put into operation on July 7, 1985, taking rail vehicles from downtown streets for the first time in 126 years. President's Conference Committee (PCC) cars had provided all the revenue service until November 1985, when the new articulated light rail vehicles (LRVs) were placed into shuttle service between the three downtown stations and Station Square.

Eventually, three LRVs were required to handle a rapidly developing lunch-time rush hour that grew as downtown workers and shoppers discovered how easy it was to hop the subway to cross the river to Station Square, a collection of trendy shops and restaurants in a renovated railroad station. Although this shuttle operation gave PAT a chance to gain some experience with the cars and the new system, the acid test really did not begin until May 1987. So, when PAT attempts to determine how well the LRVs are performing, it has a vast amount of experience from limited operation and a limited amount of experience from full operation to draw on.

GENERAL DESCRIPTION

At present, the LRVs operate over a 10.5-mi right-of-way (the downtown subway, the Mt. Lebanon line, and the South Hills Village line, with PCC cars handling the remainder of the routes. The LRV route, or the 42S, includes several miles of street running, a number of grade crossings protected by crossing flashers, grades as steep as 9 percent, three tunnels, and approximately 1.3 mi of joint running with buses on the South Busway. The entire line is double tracked. Signaling is accomplished through automatic track circuits, augmented by remotely controlled signals, all providing double block protection supported by automatic trip stop equipment.

Automatic route selection through the 17 interlockings along the line is accomplished with train-to-wayside (TTW) equipment that not only routes the vehicles but also provides a record of their progress to the movement directors at the operations control center (OCC).

The system combines state-of-the-art vehicles with PCC cars built in 1949. Because both types of cars share parts of the trackage, various LRV components had to be retrofitted to the PCC cars, including the TTW encoders, trip stop devices, and pantographs. The decision to operate a mixed fleet (45 PCC cars and 55 LRVs) was a result of both political and financial considerations. The rehabilitation of the entire rail system would have been astronomical in cost; therefore, it was tackled in two stages. Stage 1 is now complete, and Stage 2 planning is about to begin. One very evident result of this multistage reconstruction is the design of the LRVs, notably the single street-level door on each side of the vehicle. This door is used to load and unload at a number of lightly used stops and, of course, does increase dwell and running times. But the public wanted the convenience of "traditional" stops rather than high speed.

THE VEHICLE

The competitive bidding process resulted in the choice of Siemens Duewag to construct the 55 double-ended LRVs. The cars are 84 ft (25.81 m) long; 8 ft 9 in. (2.68 m) wide; 12 ft 5 in. (3.66 m) high; and weigh 43 tons (39 008.74 kg). Each vehicle seats 62 but can accommodate 263 passengers in crush load conditions. The vehicle is powered by two 100 hp motors fed by the 650 volt dc overhead. Acceleration and speed control are via a chopper system, and braking is controlled through a modulated computer system. The vehicles have three distinct, but integrated, braking systems. The dynamic force produced by the motors slows the vehicle to less than 5 mph. Friction brakes then bring the vehicle to the final stop. Magnet rail brakes are used for holding and to assist in emergency stopping. Up to three vehicles can be operated as a train. Most functions, except for traction power and lower platform door control, are trainlined.

TRAINING

The introduction of LRVs into a system served by PCC cars was not as difficult as one might think. Although the vehicles are as different as 50 years of technology could make them, many of the operating techniques are the same. Training began early for the instructors and road operations personnel. Operators also received extensive qualification time on the vehicles and on the new line segments as they became operable. A special task force was created from personnel in the operations, training, and safety divisions and charged with the responsibility of writing operating procedures for all employees connected with the system.

Formal technical training began for car house and other maintenance personnel at a much later time, although virtually all of the PAT personnel worked with the vehicle manufacturer's representatives and gained much knowledge through this contact. Although road operations personnel received some training in troubleshooting, it was subsequently decided that the cars were complex enough that roving vehicle technicians were required to minimize road delays. These technicians, who have radio-equipped trucks, can respond to the location of a vehicle, locate the trouble, and, it is hoped, have the vehicle on its way before serious delays occur.

OPERATING EXPERIENCE

As mentioned earlier, PAT's first revenue experiences came from operation of the subway local shuttles. Three cars were scheduled for this service but were rotated out on a weekly basis. Because the intended use line, the 42 line, was not yet completed and because of load restrictions on the PCC route, these vehicles were moved weekly over the PCC line after regular service hours. This procedure usually took place late Sunday of each week. Three fresh cars left the rail center at South Hills Village and the three service cars from the past week were taken back. A temporary vehicle pit was set up outside the Penn Park side of the system to accommodate daily maintenance and troubleshooting.

BRAKING SYSTEM

The pit got a workout as operators started reporting a braking problem. As the vehicle slows for a typical service stop, it decelerates to approximately 3 to 5 mph through dynamic braking. As the car reaches this speed, the dynamic braking becomes ineffective and the friction or disc brakes take over. This slows the car to a stop but, just before the final stop, a computerized control releases, then reapplies, the disc brake to alleviate the jerking typically felt when a large vehicle comes to a stop. Instead of experiencing this smooth stop, some of our operators reported a release of the disc brake and no reapplication. The car drifted through stops until the final brake—the magnetic rail brake—was applied. This rail brake application caused considerable jerking and an uncomfortable stop. This was happening at the final stages of deceleration and consequently the cars were merely creeping. To make matters worse, it was an intermittent problem, making it hard to fully understand.

Although the failures were not deemed to be of a safety-critical nature, the cars were removed from service until the situation was fully understood. Intensive testing and investigation pointed to some components of the computerized braking system, specifically the EPROMs (erasable, programmable, read-only memories). The problem was further traced to the vehicle's reverser switch. It was found that if the reverser was turned to neutral during the final disc brake release, but prior to its reapplication, the EPROMs were set for failure. With this information, the brake manufacturer was able to reprogram its system to prevent this from happening again.

DOORS

Although the new line still lacked some of the finishing touches, PAT was given an unexpected opportunity to operate it in March 1987 when a landslide, caused by an undetected water line leak, forced the closing of the Overbrook Line. Cars operated via the new alignment for three days, providing passengers with a preview of coming attractions.

Prior to the May opening, PAT had three months for operator training and general debugging of the line and cars. PAT operators did have limited operating experience, but these training exercises helped to uncover additional problems. One such problem was the doors.

Each LRV has a total of eight doors, three high-platform type and one low-platform type on each side. The high-platform doors are controlled from the operator's cab or can be set on "release" to allow passenger operation by buttons located at each door. When not in the "release" mode, these inside buttons act as stop requests. The operator not only can elect for patron door operation, but also can select to open all doors or just the front high-platform door. Whichever mode the operator decides to use, the side of operation must be chosen. The system has two center-platform stations that require the operator to select the left-side doors rather than right-side doors. In the case of the low-platform door, it has one capability only and that is to be open or closed on the end of operation. All doors close with a warning "beep" followed by a 3-sec delay and have exterior open indication lights and sensitive edges.

The sensitive edges led to one of the first door problems. They were too sensitive. This was a bothersome problem, as the edge would continually cycle the affected door and prohibit further operation of the vehicle until the problem door was cut out of service. This cut-out is accomplished by opening the circuit breakers associated with that door. This problem was easily fixed by adjustments to the sensitive edging and door hang. In the case where the problem arose in the central business district (CBD), a maintainer handled it at the temporary pit. If it happened during the exercising of the system, it was noted and adjusted at the South Hills Village Rail Center.

In addition to the one just mentioned, another door problem developed. As cold weather operating hours began to build up, so did slush. It was discovered that slush would accumulate on the thresholds of the doorways and freeze. When the door was closed, the sensitive edge would hit this hardened lump and the door would recycle and continue to recycle until the obstruction was cleared. This problem exists today. Operators are instructed how to clear the problem, but this can cause service disruptions if the procedure is lengthy. The permanent solution is to install the threshold heaters that were omitted from the final design.

As mentioned in the line description, the low-platform door has a large impact on the overall system speed because of its contribution to lengthy dwell times. To explain this a little further, out of 50 stops along the right-of-way, there are 40 low-platform stops. The impact of these low-volume, low-platform stations is two-fold. First they can be served by only one narrow door and second, the entrance steps are higher than people are accustomed to. Put this all together and longer-than-desired dwell times result. A solution would have been to have folding steps at the high-platform doors, similar to those used in Buffalo and Portland, to serve the longer platforms better. Another would be to eliminate the low-platform stops. But, during the planning stages of the system and during the public hearings, the people who use the system testified that they wanted the low-platform service. Although faster running is desirable from a transit person's point of view, the passengers seem quite content with what they asked for.

AIR CONDITIONING

Each vehicle is equipped with two roof-mounted Sutrak air conditioning units, one on each car section. The condenser coils are part of the roof-mounted system, with the compressors on the undercarriage. Because the compressor and condenser are separated vertically by more than 12 ft, problems with liquid migration and "slugging," small frozen blocks of freon, have caused premature compressor failures on a number of the cars. Not only have compressor problems arisen, but condensation discharge was experienced, too. During hot, humid days, condensation from the roof coils languished in the drip pans and "rained" on the passengers and lighting. Better sealing of the pans and drip path easily solved this problem.

Although air conditioning continues to be an ongoing problem, thanks to the willingness of the manufacturer of the air conditioning units to work with us, the passengers have been reasonably cool and therefore happy.

CORROSION

Corrosion is currently a problem on the undercarriage of the vehicle. Signs of early corrosion are appearing on critical piping, valves, and the understructure itself. The car builder is working with PAT to solve this problem and, as with most of our vehicle debugging, we anticipate a timely professional solution.

COMMUNICATION

Communications within the vehicle are threefold. A public address (PA) system is used within the car, an intercom system allows communications between coupled cars, and a third system allows communications between the vehicle and the OCC.

All of these functions are handled through the mobile data unit (MDU), located to the front and the left of the operator. There are two MDUs per vehicle—one in each cab, with one radio transmitter/receiver centrally located. Communication between the vehicle and the OCC is accomplished in one of three ways. When the car is within the confines of the rail storage yard, the operator selects the yard channel using the radio control panel to the left rear. Once the car leaves this designated area, the operator selects one of two modes. The OCC determines which will be used. As the vehicle leaves the yard, the OCC instructs the operator to switch to either the operations channel or the support channel.

The support channel is a contention-type system with all vehicles tuned in. That is to say, if the OCC wants to call car 4102, the movement director calls the car number over the air and all vehicles receive the transmission. However, only 4102 should respond. If the operator needs to talk to the OCC, the reverse occurs.

Should the OCC request that the operations channel be selected, all communications are controlled through the computer-aided dispatch (CAD) system. Through CAD, if the OCC wants to talk to car 4102, the movement director enters the car number into the computer with a keyboard and pushes the "call train" button. A data message is sent to the specific car being called and "beeps" the MDU. This signals the operator to pick up the handset and talk. Should the operator need to call the OCC, a "request to talk" button is pushed and basically the reverse happens. The movement director gets "beeped," the car number appears on the screen and, when the call is acknowledged, the operator and the director talk. At no time do the other cars receive messages as they do on the support channel.

Other CAD functions are mechanical alarms, emergency highlighting, silent alarms, canned messages, and PA announcing to one or more cars from the OCC. At this writing, this IAL/Comstock system is not on line because of numerous technical problems. The system failed a 50-day validation test and discussions are currently under way with the system's manufacturer and subcontractor.

AUTOMATIC TRIP STOP

Rear-end protection is accomplished through an automatic trip stop (ATS) system. This frequency-controlled system detects signals from wayside equipment located at each signal. If the operator violates a red or dark aspect, the car is automatically tripped and brought to a full service stop. The operator must reset the car according to established procedures and continue the run. Each time the car is tripped, a counter on the control panel advances one increment. Should a problem arise on the wayside equipment in that a signal is holding red, the vehicle can "key by" the signal by pressing the key-by button on the control panel. The vehicle then has 20 sec to advance past the fault. This function is also monitored through the use of a counter.

There have been some problems with the system in that stray signals in certain areas are causing false trips. This, coupled with the lack of experience in resetting the equipment, has lead to some lengthy delays. With the continued cooperation of the signal equipment manufacturer, and as PAT operators gather experience, this two-block, rear-end protection should prove to be a beneficial public safety device.

TRAIN TO WAYSIDE

Our rail network is somewhat complex, with a number of interlockings and switches. To maneuver vehicles through these areas safely, a computerized routing system was installed. This system reads signals from the vehicle through wayside detector loops and safely routes the car, locking out any conflicting moves. This equipment is known as TTW (train to wayside).

The car-borne control panel is located to the right of the ATS panel and consists of a three-digit dial encoder. All routes on our system can be described by using a three-digit number. Once this number has been entered, the wayside computers do the rest.

Wayside equipment is located on the track just prior to an interlocking and is connected to the routing computer at that interlocking. These computers are housed in heated signal rooms at the interlockings and can be manually taken over either at the control panel in the signal room or from the OCC. By and large, the car-borne equipment is functioning well. Some field debugging is still under way. PAT is confident that this system will function up to its potential.

PERFORMANCE

PAT's "T" system is definitely an asset to the city of Pittsburgh and Allegheny County. In its short existence, the LRV fleet has given the passengers a quiet, comfortable, and safe ride. The operators have also overcome the natural tendency to reject anything new or different and have grown to appreciate the vehicle.

The public at large also has accepted the system with open arms. Ridership as of March 1988 averaged 28,000 per day, considerably ahead of the consultant's projections. Although there are more than 2,000 spaces at the free park-and-ride lots, these are generally filled before 8 a.m. each day. The public's excitement with a subway and rail system that took nearly 80 years to build was evidenced during the July 4, 1985, grand opening of the subway. It wasn't—and still isn't—unusual to see entire families riding mass transit for the first time. PAT is looking forward to a bright future and has begun taking the initial steps toward extending the line to both the North Side and East End.

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Assessing the Performance of Portland's New Light Rail Vehicles

DENNIS L. PORTER

Tri-Met, the transit operator in Portland, Oregon, has recently completed construction of a new light rail system and put into revenue service a fleet of new light rail vehicles (LRVs). Descriptions of the LRV procurement process, the context in which it occurred, and various technical information concerning the LRVs are provided as background. A review of the performance of the LRV fleet during the first 12 months of revenue service is provided. Parameters such as reliability, availability for revenue service, energy consumption, ridership, and operating costs are examined. Particular emphasis is placed on the reliability demonstration plan (RDP)—which Tri-Met is using to monitor LRV reliability—and trends in the RDP numbers are analyzed. A brief comparison of certain productivity measures for Tri-Met bus and light rail operations is made.

THE BANFIELD LIGHT RAIL Transit (LRT) Project is the outgrowth of years of planning to improve the transportation conditions on the rapidly growing East Side of the Portland metropolitan area. It included rebuilding the existing Banfield Freeway and construction of a new LRT line 15.1 mi long from downtown Portland to the suburban community of Gresham.

In the 1970s a proposed freeway in southeast Portland was withdrawn from the Interstate system and the bulk of the funding was made available to support transit corridor projects. Planning studies were started in 1976, and the UMTA alternatives analysis process was completed in 1979 with Banfield as the priority corridor and light rail as the preferred mode. Final design was initiated in 1981. Construction was under way by 1982. The system opened for revenue service in September 1986.

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

Because of the freeway rebuilding and use of Interstate transfer funding sources, the overall Banfield LRT Project was managed jointly by the Tri-County Metropolitan Transportation District (Tri-Met) and the Oregon Department of Transportation (ODOT). In general, ODOT was directly responsible for the freeway rebuilding and Tri-Met for the transit portions, although there were many areas of overlap and shared responsibility.

The budget for the overall Banfield LRT Project is approximately $321 million, the transit portion claiming approximately $214 million. The light-rail vehicle (LRV) contract represents approximately 12 percent of the total transit portion. As of June 1988, the project was 99 percent committed and 97 percent expended. Depending upon settlement of claims, the total cost of the project may underrun the budget.

The LRT line encounters a variety of right-of-way (ROW) conditions, including downtown city streets, the median of an existing bridge, a side ROW adjacent to a one-way city arterial, a freeway ROW, a median ROW in a county arterial, and an abandoned railroad ROW. Two-thirds of the line is at-grade with numerous street crossings, and one-third is fully grade-separated adjacent to the Banfield Freeway. There are no subway sections. With minor exceptions, vehicular traffic is not permitted to share the LRT ROW and is physically separated by small curbs and other protective measures. Along the at-grade segments, the LRVs generally either have the opportunity to preempt traffic signals to optimize operations through intersections or have gated protection. For construction purposes, the LRT line was broken into four distinct line sections, eight civil/trackwork contracts, and nine major equipment/facility contracts, including the LRVs.

The downtown Portland segment imposes the majority of ROW and operational constraints found along the whole line. Block lengths are short (normally only 200 ft, property line to property line), thereby limiting overall train length; and streets are narrow (normally 60 ft, property line to property line), thereby requiring tight turning movements. There are also tight vertical and horizontal clearances where the line runs under the ramps and between the piers of two existing bridges. The downtown alignment includes a one-way loop on two adjacent streets.

The steepest grade is approximately 7 percent for 600 ft, and there are several grades of 3 to 5 percent. The minimum horizontal radius is 82 ft and occurs at four locations downtown.

There are 25 stations, yielding an average spacing of 0.6 mi. Station platform length is approximately 200 ft, and platform height (for boarding) is low, approximately 8 in. above the top of the rail at all stations. There are island platforms—left-hand, right-hand, nearside, and farside platforms, depending upon the ROW conditions. A self-service fare collection system with off-vehicle validation and on-vehicle inspection is used. Accessibility for handicapped persons is provided by a wayside lift, which is mounted on each station platform and raises a wheelchair from platform level to LRV floor level. LRT service and bus service are fully integrated, with numerous transfer points and a common fare structure. Five park-and-ride lots were built along the outer half of the line.

LRV PROCUREMENT

Predesign studies, wayside conditions, and operational preferences determined the basic type of vehicle to be procured—a large, articulated, double-sided, double-ended car. In early 1980 Tri-Met, with the assistance of the consulting firm of Louis T. Klauder and Associates, began the process of procuring the LRVs and related equipment and services. Tri-Met sought a procurement that would be competitive, conform to UMTA regulations, and yield an LRV based as much as possible upon proven design. After research of various railcar procurements, Tri-Met elected to use a two-step procurement process.

The first step of the process included issuance of a performance-oriented request for technical proposal (RFTP) by Tri-Met, submittal of technical proposals by interested car builders, evaluation of those proposals, and determination of which proposals were acceptable to Tri-Met. The technical proposals contained no prices or references to prices. The second step included issuance of the invitation for bid (IFB) by Tri-Met to acceptable proposers, submittal of bids, award of the contract by Tri-Met to the lowest bidder, and contract performance.

Before the RFTP was officially released, an extensive industry review was conducted and comments were received from numerous car builders. Four proposals were eventually received, and, after a 4-month evaluation, two were found acceptable. These were from Bombardier of Canada and Siemens of West Germany.

Bids for 26 cars, spare parts, tools, training, etc., were received in May 1981. Bombardier offered the low bid at $775,521 per car for a total amount of $21,662,212, including all incidentals. Contract award was made in September 1981. Contract provisions also allowed for escalation according to Bureau of Labor Statistics indices and specified formulas. During the course of the contract, escalation amounted to an additional $1,363,487 and change orders to approximately $650,000 (or only 3 percent). A separate modification for $650,000 required the car builder to purchase some equipment previously planned as district-furnished-equipment (DFE), raising the total contract to about $24.4 million. Also, Tri-Met supplied other DFE, such as radios, which raised the total cost to approximately $24.7 million.

Bombardier Fabrication Plan

For the Tri-Met contract, Bombardier operated under a license to the Belgian firm of Constructions Ferroviaires et Métalliques, known as BN. BN was the overall designer of the Portland LRV, particularly of the car body structure and trucks. In addition, under separate contracts, BN acted as a subcontractor and supplied Bombardier with certain components such as the truck frames, articulation, door panels, gearbox assemblies, etc. The Portland LRV is basically a stretched and otherwise modified version of the pre-Metro cars built (partially) by BN for Rio de Janeiro in the 1970s. Truck and articulation design were derivative from the Rio car and from other BN designs.

Propulsion system design and supply of hardware were by the BBC-Brown Boveri Company of Switzerland through its North American subsidiary. The Portland traction motor was based on the BBC motor for the Breda LRVs in Cleveland, although there are significant differences. The switched resistor propulsion control system is based on that of certain Swiss railways. Several other components (pantograph, door operators, slewing ring, suspension, etc.) were French or German in design and manufacture, making the Portland LRV very much European in origin.

Major car body subassemblies such as the roof, side walls, and parts of the underframe were fabricated at Bombardier plants in Quebec. Underframe assembly, shell assembly, equipment installation, car wiring, interior finishing, painting, final assembly, and static testing were accomplished at a new Bombardier plant in Barre, Vermont. Trucks were also assembled and wired there.

As previously stated, the contract was awarded in September 1981. Fabrication of the first underframe was started at Barre in autumn 1982 and the first car was moved under its own power in November 1983. Initial proof-of-design testing occurred at the Transportation Test Center (TTC) in Pueblo, Colorado, in early 1984. Table 1 summarizes the major LRV contract milestones.

LRV Description and Performance

The Portland LRV is a six-axle, single articulated car that is double-sided and double-ended. There are four double-wide, low-level doors per side. The car is approximately 89 ft long, 8 ft 8 in. wide, and weighs 90,000 lb (empty). There are 76 seats and room for 90 standees (at 4 passengers/m^2) for a design capacity of 166 passengers. Crush capacity is 256 passengers total. The car is designed for single-unit or multiple-unit operation in consists of up to four LRVs, although revenue operation is limited to two-car trains by the short downtown blocks.

TABLE 1 LRV CONTRACT MILESTONES

September 1980	Request for technical proposals issued
December 1980	Technical proposals received
March 1981	Acceptable proposals determined
May 1981	Bid
September 1981	Contract signed
October 1982	1st underframe fabrication started
December 1982	1st shell assembled
Spring 1983	1st articulation, undercar equipment, and interior equipment installed
June 1983	Carbody compression test performed
Fall 1983	1st trucks installed
November 1983	1st car final assembled
December 1983	Car #101 shipped to TTC for dynamic testing
April 1984	1st car (#103) arrived in Portland via TTC
August 1984	1st car (#102) arrived directly from Barre
Fall 1984	LRV testing started
1985	Delivery and testing
May 1986	1st car accepted, reliability demonstration plan started
October 1986	Last car accepted
Summer 1988	Reliability demonstration plan complete
October 1988	Basic warranty complete

The track gauge is standard 4 ft 8½ in. and the overhead voltage is 750 v dc nominal. The LRV operating range is 525 to 875 v dc. The required minimum horizontal curve radius is 82 ft.

The car body was constructed of low-alloy high-tensile-strength (Corten) steel. The floor structure includes corrugated sheet metal, treated plywood, and rubber flooring. It passed the flammability requirements of a modified ASTM-E119 test. The cushioned seats are on stainless steel frames, and the interior uses melamine-type panels with some fiberglass sections.

The trucks are welded steel structures from BN with rubber suspensions, in-board bearings, one brake disc per axle, and resilient wheels. The primary suspension is a rubber toroid (doughnut) from Clouth, and the secondary suspension is an inverted chevron with alternatively stacked plates of rubber and metal. The resilient wheels are from Penn Machine/Krupp and have a tire and hub separated by rubber blocks in compression to reduce wheel squeal on sharp curves. The center truck is free-wheeling. The motor truck is a mono-motor design with a right-angle drive on each end. A flexible coupling from BBC connects the gear box to the axle. A single race ball bearing slewing ring attaches the motor truck bolster to the car body, while the center truck uses a double race slewing ring to permit both car halves to rotate relative to each other and to the truck.

The BBC traction motor is a four-pole series dc motor with a continuous rating of 198 kW and 280 A at 750 v dc and 1,780 rpm. The motor is self-ventilated. The BBC propulsion control system employs a switched resistor arrangement with contactors controlled by an electronic control unit (ECU). There is no mechanical cam and no regeneration. Parallel operation of the motors is permitted in the two highest motoring positions. A unique feature of the BBC control system is its rate feedback system. The system tries to satisfy the rate request from the master controller handle regardless of vehicle load or wayside conditions (i.e., grades, etc.). Thus there is no explicit load weigh input for normal service propulsion control. Instead the system utilizes the measured vehicle acceleration (deceleration) rate in a feedback loop as an implicit indication of passenger load.

Top speed of the LRV is 55 mph with an overspeed control set at 58 mph. The maximum acceleration rate is 3 mph/sec, and the car reaches 50 mph in about 29 sec.

New York Air Brake provided the friction brake system, which features a spring-applied, hydraulically released disc brake on each axle and track brakes on each truck for use in emergency stops. The disc brake system uses one pump and control valve per truck. These three control units are car-body-mounted under the floor and adjacent to their respective trucks. Service braking is provided by dynamic braking on the motor trucks and supplemental disc braking on the center truck if necessary, that is, for passenger loadings above approximately an AW2 level (i.e., 76 seated plus 90 standees). Emergency braking is provided by disc braking on all trucks, track brakes, and automatic sanding. Spin/slide and jerk limit features are not present during emergency braking. A 4 mph/sec to 6 mph/sec rate, depending on entry speed, is required during emergency braking. Because propulsion (rate) control is effectively disabled during emergency braking, a separate load weigh system is used to modulate emergency brake rate as a function of vehicle load.

The door system is a swing plug design much like that on the General Motors Advance Design Bus with the door operator provided by Faiveley. Dellner provided the fully automatic coupler, which features a cantilever suspension, retractable electric heads, and a self-centering mechanism.

Certain portions of the Banfield LRT line have track circuits and a block signal system with wayside signals protected by an automatic trip stop (ATS) system. The ATS system uses wayside permanent magnets and on-board antennas mounted on the center truck and was provided by Siemens of West Germany. Violation of a red signal automatically brings the LRV to a stop at maximum service brake and indexes a counter.

The Portland LRV also carries a solid state data recorder, purchased separately by Tri-Met and installed by Bombardier, which continuously records certain trainline signals for purposes of testing, operator surveillance, and accident documentation.

RELIABILITY DEMONSTRATION PLAN

During the RFTP process, some consideration was given to life-cycle concerns by including in the LRV contract a requirement known as the reliability demonstration plan (RDP). As the name states, this requirement was an attempt to ensure that, in addition to meeting the traditional criteria for acceptance of cars, the car builder had an obligation to demonstrate the overall reliability of the cars in simulated or actual revenue service after initial acceptance.

The duration of the RDP was set to coincide exactly with the warranty program and runs from start of warranty on the first car until end of warranty on the last car. Individual LRV warranty is 2 years; thus the RDP period is approximately 2½ years, from May 1986 until October 1988.

Recognizing that defining and determining reliability could be complicated, controversial, and possibly counterproductive under the wrong circumstances, Tri-Met sought a simplified approach to the RDP and one in which the car builder would also benefit by its participation and cooperation. Tri-Met's intent also was and is to have a system that is easy to administer and that relies more on common sense and practicality than on theory and literal interpretation. Other more detailed and more scientific approaches might work or might be more appropriate in other circumstances. But the Portland fleet size is small, as are Tri-Met's staff resources for administering the RDP, so increased complexity was just not a possibility. With Bombardier's assistance, the RDP was fully implemented in June 1986 and already has provided much useful information to both parties. The experience has been that about 8 hours of engineering time per week and an equal amount of clerical time are required to administer the RDP.

The primary statistic used to assess reliability is mean distance between failures (MDBF) for the fleet during the RDP period. "Distance" of course is relatively straightforward to record, but "failures" requires some machinations. As described below, data are collected and processed on an ongoing basis, and total fleet mileage is divided by total fleet failures (during the same period) to yield the fleet MDBF. Complicated formulas, computations, data collection, and interpretations have been avoided, yet MDBF seems to be providing a reasonable enough measure of overall reliability to assess major trends and problem areas.

Mileage on each car is read from hub odometers by Tri-Met maintenance personnel on a weekly basis. Under Tri-Met's service plan less than 1 percent of mileage accrued is nonrevenue mileage. Also, accuracy and consistency of the hub odometers have proven sufficient for the RDP purposes. Therefore, little or no massaging of the raw mileage data is required. Since start of revenue service, the 26-car fleet has been operated on average approximately 26,000 mi per week or 1,000 mi per week per LRV. This is about 30 percent higher than estimated in the planning stage and is primarily due to higher ridership than estimated. System mileage as of June 1988 was about 2.5 million.

Concerning failures, the RDP considers any failure relevant for MDBF accounting if revenue service of the offending train is interrupted or delayed by more than 4 min as a direct result of the failure, provided there is no negligence on Tri-Met's part in either operation or maintenance of the equipment. Secondary or follow-on problems are not double-counted. Problems in the storage yard and maintenance facility are counted as relevant failures only if the train is actually entering service. Problems uncovered during normal preventive maintenance checks are not counted. Failures due to "normal" wear-out of components or consumables (e.g., headlights) or due to DFE are also not counted as relevant failures.

Within these general guidelines, Tri-Met and Bombardier have cooperatively worked out a process whereby each recorded problem is reviewed by both parties and mutual agreement is reached as to whether or not the problem is to be counted as a relevant failure for RDP purposes. The important point is that the decision on relevancy of failures is not unilateral on Tri-Met's part but includes consideration by the car builder. Approximately one-third of the problems (trouble tickets) recorded in the system so far have been determined to be relevant failures.

Compilation and processing of all RDP data have been implemented on a local-area network (LAN) of personal computers at the light rail operations facility. A special applications program, known as 3LRV, was developed on the LAN using the GURU software package to record, compute, and output all pertinent RDP parameters. 3LRV was developed to be a hierarchical, menu-driven, user-friendly data base management program.

Mileage and LRV problems (trouble tickets) are input weekly to 3LRV. Each LRV problem is defined by car number, date of occurrence, unique (trouble ticket) number, description of problem, affected system by code in accordance with car builder designations, whether or not the problem is determined to be a relevant failure, and other information related to the warranty program. In turn mileage, failures, and MDBF can be output on an individual car or fleet basis or on a weekly or yearly or cumulative-time basis, or—in the case of failures—can be sorted by system type or trouble ticket number. An example of output is given in Table 2.

Prior to start of revenue service in September 1986, about 120,000 mi had been accrued on the fleet, much of it in testing cars. In addition to the

TABLE 2 WEEKLY OUTPUT FROM 3LRV DATA BASE

MEAN DISTANCE BETWEEN FAILURES 09/10/87

Car	Rel.Fail	R.D.P	Mileage	/Current	M.D.B.F
101	11	52091	65045	09/03/87	4736
102	6	60496	63651	09/03/87	10083
103	10	55696	57882	09/03/87	5570
104	9	52199	52786	09/03/87	5800
105	13	56834	58588	09/03/87	4372
106	15	57953	60993	09/03/87	3864
107	14	58193	60141	09/03/87	4157
108	10	57124	58303	09/03/87	5712
109	10	58576	61778	09/03/87	5858
110	13	56996	61509	09/03/87	4384
111	6	56590	57620	09/03/87	9432
112	11	58484	59606	09/03/87	5317
113	8	55402	56441	09/03/87	6925
114	9	51346	53008	09/03/87	5705
115	11	55665	57532	09/03/87	5060
116	7	59690	62485	09/03/87	8527
117	10	52946	54766	09/03/87	5295
118	8	54508	56601	09/03/87	6814
119	9	61543	63500	09/03/87	6838
120	6	54888	57040	09/03/87	9148
121	5	52104	54480	09/03/87	10421
122	8	57116	58180	09/03/87	7140
123	13	51662	52848	09/03/87	3974
124	6	50809	51257	09/03/87	8468
125	12	55612	57191	09/03/87	4634
126	10	46148	47247	09/03/87	4615
Total:	250	1440671	1500478		5763

Week Mileage :	32450
Week Failures:	1
Week MDBF :	32450

performance testing, as part of the acceptance program each LRV was operated approximately 1,500 mi in a burn-in cycle that simulated revenue service and repetitively exercised most of the car systems. Mileage and failures during testing and burn-in were not included in RDP calculations, and the burn-in process was used to help identify and correct "infant mortality" and other problems not uncovered during the inspection process. About 70,000 mi of the total prerevenue service mileage was actually RDP mileage. The initial failure rate, despite the burn-in program, was reasonably high and a cause of concern to Tri-Met.

Figure 1 shows the cumulative MDBF from the beginning of the RDP in May 1986 through September 1987. It is evident from Figure 1 that there has been a significant improvement in reliability since the cars were first put into revenue service; cumulative MDBF nearly trebled, from approximately 2,000

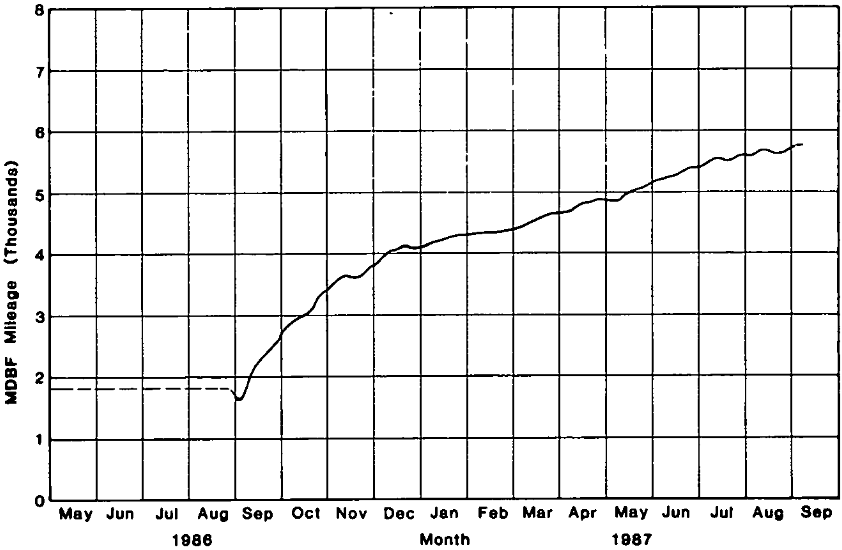


FIGURE 1 Cumulative mean-distance-between-failures data.

to almost 6,000 mi in about 12 months. As of early September 1987, the cumulative MDBF was 5,763 or an average of one failure approximately every day and a half. Figure 2 also shows the cumulative MDBF, first from the start of revenue service and second from January 1987, thereby discounting the higher failure rates present in the very beginning of the RDP program (e.g., summer 1986). For these time periods MDBF has been 6,323 and 7,523, respectively, which corresponds to about four relevant failures a week or every 26,000 mi. By June 1988, cumulative MDBF had risen to approximately 7,600, while MDBF for calendar year 1988 through June was in excess of 15,000. Figure 3 shows the monthly (noncumulative) MDBF through September 1987 and also portrays the improvement in a more aggregated way.

These data show that approximately 12 percent of the relevant failures through September 1987 occurred during the first 4 months or, using mileage as a measure, the first 4 percent of the RDP. The improvement in MDBF is a direct function of the car builder's modification program, which in turn is in response to collection and presentation of reliability data. Bombardier and Tri-Met have established an MDBF objective of 7,500 mi at the end of the RDP. On the basis of trends established to date and discounting the higher incidence of failures in the first few months, it appears that this goal will be achieved. In fact, discounting the first 4 months, the 7,500-mi objective will probably be well exceeded.

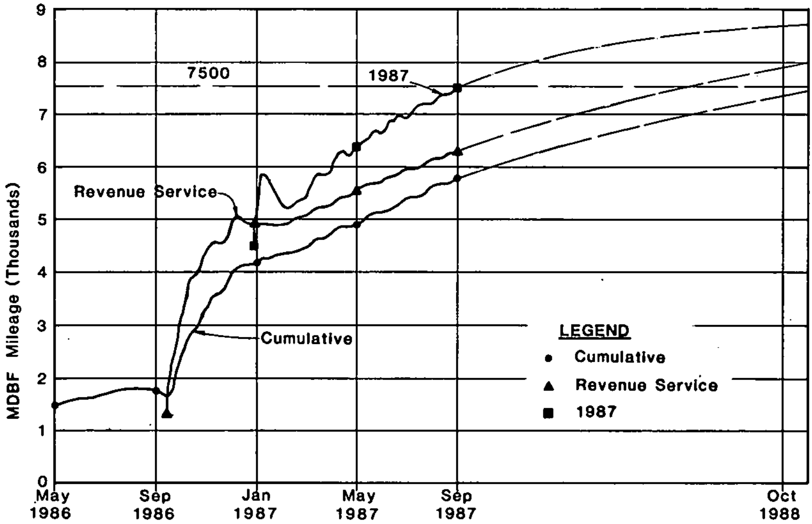


FIGURE 2 Cumulative and revenue service MDBF data.

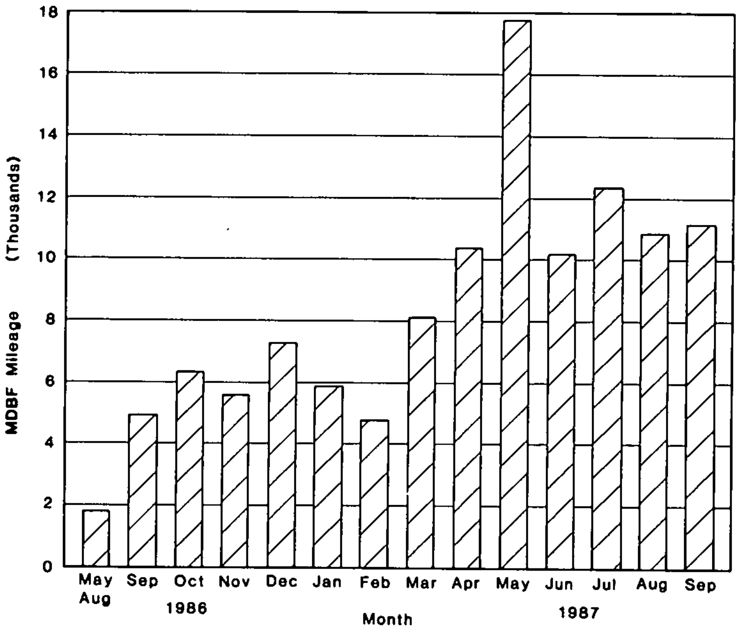


FIGURE 3 Monthly MDBF (noncumulative).

In effect the RDP has served as a management information system. For example, Figure 4 provides a breakdown of the total number of all trouble tickets and relevant failures for each major system in the car, thereby helping to establish priorities for change. Problems with the friction brake and propulsion systems have resulted in the highest incidence of relevant failures. Accordingly four major fleetwide modification programs have been implemented that have resulted in reduction in brake and motor failures and contributed to the improvement in MDBF.

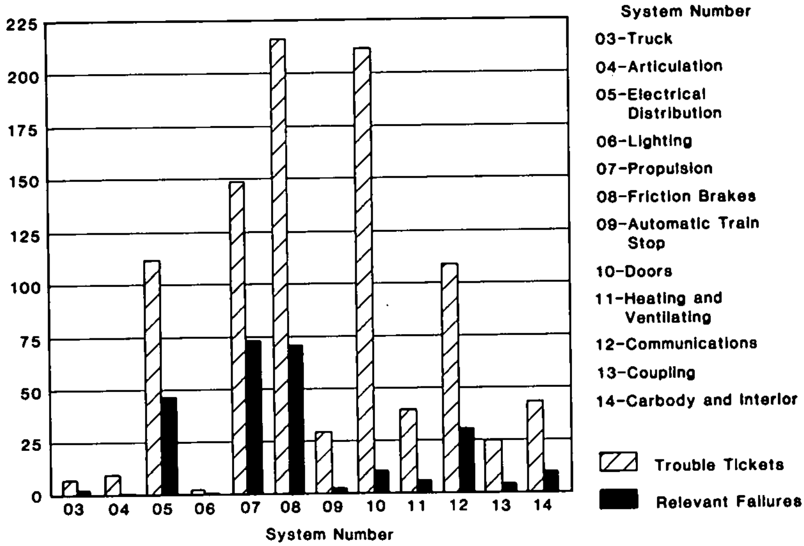


FIGURE 4 Failures per system.

Had time and resources allowed and with hindsight as a guide, Tri-Met's experience is that it would have been desirable to extend the burn-in mileage to at least 5,000 mi per car prior to acceptance to more thoroughly exorcise the early problems. Initially the Portland LRV was not as proven a design as Tri-Met had intended from the RFTP process. Many critical systems, such as the friction brakes and doors, were derived from earlier designs but had not actually been used before in the exact Portland configuration. The propulsion supplier and the friction brake supplier had not worked together before, and the critical propulsion/brake interface required substantial development. The car builder's assembly plant was essentially a new plant experiencing its own learning curve. The result of these factors was a relatively high incidence of problems as the trains first began to accrue mileage. The improvement in MDBF is a tribute to the diligence of both the car builder's and Tri-Met's staffs in identifying, troubleshooting, and correcting problems on both an ad hoc and a systematic basis.

Another indication of reliability of the cars is availability of cars for revenue service. Tri-Met routinely schedules 22 of its 26 car fleet for revenue service in the peak periods. To date this availability has always been met. In fact, maintenance statistics indicate that actual availability has averaged about 90 percent gross (regardless of reason of unavailability) or about 96 percent net (excluding routine maintenance checks).

ENERGY CONSUMPTION

Availability, consumption, and cost of energy are of vital concern to every public transit agency, particularly since the energy shortages in the 1970s. Accordingly Tri-Met established a contractual requirement for LRV energy consumption and specified a particular set of test conditions for demonstrating compliance. After a review of specifications for other transit vehicles, the requirement for energy consumption was set at 7 kilowatt hours (kwhr) per car mile, and the test conditions included an empty car with a test crew and instrumentation (AWO+), new wheels, level tangent track, a 1-mile trip repeated 10 times and averaged using a duty cycle of full acceleration from a stop to maximum speed of 55 mph, maintenance of 55 mph, full deceleration to a stop, and a 30-sec dwell with all auxiliaries running.

Testing at TTC showed that the energy consumption under these conditions was approximately 4 percent higher than allowed by contract but was considered acceptable within the accuracy of the tests. Further substantiation onsite in Portland was never accomplished, because of ROW conditions (e.g., grades and curves) and operational constraints from the signal system.

However, since start of revenue service Tri-Met has elected to undertake a program to monitor carefully the energy consumption of the system in actual operation. Prior to 1986, it was thought that all the ROW conditions (curves, grades, traffic lights, etc.), passenger loadings, wheel wear, and traction duty cycles of actual operations would contribute to a significantly higher energy consumption than seen under the test conditions. Early planning studies and cost estimates were based on a conservatively high energy consumption rate of 9 kwhr/car mile in actual operation on the Portland system. It was considered impractical to try to instrument a car in revenue service and measure direct energy usage during operation. Furthermore, without great effort the sample set of data would be small. Therefore Tri-Met decided to monitor the kilowatt hours directly from the meters of the utility companies in each of the 14 traction substations on the system. By coordinating the monitoring of the kilowatt hours and the car mileage into the same time period, it has been relatively easy to develop an empirical kwhr/car-mile statistic for actual operation of the fleet as a whole.

The average value since start of revenue service is 7 kwhr/car mile and, in addition to direct traction energy of the LRVs on the mainline, this includes substation losses, overhead line losses, and energy consumption from LRV storage in the storage yard. Passenger station power, maintenance building power, and signal power, in addition to energy of construction (technical, social, or otherwise), are not included. Substation losses have been calculated to be approximately 0.3 kwhr/car mile; overhead line losses, 0.1 kwhr/car mile; and LRV storage, the equivalent of 0.1 kwhr/car mile, making the effective or actual energy consumption at the point of usage about 6.5 kwhr/car mile. At 166 places per vehicle, this figure translates to 0.04 kwhr/place mile. No attempt is made here to trace the energy consumption numbers back to the source or generation of the electricity. However, in the Portland area much of the electricity is generated by hydropower, and average inefficiencies for converting oil or coal into electric power are not applicable in this environment.

A brief comparison of these data with those of Tri-Met's bus fleet shows a significant lower energy consumption for LRV when viewed on a per-place-mile basis. For example, based on a composite average of Tri-Met's bus fleet, the fuel consumption is about 4.1 mi per gallon in operation and the average capacity (number of places including seating and standees) is 73. Using an energy equivalence of 40.7 kwhr per gallon of diesel fuel (*1*), the average Tri-Met bus consumes about 10 kwhr/bus mile or 0.14 kwhr/place mile. This information is summarized in Table 3.

TABLE 3 CONSUMPTION OF FUEL, LRV VERSUS BUS

	LRV	Bus
Number of places per vehicle	166	73 (average)
Energy consumption		
Per vehicle mile	6.5 kwhr/car mile	0.24 gal/bus mile = 9.93 kwhr/bus mile
Per place mile	0.04 kwhr	0.14 kwhr

To repeat, these data represent energy consumption at point of usage, are composite averages for the bus, and are based on actual operation of the rail and bus fleets. In summary the data provide evidence for the proposition that, on a place-mile basis, the energy consumption of the LRV is only about one-third that of the bus as used in actual operation on the Tri-Met system.

PRODUCTIVITY

Table 4 provides a list of certain fundamental parameters describing Tri-Met's LRT and bus fleets and their respective utilizations. As in any analysis of aggregate numbers, care should first be taken in assessing the comparability of the data. Definition of terms can also often significantly influence the conclusions reached. An attempt has been made here to develop and compare similar terms, recognizing that original data are not always collected with end results in mind.

TABLE 4 COMPARATIVE OPERATING PARAMETERS

	LRV	Bus
Boarding passengers (daily)	19,700 (12%)	149,800 (88%)
Number of vehicles	26 (4%)	603 (96%)
Fleet mileage (annual $\times 10^6$)	1.3 (6%)	21.6 (94%)
Mileage per vehicle per day (full annualization)	135	100
System speed (mph)	15.7	14.0
Schedule speed (mph)	20.1	N/A
Number of transportation employees	46	978
Number of maintenance employees	53	283
Transportation employees per vehicle	1.77	1.62
Maintenance employees per vehicle	2.04	0.47
Operations employees per vehicle	3.81	2.09
Operations employees per vehicle mile ($\times 10^{-6}$)	76.1	58.4
Operations employee per place mile ($\times 10^{-6}$)	0.46	0.80
Operations employees per boarding passengers ($\times 10^{-3}$)	5.0	8.4

Daily boarding passengers are averages for the fiscal year (July 1986 to June 1987) or for the rail from September 1986. Slightly higher than average LRV ridership occurred in the first 3 months of revenue service, but recent trends in the spring and summer of 1987 indicate a return to the yearly average. These data indicate that on the basis of boarding passengers, the LRT system carries approximately 12 percent of Tri-Met's patronage with the following:

- 4 percent of the total vehicle fleet,
- 9 percent of the total capacity in places (seated plus standees),

- 6 percent of the total fleet mileage, and
- 12 percent of the total fleet capacity in place miles.

Good data are not yet readily available describing trip characteristics, especially trip length; therefore comparison of system utilization on the per-passenger-mile basis cannot be made.

System speed incorporates layovers, turnbacks, etc., and is a constructed rather than an empirical number. The LRV system speed is about 12 percent higher than that of the bus. Actual schedule speed for the LRV is about 20 mph or about 1 to 2 mph lower than estimated in the planning phases. Tri-Met is investigating ways to improve the travel speed, particularly in certain portions of the alignment where traffic signals in the reverse direction of a prior one-way street need further optimization.

During the first 12 months of LRV revenue service Tri-Met has been operating its LRV fleet approximately 30 percent more than estimated because of higher-than-anticipated ridership. This usage level is also reflected in the daily mileage per vehicle, with the LRV logging approximately 35 percent more than the average bus.

Another interesting comparison is the number of employees required to provide the various measures of service. In its operations division, which is charged with providing the actual transit service, Tri-Met is organized into maintenance and transportation departments both for bus and for rail. In this analysis, the transportation employees include vehicle operators, road supervisors, dispatchers, and administrative and clerical employees, while the maintenance employees are mechanics, foremen, cleaners, administrative and clerical employees, and—in the case of rail—all ROW (track, traction power, signal, etc.) maintenance staff. Planning, engineering, finance, and community relations staff are not included in either case.

From Table 4 it is seen that the number of transportation employees per vehicle is slightly higher for the LRV compared with the bus. Maintenance employees per vehicle is significantly higher—by about four times. Concerning the former, it is somewhat surprising that the LRV is not lower, given the ability to operate in multiple-unit (MU) consists in the peak hours with only one train operator. However, reverse economies of scale enter into the picture in that the rail dispatch and control center, which is separate from the bus, requires a minimum or threshold number of employees to maintain a similar 24-hr-a-day, seven-day-a-week operation. Concerning the latter, obviously the more complicated rolling stock and all the extra ROW infrastructure contribute to the much higher ratio of maintenance employees for rail.

On a per-vehicle basis, the rail system requires almost twice as many employees (transportation and maintenance) as the bus, while on a vehicle-mile basis the rail system needs only about one-third more employees.

However, using the statistic of employees per place mile, and considering the relatively higher capacity of large articulated LRVs, one sees that the LRT system requires only about half the work force of the bus. Similarly the LRT system is more productive on the basis of employees per boarding passenger, about 5.0 versus 8.4 ($\times$ 10^{-3}). No attempt has been made here to try to sort out or assign factors to the feeder bus network supporting the rail line, or vice versa. Statistics are based on aggregate totals and reflect only how the equipment is utilized.

The comparative statistics developed to date appear to support the contention that an LRT system with large MU vehicles and modest ROW infrastructure can provide a more productive and more efficient transit service than buses. However, the extent to which the "newness" of the LRT system, the advantages of warranty, the concentration of travel into a corridor, the particular conditions in Portland, etc., affect productivity is not known and clearly beyond the scope of this paper. Caution should be taken in extrapolating a limited situation into a generalization applicable to any other environment. Nevertheless Tri-Met's LRT experience to date has generally been a positive one that seems to offer promise for the future. As constructed and operated in Portland, the LRT mode gives an indication of the relative productivity in transit service.

SUMMARY AND CONCLUSIONS

As part of its LRV procurement, Tri-Met has implemented a reliability demonstration plan to identify, quantify, prove, and improve the reliability of the cars in revenue service operation. The resultant RDP is simple to administer, is concurrent with the warranty period, relies on the MDBF statistic as an indicator, is implemented on a computer network, and requires the cooperation of the car builder. Mileage and trouble tickets are recorded weekly, and determination of relevant failures that affect revenue service is accomplished mutually by Tri-Met and the car builder. MDBF has improved significantly since the beginning of the program and ranges between approximately 6,000 and 8,000 depending on the exact definition. Recent MDBF has been in excess of 15,000. Based on current trends it appears that the contractual goal of 7,500 cumulative will be exceeded by the end of the RDP period. The improvement in MDBF is attributed in part to the systematic identification of problems through the RDP.

A program for monitoring energy consumption has also been implemented by Tri-Met. Meters at traction substations are read directly on a weekly basis, and the average energy consumption is 7 kwhr/car mile at the substations or 6.5 kwhr/car mile at the point of usage, the train. These values are approximately one-third the average energy consumption of Tri-Met's bus fleet.

A comparison of certain productivity measures for Tri-Met's LRT and bus operations has been made, recognizing the difficulties in getting truly comparative data. The increased maintenance requirements of the LRT system, particularly for ROW infrastructure, appear to be offset by the higher capacity and utilization of the LRVs. Number of employees per place mile of service provided by LRT is slightly more than half that by buses.

Conclusions from this effort are as follows:

- A reliability demonstration plan is a very useful tool as part of a rail car procurement;
- MDBF is a useful statistic, provided confusion of terms can be eliminated;
- Early failures can be discounted in arriving at the steady-state level of reliability;
- The reliability of the Portland LRV is quite satisfactory and likely to meet contractual objectives by the end of the RDP period;
- The LRVs have substantially lower energy consumption than buses; and
- The LRT system as implemented in Portland appears to offer better productivity than do buses.

REFERENCE

1. F. Fiels. *Comparative Energy Costs of Urban Transportation Systems.* Princeton University, Princeton, N.J., 1974.

Rubber-Cushioned Wheels for Light Rail Transit

K. H. Weber and E. L. Van Sickel

For decades rubber-cushioned wheels have proven very reliable for light rail transit all over the world. These wheels reduce shock and noise, and offer other benefits. With nearly 150,000 rubber-cushioned wheels in use, the following advantages can be demonstrated: less wear and tear of both permanent way and vehicle components, reduced disturbance from noise for both passengers and people living along the track, and lower maintenance costs. Traveling comfort and running quality of vehicles equipped with rubber-cushioned wheels are superior to vehicles equipped with rigid steel wheels. Recent tests using rubber-cushioned wheels on high-speed vehicles have also been successful. Today the rubber-cushioned wheel has been proven reliable for speeds up to 160 km/h (100 mph). Further tests are being planned for speeds up to 280 km/h (175 mph).

THE AVERAGE PERSON THINKING of a rail transit system thinks of rigid steel wheels. The uninformed are often surprised to find rubber in the midst of the steel wheel. That is because for all traditional rail traffic, with the exception of light rail transit, the wheel and rail are made of steel and are the essential load-bearing members. The steel wheel and the steel rail are always used when high load capacity and safe transportation are needed.

Over 50 years ago, however, Herschfeld in the United States invented the first commercially used rubber-cushioned—or resilient—wheel. He developed this wheel so that he could build the light-weight car that became known as the President's Conference Committee (PCC) car. Prior to that time

Penn Machine Company, 905 Porter Building, Pittsburgh, Pa. 15219.

street rail vehicles had heavy trucks and heavy bodies to withstand the everyday pounding from special trackwork and rail joints. After Herschfeld perfected the rubber-cushioned wheel, he was able to lighten the truck and the carbody components to provide greater acceleration and deceleration. This improvement allowed the street rail vehicle to compete with the automobile in traffic. Since that time most light rail vehicles have been built using one type of rubber-cushioned wheel or another.

USE OF RUBBER SPRING MATERIAL

Rubber will not take high-tensile loads. Therefore, springs made of rubber should be arranged so that they are not subject to tensile loads, or the rubber will be destroyed after a very short time. On the other hand, rubber is suited to take high-compression and shear loads. In the majority of the wheel designs that have been proposed in very large numbers and varieties, the rubber is usually subjected to a combination of compression and shear loads. Under compression loads the rubber body must not be totally enclosed because in this condition the rubber reacts like a liquid. That is, the rubber is fully inelastic and rigid and offers no spring travel.

The size of the rubber bodies should be such that under operating conditions the rubber is deformed over its total cross-section. If parts of the cross-section are not properly squeezed, the rubber is subject to premature aging that gradually leads to its destruction.

If rubber is subjected to shear loads, the largest possible deflection must not result in any lengthening of the rubber. That is, additional tensile loads must not occur. Therefore, rubber bodies subjected to shear loads should always be prestressed with compression.

Under compression loads the deflections are small. Under shear loads larger deflections can be obtained. On the other hand, under compression loads the required rubber volume can be less as compared with shear loads since higher load is permitted.

Premature aging of the rubber also occurs if it is subjected to higher temperatures than acceptable. Different grades of rubber can be used that vary only in their capability to resist heat (110°C being the maximum). Apart from the formation of heat from the normal operation of the rubber wheel in service, heat is also put into the wheel from outside of the rolling operations and should be taken into consideration. This outside heat source can be from tread braking or reprofiling of the tread by means of grinding. The heat input from tread braking is generally well above the acceptable temperature that the rubber can take. Therefore, the rubber-cushioned wheel cannot be recommended for vehicles using tread brakes as the main service brake.

ADVANTAGES OF RUBBER-CUSHIONED WHEELS

Rubber-cushioned wheels were designed to reduce the unsprung masses in the wheelset resulting in the reduction of shock forces between the wheel and the rail, and to reduce the noise of operation.

In the general design of rail vehicles, the primary suspension is situated between the axle boxes and the truck frame. This suspension not only improves the traveling comfort of passengers but also reduces the shock forces because of its resilience. With traditional rigid wheelsets the wheels, axles, and other components mounted to the axle, such as gears, brake discs, roller bearings, and journal boxes, form what is called the unsprung mass. In driving wheelsets part of the mass of the motor may also be supported by the axle, which thus increases the total unsprung mass.

With rigid steel wheels the complete wheelset, with all these components, is bouncing and hammering on the track. With high traveling speeds, high dynamic forces both in vertical and lateral directions are occurring between the wheel and rail, leading to fatigue and wear of material. By lowering the unsprung mass of the wheelset the impact of the dynamic forces is considerably reduced. With the cushioning member built into the wheels the unsprung mass is limited to the two-wheel tires. Figure 1 illustrates the unsprung masses of the wheelset with rigid wheels compared with a wheelset with rubber-cushioned wheels.

The reduction of noise is also one of the advantages of rubber-cushioned wheels. With the reduction of the shock forces between the wheel and the rail as explained above, the rolling noises from traction are reduced. The largest amount of noise reduction for the passengers comes from the fact that the ground vibration is damped on its way from the source, the wheel/rail contact surface, to the bogies and the carbody. Also, the curve squeal is changed to a lower, less disturbing frequency.

Another advantage of the rubber-cushioned wheel is that it reduces shock forces tangent to the wheel tread caused by sudden acceleration and deceleration. This results in longer gear life.

MAJOR DESIGNS OF RUBBER-CUSHIONED WHEELS

First design proposals were made and patents taken out for rubber-cushioned wheels as early as 1880. First designs, however, did not go beyond the stage of testing, probably because of lack of knowledge of the characteristics of rubber.

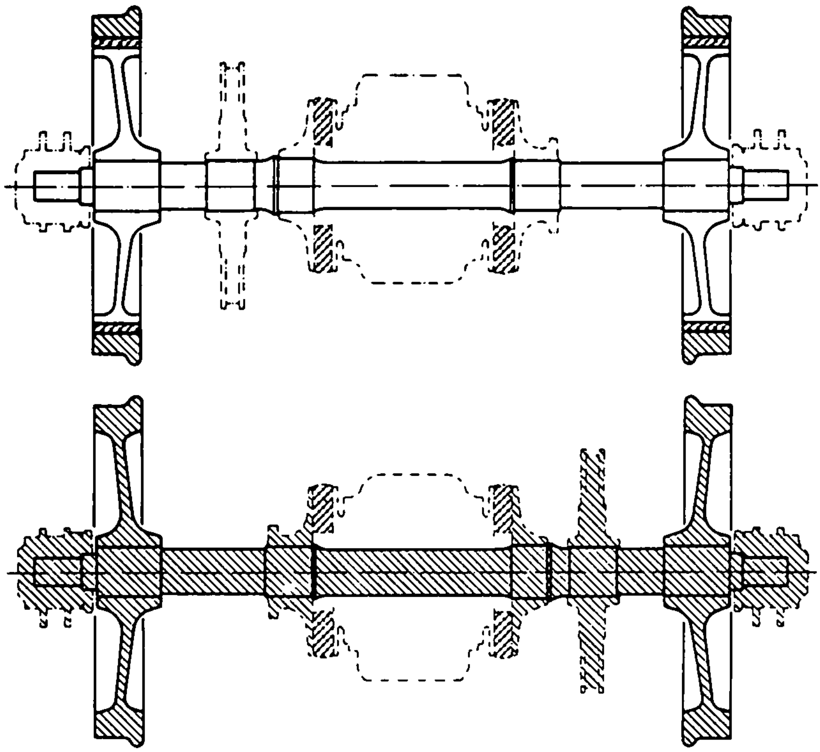
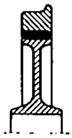


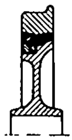
FIGURE 1 Unsprung mass of a wheelset.

Figure 2 shows basic sketches of the major designs of rubber-cushioned wheels. Next to each sketch there is information as to the direction in which the built-in rubber body is loaded (radial, axial, and tangential direction).

With certain reservations, the respective spring characteristic of each wheel can be determined from the way that the rubber is loaded. The wheel shown at the top of Figure 2 will show less deflection in the radial direction because the rubber is predominantly compression loaded. However, the wheel should show a larger deflection in axial and tangential directions as there is shear load in those directions. In contrast to the top wheel, a wheel designed like the bottom one in Figure 2 should give higher deflection in the radial and tangential directions than in the axial direction, where it would be loaded in compression.

The middle wheel shown in Figure 2 has a soft spring characteristic in the tangential direction. By changing the angle of inclination of the rubber body, the combination of compression and shear loads can be arranged to allow for a wide range of deflection in both the radial and axial directions.





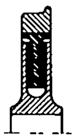


FIGURE 2 Types of rubber-cushioned wheels.

DESIGN CRITERIA

A rubber-cushioned wheel for rail vehicles should be of simple design, economical, reliable, and offer the previously mentioned advantages, such as reduction of vertical and lateral shock forces; reduction of rolling, squealing, and internal noises; and reduction of wheel tire wear. These requirements are met ideally by the wheel of the design Bochum 54, illustrated in Figure 3. This is a design that, for more than 30 years, has proved successful in light rail transit up to a wheel load of 6 metric tons.

By this time, nearly 150,000 wheels of this design have been put in use by transit authorities all over the world, including the United States. The simple design consists of three elements: the wheel tire, the rubber elements, and the wheel center. In line with the best practice for the use of rubber as a spring element, the rubber bodies are built in between the wheel tire and the wheel center and are prestressed by high radial pressure. This ensures that in the critical axial and tangential directions most of the deformation of the rubber takes place as shear loads.

Assembly of the wheel is accomplished easily by a special pressing-in device (see Figure 4). The wheel center is pressed into the rubber-lined bore of the wheel tire by means of a cone. The rubber blocks are designed so that a static radial deflection of 0.5 to 0.7 mm and an axial deflection of approximately 2 mm are obtained under service conditions. The spring rate in

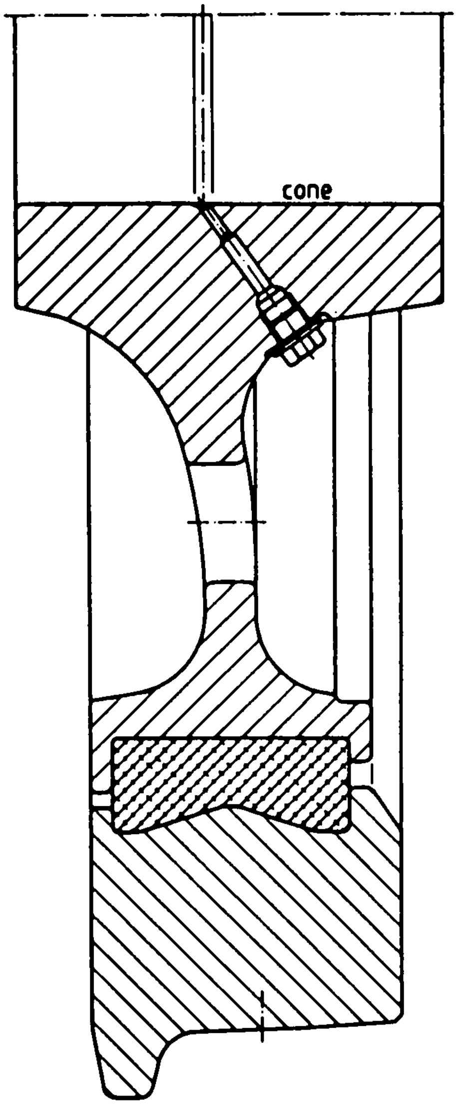


FIGURE 3 The Bochum 54 rubber-cushioned wheel.

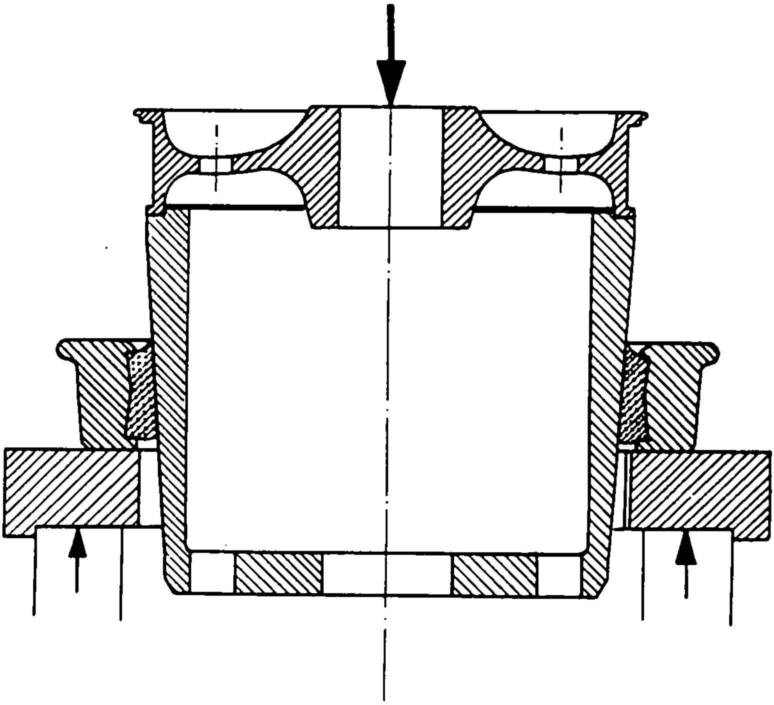


FIGURE 4 Assembly of the Bochum 54.

transverse, tangential, and radial directions has been adapted for various types of vehicles by changing the size of the rubber blocks to obtain optimum spring characteristics for each application.

The wheel illustrated in Figure 5 has been developed based on the same principles of design as the Bochum 54 wheel. This wheel is marketed under the name Bochum 84 and consists of four construction members: the wheel tire, the rubber blocks, the wheel center, and the detachable ring (see Figure 6). The detachable ring is fitted to the wheel center by a cônical pressfit. In addition to the pressfit, the detachable ring is secured to the wheel center with bolts, although the pressfit alone is enough to hold the ring in proper position under load conditions occurring in service.

For easy disassembly the detachable ring is provided with an oil injection hole so that oil pressure can assist in taking off the ring. Assembly and disassembly of the rubber-cushioned wheel design Bochum 84 can be accomplished easily with hand tools. In the case of wheelsets with inner roller bearings, the wheel can be equipped with new tires with the axles still under the vehicle.

Wheels of this new Bochum 84 design are now being used under the new light rail vehicles in Grenoble, France, and have been ordered for light rail vehicles in Lausanne, Switzerland. Under service conditions, similar performance can be expected from both wheel designs as they are manufactured to more or less identical spring characteristics. The two wheels are equal with regard to reduction of shock and noise.

FIELD TESTS OF BOCHUM 54 AND 84 WHEELS

To prove that rubber-cushioned wheels have the advantages claimed, tests have been carried out with a number of transit authorities to measure reduction of both shock and noise compared to vehicles equipped with conventional rigid steel wheels. We will discuss here some tests run with transit authorities in Hamburg (Hamburger Hochbahn AG) (*1*) and Vienna (Wiener Verkehrsbetriebe), among others.

Reduction of Shock

A steel plate 2 mm high was welded on the rail head to simulate a badly maintained rail joint or a frog point on a turnout. The test vehicles passed over this steel plate at speeds of 30 km/h, 50 km/h, and 75 km/h. The test results summarized in Figure 7 clearly show the advantage offered by the rubber-cushioned wheel. With the rubber-cushioned wheel, the peak values of the shock forces are lower by approximately 30 to 40 percent at 75 km/h.

The effect that speed has on the shock forces is illustrated in Figure 8. This diagram illustrates the accelerations at the rail, at the journal box, and at the bogie or truck frame.

Measurements of the bending stresses occurring in the main beam of the truck frame made in the Hamburg tests show that the pulsating bending stresses are reduced by an average of 16 percent for vehicles equipped with rubber-cushioned wheels as compared with vehicles with rigid wheels. According to test data, engineers can take into consideration for stress calculations a reduction of 50 percent of the acceleration peaks for lateral and vertical loads when using rubber-cushioned wheels.

Figure 9 illustrates the acceleration peaks determined for the stress calculation of the construction members used on wheelsets with rigid wheels and

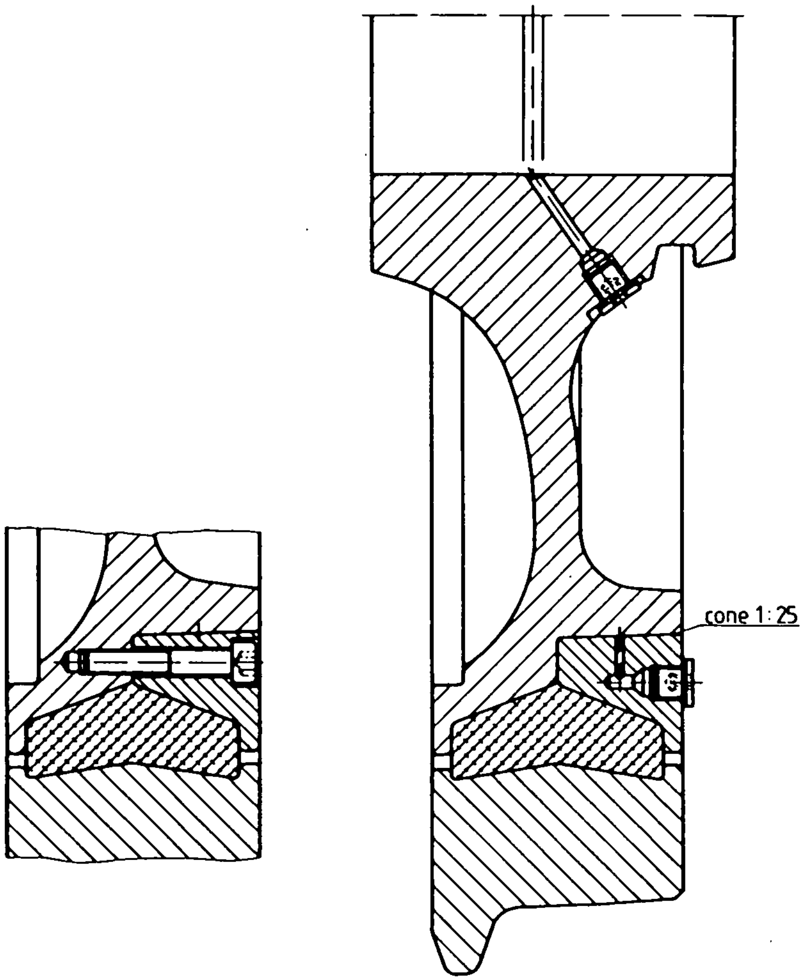


FIGURE 5 The Bochum 84 rubber-cushioned wheel.

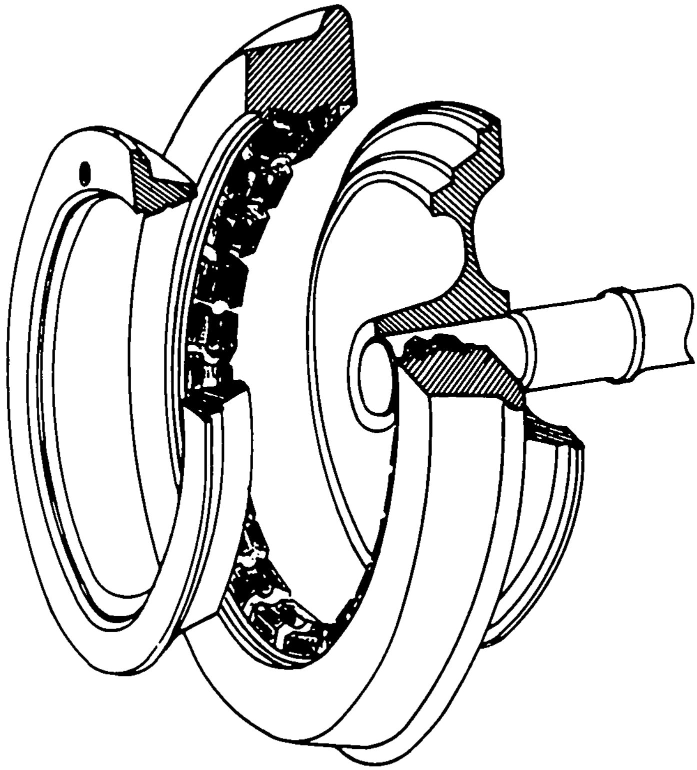


FIGURE 6 The Bochum 84 wheel.

rubber-cushioned wheels, respectively. These values have been established for a new guideline for calculations issued by the German Association of Public Transit Authorities (VoV) (2). In the design of wheelsets, dynamic loads must be added to the static loads that the wheelset must carry. These dynamic loads can be reduced by 25 percent in the lateral direction and 37.5 to 50 percent in the vertical direction when rubber-cushioned wheels instead of rigid wheels are used.

Similar reductions of dynamic forces have been taken into consideration in the stress calculations for axles. Therefore, in the design of axles for wheelsets with rubber-cushioned wheels the dimensions can be reduced. Conversely, tests have shown that such axles with smaller dimensions designed for the use of rubber-cushioned wheels have actually cracked after a few million load cycles when used with rigid wheels.

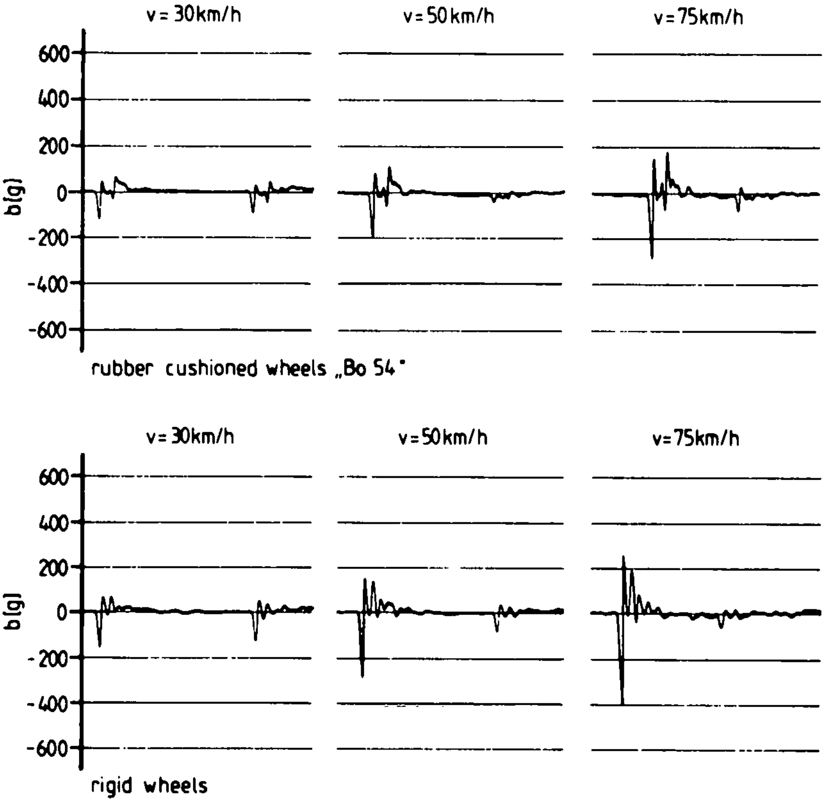


FIGURE 7 Impact acceleration at the rail.

These tests clearly demonstrate that vehicles using rubber cushioned wheels are subjected to less stress. This substantiates the claimed advantage of increased traveling comfort, less impact on both the bogie and the rail, and reduction of overall maintenance costs.

Reduction of Noise

Along with the measurement of shock reduction, the sound emission of the vehicle and the noise level inside the vehicle were measured. Figure 10 illustrates the sound level recordings taken at a distance of 6 m from track center at a height of 1.4 m. Although rigid wheels show sound level peaks to approximately 90 dB(A), the value for rubber-cushioned wheels recorded in the same frequency range amounts to a maximum of 85 dB(A). Average differences of 3.5 to 4 dB(A) in favor of the rubber-cushioned wheel were

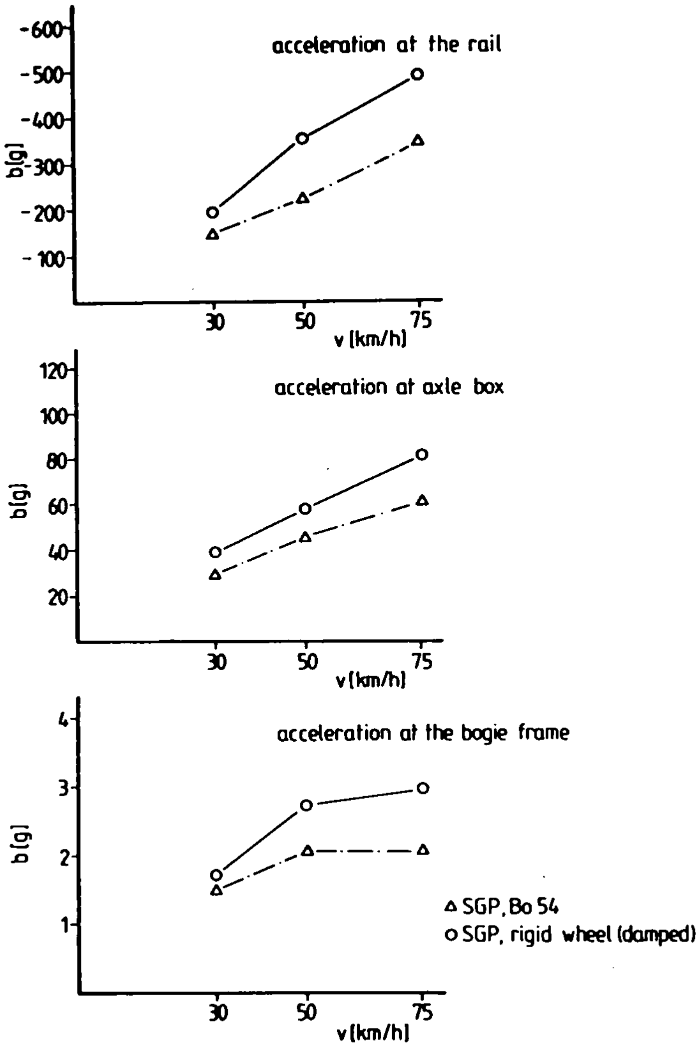


FIGURE 8 Impact acceleration at rail, axle box, and bogie frame.

main level direction of oscillation	direction of oscillation	yield point	fatigue
with rubber cushioned wheels	vertical	20-30	15-20
	horizontal transverse	4-5	3-4
with rigid wheels	vertical	30-40	20-30
	horizontal transverse	6-8	5-6

FIGURE 9 Acceleration amplitudes (m/s^2) as proof of strength.

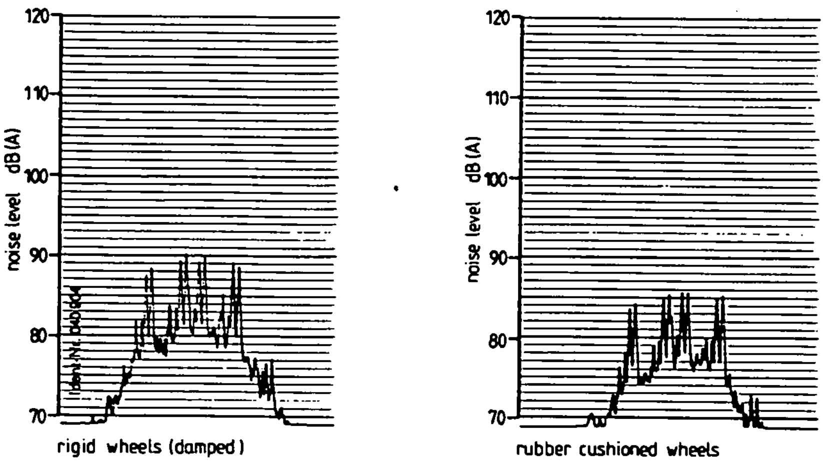


FIGURE 10 Noise level.

measured. Inside the car the sound level transmitted by air is lower by 3 dB(A), with the noise coming in a lower frequency range that is less disturbing to the passengers. All of these results were based on tests on tangent track with continuous welded rail plus ballast and tie construction. They represent measurements of the rolling noise.

Curve squeal of rigid wheels is generally eliminated with a rubber-cushioned wheel. Under some adverse conditions squealing might still be heard, but because of the good damping characteristics of the rubber blocks the noise level is reduced by approximately 8 to 10 dB(A) compared with rigid wheels. This reduction of noise by rubber-cushioned wheels not only benefits the people riding in the vehicle but also is much less disturbing to the people living along the track.

Reduction of Wear

For light rail vehicles the life of a wheel is determined by the wear of the flange rather than by the wear of the tread. This is because most light rail vehicles travel around fairly sharp radius curves in comparison to main line or heavy rail transit. When the flange is worn to its limit, tread and flange contours require recontouring. To reproduce the original size of the flange, it is necessary to machine off good material from the tread during the machining operation. With the use of rubber cushioned wheels, either Bochum 54 or Bochum 84, wear at the tread, and particularly at the flange, is reduced. The reduction of the peak loads in both the vertical and lateral directions, as mentioned above, leads to less wear on the tread. In addition, flange wear is reduced by the spring characteristics in the axial direction. This allows the shock forces resulting when the flange hits the rail, particularly when negotiating curves, to be absorbed elastically. Also, the forces on the flange cause the tire to rotate about a vertical axis, thus smoothing the angle of attack of the wheel towards the edge of the rail. Wear is proportional to the product of force and angle of attack. Thus the wearing components are changed to smaller values, which results in reduced wear.

Experience by many users shows that rubber-cushioned wheels increase the mileage as compared with rigid wheels by between 25 and 40 percent. This obviously is an economic advantage because of longer periods between reconditioning operations, reduced down time for vehicles, and reduced general maintenance costs.

Maintenance

Experience with a number of users has shown that a mileage life of 350,000 to 600,000 km is quite common with rubber-cushioned wheels with axle loads of 9 to 12 metric tons. Under favorable operating conditions a mileage life of 1.1 million km has been reached.

The rubber-cushioned wheels do not require the user to observe special maintenance instructions. Reconditioning of the tread and flange profile can be done on standard underfloor grinding machines or turning lathes in the same way that it is done for rigid wheels. The only precaution needed is that, when the tread by is reprofiled by grinding, care should be taken that the temperature of the surface of the bore of the tire is kept within acceptable limits so the rubber will not age prematurely. If a user is going to reprofile wheels by grinding, rubber material that is able to take temperatures of 100°C without risk of losing its damping and spring characteristics should be used.

Re-tiring of the rubber-cushioned wheel is done at room temperature on a specially designed pressing-in device, either with a single wheel or with a complete wheelset. Re-tiring on a loose wheel is particularly advantageous for wheels that have been equipped with oil pressure-assisted conical pressfits to the axle. The conical pressfit with a taper of 1:150 or 1:300 has proven itself in service in Europe for over 15 years. There have been no problems with regard to proper seating of the wheel on the axle. This practice should be considered in America. As the wheels do not require any special shrink fit or press-on fit tolerance, the wheels can be stored in finished machined condition for use at random, thus speeding up the rewheeling operation.

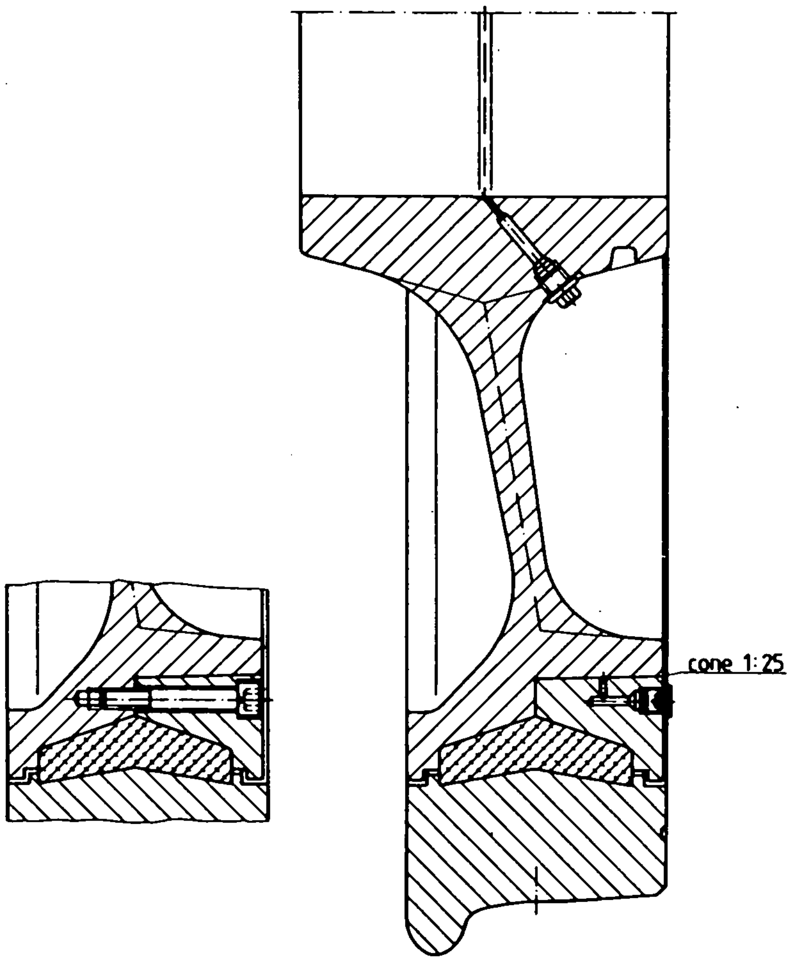


FIGURE 11 Bochum 84 wheel for high speeds.

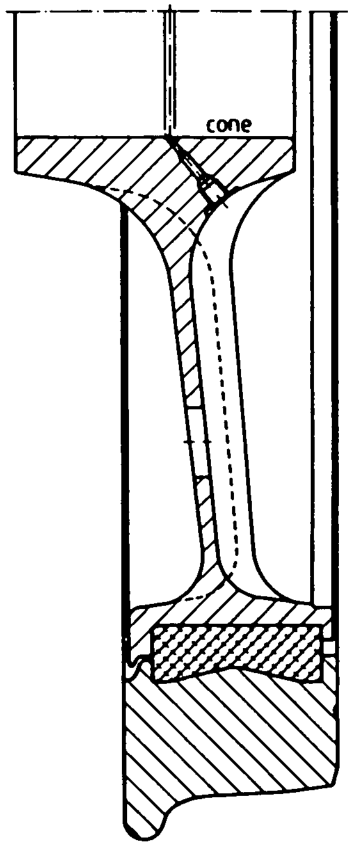


FIGURE 12 Light-weight rubber-cushioned wheel.

The natural useful life of the rubber blocks is approximately 10 to 12 years. Normally the rubber blocks are replaced during the re-tiring operation. If the rubber blocks have not been subjected to excessive peak loads during service, they may be reused for another cycle of operation. However, rubber blocks with built-in shunts should be replaced during each re-tiring operation. The contact surface between shunt and wheel center and wheel tire, respectively, must be coated properly with an anticorrosive, but conductive, agent such as zinc paint to ensure low resistance to the current.

The Bochum 84 wheel does not need a special pressing-in device. This wheel design is assembled easily using only hand tools.

If the vehicle is parked for a long period, the rubber blocks will take a certain "set." That is, the wheel tire will be eccentric in relation to the wheel center. This is not a problem because after a few turns of the wheel the true running characteristics of the wheel are quickly reestablished.

PROSPECTS FOR RUBBER-CUSHIONED WHEELS

Bochum 54 and Bochum 84 wheels are presently adapted for use under high speeds (see Figure 11). As of today, the rubber-cushioned wheel has proved reliable in service up to a speed of 160 km/h (100 mph). In early 1989, the wheels will be tested under vehicles of the German Federal Railways at speeds up to 280 km/h (175 mph).

In addition to this development, steps have been taken to further reduce the weight of the wheel. The design of a wheel center with a tangentially corrugated web is one step in this direction. This design offers a reduction of weight by approximately 30 to 35 kg for a wheel having 900 mm diameter tread (see Figure 12).

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PART 5

Operations and Maintenance

Peer Reviews

Good Advice at a Reasonable Price

CAMERON BEACH

Peer reviews conducted by groups of transit professionals brought together as a panel examine new starts or major changes to rail transit systems. This process represents a cost-effective method of gaining high-level "hands on" expertise at a minimal cost to the property requesting the review. The process is analogous to "networking," a common term for today's computer-minded population.

LIKE MANY OTHER NEW rail transit operations, the Sacramento Regional Transit District availed itself of the peer review process. Peer reviews are conducted by groups made up of public transportation executives from transit systems throughout North America. They are invited periodically to review a system's plans and procedures prior to opening for revenue service.

Typically, transit properties are asked to send managerial-level personnel with a high degree of technical expertise to the project being reviewed. All travel and lodging expenses are paid by the host system, while salaries of the individuals involved are the responsibility of their respective employers.

A typical peer review lasts 3 days, excluding travel time. Generally, the first day of a review is spent on introductions, orientation, and a tour of the system itself. On the second day, the peer review panel examines construction drawings, operating procedures, rule books, operating plans, and system details. This is usually accompanied by presentations from the staff of the project being reviewed. Additional field inspections may be scheduled as required.

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

On the third day, the peer review panel meets privately and drafts a report to the senior management of the host property explaining their findings, conclusions, and recommendations. Given the short time limit, this review is usually oral but may be followed with a more detailed written report, depending on the needs of the system. The written report is generally a series of recommendations in a line item format. In Sacramento, this report was circulated to staff and a written response to each recommendation was prepared. This document, in turn, was forwarded to the board of directors for review. Each review panel member also received a copy of the reviewed property's comment.

Prior to its opening in March 1987, the Sacramento Regional Transit District conducted five such peer reviews during design and construction. Specific areas that were examined were operations, start-up, construction management, safety, and system security. Panel members came from systems in Portland, San Jose, San Diego, San Francisco, Edmonton, Calgary, Boston, and Philadelphia. In each case, the panel made several recommendations in specific areas that it felt needed attention. Most of these recommendations were taken to heart by the staff in Sacramento as well as the board of directors.

The peer review process alleviates dependency on high-priced consultants. Each of Sacramento's peer reviews was conducted for less than $5,000. This was money considered well spent, because the same level of outside professional consulting would have cost easily 10 times that amount.

Peer reviews are beneficial not only to the system being reviewed, but also to the panel members themselves. These individuals are heavily involved in day-to-day operations at their own systems and find the peer review process an excellent forum for exchanging information. An additional benefit of this process is the ability to call on your peers should an operating problem develop once the system is in operation. The relationships built during this process become an excellent base for "networking" solutions to complicated technical or operational problems.

In recent years, expertise in the electric railway industry has become a scarce commodity. The system in Edmonton, Alberta, was on the cutting edge of the rebirth of light rail in North America when it opened in 1978. The stagnation the industry had undergone from the late 1930s through the late 1970s left virtually no one in North America familiar with street railway operation. Quite often, systems have had to look to their European counterparts, where rail transit flourished after World War II in contrast to the abandonments that occurred in North America. George Krambles, former general manager of the Chicago Transit Authority, is one of the few holders of a degree in electric railway engineering. In fact, this degree was last offered by the University of Illinois in 1940.

Without the networking ability available through the peer review process, most systems would have a difficult time finding the expertise necessary to design, construct, and operate a light rail transit system. Most of today's rail transit operating managers acquired their expertise by working on one of the new systems being constructed. The peer review process has proved invaluable in assisting these individuals to gain the expertise needed to manage and operate the multimillion-dollar light rail systems now in service in North America.

Edmonton Transit's Light Rail Transit Experience

JOHN F. NICOLL

The City of Edmonton in Alberta, Canada, operates an integrated transit network that uses 24 light rail cars in conjunction with 530 buses to meet peak hour demand. The light rail transit (LRT) system, which opened in 1978, is still being expanded. In the 10 years of the system's operation, the staff has solved a variety of problems that ranged from the tracks not built to standards that yield a comfortable ride for LRT passengers to excessive rail wear to confusing signals. Edmonton's severe weather presents the staff with other, continuing problems from ice in the switch points in winter to expansion ripples in the rails in summer. Also, a railroad tunnel used by light rail vehicles is subject to flooding and has given the transit staff experience dealing with track washouts. Procedures for dealing with these and other problems and equipment are outlined.

EDMONTON TRANSIT IS OWNED and operated by the City of Edmonton and operates 530 buses and 24 light rail cars in the peak hour in an integrated transit network. The transit system is supported 50 percent by the farebox revenue and 50 percent by the local property tax and a provincial operating grant of $8.00 per capita. Light rail transit (LRT) capital construction is funded 75 percent by the Province of Alberta and 25 percent by the City of Edmonton debentures.

Edmonton opened the LRT line in April 1978. The line opened with two underground and three surface stations. The track ran for 6.9 km, 2 km underground and 4.9 km on the surface, on a railroad right-of-way. The system began operating with 14 Duewag RTE 1 articulated cars. The surface right-of-way is leased from the Canadian National Railway; however LRT does not share the railroad's tracks. The Edmonton is unique to LRT in that it

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is one of the few systems in North America that goes underground in the city center.

Since its opening, the system has expanded 2.2 km northward into a residential district, Clareview, and further west into the downtown area. An additional 23 cars have been purchased. Construction is under way on an extension to the Government Centre and on to the university. The extension to the university will involve crossing the river and another section of tunneling.

TRACKWORK

We started with a definite heavy rail bias in the design of the LRT system. We learned the subtleties of LRT operation and construction and the differences between heavy rail and LRT. Edmonton now boasts engineering companies that are at the forefront of the state of the art in LRT design and construction.

Edmonton's surface trackwork consists of conventional wood tie, cut spike, and ballast. Underground installations of direct fixation use the pandrol clip and the landis plate. The new trackwork will be direct fixation on concrete plinths, designed by a local engineering firm. One of the initial difficulties was that the track was not built to the standard that we have found is necessary for a comfortable ride for LRT patrons. Gauge varied greatly on the system, causing a large amount of car hunting from side to side as the car moved from one rail to the other. In some places the gauge of the track was out of tolerance by 12.5 mm to 15 mm ($^1/_2$ to $^3/_4$ in.).

A difficulty we still have is with the quality of the ballast used on the line. The ballast has very few crushed faces and is often small rock, making it more like a bed of marbles at times than good stable ballast. As a result it is difficult to maintain track line and cross level, qualities that also affect the ride of the car. New ballast specifications include substantially larger rock with a greater percentage of crushed faces.

We were not satisfied with the original quality of the trackwork and in subsequent projects we carefully monitored the work and the tolerances used. We considered concrete ties for our Clareview extension. However, at the time the use of concrete ties was still in its infancy for LRT and there was a relatively high price difference. We decided to try the standard tie and ballast construction again, using better ballast and paying more attention to the quality of the construction. The quality of the track built was significantly better than what we had before, but obtaining the tight tolerances that LRT requires was still a problem with the wood tie. It was still not possible to achieve a gauge tolerance better than 6 mm using the standard wood tie and spike.

A major effort was put into scheduling the activities on the track area so that one contractor did not destroy or damage the work of another. This time we built the road bed and then brought in the ductline construction activities and catenary mast base construction contractors. When these contractors were finished, the track area was made available to the track contractor. Once the track was laid, no one was allowed on the track unless it was on track-mounted equipment. This paid dividends as there was no damage to work already done.

Rail wear was one of the first problems we had to contend with. We experienced rapid and aggressive wear on the outer rail of the 150 m radius curve. This curve was also wide in gauge by up to $^3/_4$ in. The gauge widening helped accentuate tracking difficulties of the cars in the curves and aggravated rail wear.

The rail in this curve was regular carbon steel. In a matter of months a very course type of wear started at the gauge corner of the high rail. The metal was being stripped from the rail in shavings and was dropping to the floor. Eventually enough metal had been removed from the gauge corner of the upper rail to make the rail conform to the inverse shape of the wheel. At this time the wear on the upper rail slowed down somewhat, but was replaced by severe corrugation of the lower rail. This all took place within a period of 3 months. We tackled the corrugation problem by surface grinding the rail with a portable surface grinder used for grinding rail welds. Because the curves were not that long, it was possible to accomplish this task manually by operating several night shifts every so often.

We also improved our lubrication techniques. Initially we had an automatic rail lubricator installed. But getting it to work properly was impossible. Most of the grease was thrown to the track floor rather than being applied to the rail. We eventually discarded the automatic lubricator in favor of a system of manual greasing. As we improved the lubrication of the rail we observed an improvement in the condition of the upper rail. Instead of wearing very coarsely, it started to take on a polished appearance. The rail was starting to work harden.

In dealing with the initial wear problem we assumed that the problem was too excessive a side force on the rail, so we reduced the speed of the trains through the curves, a move that would ultimately prove retrogressive. We designed a restraint rail system for the lower rail that would contact the back of the wheel. The restraint rail, which had a replaceable wear bar, was to help guide the trucks of the car through the curves and to help steer them. Pulling the lead wheel down was intended to steer the truck into the curve and adopt a less cutting approach to the curve.

The restraint rail was a success to a degree. With it in place we could allow higher speeds in the curve. With the higher speeds there was a greater lateral force on the car pushing the car against the upper rail. This increased force helped the trucks to negotiate the curve. By reducing the angle of attack of the front wheels approaching the rail, the tendency of the wheel to cut the rail was reduced.

With the higher speeds and the improved lubrication the condition of the upper rail improved. The wear bar on the restraint rail was barely touched and has lasted quite well. However, by this time the upper rail had up to 1/2 in. wear on the gauge face, approaching the wear limits we had established. We replaced this rail in 1983 with chromium alloy rail and have had much better success with it.

We have learned that proper lubrication is essential in developing and maintaining a smooth work-hardened surface on the rail. Without lubrication rail wear quickly becomes very coarse, which is hard on the rail and hard on the wheel flanges. We had a derailment that was caused by a situation in which the rough flanges of a wheel negotiating a tight curve in the yard created enough friction to make the wheel climb out of the curve. This rough flange wear was due to a breakdown in the quality of the lubrication of the rail in the curves and the corresponding rough rail surface.

A similar situation occurred recently on one of our number 6 turnouts due to lack of lubrication. The manual lubrication rate fell behind on a long weekend. A car that recently had its wheels turned was being taken for a test run. The center bogie, which is much lighter than the powered bogies, derailed on the closure rail of a number 6 switch. The friction between the newly cut wheel without any lubricant and the dry closure rail was enough to cause the wheel to climb the rail as if it were a ramp. We have revised our procedures to make sure that the switch points are adequately lubricated and even more so if a car with a new set of wheels or recently turned wheels is to be released into service for the first time.

Edmonton's extreme weather conditions also presented problems. The highest temperature that we have recorded on the rail in the summer is 60°C. We can get temperatures as low as –40°C in the winter. We had a fair amount of difficulty due to freezing ice and snow in the switch point area when we used hot air switch point heaters. We have discontinued using heated forced air and rely instead on the air curtain type of switch blower. The energy requirements are less, the frost heave damage to the subgrade and alignment is less, and the blowers are more effective at keeping the switches clear of snow.

In the summer the solar heating of the rail and the high ambient temperature create expansion ripples in the rail. The continuous rail expands, and although it is held in place by the ballast, it still deviates from a true line and gauge. Our car ride deteriorates in the summer with rail expansion.

We have had two instances of rail pullaparts in 10 years of operation. The pullaparts occurred at weld locations when the temperature was below

–20°C. The remedy is to pull the rail back together with a 120-ton hydraulic puller and install a bolted joint. Then in the summer the welded joint can be replaced. We inspect the track visually in detail every quarter and have the rail inspected ultrasonically approximately every year to be sure we have done our utmost to protect public safety. The ultrasonic inspection has picked up rail defects that have since been repaired or the rail has been replaced. In light rail operation a reasonable testing frequency would normally be every 2 years.

We have noticed recently that cars tend to take on a shimmy in the idler bogie area in certain areas of the track, particularly where the gauge is less than 1435 mm. We are not sure why this did not happen before; it may be due to the revised part worn-wheel profile that we have started using, but it does not correlate directly to the time that we started running the new wheels. The shimmy occurs in areas of track that previously did not have problems. Some thought is being given to whether tie shrinking is causing the areas of narrow gauge. Wood can shrink up to 3 to 4 percent. With a gauge of 1435 mm that would be approximately 6 mm.

In our studies of this problem of center truck stability, we have found that the rate at which gauge varies is possibly one of the most significant forces on the stability and ride quality. This is perhaps because the gauge change occurs over a relatively short distance and could set up an oscillation in the truck if several sections close together have an excessive rate of gauge change. The one thing we do know at present is that the wheel profile we are using is extremely susceptible to narrow gauge. Wide gauge does not bother it as much, nor do errors in cross level, nor errors in line, provided that these errors are within a reasonable range.

There have been no major problems created by snow, but it is important that the flangeways in the crossing and frogs and the switch point area be kept clear of snow to avoid derailments. We have had one occurrence of a train derailing in the yard on wind-packed snow. We have a switch snow blower to keep the yard switches free of snow and the crew uses backpack-mounted portable blowers as well.

In 10 years we have had three once-in-50-years rain storms, one with a tornado. In one area of the system the line passes under the Canadian National tracks in a tunnel. Unfortunately this tunnel is lower than the storm sewer in this area of the city. As a result the tunnel has flooded three times. The force of the water coming from the sewer manholes has caused two track washouts. This is not the type of event that we would normally build a contingency plan around; however, we are getting pretty good at responding to it.

The washouts were the most extensive damage that the track has suffered and we were able to respond to the emergency because of planning and equipment on hand. Our planning is designed to let us respond to any kind of problem, with a particular emphasis on derailments and track damage. We have been able to respond well to these events because we have the right equipment or know where we can get the equipment readily. Personnel are available who know how to use the various equipment such as pumps, rerailing trucks, hy-rail equipment, etc.

One thing we have learned from the two washouts is the importance of having a well-organized repair site. It is essential that one person coordinate all repair activities. There is a tendency for people to attempt to do too much themselves or to work too long. It is important that the site coordinator schedule the work force so that all repair crews have enough rest to work safely. There is a tendency to work the entire force full out at the onset of a problem and then not to have any rested workers to continue the work.

In an emergency track repair situation it may be possible to restore limited service on another track. In emergency situations it is important that the normal operating rules and practices be followed. There is a tendency for the maintenance staff to rush the job and, in their preoccupation with the immediate repair, to neglect some of the operating procedures. We have found it advisable to designate an operating person to control traffic at the repair site to relieve the maintenance staff of this duty and also to ensure that proper and safe movements are made. This person serves as the liaison with the control center.

The following tools are used in our day-to-day rail maintenance and emergency repair work. Some of them may not be applicable to all rail systems.

Gauge-measuring tool, geismar or equivalent;
Rail puller, hydraulic, 100 tons or more;
Rail bender, manual;
Weld profile grinder, switch point grinder;
Rail saw, rail drill, and supply of bits;
Tamping tools, hand, automatic;
Shovels, lining bars;
Track wrenches;
Guard rail wrench;
Spike mauls;
Claw bars;
Level board;
Rail thermometer;
Track shovels;
Track jacks, 15 tons;
Adzes;

Rail tongs, tie tongs, or equivalent;
Large pipe wrench;
Lining jacks;
Snow brooms, snow shovels, ice picks;
Wrenches;
Push carts;
Track speeder, or pickup with hy-rail wheels equipped with brakes;
Spike puller;
Snow blower, powered;
Air compressor;
Multipurpose truck with hy-rail wheels and crane, and tilting box;
Lining machine;
Tamping machine;
Ballast regulator;
Extra low-boy rail trailer to accommodate nonrail vehicles;
Water tank;
Emergency light plant and lights;
Chain winches;
Gauge bars;
Tie plugs and spare parts as needed;
Hand tools;
Flashlights;
Gloves;
Protective equipment, i.e., glasses and clothing; and
Reflective vests.

TRACTION POWER

Edmonton has enjoyed much success with its traction power system. The system is a combination of in-house design and outside consulting. We are still following the design guidelines laid out in 1976.

The overhead is a simple catenary system of 4/0 contact wire and a 4/0 messenger wire. The contact wire is alloy 80 cadmium copper and the messenger wire is hard drawn copper wire. Our original system is designed to operate three-car trains and does not have any parallel feeders in addition to the catenary. The newer sections of the system are being built to a design standard for operation of five-car trains and incorporate a 500 mcm feeder in parallel to the catenary. The catenary is auto-tensioned throughout with a small section in the tunnel that is fixed-tension. The contact wire is tensioned to 1300 kgm force and the messenger wire is tensioned to 1100 kgms force.

The typical tension length is 1100 m with a midspan anchor in the middle. The nominal spacing of the catenary masts is 55 m with a maximum design spacing of 60 m in the open route. One of the primary limiting factors in the design of the catenary system is the supporting strength of the masts under the worst-case loading of 12.5 mm of radial ice and 400 Pa of wind pressure at −20°C.

The dc feeders from the substation to the catenary are two 1000 mcm copper feeders from the dc breakers to the catenary system. The feeders are connected to the catenary at the midpoint of the acceleration zones downstream from the stations. The circuit section breaks are usually located upstream from the stations so that the trains are not drawing power as they cross the section isolator. The section isolators provide total circuit isolation—the skids of the isolator are not energized. The catenary is sectioned so that each track between stations is a separate circuit. This increases our flexibility of operation. To reduce the catenary voltage drop for trains starting between stations, the catenary circuits are fed from each end of the circuit.

The substations contain two transformer rectifier units of 1 megawatt each. To improve reliability we split the substation into two halves. The system can still operate with one transformer rectifier unit out of operation. The criteria that we established for available voltage to the car were nominal voltage of 600 volts plus 10 percent (720 volts) and minus 20 percent (420 volts minimum). The rail network or the negative circuit is not grounded to reduce the interference of our system on other underground metal installations. We established a criterion for a maximum voltage drop in the rail of 15 volts to limit the amount of stray current that might occur. For short periods of time we now allow a maximum of 50 volts rail voltage drop, although there are few circumstances that could occur on our system to create this large a rail voltage drop except for the loss of the power station at the end of the line.

We initially raised an alarm at the power control center if the system voltage exceeded 15 volts rail-to-ground and shut down the substation if the rail-to-ground voltage exceeded 45 volts to ground. After a few years of experience we modified this approach. At 45 volts a motorized disconnect switch connects the rails to ground. We were finding that there were too many nonsystem occurrences that could create a potential to ground that had nothing to do with our LRT system, yet our protective relaying saw it and locked out the entire system. The system was shut down once because of a lightning strike in the north end of town. The ground rose in potential with respect to the ground 7 km away. The measuring devices in the substations measured the potential and activated the lockout relays. At night when the system is shut down, the switches are opened and the relays reset. There are more sophisticated circuits available now that do the same thing now using thyristors.

The substations employ di/dt relays as well as time overcurrent relays for the circuit protection. The rate-of-rise relays have responded very well and take out any circuit fault immediately and are very good at discriminating between regular loads and faults.

Most of our catenary problems were discovered early and have occurred because of construction defects or minor design flaws that were not noticed. The biggest bug of a catenary system is ensuring a totally smooth underrun. Anytime it's not achieved, the pan gets snagged in the catenary and something has to give. Usually it's the pan.

TRACTION POWER TROUBLES

The following list of problems is typical of those that can be expected with a catenary system. We report each incident that delays the LRT operation significantly on an incident report. The catenary failures and solutions below are drawn from those incident reports and represent the majority of the failures that we have had.

- Pantographs snagged:
  Midspan anchor too low, too slack, snagged pantograph—raise midspan anchors;
  Pantograph snagged section isolator—install properly;
  Pantograph snagged on crossover—repair loose fittings;
  Contact wire fasteners (clips) coming loose in threads—apply locktite;
  Contact wire terminations being jerked loose—repair; and
  Contact wire clip loose—tighten all.
- Broken equipment:
  Missing carbon from pan, snags wire and pulls wire out of clip—replace and repair any hard spots on the line that may be hitting the pans exceptionally hard;
  Broken tunnel arm hanger—repair;
  Broken contact wire hanger, hanger carrying current insufficient c jumpers—repair or add missing c jumpers; and
  Faulty tunnel arm hangers, design flaw—manufacturer replaced.
- Miscellaneous failures:
  Lightning arrestor blown, did not interrupt follow-through current—replace;
  Fallen overhead power line onto catenary—repair;
  Minor electrical short in car junction box—repair;
  Material dropped from an overpass while under construction;
  Track crew lifted crane into catenary—revise procedure and put limits stops on crane; and
  Arcing between pan and contact wire while lowering pan (at very low contact wire heights pan does not drop far enough or fast enough to

extinguish arc, wire burns through)—in new construction raise height of contact wire.

The catenary has been relatively trouble-free. We are now enjoying a mean time between failures of about $1\frac{1}{2}$ years. We have replaced approximately 100 m of contact wire in areas where the contact wire changed height rapidly and the pantograph created a greater uplift pressure on the contact wires.

SPECIAL EQUIPMENT

By and large catenary maintenance and substation maintenance can be done with the usual tools of the trade. However there are a few special items that are required:

- Bucket or lift truck equipped with rail wheels,
- Rail-mounted reel trailers to carry reels of contact wire and messenger wire ready to go at all times in case of major wire tear-downs, and
- Parallel clamps for contact wire pulling (normal line clamps are curved and will kink the contact wire).

SIGNAL SYSTEM

Edmonton has a basic two-aspect signal system that is patterned after the European approach to light rail signaling. The Edmonton system relies on the motorman to operate the vehicle safely. Failsafe systems are used to prevent hazardous conditions from occurring during normal operations, and are designed to be activated in the event of system or human failure. They are not intended to hamper normal operations.

Automatic signaling equipment provides the level of efficiency that is required with the safety demanded of an LRT system. The systems prevent train-on-train and other types of collisions with fixed objects, and with conflicting automobile or pedestrian traffic. They also provide service efficiency through automation, performing routine and repetitive tasks, and enforce operating and safety rules, and equipment restrictions.

To prevent any mode of collision, the system is separated in a simple system of discrete signal blocks. The block cannot be longer than the distance between two stations but may be shorter if the distance between stations is relatively long. The governing factor on block length is the time it takes for the train to clear the block and allow another train to approach. Edmonton is operating on a basic 5-min schedule and will be for several years to come, so the blocks are designed to clear a train in a maximum of $2\frac{1}{2}$ min. This difference in schedule and block time allows the system to remain on schedule even if one train is off schedule. In rush hour, where the travel time for blocks was very close to the design headway, the blocks can constrict the whole system, passing on delays to the following trains.

In addition to collision prevention the signal system also provides grade crossing protection and automatic route selection. All traffic conflicting traffic with an established route is prevented by the system.

The signal system also provides full grade crossing protection and preemption. At locations where the LRT system crosses a roadway the tracks are protected by gates. Traffic gates with barriers are the most effective for maintaining LRT's right to cross the roadway with the level of safety required and at the speed necessary to provide a competitive and efficient service.

In addition to the gate operation, there is an extended approach feature. If a train is within 15 sec of calling the gates down from the opposite direction, the gates will be held down waiting for the next train. The extended approach uses the next track circuit to the call-on circuit. This feature was more desirable than starting traffic moving across a crossing only to have another train immediately close it again.

A feature on Edmonton's system that is not common in North America is verification that the call-on circuit is operating. A call-on signal is located 222 m in advance of the crossing and changes from amber to green when the crossing protection is activated. The signal is protected by a train-stop magnet and will shut down a train that runs the amber light. The stopping distance for the crossing is not worst-case and allows for the use of the vehicle's dynamic brakes. The call-on signal concept came from a European supplier and we continue to use it. Although it is redundant with failsafe signaling, it is another check on the operation of the crossing call-on. Also, in possible future operations we might use something other than a track circuit to call on the gates. With the call-on signal we could use wheel detectors for gate activation knowing that, if they did not work, the train would not be allowed into the crossing. This is not something that we will be able to pursue for almost 10 years, as our next extensions will be in tunnels.

Our system has two main aspects, red and green. In addition to the main aspects we will also show a white lunar signal to the side of the signal if the line is in the divergent direction.

Originally our call-on signals were also red and green. This created some confusion. A call-on signal is not treated as seriously as a block signal, because it does not protect train movements. Its sole purpose is to provide protection to the crossing. We therefore allow a stop-and-proceed rule for the motorman at call-on signals if the signal is amber and control is not available. However there was confusion with block signals, which could not be passed except with special permission of control. The other area of confusion occurred at signals that were a combination block and call-on signal. The difficulty was that 99 percent of the time when a motorman approaches a call-on signal it changes to green. The same cannot be said of a combined call-on and block signal. About 10 percent of the time the train would approach the signal but, because the block ahead was occupied, the signal would not turn green. The time available to stop was now limited and required a relatively sharp stop.

The call-on signal lenses were replaced with amber lenses and at the combination signals another aspect was added, amber for the crossing only, with red reserved for the block. Now the motorman knows that an amber signal is for a crossing and should change as the vehicle approaches, but that he has to stop at a red signal. This system is a little different than that used in the rest of North America where the amber signal indicates the status of the next block. Given the expansion plans for the next 10 to 20 years there should be no major need to change the aspect system that we have now.

One failing of the system is that it lacks a communication system between the wayside and the vehicle aside from radio communication. A continuous cab signaling system was ruled out when we first installed the signal system because of the cost and a belief that LRT systems did not need signal systems. But it would be a useful feature if we could provide continuous information to the motorman about the route ahead. Our system is a point system; it clears a vehicle for the track ahead at a point on the line and at a point in time. If something happens to change the condition ahead of the vehicle, there is no way to communicate that information to the motorman via the signal system.

A continuous information system about permissive speeds and some form of on-board monitoring of actual speed would have been a preferable method of speed control to the speed check method that we use. If an operator is speeding in a given area, the train is automatically forced to a stop via a train-stop magnet and the motorman is required to report the shutdown to control. The speed checks are easily spotted and every operator knows exactly where they are. There is no means to prevent speeding once the train is past the speed check.

When LRT operations began, this speed check system was fraught with many difficulties and its reliability was questionable for a couple of months. The manufacturer redesigned a critical circuit board to solve the problems, but the damage had already been done in the minds of the people that the system is intended to serve.

SIGNALING SYSTEM UPDATE/PROBLEMS

There have been very few problems with the signal system over the past 10 years. The system as supplied works as it was intended.

The signal system uses line frequency track circuits and two-phase motor relays for train detection. The motor relays have functioned well and we have not had any failures of the relays. Initially I had a concern about using the line frequency, but we have had no problems with line frequency interference or false picking of the relay. With the motor relay the track voltage must be present at the correct phase angle with respect to a reference voltage present in the signal room.

Some of the initial problems we have had with track circuits were a significant number of false occupancies during our first few months of operation due to iron fillings and cuttings left in the insulated joints. We remedied this in future work by insisting on glued insulated joints rather than the separate joints.

The European signaling technology uses a significantly different approach to vital relays than does the North American version. Rather than individual relays with multiple contacts, smaller relays and more checks on relay position are used. The relays are rack-mounted and are covered by common opaque covers. We initially experienced some difficulties with dust in the relays because the covers aren't sealed. Troubleshooting a circuit meant removing the covers to see the relay position. The unnecessary removing of covers disturbed dust and created more problems. We replaced the original covers with clear plastic ones of our own design from a local plastics manufacturer. Now all the relays are visible and it is not necessary to remove the dust covers for troubleshooting. We also air conditioned the relay rooms, not for the sake of the equipment but to stop the staff from leaving the doors open in the summer to cool down the room. We also installed built-in vacuum cleaners to take the dust to the outside in cleaning operations.

Our winter conditions create the most problems for our track circuits. The track circuits in the road crossings are the most difficult to set in the winter when Edmonton is exposed to many different types of weather. Another factor is the salt that is spread on roadways to melt snow. The cars carry salt from the roadway onto the crossing and drop salt and sand into the crossing.

When the weather is mild and dry the crossing is also dry. The resistivity of the crossing is high and signal losses are relatively low. But when the weather is wetter and snowing, the crossing is wet and laden with salt. A significant reduction of resistivity and larger signal losses occur as a result. If the temperature drops below the point at which salt water melts ice and freezing occurs, then the crossing resistivity goes up with a reduction of signal losses.

Because it warms up during the day and cools down significantly at night, ice and snow melt and refreeze, creating a large swing in conditions over a 12-hour period. To reduce the effects of this we try hard to keep the crossings as clean as possible, and to prevent moisture from entering the crossing and particularly from filling the spaces between the rails and concrete crossing blocks. We try to get good drainage and will be experimenting this year with a new high-density plastic crossing insert that should give us greater insulation value. A rubber crossing insert tried in the past helped, but the cost to retrofit our nine grade crossings was too high. This is an area in which an automatic gain control track circuit would be extremely helpful.

We found out early that sand and track-circuited tracks do not mix very well. We had one occurrence of a train ghosting on a track circuit at the end of the line. In attempting to get good adhesion for acceleration, one of the operators was using large quantities of sand. The sand was being crushed and forming a silica layer on the rail that was reducing the shunt. We removed the manual sanding feature from the cars and constantly keep an eye on the amount of sand build-up on the rails. A feature that helps to prevent ghosting is that the signal system needs to see a sequential dropping of track circuits if it is to allow the last track circuit to pick up when it is cleared.

In extremely cold weather sand from the braking, sand from the road crossings, and graphite from the lubrication all combine to form a very tough ice that can coat the rail and prevent a good shunt. When the ice reaches −30°C it is extremely hard and the weight of an a empty car is insufficient to break through it. When temperatures are that low, we use alcohol to clean the worst areas of build-up, which are usually just past a road crossing.

When we put the system in, the cost of providing a battery backup and inverters for the track circuits was prohibitive, so we installed diesel generators in the signal rooms. The generators provide enough power to operate the signal system fully should we lose commercial power, which we obtain from the traction substation next door. The generators, however, have a momentary power loss that is tolerable for most of the applications. The one application that we have found that cannot tolerate a power outage is the centralized traffic control system and the microprocessors that operate it. The centralized traffic control (CTC) system was installed as a retrofit. We have found out the hard way just how much of a nuisance and detriment to the system operation a minor glitch can be. The centralized traffic display is an essential item that must remain up and in full working order, all the more so when there are other system problems. If the CTC shuts down, radio communications must be relied on. We are now in the process of installing inverters and battery packs for the CTC system.

When the LRT system began operating we only had minimal event recorder capacity. Because we believed it desirable to record the events on line, we installed a series of 48 pen recorders in the signal rooms. Our experience with the pen recorders and the maintenance required has led us to purchase a solid-state data logger. We will record all system activities for upwards of 1 week on data loggers and then download the information to a microcomputer for analysis or printing if required.

One of our primary reasons for increasing our capacity to analyze events is to recreate the circumstances immediately before any event. The signal system does the job it is required to do, but it would be useful if it could communicate up-to-date information to the train operators and to the train-borne equipment itself. The decision not to have this feature was a dollar trade-off when the system was installed and is not the fault of the system that we are using.

Enhancing the Selection Process for Operations Control Center Personnel at San Diego Trolley, Inc.

PETER TERESCHUCK

The safe and efficient operation of a given rail transit system is, to a great extent, determined by the proficiency of personnel assigned to the operations control center (OCC). If a transit agency is fortunate enough to hire experienced personnel, as was the case in San Diego when the trolley began operations, many of the problems associated with inadequate job performance can be avoided. Even with experienced personnel, though, changes in assignments may be necessary as a direct result of performance deficiencies. When the management of San Diego Trolley evaluated its own situation, with more recently hired employees being considered for promotion to train controller, it was soon found that promotion was based, in large part, on demonstrated ability in lower classifications (e.g., train operator). The desire to avoid misjudging candidates, coupled with the results of extensive research on job demands of the controller position, caused San Diego Trolley to evaluate its promotion and hiring practices, and to develop appropriate enhancements to the existing process. Because certain parallels could be drawn between train controllers (or dispatchers) and air traffic controllers, the Federal Aviation Administration selection process was used to develop revised hiring and promotion practices. Various tests designed for general personnel selection were evaluated. The end result is an extensive battery of psychological and general aptitude tests that allows the management team to evaluate a candidate thoroughly against specified job-related elements and personality traits that have been found to be present in successful train controllers. These enhancements have proven to be extremely effective, and have resulted in the selection of higher-quality candidates for certain safety-critical positions.

San Diego Trolley, Inc., P.O. Box 121544, San Diego, Calif. 92112.

THE METROPOLITAN TRANSIT DEVELOPMENT BOARD (MTDB) has overall responsibility for planning, designing, and constructing mass transit guideways in the San Diego metropolitan area. In 1980 the MTDB created San Diego Trolley, Inc. (SDTI), as a wholly owned subsidiary to operate and maintain the light rail transit (LRT) system that was then under construction and scheduled to begin revenue service in July of the following year.

The initial line, extending 16 mi from downtown San Diego to the Mexican border at San Ysidro, opened on July 26, 1981. This line, which has been characterized as a basic yet functional system (incorporating only proven technology and off-the-shelf equipment), proved extremely successful.

When service was first initiated, the trolleys operated from 6 a.m. to 8 p.m.; peak-time headways were 20 min. The average daily ridership was approximately 11,000 passengers.

Within a few years, the operating hours extended from 5 a.m. to 1 a.m., the frequency of service had been increased to every 15 min throughout most of the day, and average daily ridership had exceeded 20,000 passengers.

The success of the initial 16-mi line accelerated plans to expand the system with a 4.5-mi extension to Southeast San Diego. This new line opened on March 23, 1986. The combined system currently carries approximately 28,000 passengers per day and continues to experience the success it has enjoyed since the first line opened in 1981.

BACKGROUND

The trolley's principal management personnel were hired in November and December 1980, just seven months before the scheduled beginning of revenue service. Because SDTI was not part of an existing functional entity, the entire operating and maintenance staff had to be hired and trained in this brief period. This situation, although initially perceived as a significant problem, ultimately was considered to have contributed to the successful start-up of the system.

Because there was no real break-in period during which new hires could learn the ropes, considerable emphasis was placed on hiring only experienced personnel. This was considered essential for all key line supervision and controller (dispatch) positions. Accordingly, management solicited résumés and applications from other rail transit agencies and local railroads (e.g., the Santa Fe and the Southern Pacific).

This effort resulted in the hiring of a team of 12 key first-line supervisors, who had a combined total experience level exceeding a century. It was the depth of this initial group of employees that allowed the generation of successful training programs and that resulted in the development of substantive regulations and procedures for newly hired personnel in the hourly classifications.

INITIAL EXPERIENCE

The initial organizational chart was simple; it called for a manager of transportation, a layer of 12 midlevel supervisory personnel, and 17 train operators. The result of this bare-bones structure was often that employees performed multiple functions in areas that were beyond the normal scope of responsibilities on the regular supervisory level. The group was frequently called on to provide assistance in training, safety, marketing, special events, and operations planning and scheduling. Although complicated, the arrangement worked very well.

The trolley's immediate success was, to a great extent, the direct result of the proficiency of the operating staff and its ability to handle the myriad operating problems that routinely occur on rail transit systems. This level of experience, along with a simple and straightforward approach to developing the system, produced an operating environment that suffered few, if any, setbacks.

THE MATURING SYSTEM

The success of the San Diego Trolley took the form of widespread acceptance from the communities it served and from tourists who used the system for special-purpose trips. All this translated into increased ridership, which reached 18,000 to 20,000 passengers per day several years after the line opened. These ridership levels caused SDTI to extend the 15-min headway and the hours of service (to a point at which the service day stretched from 5 a.m. to 1 a.m.). Because of this, the operating staff more than doubled in size, from 29 employees in 1981 to 65 employees in 1987. The expansion included supervisory as well as train operator positions.

The midlevel supervisory positions (controllers and supervisors) were the most significantly affected. While monitoring the initial group of supervisory personnel as they carried out their assigned responsibilities, upper management observed that some employees could function adequately in line supervisor positions but not in the more stressful environment of the control center. This situation caused SDTI to examine the middle management structure and to attempt to determine how best to evaluate candidates for supervisory positions—both within the control center environment and on assignments on various line segments.

Consequently, SDTI conducted an internal evaluation to determine whether it was necessary to modify the training or selection process to compensate for the perceived shortfalls in the maturing system. This evaluation produced the following conclusions:

- The original, experienced personnel were being promoted or otherwise moved to positions with expanded responsibilities.
- The dual qualification as controller/supervisor that was essential to maintain flexibility when the staff was small could not be expected to address adequately the needs of the organization as it expanded.
- Employees hired after start-up, lacking the experience level of the initial staff, appeared to be adequate in the category of field supervision, but only marginal when called on to qualify in the controller category.
- Within the transit field in general, most promotions are made solely on the basis of either seniority or acceptable performance in entry-level positions. SDTI appeared to be following this practice.
- Internal training programs for midlevel positions seemed to be adequate for minimum qualification within the various categories.
- The central control environment, with the attendant restrictions on movement and the stressful nature of the work, appeared to generate unusual anxiety that translated to performance difficulties on the part of personnel assigned there.

On completion of this initial evaluation of the status of certain midlevel supervisory positions, it became quite clear that SDTI would have to realign the job classifications. It was also obvious that the company would have to undertake a more in-depth analysis of the unique characteristics of the controller position and develop a selection process that was more expansive than the rudimentary process that had been used heretofore.

THE FOLLOW-UP EVALUATION

The initial part of this process involved a simple review of the position of controller and the identification of a number of conditions that an employee experiences in the classification. There was also a cursory review of characteristics that were considered essential to effective functioning within the controller category.

Conditions Experienced Within the Classification

By interviewing existing personnel, SDTI management was able to identify a number of conditions frequently experienced by controllers. The effort focused primarily on those conditions experienced most often. The list included the following:

- High stress,
- Psychological strain,
- Occasional boredom,
- Restricted working environment,
- Ability to handle multiple tasks simultaneously, and
- Ability to accept constructive criticism.

Several of these elements were identified by scientists from the Institute for Social Research at the University of Michigan, who have performed extensive research on job demands as well as on worker health and occupational differences. During this research, they analyzed data (including variables related to demography, personality, stress, psychological strains, and health-related behaviors) from a broad spectrum of occupations.

These researchers concluded that there was some correlation between railroad "dispatchers" and air traffic controllers, as they both were involved in "monitoring and dispatching of major conveyances in the nation's transportation system." Train dispatchers reported "greater workloads, more work than was preferred, more responsibilities, more boredom, and more requirements to concentrate than was otherwise felt acceptable" (*1*).

Characteristics for Successful Performance

SDTI functions according to a rigid policy of adherence to rules and regulations. Because successful performance within the controller classification requires that individuals possess strong leadership qualities, the following characteristics were identified as being desirable among controllers:

- A high stress threshold,
- An ability to function within a controlled environment,
- A somewhat dominant and assertive personality,
- An ability to think abstractly,
- A well-organized and methodical nature, and

- Self-assurance and a strong ability to exercise control.

These characteristics represent elements that were identified in existing employees in the controller classification.

Further Evaluations and Conclusions

Because of the correlation between the controller position and air traffic controllers, SDTI contacted the Federal Aviation Administration (FAA) and asked for reference material that could be helpful in gaining insight into the selection process of air traffic controller (ATC) candidates. In response, SDTI received numerous documents on studies and evaluations that had been done over the years (2).

In conjunction with this effort, SDTI requested assistance from a local psychological testing service that provided employers with a wide range of tests to screen personnel for specific positions. Their work included on-site observation of personnel within the controller position and interviews with successful employees, as well as consultation with management.

After reviewing the available material, evaluating the existing SDTI screening procedures, and consulting with principals in the psychological testing service, SDTI determined that it would be desirable to administer a battery of tests to controller applicants. This was considered essential if candidates were to be evaluated on a wide range of elements important to the position.

ENHANCED SELECTION PROCESS

The exams were selected on the basis of their successful use within the FAA for ATC candidates, their inclusion in SDTI's existing procedures involving psychological testing, or their ability to predict which candidates possessed generally high aptitude and reasoning powers.

Tests of Adult Basic Education

The local psychological testing service spent considerable time evaluating the controller position by reviewing routine material that controllers are required to read, comprehend, and act on. Also noted during this process was the level of written expression that was required as well as language mechanics that were needed to function at an efficient level.

The Tests of Adult Basic Education (TABE) is a widely used survey that measures overall achievement in reading, mathematics, and language mechanics. The reading ability is grade-normed and related to the minimum level of reading expertise required to understand the variety of material to which a controller is exposed. Use of this test was considered essential to avoid the adverse experience mentioned previously (when employees were promoted strictly on the basis of their performance in lower classifications or seniority).

Minnesota Multiphasic Personality Inventory

SDTI had previously incorporated the Minnesota Multiphasic Personality Inventory (MMPI) test as a prescreening tool to identify certain character traits that appeared to present potential problems based on known characteristics of the controller position. This test identifies elements that represent maladjustments or negative characteristics. It is therefore considered to be an "exclusionary" test by determining elements that tend to disqualify persons from the intended position.

The MMPI is an extensive psychological test widely considered to be the most reliable, valid, and defensible test on the market today. Use of such personality tests for personnel screening dates back to 1920 when draftees were given the test to identify those who were psychologically unfit for military service. The use of the MMPI later involved research to detect possible psychological problems among candidates for pilot training or other specialized classifications, including submarine school.

The sophisticated scoring and rapid interpretation yields over 100 psychological scales that test for the following:

- The presence of severe emotional disturbance, including schizoid personality, manic depressive psychosis, paranoia, or other evidence of emotional instability;
- Neurosis of an incapacitating magnitude, including overly immature individuals with excessive impulsivity;
- Characterological or personality disorders involving antisocial characteristics and addiction potential; and
- Other traits that include openness to evaluation, social facility, and stress tolerance.

Also highlighted by the MMPI test are a number of content themes that indicate various tendencies that may be expected from the candidate being tested:

May be overly sensitive in interpersonal relationships.

May have problems with passivity and lack of assertiveness.
May have low self-esteem.
May be overly self-centered.
May be intolerant of the views of others.
May be mistrustful of others.
May be overly rigid and inflexible in his (her) thinking.
May show some discomfort in social situations.
May have feelings of alienation.
May harbor hostility towards others.
May have temper-control problems.
May not deal effectively with anger if provoked.
May have antisocial attitudes.
May have attitudes that run counter to societal norms.
May have some unconventional beliefs or attitudes.
May show irresponsible attitudes.
May sometimes disregard rules when it suits him (her).
May have problems with authority.
May tend to question supervisory decisions.
May be experiencing family discord that interferes with his (her) functioning.
May be prone to feeling anxious.
May show low energy or lack of enthusiasm.
May have problems with somatic distress.
May be overly sensitive to criticism.
May show some disregard for the feeling of others.
May show a pattern of narrow interests.
May be inappropriately aggressive.
May have a cynical attitude toward life.

The ability to score this test and report findings on a low-cost basis for industry is the result of years of work on the part of James H. Butcher of the University of Minnesota (*3, 4*). Until he summarized the scoring of the MMPI test, it required substantial high-cost evaluation on the part of trained professionals in the field of psychiatry.

Sixteen Personality Factors Test

In reviewing material from the FAA, SDTI found that the 16 Personality Factors Test (16PF) was administered to all ATC candidates as part of an effort to expand the battery of tests and to identify personality characteristics not otherwise measured.

Because the MMPI test is considered exclusionary, it was determined that a test containing inclusionary factors was important to provide balance to the process. The 16PF is just such a test. It is an objectively scorable questionnaire devised by psychologists to provide the most complete coverage of personality in a brief time frame. The test was designed for persons age 16 and above. The grading level is appropriate for individuals whose educational level is equivalent to that of the normal high school student.

The inclusionary aspect provides the evaluator with positive personality traits that are considered desirable in the classification for which the candidate is applying. The evaluators must then compare the applicant's identified personality traits against those required of the position being sought.

This test highlights personality factors that show whether a person is (among other things) concrete-thinking, tough-minded, self-reliant, shrewd, dominant, and emotionally stable (see Table 1).

How Candidates Are Rated

Once the full battery of three tests has been given to a prospective candidate, a representative from the psychological testing firm scores each test and then interviews each candidate. On the basis of all aspects of the testing and interview, each candidate is rated on a scale from A through F.

A candidate rating an A is considered an overall excellent prospect, whereas a person generating an F is considered to have failed the evaluation process. Applicants receiving scores of A through C are usually considered serious candidates and customarily are hired or promoted. Candidates rating below C are usually considered undesirable unless they are existing employees and have demonstrated certain capabilities in higher levels.

CONCLUSIONS

SDTI's experience with incorporating a battery of tests to enhance the selection process of control center personnel has been positive. This process appears to have led to the selection of employees who are efficient and well-adjusted in the controller position.

Based on this experience and that of the FAA, transit agencies should give serious consideration to incorporating various combinations of tests to expand or enhance the selection process of control center personnel. By incorporating a series of tests, transit agencies can expect the following:

- Psychological and general aptitude tests will have to be evaluated to determine their validity and to ensure that they are nondiscriminatory;
- Local collective bargaining agreements will have to be reviewed to determine if they prohibit use of such tests for hiring or promoting;

TABLE 1 PRIMARY SOURCE TRAITS COVERED BY 16PF TEST

Factor	Low Sten Score Description (1–3)	High Sten Score Description (8–10)
A	**Cool**, reserved, impersonal, detached, formal, aloof; sizothymia	**Warm**, outgoing, kindly, easygoing, participating, likes people; affectothymia
B	**Concrete-thinking**, less intelligent; lower scholastic mental capacity	**Abstract-thinking**, more intelligent, bright; higher scholastic mental capacity
C	**Affected by feelings**, emotionally less stable, easily annoyed; lower ego strength	**Emotionally stable**, mature, faces reality, calm; higher ego strength
E	**Submissive**, humble, mild, easily led, accommodating; submissiveness	**Dominant**, assertive, aggressive, stubborn, competitive, bossy; dominance
F	**Sober**, restrained, prudent, taciturn, serious; desurgency	**Enthusiastic**, spontaneous, heedless, expressive, cheerful; surgency
G	**Expedient**, disregards rules, self-indulgent; weaker superego strength	**Conscientious**, conforming, moralistic, staid, rule-bound; stronger superego strength
H	**Shy**, threat-sensitive, timid, hesitant, intimidated; threctia	**Bold**, venturesome, uninhibited, can take stress; parmia
I	**Tough-minded**, self-reliant, no-nonsense, rough, realistic; harria	**Tender-minded**, sensitive, overprotected, intuitive, refined; premsia
L	**Trusting**, accepting conditions, easy to get on with; alaxia	**Suspicious**, hard to fool, distrustful, skeptical; protension
M	**Practical**, concerned with "down-to-earth" issues, steady; praxernia	**Imaginative**, absent-minded, absorbed in thought, impractical; autia
N	**Forthright**, unpretentious, open, genuine, artless; artlessness	**Shrewd**, polished, socially aware, diplomatic, calculating; shrewdness
O	**Self-assured**, secure, feels free of guilt, untroubled, self-satisfied; untroubled adequacy	**Apprehensive**, self-blaming, guilt-prone, insecure, worrying; guilt proneness
Q_1	**Conservative**, respecting traditional ideas; conservatism of temperament	**Experimenting**, liberal, critical, open to change; radicalism
Q_2	**Group-oriented**, a "joiner" and sound follower, listens to others; group adherence	**Self-sufficient**, resourceful, prefers own decisions; self-sufficiency
Q_3	**Undisciplined self-conflict**, lax, careless of social rules; low integration	**Following self-image**, socially precise, compulsive; high self-concept control
Q_4	**Relaxed**, tranquil, composed, has low drive, unfrustrated; low ergic tension	**Tense**, frustrated, overwrought, has high drive; high ergic tension

NOTE: Terms in bold type are the technical names for the factors and are explained more fully in the handbook.

- Slightly higher costs can be expected for administering and scoring the tests;
- The selection of candidate personnel will be somewhat more complex and, thus, more time-consuming;
- Selected personnel for key positions will be more likely to qualify and become proficient in a control center environment; and
- Employees will be better adjusted to the unique environment within a control center and less likely to develop or display negative personality traits that are counter to an efficient operation.

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Hiring Productivity for Maintenance Staff

RUDY F. LUEPKE

By gearing the employment process to hire productivity, light rail transit systems can build maintenance staffs that function more efficiently and cost-effectively despite their smaller sizes. To do this, standards must be set for the various maintenance disciplines; candidates must be tested for ability, attitude, and trainability; and cross-training must be provided.

TRANSIT PROPERTIES NEW TO rail system maintenance must develop the ability to achieve a goal of having a qualified, productive work force at the outset of new revenue service.

The difference between a successful productive maintenance team and a mediocre "warm body" work force is hiring people that have the abilities and proper attitudes, and that are trainable to meet the system's maintenance needs. Accomplishing this task within a unionized transit organization means setting standards within the various maintenance disciplines and specifying how employees are to progress within the maintenance groups. The selection process of maintenance personnel is paramount in establishing the appropriate base for maintenance operations. It is with this selection standard that the number of maintainers required and the tone of the various maintenance disciplines will be set.

If the existing maintenance work force is to be used, prequalifications of these employees must be established early. This will allow senior qualified employees to be selected as opposed to senior employees only.

Involvement in the design and construction of the system will help in determining the disciplines needed to maintain a rail system and specifically

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what areas will need qualified employees during prerevenue operations. This concept will play a big role in the success of a start-up and the productivity of the work force.

If it is known that the maintenance people are to come from the existing bargaining unit, it is important that selection standards be set so that only those workers who are trainable are selected. Trainability means having the proper attitude and ability for the specific maintenance discipline as well as being able to pass an examination to verify the prospective employees' trainability.

Knowing the depth of the maintenance required, the testing must be set at levels consistent with learning and understanding the appropriate maintenance information. This ensures proper and safe maintenance performance within the system. Testing for reading comprehension, math, and sentence structure have been found to be good standards in looking for the right person for the job. In gauging trainability it is also important to evaluate the employees' attitude. Good attitudes foster team effort and enhance maintenance practices.

Employees who can pass the testing phase can be considered prequalified, which gives them a 90 percent chance of successfully completing the required training for the specific maintenance discipline. This same technique can be used when bringing in new employees from the street with, of course, the appropriate background.

When establishing the various disciplines within the maintenance group, it is essential that disciplines not be written so specifically that employees cannot be cross-trained to work in other disciplines if the need arises. A broad and diversified rail maintenance group will greatly enhance the productivity of a work force and keep the maintenance budget within reason. Ideally, the intent of maintenance staffing concepts should be laid out and presented to the bargaining unit executive officers well in advance of the need for personnel. However, it does not mean that this staffing concept could not be implemented at any reasonable time, even with the staff currently in place.

The importance of establishing an apprenticeship program for the various disciplines with the same basic selection process will enhance the ability to have qualified workers when the system needs them. These programs provide a lead time when encountering additional future maintenance responsibilities as well as lower production costs.

The hiring of productive workers creates several advantages: a smaller work force, positive input to the maintenance programs, cost-effectiveness, and a better capacity for cross-training maintenance employees. Union bargaining agreements can make the maintenance work force unnecessarily large. But the concept of trainable workers allows for flexibility with the smaller work force.

The experience with this concept has, in one known case, accounted for annual savings of approximately $200,000. This figure will be multiplied as the years go by or as the maintenance system responsibilities increase.

California Public Utilities Commission Light Rail Transit Regulatory Development Program

W. R. SCHULTE, M. T. FLANIGON, AND J. S. RICH

The California Public Utilities Commission (PUC) has legislative authority to regulate safety on rail transit systems in the state. This paper outlines the history, current practice, and future application of the PUC's safety regulation. The development of a formal program employing safety planning criteria, standards, and guidelines to accomplish regulatory goals is discussed in detail. The successful application of this programmatic approach to the recent start-up of the Sacramento and San Jose light rail systems is described.

THE HISTORICAL BASIS FOR today's safety oversight of the rail transit industry in California lies with the California Railroad Commission, which was established in 1911 as part of the reform movement that swept Governor Hiram Johnson into office. In 1946, the name of the commission was changed to the California Public Utilities Commission (PUC). The PUC regulated service, safety, and fares on the L.A. Railway, Pacific Electric, Key System, and all other electric railways in the state. Today, in the absence of any privately owned and operated rail transit systems, PUC regulation of light rail systems is limited to safety.

Until very recently, the PUC's safety regulation has principally involved after-the-fact reviews of new projects, operational safety inspections, and accident investigations. It was only with the passage of Assembly Bill 3209, approved July 24, 1986, that Section 99152 of the Public Utilities Code was

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amended to add new requirements for the development of a formal PUC safety oversight program with increased scope employing safety planning criteria, standards, and guidelines. Just as technical advancements have stimulated a rebirth of interest in light rail systems, so too have advancements been made in California's regulatory program to deal more effectively with today's modern rail transit industry. In keeping with the new industry requirements, a more clearly defined rail transit safety oversight program has been established to provide an improved level of light rail transit system safety in California.

PROGRAM GOALS AND OBJECTIVES

PUC policy is based on an understanding that the operators of the light rail systems have the ultimate responsibility for safety, while the PUC staff's role is one of safety oversight. The goal of this policy is to develop an independent and effective program for the oversight of safety-related activities during all life-cycle phases of each system using established safety planning criteria, guidelines, and standards. The purpose of this goal is to ensure that applicable safety requirements are identified and addressed by the responsible rail transit properties as they move from conceptual design to daily revenue operations.

The objectives of this policy include, first, development of a programmatic approach that relies heavily on existing published standards; second, development of regulations that require each light rail property to establish a system safety program that identifies, documents, and evaluates safety hazards and either eliminates or reduces them to an acceptable level; third, development of a standardized accident investigation and reporting system; and, fourth, development of a manual of standard practices and procedures that require the PUC to perform its oversight role in a consistent, uniform, and effective manner with appropriate documentation. These objectives have been used as the basis for the PUC's safety oversight program. The program has been divided into two separate phases, which are described in detail below.

PHASE I—STEP 1

Phase I, Step 1 of this program is to develop a new general order containing regulatory requirements for the development and application of system safety programs to be used by all public rail transit properties in the state. The new general order will complement the existing general orders dealing with rail transit safety by adding requirements that will be made mandatory for all new systems and system additions contracted for after the general order becomes effective. The order may be made retroactive for existing systems. The order is to be generic in nature and applicable to all rail transit properties. It will require each property, whether light or heavy rail, to prepare a comprehensive system safety program plan supplemented by appropriate implementing project plans, specifications, drawings, procedures, and instructions covering the total scope of design, procurement, construction, testing operation, and maintenance.

The order will also establish the basis for scheduled reviews and necessary revisions to ensure that each property keeps its system safety program up-to-date. Each property will be obligated to submit its system safety program plan to the PUC staff for review and acceptance within a given time period after the order is published. Further, the order will establish the authority of the PUC staff to verify each property's conformance to its approved system safety program plan through a PUC oversight program of on-site inspections, audits, and document reviews with preestablished witness and hold points.

Modeled after MIL-STD-882B, System Safety Program Requirements, the order will be in keeping with selected requirements from MIL-STD-9858A, Quality Assurance Program Requirements. The order will complement those contained in the published guidelines of UMTA, the American Public Transit Association, and others for preparation of system safety program plans. It also will be compatible with the existing system safety program plans being used by the rail transit properties in California.

PHASE I—STEP 2

Step 2 of Phase I will be to develop a set of design and performance safety standards and guidelines. These standards and guidelines will contain recommended safety practices for track and station construction, signaling systems, train control systems, communication systems, vehicle design and manufacture, preoperational testing and certification, system operating rules, preventive maintenance programs, etc. The standards will be contained in General Order 143-A, which has been developed through a consensus among representatives of the PUC staff and the California light rail transit industry. In early August, a final draft of General Order 143-A will be released for public comment prior to PUC hearings later in 1988.

A separate set of guidelines will be developed to clarify and expand upon the general order standards. The guidelines will be a living document, which will be revised and updated as conditions warrant.

Each transit property will be free to apply for exemptions or deviations from these requirements. When deviations are proposed, however, the transit property will be expected to describe, as a part of its system safety program, the basis for the deviation and present evidence to show that it is an acceptably safe alternative. The subjects covered by these PUC standards and guidelines will be some of the same ones each property must address in its system safety program plans required by the new general order prepared under Step 1 of Phase I.

PHASE II

Phase II of this program is to prepare a manual of PUC staff practices and procedures to provide the standardization, structure, organization, and individual accountability necessary to manage the day-to-day operation of the PUC's oversight program effectively. The manual, currently being prepared, will contain procedures and instructions to direct, guide, and monitor PUC staff activities. The procedures and instructions will be sufficiently flexible to deal effectively and economically with both light and heavy rail systems in all stages of design, procurement, construction, testing, operation, and maintenance.

Phase II began with the preparation of an overall policy statement to serve as a foreword to the manual. This was followed by the development of procedures and instructions for the PUC safety oversight program as it generally applies to all transit properties. Following the development of these general procedures and instructions, property-specific supplements are being prepared to describe more exactly the procedures to be followed by the PUC staff in their day-to-day safety oversight dealings with each of the different transit system properties. When completed, the first of these supplements will be a set of internal coordination procedures for controlling formal and informal communications, meetings, and correspondence between the various branches and sections of the PUC staff and each of the transit system properties.

The rest of the activity under Phase II will concern the preparation of whatever other transit property-specific procedures and instructions are needed to supplement the general procedures and instructions.

The specific procedures and instructions that are being prepared under Phase II cover the organization and reporting relationships within the rail transit safety section of the transportation division and the other divisions, branches, and sections that make up PUC's staff. They also cover the duties and responsibilities of the staff in the form of job descriptions giving titles and classifications for personnel dealing with rail transit safety oversight. Further, they will include general instructions for performing the design reviews, inspections, examinations, audits, and other oversight activities that are common to all transit system properties. Coordination plans for controlling communications between the PUC staff and each of the transit properties, accident investigation procedures, and requirements for the preparation of routine records, reports, and other documents by PUC staff will also be included.

CURRENT LIGHT RAIL PROJECTS

Obviously, in the case of the Sacramento Regional Transit and Santa Clara County Transportation Agency light rail projects, the PUC staff has had to employ a safety oversight program without completing all the program elements outlined above. Consequently, the staff looked at each property, focusing attention on what it had developed internally to serve as a safety assurance program. After reviewing the transit agency plans, the PUC staff added a complementary oversight program to make certain that full compliance with the applicable general orders was achieved.

The staff found that the construction management, start-up, and preoperational testing programs already in place readily addressed the PUC's safety concerns and created a sound foundation on which to build the PUC's own safety oversight program.

A single staff member from the rail transit safety section was designated project manager for the safety oversight program at Sacramento. Another staff member filled this role at Santa Clara. Appointing a single individual to manage the implementation of the program coordinated the PUC staff's functions. This approach also allowed the transit agencies' staffs to have one contact at the PUC who could answer questions, track formal submittals, and troubleshoot problems within the separate organizational units at the PUC.

In addition to the staff technical oversight reviews, the PUC and the transit properties have developed management overview groups (MOGs), which meet on a periodic basis to discuss management issues, such as project scheduling, mutual assistance, budget, political constraints, and review problems. The MOG meetings are not intended to focus on technical issues; rather they deal with program-related issues to ensure that the overall review program runs smoothly and effectively.

OVERSIGHT IN SACRAMENTO

In the case of the Sacramento Regional Transit (RT) project, their system safety certification, simulated revenue service, and system integrated testing programs served as the foundation for our safety oversight program. The PUC's safety oversight program simply consisted of a preplanned set of sampling inspections, witness points, and document reviews to verify the efficacy of the Sacramento RT Metro programs. One of the more important sampling inspections included in the PUC's safety oversight program was a survey to verify compliance with PUC orders for grade crossing protection and the adequacy of the light rail system from a traffic engineering point of view. This inspection identified and documented light rail vehicle (LRV)/automobile points of potentially hazardous conflict. The results of this inspection were used to advantage by RT Metro in making its traffic concerns known to the responsible city traffic engineers.

By using RT Metro's own performance and acceptance criteria in the area of wayside signaling, the PUC staff identified a signal system discrepancy. Periodic failures of a signal recorder were observed by PUC staff and related to regional transit management. This ready access to RT management was an important element in the success of the oversight program as it allowed the PUC to maintain effective communications without having to depend on a cumbersome formal process. The PUC believes that its safety oversight program served RT Metro well in this instance in that RT was able to make the necessary corrections well before final acceptance occurred. Early identification of problems allowed early resolution without causing any additional expense to the property.

As a final step in RT's safety certification program, the property prepared a document, signed by the general manager, attesting to the fact that all unacceptable hazards had been eliminated, all specified safety requirements had been complied with, and the systems, subsystems, components, structures, and equipment included in the project had been found safe for revenue service. Review and acceptance of this certification statement by the commission marked the end of the PUC's safety oversight program for start-up of the Sacramento RT Metro light rail system.

OVERSIGHT IN SANTA CLARA

Oversight activity on the Santa Clara County Transportation Agency (SCCTA) Phase I light rail project proceeded on a similar course to that followed in Sacramento. (Phase II is still under construction as of this writing.) Through a combination of sampling inspections, document reviews, and selective witness points, PUC staff specialists confirmed compliance with state safety standards in the areas of vehicle performance, traffic engineering, interlocking signaling, traction power, trackwork, and station construction. Additionally, by means of firsthand observations and document reviews, PUC staff evaluated SCCTA's operations and maintenance training programs, operational rules and procedures, and emergency preparedness planning.

The major focus, however, was on oversight of the SCCTA internal testing and safety certification program. The program required preparation of approximately 1,000 checklists, which identified safety-related requirements, verified that the requirements were covered in the design drawings and specifications, and then finally verified that the requirements had been met satisfactorily in the completed equipment, hardware, personnel training, or operating procedures. PUC staff reviewed all of the checklists to verify that the safety requirements had indeed been complied with. The last step in the certification process was the formal submittal of a statement signed by the agency director stating that the certification process had been completed and that the system had been found safe to operate.

By monitoring the safety certification process—as well as overseeing the integrated and simulated revenue service testing conducted by the SCCTA—PUC staff was able to verify that the process used to identify and eliminate or to control hazards was effectively applied to Phase I of the light rail project. This approach to safety regulation appears to have worked well for both the PUC staff and the SCCTA.

SUMMARY

With the experience gained on the Sacramento RT Metro and SCCTA projects, the PUC has been able to further refine and develop its own safety oversight program. Thanks to the cooperation of the light rail systems' personnel, the state is forming an internal safety structure that ultimately will eliminate or control hazards to public safety. Both of the transit systems have accepted and addressed the most basic principle of PUC oversight: that the final responsibility for safety resides with the rail transit property itself. The PUC has, in turn, accomplished its legislative mandate by instituting an effective safety oversight program. Through this cooperative focus on safety, the most important goal of all is achieved: minimal risk to rail transit passengers and employees in the State of California.

Toronto's Harbourfront Line
Light Rail Transit in Reserved Right-of-Way as a Local Transit Alternative

R. M. TOPP AND G. W. CARR

Recent light rail transit (LRT) developments in North America are demonstrating the success of LRT as a high-capacity transit mode linking the suburbs with the downtown. This paper examines a somewhat different application of LRT technology planned for the City of Toronto: that of an upgraded local transit service operating within the downtown area, but generally unaffected by downtown traffic conditions. An LRT line operating in a dedicated right-of-way was recently approved for construction in the center of a roadway along the waterfront of Toronto's downtown in conjunction with major development proposals. The portion of the line connecting to the subway would be constructed subgrade. This will be the first new streetcar line built in Toronto in more than 60 years. The decision is expected to promote a high modal split to transit by ensuring that the new workers and residents being drawn to this area are provided an attractive alternative to the automobile before they have developed automobile-oriented travel habits. This paper provides a description of the facility and discusses the rationale behind many of the decisions that were made by the transportation professionals involved in its design, including the requirement for a dedicated right-of-way, the choice of fixed rail technology, and the traffic engineering problems associated with proper integration of the LRT and automobile traffic at existing and proposed signalized intersections.

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TORONTO IS A WATERFRONT city and, like many such cities around the world, it grew from the shipping harbors on its shoreline. However, with the advent of commercial railways in the 19th century, reliance upon the waterfront diminished and the city's focus shifted further inland. The waterfront subsequently evolved into what was largely an industrial wasteland, cluttered with abandoned factories and shipping warehouses.

An ambitious plan for waterfront renewal is now under way and is bringing people back to the area. The plan is to create a neighborhood with a diverse mix of residents and workers, and an unusually high proportion of parks and public activities that would become an extension of downtown Toronto.

The Harbourfront light rail transit (LRT) line, which recently began construction, was proposed to assist in providing the public accessibility so crucial to the creation of a world-class waterfront, and to help prevent such a significant development from creating traffic chaos. The line will operate on a dedicated right-of-way and therefore be largely removed from the effects of traffic congestion. (In Toronto "LRT" is synonymous with exclusive right-of-way operation.) It will serve as a feeder route, connecting the waterfront developments to the downtown subway system.

HARBOURFRONT LRT DESCRIPTION

Construction on the 2.13-km Harbourfront LRT line began late in 1987. It will be below ground for 0.67 km from a turnback loop at Union Subway Station, thence south under Bay Street, a major downtown arterial roadway, to Queen's Quay, the collector roadway serving the existing and future developments along the waterfront (see Figure 1). The line will come to grade at a portal on Queen's Quay immediately west of Bay Street on a ramp 65 m long with a 7.5 percent rise. It will continue west along Queen's Quay in a dedicated right-of-way to a turnback loop at Spadina Avenue. The at-grade portion of the right-of-way will be on a center median that is raised approximately 125 mm (5 in.) above adjacent traffic lanes (except at intersecting roadways). The right-of-way will have a minimum width of 6.72 m along the midblock sections and 7.76 m at platform locations.

The facility will include a subgrade station at Union Station and another on Bay Street immediately north of Queen's Quay. Platforms will be provided in each direction along Queen's Quay at York Street, Simcoe Street (a proposed roadway), and Rees Street, and at the turnback loop at Spadina Avenue. All platforms on the at-grade section will be a minimum of 30 m long and 1.50 m wide to accommodate a train of two nonarticulated cars. The side platforms at the below-grade Bay/Queen's Quay Station will be 36 m long and 2.50 m wide with connections to adjacent developments. The station design will allow pedestrian crossings at the subgrade track level via a controlled

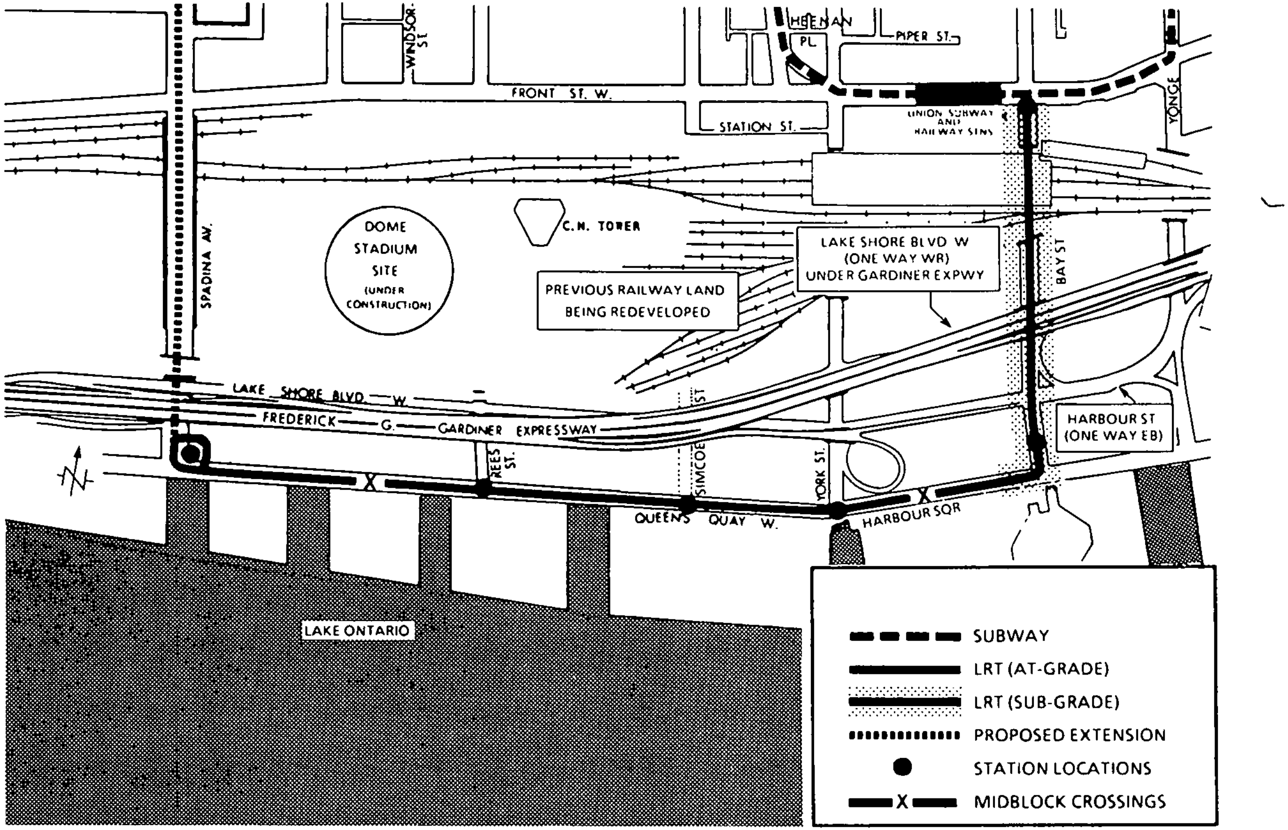


FIGURE 1 Harbourfront LRT alignment.

crosswalk to eliminate the need for patrons to cross at street level. This form of crossing is believed to be a first for North America.

The platform at Union Station loop will be 45 m long in order to accommodate two articulated cars simultaneously. It will be connected to the existing subway mezzanine level at Union Station by an underground passage equipped with a set of stairs and an escalator.

Initially, single vehicle operation has been proposed with President's Conference Committee (PCC) cars or Canadian light rail vehicles (CLRVs) from the existing fleet, with future upgrading to articulated light rail vehicles (ALRVs). Ultimate demand levels may be accommodated by operating ALRVs at 2-min headways with an average operating speed in the order of 12 mph. Traction power of 600 volts dc will be provided through two substations, with side-pole support for overhead wires.

The total project cost is estimated to be $51 million (U.S. $38 million) in escalated dollars (not including rolling stock). The line is scheduled to open late in 1989.

DEDICATED RIGHT-OF-WAY

Planners recognized early in the study process that if major developments close to the downtown area were to be given the go-ahead, a transit service would have to be provided that would afford new workers and residents an attractive alternative to the automobile. When future traffic conditions were considered in light of projected transit demands, it became obvious that an efficient transit service connecting the waterfront to the downtown could only be provided if it operated in its own right-of-way and was therefore generally free from interference from other traffic.

Current and Future Traffic Volumes

The Harbourfront LRT will operate under Bay Street south from Union Station to Queen's Quay and then west on Queen's Quay to a turnback loop at Spadina Avenue. This section of Bay Street is currently a major downtown arterial roadway and its intersections with Lake Shore Boulevard (one way westbound) and Harbour Street (one way eastbound) are major access points to and from the Gardiner Expressway. Current volumes in the p.m. peak hour are shown in Table 1. Even with an efficient transit service in the area, it is anticipated that once the future developments in the waterfront are completed, certain of the movements shown in Table 1 may exceed the available capacity of the intersection.

Weekday traffic congestion on Queen's Quay is also a price that will be paid for new developments in the area, not only because of the sheer

TABLE 1 TRAFFIC VOLUMES IN THE P.M. PEAK HOUR

Intersection	Approach Volumes (vehicles/hr)		
	Through	Lefts	Rights
Bay and Lake Shore			
Northbound	571	154	0
Southbound	319	0	427
Westbound	2,045	176	80
Bay and Harbour			
Northbound	260	0	17
Southbound	348	173	0
Eastbound			
Harbour Street	720	832	0
Adjacent ramp from Gardiner Exp.	258	0	35

increases in traffic volumes, but also because of the variety of movements to and from developments adjacent to the roadway. Queen's Quay west of Bay Street does not have weekday traffic problems now, as it has very limited office and commercial development. It is, however, subject to severe traffic congestion on weekends and holidays from the late spring to the early fall due to the recreational and tourist attractions aleady in place.

During such weekend periods of congestion the existing local bus service often inches along with the rest of the traffic, and there are few incentives to encourage motorists to switch to a transit service with such conditions.

Future Demand

When all of the planned development is completed (much of which is already under construction), there will be an additional 138 500 m^2 (about 1.5 million ft^2) of office floor space in the vicinity of this section of Bay Street and adjacent to Queen's Quay.

The demand for the LRT service is not limited to development on the waterfront. The major railway yard facilities located west of Bay Street and north of the Gardiner Expressway are also a site planned for extensive redevelopment (see Figure 1). The catalyst for this development is the SkyDome, metropolitan Toronto's new domed stadium, under construction and scheduled to open in 1989. Approximately 127 600 m^2 (about 1.37 million ft^2) of floor space is planned within a convenient walking distance of this section of Queen's Quay.

When these developments are completed, the new transit service will be required to carry an estimated 3,800 passengers south from Union Station on an average weekday morning rush hour. There are only two surface routes in the Toronto Transit Commission (TTC) system that have a peak-point, peak-hour demand near this level, but they are both bus routes operating on major suburban arterial roadways in the northern metropolitan area and have multiple branches, including express services. The practical capacity of a regular bus service in mixed traffic conditions in this area is generally considered to be little more than 3,000 passengers per hour, a scheduled headway of approximately 1 min.

ALTERNATIVES FOR DEDICATED ROW OPERATION

Once the need for a dedicated right-of-way (ROW) had been recognized, three principal alternatives were considered in addition to LRT in a permanently designated median ROW:

- Diesel buses in reserved curb lanes;
- Diesel buses in a dedicated median lane; and
- LRT in a median lane with a legislated ROW in peak periods only.

A brief outline of the reasons for rejecting these alternatives follows.

Buses in Reserved Curb Lanes

Due to the numerous driveways and accesses to adjacent developments along Queen's Quay, right-turning automobiles would need to share the curb lanes even if these lanes were to be reserved for buses. The large number of right-turning automobiles expected at various points along Queen's Quay, combined with interference to right turns from heavy pedestrian volumes on adjacent sidewalks, means that this alternative could be expected to offer little or no improvement over mixed traffic conditions.

Bus Lanes in the Roadway Median

Operation on a reserved ROW in the middle of these roadways would offer a higher level of priority than curb lanes; however, diesel bus operation would require a wider right-of-way than fixed rail (about 7 m as opposed to 6.72 m). Buses are not as comfortable as light rail vehicles, are environmentally inferior because of noise and fumes, and their lower carrying capacity per vehicle results in a higher operating cost. Furthermore, if any portion of a bus line were to be constructed subgrade, special requirements for ventilation would be required.

LRT with Exclusive Peak-Period ROW

Government staff of the City of Toronto, which has jurisdication over Queen's Quay, initially favored legislating an LRT right-of-way providing the required exclusivity in peak periods only by lane markings or overhead signs. The TTC strongly opposed this, based largely on a judgment call that legislation that could be weakened, modified, or even eliminated by a future city council vote was not a sufficient guarantee of exclusivity. Such a guarantee was considered essential because the very large capital investment would be of questionable value if any portion of the line eventually operated in mixed traffic conditions.

Given the level of traffic congestion in Toronto's downtown as well as the significantly greater cost of LRVs versus buses, it is the TTC's position that it would not be economical to build another streetcar line in mixed traffic conditions.

SUBGRADE ALIGNMENT ON BAY STREET

The decision to grade-separate a portion of the Harbourfront LRT line arose from the realization that, in addition to full right-of-way protection, the projected high level of demand would require fully integrated, fare-paid transfer facilities at Union Station, which is the principal subway and inter-regional rail terminal in downtown Toronto. After examining a number of design alternatives, it was recognized that the most feasible method of achieving these two requirements would be by grade-separation. The initial design was prepared with a short subgrade alignment from Union Station south to immediately north of Lake Shore Boulevard.

However, the Metropolitan Toronto Department of Roads and Traffic understandably expressed concern that the operation of LRT on a dedicated ROW would reduce the capacity of the heavily used intersections on Bay Street, particularly at Lake Shore Boulevard and at Harbour Street. For example it was estimated that with the anticipated traffic growth in the area, the LRT on the surface would have the effect shown in Table 2 on delay to the average motorist traveling through the intersections in the peak hour.

In addition, from 1980 to 1985 the intersections of Bay Street with Lake Shore Boulevard and Harbour Street consistently appeared in the listing of the top 20 accident locations in metropolitan Toronto. In fact in 1982 they were actually the first and second worst accident locations in the metropolitan area. The reasons for this accident history are high traffic volumes (and consequent congestion), visiting motorists' unfamiliarity with the area, and reduced visibility (at Lake Shore Boulevard) due to the support structure for the Gardiner Expressway overhead. It was therefore concluded that the

TABLE 2 AVERAGE DELAY PER VEHICLE IN THE P.M. PEAK HOUR

Intersection	Existing Traffic	Future Traffic: LRT At Grade	Future Traffic: LRT Subgrade
Bay-Lake Shore	110	160	125
Percent increase		+45	+14
Bay-Harbour	165	340	170
Percent increase		+105	+3
Bay-Queen's Quay	25	75	70
Percent increase		+200	+180

introduction of an exclusive-median LRT system passing through these intersections at-grade would further aggravate a situation that was already a cause for serious concern.

With these factors in mind, the design was modified to extend the subgrade section from immediately north of Lake Shore Boulevard to just south of Harbour Street and thus avoid interference with the operation of these intersections.

Further extending the grade separation onto Queen's Quay had a number of advantages. With the previous design and the LRT tunnel portal located on Bay Street, the station at the Bay-Queen's Quay intersection was proposed to be located at grade on Queen's Quay, immediately west of Bay Street. Boarding and alighting patrons would use island passenger platforms adjacent to the LRT right-of-way, which they would access using the intersection crosswalk on the appropriate signal phase (as is illustrated later in Figure 3). This stop location was expected to be the line's second busiest (next to Union Station). It would, however, be located south of major developments on either side of the lower end of Bay Street, result in an unacceptable stop spacing to Union Station, and lead to capacity problems in the long term without provision of an intermediate station. Because of this last reason, a station would also have to have been built under Bay Street immediately north of Harbour Street.

If the subgrade portion were extended beyond the Bay-Queen's Quay intersection, these two stations could be consolidated into one subgrade facility under Bay Street, north of Queen's Quay, at a location more central to the adjacent developments. The majority of transit patrons would thus have a quicker travel time with elimination of one stop and the requirement to travel at grade through the busy Bay-Queen's Quay intersection. The absence of the LRT would also permit greater flexibility to deal with future traffic volumes traveling through this intersection. In addition, the large volume of patrons destined for the Bay-Queen's Quay area would be served much more conveniently with a subgrade, weather-protected station as opposed to at-grade island platforms.

Higher cost was the only major disadvantage to the proposal to extend the subgrade portion of the line beyond the Bay-Queen's Quay intersection. To assist in this decision, the contract documents specified that interested construction firms prepare bids for both options. The final decision to further extend the tunnel section of the line was made only after studying these comparative bids.

INTEGRATION OF LRT INTO THE QUEEN'S QUAY TRAFFIC SYSTEM

As indicated previously, the LRT will be operated on a raised center median, 125 mm (5 in.) above the adjacent traffic lanes. This will keep automobiles from infringing on the right-of-way but, with rounded edges provided along the median, will not represent a barrier in the event of an emergency. The initial proposal was for LRT operation in the center of Queen's Quay on the road surface, but with tracks bordered by 6-in. curbs to guarantee an exclusive right-of-way. This design was rejected because the raised median allows easier crossing by emergency vehicles, and because the raised-curb concept would allow garbage and debris to collect and make snow removal and drainage more difficult.

As shown in Figure 2, the total right-of-way of Queen's Quay required at midblock locations is 27 m, which will provide for a 6.72-m LRT right-of-way, two traffic lanes in each direction, and 3-m sidewalks on each side of the street. At intersections this right-of-way varies, but typically widens to approximately 31 m to accommodate a left turn lane and a 1.5-m wide platform.

The LRT median will come to grade at the six intersecting roadway/driveways that are shown in Figure 1. The TTC required that all crossings be signalized to allow consideration of greater priority for the LRT and enhance the safety of the operation.

Passenger platforms at York, Simcoe, and Rees streets will be constructed on the far side of the intersection for two conventional reasons:

- To make the most efficient use of the road right-of-way. Left turn lanes are provided on Queen's Quay in at least one direction at each of the three intersections, and the required roadway right-of-way is minimized if the platform is located on the far side of the intersection in the "shadow" of the left turn lane (see Figure 3).
- To provide the greatest potential for transit signal priority (discussed later).

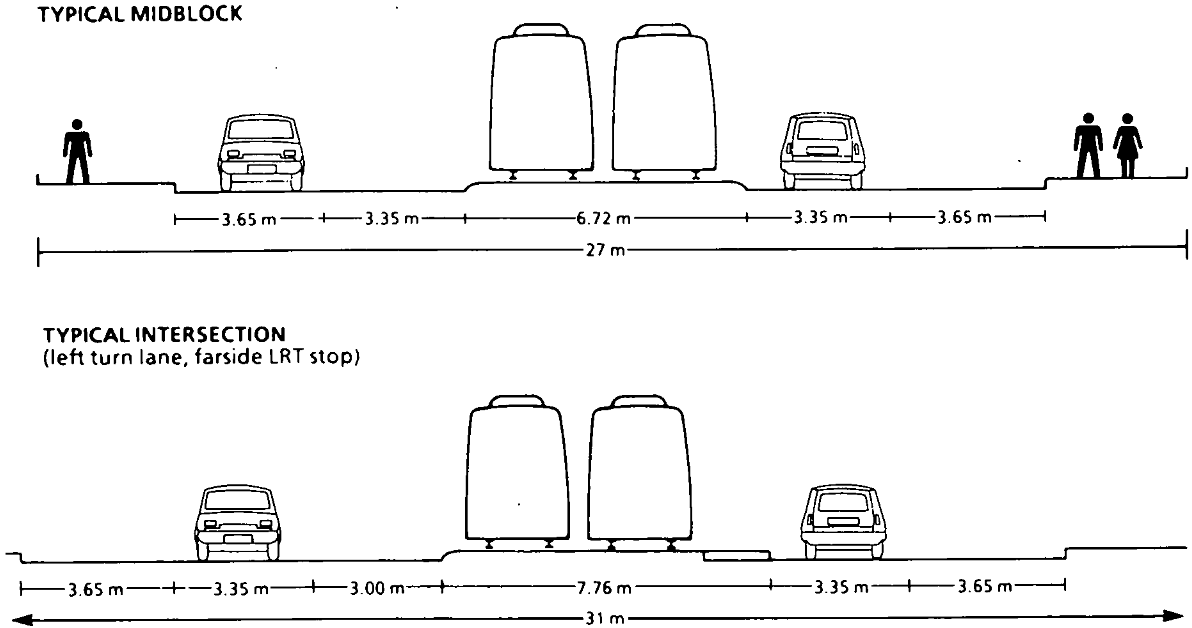


FIGURE 2 Harbourfront LRT at-grade cross-section dimensions.

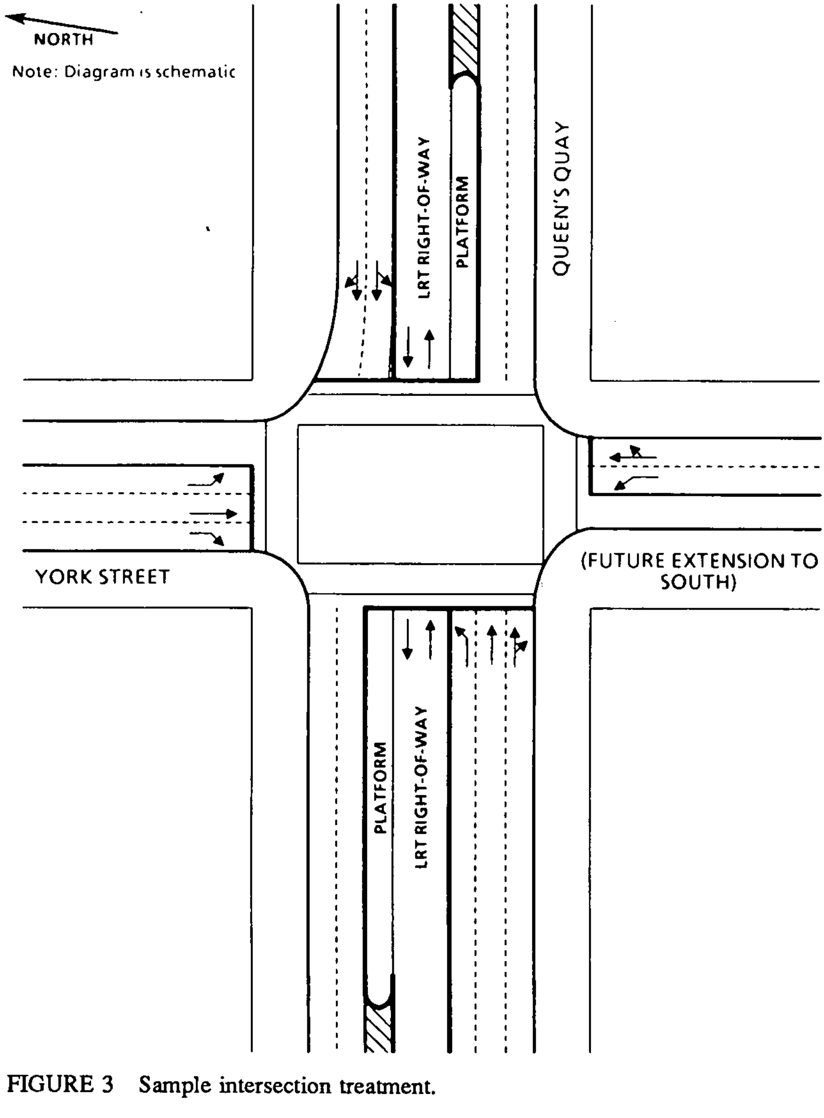


FIGURE 3 Sample intersection treatment.

Traffic Signal System

If separate left turn lanes were to be incorporated on Queen's Quay at all signalized crossings as illustrated in Figure 3, the preferred signal phasing would be as follows:

- Phase 1—east-west left turn phase for traffic in left turn lanes,
- Phase 2—east-west green phase for LRT and through/right-turning traffic, and
- Phase 3—north-south green phase.

At the two midblock crossings it was not possible to widen the right-of-way of Queen's Quay to incorporate left turn lanes in addition to the two traffic lanes in each direction. It was also not feasible in light of anticipated traffic volumes to designate one of the two traffic lanes for left turns only. For this reason the curb lane at such locations will be designated for through and right-turning traffic and the second lane will be designated for through and left-turning traffic. The locations where left turns are to occur from a lane that is shared with through traffic cannot use the phasing outlined above.

The Metropolitan Toronto Department of Roads and Traffic has proposed a signal phasing that would incorporate callable signal phases for the LRT line. This phasing scheme is shown in Figure 4 and would operate as follows:

- Phase 1—green signal for all eastbound automobile traffic and east-west pedestrian flow on the south side of intersection,
- Phase 2—green signal for eastbound and westbound LRT—only if required (callable),
- Phase 3—green signal for all westbound automobile traffic and east-west pedestrian flow on the north side of the street,
- Phase 4—same as Phase 2 (callable),
- Phase 5—green signal for all north-south automobile and pedestrian movements,
- Phase 6—same as Phase 2 (callable).

Note that due to capacity restraints, Phase 6 would not be available if both Phase 2 and Phase 4 had already been required for that signal cycle. That is, a maximum of two LRT phases could be called per cycle, but the phase would be available at three separate times within each cycle.

For consistency, this phasing scheme is being proposed even at those intersections with exclusive left turn lanes.

As stated before, LRT platforms will be located on the far side of the intersection to permit the greatest flexibility for transit priority at intersections. Although the details are still being finalized, the concept of the

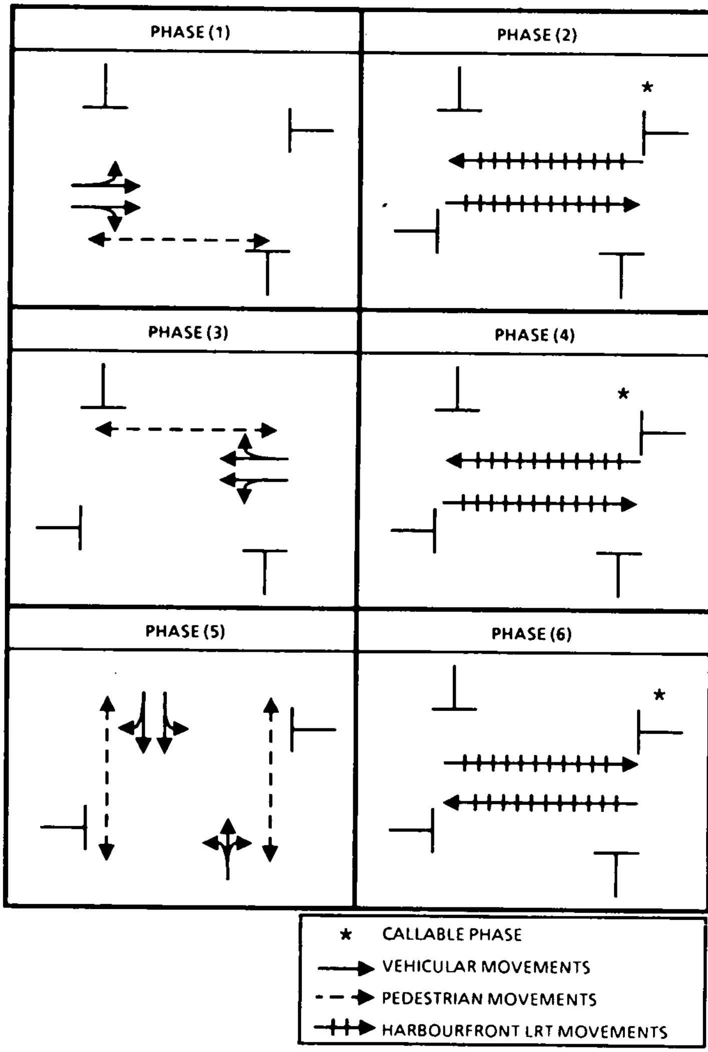


FIGURE 4 Proposed traffic signal phasing for midblock intersections.

intended design is that of traffic signal actuation by the LRV when it has traveled a short distance from a far-side platform, at a point well in advance of the downstream signal. Still under study is the extent to which signal timing and phasing can be adjusted within the framework illustrated in Figure 4 and thereby minimize signal delay to the LRT.

Queen's Quay-Spadina Turnback Loop

The turnback loop at the line's western terminus is illustrated in Figure 5. The loop will operate in a counterclockwise direction, with the entrance onto Spadina Avenue incorporated into the existing Spadina Avenue-Lake Shore Boulevard intersection. The northbound stop bar on Spadina Avenue would be relocated to south of the loop exit so that the LRVs could access the median right-of-way during the green phase (Lake Shore Boulevard is one way eastbound at this point). At the entrance to the loop from Queen's Quay, a "half" signal would be implemented to control westbound (but not eastbound) automobile traffic whenever an LRV is waiting to enter the loop.

The loop was designed to allow additional trackage to be added at a future date to accommodate an extension of the LRT line north on Spadina Avenue, including track for LRV storage in advance of the conclusion of a SkyDome event. Although service will terminate at Queen's Quay, a 0.83-km length of track is required on Spadina Avenue to allow vehicles to run-in to service from King Street. The proposed extension of LRT service along Spadina Avenue is discussed briefly in the following section.

PROPOSED EXTENSION

When the recommendation for a Harbourfront LRT was made to the metropolitan Toronto Council in 1985, it was intended as the first phase of a longer line that would continue north on Spadina Avenue from Queen's Quay to the east-west Bloor-Danforth subway line, as is illustrated schematically in Figure 6. Although the council approved the Harbourfront LRT, the second phase—referred to as the Spadina LRT line—was referred back for further study of the impact it may have upon the traffic on Spadina Avenue and upon the communities through which it would operate. These communities, which include Toronto's Chinatown, the Garment Industry, and the Kensington Market, make Spadina Avenue one of the most diverse neighborhoods in metropolitan Toronto.

The Spadina bus service carries 2,500 passengers south from the Bloor-Danforth subway line every weekday a.m. peak hour. It is the third busiest surface route of the approximately 130 routes in metropolitan Toronto and is nearing the practical capacity for bus service in mixed traffic.

The construction of the SkyDome was only one aspect of a major development package that was approved for the whole of the railway lands north of the Gardiner Expressway and on both sides of Spadina Avenue (see Figure 1). It has been estimated that with these developments this peak-hour demand will grow from 2,500 to 5,600. Crowded buses, bunching of vehicles, and reduced running speeds are already becoming increasingly characteristic of this route.

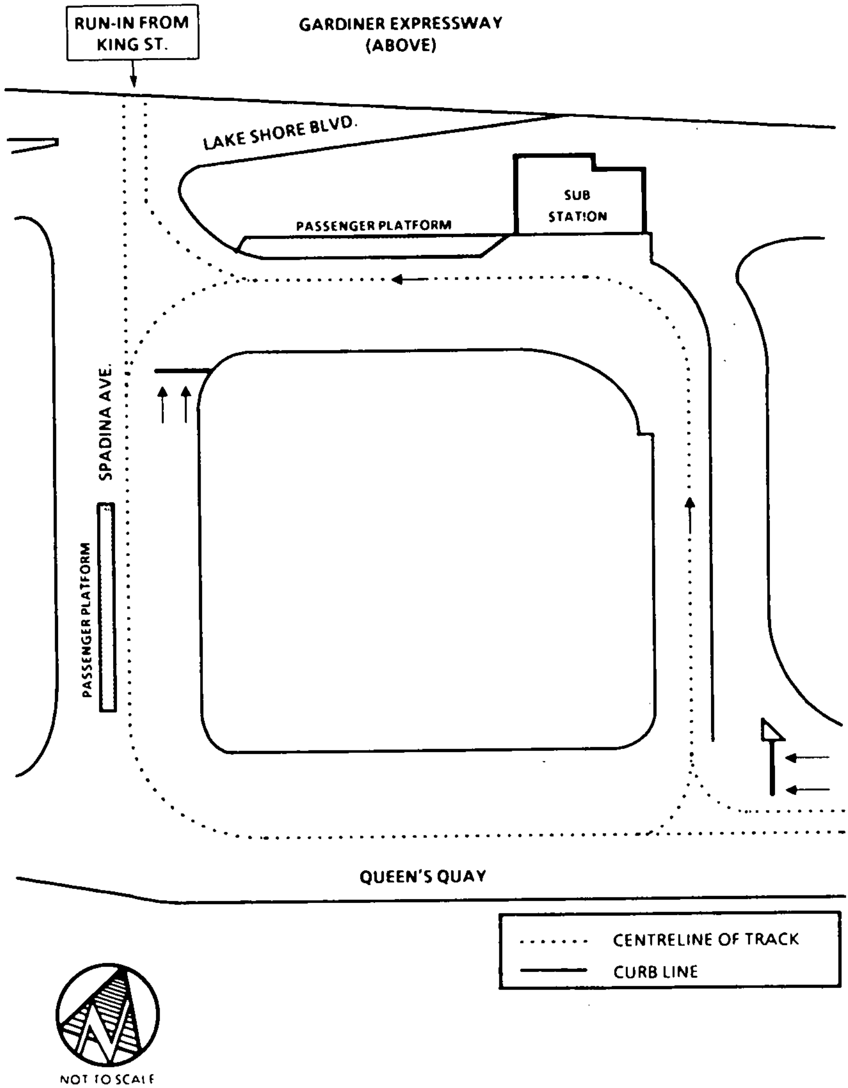


FIGURE 5 The Queen's Quay-Spadina turnback loop.

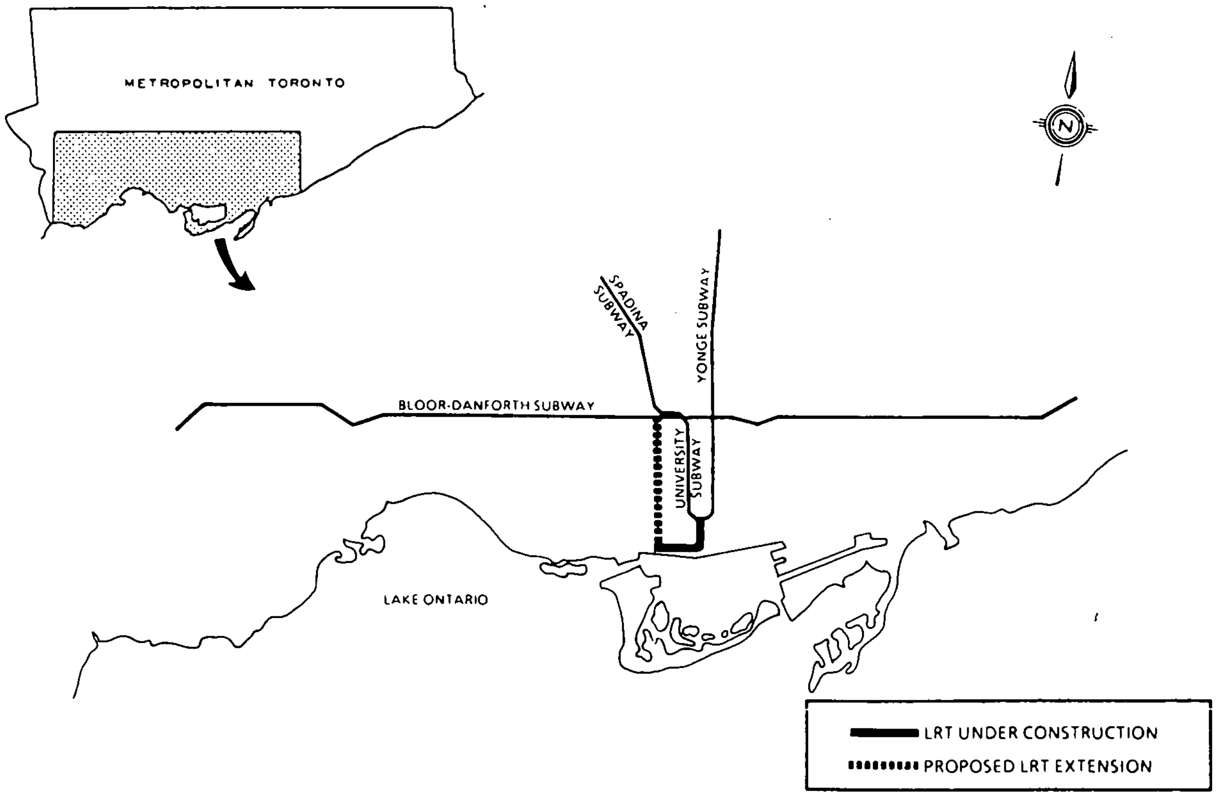


FIGURE 6 The Harbourfront LRT line and proposed Spadina extension.

Due to the wide right-of-way of Spadina Avenue (about 130 ft), this location may lend itself well to a center-median LRT. The proposal is currently under extensive study in response to strong concerns expressed by the public, such as the resulting reduction in on-street parking (a section that has angled parking would have to be converted to parallel parking, resulting in the loss of about 100 on-street spaces), the reduced number of points at which left turns would be permitted across the center of Spadina Avenue, and the possibility of additional traffic infiltration through adjacent neighborhoods as a result.

Light Rail Transit Tracks in Pavement

ROBERT E. CLEMONS

One of the important features of light rail transit (LRT) is the ability to locate tracks in downtown streets and transit malls, thus eliminating the high capital cost of grade-separated aerial structures or subways. The designs of transit tracks in pavement have evolved over the past 100 years in domestic streetcar systems. This paper traces this evolution by looking back at the initial streetcar track designs, by reviewing the development of heavy streetcar tracks, and finally by reviewing the track details and costs of seven recent North American LRT projects. Comparison of these seven projects shows a wide variation in design criteria and a resultant cost range of $67 to $270 per single-track feet. The conclusion is that much work remains to be done to establish cost-effective design criteria for transit track in pavement.

THE FIRST PRACTICAL STREET railway in the United States was opened for service 100 years ago, in February 1888, by Frank Sprague in Richmond, Virginia. The system consisted of 12 mi of track, 40 vehicles with two 7½-hp nose-mounted traction motors, a 500-volt dc overhead wire distribution system, and underrunning pole trolley, and included an 8 percent grade. So successful was this project that within 3 years 200 street railway systems were in operation or on order.

Track designs for these early systems were based on steam railroad technology modified to allow installation of paving stones above the crossties as shown in Figure 1.

Typical track of this era was subject to rapid deterioration because of inadequate funding, poor drainage, low-quality materials, deferred maintenance, and the pavement covering the track. The more successful properties developed the deeper girder rails that eliminated the need for rail chairs,

Bechtel Civil Inc., P.O. Box 3965, San Francisco, Calif. 94119.

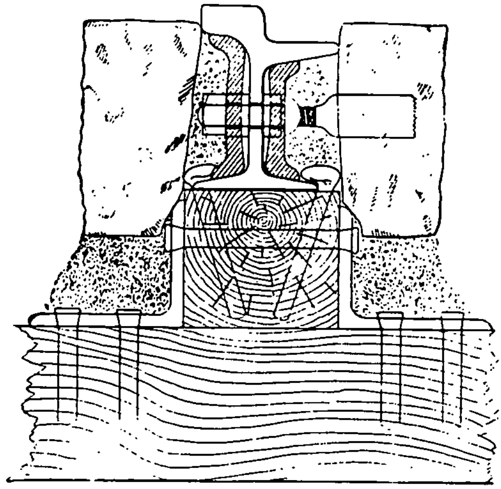


FIGURE 1 Track construction circa 1892.

increased the vertical bending strength, and provided a uniform flangeway. Increased streetcar weight and speed and increased weight and speed of trucks that also operated on the trackway led to the concrete encasement of the timber or steel crossties, and eventually the entire track structure. An example of a heavier streetcar track design is shown in Figure 2.

LIGHT RAIL TRANSIT TRACK

Today's light rail transit (LRT) track has evolved from yesterday's streetcar track, adapting to a wide range of new technical and aesthetic requirements. The keystone, however, remains cost-effective design. Today's light rail philosophy is the same as yesterday's: the minimum design for the expected service. Other important features are as follows:

- Flexibility—changes over the project life to accommodate changes in demands or patterns;
- Low maintenance—always the goal to achieve a balance between capital cost and annual expenses;
- Capacity increase—by increasing speed, size, and weight of vehicles, utilizing exclusive or semiexclusive trackways, and implementing progressive or preemptive traffic control systems;
- Stray current control—to electrically isolate the running rails from underground facilities and utilities;

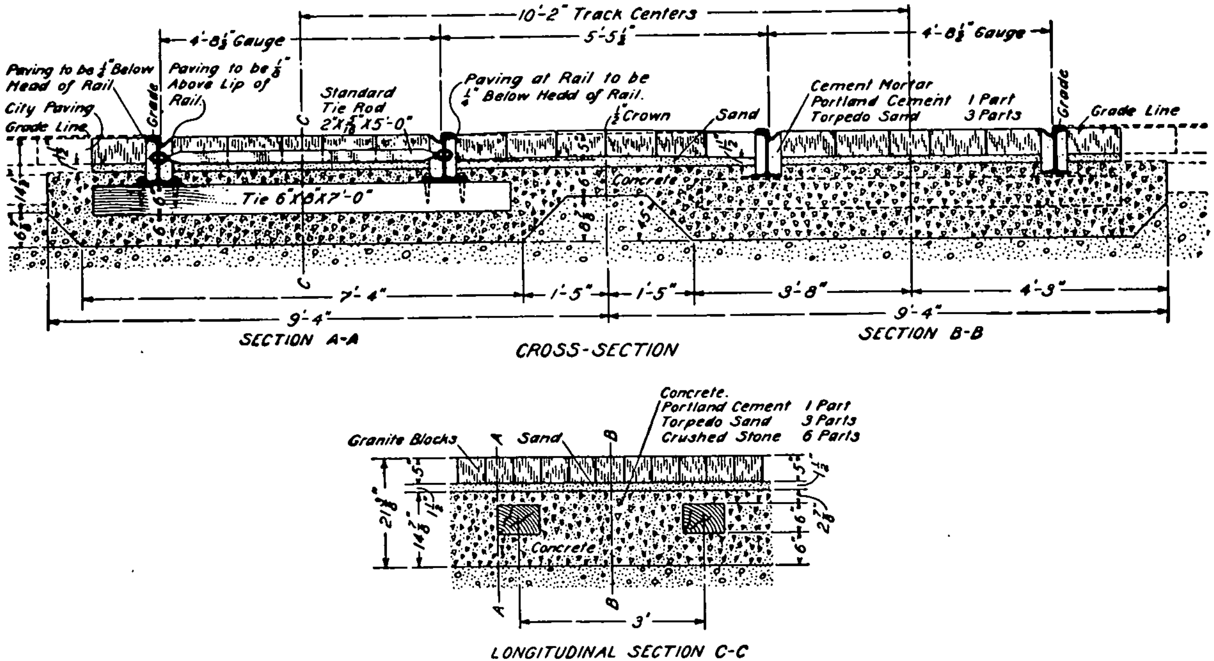


FIGURE 2 Paved truck design for heavy streetcars circa 1915.

• Ground vibration damping—to isolate the track structure from adjacent buildings;

• Urban design—both the location and appearance of the tracks to contribute to the environment.

LIGHT RAIL PROJECTS

Tables 1 and 2 presents general data for seven light rail projects that include paved-type track. More detailed information is presented in the following sections for each project; detailed cross sections are included.

TABLE 1 GENERAL DATA FOR LIGHT RAIL PROJECTS IN SAN FRANCISCO, CALGARY, AND SAN DIEGO

	San Francisco	Calgary	San Diego
Contract no.	MR642	–	LRT11
Cost ($ millions)	–	–	3.7
Bid date	1977	7/79	11/79
Service date	–	6/81	7/81
Single track (mi)	1.0	2.4	3.1
Rail section	104ER	Ri60	90RAA
Cost date	–	6/80	6/80

TABLE 2 GENERAL DATA FOR LIGHT RAIL PROJECTS IN BUFFALO, PORTLAND, SAN JOSE, AND SACRAMENTO

	Buffalo	Portland	San Jose	Sacramento
Contract no.	1Z0081	LS-4B	Mall	85-02
Cost ($ millions)	16.9	20.8	29.3	12.1
Bid date	10/81	5/84	2/85	4/85
Service date	10/85	8/86	12/87	9/86
Single track (mi)	2.5	2.2	0.5	–
Rail section	128RE	Ri59	Ri59	115RE
Cost date	2/83	2/85	6/86	1/86

Cost Comparisons

Bid price comparisons for six projects are summarized in Table 3. The total price per single-track foot varies from $66.52 to $269.87. It must be noted that some of the costs presented are not strictly comparable in terms of escalation or breakdown. However, the trend toward more complex and costly paved track is very apparent.

TABLE 3 BID COST COMPARISON

Item	Description	$ U.S. per Single Track-Foot Calgary	San Diego	Buffalo	Portland	San Jose	Sacramento
Owner-Furnished Material							
1	Rail	(19)	15.00	27.11	19.52	19.52	18.21
2	Crossties	A	7.50	A	A	A	7.84
3	OTM	A	3.75	A	A	A	3.75
4	Tie bars	(19)	A	(6)	1.49	A	A
5	Total	(19)	26.25	27.11	21.01	19.52	29.80
Contract Work							
6	Install track	(19)	25.56	140.00	18.00	135.00	20.00
7	Rail welds	(19)	5.24	(6)	10.67	(6)	7.50
8	Ballast	A	6.76	A	A	A	8.08
9	Track slab	B	A	49.15	15.12	(6)	A
10	Base course	A	A	?	2.42	(6)	A
11	Filter fabric	A	A	A	A	A	1.33
12	Rail elastomer	(19)	A	(6)	168.00	A	A
13	Tie bar coating	(19)	A	A	2.80	A	A
14	Insulating membrane	(19)	A	(6)	A	(6)	A
15	Pavement	B	B	(6)	B	B	B
16	Reinforcing	B	B	16.57	B	B	B
17	Mobilization	(19)	2.71	7.54	31.85	18.16	?
18	Total	(19)	40.26	213.26	248.86	153.16	36.91
19	Grand total	223.58[a]	66.52	240.37	269.87	172.68	66.71

NOTE: (*X*) = cost included in item *X*. A = not required in design. B = cost excluded.

[a]Converted at the rate of $1 Can. = $0.868 U.S. ($1700 Can./route meter) [0.868/(3.3 × 2)] = $223.58 U.S./track foot.

San Francisco Paved Track

The paved track design of the San Francisco Municipal Railway is typical of the many streetcar systems that flourished prior to World War II. This design was used when Municipal Railway's surface tracks in West Portal Avenue were reconstructed in 1977.

The paved track consists of 104 ER7B girder rail with the plates and pads spiked to treated crossties spaced at 24 in. on center as shown in Figure 3. The crossties are supported in compacted ballast level with the top of the crosstie. The rails were then thermite welded into continuous strings. Non-reinforced concrete is placed over the crossties and up to 2 in. below the top

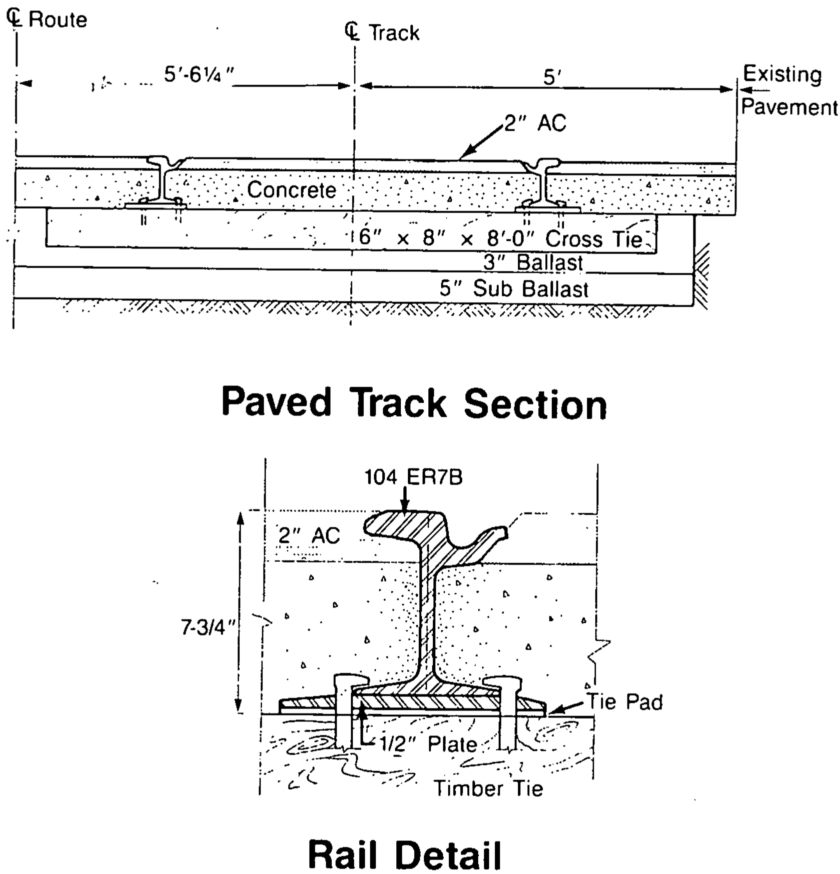


FIGURE 3 Paved track design, San Francisco.

of the rail. Asphaltic-concrete (AC) pavement material is then installed level with the top of the rail.

The track was reconstructed in a center trench while two-way traffic was maintained on West Portal Avenue and on all cross streets. Comparable cost information for this track is not available.

Calgary Paved Track

The Seventh Avenue Transit Mall is the downtown surface portion of Calgary Transit's C-Train Light Rail Project. The double-track transit mall is located on Seventh Avenue S.W. from Third Street S.E. to the terminal station near Ninth Street S.W. The mall contains approximately 12,700 single-track ft of paved track. Construction of the mall began in July 1979 and revenue service on the system began in June 1981.

The paved track consists of two-track reinforced track slab placed on 2 in. of styrofoam insulation as shown in Figure 4. The Ri-60 girder rails were sandblasted and coated with polyurethane off-site, and then thermite welded into one-block lengths and connected with coated gauge rods. After blocking and wedging to line and profile, a two-component polyurethane elastomer was poured under and around the rail base to anchor the rail to the track slab and to provide resilient support of the rails. A full-depth concrete pavement was placed with a slot for each rail. Expansion joint sheet was installed on the sides of the slots, and the slot was filled with concrete and capped with an asphalt seal. Electrical insulation for stray currents was provided by the 20-mil polyethylene sheet on the top of the track slab and the 30-mil polyurethane coating of rails and tie bars.

The mall construction was done in two seasons. The work was completed one block at a time so an entire section of Seventh Street would not be out of service for an entire construction season.

The track costs shown in Table 3 were furnished by Calgary Transit staff without breakdown. The cost is an average per unit length, including design, procurement, construction, and construction management of the girder rails, gauge rods, polyurethane coatings and elastomeric pads, polyethylene sheets, expansion joint material, and special trackwork; but excludes civil and utility works, track slab, and pavement.

San Diego Paved Track

The City Centre Contract LRT-11 is the downtown segment of the San Diego Light Rail Guideway Project of the Metropolitan Transit Development Board. The double paved tracks are located in C Street from the Amtrak

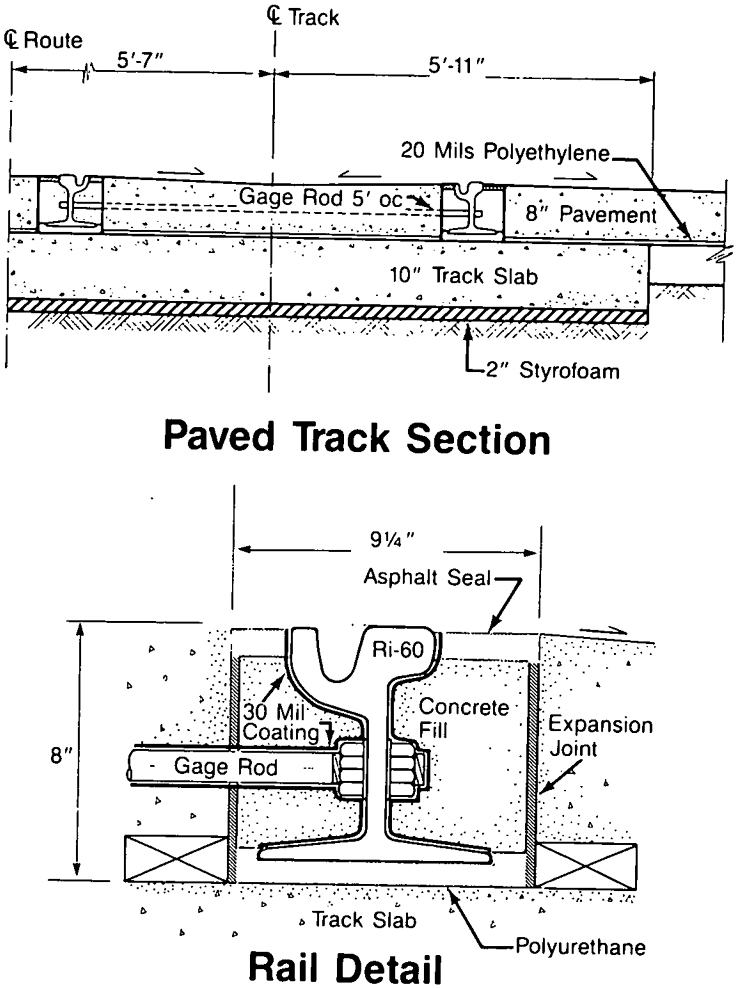


FIGURE 4 Paved track design, Calgary.

Station to 12th Avenue and on 12th Avenue from C Street to Commercial Street. This segment contains 15,886 single track ft of paved track and 418 of curved paved track with braces and guard rail, excluding special trackwork units. The pavement in the exclusive trackway is asphaltic concrete except at cross streets where concrete pavement is used to accommodate the heavy traffic. Bids to construct the City Centre contract were opened in November 1979. Construction was completed within 190 working days, and revenue service began in July 1981.

The paved track consists of conventional timber crossties in rock ballast supporting 90 RA welded tee rail as shown in Figure 5. The crossties are treated softwood spaced 24 in. on center. The plates are American Railway Engineering Association (AREA) plan 2, and the rail anchors are True Temper boxed on every other crosstie. The ballast is AREA #4 gradation, 6 in. deep under the crosstie and placed on compacted subgrade. The 25-m rails were thermite welded in place to form continuous welded rail. Flangeways were formed when the AC pavement was placed.

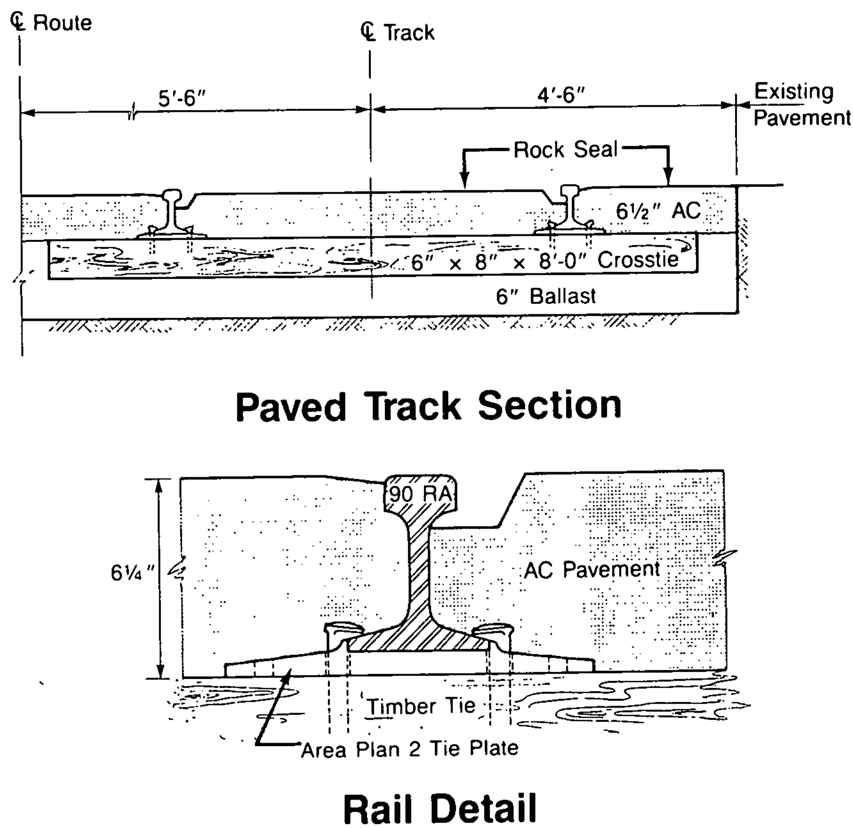


FIGURE 5 Paved track design, San Diego.

Cross traffic at each intersection was maintained as well as pedestrian movements and access to all buildings.

The track costs shown in Table 3 are based on an evaluation of bid costs and the plans and specifications for the contract. The rail, crossties, and other track materials (OTM) were all furnished by the owner, and the costs are calculated from the delivered contract prices. The item to install paved track includes the cost to store and install all owner-furnished materials and to furnish and install insulated rail joints. Separate costs are listed to furnish and install rail thermite welds and ballast. Mobilization cost is an allocation of that bid item for the paved track installation. The paved track costs do not include excavation, site work, pavement and other steelwork, utility relocations, or electrical connections and ducts.

Buffalo Mall Track

The Buffalo Mall is the downtown surface portion of the Buffalo Light Rail Rapid Transit Project of the Niagara Frontier Transportation Authority. The double-track transit mall is located on Main Street between South Park Avenue and Tupper Street at the subway portal. All mall track is installed under contract 170081, which includes 10,827 single-track ft of standard mall track as shown in Figure 6 and 2,334 single-track ft of continuous floating slab mall track. Bids for contract 170081 were opened October 6, 1981. The contract was awarded for $16.94 million and all work was completed within 730 calendar days. Revenue service began in April 1985.

Standard mall track consists of a nonreinforced concrete slab that supports 128 RE-7A girder rails held to gauge by threaded rods through the rail webs. A nominal 3-in.-thick leveling course of epoxy-modified grout supports the rails to the design profile. The track slab is poured on compacted select backfill. Vibration damping is provided by a continuous $^{3}/_{16}$-in.-thick elastomer pad under the base of rail. A $^{1}/_{16}$-in.-thick layer of rubberized asphalt over the base of rail, grout leveling pad, and top of the track slab provides a permanent, flexible, monolithic water and moisture barrier. The contractor elected to electric weld the girder rail into strings approximately 700 ft long and thermite weld the strings together in the field.

After installation to line, profile, and gauge, the track was anchored against thermal movement by placing large concrete weights on the rails. The rails were field welded. The first step in pavement installation was the filling of all volume below a line $5^{1}/_{2}$ in. below the top of the rail with a hot-mix roller-compacted asphalt fill material. The pavement is a $5^{1}/_{2}$-in.-thick reinforced concrete layer poured on the asphalt fill and around the girder rails.

Construction scheduling required most of the standard mall track to be substantially completed within 216 calendar days from site availability. Main Street was closed to vehicular traffic for the duration of the mall track construction. Two-way traffic on all cross streets was maintained on at least half of each intersection.

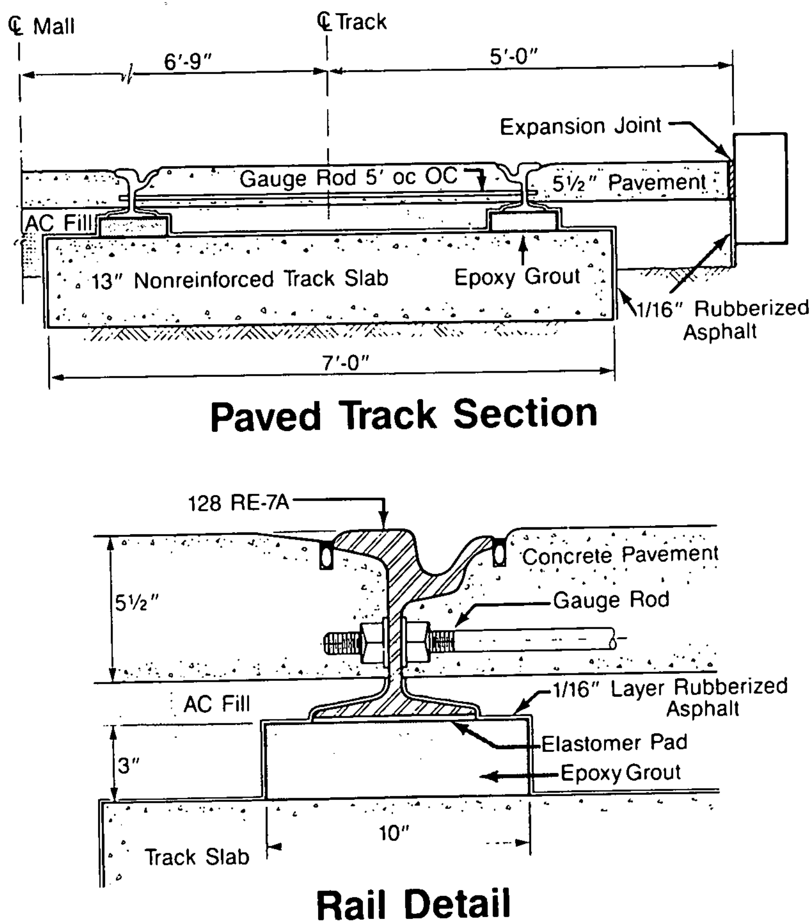


FIGURE 6 Paved track design, Buffalo.

The track costs shown in Table 3 are based on an evaluation of bid costs and the plans and specifications for the contract. The 128 RE-TA girder rail was furnished by the owner. Contract costs are based on the pay item to install track, which includes all costs to furnish and install the grout leveling course, continuous elastomer pad and adhesive, rubberized asphalt material, asphalt fill material, gauge rods, concrete pavement, rail welds and joints; and to install the owner-furnished girder rail. The cost per foot of track slab is calculated from the pay item for a cubic yard of track slab concrete. The reinforcing cost is based on an assumed amount of steel in the concrete pavement. Mobilization cost includes an allocated amount of the items for mobilization maintenance of traffic, and engineer's facility.

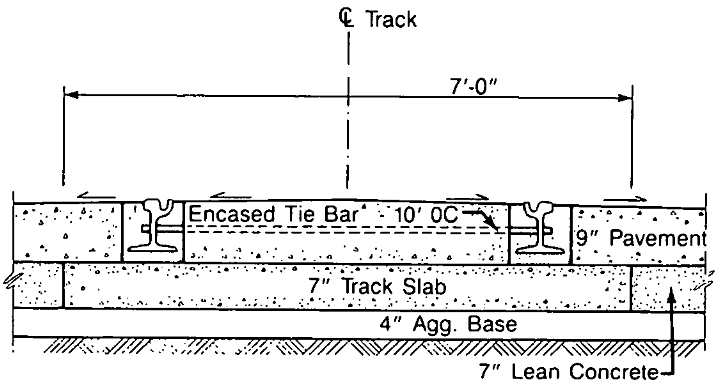
Costs excluded from Table 3 include initial street excavation and subgrade preparation, utility relocation, special trackwork units, continuous floating slab mall track, granite curbs and the street improvements outside the track zone, and all drainage facilities within the track zone.

Portland Downtown Track

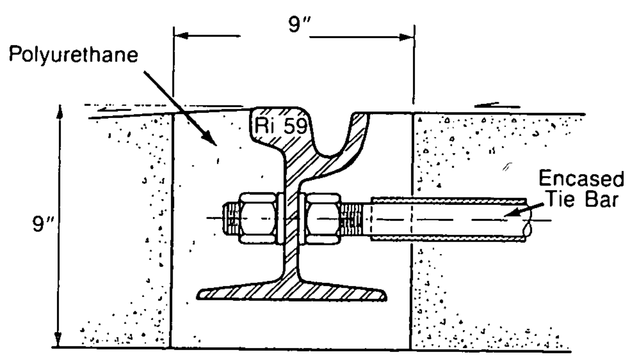
Line Section LS-4B is the downtown segment of the Banfield Light Rail Project of the Tri-County Metropolitan Transportation District (Tri-Met) of Oregon. All tracks are embedded in street pavements and are located on N.W. First Street from N.W. Everest Street at the foot of the steel bridge approach to S.W. Morrison Street. There the tracks divide onto the one-way couplet formed by S.W. Morrison Street (northwest bound) and S.W. Yamhill Street (southeast bound) to the downtown terminal at 11th Street. This segment contains 11,823 single-track ft of paved track excluding the special trackwork units. The pavement in the track zone is Belgian blocks with limited amounts of concrete pavers, brick, and poured concrete. The paved track design and configuration are the same for all types of pavement. Bids to construct line section LS-4B were opened on May 17, 1984, with construction scheduled to begin in June 1984 and to be completed in November 1985. Total low bid for the contract was $20.76 million. Revenue service actually began in September 1986.

The paved track consists of a reinforced-concrete slab that supports Ri-59 girder rails held to gauge by tie bars as shown in Figure 7. The concrete slab is supported by a 4-in. layer of aggregate base over a compacted subgrade. Electrical isolation and vibration damping are provided by fully encasing the girder rails and the bars in a poured polyurethane elastomeric material. All surfaces of the rails and tie bars, and the top of the track slab, were cleaned and primed to ensure a bond with the polyurethane to maintain proper alignment and electric isolation. The two-component polyurethane materials were pumped and mixed in automatic equipment and placed in the rail slots formed by the previously installed pavement materials. Since the chemical set of polyurethane is sensitive to water, heat blowers and tents were used during installation to eliminate all moisture. The 25-m-long rails were thermite welded after installation to eliminate weaker bolted joints and reduce the electrical resistance in the traction power return circuit.

Construction scheduling included specified access and completion dates for each city block of the project. During this period, all traffic was removed from that block except for emergency vehicles. A specified number of lanes of cross traffic was maintained at each intersection. Pedestrian movement and access to all buildings were maintained throughout the project.



Paved Track Section



Rail Detail

FIGURE 7 Paved track design, Portland.

The contract specifications required the contractor to perform low-voltage track-to-earth electrical resistance tests during and after track construction. Completed sections of double track (four rails with electrical crossbonding) were required to have a resistance of at least 100 ohms per 1,000 route ft. This seems to be the first time that the acceptance of railroad or transit track was based on electrical resistance testing. The tests were very useful in determining short circuits to ground. Although all accepted sections of track tested above the minimum resistance, the test results varied so widely that it was impossible to calculate an average resistance for this track design.

The track costs shown in Table 3 are based on an evaluation of bid costs and the plans and specifications for the contract. The Ri-59 girder rail and tie bars were furnished by the owner. Contract costs are based on pay items to install track and to furnish and install rail welds, track slab, aggregate base course, polyurethane rail elastomer, and polyurethane coating of tie bar. Mobilization costs include an allocation of bid items for mobilization, traffic control, signs, and flagmen. Costs not included in Table 3 are the excavation of the track trench, preparation of subgrade, relation of utilities, all pavement and street work, all special trackwork units, and all miscellaneous trackwork items such as track drains, electric boxes, and wheel stops.

San Jose Transit Mall Track

The San Jose Transit Mall is the downtown portion of the Guadalupe Corridor Light Rail Project of the Santa Clara County Transportation Agency. The transit mall is located on First Street (southbound) and Second Street (northbound) between San Carlos Street and St. James Street. The mall contains two types of embedded track:

- Type A—Mall track, 4,499 track ft. The top of the concrete track slab is depressed 4½ in. below the top of the rail to allow installation of granite pavers.
- Type B—Mall track within street right-of-way, 1,770 track ft. The concrete track slab extends up to the top of the rail to form the pavement surface (see Figure 8).

Bids to construct the mall track were opened on February 7, 1985, and revenue service began in December 1987.

Both types of mall track consist of a reinforced-concrete track slab with slots for the installation of Ri-59 girder rail. The slab is supported by a 4-in. layer of asphaltic concrete. Noise and vibration isolation are provided by ½-in.-thick closed-cell neoprene panel installed vertically between the side of the track slab and the adjacent concrete pavement. Electric isolation is provided by a 100-mil-thick dielectric barrier of geotextile fabric and multiple polyethylene sheets under and up the side of the track slab. The Ri-59 rail is clamped down to embedded anchor bolts and steel plate, and the rail slot is filled with lean concrete.

Track costs shown in Table 3 are based on an evaluation of bid costs and the plans and specifications for the contract. The Ri-59 girder rail was furnished by the owner at a unit cost assumed equal to the cost that Portland paid the same supplier in 1984. The single-track-foot bid cost for mall track

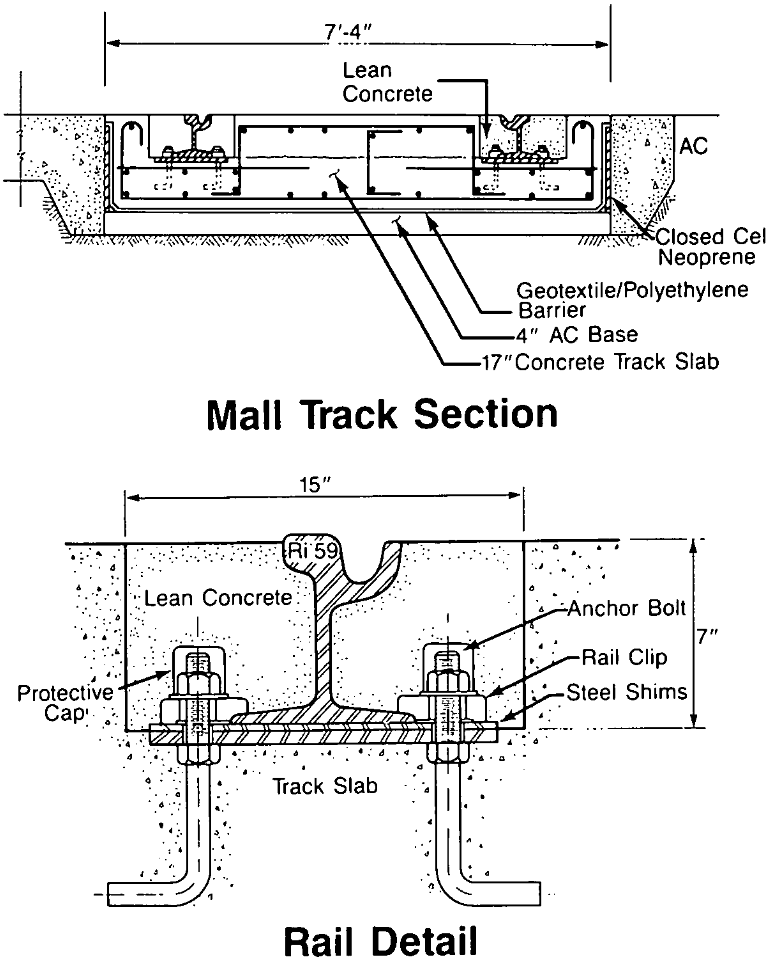


FIGURE 8 Paved track design, San Jose.

varied from \$135 for Type A to \$285 for Type B. These costs include subgrade preparation; furnishing and installing aggregate base, AC base, track slab, noise and vibration isolation panels, electric isolation barrier, lean concrete, and rail clamps; and installation of owner-furnished rail, including welds and crossbonds. The costs shown on Table 3 are for Type A without the granite pavers. Mobilization costs of \$18.16 per track foot include allocations of bid items for general cost and right-of-way and traffic control.

Sacramento Mall Track

Contract 85-02 contained all the paved track in Central Sacramento of the RT Metro of Sacramento Regional Transit District. The double paved tracks are generally located on 12th Street, the K Street Mall, the Seventh and Eighth Street one-way couplet, and the O Street Mall. Bids on Contract 85-02 were opened on April 9, 1985. Subsequently, this contract was divided and rebid as two smaller contracts.

The K Street Mall paved track consists of conventional timber crossties in rock ballast supporting 115 RE welded tee rail as shown in Figure 9. The crossties are treated softwood spaced at 24 in. on center. The tie plates used are AREA plan 7. Ballast to a minimum depth of 8 in. under the crosstie is placed directly on a compacted subgrade reinforced with a filter fabric. The

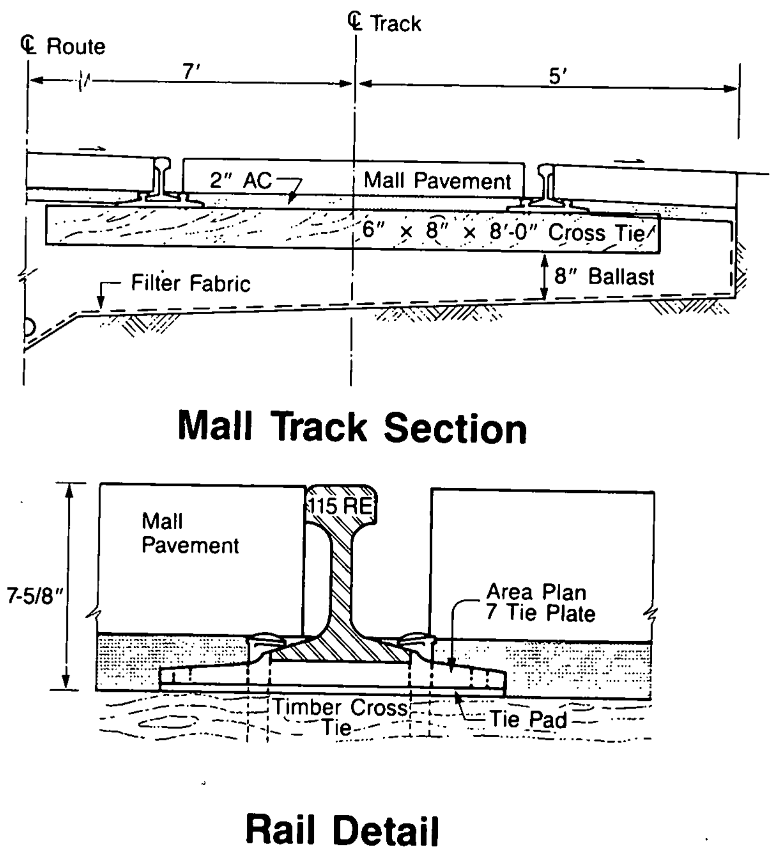


FIGURE 9 Paved track design, Sacramento.

rails were thermite welded in place to form continuous welded rail. Flangeways were formed in the mall pavement.

The track costs shown in Table 3 were furnished directly by Sacramento staff. OTM costs were assumed equal to those in San Diego.

CONCLUSION

The design of track in pavement has evolved in many different directions over the past century. These seven projects reflect some of these differences and a wide range in the initial track costs. The principal reason for these differences is the criteria established by each property for its track. Some properties demand minimum initial cost, while others are willing to spend more to build paved track to reduce annual maintenance expenses or to achieve electrical insulation and vibration damping properties.

This paper is a start in the process of determining the long-term benefits of these seven designs and developing cost-effective design criteria for future LRT track in pavement. The development of such criteria is a long-term research project—a worthwhile one that deserves the support of TRB or the American Public Transit Association.

Operational Enhancements

Making the Most of Light Rail

PAUL C. TAYLOR, LEO K. LEE, AND WARREN A. TIGHE

The at-grade light rail system between Long Beach and Los Angeles, a 22-mi double-track line, crosses 85 streets at grade. The five local jurisdictions involved in the system were understandably concerned about the traffic impact of light rail vehicles (LRVs) arriving at a peak headway of 6 min. The problems facing the designers were compounded by the adjacent Southern Pacific at-grade freight train operation, and by the proximity of major signalized intersections. The solution involved an assortment of integrated light rail and street traffic operational enhancements. In the exclusive right-of-way segments LRVs were given full priority over street traffic at all times at most major crossings. In the median alignment segments, special traffic signal software was designed to provide integrated LRV priority without the disruption of full preemption. All stations were designed with high-level platforms to minimize passenger loading times and to make handicapped access easier. Automatic overrun protection implemented via cab signaling allowed at-grade crossing gates to remain in the up position while LRVs dwell at nearside station platforms. At several locations streets were closed, turn movements prohibited, or streets converted to or from one-way operation to allow more efficient operation of automobiles or LRVs. The result of these operational features is an economical at-grade light rail system that meets the objectives of a reasonable LRV travel time and an acceptable level of service and safety for automobile traffic.

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THE ROLE OF TRANSIT as a primary means of personal transportation has been given increasing emphasis in recent years, due partly to the increasing financial and opportunity constraints of road building to meet ever-increasing transportation demands. Such a dominant need for transit in a modern city setting demands that great attention be given to the choice and form of this transportation mode.

Traditional forms of transit can be categorized as road-based or rail-based. The definition of road-based and rail-based transit cannot be interpreted literally. There exist today rubber tire "trains" running on a fixed guideway (i.e., Montreal, Paris) and also rail vehicles sharing roadway spaces with other automobiles. The classification here is intended to differentiate transit vehicles running on a fixed guideway (rail-based) versus transit vehicles operating freely on the road together with other traffic (road-based).

Whereas road-based transit, primarily buses and trolley buses, generally requires less capital investment, its rail-based counterpart is favored where its potential for higher capacity, lower travel time, or lower operation costs can be realized. Buses also offer more operational flexibility and can penetrate residential and business areas more effectively to provide a broader service area. Hence the common adoption of a rail-based system for regional transit services and a road-based system for local transit services.

Even within the rail-based transit mode, one has a wide choice of different systems for any urban environment. The spectrum of urban rail-based transit systems usually begins, at the lower end, with simple and relatively inexpensive systems such as streetcars, exemplified by San Francisco's Municipal Railway (Muni) system. They operate mainly in public roadways, sometimes within the same shared right-of-way. In many respects, these streetcar systems operate like buses. They therefore lose the speed advantage of a rail system.

On the other end of the spectrum is heavy rail transit, typically high-speed vehicles operating in a grade-separated environment, exemplified by the subway and metro systems in many large urban areas. Although heavy rail transit usually has a higher passenger-carrying capacity, it is also considered the most expensive form of transit in terms of capital costs. Its implementation is therefore confined mostly to corridors of very high demand.

Between these two ends of the spectrum lies the light rail transit (LRT) system. LRT can provide high-capacity, high-speed service where appropriate while still operating at grade in street rights-of-way where necessary. The flexibility of LRT is of great assistance to the transit system designer in achieving a compromise between cost and operating speed, in balancing efficiency versus safety, and, most important, in providing an attractive mode of transit operation at a reasonable cost.

The Long Beach-Los Angeles LRT Project strives to provide an appropriately balanced transit system design by making the most of LRT's flexibility.

This paper discusses the design features of the project, with emphasis on the variety of the methods employed to maximize the system's cost effectiveness. It also addresses some of the problems encountered and how the conflicting needs of different agencies were met.

CHARACTERISTICS OF THE SYSTEM

The Long Beach-Los Angeles LRT system represents the first line of what ultimately is to be a 150-mi rail transit system planned for Los Angeles County. It presently is a 22-mi double-track line between downtown Long Beach and downtown Los Angeles. Almost the whole line operates at grade within either existing street right-of-way or exclusive rail right-of-way shared with other tracks. The alignment passes through five different jurisdictions: the City of Los Angeles, Los Angeles County, the City of Compton, the City of Carson, and the City of Long Beach. It crosses 85 roadways at grade and will operate at a peak headway of 6 min through 20 stations. All station platforms are elevated to reduce passenger boarding time and to provide added convenience for the handicapped and elderly. Final design commenced in 1985. Revenue operation service is scheduled to begin in mid-1990.

This 22-mi light rail line can be divided into three segments: downtown Los Angeles, downtown Long Beach, and the "midcorridor" linking them. The two downtown segments, with their inherent urban characteristics, possess design and operational characteristics that are drastically different from those of the midcorridor segment. In the downtown segments, the light rail vehicles (LRVs) will operate in a street-running mode, whereas in the midcorridor they will operate in a high-speed exclusive right-of-way.

Exclusive Right-of-Way Operation

The LRT alignment through the midcorridor is an 18-mi segment, with light rail operating in the existing Southern Pacific Transportation Company (SPTC) right-of-way alongside active freight tracks.

The normal operating speed of LRVs through the midcorridor will be 55 mph. There are no grades, curves, or other factors that would limit the maximum speed to significantly less than that under normal conditions.

The LRV chosen for this project is representative of modern LRVs. Each articulated car is approximately 90 ft long. All facilities in the midcorridor are designed to accommodate three-car LRV consists. This segment is being fitted with cab signal-based train protection.

Road Traffic Impacts of At-Grade Operation

Along the 18-mi mid corridor, the line will traverse 38 street crossings at grade. These crossings range from minor residential collector streets to major highways carrying in excess of 30,000 average daily traffic (ADT). Table 1 lists the projected year 2000 ADT on some of the major and secondary crossings.

TABLE 1 DAILY TRAFFIC VOLUMES ON MAJOR AND SECONDARY STREETS

Street	ADT	Jurisdiction	Classifieation
Vernon Ave.	13,257[a]	City of LA	Major
Gage Ave.	29,000[b]	LA County	Major
Florence Ave.	39,000[b]	LA County	Major
Nadeau St.	15,000[b]	LA County	Secondary
103rd St.	17,000[b]	City of LA	Secondary
Imperial Hwy.	41,500[b]	City and County	Major
El Segundo Blvd.	25,956[a]	LA County	Major
Rosecrans Ave.	29,555[a]	Compton	Major
Compton Blvd.	22,500[b]	Compton	Major
Alondra Blvd.	20,477[a]	Compton	Major
Del Amo Blvd.	40,500[b]	LA County	Major
Wardlow Rd.	N/A	Long Beach	Major
Spring St.	N/A	Long Beach	Secondary

NOTE: ADT = average daily traffic in year 2000; N/A = not available.
[a]Source: SCAG's *San Pedro Bay Ports Access Study*.
[b]Estimate based on PB/KE's *LRT Traffic Impacts at Grade Crossings in Mid-Corridor*.

All 38 at-grade street crossings in the midcorridor are fitted with railroad-standard protection equipment in the form of gates, flashers, and bells. This is required by the California Public Utilities Commission (CPUC) because the LRT tracks will share the crossings with the SPTC track and because of the LRT's high speed of 55 mph. The gates and the associated bell and flashing lights will be automatically activated some 25 sec before the LRV arrives at the crossing. After the LRV has crossed the street, the gates will return to the upright position, and automobile traffic will be able to proceed. The total time from first activation of the flashing lights until the gates return to the upright position will be between 30 and 36 sec, depending on the location. In effect, by stopping the street traffic whenever an LRV approaches, the LRV can maintain a high speed of operation through the midcorridor.

The amount of additional traffic delay caused by LRT varies from crossing to crossing and is highly dependent on the crossing's proximity to a major intersection and on traffic volumes. Where the crossing has adequate excess capacity, as is usually the case, the impact of LRT is light. Because the duration of each LRT passage, as discussed previously, is only 30 to 36 sec, the traffic queues formed as a result of an LRT preemption normally will be short. Where this is not the case, LRT impacts can be adequately mitigated by suitable geometric modifications, traffic management techniques, and fine tuning the traffic signal operation. Table 2 illustrates this through a comparison of the base case (without the project) traffic delay versus the "with LRT" traffic delay at the major crossings.

TABLE 2 YEAR 2000 AVERAGE DELAY PER VEHICLE AT MAJOR MIDCORRIDOR CROSSINGS

Crossing	Base Case (sec)	With LRT (sec)
Vernon Ave.	28	42
Gage Ave.	17	31
Florence Ave.	22	47
Imperial Hwy.	58	51[a]
El Segundo Blvd.	26	38[a]
Rosecrans Ave.	44	39[a]
Compton Blvd.	56	57[a]
Alondra Blvd.	35	50[a]
Wardlow Rd.	30	35[a]

NOTE: Assumed one freight train arrival per peak hour.
[a]Mitigated through roadway geometric modifications.
SOURCE: DKS' traffic impact analysis reports for midcorridor crossings.

LRT impacts can usually be mitigated adequately through minor roadway widening and prohibition of certain turning movements, without the need for expensive right-of-way acquisition or grade separation. Of all 38 crossings in the midcorridor, only one requires grade separation because of traffic, and there the problem is not light rail's impact on traffic but the impact of a nearby freeway ramp on light rail operation.

Minimizing LRT/Automobile Conflict

As discussed above, railroad grade crossings operate by stopping the street traffic whenever an LRV approaches. If there is a traffic signal at or close to the crossing, it is preempted, which means its normal operation is suspended and a special phase sequence introduced to clear the tracks and service nonconflicting movements until the LRV has passed. The same type of operation will be used for LRT at all of the 37 at-grade street crossings in the midcorridor.

At locations where the impact of signal preemption on road traffic is judged to be too severe, it is possible to control the LRV arrival time at a crossing so that, instead of arriving randomly, they arrive at selected times. All of the major streets crossed by LRT in the midcorridor have coordinated, signalized intersections at, or on either side of, the crossing. The traffic signals cause traffic to arrive at the tracks in bunches, rather than allowing it to be evenly distributed over time. The length of the traffic signal cycle is typically in the range of 60 to 90 sec, which means that similar bunches of traffic arrive at the LRT tracks every 60 to 90 sec. Because a crossing LRV requires the gates to be active for only 30 to 36 sec, one method of minimizing delay to street traffic at these crossings during periods of peak traffic is to make the arrival time of the LRVs coincide with that part of the traffic signal cycle when traffic at the crossing is at a minimum (the "window"). In this way most of the traffic will not be stopped by the lowered gates.

The most practical means of controlling the arrival time of an LRV is to hold the LRV at the upstream station. The LRV will pull into the station normally, but instead of closing the doors and moving off as soon possible, it will wait at the station until a signal indicates that the LRV should depart in order to arrive at the major crossing downstream at the optimum point in the traffic signal cycle. Once it moves off, the LRV travels at maximum speed to the next station. Figure 1 illustrates the window operation in a time-space diagram.

While the window concept is a form of low-cost mitigation for LRT impact, its implementation delays the LRVs. However, for LRVs and other traffic to share the same road space, the impacts must be balanced so that no one system suffers to the extent that it will negate the overall objective of moving people efficiently and expeditiously. The application of the window concept must be subject to careful scrutiny to assess the relative benefits enjoyed by road traffic versus the extra delay imposed upon LRV patrons. If the overall delay to all commuters—automobiles and LRV patrons together—is computed for the two scenarios, then the alternative causing the least overall delay can be identified.

Table 3 shows the overall delay to commuters under the two alternatives at major midcorridor crossings. It is evident that in all cases the no-window (referred to as "full preemption") is preferable to the isolated application of the window concept at any one crossing, because this would minimize the overall delay to all commuters. However, if two or more crossings are considered together as a system of coordinated windows, the benefits and

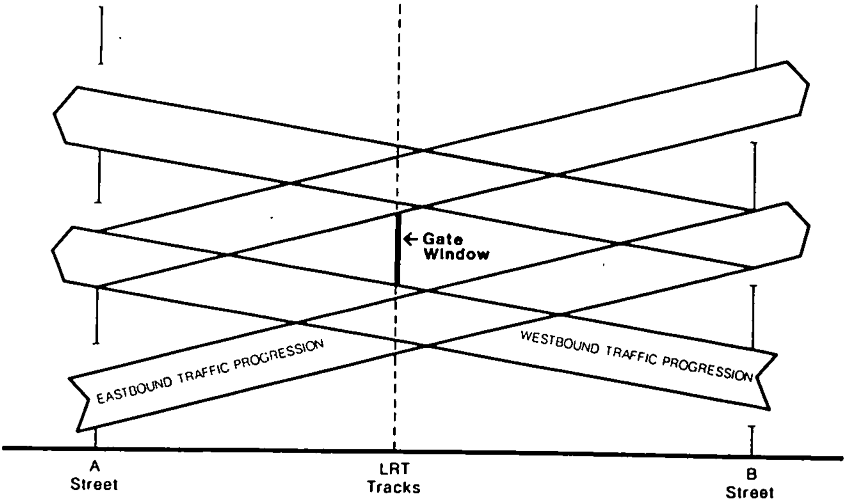

FIGURE 1 Time-space diagram showing gate window.

TABLE 3 OVERALL COMMUTER DELAY (MOTORISTS AND LRT PATRONS) AT MAJOR MIDCORRIDOR CROSSINGS

Crossing	Window Concept (person-hr)	Full Preemption (person-hr)
Vernon Ave.	48.1	30.6
Gage Ave.	52.2	30.8
Florence Ave.	78.1	62.7
Imperial Hwy.	209.0	122.0
El Segundo Blvd.	52.0	26.0
Rosecrans Ave.	72.5	39.2
Compton Blvd.	71.7	37.2
Alondra Blvd.	59.6	20.6
Wardlow Rd.	63.3	34.0

NOTE: Assumed one freight train arrival per peak hour.
SOURCE: DKS' traffic impact analysis reports for midcorridor crossings.

practicability of the window are enhanced. One coordinated window system that is considered most feasible is the Florence-Gage system. Due to the optimum distance between these two streets, the provision of a station at both ends, and traffic signals along both streets operating with the same cycle length, it is feasible to implement a system whereby LRVs leaving the station at one end will cross both streets at the optimum window. The same will apply for both directions of travel. Figure 2 shows how this is possible.

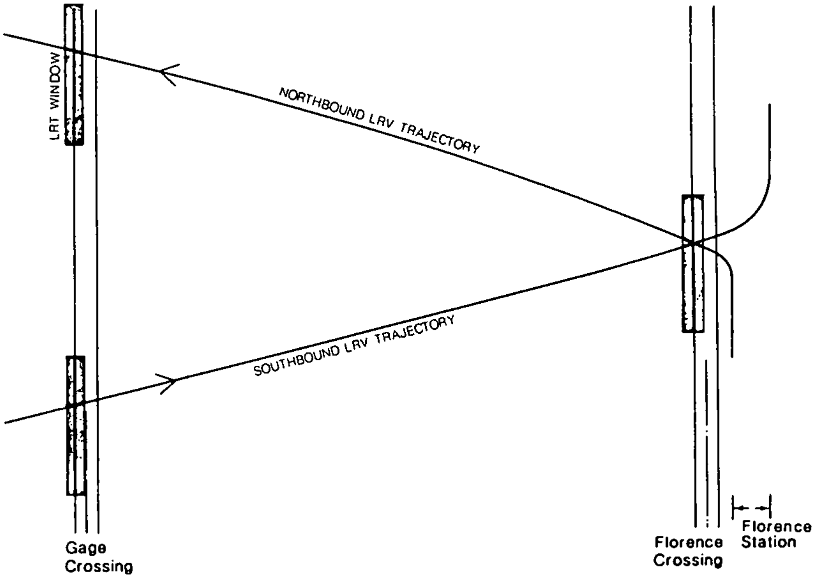

FIGURE 2 Gage and Florence signal coordination opportunities.

An LRV's travel time between the two crossings at normal operating speed is approximately half the cycle length of 80 sec at both streets. Two-way LRV progression through the LRV arrival windows can therefore be achieved by maintaining a time offset between the windows of approximately 40 sec. A southbound LRV will be held at the upstream station until it is time to leave for arriving at both the Gage and Florence crossings during the LRT window. The same is true for LRVs traveling in the opposite direction.

With this coordinated window concept, the impact of LRT operation on the major streets can be minimized while reducing the negative impacts to the LRT operation itself. At the Florence and Gage intersections the transit authority and local jurisdictions will evaluate LRT operational impact after revenue operations begin and decide whether to employ the window approach. Extension of the window concept to other crossings in the corridor is not practicable because of incompatibility of cycle length requirements and jurisdictional boundaries.

Street-Running Operation

In the downtown segments at either end of the light rail line, the tracks are located in the median of two-way streets and to the side of one-way streets. The LRT tracks pass through 47 street intersections in these segments. Railroad gates cannot be installed at these crossings because of space constraints and the excessive delays they would cause. Instead, conflicts between automobiles and LRVs are avoided either by prohibiting automobile movements across the tracks or by using traffic signals that control LRVs as well as automobiles. LRVs must be prepared to slow down and stop at signalized intersections just as any other vehicles would. LRVs are basically driven on sight and the drivers have to react to the environment and operate their vehicles like buses. LRVs will be subject to the normal rules of the road and will observe the same speed limits as automobiles running parallel. The highest speed limit in the downtown segments is 35 mph.

In both downtown Los Angeles and Long Beach, the LRV operates in a dedicated right-of-way within the roadway. Mountable curbs are installed on both sides to prevent general traffic from entering the LRT right-of-way. Only emergency vehicles are allowed to use the track area for emergency access. Except at intersections, the LRVs do not interact with other traffic.

In downtown Los Angeles, LRT interfaces with the metro station at Seventh Street. It then runs underground for approximately one-third mile, surfacing near 12th Street, and then continues at grade in a side-running alignment along one-way Flower Street. It turns into the median of Washington Boulevard and continues to Long Beach Avenue. At Long Beach Avenue, the tracks enter the midcorridor's exclusive right-of-way.

The choice of center-running versus side-running was given considerable attention. Generally, from a traffic point of view, center-running is more appropriate for two-way streets whereas side-running is best for one-way streets. A side-running LRT system on a two-way street poses serious access hazards from driveways and minor streets unless all uncontrolled intersections are either closed or signalized. In contrast, center-running LRT in a one-way street would cause access problems, because it is almost impossible to direct traffic to the proper side of the street should vehicles wish to turn at some downstream intersections. This is the rationale for selecting side-running operation along the one-way Flower Street and center-running operation along the two-way Washington Boulevard.

In downtown Long Beach, at the Willow Station near 27th Street, the LRT tracks leave exclusive right-of-way and enter the median of Long Beach Boulevard. The alignment follows Long Beach Boulevard for about 3 mi, and then forms a one-way clockwise loop round First Street, Pacific Avenue, and Eighth Street. On First Street the system operates in a transit mall where it interfaces with buses.

Traffic Signal Operation

Due to the location of the LRT tracks relative to the parallel running automobile traffic, the LRV conflicts with left-turning traffic. A separate traffic signal display therefore is required for LRVs. Likewise, all left-turning automobile movements must be protected with an exclusive left-turn phase.

LRV detectors located between the tracks send signals to the traffic signal controllers to request or cancel the LRT phase. In the absence of any request, the traffic signal controller would not provide a green display to LRVs, distributing all the green time to road traffic instead. An advance LRT call detector, usually located near the upstream intersection, detects the arrival of an LRV, and requests the controller to provide an LRT phase. With built-in software logic, the controller determines the most appropriate manner to provide the LRT green indication without causing excessive delay to traffic. At some busy intersections during peak hour this may mean that the LRV has to stop and wait for its turn without getting any priority. A call/release detector, usually located close to the LRT stop line, senses the LRV's departure and signals the controller to terminate the LRV phase. The call/release detector also serves to request another LRV phase should the advance call detector malfunction or should the LRV fail to clear the intersection due to some unusual occurrence.

Although LRVs will not be able to "preempt" the traffic signals in the street-running mode, they will be able to receive priority treatment at some intersections at some times of the day. This priority treatment could consist of two alternative forms: partial priority or full priority.

Partial priority widens the green window for LRVs at a coordinated traffic signal. (The green window is the amount of time in the signal cycle during which an LRV can pass through the intersection.) Along Flower Street, for example, the window coincides with the green time provided for southbound motorists. Along Washington Boulevard, the window occurs when both eastbound and westbound movements receive a green light. This window is widened beyond the normal length of the LRT-phase green time by allowing the LRT phase to start earlier than normal (early green), or by allowing the LRT phase to finish later than normal (extended green). In each case, the extra time given to the LRT phase must be taken from other phases within the fixed-length cycle. A wider window reduces the probability that an LRV would have to stop at the signal. Motor vehicles running parallel to the LRT tracks would also benefit from the extra green time of a wider window.

The partial priority proposed for implementation in the downtown Los Angeles and Long Beach segments attempts to minimize disruptive effects on road and pedestrian traffic. The extra length of the LRT phase would be limited, and no phase with a demand would be skipped in any cycle. The shortening of phases would not violate any minimum times preset in the controller, but pedestrian service could be suppressed if the signal operator permits it.

Full priority involves temporarily changing the normal signal operation in order to display an LRT green signal at, or soon after, the LRV arrival time. Full priority may result in shortening one phase or skipping one or more phases entirely. Full priority provides the optimum operating conditions for LRT but also can lead to intolerable automobile delay for side-street and left-turning traffic if used indiscriminately.

When full priority is used in a coordinated system, some signals often get out of step with the others. It can take several cycles to get them back into step. In fact, the traffic signals may not get back to coordinated mode during peak periods when 6-min LRV headways are used. Because the majority of intersections in the downtown segments will be operating at or near capacity during peak periods, full priority would cause excessive delay to side-street traffic. However, full priority may be appropriate at some intersections during off-peak periods when LRT headways are longer and vehicular traffic volumes are smaller.

Custom-designed software in the traffic controller will enable all intersections to provide full-, partial-, or no-priority operation. The type of priority can be adjusted in any of the following three ways:

- Time-of-Day—The degree of priority would vary by time of day. Little or no priority may be provided in the peak periods, whereas full or partial priority may be provided in off-peak periods.
- Vehicle Response—Vehicle detectors can be installed so that the level of priority can be reduced or deactivated once excessive traffic queues are detected.
- Manual—Level of priority treatment can be altered manually at the controller cabinet or from the traffic signal control center.

By providing different levels of priority, LRT operation efficiency can be maximized without excessive negative impact on road and pedestrian traffic. Such flexibility is further enhanced with the centralized traffic signal control system installed in downtown Los Angeles called ATSAC.

The ATSAC (Automated Traffic Surveillance and Control) System installed in Los Angeles is an enhanced form of the urban traffic control system (UTCS). In broad terms, ATSAC is a computer system that links and gathers information from all traffic signal controllers. It serves four major functions:

- Compilation of all traffic data collected from detectors in the streets,
- Optimization of traffic signal timings and coordination to minimize traffic delay,

- Fault monitoring, and
- Manual override at the central level.

Currently ATSAC controls 120 signals in the so-called Coliseum System installed in the City of Los Angeles prior to the 1984 Olympic Games. When the LRT begins operation, the ATSAC system will be extended to control another 216 signals in downtown Los Angeles.

The LRT alignment traverses 11 intersections that would be under ATSAC control, from west of Los Angeles Street along Washington Boulevard and all of the Flower Street alignment. Due to the inherent benefits of ATSAC to both LRT and traffic operation, a cooperative agreement has been reached with the City of Los Angeles to extend ATSAC to cover the rest of the LRT alignment along Washington Boulevard east of Los Angeles Street. This will be implemented as part of the project. Special software will be developed at both the master and local levels so that all LRT control parameters are available within ATSAC.

Traffic Impacts and Mitigations

Although at-grade light rail operation requires less capital investment than a fully grade-separated system, it is generally true that the former creates a higher degree of negative traffic impacts. At-grade LRT operation on the Long Beach-Los Angeles system will have the following main impacts on street traffic:

- Reduced roadway space,
- Reduced parking space,
- Reduced accessibility to adjacent land uses, and
- Increased delay and travel times.

Where LRT will operate within the same right-of-way with other traffic, one obvious impact will be the loss of space available to automobiles and pedestrians. This loss will be compensated through reduced lane widths, reduced sidewalk widths, or through deletion of on-street parking.

For safe and reliable traffic control, all LRT/road intersections should be signalized. However, excessive signalization would increase vehicular traffic delay. Therefore, some minor intersections or driveways will be closed. In the center-running configuration, it is sufficient to close the median next to the tracks, so that a right-in/right-out configuration can be maintained for the side street. In the side-running configuration, minor crossings or driveways will be closed where possible and alternative access provided. Furthermore, due to the conflict between LRVs and left-turning movements, all left-turn phases will be protected. This will increase the number of signal phases in a cycle, increase the lost time involved in phase changes, and generally reduce the efficiency of traffic signal operation. Where such impacts would lead to an unacceptable level of service for motorists, additional traffic lanes are being added to compensate.

Other low-cost mitigation measures being employed on the project include:

- Roadway widening within the same right-of-way, at the expense of sidewalk widths, or with limited right-of-way acquisition;
- Geometric reconfiguration such as realigning curbs, relocating bus stops, converting from two-way to one-way streets, traffic rerouting, etc.;
- Restriping to provide adequate lanes within existing right-of-way;
- Signal redesign to increase operational efficiency; and
- Signal timing overhaul to increase coordination and reduce overall vehicular delay.

The impacts and extent of mitigation measures to be applied through the downtown segments of Los Angeles and Long Beach are listed as follows:

Downtown Los Angeles

- Loss of 316 parking spaces (64 percent of existing)
- Roadway widened at all locations along LRT alignment
- Medians closed at all nine unsignalized intersections
- Additional traffic signals at two locations
- Left-turn prohibition at two signalized intersections
- Traffic signal upgrades at all 20 traffic signals
- Driveway closed at three locations
- Driveway signals at all 10 open driveways

Downtown Long Beach

- Loss of 347 parking spaces (57 percent of existing)
- Approximately 80 percent of roadway widened along LRT alignment
- Medians closed at all 16 unsignalized intersections and 1 signalized intersection
- Additional traffic signals at three locations
- Left-turn prohibition at four signalized intersections
- Traffic signal upgrade at all 28 traffic signals
- No driveway closed

These mitigation measures were developed through extensive liaison and coordination with the local jurisdictions and responsible agencies, through compromise between various conflicting demands and design parameters, and through cooperation of all parties concerned with an aim toward providing an efficient and reliable transportation system at a reasonable cost.

Driveway Access Control

As discussed earlier, one problem of side-running operation is the control of driveway access. Whereas in the center-running configuration, medians can be closed and minor street and driveway access can be maintained, the side-running configuration can confront this problem only through active control, because some driveways do not have alternative access and cannot be closed. Full signalization is not warranted here due to the close spacing between driveways and the low volumes of traffic accessing these driveways. Some form of low-cost, effective active control measures need to be implemented.

Figure 3 illustrates the form of control designed for driveway access along Flower Street in downtown Los Angeles. Vehicles exiting from driveways usually have adequate sight distance on both sides to spot oncoming LRVs and they can stop and wait on the sidewalk. Stop sign control is adequate, augmented by a special sign to remind drivers to look both ways for LRVs even though they are entering a one-way street.

Drivers turning left into a driveway across the tracks do not have a good vantage position to determine whether LRVs are approaching from behind. The form of active control proposed here is a "secret" sign for the left-turning traffic. The sign is normally blank and left-turners can turn with usual caution. However, when an LRV approaches from either direction, the sign will show a no-left-turn symbol, advising drivers to wait to make the turn until the LRV has crossed. All signs along a block will be cabled directly to both of the upstream controllers so that the same signal that lit the LRT phase activates these signs. In this manner, an inexpensive, reliable, and effective method of active control will be provided to rectify the potentially unsafe condition.

CONCLUSION

The design of a light rail system, similar to all other engineering design work, requires a balance between cost and safety. Often, questions are posed about how safe is safe and how much money should be spent to further improve the safety of the system. The underlying principle behind all engineering design is to determine the safety threshold beyond which the marginal safety gain does not justify additional expense. A building may be designed to withstand an earthquake of scale 8, for example, or a storm drain system may be designed for a once-in-a-century storm. In light rail design, the additional

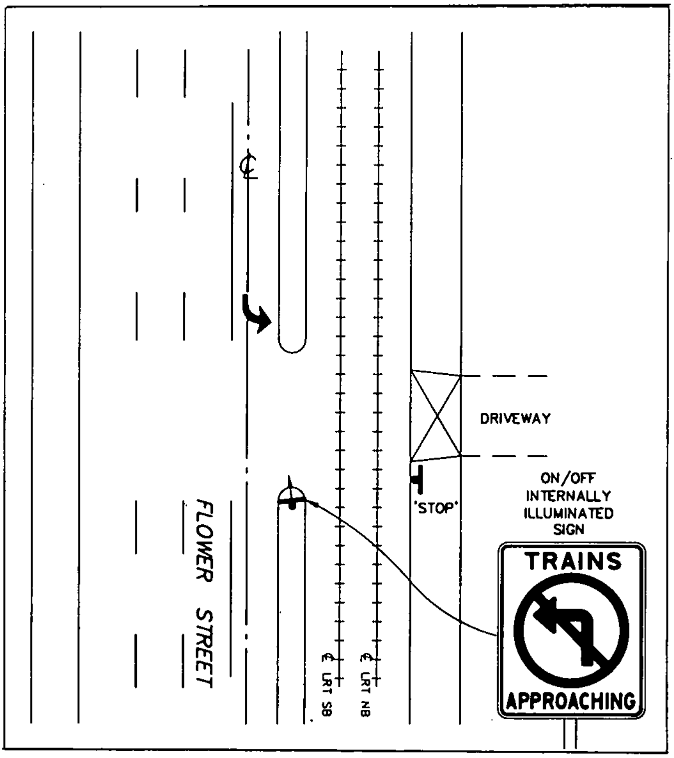

FIGURE 3 Typical driveway control on Flower Street.

expense is measured not only in terms of construction costs, but also in terms of reduced operating efficiency for LRT, automobiles, or pedestrians.

The design of the Long Beach-Los Angeles Rail Transit Project demonstrates the successful application of engineering techniques to make the most of LRT's flexibility. Special efforts are made to mitigate negative impacts on automobiles and pedestrians. Special efforts are also required in jurisdictional liaison, coordination, and communication. Through application of traffic engineering techniques, rigorous operational analysis, and close project coordination among designers and the local jurisdictions, a truly safe, reliable system can be provided at a reasonable cost, without resorting to expensive grade separation or creating a myriad of safety control mechanisms.

Operational Analysis of At-Grade Light Rail Transit

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At-grade operation of light rail transit (LRT) presents many analytical problems not normally encountered in traffic engineering analysis. In particular the noncyclical and directional nature of LRT arrivals renders traditional intersection and network analysis techniques inappropriate. In planning or designing an LRT system, the information often required by decision-makers includes delay to LRT due to street traffic, delay to street traffic due to LRT, length of queues when LRT affects traffic signals or at-grade crossings, short-term and long-term levels of congestion at at-grade crossings, and the impacts of combined events such as back-to-back rail vehicle arrivals. Computer-based tools have been developed to provide this information in both the planning and design stages of LRT system projects, including estimating average degree of saturation at a traffic signal during an hour of LRT operation, estimating cycle-by-cycle delays and queue length at a preempted fixed-time signal with LRT arrivals at preset headways, and estimating LRT delay in a fixed-time coordinated signal system with partial or no LRT priority. A new general purpose network simulator has been created that will realistically model light rail vehicles in a street environment with vehicle-actuated and coordinated traffic signals and other controls.

NORTH AMERICA IS EXPERIENCING a boom in light rail transit (LRT) after more than half a century of devotion to the automobile that saw the demise of all but a few LRT systems. More and more cities are turning to light rail as an economical alternative to their traffic-clogged freeways and urban streets. Urban development in many areas has reached the stage at

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which freeways will not be able to provide the capacity required in the future, particularly for commuting. LRT provides an alternative means of increasing the transportation system's capacity without the capital intensiveness and dislocation associated with new freeways or new heavy rail or metro lines.

A number of cities in North America are planning new or extended LRT systems that involve at-grade operations and the challenge of integrating LRT with street traffic. The operational analysis of both automobile traffic and light rail with at-grade operations is difficult at the best of times but is becoming more important as planners and engineers strive to develop the most efficient systems possible with the resources available. Major investment decisions such as grade separations and vehicle fleet size hinge on the quality of the analysis. This paper describes the analytical tools used by the authors for the planning and design of at-grade operations on six different LRT systems.

BACKGROUND

San Francisco led the way for modern light rail on the West Coast with the introduction of the 3.2-mi (5.1-km) Market Street transit subway for the San Francisco Municipal Railway (Muni) as part of the Bay Area Rapid Transit (BART) project. The new subway linked all five of Muni's surviving streetcar lines, which were rehabilitated and reequipped with 140 Boeing Vertol articulated standard light rail vehicles (LRVs). Two at-grade extensions to the system are being designed.

With the opening of the San Diego Trolley in 1981, San Diego became the first U.S. city since the early part of the century to open a new light rail system. Linking downtown San Diego with the Mexican border, it uses Siemens/Duewag U2 articulated vehicles. New lines are partially completed or planned as part of an ultimate regional light rail system of 113 mi (180 km).

Sacramento's Regional Transit District (RTD) opened an 18-mi (29-km) RT Metro in 1987 utilizing U2 cars on abandoned freeway segments, old and existing railroad rights-of-way, shared street alignments, and a transit mall. Currently operating on both single- and double-track segments, RTD plans full double tracking and future development in four corridors. This will extend the two existing lines and add two new lines radiating from downtown to the airport and major residential areas.

The Santa Clara County Transportation Agency (SCCTA) opened the first stage of the Guadalupe Corridor light rail line at the end of 1987, using Canadian UTDC articulated cars. The line, linking residential areas with downtown San Jose and the Silicon Valley industrial parks, will operate in a mixture of environments—in the median of an expressway, on-street, and in a downtown transit mall.

The Los Angeles County Transportation Commission (LACTC) has two light rail lines under construction. One is a 21-mi (34-km) line from downtown Los Angeles to Long Beach, scheduled to open in 1989. The second line runs from Norwalk to El Segundo and will operate mostly in the median of the new Century Freeway. Sixty miles (96 km) of LRT line are expected to be in operation or under construction by the end of the century. Using Sumitomo articulated vehicles, the lines will operate in the full range of environments—subway, railroad right-of-way, freeway median, and on-street.

Work has recently resumed on the design of a 14-mi (22 km) LRT system in the Woodward Avenue corridor in Detroit, Michigan. Much of the system is planned to operate at-grade in median and side-running alignments. The project was delayed while all resources were focused on the completion of Detroit's downtown people mover.

These six projects have involved the authors in operations analyses at various stages of the LRT development process, such as corridor selection, alternatives analysis, environmental impact assessment, alignment selection, preliminary design, and final design. The analyses have been used for different purposes, including estimating LRT travel time and energy consumption, assessing impacts on automobile traffic and pedestrians, determining the need for grade separations, and selecting the best design alternative. The level of detail and confidence needed in each analysis varied depending on its purpose and the stage of the LRT development process. In all cases, the analyses focused on the interaction between road and rail vehicles at those points where automobiles are able to drive on or across the LRT tracks.

THE ANALYSIS CHALLENGE

At-grade LRT presents special challenges not found in traditional rail or road traffic operations analysis. This is due to several factors. The wide variety of geometry, traffic control devices, and operating conditions encountered within a single LRT project all require consistent analysis. The sporadic and random nature of the interaction between LRVs and road vehicles must be considered. And the interdependence of events occurring at adjacent grade crossings, or during consecutive LRV arrivals, also comes into play.

Variety of Conditions

The following are some of the different conditions encountered in these LRT projects:

- Single or double track;
- Headways varying from 2 min to 20 min;
- Tracks located in a separate right-of-way, at the side of the street, in the street median, or in a traffic lane;
- One-way or two-way streets;
- Freight trains on the same tracks or on adjacent tracks;
- Signalized or unsignalized intersections;
- At-grade crossings or grade-separated crossings;
- Crossings at midblock locations, beside intersections, within intersections, or at driveways;
- LRT tracks crossing straight across the roadway, turning within an intersection, turning midblock from the median to side-running or separate right-of-way, branching, or within a traffic lane (mixed flow);
- Crossings closer together than the maximum length LRV, or crossings of two legs of an intersection to form a triangle;
- Nearside and farside stations;
- Traffic signals that are fixed time or actuated, coordinated or uncoordinated, and preempted or not preempted; and
- Various degrees of LRT priority at traffic signals, ranging from no priority, through window stretching, to emergency-vehicle-style priority (*1*).

To maintain credibility and to allow accurate comparison of alternatives, the operations analysts were required to be consistent in the conduct of analyses from one situation to the next, and from one stage of the project to the next. Yet the situations at different crossings or in different alternative designs for a single crossing were often totally different, as indicated by the list of variations above. Similarly, the levels of detail needed at different stages of the project differed substantially. When different analysis tools or techniques were used for different situations or stages of the project, the results often appeared inconsistent. The credibility of the analysts was not helped by the need to make different simplifying assumptions for different analyses.

Sporadic and Random Arrivals

LRVs do not arrive at fixed headways and do not always arrive separately. Even if the schedule calls for uniform headways, schedule adherence is never perfect, especially in an at-grade LRT system. In double-track sections, the LRVs traveling in opposite directions may arrive at the crossing simultaneously, one immediately after the other, or at various separation times. If they happen to arrive at a crossing simultaneously, the impact on automobile traffic is much less than if they arrive at different times. If one LRV arrives immediately after another (in opposite directions), the overall impact may be much greater than for separate arrivals. It was found necessary to consider all possible arrival patterns and assign probabilities of occurrence of each pattern.

Interdependence of Events

LRV arrivals at crossings separated by time or distance were often found to influence each other, rather than being independent, as assumed by most analysis techniques. For example, an LRV that arrives at a traffic signal shortly after another LRV in the opposite direction may be subjected to additional delay if the LRV priority measure in the signal controller is excluded from operation in consecutive signal cycles. Such interdependency can invalidate the assumption of random arrivals normally used in assigning probabilities to alternative arrival scenarios. Traffic signal coordination further complicates attempts to estimate LRV arrival patterns and their probabilities of occurrence.

ANALYSIS TECHNIQUES AND APPLICATIONS

Several different analysis procedures and associated computer programs have been developed for use on LRT projects.

Basic Capacity Analysis

The first step in analyzing alternative at-grade arrangements, whether at intersections or at midblock crossings, is to perform a basic traffic capacity analysis. Although this is often limited because of its reliance on average arrival and departure rates, fixed cycle lengths, and predictable headways, it does provide a primary screening process that eliminates alternatives with obviously insufficient capacity.

For this purpose, computer programs were developed that follow the 1985 Highway Capacity Manual (HCM) (2) operations analysis procedures to determine volume/capacity ratio, average delay, and level of service at an intersection or midblock crossing at which signal cycle length and LRV headways are assumed fixed and constant. In this software the HCM methods are extended to include percentage of vehicles stopped and probabilistic measures of queue length (*3*).

Midblock at-grade crossings were treated as a traffic signal with a cycle length equal to the average LRV or train headway. At crossings where LRVs were subject to traffic signal control, the impacts of LRT were assumed to be represented by the average signal timing, taking into account the appearance of extra LRV phases or LRV priority in some cycles. On the basis of these assumptions, the computer programs were used to analyze the capacity of a crossing to cater to automobile traffic and LRVs. While this identified crossings that do not have sufficient capacity to serve demands over a period of time (such as the peak hour), it did not adequately analyze the effects of variable headways and back-to-back arrivals. It provided a reasonable approximation for low-frequency, single-track crossings, such as found in Sacramento, where LRVs operate on 15- to 20-min headways. It is clear from Figure 1 that the typical intersection with LRT phasing presents complexities that cannot be handled by this approach in high-frequency situations.

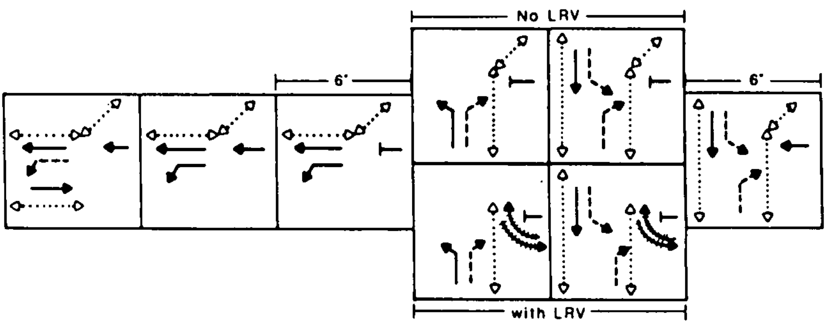

FIGURE 1 Typical phasing for on-street LRT operation.

Variable LRV Headway

The next level of analysis sophistication was developed to account explicitly for the fact that LRVs do not arrive at fixed headways and do not always arrive separately. Another computer program was developed for these situations. A time-series pattern of LRV arrivals was superimposed on the traffic signal cycle, determining periods during which each automobile movement may or may not flow. Where freight trains used the same right-of-way, the train arrivals were also added into the event pattern. The queue growth and decay patterns were then modeled to derive delays and queue lengths.

To investigate the effect of variations in headways, several runs were made with different headway assumptions. The results were used to estimate the range of impacts, the worst case, and the average condition. This procedure was found to be useful in investigating both levels of service and the potential for queue interference at adjacent intersections.

As an example, this software was used recently in analyzing alternatives for a Muni Metro extension in San Francisco. The Embarcadero subway station has a double-track, stub-end terminal with scissors crossover and is the terminus for all five Muni LRT lines. Although early plans called for an underground loop, current planning calls for a surface turnback facility with a new station along the waterfront Embarcadero. Figure 2 illustrates the 90th percentile queue lengths expected on each approach of LRT at-grade crossings for one of the alternatives investigated, indicating the extent of disruption that queueing will have on adjacent intersections.

Another application of this technique to an unusual combination of mid-block crossings adjacent to a preempted signal is illustrated in Figure 3. The worst-case pattern of LRVs at the crossing was shown to cause the tracks to be blocked by queues that could not always be cleared without oversaturating the cross street.

LRV Travel Times

In many applications, traffic conditions dictate that light rail cannot be given full priority or preemption at all grade crossings or intersections. Various schemes giving LRT partial priority or even no special priority introduce delay to LRVs that needs to be quantified in order to compare alternatives and refine travel time and fleet size estimates. Statistical measures of travel time through one or more fixed cycle-length signalized intersections were derived using another computer program. Predetermined LRV windows were coded to model full priority, partial priority, or no priority for light rail at a series of signalized crossings. Estimates of the mean and standard deviation were calculated for travel time (and hence delay) on each link and overall. Table 1 illustrates the type of information that can be derived from this model, which is particularly useful at the planning level as input to economic evaluation and supplementary to basic capacity analysis. This approach gave more accurate results than the available heavy rail simulation models, which typically introduce intersection delay as an exogenous variable rather than calculating it.

Comprehensive Operational Analysis

Each program just described offers an improvement over simple intersection capacity analysis and continues to be appropriate when the underlying assumptions are valid and the approximations are adequate. However, none offers integrated analysis of LRVs and automobile traffic with the flexibility to model all situations accurately, including vehicle-actuated signals (isolated and coordinated) and variable LRV headways on single or double track. For this purpose, the authors developed a microscopic simulator called ROAD-TEST (*4*).

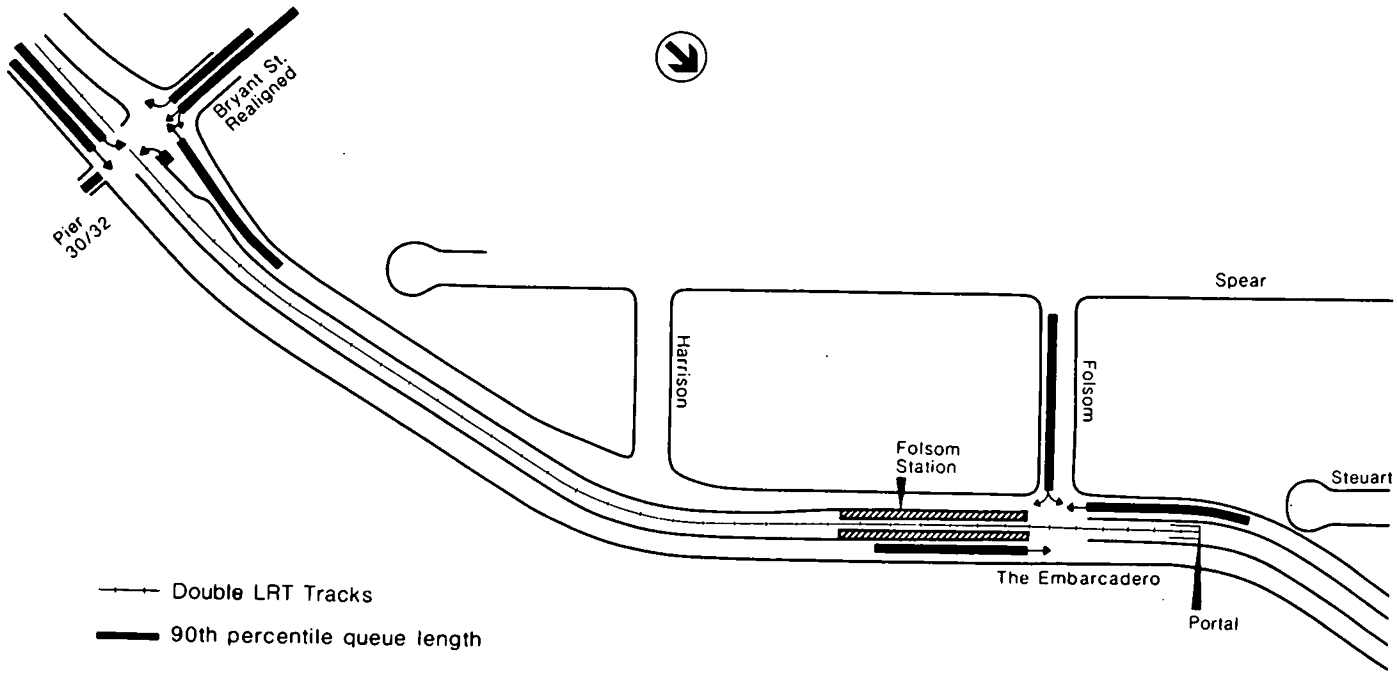

FIGURE 2 Expected 90th percentile queue lengths at signalized intersections with full LRT priority.

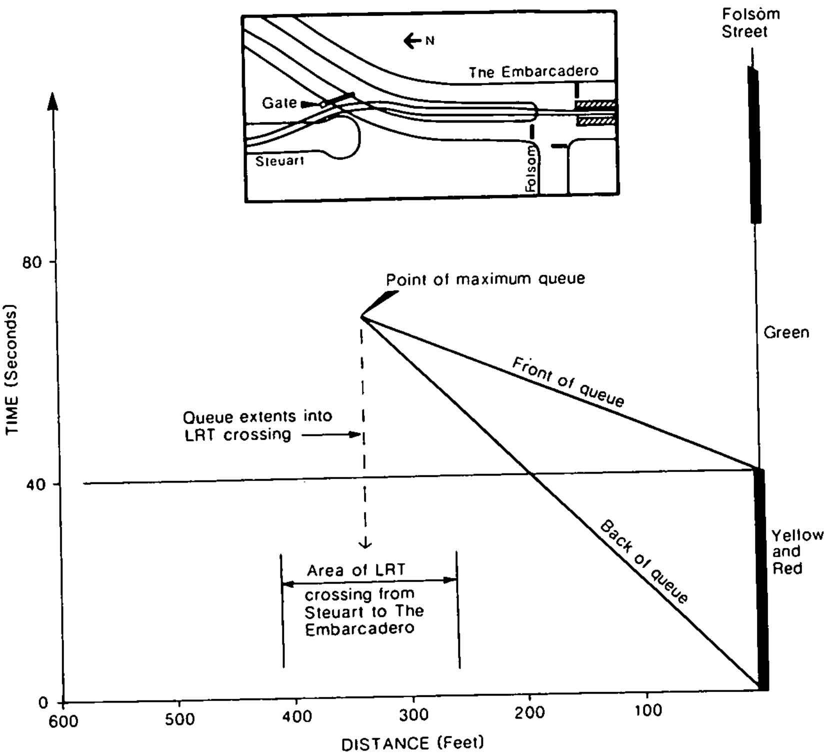

FIGURE 3 Queue behavior at preempted signal adjacent to gated crossing.

TABLE 1 LRT DELAY WITH PARTIAL PRIORITY WITH AT-GRADE LRT IN EMBARCADERO MEDIAN IN SAN FRANCISCO

	Northbound	Southbound
Percent stopped		
Bryant	58	59
Folsom	24	28
Average delay (sec/train)		
Bryant	14	14
Folsom	3	3
Total average delay (sec/train)	17	17
Range (sec)	0–45	0–46

ROADTEST is a microscopic rail and road traffic simulation model. It simulates the movement of all the individual vehicles in a road and rail network of any size and any complexity. It simulates both automobiles and LRVs, and can also simulate freight trains, buses, pedestrians, and other vehicle types if needed. Both traffic signals and train control signals are modeled in detail, including vehicle detectors and track circuits.

Various output reports at different levels of detail show statistics for measurements such as travel time, delay, stops, queue lengths, time and duration of events, etc. These statistics can be disaggregated in various ways, including by network segment, vehicle type, or route. As part of its output, ROADTEST also produces an animated graphical display of the network and vehicles in each time slice (e.g., one-fifth of a second). The user has complete control of the display via zoom, pan, slow motion, freeze, and similar commands. One of these movie frames is shown in Figure 4.

The animated display has proven to be invaluable in checking the performance of the model and simplifying the calibration process. It also provides observers with visual confirmation that this is a realistic and accurate model, thus removing one of the greatest barriers to acceptance of traditional computer model outputs. It shows LRT and traffic operations at a greater level of detail and understanding than is possible with numerical output alone.

ROADTEST directly addresses all of the problems and limitations associated with the other analysis techniques discussed above. It can model any situation encountered, with both rail and road vehicles, and any signal system or network. Thus it provides a single consistent source of accurate operations analysis data. It can also be used for failure management planning, schedule development, and supervisor training.

Table 2 shows output from a ROADTEST simulation of one of the critical intersections involved in the San Francisco Muni Metro extension project. These individual time period results were found useful in identifying short periods of oversaturation within a peak period that otherwise had an acceptable average performance.

SUMMARY AND CONCLUSIONS

The authors' analysis of at-grade LRT operations on six different LRT systems presented many challenging problems. At-grade light rail systems require an extraordinary analysis effort due to:

- The wide variety of geometry, control devices, and operating conditions encountered within a single LRT project, all requiring consistent analysis;
- The sporadic and random nature of the interaction between LRVs and road vehicles; and

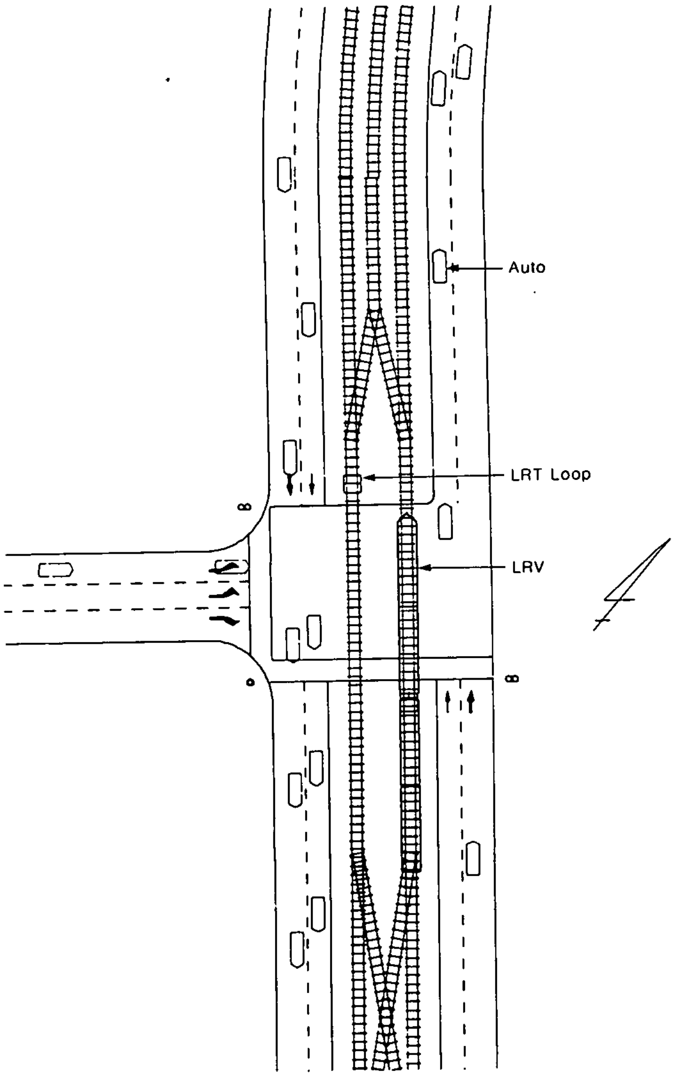

FIGURE 4 Computer-assisted-drafting plot of ROADTEST animated screen.

TABLE 2 ROADTEST TRAVEL REPORT

SAN FRANCISCO MUNI METRO EXTENSION
EMBARCADERO AT FOLSOM

Included Vehicle Types: compactcar midsizecar largecar
Entry Locations: EB_IN_5_IN EB_IN_6_IN EB_IN_7_IN
Exit Locations: NB_OUT_8_OUT NB_OUT_9_OUT SB_OUT_10_OUT SB_OUT_11_OUT

Time Period (Hr:Min)	No. of Vehs	Distance Travelled (Miles)		Travel Time (Mins:Secs)				Ave Speed (mph)	% Vehs Stop	Number of Stops					Stopped Delay (Mins:Secs)				
		/Hr	/Veh	/Hr Total	------/Veh------ Ave	Min	Max			/Hr Tot.	--------/Veh------ Ave	Min	Max	s.d.	/Hr Total	---------/Veh------- Ave	Min	Max	s.d.
00:00 to 00:05	32	510.8	0.21	00:25:45	00:48	00:23	01:19	16.0	84%	324	0.8	0.0	1.0	0.4	01:15:01	00:11	00:00	00:52	00:12
00:05 to 00:10	45	938.4	0.21	00:27:44	00:36	00:23	01:01	20.9	76%	408	0.8	0.0	1.0	0.4	00:47:24	00:05	00:00	00:28	00:07
00:10 to 00:15	44	899.6	0.21	00:27:39	00:37	00:22	00:57	20.4	68%	360	0.7	0.0	1.0	0.5	00:46:53	00:05	00:00	00:27	00:07
00:15 to 00:20	40	775.0	0.21	00:26:36	00:39	00:21	01:00	19.4	73%	348	0.7	0.0	1.0	0.5	00:59:57	00:07	00:00	00:25	00:07
00:20 to 00:25	59	1014.0	0.21	00:44:08	00:44	00:22	01:31	17.2	83%	612	0.9	0.0	1.0	0.4	01:31:38	00:07	00:00	00:59	00:11
00:25 to 00:30	45	737.5	0.21	00:35:16	00:47	00:23	01:29	16.4	78%	420	0.8	0.0	1.0	0.4	01:19:34	00:08	00:00	00:57	00:13
00:30 to 00:35	52	1130.9	0.21	00:30:42	00:35	00:20	00:56	21.7	69%	432	0.7	0.0	1.0	0.5	00:49:44	00:04	00:00	00:23	00:07
00:35 to 00:40	37	765.2	0.21	00:22:59	00:37	00:22	00:54	20.7	68%	300	0.7	0.0	1.0	0.5	00:48:33	00:06	00:00	00:26	00:09
00:40 to 00:45	54	1192.7	0.21	00:31:26	00:34	00:21	00:56	22.1	56%	360	0.6	0.0	1.0	0.5	00:38:28	00:03	00:00	00:25	00:07
00:45 to 00:50	50	1080.3	0.21	00:29:47	00:35	00:21	00:55	21.6	70%	420	0.7	0.0	1.0	0.5	00:48:28	00:04	00:00	00:24	00:07
00:50 to 00:55	48	1014.2	0.21	00:29:10	00:36	00:24	00:53	21.1	75%	432	0.8	0.0	1.0	0.4	00:50:34	00:05	00:00	00:27	00:06
00:55 to 01:00	75	1340.9	0.21	00:53:54	00:43	00:20	00:57	17.9	87%	780	0.9	0.0	1.0	0.3	01:23:32	00:05	00:00	00:27	00:07

ONE HOUR SUMMARY

Time Period (Hr:Min)	No. of Vehs	Distance Travelled (Miles)		Travel Time (Mins:Secs)				Ave Speed (mph)	% Vehs Stop	Number of Stops					Stopped Delay (Mins:Secs)				
		/Hr	/Veh	/Hr Total	------/Veh------ Ave	Min	Max			/Hr Tot.	--------/Veh------ Ave	Min	Max	s.d.	/Hr Total	---------/Veh------- Ave	Min	Max	s.d.
00:00 to 01:00	714	13096.7	0.21	08:20:25	00:42	00:20	01:34	18.3	76%	546	0.8	0.0	2.0	0.4	01:20:16	00:06	00:00	01:06	00:09

• The interdependence of events occurring at adjacent grade crossings or during consecutive LRV arrivals.

A range of analytical tools has been developed that permits study of LRT and related automobile operations to varying levels of detail with concomitant levels of accuracy. The most sophisticated of these is the ROADTEST simulator, which integrates LRVs and automobile traffic into a single task using a general purpose network simulation procedure.

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Designing At-Grade Light Rail Transit

GERALD D. FOX

The ability to operate at grade, interfacing with traffic and pedestrians, is a key characteristic of light rail transit (LRT). It can reduce construction costs, improve access to important trip generators, and justify rail development in corridors where more costly construction may not be warranted. It can also reduce transit reliability, interfere with traffic movements, and reduce operating speed. Effective intersection control and traffic interface design are the key elements in successful at-grade LRT design. Yet experience in this field is still limited, and beset with misconceptions that can distort, or even foreclose, a project in the planning stages, before potential problem resolution can occur. This paper discusses some of the commonly perceived problems that confront at-grade LRT designers and outlines some of the potential design responses, some of which were used on Portland's recently opened LRT.

ONE OF LIGHT RAIL'S strong points is its ability to operate at grade, interfacing with traffic and pedestrians. This can reduce construction costs, improve access to important trip generators, and justify rail development in corridors where more costly construction may not be warranted. But it also can present system designers with serious problems.

Although minimizing cost is almost sacred, when it comes down to details, its constituency is rather less solid, particularly as the project progresses from a proposal to a commitment. For instance, operating staff prefers as much grade separation as they can get. It makes a line easier and cheaper to operate. Designers may feel no compelling urge to promote the least costly option. Less cost may mean more risk and, after all, design fees are usually tied to project cost.

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Furthermore, the purveyors of proprietary expensive transit systems (PEPS) have a vital interest in not minimizing light rail transit (LRT) costs. More costly alternative systems appear more competitive if the cost of LRT can be kept as high as possible. For their part, local agencies like to piggyback other improvements, such as utility upgrading, street redevelopment, etc., onto LRT projects. These may be excellent programs, but they may not be true costs of the LRT construction. And people like to hear, and readily believe, that their city is different, as in "It might be good enough for Portland (or Zurich, or San Francisco), but it won't work here."

This paper discusses some of the commonly perceived problems that confront designers of at-grade LRT and outlines some of the potential design responses, many of which were considered or used on Portland's recently opened LRT.

Experience in at-grade LRT design is still limited and beset with misconceptions that can distort development of an LRT project before analysis has even begun. Most commonly at-grade operation is considered to have "unacceptable" impact on traffic, or to lead to excessive delays to LRT operation. Grade separation is often proposed before the trade-offs and alternatives have been properly analyzed. How to solve a problem is sometimes addressed, and included in the design of a system, before the problem is defined and before any determination is made about whether it needs to be solved. But the development of an effective at-grade design profoundly affects the cost, performance, and feasibility of an LRT project and is therefore a central element in developing transit alternatives.

DESIGN PHILOSOPHY

The design philosophy of a transit agency is pivotal to the success of the development of a low-cost LRT system. It must be actively supported by the agency staff and is best reinforced by reference to other operating systems, or elements of them. Fortunately there are a growing number of North American and European "reference systems."

A low-cost design philosophy is the product of several design principles. Keeping things simple is a principle that calls for constant vigilance. Use existing technology, do not invent new solutions to a technical problem where solutions already exist, and always ask first whether a problem needs to be solved before asking how to solve it.

Another important design goal is to maintain service when a component of the system fails, with as little delay and inconvenience as possible. Hence "How does it work when it doesn't work?" becomes a key question. Most elements in a transit system will periodically fail, particularly vehicles, fare equipment, traffic control equipment, and power supply elements.

The potential to upgrade LRT in the future can be a major inference for current design. It is usually not necessary to solve the problem of what happens when the ridership is 10 times higher and traffic levels are 5 times higher in 30 years' time. First, predictions may not happen and, second, if they do, the system's success will be so great that further expenditure will be readily justified. Trying to solve all these potential problems initially may lead to not being able to afford any system at all. Then there are the "might-as-wells." This is an insidious situation in which a decision to improve one element of a system is taken as a justification to improve another element. This approach can rapidly lead to escalating costs and is a frequent threat to cost-effective design.

Finally, don't solve nonproblems. During the design of an LRT system, numerous potential problems will be postulated. Not all of them will occur, and for those that do, there may be several solutions. Examples might include whether to fence a particular segment of LRT track, or whether stop sign control is adequate at a minor intersection.

AT-GRADE DESIGN ELEMENTS

At-grade design issues include parallel traffic capacity, cross traffic impacts, turning traffic, grade separation, crossing protection, and gated crossings.

Parallel Traffic Capacity

The issue here is the impact of LRT on parallel traffic capacity, which is created because the LRT occupies part of the street right-of-way. The first consideration is the amount of available right-of-way. In some cases the available right-of-way is sufficient to accommodate both LRT and the existing traffic. A further consideration is the relative importance of people-moving capacity versus automobile traffic capacity. Typically just two LRT trains an hour in a traffic lane will move more people than the traffic lane that they replace. The very concept of preserving existing automobile capacity has become more open to question in recent years as urban design goals have changed. The reduction of traffic capacity in central city streets to provide improved street amenities, pedestrian malls, and transit malls has become an increasingly successful central city strategy. LRT is highly consistent with such urban amenity improvement strategies, as is shown, for instance, by the new LRT malls in both North America and Europe.

A further consideration is that the traffic capacity on a street segment is usually limited by the adjoining intersections and not by the segment itself. A common LRT design response might be to widen the intersections only in order to match traffic capacity at both the intersections and the segment between.

A special parallel traffic condition is the merging of LRT into a traffic lane. Because LRT trains are too long to weave into traffic, LRT merges must be controlled by traffic signals, and such control seems to be a very effective design technique. In Portland the LRT is merged into traffic lanes to share use of a major bridge across the Willamette River. In Europe signal-controlled merges are often found that enable LRT trains to enter a mixed traffic lane after a station.

Cross Traffic Impacts

The impacts of LRT on cross traffic capacity will range from zero to significant, depending on the method of crossing control, the degree of preempt, and lane configurations. For instance, crossings may be controlled by gates, traffic signals, or passive devices such as stop signs. Gated crossings typically take longer to operate, and hence increase cross traffic delay. Gated crossings are most effective where LRT speeds are high or the crossing configuration is not readily controlled in a safe manner with traffic signals. Increased gate time arises from the actual operating time required to provide warning and lower the gates, as well as the regulatory "advanced warning" time (typically 20 sec) between the lowering of the gate and the arrival of the train. Traffic signals typically require less clearance time between the cross street red and train arrival time, the amount being a variable determined by train speed. Typical values range between 10 sec for 35-mph train speed and 5 sec for train speeds around 15 mph.

Then there are the existing upstream and downstream traffic constraints. There is no point in providing more capacity at an LRT crossing if traffic capacity is already constrained by the performance of upstream or downstream intersections. Furthermore, if LRT does not preempt an intersection, or moves within an existing signal progression, it will have little or no impact on cross traffic capacity. This fact provides an important starting point for LRT at-grade design, because not all intersections on an LRT line will have critical capacity problems. Thus the amount of preempts that may be possible can be varied according to the traffic requirements, starting at zero preempt and zero cross traffic capacity interference.

Stop location and preempt or lack thereof are closely related. For instance if a nearside stop is provided at a nonpreempt intersection, train delay will be minimized, and the greatest delay will be the length of the red cycle. If the train is moving with a signal progression, and stops at a nearside station, it will experience no delay at all if the stop duration matches the length of the red cycle.

Preempt can also be made conditional, for instance by a queue detector, which limits the preempt in the event that cross traffic reaches a certain queue length, or by a rulebook, which requires train operators to observe traffic conditions before calling for a preempt. Such systems provide considerable flexibility, allowing LRT priority except where this priority creates more than a given level of traffic congestion.

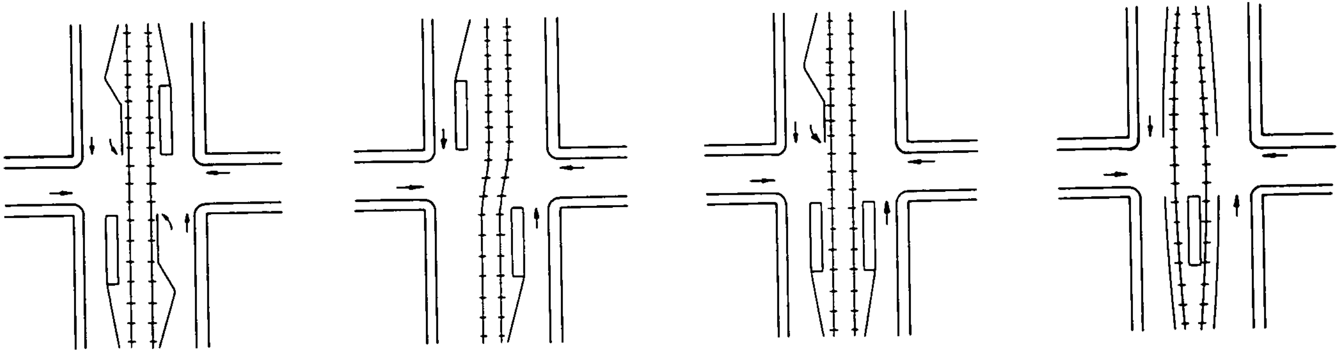
Intersection control and its impact on traffic are also tied to stop platform locations. For instance at an intersection with full preempt, platforms should be located on the far side of the intersection, so that train arrival time can be accurately predicted. Traffic delay is then minimized. If the LRT system has stationary preempt capability (such as with pushbuttons, or cab-actuated preempt calls) nearside platforms can be used, and any range of preempt from full to conditional can be applied with equal facility.

A further consideration is the need to optimize street geometry, particularly the balancing of turn pockets with the placement of passenger platforms. One consequence of this consideration is the frequent use of offset platforms on at-grade LRT. Figure 1 illustrates some relationships among geometry, preempts, and platform locations.

TURNING TRAFFIC

Traffic turning across LRT tracks at intersections poses several special problems. If the LRT is in the median of a two-way street, a separate left turn phase must be provided if traffic is to go on the parallel green. A left turn lane or pocket is then needed to store traffic during the LRT phase. The left turn pocket increases the required right-of-way, and competes with a station platform if one is planned. Thus farside platforms often work better where left turns are planned. Where right-of-way is tight, a right turn loop may be used in lieu of left turns. This option increases intersection capacity by eliminating the left turn signal phase, and reduces right-of-way needs, but may not operate well for large turning volumes (depending on loop geometrics). Prevention of illegal left turns is an important safety element of this design, requiring close attention to signing, striping, and curb configuration.

Where LRT operates beside a street, the main problem is control of right turns. Unlike in Europe, where right turn on red is not permitted, LRT designers in the United States have to control right turns. "No right turn on red" signs are often insufficient, and train-activated protection is often needed. This may consist of audible warning, flashing "train" signs as used on Holladay Street in Portland, or even gates. The combination of nearside stops with stationary preempt is sometimes an effective way to control right turns safely.



1 Offset, Far Side Platforms

Best configuration if:

Full pre-empt

Left turns

Provides:

Efficient use of r.o.w.

Clear, safe layout

Straight track

2 Offset Near Side Platforms

Best configuration if:

No pre-empt

Awkward layout if:

Left turns needed.

Track offset limited by geometrics.

Requires stationary acuation if pre-empted.

3 Facing Platforms

Consider if:

Major destinations all on one side of intersection.

Asymetrical traffic needs of r.o.w.

Can work with pre-empt one way only.

Provides straight track.

4 Island Platforms

Least station cost.

Improves traffic and pedestrian safety if high platforms are used.

FIGURE 1 Geometry, preempts, and platforms.

Where LRT is to be placed on one-way streets, the tracks should, if possible, be to the left of the traffic. Turning movements conflicting with LRT then become left turns, which are more controllable, and track and lane configurations conform more closely to motorists' directional expectations. If a single LRT track is operated to the left of traffic in the counterflow direction, turning movements can be better accommodated at intersections, and uncontrolled turns into driveways can be permitted.

By contrast, if LRT is operated in the same direction as traffic on a one-way street, turn control becomes difficult. In downtown Portland, where a single track runs on a one-way street, turns across the track were initially prohibited at many intersections, and a high incidence of illegal turns resulted. The intersection control is now being changed to permit turns, requiring that trains pass through these intersections on their own "all red" phase.

Figure 2 illustrates some common LRT turn relationships.

Grade Separation

Grade separation of LRT at major intersections or in downtown areas is often proposed to alleviate potential traffic impacts. However it is often proposed prematurely, without analysis of at-grade solutions first, and without appreciation of the potential negative consequences.

Preservation of traffic capacity is seldom, of itself, a sufficient reason for grade separation, particularly if LRT can use the same signal phase as parallel traffic. This cannot occur when LRT is turning across the traffic flow. Grade separation is particularly costly where a station is involved, because a grade-separated station usually involves elevators or escalators, and is constructed on a structure. Because the case for grade separation usually appears strongest at major cross streets, which is also where stations are located, this condition is a common design problem. Moreover, because a goal of grade separation is usually higher train speed, this goal is lost if a station is located at the same place. Look very hard at the cost/speed/capacity relationships for stations at arterial intersections. Placing the station with offset platforms on the approach side of the crossing without preempt can yield a low-cost design with little or no traffic impact, and only minor (half cycle length) train delay.

A second problem with grade separation is passenger access time, which is the time it takes passengers to get to a train. Frequent stations, surface operation, and barrier-free fare collection reduce access time. Grade-separated stations (which are also usually spaced further apart because of cost) increase access time. Because a passenger's trip time is the sum of access to the line, wait time, travel time, and access time to destination, access time is very important to passengers. Grade separation may make the

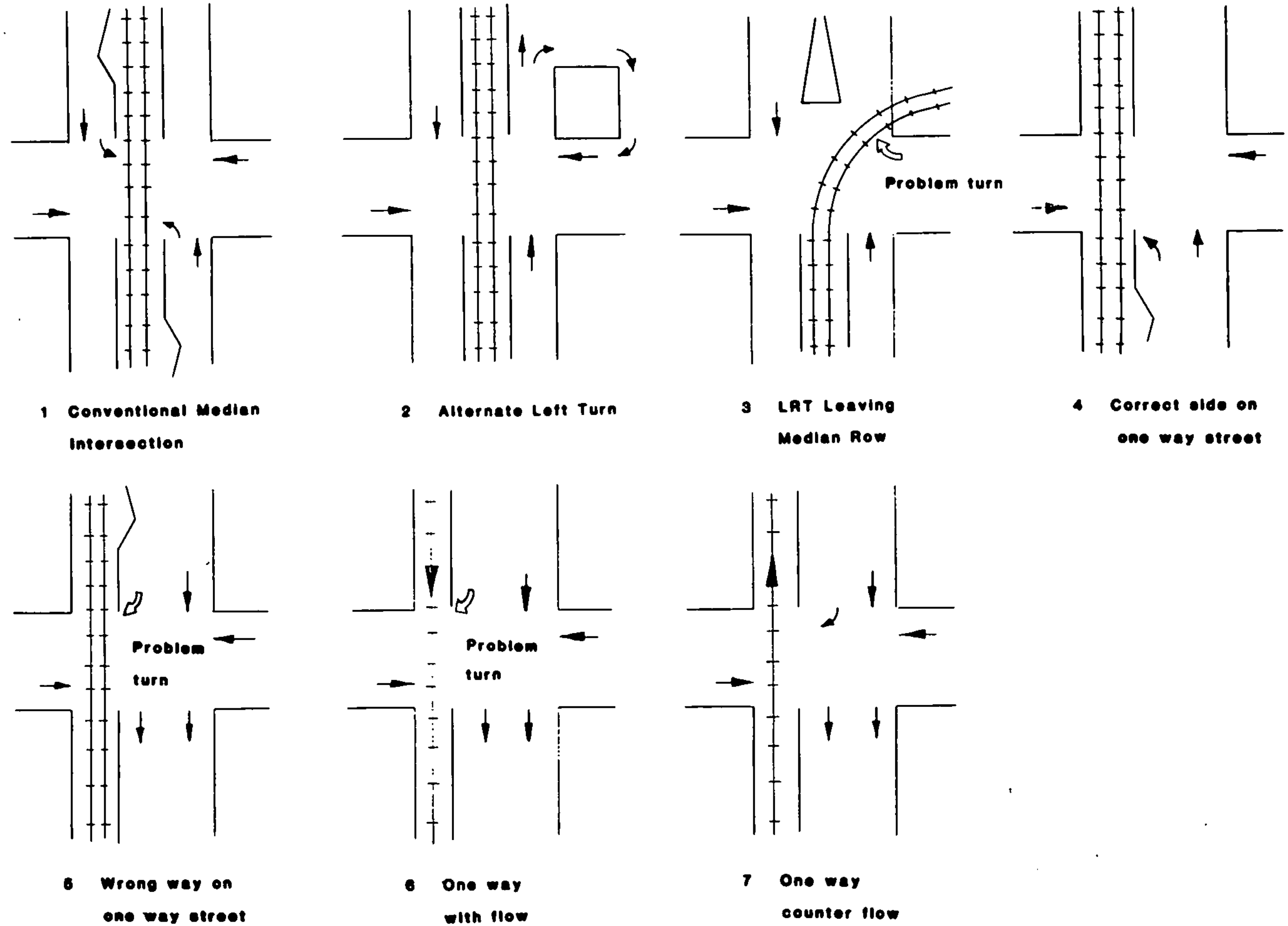


FIGURE 2 Some LRT/traffic turn relationships.

trains go faster, and the passenger go slower, all at considerably greater expense.

Related to this issue is the impact of station spacing on attainable speed. Figure 3 illustrates how station spacing affects average speed, and how maximum speed is of little importance when stations are closely spaced. Thus for stations spaced at 2,000 ft and a train limited to 20 mph [typical of LRT in a pedestrian or other central business district (CBD) situations], average speed will be 14 mph. A grade-separated system with a top speed of 50 mph will average about 18 mph. For that reason, when access time is also considered, the surface operation will compare well for all but the longest journeys.

Crossing Protection

The alternative types of crossing protection merit some comment. Where speeds are low, passive protection, such as stop signs, may be sufficient, depending on traffic conditions and street configurations. At one Tri-Met station, a four-way stop is used for both traffic and train control, with good effect, no delay to trains (which stop for the station), and no preempt. Where trains run on the edge of the street, stop signs on the nearside may not always be effective because of motorists' tendency to creep into the street.

The majority of LRT crossings at intersections are controlled by traffic signals. LRT may follow the signals, as does other traffic, or may have its own phase and signal aspects. Where LRT has its own phase, LRT signal aspects should be different from traffic signal heads, and should be designed to avoid confusing motorists who may see them. Thus certain colors, particularly green, should not be used, because motorists with poor vision may not distinguish between a T or X signal and a regular 0. Tri-Met has adopted the European bar signals, 1 for "go," – for "stop." Inclined bar signals may be used at junctions to indicate both "go" and position of a track switch.

The effectiveness of traffic signals for LRT crossings depends a lot on the intersection configuration. If the LRT is located in a median, or on the "correct" side of a one-way street, traffic signals work well, although speed is generally somewhat restricted. In Portland, traffic signals are not used if speed is over 35 mph. Raising this limit is currently under consideration. However because of station stops, the total time saved on a 5-mi section of line by raising top speed from 35 mph to 45 mph is only about 2 min.

Where unusual street configurations occur, traffic signal control is less effective, and higher levels of violation are found. Configurations in which turns are prohibited, or the LRT turns out of the right-of-way, or the streets are not perpendicular can all cause problems. Supplementary active protection in the form of flashing "TRAIN" lights is used by Tri-Met in such

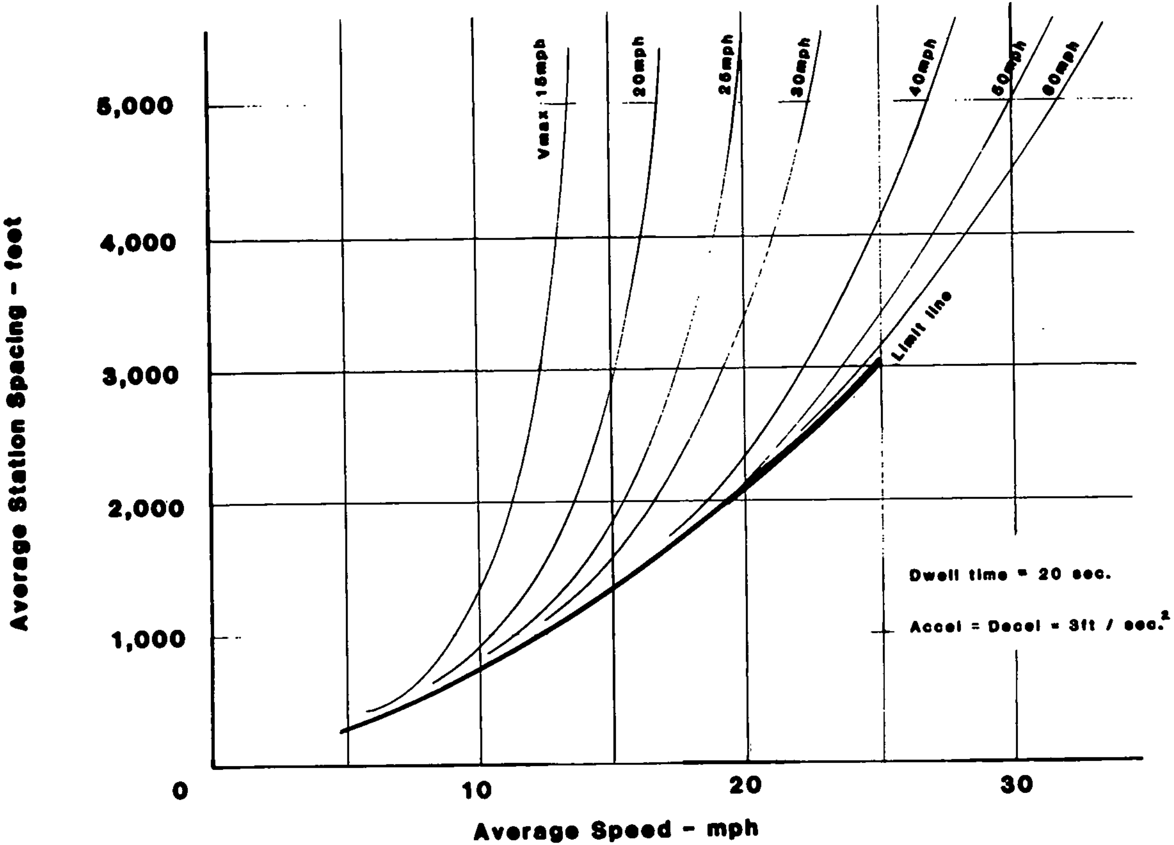


FIGURE 3 Station spacing versus average speed.

situations, and has shown promise. Because these lights are supplementary to the traffic signals, and are powered off the preempt circuit, no major circuitry or detection is required for their use.

A major advantage of traffic signals is the flexibility of the new controllers, particularly the 170 controller, to accept custom programs designed for LRT, and the ease with which control timing may be changed in the field. Moreover, use of standard traffic control hardware makes maintenance both inexpensive and fast with existing personnel and skills.

Gated Crossings

In certain situations, railroad gates may be preferred. Railroad gates actuated by track circuits are considered extremely reliable and are designed to fail in a safe condition (down). Developed for use on railroads, where trains cannot stop for crossings, they are often used where LRT speeds exceed about 35 mph. For instance, gates are used at arterial crossings not located in intersections, where traffic signals are often ineffective, or where unusual intersection configuration makes traffic signal control unreliable.

On Calgary's North East Line, part of which operates at up to 50 mph on an expressway median, gates are used to control left turns across the tracks in conjunction with traffic signal control of other conflicting movements.

At low-speed crossings where gates are used, less costly loop or overhead detectors can be used for actuation, provided provision is made for the train to stop in the event of nonactuation and provided the regulatory agency will permit such actuation.

Although safer than traffic signals, crossing gates have drawbacks. Their operation cycle is slower, so that they increase traffic interference significantly. The installation cost is significantly higher. They require more maintenance and are prone to minor collision and vandalism damage.

TRAFFIC NETWORK RESILIENCY

A frequent design goal is to try to preserve the traffic status quo, or even to provide for future additional traffic capacity as part of LRT design. The introduction of LRT into a transportation network will lead to trip diversion from bus and automobile to LRT. It can change the function of the streets it runs on to greater pedestrian orientation, and above all, the period of street disruption or closure necessary for construction will force new traffic patterns to develop.

Thus instead of preserving the traffic status quo, the LRT designers should evaluate the actual traffic needs on the basis of access requirements and the availability of alternatives for through traffic before arriving at a proposed street design and traffic mix.

When LRT was built on Holladay Street, an arterial street in Portland, the three existing traffic lanes were replaced by two lanes plus LRT. However, following over a year of street closure for construction, traffic never returned to its former levels. Two years later the Oregon Convention Center was located on this street, largely because of the LRT, and Holladay Street was reduced to a one-lane local access street serving the new convention center and its direction reversed. More people than ever before are traveling the street (by LRT) and the traffic network has adjusted itself.

SPEED PROFILES

A speed profile is a graphical representation of line speed related to time or location. It can be a valuable tool in developing alignment design. For instance it enables measurement of the schedule consequences of alternative designs at a specific location. Figure 4 shows alternative speed profiles for a sharp curve on the Portland LRT at 97th Avenue. Increasing curve radius or superelevation to achieve 15 mph rather than 10 mph produces a 17-sec time saving.

Similarly comparisons can be made of time savings from specifying cars with higher top speeds or greater acceleration, or from reducing station or traffic delays.

Consideration of speed profile will often guide designers to group speed impacts, for instance by placing a station near a low-speed curve, or by preferring to invest in grade separation where increased speed can result (i.e., where there is no station stop).

Figure 5 shows conceptually three speed/time profiles for a section of line, including an intersection and a farside station. Profile A is grade separated, but must stop for the station anyway. Profile B is at-grade with preempt. Profile C is at-grade without preempt. The train stops for a traffic signal and then for the station. The respective travel times for the segment are as follows:

A. Grade separated, 50 mph max: 65 sec,
B. At-grade, preempt, 35 mph max: 74 sec, and
C. At-grade, no preempt, 35 mph max: 105 sec.

For this situation, grade separation saved 9 sec, but preempt saved 31 sec.

On the proposed LRT extension to Portland Airport, the LRT must exit the median of a freeway. The original proposal required a 1,000-ft elevated

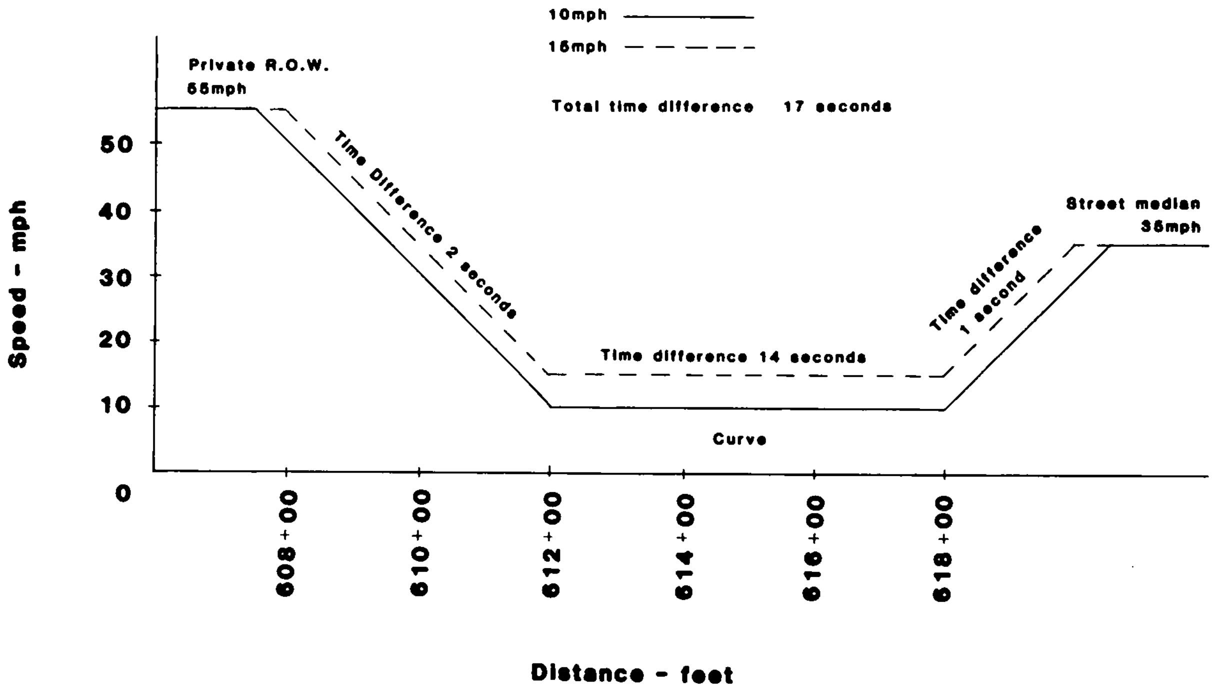


FIGURE 4 Speed profiles for 97th Avenue curve: 10 mph versus 15 mph.

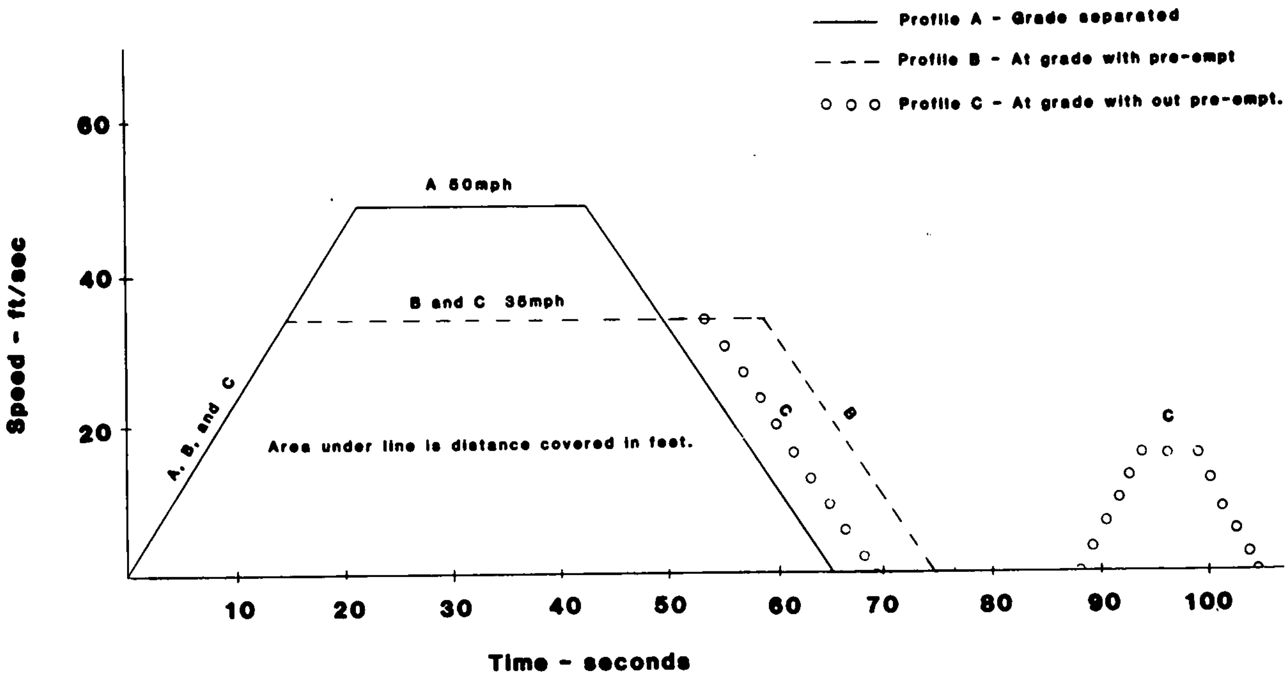


FIGURE 5 Speed profile for a line segment with intersection and farside station.

structure to lift out of the median, over the freeway lanes, and descend to grade. However, by reducing LRT speed to about 15 mph it becomes possible to curve down into a nearby existing underpass to exit the freeway median instead of building the elevated structure. And by placing a station at the end of this curve, the curve delay is shared with the station delay, resulting in a large cost savings and little operating time loss.

CONCLUSION

In setting out these guidelines for at-grade design an attempt has been made to set up a thought process that the designer can use to weigh alternatives and avoid being stampeded into costly design solutions where such may not be warranted. If these guidelines help the designer to keep it simple, to avoid the "might-as-wells," and head off the PEPS, then it has been well worthwhile.

Delay at Light Rail Transit Grade Crossings

BRUCE RYMER, THOMAS URBANIK II, AND
JAMES C. CLINE, JR.

The concept of light rail vehicles (LRVs) operating at grade and alternately sharing the right-of-way perpendicular to the flow of automobile traffic is an attractive transit idea because of the potential cost savings to transit agencies. This paper is a partial review of an evaluation of the potential delay impacts on automobile traffic imposed by LRVs operating at grade. This report can assist decision-makers in determining where grade separations are appropriate. Also presented is a methodology for summarizing the operational characteristics of a light rail transit grade crossing with a single parameter, the crossing-volume-to-capacity ratio. The analysis centered on computer simulations using FHWA's NETSIM model. Results indicated that for light rail transit crossings located in excess of 400 ft from any adjacent intersection, the delay imposed on the motoring public warranted a grade separation only at very high traffic volumes or very short LRV headways.

INCREASED CONCERN OVER GROWING urban automobile congestion has regenerated interest in light rail transit (LRT) as a viable mass commuting alternative. LRT's attractiveness lies in its potentially lower implementation costs versus the much higher costs of a heavy rail system. Because of power supply hazards and operational objectives, heavy rail systems are usually totally grade separated from surrounding automobile traffic, making the initial capital costs very high.

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By comparison, the lower costs of an LRT system result from the less stringent design requirements. One of the key factors is the lack of an absolute requirement for the complete grade separation of an LRT line. LRT can be run in the traveled way, in roadway medians, or on semiexclusive rights-of-way. Although these arrangements use at-grade crossings, the possible impact of the light rail vehicle (LRV) on crossing automobile traffic has not been adequately evaluated.

One measure of this impact is the additional delay experienced by the vehicular traffic because of LRVs crossing the roadway. Delay can be used for a relative comparison of the impact with other crossings, or it can also be used in economic analyses by assigning a value to this delay time. The objective of this report is to study the vehicle delay impact to traffic of at-grade crossings on an LRT line operating on semiexclusive right-of-way. The calculation of this vehicle delay will be quantified for ease of application. Vehicle delay can then be used as one of the criteria for considering grade separation of these at-grade crossings.

LITERATURE REVIEW

Although much attention has been paid to the topic of LRT, limited research has been done on assessing the impact on traffic of at-grade crossings. The following paragraphs focus on the previous work that has been done in analyzing this impact and the appropriateness of using person delay as a method of evaluation.

The most recent work on this topic (*1*) established the criteria for the grade separation of LRT and busway crossings from the closure time and the resulting loss of capacity. The resulting warrants are a function of the average daily traffic crossing the tracks and the volume of transit units on the system per hour. Another report (2) noted the need to avoid severe disruption to the traffic flow as a result of a grade crossing. While capacity and level of service are important parameters in traffic analysis, they do not fully describe the magnitude of the impact on the roadway system. A more quantitative method should be used that can evaluate different operational and geometric conditions with respect to their total impact on the traffic flow.

Two reports (*3*, *4*) suggest the use of delay in analyzing grade crossings. The use of person delay provides a quantitative measure of the impact on the traffic stream. This methodology also provides a way to evaluate the user benefits and costs of LRT grade crossings. Different geometric and operating scenarios can also be compared on the same basis.

There are different alternatives for the control of traffic at the crossing. These can range from conventional traffic signals to railroad crossing gates.

The conventional traffic signals are more efficient in terms of delay to motorists, but the crossing gates provide a higher degree of safety (*3*).

The impact of an LRT grade crossing should be evaluated not only for the crossing itself, but also for the surrounding network. Any effect on nearby intersections and roadways should be included in the total assessment of impact. These effects may be limited, but they cannot be neglected in analyses of the problem (*3, 5*).

Recent work (*6*) has also shown that the crossing clearance time can be varied to reflect a broad spectrum of operating conditions. This crossing clearance time is defined as the time it takes for the LRV to negotiate the crossing and for the crossing gates to operate. The length of the train, the speed of the train, and the location of the station can all be reflected in the calculation of the total clearance time.

Several priority schemes can be implemented into the control plan for an at-grade crossing (*7*). These schemes can range from an unconditional priority at all times for the LRVs to a situation in which the LRVs must wait for an acceptable gap in the traffic stream. The worst case for the automobile traffic exists when the unconditional scheme is implemented.

It has been concluded from the literature and current practice that person delay as a measure of effectiveness will provide a method of associating a quantifiable user cost with the operation of an LRT system with at-grade crossings. These costs can then be used as part of the criteria for the grade separation of a crossing. It is clear from this review of the current literature that there has been limited study of this problem using person delay. The current trend toward LRT technology utilizing at-grade crossings further indicates the need to expand the depth of knowledge in this field.

STUDY PROCEDURE

The development of the procedure for this study was guided by several requirements. The chosen methodology must allow the evaluation of a large range of conditions in a roadway network. A fairly large data base was also required to provide a sound statistical analysis of the results. The absence of adequate study locations because of the inability to control the variables at the crossings indicated a need for a comprehensive network model. For these reasons, the NETSIM program, developed for FHWA, was chosen for this analysis.

A key assumption made in the design of this procedure should be noted at this point. In all scenarios, the worst-case condition will be analyzed. The investigation of a complete spectrum of operational improvements is beyond the scope of this study. Examining this worst case will fix the upper boundary. A crossing that does not warrant grade separation under these conditions can be discarded as a possible candidate for grade separation. Crossings that do have substantial delay under these conditions should be studied further to see if possible operational improvements could lower the user costs of the grade crossings to a point where a grade separation is no longer needed.

LRT Grade Crossing Simulation

The NETSIM model was chosen for this analysis for several reasons. It is a microscopic, stochastic simulation model. It was developed as an evaluation tool for use on urban street networks. Many different operational strategies can be implemented, but there is no optimization algorithm for the timing of the signals. Intersection control can range from a yield sign to a fully actuated controller. The model also provides an algorithm for the operation of buses in the network. Queue discharge rate and free flow speed are also specified for each link (*8*).

One other key input to the program is a random number seed. The stochastic nature of the program requires this number to be changed for each simulation run. Many of the characteristics of traffic flow are determined as a function of these random numbers. To preserve the validity of the results, each run was made with a different random number obtained from tabulated listings (*9*). The randomness built into this model also requires that each set of conditions be evaluated several times. In this study, each separate case was run three times. This number of simulations is within the practical limits of the computer facilities and is in accordance with previous work.

The output from a NETSIM simulation run includes a list of all input parameters and a tabulation of all operational statistics. These results include delay, number of trips, percent stop delay, travel time, vehicle miles of travel, and the number of cycle failures. This information is broken down on a link-by-link basis. The level of detail and flexibility in both the input and output allowed the model to be adapted to the study of this problem.

While NETSIM is not specifically designed for the simulation of LRT grade crossings, the networks can be coded to represent them. The LRT tracks are modeled as single-lane roadways. The grade crossing is represented as a fully actuated intersection of these "tracks" and the crossing roadway. The crossing roadway is given a short minimum green and is set on recall. The minimum green plus amber for the tracks is set as the crossing clearance time. This will account for the crossing gate operation time and the time for the train to negotiate the crossing. The LRV arrivals at the crossing are represented by buses operating on the "track." This bus algorithm allows the buses to be discharged at a specified headway. The difference in the operation of the bus and LRVs is accounted for in the crossing clearance time.

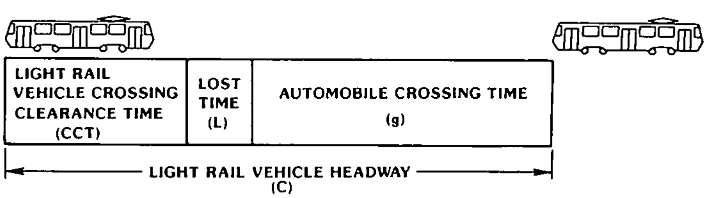
This model allows the roadway volume, roadway cross-section, LRV headway, and clearance time to be varied in the same network.

It should be noted that this model provides unconditional priority for the LRVs. This scenario is the worst case for automobile traffic. No allowance is made for nearby signals and possible progression. When this model of the interaction between the LRVs and the automobile traffic is used, the LRVs (buses) will be discharged onto the network from one direction only. The headway assigned to the model will refer to the mean time between roadway closures. The effect of two-way operation can be estimated by calculating the mean time between road closures. This model does not take into account the effect of a simultaneous arrival of two LRVs at a crossing during two-way operation. It is felt that the impact to traffic would be greater for two separate closures than for two overlapping arrivals. Further study involving different priority strategies will be needed to account for this.

Development of Crossing-Volume-to-Capacity Ratio

At an at-grade crossing, the LRT tracks and the automobile right-of-way occupy the same space. At some time, both modes of transportation will be vying for the same space simultaneously. The problem at an at-grade LRV crossing consists of the allotment of time between the LRVs and the automobiles.

Referring to Figure 1, headway is the time gap between the front of one LRV and the front of the following LRV. The crossing clearance time (*CCT*)



$$g = \frac{C - (CCT + L)}{C}$$

Light Rail Vehicle Headway = Cycle Length = C
Light Rail Vehicle Crossing Clearance Time = CCT
Lost Time = L
Automobile Crossing Time = g
All Units in Seconds

FIGURE 1 Light rail vehicle headway relationship.

has three components: the time involved in the lowering of the guard gates (or some other safety device or warning signal), the time the LRV actually occupies the roadway, and the time consumed in raising the guard gates. For purposes of this study, the crossing clearance time ranged from 30 to 50 sec. A longer LRV is accommodated by a greater crossing clearance time. Lost time is the fragment of time spent in starting the waiting automobiles once the guard gate is raised and the LRV has cleared the right-of-way. Lost time was assumed to be 4 sec.

Automobile crossing time (g) is just a ratio that represents the portion of time available for the motorists to cross the tracks. Obviously, this number will vary between 0 and 1. A larger ratio reflects more crossing time for the automobiles. Note that as the LRV headway (C) increases and approaches infinity, the automobile crossing time (g) approaches 1. This situation is very similar to a traffic signal; the fraction of time available for automobiles to cross the LRT tracks is analogous to the green time on a traffic signal head.

$$g = \frac{C - (CCT + L)}{C}$$

where

$$\begin{aligned} C &= \text{LRV headway = cycle length,} \\ CCT &= \text{LRV crossing clearance time,} \\ L &= \text{lost time, and} \\ g &= \text{automobile crossing time.} \end{aligned}$$

(All units are in seconds.)

The automobile green time is then used in the calculation of the crossing-volume-to-capacity ratio (Xcr). But first another parameter must be introduced. Within the Xcr ratio is a second ratio, the demand/saturation ratio (v/s). This demand/saturation ratio is essentially a percentage that reflects the demand-to-supply relationship of the roadway that serves the automobiles.

$$v/s = \frac{\text{(Actual Number of Automobiles per Lane per Hour)}}{\text{(Saturation Level of Automobiles per Lane per Hour)}}$$

So, Xcr consists of two ratios—one ratio that indicates the portion of time that is available to the automobiles to traverse the tracks (g), and the other ratio that shows the operational capacity of the roadway segment (v/s).

Crossing-Volume-to-Capacity Ratio = Xcr = $(1/g)(v/s)$

Xcr is inversely proportional to the time available for the automobile crossing time (g) and directly proportional to the demand/saturation ratio. The automobile crossing time (g) decreases as lost time and LRV crossing clearance time increase, which in turn penalizes the operational capacity of the roadway segment.

Isolated Crossing

An isolated crossing is defined to be unaffected by any adjacent intersections or conflicting flows. Only vehicles crossing the LRT tracks will be affected by the crossing LRVs. The objective in this case is to determine the relationship, if any, between the delay per vehicle and the crossing-volume-to-capacity ratio. Figure 2 illustrates the network to be used in this study. Four key variables were analyzed for their effect or combined effect: roadway cross-section, roadway crossing volume, LRV headway, and total clearance time. Cross-section was varied from two to six lanes. Volume ranged from 250 vehicles to 1,000 vehicles per hour per lane. LRV headway varied from 2.5 to 12.5 min. Crossing clearance times of 30, 40, and 50 sec were evaluated.

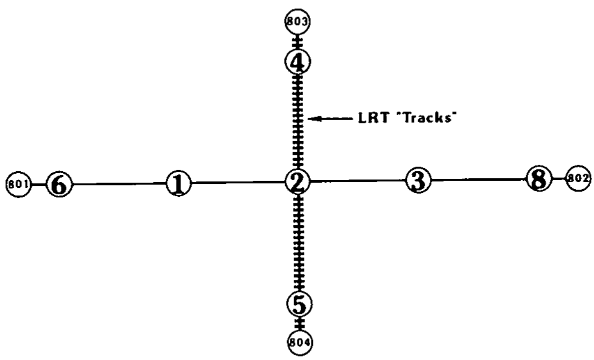


FIGURE 2 Isolated crossing—link/node diagram.

STUDY RESULTS

The purpose of the isolated crossing analysis was to find a mathematical model that would represent the relationship between the crossing-volume-to-capacity ratio (Xcr) and average automobile delay. Delay calculation methodology used by Webster (*10*) and the Highway Capacity Manual (*11*) indicates that volume/capacity ratio is a key parameter for computing delay per vehicle. Each variable—roadway volume, roadway cross-section, LRV headway, and clearance time—was varied through a complete range of values. A total of 384 simulation runs were completed for this case. The Statistical Analysis System (SAS) was used to analyze the resulting data (*12*).

The NETSIM model does not contain any options that simulate LRV operation. It was necessary to select inputs to NETSIM such that the bus traffic simulation option approximated LRV operation. The bus delay statistics were subtracted from the overall system delay statistics. The average delay per vehicle was then calculated from these adjusted values for each simulation run. The resulting data points were then plotted for comparison and analysis.

The effect of LRV headway on delay per vehicle is illustrated in Figure 3. Crossing clearance time and the roadway cross-section are held constant as the traffic volume is varied for different headways. The resulting curves show that decreasing the LRV headway increases the delay per vehicle on the crossing roadway. It also shows the nonlinear relationship between delay per vehicle and traffic volume.

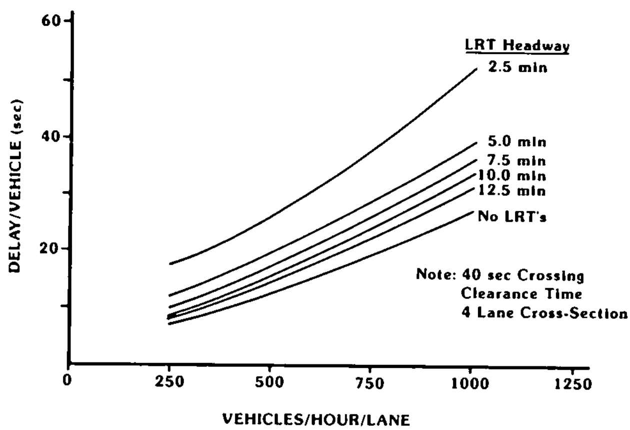


FIGURE 3 Effect of LRT headway on delay.

The effect of crossing clearance time is shown in Figure 4. The roadway cross-section and LRV headway are held constant as the traffic volume is varied for different crossing clearance times. An increase in crossing clearance time results in an increase in delay per vehicle.

The effect of roadway cross-section on delay per vehicle is illustrated by Figure 5. LRV headway and crossing clearance time were held constant while

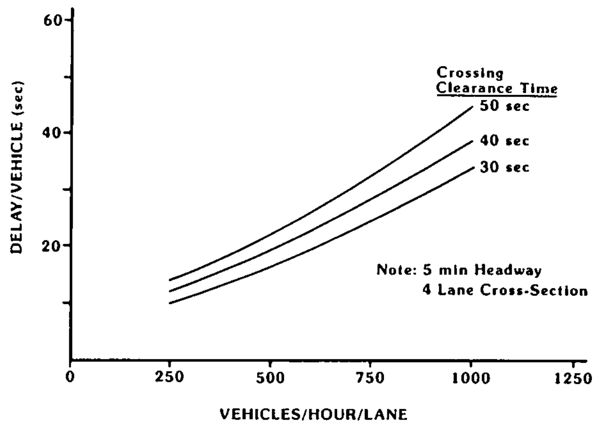


FIGURE 4 Effect of crossing clearance time on delay.

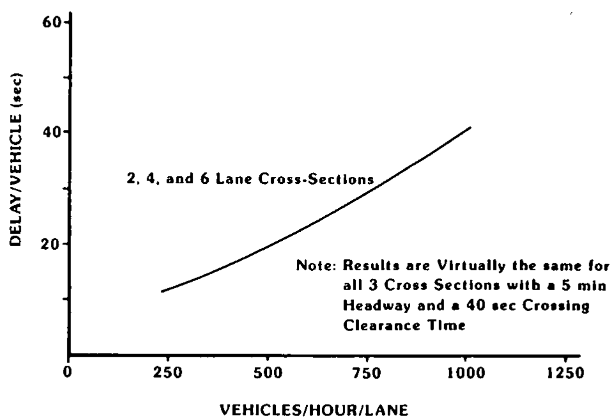


FIGURE 5 Effect of roadway cross-section on delay.

traffic volume and cross-section were varied. Traffic was uniformly distributed over the number of lanes and the delay remained constant. Larger cross-sections will accommodate more traffic, but if the demand/saturation ratio per lane is constant, the average delay per vehicle will remain constant.

The relationship between delay per vehicle and the crossing-volume-to-capacity ratio is shown in Figure 6, which shows a definite relationship between these two variables. This function appears to be nonlinear. Regression analysis was performed on the data sets to determine the best relationship between these two values for this data set.

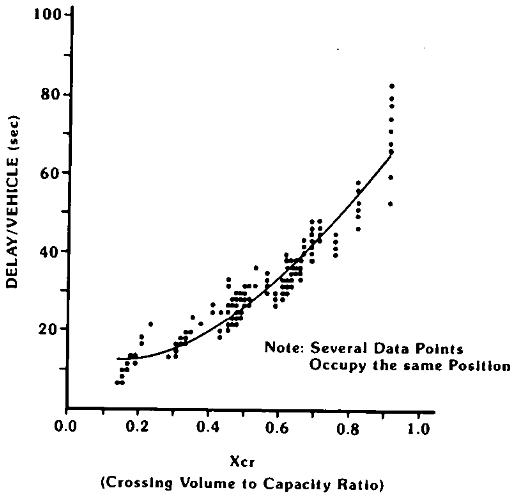


FIGURE 6 Scatter plot with prediction curve.

The following equation was found:

$$\text{Delay/vehicle (sec/veh)} = 9.56 + 67.26\ (\text{crossing volume/capacity})^2$$

The R-squared for this model is 0.92.

It should be noted that the equation includes an intercept term. There is no reason to expect a nonzero intercept term, as a single vehicle proceeding through the system should incur no delay. However, the model suggests that when the crossing-volume-to-capacity ratio is very low, an inherent delay of 9.56 sec per vehicle is unavoidable. If there are no LRV crossings, zero delay should be experienced by the motoring public. In actual application, the effect of the intercept term creates unrealistic delays at low volumes. Therefore, it was felt that the equation developed for the isolated crossing should be modified. The original data from the NETSIM runs were retained and the resulting relationship was determined:

$$\text{Delay (sec/veh)} = 91.16\ Xcr^2$$

The modified equation is more appropriate because there is no intercept term. From a planning viewpoint, the modified equation and the original equation yield similar results.

Refer to Figure 7 for a comparison of the original delay equation and the modified delay equation. The modified equation produces conservative delay estimates for *Xcr* below 0.6. For values of *Xcr* greater than 0.6, the modified equation yields a somewhat higher delay than the original equation. It should be noted that the delay equations follow an x^2 relationship that is consistent with the delay function used in the Highway Capacity Manual.

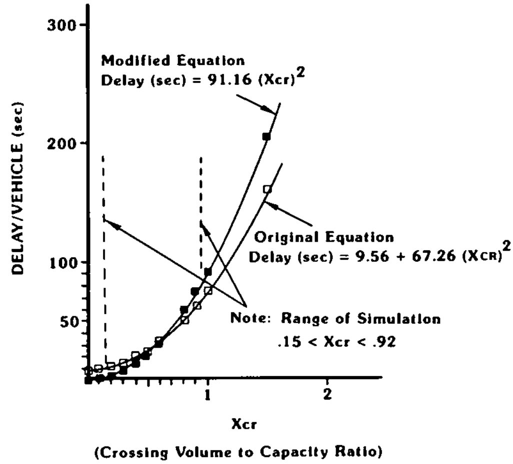


FIGURE 7 Original delay equation versus modified delay equation.

This equation represents an estimate of the systemwide delay that includes both the inherent automobile base delay and the incremental delay induced by the LRVs. To obtain the incremental delay of the LRVs, the base delay is subtracted from the total delay. Once the incremental delay is determined, a benefit/cost evaluation can be made. Summarized in equation form:

$$\text{Automobile delay due to LRT (sec/veh)} = 91.16\,Xcr^2 \text{ (with LRVs)} - 91.16\,Xcr^2 \text{ (without LRVs)}$$

ECONOMIC ANALYSIS FOR GRADE SEPARATION

The objective of this analysis is to translate the results of this study into economic terms. In other words, will the savings in delay time to the motoring public offset the construction costs of a grade separation? This analysis is intended to be used as a planning tool for evaluating isolated crossings.

The study developed a relationship that quantified the delay time experienced by the motorist because his right-of-way is obstructed by LRVs. The economic analysis places a monetary value on this delay time and then projects, over the course of 20 years, whether or not the expense to the motoring public because of the delay would justify building a grade separation for the LRVs.

A grade separation costs somewhere between \$3 million and \$5 million (or more), depending on site-specific conditions. If the public's delay time (the time spent waiting for the LRVs to cross) is equal to or exceeds the construction cost of a grade separation, then the grade separation is warranted.

The economic evaluation assumed a Texas urban traffic distribution developed by Urbanik (*13*). Once the average daily traffic count at a point is determined, the urban distribution is used to assign an estimated amount of traffic to each hour of the day. By assuming an hourly volume and varying the crossing times for the LRVs, an economic assessment of the delay can be evaluated. For purposes of this study, occupancy of each automobile was set at 1.25 persons. A value of \$7.80 per vehicle-person-hour was allotted for the delay time. This \$7.80 reflects the value of time to the motor vehicle occupants and associated vehicle operation costs (*14*).

The 24-hour day was divided into two demand periods, peak and off-peak. During the off-peak periods the LRV crossings were held at a constant crossing frequency of once every 15 min (900 sec). In the peak periods, when the traffic demand is heaviest, the LRV crossings were varied in frequency and duration. The delay was accrued only between the hours of 6 a.m. and 9 p.m. with 6 a.m. to 9 a.m. and 4 p.m. to 7 p.m. representing the peak traffic demand periods. Given that the LRVs were operating on some timetable, the delay they prompted at an isolated crossing was then calculated. Yearly delay was based on 250 working days. A net present worth approach with a 5 percent interest rate and a 20-year project life was used to assess the current economic value of the delay. No traffic growth for the average daily traffic was assumed during the 20-year project life.

Tables 1 through 3 were generated with the isolated delay relationship. The crossing-volume-to-capacity ratio (Xcr) varied from a low of 0.05 to a high of 1.24. The NETSIM simulations applied only to Xcr ratios below 0.92. The region above 0.92 is extrapolated (refer to Figure 7). The tables indicate that at low average daily traffic volumes and low LRV crossing frequencies, the delay imposed on the motoring public does not offset the cost of building a grade separation. However, at high average daily traffic volumes and frequent LRV crossings, the grade separation may be warranted.

TABLE 1 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (30 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	10,200	81,400	272,600	651,000	1,271,400	2,197,000
24	3,100	24,600	82,900	196,600	384,000	663,600
12	1,400	11,100	37,100	88,000	171,900	297,000
8	950	7,500	25,400	60,400	117,900	203,800
6	750	6,000	20,200	47,800	93,300	161,300
4	550	4,500	15,200	35,900	70,200	121,300

NOTE: LRV crossing clearance time = 30 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.

TABLE 2 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (40 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	20,900	167,400	563,900	1,335,900	2,609,000	4,509,000
24	4,500	36,300	122,700	290,800	567,900	981,400
12	1,900	15,100	50,600	120,000	234,400	405,100
8	1,300	10,100	34,000	80,700	157,700	272,400
6	1,000	7,900	26,700	63,400	123,800	213,900
4	750	5,900	20,000	47,300	92,400	159,700

NOTE: LRV crossing clearance time = 40 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.

TABLE 3 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (50 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	50,200	401,700	1,355,800	3,213,700	6,276,800[b]	10,846,300[b]
24	6,500	51,800	174,900	414,600	809,700	1,399,200
12	2,400	19,500	65,600	155,600	303,900	525,200
8	1,600	12,800	43,200	102,400	200,100	525,200
6	1,200	10,000	33,600	79,700	155,700	269,000
4	900	7,400	24,900	59,100	115,500	199,600

NOTE: LRV crossing clearance time = 50 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.
[b]X_{cr} ratios greater than 0.92.

Tables 1 through 3 apply only to isolated LRV crossings, or crossings located in excess of 400 ft from any adjacent signal. For grade separations with project lives of 50 years, multiply the table figures by 1.5 to obtain the net present worth.

CONCLUSIONS

The operational characteristics of an isolated LRT grade crossing can be described by a single parameter. This parameter is the crossing-volume-to-capacity ratio. This one parameter is composed of the LRV headway, the crossing volume per lane, lane saturation, lost time, and the crossing clearance time. It should be noted that the crossing-volume-to-capacity ratio does not account for the degree of progression on the roadway system. Heavily platooned arrivals are not accurately analyzed on the basis of this value.

Although only general conclusions could be drawn, the location of an isolated LRT crossing operating with unconditional preemption does not affect the traffic greatly for the crossing conditions studied. The economic analysis suggests that most isolated crossings (more than 400 ft from a traffic signal) will not justify grade separations on the basis of delay imposed on the crossing automobile drivers and their passengers.

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An Evaluation of Automated and Conventional Rail Technology for the Century Freeway Rail Line

RICHARD M. STANGER

The Century Rail Transit Line will operate for 17 mi in the median of the Century Freeway now under construction in Los Angeles. It will also extend initially for 3 mi on exclusive right-of-way into the large El Segundo aerospace employment center. In 1986 the Los Angeles County Transportation Commission staff evaluated the potential of fully automating this line. The paper summarizes this evaluation, looking first at improvements short of full automation, then at the benefits of full automation based on the experience of VAL and SkyTrain. It notes that the real benefit of full automation may come not so much from trade-offs between capital and operating costs, but from the revenue potential of frequent, all-day operation. The paper then compares the use of automated-guideway transit vehicles with a conventional light rail vehicle modified to be fully automated. It concludes that automating the Century Line appears to be justified, and that the use of conventional light rail vehicles modified to allow unmanned operation should be an integral part of a decision to automate.

THE CENTURY RAIL TRANSIT LINE will operate in the median of the Century Freeway now under construction in Los Angeles. It is oriented east-west for 17 mi between Norwalk and the coast, passing about 8 mi south of downtown Los Angeles. At the coast it branches out north and south to serve

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major growth centers. The first extension, to be completed in 1993 with the Century project, serves the large El Segundo aerospace employment center. The line is expected to cost $390 million in escalated dollars.

The Century-El Segundo rail line will be fully grade-separated. Given this circumstance, members of the Los Angeles County Transportation Commission (LACTC) asked the staff in mid-1986 to evaluate possible ways of improving the line's performance, specifically by considering fully automated, or unmanned, operation.

BACKGROUND

Over the past 4 years two urban, public, unmanned transportation facilities have opened with convincing success. The first was the VAL system in Lille, France, an 8.5-mi line with 18 stations. On a typical weekday 120,000 riders use the system. Less than 3 years later the SkyTrain system opened in Vancouver, Canada, and carried 150,000 riders per day by summer 1986. Although much of this ridership was induced by Expo '86, it nevertheless showed the capability of the SkyTrain system, which now carries about 70,000 riders each day.

The technology has existed for some time to run fully automated trains; in fact most rapid transit systems since the Bay Area Rapid Transit (BART) system in San Francisco have employed the capability. Yet the step of removing the motorman remained. The contribution of the VAL and SkyTrain systems may be more in their taking this step in a full urban transport application than in proving the technology. It will now be easier for others to follow suit. The conversion of the Line D rapid transit in Lyon, France, to unmanned operation is a case in point.

OPERATIONAL IMPROVEMENTS SHORT OF FULL AUTOMATION

Service can be improved short of full automation by increasing the maximum speed of the vehicles or by increasing the frequency of service by vehicles controlled by operators on a semiautomatic basis. Both of these tactics, however, have serious drawbacks.

Increasing Speed

Because the Century rail project is in the median of a freeway and stops at relatively few stations, it will provide an impressive average operating speed of 37 mph, including stops. During rush hours, when parallel automobile speeds are expected to be quite slow, the rail speeds will be especially attractive.

Nevertheless, it is possible to increase the travel speed. There are two ways this might be done. First, a faster vehicle might be specified, that is, one with a higher maximum speed. If the speed is fast enough, the round-trip time could be reduced one headway. This would allow one train to be saved, which might offset the extra cost of the faster propulsion system.

A maximum speed of 65 mph would save a three-car train, saving roughly \$3.6 million in fleet costs. It would also reduce the estimated 30-min travel time from Norwalk through El Segundo by 2 min. While not technically infeasible, there is no articulated light rail vehicle currently in existence operating at that speed, nor do the new automated systems operate above 55 mph. Vehicle engineers advise that problems may exist with stabilizing an articulated vehicle at 65 mph at truck spacings of about 30 ft. Changes in the truck design, perhaps with some risk, may be necessary.

The vehicle would also need bigger motors with forced-air ventilation, and similar control electronics design changes to handle the increased power rating. Other lower cost changes would also be needed on the vehicle. The estimated increase for these propulsion system changes was calculated to be 4 percent of the vehicle cost, or \$2.5 million for the full fleet. This estimate does not address the possible truck redesign.

Because a higher-speed vehicle draws more power, the capacity of the traction power transformers would also need to be increased, adding up to an estimated 5 percent, or \$900,000, to the cost. (The fact that a three-car train is saved may, however, reduce overall power consumption. This possibility was not pursued in detail.)

Finally, automatic trip stops are required along the tracks when speeds of rail transit vehicles exceed 55 mph. The cost of adding these items was estimated to be \$100,000. By coincidence, the cost savings from reducing the number of rail vehicles if the rail cars had a maximum speed of 65 mph approximates the additional cost to make the remaining vehicles capable of operating at 65 mph. It should be noted, however, that the 7 percent speed increase could have an indeterminate, but positive, effect on revenues.

The second way to increase speed might be to have trains skip certain stations completely by using express trains. To do this in the best manner, properly located bypass tracks would be needed in addition to the usual two tracks serving the station. Unfortunately, there is no room for such bypass tracks. The width that was saved when the busway/high-occupancy vehicle (HOV) facility was changed to rail is now dedicated for carpool lanes. Although full express service is not possible, it is still possible to have certain stations skip-stopped in a modified express service.

In sum, increasing the speed to 65 mph would cut end-to-end travel time by 7 percent, or 2 min, and reduce the fleet size by one train for a savings of $3.6 million. However, it would increase vehicle and traction power costs by $3.5 million and raises concern about the ability of articulated vehicles and trucks to accommodate the high speed.

Increased Frequency with Operator

Another way to increase the quality of service is to reduce the headway between trains so that waiting time is lessened. The present operating concept for the Century-El Segundo line during rush hours (in the year 2000) is to have three-car trains every 6 min, with a total of 11 trains on the line. Instead, two-car trains every 4 min, or one-car trains every 2 min, could be run.

Most new rail transit systems introduce semiautomated operation before sustained 3-min headways are reached. The supposed benefit is operational: more consistent braking and acceleration and tighter schedule adherence (although this is debatable). The problem with semiautomation is that it does not reduce the number of vehicle operators required. The system ends up having to not only maintain a more sophisticated signal system, but also cover higher labor costs. Four-min headways would require 17 operators instead of the 11 needed at 6-min headways; 2-min headways would require 33 operators. The benefits of high-frequency service can best be captured by converting to full automation. In that case, no operators would be needed for any operating plan.

As a point of reference, it would be useful to derive the cost of operating shorter headways with attended trains. We will assume 4-min headways all day with two-car trains in the rush periods, one-car trains off-peak. Evening and weekend operation would be with one-car trains every 8 min. This would be equivalent to service expected of a fully automated system. The result is an increase of 21 vehicle operators and an annual cost increase of $695,500. Semiautomated operation, therefore, cannot be justified.

FINANCIAL BENEFITS OF FULL AUTOMATION

Fully automating the Century Line would mean labor costs could be cut along with the capital cost of building longer platforms needed to accommodate longer, nonautomated trains operating less frequently than the shorter, automated trains would. At the same time, full automation would mean installing an expensive signal and control system. But it also may mean significant ridership gains that could boost farebox revenues without adding to labor costs.

Labor Costs

Table 1 compares the staffing levels of two guideway transit systems that make money or are close to doing so. The first is the automated VAL system developed by Matra in Lille, France. The second is the automated SkyTrain system developed by UTDC in Vancouver, Canada. The two automated systems, although shorter than the Century Line and with rather close station spacings, have attracted over 100,000 riders on a typical day. The high ridership depends a lot on the corridor being served; both cities have relatively dense corridors with good feeder bus services.

The labor productivity of the VAL system is very high, probably as high as any system anywhere. It appears to stem principally from a staffing philosophy that minimizes the number of roving and security staff. (Some functions are contracted out, but not for major areas of work.) The vehicle themselves

TABLE 1 STAFFING LEVELS OF SELECTED AUTOMATED SYSTEMS

System Characteristics	Lille VAL 1987	Vancouver SkyTrain 1987
Line length (mi)	8.5	13.3
Number of stations	18	15
Daily passengers	100,000+	70,000
Annual passengers	27,700,000	21,000,000
Peak hour trains	18	20
Peak hour vehicles (total)	76(108)	80(114)
Number of employees		
Administration	26	22
Operations		
Vehicle operators	0	0
Central	28	26
Roving	20	95[a]
Other	0	3
Maintenance		
Vehicle	31	76
Power and comm.	18	28
Trackway	24	22
Other	12	33
Security	26	0
Total	185	309

[a]Includes security.

also appear to either need less maintenance, or are maintained very efficiently. (For example, the workshop closes down at 5 p.m. weekdays and there is no vehicle or control system maintenance staff on duty during the night shift and on holidays.) The Lille system clearly takes full advantage of the automated concept.

The operation of the Vancouver SkyTrain represents another staffing philosophy employed by automated-guideway transit (AGT) systems. The new London Docklands Light Railway employs this concept as well. In this case, a decision has been made to have approximately one attendant per train throughout the day. These roving rapid transit attendants (RTAs) check fares, provide security, assist patrons, and can operate the train should the automated operation falter. RTAs are paid operator's wages but have a broader job description. The result is a roving force on SkyTrain 2.5 times larger than that of VAL.

Table 2 summarizes the staffing necessary for a combined Long Beach-Los Angeles and Century-El Segundo system with the main yard in Long Beach and a satellite yard near at the western terminus. The left side of the table assumes conventional light rail operation on both lines; the right side assumes the Century-El Segundo line is automated (either AGT or automated LRV). Because of the more sophisticated electronics, it is assumed that with full automation three additional control technicians are needed in the maintenance area.

The number of roving staff varies whether the VAL or the SkyTrain staffing philosophy is adopted. On the one hand, the number of fare inspectors and transit police has been kept to the level of conventional operations. A net labor savings of $1.261 million per year is possible if a VAL staffing philosophy is used. If an RTA is assigned to each train, a net labor savings of $509,000 can be achieved each year. These levels of saving represent, 4.5 percent and 2 percent, respectively, of the total estimated operating and maintenance costs of these two lines.

It should be noted that the shift from a train operator in the cab to an RTA provides both the transit authority and riding public with an employee capable of numerous tasks useful to the user. Because of this—and, perhaps, ironically—automation can provide a more personal touch than typical conventional rail operations.

Capital Costs

Assuming automation is achieved using a standard rail vehicle without either linear induction motor or rubber tire technology, the introduction of automation on the Century-El Segundo Line would be relatively straightforward.

TABLE 2 ANALYSIS OF STAFFING WITH AND WITHOUT AN AUTOMATED CENTURY RAIL LINE

	No. of Employees							
	Manual Operation[a]				Automated Century			
	LB-LA[b]	Century[c]	Central Control	Total	LB-LA[b]	Century[c]	Central Control	Total
Administration	–	–	12	12	–	–	12	12
Operations								
Vehicle operators, etc.	74	44	–	118	74	–	–	74
Central control	–	–	35	35	–	–	35	35
Roving	13	9	–	22	13	9 (35)[d]	–	22 (48)[d]
Other	5	5	–	10	5	5	–	10
Subtotal	92	58	35	185	92	14 (40)[d]	35	141 (167)[d]
Maintenance								
Vehicle	80	25	–	105	70	30	–	100
Power and comm.	31	–	–	31	31	–	–	31
Trackway	17	–	–	17	17	–	–	17
Other	34	6	–	40	34	8	–	42
Subtotal	162	31	–	193	152	38	–	190
Security	45	29	5	79	45	29 (19)[d]	5	79 (69)[d]
Total	299	118	52	469	289	81 (97)[d]	52	422 (438)[d]

[a]Derived from draft O&M plan prepared for LB-LA and Century lines.
[b]Long Beach yard.
[c]El Segundo yard.
[d]Parentheses indicate staffing with train attendant philosophy.

After assessing the cost of a standard wayside-based train control system, it was decided to opt for a moving block system. This lowered the cost estimate by a factor of two. The total cost estimate for the train control system was $21.4 million. A train control system compatible with the cab signal system of the Long Beach-Los Angeles line was estimated to cost $19 million for the Century-El Segundo line; thus the net increase in wayside equipment is $2.4 million.

Costs were not derived for the rubber-tired technology used by the VAL system. Should a new technology be selected, the cost of the guideway could increase significantly. The Matra system in Lille uses a rubber-tired vehicle that needs a fairly complex concrete channel for guidance. The Lille system also uses platform doors (which were not costed here).

It is estimated that the automated operation with short headways could also save the future cost of having to expand the platforms to accommodate four-car trains, an estimated $1 million.

Revenue Implications

The VAL and SkyTrain systems are successful because they have attracted a significant number of users. The more ridership a system attracts, the more revenue is generated at the farebox and the less operating subsidy is required. The capital and labor cost trade-off, reviewed above, is then only half of the picture. As important is the question: Do automated systems—simply because they are automated—attract greater ridership?

This is a very difficult question to answer, although it is a pivotal one. In Los Angeles, patronage models rely on home-based work-trip data that do not reflect other types of trips, such as school, shopping, or recreational trips. Instead, factors are used to increase work trips to daily trips and these factors are derived from existing transit experience; but transit systems do not run frequent off-peak service because of costs or apparent lack of demand.

New automated systems appear to have tapped this latent off-peak demand. In discussions with VAL officials it emerges that while peak hour ridership is slightly higher than expected, the big surge in ridership occurred because of off-peak growth. One reason is the frequent service throughout the day. Attended systems can run frequent trains midday as well, but usually do not because of added labor costs.

Do these same conditions hold for the Century/Coast Line? The Coast Line, in particular, has a diversified land use distribution with major activity centers capable of generating off-peak trips. The Century corridor does not have this land use pattern but does have good north-south feeder bus services along major arterials and a population that is transit-dependent. Experience with buses also shows that only about 30 percent of trips are work-related, a very low percentage. Bus services also have high midday and weekend demand, with much of the recent transit ridership growth occurring during these periods. There appears to be a stronger-than-usual off-peak transit market in Los Angeles. The Century/Coast corridors should be able to support high-frequency, all-day rail transit service. If so, then a high-frequency Century/Coast Line should generate substantially more revenue. This would lower operating subsidies as effectively as would lowering labor costs. Precisely how much is too difficult to say. At an average fare of 50 cents, only 6,000 new daily riders (7.5 percent of expected Century Line patronage) would generate $1 million more in annual revenues.

CHOICE OF VEHICLE, ASSUMING FULL AUTOMATION

Assuming the decision to fully automate has been made, the next decision is whether to stay with a conventional light rail vehicle (LRV) or to procure AGT vehicles. Each offers benefits and drawbacks.

Vehicle Type

AGT vehicles are much smaller than the 90 ft Long Beach-Los Angeles LRV. Typically about 40 ft long, AGT vehicles still cost 60 to 80 percent of what LRVs do. Because of this, assembling a 42-vehicle Century-El Segundo fleet would cost $12.6 million more if AGT vehicles were chosen. Procuring AGT vehicles would also introduce a third vehicle into the Los Angeles rail fleet already using Metro Rail and light rail cars. A new spare parts inventory would be required as would different maintenance equipment, tools, and more training for maintenance staff.

On the positive side, an AGT vehicle would come packaged with its control system, and this package would more than likely be already proven under automated operation. The same cannot be said of LRVs used as automated vehicles. Smaller vehicles would also be run two at a time for capacity reasons. A larger vehicle can be run only as single unit, which might reduce system reliability.

Vehicle Maintenance

If the system's present LRV is used as an automated vehicle, then no change in maintenance strategy is necessary. Anything but light maintenance can be done by taking the LRV to the Long Beach-Los Angeles Line's central yard. If an AGT vehicle is used, the yard near El Segundo might not be adequate. A new yard of larger size might be necessary, but finding such a site would be a difficult task.

The AGT vehicles have at most an emergency panel for manual drive. Thus vehicles needing service could not be driven to the Long Beach-Los Angeles yard where the heavy maintenance work for the fleet is located. They would have to be towed. Their wheel diameters, coupler heights, and design, however, are not compatible with LRVs. Maintenance equipment, such as jacks and lifts, wheel truing machines, and tools, will probably be incompatible as well. From a maintenance standpoint, there is no benefit in having another type of vehicle in the fleet.

On the other hand, suppliers of proprietary vehicles emphasize their elaborate built-in diagnostic systems, which conventional rail vehicles do not have. As a result, maintenance is more preventive with less shop time required. New systems also rely more on component change-out, which lowers shop time.

CONCLUSIONS

Based on this evaluation, the conclusion is that full automation of the Century-El Segundo line may be an attractive option, but only if conventional light rail technology is used that is compatible with the Long Beach-Los Angeles Line. Automation seemed justified because potential labor cost savings and possible higher revenues generated by frequent, all-day service outweighed the one-time extra capital cost. Conventional light rail technology seemed better than proprietary AGT technology for reasons of system compatibility and fleet cost.

In early 1988, LACTC voted to automate the Century-El Segundo Line. It did so with the provision that an LRV be used—a 90-ft articulated vehicle. However, the vehicle is to be modified in several ways. First, third-rail power collection will be used. Second, the vehicle speed is to be increased to 65 mph. Third, the vehicle is to be made lighter by the use of stainless steel or aluminum, rather than the rolled steel of the Long Beach-Los Angeles LRV. All three of these changes were made because the right-of-way is now 100 percent exclusive. The catenary was felt to be unaesthetic; the steel body, useful for ease of collision repair, no longer necessary; and the higher speed primarily the result of the lighter vehicle. The Century-El Segundo Line will open for operation in late 1993.

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Scheduling Techniques for Maximizing Urban Passenger Rail Service While Minimizing Vehicle Requirements

COLIN F. WHEELER

A variety of techniques for maximizing the utilization of rapid transit vehicles exist. The use of one or more of these techniques would be appropriate for operators of light rail, commuter rail, or heavy rail transportation systems attempting to minimize fleet size and by properties faced with a rail car shortage. Methods include the use of fallback scheduling, skip-stop scheduling, zonal scheduling, reverse-direction deadheading, Dutch switching, and shortening headways while operating more low-capacity trains. Examples of agencies currently using each technique are provided.

WITH THE INCREASINGLY HIGH acquisition costs of new rapid transit vehicles and continuing pressure from the federal government to reduce capital and operating expenditures, it is important that operators of urban passenger rail services minimize the size of their rail vehicle fleets. Providing the greatest amount of rail service with the least amount of equipment can be accomplished with various scheduling techniques, whether used as permanent measures or as short-term remedies for dealing with a car shortage caused by an increase in demand beyond existing capacity or a high rate of vehicle malfunction.

Because total vehicle requirements are determined by peak vehicle requirements, most of the following techniques reduce the round-trip cycle times of vehicles on a rail line to a level at which some equipment can be circulated through the line more than once during the peak, thus reducing the number of

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pull-outs required and thereby saving vehicles. This is generally accomplished by shortening each train's recovery time or by reducing the running time along the entire line or a portion of it. The last two techniques in this paper, however, allocate high-capacity trains only to those segments of a line where the capacity is needed (Dutch switching), and only during those times when this greater capacity is absolutely needed (shorter headways plus more low-capacity trains).

FALLBACK SCHEDULING

Fallback, or dropback, scheduling is designed to make intensive use of vehicles. Each train is scheduled for a minimum amount of recovery time. Because operator break time is not only desirable but often mandatory due to labor contracts or local laws, operators are required to back-trade with (or "fall back" to) either their immediate follower or a subsequent vehicle after each trip so that they can take their breaks. Consequently, the number of operators assigned to a line at any one time when fallback scheduling is employed exceeds the number of trains in service on the line.

As an example, consider a hypothetical line on which 10-min headways are operated in both directions with 10-car trains that have a 120-min round-trip running time (excluding layovers). If trains are given layovers of 10 percent of the round-trip running time plus 5 min (a commonly used formula for calculating required operator break time), 14 trains, 14 operators, and 140 cars would be required on the line at any one time. However, if fallback scheduling is used and trains are given only 5-min layovers at each terminal, 13 trains, 14 operators, and only 130 cars would be required.

With fallback scheduling, operator break time is determined by the line's headway in relation to the number of departures operators are required to fall back to (e.g., a 5-min headway would result in a 15-min break if operators were instructed to fall back three trains). Although the back-trading of operators can occur at any point along the line, the time required to change operators dictates that it occur at only one, or both, of the line's terminals rather than at intermediate stations. Although it is generally desirable to schedule operator train assignments in advance, it is sometimes appropriate to instruct operators to join a pool of other operators taking their breaks at relief points. This is particularly true when changes are frequently made to a line's operating schedule by supervisory personnel to match capacity to demand as closely as possible on a day-to-day basis. In such a situation, a supervisor assigns operators to specific departures, and operators do not know in advance which trains they will operate during the course of their shift. To minimize operator overtime, it is important that the supervisors assigning operators to departures be aware of how much time each operator has worked before the end of the shift.

An additional benefit of fallback scheduling is that, by reducing the number of vehicles operating on a line, the likelihood that terminals will be scheduled beyond their capacity is reduced. Not only does fallback scheduling minimize vehicle requirements, larger properties operating long trains with short layovers also use this technique because of the lengthy amount of time it takes for operators to walk from one end of a multicar train to the other.

An inherent disadvantage of fallback scheduling is that, because of reduced vehicle recovery time, it can lead to a reduction in schedule reliability. This method is most successful; therefore, when it is used on lines on which, by virtue of an exclusive right-of-way, transit preferential traffic signals, etc., short layovers will not severely affect the quality of the line's on-time performance. To provide at least a minimal amount of recovery time, most properties currently using the fallback technique schedule their trains for layovers of at least 3 min.

One common way of dealing with the reduced ability to recover from service delays of extended duration created by fallback scheduling is the deployment of strategically located "gap" trains. In the event of a major disruption in service, these trains are dispatched to cover the trip or trips missed by the train caught in the delay. Upon its eventual arrival at one of the terminals from which gap trains are dispatched, the delayed train becomes the new gap train. Although the use of gap trains reduces the amount of vehicle savings that fallback scheduling makes possible, the ability of such trains to minimize the negative impact on schedule reliability justifies their use.

A second disadvantage of fallback scheduling is that it increases labor costs beyond the absolute minimum level that would exist if this technique were not used. A final drawback of fallback scheduling is that some operators who prefer to stay with the same vehicle for most or all of their shift may object to changing trains for each trip.

Fallback scheduling is commonly used on both light rail and heavy rail systems throughout North America. Properties making extensive use of this technique include New York's Metropolitan Transportation Authority (MTA); the Washington (D.C.) Metropolitan Area Transit Authority (WMATA); Pittsburgh's Port Authority of Allegheny County (PAT); San Diego's Metropolitan Transportation Development Board (MTDB); and the Toronto Transit Commission (TTC).

SKIP-STOP SCHEDULING

Unlike fallback scheduling, skip-stop scheduling reduces vehicle cycle times not by shortening layovers but by increasing the speed with which trains operate over a line. Skip-stop scheduling is essentially the overlapping of two or more different versions of limited trains. Trains make different sequences of stops along the same route. By bypassing a portion of a line's stations, total vehicle dwell times can be reduced significantly. To identify the different stop sequences, trains are usually identified as "A" trains, "B" trains, or, sometimes, "C" trains. Most commonly, only "A" and "B" trains are used, in which case each rail station is designated an "A" station, a "B" station, or an "AB" station. "A" and "B" trains are scheduled to alternate with one another, with "A" trains stopping only at "A" and "AB" stations, and "B" trains stopping only at "B" and "AB" stations. Because "A" and "B" trains do not pass each other, they can use the same tracks. Ideally, there should be a high degree of travel between the stations served by each type of train. Although this may be hard to accomplish, origin-destination surveys may aid in determining which stations should be linked together under the same stop category. Common stations, served by both "A" and "B" trains, are usually major focal points of activity, such as timed-transfer centers, major downtown stations, or park-and-ride lots.

The following example illustrates the ability of skip-stop scheduling to save cars. If the running time from one terminal of a line to the other is the same as that used in the example illustrating the use of fallback scheduling (i.e., 60 min when trains stop at all stations), the round-trip running times of local, or all-stop, trains would be 136 min (assuming that trains are given 8-min layovers at each terminal). If peak demand levels are such that 10-car trains operating on 10-min headways are required, 14 trains and 140 cars must be operated. However, if skip-stop scheduling is employed and the running time from one terminal to the other can be reduced to 50 min, the round-trip running time of skip-stopping trains would be 114 min (assuming that trains are given 7-min layovers at each terminal). By operating 5-car trains on 5-min headways (10-min service to each type of station) the operator would be able to provide an amount of capacity equal to that provided by local service only, but would be able to realize a savings of 25 cars (23 trains and 115 cars would be required with the operation of skip-stop service). As this example shows, skip-stop scheduling generally has a greater potential for reducing vehicle requirements than does fallback scheduling.

There are two variations of the skip-stop scheduling technique. Under one variation, "A" trains are scheduled to travel locally from the extremity of a line to a point midway along the line, after which they begin skip-stopping until they reach the line's other terminal (usually a region's central business district). Under this strategy, "B" trains are scheduled to begin service at the point where "A" trains start skip-stopping, and stop at the stations bypassed by "A" trains. Another variation is to schedule both "A" and "B" trains to begin service at the outer terminal of a line and to stop at alternating stations on their way to the other terminal of the line.

Aside from the reduction in vehicle requirements made possible with this technique, the decrease in travel times provided by skip-stop service can be a valuable marketing tool for increasing ridership. One drawback of skip-stop scheduling, however, is that passengers wishing to ride from an "A" station to an "B" station, or vice versa, must change trains at an "AB" station. Another disadvantage is that skip-stop scheduling often leads to a deterioration in the frequency of service provided to stations served by only one type of train. A third drawback is that it results in an inconsistency of service, which can be confusing to passengers. A final disadvantage of this technique is that it can antagonize passengers if they are frequently passed by trains not scheduled to stop at their station. To identify the stop designation of trains, it is imperative that cars display the proper signage, especially on outbound trips.

Although this technique is most commonly used on heavy rail and commuter rail systems, there is no reason that it could not be used on light rail systems as well. The Chicago Transit Authority (CTA) is the major user of skip-stop scheduling in North America. Other users include Boston's Massachusetts Bay Transportation Authority (MBTA) commuter-rail service (the Attleboro Line); Philadelphia's Southeastern Pennsylvania Transportation Authority (SEPTA) (the Market-Frankford subway-elevated line); and New Jersey's NJ Transit (the Morris and Essex line east of Summit, the North Jersey Coast line west of Matawan, and the Boonton line). Skip-stop scheduling was recently reintroduced on the New York MTA's "D" and "Q" lines. Visitors to Expo '86 in Vancouver, British Columbia, will recall that the monorail used at the fair used skip-stop scheduling.

ZONAL SCHEDULING

Zonal scheduling is similar to skip-stop scheduling in that vehicle cycle time is reduced by increasing average train speed. But this technique involves the operation of limited or express service between one terminal of a line and different sections along the line. Rather than operating limited trains over the entire length of a line, as with skip-stop scheduling, trains operate locally within designated zones and then travel express to the major terminal of the line. Because of the ability of zonal scheduling to reduce the travel time between the extremity of a line and the line's major terminal, this technique is best suited to lines on which passenger demand is oriented primarily toward a single station or group of stations instead of being evenly distributed along the line.

Similarly, zonal scheduling is best suited to longer lines on which the operation of local service over the entire length of the line would make for a very slow (and therefore unattractive) trip from one end to the other. This technique is also appropriate on lines on which demand for arrival times in, and departure times from, a specific terminal is heavily peaked. In North America, zonal scheduling is used primarily by operators of commuter rail lines providing long-distance, highly peaked service to and from large cities.

As with skip-stop scheduling, there are a variety of substrategies for zonal scheduling. Under true zonal scheduling, a line is divided into a series of zones and trains are scheduled to operate only between their assigned zones and a common terminal with no intermediate stops. The line is, in effect, segmented into several different services. Although each zone is provided with a high level of service to and from the common terminal, little or no service is provided to and from the other zones on the line. Each zone should be situated so that trains are approximately at their capacity as they pass the zone boundary departing for, or arriving from, the major terminal. Because this strategy involves a great deal of short-lining, train volumes on a line's inner portion(s) are much heavier than they are on its outer portion(s). Examples of this variation include Chicago's Metra commuter rail service (the Chicago-Aurora line operated by the Burlington Northern Railroad); and NJ Transit (the Northeast Corridor service).

Closely related to the previous strategy is a variation of zonal scheduling in which zones are not specifically designated, but long-line express trains are operated in combination with short-line local trains. A drawback of this method is that passengers wishing to travel between a station along the long-line portion of a line and a station along the short-line portion must transfer at a common station served by both local and express trains. Examples of this strategy include Philadelphia's Port Authority Transit Corporation (PATCO) (the Lindenwold line); and Boston's MBTA commuter rail service (the Stoughton and Franklin branches).

Another variation, which differs from the previous two in that short-line trains are not used, operates all trains over the entire length of a line with each train traveling a different distance on an express basis. This strategy is best suited to lines on which there is a large amount of travel between the two terminals and on which demand is sharply peaked in one direction. An example of this variation is California's CalTrain commuter rail service between San Francisco and San Jose.

These three variations of zonal scheduling technique have a number of characteristics in common. First, they each involve the operation of express trains. Whenever express service is operated on a line, there must either be a third track for peak direction express service, or headways must be wide enough to provide a "window" through which express service can operate. The operation of express service works best when separate tracks are available exclusively for express trains. The use of express tracks also maximizes time savings for express trains and thus provides the greatest potential for minimizing vehicle requirements. Obviously, the additional capital cost of laying such tracks must be weighed against the various benefits of doing so (including the ability of express service to attract ridership).

With careful scheduling it is possible, however, to operate express service on lines with passing sidings at appropriate locations along the line. This method can also be employed on lines without separate tracks or passing sidings if headways are long enough and if certain scheduling precautions are taken to prevent slow local trains from getting in the way of fast express trains. When the latter condition applies, express trains should be scheduled during the morning peak to arrive at the line's major terminal just behind local trains and, during the afternoon peak, be scheduled to depart from the line's major terminal just ahead of local trains. This, incidentally, is just the opposite of bus operations in which, to equalize passenger loads, local buses are generally scheduled in the morning to arrive at a line's major terminal just behind express buses and to depart in the afternoon from a line's major terminal just ahead of express buses. Because the ability of express trains to achieve a time savings over local trains is directly related to the amount of time express trains are operating in that capacity, the operation of express and local trains over the same tracks is most successful on relatively short lines.

The scheduling of CalTrain's peninsula service between San Francisco and San Jose provides an example of the scheduling of express and local service over the same tracks. During the morning peak, trains are scheduled to arrive in San Francisco approximately 5 min apart, with the first train having traveled local for most of its trip, and the second having operated express from a station somewhat farther away from San Francisco than the first train. This sequence is continued for three more trains before all-stop service resumes. In the afternoon, trains are scheduled to depart from San Francisco approximately 4 min apart, with the first train traveling express for most of its trip, and the second operating express to a station somewhat closer to San Francisco than the first train. As in the morning, this sequence continues for three more trains before all-stop service resumes. Although an automatic block signaling system is used, the scheduling of express trains in this way helps to spread trains out and thus minimizes the likelihood that one train will overtake another.

Another inherent feature in nearly all variations of zonal scheduling is the use of short-lining. Whenever short-lining is used, the line must have one or more midroute turnbacks, and short-lining trains must be able to remain in a pocket track without fouling the blocks of either of the mainline tracks until the schedule dictates that they are needed for a trip in the return direction.

Although the short-lining of trains can occur at more than one point along a line, the greater the amount of short-lining, the more difficult it is for passengers to travel between a line's inner and outer segments. Consequently, the main drawback of short-lining is that it involves a deterioration in the quantity of service provided to a line's extremity. Another disadvantage of short-lining is that it results in an inconsistency of service, which can be confusing to passengers—especially new users of a system. To prevent passengers wishing to make a long-line trip from boarding a short-line train, outbound trains must display their destinations. To allow passengers to travel between a line's inner and outer segments without having to wait for more than one headway, it is recommended that long-line trains be preceded by no more than one short-line train.

Because the adoption of zonal scheduling can lead to passenger animosity if passengers at inner stations are regularly passed by trains operating express from outer zones, this technique works best on lines on which express trains reach their maximum capacity approximately at the point where they begin operating express (i.e., where passengers at inner stations realize that there is no room for them on board the express trains). As express service is very desirable to most passengers, a side benefit of this method is that its adoption can lead to an increase in patronage along the extremity of a line. As previously mentioned, the major disadvantage with zonal scheduling is that it does not allow passengers to travel between two zones without having to transfer at a common station served by all trains.

REVERSE-DIRECTION DEADHEADING

As with bus operations, one way of reducing the number of required pull-outs is to deadhead equipment back to either the beginning of a line or a point midway along the line. This technique can also be used on rail lines with either passing sidings or, ideally, separate tracks dedicated exclusively to use by express and deadheading trains. Because the deadheading of trains on lines with only passing sidings can be difficult to schedule and can present safety hazards, it is recommended that this technique be employed only when additional tracks are available. Reverse-direction deadheading is particularly appropriate on lines on which demand is strongly peaked in one direction, such as on many commuter rail lines. This technique can also be used, however, on both light rail and heavy rail systems, and is most commonly used in combination with the various forms of zonal scheduling. Although trains do not generate revenue while they are deadheading, this drawback is offset by the fact that their repositioning makes it possible for them to pull one or more additional high-revenue peak-direction trip(s).

A side benefit of reverse-direction deadheading is that by reducing the number of stops and accelerations trains are required to make, power consumption can be lowered somewhat. The main disadvantage with this method is the deterioration in the quantity of reverse-direction service, which discourages much back-haul activity from being made on the line. A second drawback is that it can antagonize passengers wanting to make reverse-direction trips if they are regularly passed by empty trains traveling in the direction they wish to go. A variation of this technique, designed to respond to the previous two disadvantages, is to have deadheading trains travel instead as limited trains, stopping at only the stations with the heaviest demand on their way back to the end of the line.

Examples of properties making use of this technique include Newark's Port Authority Trans-Hudson Corporation (PATH), which deadheads every second train in the reverse-peak direction between the World Trade Center and Newark; NJ Transit, which uses deadheading extensively on its multiple-track lines; Philadelphia's PATCO; and Toronto's GO Transit commuter rail service.

DUTCH SWITCHING

A somewhat obscure technique for minimizing vehicle requirements, Dutch switching is essentially the short-lining of cars rather than trains. At one time Dutch switching was used extensively by operators of interurban rail systems throughout North America. Now used primarily by intercity railroads, this technique (also referred to as car dropping) is designed to match capacity as closely as possible to demand along each segment of a line. Trains originating at a line's major terminal and passing through the peak-load point are composed of enough cars to provide adequate capacity through the portion of the line with the heaviest demand. As trains proceed toward the extremity of the line and demand drops off, cars are detached from each train at appropriate locations and temporarily stored on pocket tracks. These dropped cars are attached shortly thereafter to the front of trains traveling in the opposite direction along the line. Dutch switching is similar to the "changing gauge" practice used in the commercial aviation industry (i.e., multistage flights are scheduled to make one or more changes in aircraft size).

To illustrate the use of Dutch switching, if one portion of a line requires trains with 10-car consists, and the other portion requires trains with 5-car consists, trains passing from the 10-car section to the 5-car section must drop their last 5 cars before proceeding. These dropped cars are then coupled to the front of the next train traveling from the 5-car section into the 10-car section.

The principal advantage of this method is that it provides frequent trains to all sections of a line without requiring heavy use of cars. Dutch switching requires careful scheduling to ensure that the window of time between the dropping and adding of cars is long enough to prevent trains traveling from the heavier demand section into the lighter-demand section from missing their connections due to late arrivals. To allow for the time it takes trains to add and drop cars, it is also important that an adequate amount of dwell time be built into the schedule at the point(s) where Dutch switching occurs.

Because of this required dwell time and the fact that most heavy rail lines operate with headways approaching the amount of time it takes to couple and uncouple cars, this technique is best suited to light rail and commuter rail systems. Dutch switching can be employed anywhere along a line where a pocket track of adequate length is available, and it can, if necessary, be employed at more than one location. Ideally, a third, center track should be available at the point(s) where Dutch switching occurs. It is recommended that a supervisor be stationed at the point(s) where Dutch switching takes place so that he or she can assist in the coupling and uncoupling of cars. To speed operations, it is also recommended that inbound passengers be allowed to board dropped cars prior to the arrival of the next inbound train.

Dutch switching is best suited to longer lines on which long stretches of the line require significantly less capacity than other sections, but over which it is still desirable (e.g., for political reasons) to operate a relatively high level of service. This technique is not to be confused with the practice employed by San Francisco's Municipal Railway (Muni) of dividing multicar trains at a point midway along the line and operating each car to different branches as a separate train. Although similar to Dutch switching, this technique requires additional operators to run the branch-line trains.

Dutch switching is also well suited to lines on which headways cannot be shortened further, meaning that long trains must be operated through those portions of the line with the heaviest demand. Instead of operating long trains along the entire length of the line, train length is reduced at one or more stations along the line. A side benefit of Dutch switching is that, because trains of shorter length (and therefore less weight) are operated over portions of a line, power consumption is lower than it would be if long trains were operated over the entire length of the line. So that passengers will be segregated into the correct cars, it is imperative that all cars in a train, not just the head car, display their destinations. It may also be advisable for operators to announce over the public address system the vehicle numbers or locations of the cars that will be dropped at some point along the line.

Disadvantages of this technique include the difficulty some passengers may have with understanding that although the train they are on will traverse the entire length of the line, the car they are in will not necessarily do so as well. Other disadvantages include a possible increased rate of coupler fatigue as a result of the frequent joining and cutting of trains, and the safety issues involved with the coupling of cars with passengers on board.

A good example of the use of this technique is Chicago's South Shore and South Bend commuter rail line on which trains destined for or arriving from South Bend, Indiana, drop and add cars in Gary and Michigan City. Dutch switching was also used at one time on the 90-mi-long Chicago North Shore and Milwaukee interurban line; cars were dropped from northbound trains and added to southbound trains in Waukegan, Illinois. Variations of this technique were also used in New York and in New Jersey.

SHORTER HEADWAYS PLUS MORE LOW-CAPACITY TRAINS

The technique described in this section is similar to Dutch switching in that it is designed to match train length with demand as closely as possible. Unlike Dutch switching, however, this method involves a temporal, rather than a spatial, matching of capacity to demand. Under this technique, the number of cars on trains passing through the peak-load point during the shoulders of the peak is reduced to an absolute minimum and, to maintain adequate capacity, headways are shortened. High-capacity consists are operated only on those trains passing through the peak-load point in the peak direction at the peak of the peak. For example, rather than operating a line with 11 two-car peak trains (22 peak cars) providing a 7.5-min peak headway, 14 peak trains could be operated. Four of these would be two-car trains scheduled to pass through the peak-load point during the peak of the peak. Ten would be one-car trains scheduled to pass through the peak-load point during the shoulders of the peak. The latter schedule would provide a 5-min peak headway but would require only 18 cars, a savings of four cars.

Because this technique involves the operation of a single headway throughout the peak and the assignment of high-capacity consists only to specific trains, it is most appropriate on lines with sharp peaking characteristics. Although this technique can be attractive to the public because of the increased frequency of service, its main drawback is that it can be expensive to operate because of additional manpower requirements. This may be difficult for an agency to justify, in light of the fact that reduced labor costs are supposed to be one of the main justifications for the construction of a rail line. The increased revenue resulting from the appeal of high-frequency service and the decreased maintenance and power consumption needs resulting from the reduced peak vehicle requirements may act to offset this disadvantage, however.

Although this technique can be used on any type of rail system, it would be inappropriate on a line with a peak demand period of a long duration (i.e., most of the trains on the line pass through the peak-load point during the peak of the peak), and very short lines, where it would be impossible to schedule low-capacity trains to "miss the peak." Although it perhaps goes without saying, if this method is adopted and very short headways are operated, it is important that the line have a very good automatic block signaling/automatic train stop system.

CONCLUDING REMARKS

An additional technique for reducing round-trip vehicle cycle times that has not been addressed because it does not pertain directly to scheduling is that of simply increasing the maximum authorized speed along sections of a line where it is possible to do so without compromising high levels of safety. Segments of a line with an exclusive right-of-way or through which station spacing is long are particularly well suited to this method. Agencies attempting to increase the speed limit along all or a portion of a line should be aware that, in general, the faster trains are expected to operate, the longer the block lengths should be.

Another way of dealing with a car shortage that has not been discussed is that of arbitrarily canceling trains or operating shorter consists on those days when not enough rail vehicles are available. Because both of these practices are likely to elicit a great deal of passenger criticism as a result of missed connections or overcrowded trains, it is recommended that they be avoided if at all possible.

Although the scheduling techniques described in this paper are relatively low-cost ways of dealing with a car shortage problem, other more expensive measures for addressing this problem exist, such as the implementation of a self-service fare collection system and the construction of high-level loading platforms (both of which would increase the speed of operation). Other measures include changing the vehicle seating configurations to increase passenger capacity (an action that would allow fewer vehicles to provide the same capacity as that provided with the old seating configuration), and increasing the peak/off-peak fare differential (an action that would shift some demand away from the peaks, thus enabling peak capacity to be reduced).

Because peak vehicle requirements determine peak spare ratios, it is conceivable that an agency could choose to employ any of the above methods only during the peaks. It is also conceivable that more than one of these methods could be employed at the same time (e.g., zonal scheduling used in combination with reverse-direction deadheading). Although the operation of one or more of these techniques on a routine basis would allow an agency to minimize vehicle acquisition costs and maximize the number of maintenance hours available per rail vehicle, agencies could also choose to implement one or more of these methods on a contingency, as-needed basis, substituting them for the regular rail schedule only on those days when not enough rail cars are available.

Potential Benefits to Transit in Setting Traffic Signals

SAM YAGAR AND BEN HEYDECKER

Although it is common to optimize signal settings for fixed-time operation, this serves neither transit nor private vehicles adequately when their interaction is not considered appropriately in defining the total system. The TRANSYT model claims to account for transit operation along with private vehicles, but there are some potentially fatal flaws in its representation of mixed transit and private operation. However, incorporating additional modeling techniques can lead to more realistic representations. The resultant modeling formulation is applied to a 4-mi streetcar route in central Toronto to estimate an upper bound on the potential savings in streetcar delays due to setting traffic signals to accommodate streetcar operation. This is done by considering the idealized case where dwell times are kept constant at each given stop, varying only from stop to stop, so that a fixed-time traffic network can respond best to the streetcar arrivals. The potential gain may be worthwhile and practical effects, such as varying dwell times, should be incorporated into the modeling procedure.

A NUMBER OF MODELS are available for calculating red-green splits for traffic signals and offsets between the green phases at adjacent intersections. Although each attempts to find a global optimum, the modeling and optimization procedures vary from model to model. TRANSYT (*1*) is the most commonly used model for networks of fixed-time traffic signals. It has been applied and tested many times throughout the world during the past two decades.

Models for optimizing the performance of a fixed-time network of traffic signals, such as TRANSYT, are geared to minimizing aggregated measures

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of vehicle stops and delays, regardless of vehicle occupancy. If a certain type of vehicle, such as a streetcar, has a different speed from other vehicles, it can be given a higher weight in the optimization function using the more recent versions of TRANSYT (2). It would therefore appear on the surface that TRANSYT can give due weight to streetcar speeds in setting signal offsets by playing the benefits to streetcars against losses by private automobiles according to respective weights set by the analyst. For example, these weights might represent vehicle occupancy and operating costs.

Although this is the case when transit runs on exclusive rights-of-way and does not interact with other traffic, except by sharing a common green phase, it does not hold for mixed operation. TRANSYT ignores the fact that streetcars hold up private cars and other traffic when loading passengers. Therefore, it fools itself into thinking that private cars have moved downstream when they are in fact waiting for the streetcar to load. It thus tries to turn signals green too soon, and does not represent either streetcars or private car traffic properly in terms of desired offset between intersections. Other traffic signal models have not attempted to represent streetcars to the extent that TRANSYT has.

A modeling procedure for representing the effects of cars waiting while streetcars load and unload passengers is summarized below. This procedure advocates the use of additional dummy links, whereby the stopped transit vehicle holds up private car traffic in one or more lanes, to provide a more realistic representation of the mixed flow. This brief description is followed by a summary of the application of the procedure to a 4-mi stretch of mixed streetcar and private vehicle operation in downtown Toronto. To model the complex interaction between transit and private automobiles, an initial assumption of fixed transit dwell times at any given stop is made. This allows one to estimate an upper bound on the potential savings in total person delay that can be achieved by considering both public transit and private car traffic when calculating signal timing plans. The value of this potential saving can be compared with the costs of implementation to determine whether a global type of optimum, which considers transit speeds and loading time distributions, is worth pursuing.

MODELING WITH TRANSYT

Figure 1 illustrates how TRANSYT models the flow surrounding an intersection, node 1 in this case. The dashed lines represent the links on which streetcars flow to and from node 1, while the solid lines represent the links on which private cars travel to and from node 1. The common labeling procedure for links is to have the first digit represent the downstream node of the link, while the latter digits represent type and direction of flow. For example,

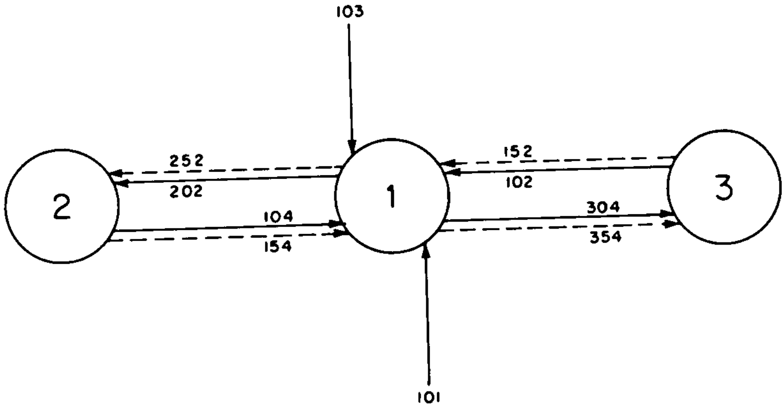

FIGURE 1 Modeling with TRANYST: intersection with shared stop lines eastbound and westbound.

in the parallel links 102 and 152, the high order 1 means into node 1, and the low order 2 means westbound. The middle 0 in 102 represents cars, while the 5 in 152 represents streetcars. Note that the cross-street traffic on links 101 and 103 has no streetcars.

Now, parallel links such as 104 and 154 can operate independently and share a common green phase at node 1. However, TRANSYT allows them to also share common lanes by specifying a "shared stopline" at node 1. However, it does not allow streetcars on link 154 to delay cars on link 104 while loading. Instead it assumes that the private cars pass streetcars loading in an adjacent lane, and effectively go through or over streetcars loading in the same lane. This is unrealistic, as all lanes must stop for loading streetcars unless there is a refuge island, in which case only cars in the shared lane are held up.

MODELING STREETCAR STOPS

Figure 2 represents an expanded model for node 1 that allows for streetcars or buses to hold up all lanes in their direction while they are loading or unloading passengers. The dummy node 21 and the dummy links leading into and out of node 21 are used to represent the delaying effects in the eastbound lanes, i.e., of link 154 on link 104. Similarly, dummy node 41 and its associated dummy links are used to stop all westbound traffic while transit is loading or unloading passengers. Note that all dummy links are coded with the number of the dummy node, whether it is their upstream or downstream node, to avoid confusion with the real links. The last two digits of dummy

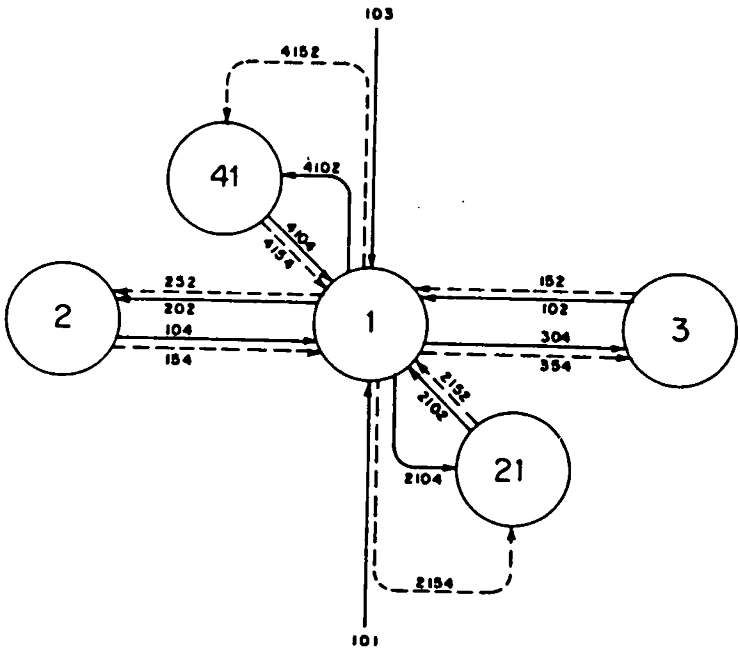

FIGURE 2 Additional dummy links allow full or partial blocking of an approach.

links entering a dummy node represent the direction of flow (e.g., 4102 is for westbound cars into dummy node 41). To draw attention to the fact that dummy links out of a dummy node have that originating dummy node's prefix, the opposite direction is used for the suffix of the dummy return links (such as 4104) for the westbound flow (i.e., as if link 4102 had taken vehicles west from node 1 and link 4104 was bringing them back east to node 1). Although somewhat confusing, this convention was adopted, after the possibilities were considered, for lack of a better one.

The key to making this formulation work is in the parameters specified for the dummy nodes. The purpose of the formulation is to require cars and trucks to wait while streetcars load and unload passengers. The procedure is described below for eastbound traffic.

Links 104 and 154 queue together at a shared stopline for the eastbound green at node 1, having traveled from node 2 at their respective cruise speeds. Cars and trucks from node 104 then take links 2104 and 2102 in sequence to link 304. Because link 2102 has the same green time as link 104, the traffic from link 104 continues through the intersection to link 304 if link 104 has a green indication, unless there is a streetcar loading. Link 2104 is red to this car and truck traffic when, and only when, the streetcar on link 2154 is loading or unloading. This is accomplished by giving link 2154 preemptive priority at node 21 (through the highest possible weight of 9999), the minimum green time of only 1 or 2 sec, and an amber time that reflects the dwell time while the streetcar is loading or unloading.

Although it must be assumed that streetcars arrive at the same time in each cycle in order to model fixed-time transit priority, this is felt to be a reasonable requirement for fixed-time priority to work at all. It will give some upper bound on the potential benefits from fixed-time priority. For, if streetcars cannot arrive at about the same point in the cycle for uncongested operation (a requirement of TRANSYT), then there is no point in presetting signals to accommodate them. Only tests on Queen Street and other networks can provide some indication as to the extent to which fixed-time transit priority can improve overall operation.

After the streetcar has passed through node 21, its travel along link 2152 takes a time equal to its dwell time. If it gets back to node 1 while the signal is still green, it can continue on to node 3 on link 354. Otherwise, it must wait for the next cycle. The entire process at the intersection is realistic, as the streetcar can begin to load or unload into the red period as long as it reaches node 1 from link 154 before the end of green. However, it can only pass through the intersection if the signal is still green when the loading and unloading have finished.

After cars have passed through node 1 the first time (on link 104), they simply continue through node 21 and back to node 1 via links 2104 and 2102, instantaneously if there is no streetcar loading. However, if they are following a streetcar, they must wait on link 2104 until the streetcar has left. The amber time of link 2154 delays them by enough to allow the streetcar to get back to node 1 just ahead of them. If the signal turns red before the streetcar has finished loading, the vehicles are delayed on link 2102 until it turns green again.

Now, because links 104 and 2102 theoretically could both be serving queued cars in parallel, the streetcar's effect on intersection capacity could be lost on link 104. However, the capacity constraint is handled properly on link 2102. Link 2102 accepts vehicles immediately after link 104 when there are no streetcars, because link 2104 would have a red indication and zero travel time. However, when a streetcar stops, cars are queued on link 2104 and cannot reach the intersection, whose capacity goes begging for vehicles stuck behind a streetcar. This use of a series of links to model a streetcar stop breaks down the component delays at an intersection, as an event-oriented simulation would do, and actually allows TRANSYT to directly account for carry-over to the next cycle.

Pedestrian refuge islands have the effect that streetcars hold up only one lane while allowing other lanes of traffic to pass by. This is illustrated in Figure 2 by the addition of through lanes 112, 212, 114, and 314, which are not affected by the dummy transit priority considerations. Links 304 and 314 could each specify links 114 and 2102 as partial upstream links in the TRANSYT-7F input file to allow for lane changing.

APPLICATION TO TORONTO'S QUEEN STREET CORRIDOR

Figure 3 illustrates the Queen Street corridor in Toronto that was studied. Figure 4 illustrates how a portion of the Figure 3 network was modeled for optimization using the TRANSYT-7F (*3*) model, as per the discussion that accompanied Figure 2. Nodes 7 through 12, from Bay Street to Bathurst Street, represent the signalized intersections along Queen Street, and the four links joining each pair of these nodes represent streetcar and private vehicle flows in the eastbound and westbound directions.

For example, between nodes 7 and 8, links 802 and 852 represent private car and streetcar flows westbound, while links 104 and 154 represent their respective eastbound counterparts. Nodes 67 through 75 represent signalized intersections on the parallel one-way westbound arterial Richmond Street, which has no streetcars but requires progression in order to move greater volumes of private vehicles efficiently, as an alternative to Queen Street. The nodes 27 through 32 and 47 through 52 are dummy nodes linked to the other part of the network by dummy links. These dummy nodes and links are employed to represent the delaying effects on private traffic caused by streetcars loading at signalized intersections. The effects of streetcars loading at midblock locations can be captured without the use of these dummy links, and are therefore handled properly by TRANSYT. This is accomplished by giving both streetcars and other traffic travel times that reflect the respective delays caused by the midblock stop. The added complexity of a traffic signal with mixed loadings during green and red signal phases is not present at midblock stops, thus obviating the need for the dummy nodes described in Figure 2 for most midblock stops.

There is an underlying pattern to streetcar arrivals created by upstream signals. This is followed by a given random distribution to represent the loading and unloading of passengers at each streetcar stop. Therefore, the arrivals of streetcars are somewhat, but not totally, predictable. If they arrived at random, there would be no use trying to anticipate them in a network of fixed-time signals. On the other hand, completely deterministic streetcar

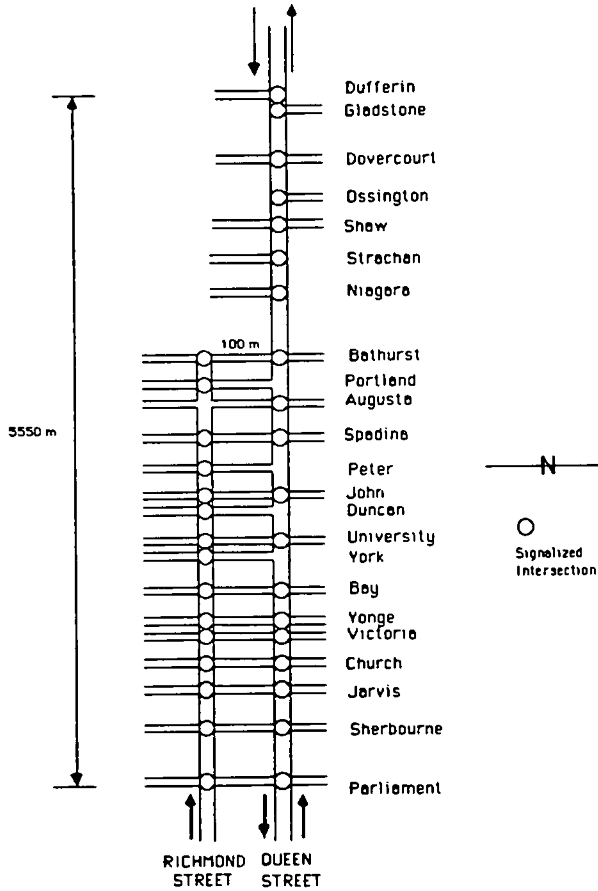

FIGURE 3 Queen Street Corridor.

arrival times present the greatest potential for fixed-time optimization. The actual case is somewhere between these extremes.

This application attempts to estimate an upper bound for the potential savings for the Queen Street network by assuming fixed stop times. If these potential benefits are not significant, then there is no point in considering the rather drastic operating measures, such as limiting the stop times for streetcar stops, that would be required to implement fixed stop times. On the other hand, a somewhat tighter operation might be made more feasible if the estimated potential benefits were too good to ignore. Riders might be willing to accept reasonable cutoff times for loading if fixed stop times could lead to faster streetcar trips and thus reduce their trip time significantly. The long

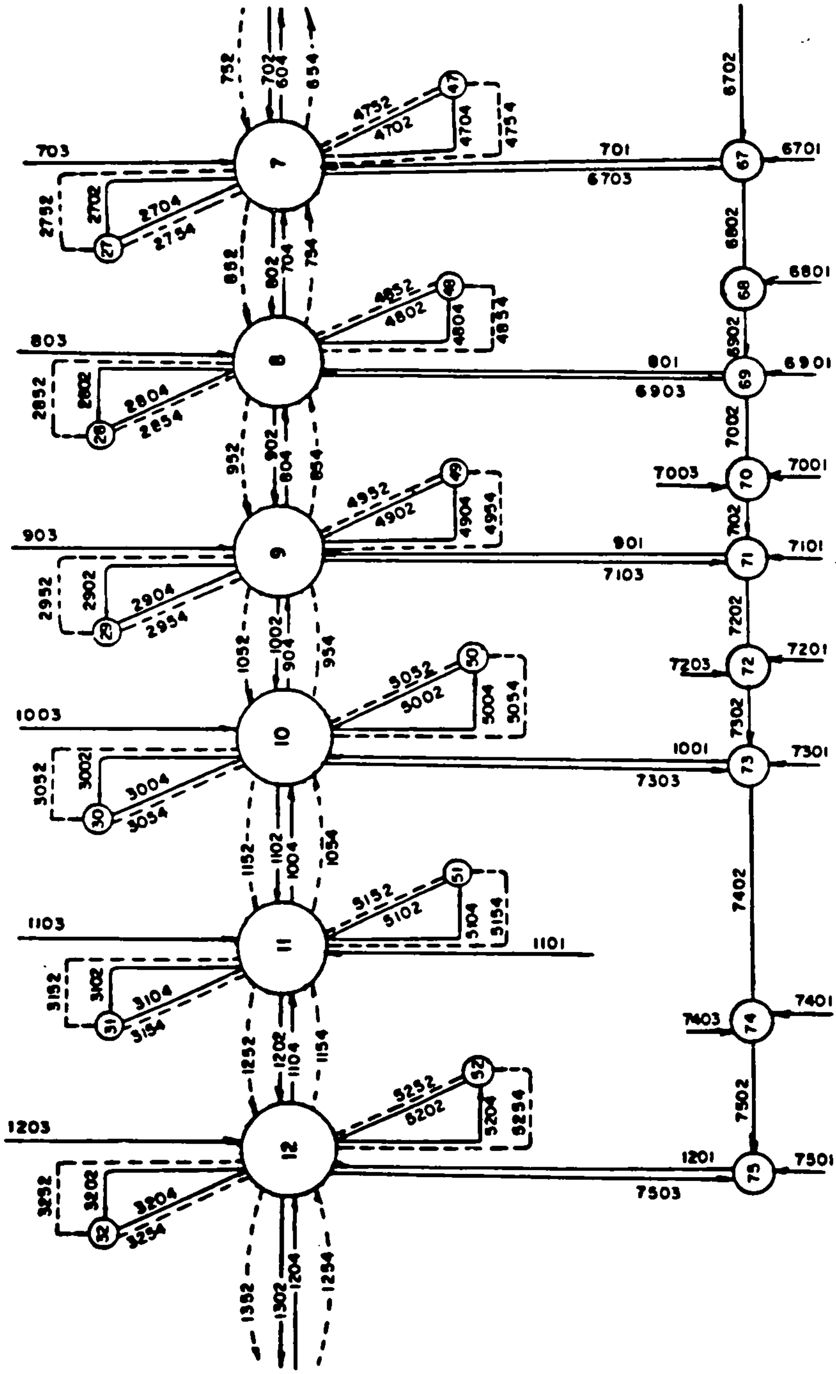

FIGURE 4 Model representation of Bay to Bathurst portion of Queen Street corridor.

loading times are often caused by crush loading, in which it takes much longer to board each incremental individual. Because loading often has to be cut off anyway, it might be advisable to cut it off when it becomes inefficient. This is similar to the gap-out procedure in which the traffic signal green phase is terminated to avoid wasting valuable green time in waiting for stragglers. Also, the operating authority might consider measures to reduce or standardize stop times if the number of streetcars to serve the route could be reduced significantly.

For this test, the representative fixed stop time used for a given stop was the average plus one-half of the standard deviation of actual stop times at that stop. Although cutting off stop times at these values would leave passengers waiting for the next vehicle, the time allowed is more than sufficient on average. The potential benefits corresponding to this type of operation would have to be weighed against added operating costs and delays to those who have to wait for the next streetcar. The potential benefits are estimated below, along with corresponding disadvantages. Implications for partial and practical implementation are then discussed.

RESULTS OF TRANSYT-7F RUNS

The corridor in Figure 3 was studied to estimate delays to streetcars and private traffic under TRANSYT-optimized traffic signal settings for each of the following scenarios:

- Streetcars having nominal weights equivalent to 5 private vehicles, and
- Streetcars having weights equivalent to 100 private vehicles.

Data used for the TRANSYT runs were derived from p.m. peak period operation in Toronto. Table 1 shows estimates of delays to streetcars and private vehicles under the following scenarios:

- Nominal streetcar weight equivalent to 5 private vehicles, and
- High streetcar weight equivalent to 100 private vehicles.

It would appear that the potential benefit from accommodating streetcars in the setting of traffic signal offsets is significant. On the surface, there is a potential saving of up to 25 percent of delays at traffic signals without unduly affecting private traffic. However, there are a number of implications in the requirement for fixed bus stop times, which are discussed below.

DISCUSSION

Although the TRANSYT results represent a specific network with specific data, it is felt that they are typical of what one might expect for other two-way

TABLE 1 PEAK HOUR DELAYS ESTIMATED BY TRANSYT-7F

	Streetcar Weights			
	5	100	Difference	Percent
Streetcar delays (hrs/hr)	14.43	10.76	−3.67	−25
Delays to private vehicles (hrs/hr)	657	656	1	0

mixed streetcar routes having on the order of 20 traffic signals. There was a considerable mix of average stop times and a network of traffic flows in all directions that had to be considered.

We feel that the default level of platoon dispersion contained in TRANSYT-7F is rather high for Toronto, where platoons tend to stay more compact than what was assumed in the calibration of the TRANSYT model. This would therefore justify additional consideration for cars in determining optimal signal offsets, and they might be hurt more when TRANSYT favors streetcars. Therefore the loss of only 1 car hour per hour in Table 1 is probably low, and a more realistic estimate would have to be weighed against gains by streetcars.

This feasibility study considered the afternoon peak period from 4 to 6 p.m. There are presumably some distinct patterns within this 2-hour period, as there would be for the whole day. Consideration of this time-based information would reduce the random variation in stop times while increasing the analytical complexity of the problem. The average stop times presumably could then be reduced at the cost of a more complex operation, which would see these stop times varying according to a predetermined pattern. This study has estimated the potential payback from such efforts to guide future development efforts either toward or away from a policy of tighter schedule adherence combined with setting of fixed-time signals to accommodate streetcar progressions.

After discussion with transit officials, the authors have determined that, although savings of the estimated magnitude are significant, they would not likely justify the drastic operating measures that are required considering present existing operating procedures and technology. However, even a fraction of this gain would be worthwhile if it could be accomplished through merely resetting traffic signal offsets. It is therefore suggested that further alterations to the modeling procedure described in Figure 2 be considered to try to accommodate random stop times within the existing statistical distributions.

CONCLUSIONS

Further work in the modeling of mixed transit and automobile flows is warranted. The potential gains from fixed-time priority to transit are too great to ignore. It would be worthwhile to estimate the trade-offs between delays to streetcars and private vehicles if appropriate high weights could be given to streetcars in setting traffic signals without having to seriously alter existing transit operations. Although streetcar delays due to traffic signals might be reduced by upwards of 25 percent without significant increases in car delays, about half of this potential gain would have to be forfeited in the excess stop times required to make a fixed stop time practical.

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