

Cost-Effective Application of LRT Systems Technology

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The purpose of any transit mode is to provide sufficient speed, comfort, and capacity to attract and serve its ridership. These factors form an equation that must be in equilibrium with the total cost of the mode. For light rail transit (LRT), total cost-effectiveness is bounded by bus service at the lower end and rapid ("heavy") rail service at the upper end of LRT's range of applicability. Subsystem technology must be applied to fit the requirement of total system cost-effectiveness, or the rational equilibrium can be lost.

Applications of technology, for each major subsystem, that may be considered to satisfy the objective equilibrium are discussed and illustrated.

Careful consideration of these factors is necessary because much of LRT's attraction lies in its potential economy compared to rapid rail and automated guideway systems. To take full advantage of LRT's cost saving opportunities, system developers today should specify so-called "service-proven, off-the-shelf" hardware to

- * Ensure availability and price competition during bidding,

- * Avoid engineering and development costs associated with experimental designs, and

- * Minimize the break-in delays, retrofits, and costs often encountered with unproven new equipment.

These are important considerations for rail transit proponents, those in the agencies building and operating LRT as well as those in the supply and

construction industries fabricating equipment and fixed facilities. Most second-tier cities in the 0.5 to 1.5 million population range simply cannot afford the higher cost technologies, and most do not really need them. If the limited funds available for rail construction are to be used most effectively, indeed, if a viable market for suppliers is to remain, it is crucial that system designers avoid the unnecessary solutions of some recent projects the costs of which appear likely to upset the economic equation justifying LRT.

The key question for LRT system planners and designers in any given set of circumstances is, "How much is enough to accommodate initial system demand and to allow for ready future expansion?" LRT operations in different urban settings differ from one another as well as from rapid rail or automated guideways in several respects: service frequency, speed, use of single-track running, and right-of-way type. What are the impacts of location, level of service, and budget on system requirements and designs? How can LRT systems avoid gold-plating and give effective service with low operating and maintenance costs, yet remain buildable within today's tight capital budgets?

Fortunately, LRT subsystem design applications that can serve as standards to achieve these goals have been evolving. At the same time, technology improvements that can improve performance per unit of total cost continue to be made. When proven, these may be considered. Some sample applications

and their advantages are discussed hereafter, as are other possible applications and progress.

LRT RIGHTS-OF-WAY

Buses (and streetcars) running in mixed traffic on local streets are hard pressed to attain average speeds of more than 16 km/hr (10 mph) whereas rapid rail trains operating on fully grade-separated rights-of-way (ROW) typically average 32 km/hr (20 mph) or better. LRT system speeds generally should be between 16 and 40 km/hr (10 and 25 mph).

LRT ROWs largely determine system performance: greater separation of the ROW from conflicts with other traffic leads to higher schedule speed and reliability for any given combination of alignment, station spacing, and vehicle performance. In general, improved performance diverts patronage to transit. This balance is quite explicit and confronts the designer with an important choice in making the trade-off between speed and cost for a given carrying capacity, which must match that portion of projected demand for the transit service that can be expected to be diverted from automobiles because of the greater speed of transit.

The distinguishing feature of LRT is its capability to operate on all three of the basic ROW types: exclusive, semiexclusive, and mixed traffic. Some systems, such as San Francisco's Muni Metro, employ a full variety of ROW types that take advantage of and respond to the geographic and community characteristics of each line segment.

TRACK AND ROADBED

Whereas type of ROW has a primary influence on system speed, installation and maintenance of the trackway is a major factor in total system cost. The use of rail does not automatically invoke main-line railroad standards. LRT track is, in fact, a guideway to accommodate considerably different axle loads and speeds. By tailoring design to real LRT needs instead of irrelevant freight railroad standards, designers can conserve on the costs of building and maintaining LRT trackage.

A wide selection of track materials is available for LRT, including rail, ties, special trackwork, and other track materials (tie plates and pads, joint bars, spikes and clips, rail anchors, and so forth). A substantial amount of development over the years now presents the system designer with several decisions having to do with types of materials, their design, and their application in different ROWs.

Track Structure and ROW Type

On exclusive ROW, an "open" track structure generally is used, with the assembled components (rails, ties, fastenings) exposed and held in place by a bed of ballast, usually crushed stone. In shared ROW, the track structure is embedded in the street paving material. Examples of both track structure types may be found on semiexclusive ROWs; the choice is dependent on local factors such as ROW width, drainage needs, and whether the LRT ROW must be capable of being used by others (e.g., emergency vehicles). If only the needs of LRT are considered, an "open" track structure is preferable wherever feasible because exclusive LRT ROW use is thus ensured.

A Significant Decision: Car Wheel Profile

LRT and streetcar systems operating or under construction in North America generally use either of

two long-established car wheel cross-sectional profiles: street railway or railroad. The profiles specify tread width, tread taper, and flange depth. Street railway wheels have narrower treads, no tread taper, and shallower flanges compared to railroad wheels.

Street railway wheels allow the designer to use a broader range of special trackwork designs, particularly turnouts (track switches) of the "flange bearing" type through which cars are carried on their flange edges instead of their wheel treads. Such designs provide more positive guidance around sharp curves, some as tight as 12-m (40-ft) in radius, found on older street railways.

Because modern light rail vehicle (LRV) designs typically require curve radii of 25 m (82.5 ft) or more, the wheel guidance issue is less critical. This has allowed new systems to use the standard railroad wheel flange profile. The advantages of doing so are operational and economic. Flange bearing frogs and shallow flange points necessarily restrict speed to avoid derailments. Further, street railway-type special work must be fabricated to special order for each installation. However, this hardware, with its grooved flangeways, sometimes is preferred for trackage in streets because it results in fewer holes and slots than does standard railroad special work.

Use of railroad-type track lets designers tap a broader market from which standard materials may be purchased "off-the-shelf" from several suppliers. This enhances competitive bidding prospects. Railroad standard special work also allows higher operating speeds to be achieved than can be achieved with comparable street railway hardware.

Good Drainage is Key

As with any type of engineered civil structure, good drainage is the key to successful design. Grading must be such that water always flows away from the track structure. Underdrains and side drains must be employed wherever required because adequate drainage is by far the most important consideration in achieving a cost-effective track structure. When sufficient drainage channels are not provided, or are not kept clear, silt and other debris foul the roadbed. This causes the roadbed to fail to support the track structure, which then loses its line and surface smoothness, contributing to increased maintenance costs and poor ride quality, which in turn drives down patronage and fares.

Subgrades and Ballast

Subgrades must be properly prepared. Then the designer must decide if subballast is to be used and, if so, the depth of section. Soil type and condition, amount of rainfall, freezing and thawing cycles, and design loads are some of the factors that must be considered.

In Sacramento, relative subgrade compaction of 95 percent for a depth of 6 in. and a width sufficient to accommodate the ballast was specified. Because the area has no ground frost, low average annual rainfall [46 cm (18 in.) per year concentrated in four winter months], and relatively light vehicle axle loads (about 9 metric tons or 10 short tons), no subballast was deemed necessary.

As an added measure of protection for the track structure, Sacramento did specify use of filter fabric. A 227-g (8-oz) blanket 4.3 m (14 ft) wide is being placed under the entire 29.40-km (18.3-mi) main line as well as under all yard and passing tracks.

Double and triple thicknesses were specified where extra protection was deemed necessary. This relatively inexpensive material helps distribute vehicle loads over a greater cross-sectional area of the subgrade, provides added drainage, and prohibits small solid particles ("fines") from contaminating the ballast.

Ballast functions to support and anchor the track structure and to drain moisture from it. Crushed stone is the most common ballast material. Ballast must be hard and angular to enhance its anchoring function, and it must be of proper size. Ballast that is too large will not properly anchor the track; overly fine ballast will become too easily clogged with silt, resulting in poor drainage, damage to the track structure, and resulting extra maintenance costs.

Ballast grades specified for Sacramento are typical: No. 4 for open track (3.8 to 1.9 cm or 1.50 to 0.75 in. in diameter), and No. 5 for trackage in paved streets (2.5 to 1.0 cm or 1.00 to 0.40 in. in diameter). Because of their tendency to deteriorate more rapidly into fines that inhibit drainage, crushed slag and limestone were not permitted.

Crossties

Selection of the crossties that support the rails presents the LRT system designer with another set of choices. Since the dawn of railways, wood has been the most common material for ties, but wood's position has been challenged by concrete ties during the last two decades.

On the West Coast, Douglas fir ties cost about one-third as much initially as concrete. The region's generally mild climate makes possible tie lives of 30 to 40 years. Some wood ties on California railroads are in good condition after more than 50 years of service. Where moisture levels are higher, concrete is better able to compete.

Tie size also must be decided. Typical ties are 2.4 to 2.7 m (8 to 9 ft) long and have cross sections of 15 x 20 or 18 x 23 cm (6 x 8 or 7 x 9 in.). It was determined that for the light LRT axle loads in Sacramento a tie 2.4 m (8 ft) long and 15 x 20 cm (8 x 9 in.) in cross section would be adequate. It is noted that this size Douglas fir tie competes directly with the stud (5 x 10 cm or 2 x 4 in.) used in house construction. Availability and price therefore are tied to the strength of the housing industry.

Additional design decisions related to wood ties are the type of treatment to be applied to control insect attack and whether the ties should be pre-drilled for spiking.

Rail

Rails are the most expensive component of the track system. For LRT, rails as light as 33 to 37 kg per linear meter (80 to 90 lb per linear yard) are structurally adequate. Consideration must be given to other factors, however. Because most LRT systems use overhead wires to distribute traction power, the running rails must act as the negative ground return portion of the circuit. As a result, stray currents become of major concern to all utilities that may have metal pipes near the system. To reduce these concerns as much as possible, a rail section should be used that provides the least electrical resistance within the limits of economic realities; and the number of rail joints should be minimized.

Further considerations are rail availability and compatibility with special trackwork. The 115-lb

"RE" section possesses these desirable features. At present, fewer than five mills produce rails in the United States. Many other countries produce good-quality rail; but federal "Buy America" regulations make it difficult for foreign suppliers to bid successfully on federally funded projects.

All curves of 90-m (300-ft) radius or less should be protected with a guardrail on the inside rail, against which the backside of an LRV's inside wheels can rub when traversing the curve. This protects the outside running rail and wheels from excessive wear. For in-street running, designers must choose between regular "tee" rail and girder rail, which provides a metal flangeway as part of the rail; in effect, an integral guardrail. Although it provides a cleaner design for in-street track, no girder rail is produced regularly in the United States. One U.S. mill will roll girder rail on special order. LRT system developers must evaluate whether the associated delays and extra costs are compatible with their project schedules and budgets or whether their designs can be accommodated to "tee" rail. An offsetting cost factor favoring girder rail is that it reduces the crumbling of adjacent pavement.

Rail metallurgy is another design issue. A Brinell hardness of 269 is adequate for most LRT systems. Because most LRT properties now use continuous welded rail (CWR), it is desirable to have rail rolled and delivered in lengths as long as possible.

A particularly troublesome design issue for LRT systems is the use of existing highway bridges. Many older structures will be incapable of supporting the added live load of LRVs plus track and ballast. If CWR is used, a problem is created in that most highway bridges have joints 60 to 90 m (200 to 300 ft) apart. These joints are designed for substantial movement. Considerable forces result from changes in structure length, whereas the rail length does not change because it is continuous and heavily anchored. A fastener that can withstand these forces must be employed or expensive rail joints must be used. The designer will be required to conduct a thorough study to determine the most economical method to employ in any particular situation.

For the truly economy minded, installation of used rail may be considered. There is an abundance of good, used 115 RE rail around the United States. Tie plates are another item that can be purchased used for about one-fourth the price of new. In Sacramento new rail is being installed on used plates.

Special Trackwork

Special trackwork is the single most difficult track item to procure. In Sacramento, following modern design ideas, it was decided to minimize joints. This design criterion applied to turnouts as well as ordinary track. Specifications were written that require that switch points and frogs be designed to accommodate welding. Because each supplier uses its own welding design, it was necessary to analyze each one during the bidding process to determine product comparability. For new systems, at least 6 months' lead time should be allowed between notice to proceed and first delivery. More time will be needed for in-pavement and other unique design turnouts. To the extent possible, the types of turnouts used should be standardized to obtain shorter delivery times and more competitive bids.

Summary--Track and Roadbed

The desirability of track and roadbed designs that can be built and maintained economically has been

stressed. Good drainage is crucial. Track materials that are readily available can reduce initial costs through more competitive bidding and ongoing upkeep because replacement components will be easier to locate and cheaper to purchase. There are some ROW conditions, particularly in streets and malls, under which unique, special-design trackwork may be unavoidable. However, its use should be limited to achieve overall economy in track and roadbed.

TRACTION POWER

High voltage, obtained at commercial frequency from an electric utility, is transformed and rectified to low voltage at trackside substations. This current is distributed to train pantographs through overhead wires. This interface must be designed to provide continuous sliding contact at any speed and under any climatic conditions.

Voltage

New LRT systems in North America are standardizing on either 600 or 750 volts, direct current (DC). Higher voltages allow the power transmission distance to be increased, thus enabling the use of fewer substations with smaller conductors. However, greater distances between power supply points increase the probability of more trains in any section, thus requiring substations with a higher power rating. Under such conditions, the benefit of reduced conductor size and increased spacing of substations may not be fully realized.

Substations

The alternating current commercial distribution voltage (e.g., 12 kV) from a public power utility is transformed to lower voltage and rectified to direct current in substations placed at intervals along the LRT line.

Some designers of new LRT systems prefer to use an increased number of smaller, more closely spaced substations to improve reliability through redundancy and to lower the costs of substation construction. The cost issue involves a trade-off between substations and the size of the overhead distribution conductors for the proposed LRT service. This trade-off usually is analyzed by specially developed computer programs that consider:

- * Physical and performance data of the proposed LRVs;
- * Track data including speed limits, geographical characteristics, and station stops;
- * Train frequency, dwell times, and method of operation;
- * Availability and reliability of public utility power supply circuits; and
- * Availability of sites for substations.

As examples of the range of possibilities, the new LRT systems in San Diego and Sacramento use 600- and 750-volt (respectively), 1000-kW substations spaced at intervals of between 1 and 2 miles. This is sufficient to support trains of four medium-performance cars running on headways no shorter than 10 min. The reconstructed Shaker Heights LRT lines in Cleveland use two 3000-kW and two 1500-kW substations--just four in all--to supply 10.6 mi of route serving more frequent, though shorter, trains of high-performance cars.

In all cases a properly designed system allows

one or more substations to be out of service yet still permits operation of adequate service during the time required to perform repairs or maintenance. To achieve this capability, it is important to obtain primary power for adjacent substations from separate public utility circuits.

Substations of the size mentioned can be obtained either as modules preassembled in a factory and shipped to sites (such modules require minimal installation) or conventionally built with the heavy equipment installed and connected on site.

Two basic types of overhead wire power distribution systems typically are used for LRT systems: trolley wire and catenary. The former provides a single contact wire over each running track and is used in aesthetically sensitive areas such as downtown locations. It is generally supported electrically by parallel feeders that on modern systems generally are laid underground in conduits and connected to the contact wire approximately every 120 to 150 m (400 to 500 ft).

Catenary systems employ a configuration of one or more messenger wires from which a horizontal contact wire is suspended by means of flexible droppers.

The choice of system often is influenced more by political or aesthetic considerations than by technical design parameters. However, the designer must consider the increased cost of underground ductwork and more closely spaced supporting poles for trolley wire versus demands for unobtrusive aerial wires.

Overhead Contact Wire Hardware

In the free world fewer than 10 firms manufacture the hardware specially designed to support, insulate, and register the wires above the track. These manufacturers have developed and improved their own range of hardware since the early 1900s. It is therefore sensible for the designer to prepare drawings and specifications in a way that permits these manufacturers to respond with time-proven hardware. The designer who wishes to start from first principles, or with only reference to a catalogue, is courting disaster and extra expense. An experienced designer who has intimate knowledge of the hardware ranges can make all the difference between an almost maintenance-free and a troublesome system.

Supporting Systems

The trolley wire or catenary is supported by steel, spun concrete, or wood poles with cross span wires, portals, headspans, or cantilever arms supporting the power distribution wires.

The choice of pole type often is influenced by aesthetic requirements along the route. Steel poles, either tubular or "H" section, are slim and less obtrusive but require concrete foundations to distribute the imposed forces to the ground. Concrete or wooden poles can be directly "planted" and the ground backfilled. These are more tolerant of abuse by maintenance personnel because there is no dramatic change of stress at the top of the foundation.

Cross span wires typically are used with trolley wire construction in downtown areas where overhead "clutter" is to be kept to a minimum.

Cantilever arms are used when poles can be located adjacent to the track. On double-track lines, transit authorities often favor poles located between tracks (the so-called "boulevard" arrangement) with cantilever arms mounted back-to-back on a single pole. This choice of arrangements should be thoroughly investigated because there are a number of advantages and disadvantages to be considered in comparison

with poles located on the outside of the tracks of a double-track line:

- * Fewer poles;
- * Larger diameter poles to absorb greater horizontal wind and radial loads on the wires;
- * Shutdown of both tracks if derailed train destroys pole or poles; and
- * Greater distance between tracks to accommodate center poles, which may increase costs for ROW by more than the amount saved on poles.

A headspan is similar in design to a cross span, except that a supporting cross track messenger is used. Headspan construction is employed in multitrack situations or where obstructions require poles to be situated some distance from the tracks. Alternatives to headspans are portals or bents, often used on main-line railroad electrifications. The use of rigid structures to support the equipment does simplify the wiring, provide a degree of mechanical independence, and from an aesthetic viewpoint generally allow the use of shorter poles than headspans. However, the structures must be painted from time to time, which requires a power shutdown. When headspans or portals are used in like situations the overall cost of the two is similar.

Fixed or Constant-Tensioned Conductors

The size of poles and hardware is directly proportional to the tension of the wires. The tensions, in turn, are determined by the dynamic interface of the LRV pantograph and the catenary configuration to provide optimum current collection under all climatic conditions.

The tension of fixed equipment, which has the wires connected directly to the terminating poles, varies with ambient air temperature and heating due to conductor currents. In winter the tension can be twice that required for ideal current collection by the pantograph. In summer, particularly with a heavily used system, the wires can sag to such an extent that they may come into contact with the vehicles. To allow for these extreme conditions, designers of fixed tension systems must provide larger poles, foundations, and hardware to withstand the high tensions caused by extremely low temperatures. This, of course, increases costs.

To avoid these higher costs, many modern systems are using constant-tensioned equipment, generally referred to as "balance weight" equipment. The individual lengths of contact wires and messengers in this design are limited to approximately 1.6 to 2.0 km (1.00 to 1.25 mi), and the wires are anchored at midpoint to stop movement along the track. They are allowed to expand or contract, according to the temperature, to or from each end, where the tension is maintained by means of a set of weights and pulleys. This has the advantage of limiting the tension to the required design conditions that permit optimal current collection. However, the reduced lengths of wires require overlaps at the changeover points between succeeding lengths of equipment, and these require extra poles.

The designer, therefore, must review local annual temperature variations and, ideally, use a purpose-written computer program to simulate the dynamic system under various temperature conditions before choosing a "fixed tension" or "balance weight" system. In the extreme temperatures of Edmonton, Canada, balance weight equipment was found to be essential. In the warm climates of Florida or Southern California, less expensive fixed-tension equipment might be adequate, depending on forecast vehicle speeds.

Aesthetics

Power distribution system aesthetics is one of the most discussed community concerns during development of an LRT project. Designs must both accommodate system needs and minimize the amount of visible electrification hardware.

The "overhead clutter" issue is of most concern to communities where LRT alignments use exiting streets. New LRT systems in North America have responded to their communities and their project budgets by using trolley wire in streets and catenary construction on private ROW. Wires can be tastefully integrated into the environment. They certainly can be less obtrusive than the power lines that follow nearly every main street in the United States.

A significant issue is the number, height, and size of poles. Longer spacing between poles can be achieved with catenary, up to 60 m (200 ft), than with trolley wire, 30 to 37 m (100 to 120 ft). The new equipment being installed in San Diego's Commercial Street has been designed to provide an extremely low-profile catenary that is expected to be almost as unobtrusive as the trolley equipment previously installed in C Street and 12th Avenue.

In street ROWs the impact of trolley wire's closer pole spacing may be reduced by using the same poles for other functions such as street lighting. Obviously, the additional loads from the overhead equipment will necessitate larger diameter poles than would be needed for just lighting, but the slight increase in overall size does not have significant visual impact.

The desired goal is for the distribution system elements, taken together, to intrude as little as possible on the environment and for capital costs to be kept under control.

Summary--Traction Power

New North American LRT systems are standardizing on 600 or 750 V DC for which substation equipment is readily available. Overhead distribution systems must be tailored to the needs of each project, and this involves choices that must integrate consideration of LRT operational needs, climatic conditions, and environmental aesthetics. Careful design of these systems will result in the least obtrusive distribution system possible that will use equipment proven by years in service and control future maintenance problems and costs.

SIGNALS

Signaling provides block and switch protection and supervision in areas of high-speed operation, block supervision where required for street operation, protection at hazardous grade crossings, and supervised coordination in proximate vehicle traffic schemes to the extent these functions really are required for system performance and safety.

Types of LRT Signal Systems

Six typical LRT signaling designs and their respective effectiveness may be identified:

- * No signaling at all--operation performs as fixed-gateway vehicle in free-wheeled community (i.e., a streetcar) with no resultant service speed improvement over a bus operation;
- * No signaling except preferential at cross traffic--uses signal preemption devices such as

overhead wire contactors, wheel detectors, induction couples, or other nonvital devices to improve speed by virtual elimination of intersection delays;

- * Supervision of track switch facing points (tongue)--uses power on/off switches, time sequencers, induction couples, or other nonvital devices to improve speed by elimination of stops to throw switches; allows trains to keep moving;

- * Block supervision (single track in low-speed operation)--similar to preemptive devices; allows an opposing LRV to advance without incurring schedule delay (system speed is improved) if possible to do so;

- * Block and switch protection--uses basic railroad signaling technology to provide safe operation by assuring clear line within safe stopping distance; allows relatively high maximum operating speeds such as are generally achieved on those portions of the system on semiexclusive or exclusive ROW; and

- * Grade crossing protection--basic railroad signaling technology; gates and flashers provide an actual clear path for LRV movement; eliminates slowdowns to determine if grade crossings are clear; generally recognized as the least hazardous type of crossing protection; allows improved system operating speed.

Signal Technology Application

The designer is obliged to consider the signaling technology available for system operating performance for the least total cost. Within the scope of LRT applications, a well-established catalogue of developed and used (i.e., proven) technology is available:

- * Preemptive controls for traffic coordination, street block control, and like supervisory functions include contact wire-pantograph or wire-trolley shoe switches, or short track circuits.

- * Switch control, a form of localized train identification, includes power "on" sections, local speed monitors over the measured length of track circuits, and frequency selectable induction between fixed and mobile induction coils.

- * Track circuit train detection, which automatically causes vital relay logic to provide block signaling. The same basic technique effects switch control and locking for high-speed operation. Track circuits are the conventional means of controlling gates in all high-speed operations with protected grade crossings (as distinguished from preemptive crossing signaling).

- * Other technologies, such as cab signals, classification yards, automatic train operation, and the like, which generally are not suitable to or required for LRT operation.

Thus signaling design must consider not only what technology is available but also the rational assemblage of equipment for a particular application. Signal systems are characterized by custom development or specification for each transit-operating entity to provide a level of safety that will enable that operation to attain an enhanced commercial speed.

If the development is insufficient, no advantage over unsignaled operation is achieved: and train speeds remain similar to those of streetcars of an earlier era. If signal development is excessive, the extra marginal advantage cannot be used--a condition known as "oversignalization." Both conditions result in added system inefficiencies and unnecessary total costs.

Sacramento--A Case in Point

The design of Sacramento's new LRT system illustrates the use of various signaling techniques to provide the type and degree of protection most appropriate to each segment of the line. In general, the system consists of two radial routes joined for through running in the central business district (CBD). Although through operations are expected to be the rule, patronage projections indicate unbalanced traffic so that in peak service some midline switching will be required. The track plan provides a basic, single-track main line with long sections of double track (about 40 percent of the route length) to enable meets at speed.

The basic operating challenge is to achieve a competitive commercial speed. The CBD streets and inner radials require priority traffic coordination to "keep moving." The outer portions of the radial legs require the best performance of which the trains are capable. Overall, signaling is being installed to accommodate the two types of operation indicated by the previously stated requirements:

- * Street speed running--self-supervised block indicators and traffic signal and lane coordination devices with LRT prioritization at most intersections. Spring-operated track switches will be controlled by the track layout and the system modus operandi.

- * High-speed running--block signaling and end-of-double-track automatic interlocking will be provided. Gate and flasher protection will be installed at all outer area road crossings as well as at blind or hazardous inner area street crossings.

The entire system is to be self-supervised and relies on radio telephone reports for exceptions to expedite remedial actions. Basic system discipline will depend on the LRV operators, a concept compatible with small operations. In Sacramento's case, no more than eight trains will be on the line at any given time.

Other Signaling Applications and Progress

Several other signaling techniques may soon become available to offer further opportunities for LRT cost savings while providing suitable levels of protection and control. Some of these are

- * Block protection by check-in and check-out using simplified track equipment to indicate occupancy of a track block. Such an arrangement avoids the need to "cut" the track into track circuits and to deal with the electrical coordination necessitated by superposition of track circuits on the traction power negative feed. Thus the check-in/check-out scheme enhances the use of continuous welded rail, eliminates the specialized bonding for negative traction power distribution, and removes the possibility of power-induced interference in the signaling controls. It also is compatible with systems operating on relatively long headways as well as those in which there is a need for train detection in long sections of paved trackage. Currently, the system is under development and is to be demonstrated on the San Diego trolley.

- * Where LRT headways and the number of trains operating make simple, two-way radio communication cumbersome, improved self-supervision may be obtained using automatic radio data transmission based on "seeing" passive wayside transponders. These allow automatic monitoring of vehicles on a central dis-

play. Several examples of equipment for this type of monitoring are operating on bus systems.

* In addition to vehicle location monitoring, safe, high-speed, narrow-band inductive transmissions may be used to control track switches from LRV-mounted route request equipment. This is a system used on some European LRT systems and exemplifies the proven, available equipment for this kind of control.

* If an LRT system track plan consists entirely of double-track lines, protection is limited virtually to following movement control based on least allowable close-up headway; grade crossing protection; and, in some cases, track switch control. This indicates a simple block signaling scheme on exclusive ROW portions of the system and possibly no block signaling elsewhere (i.e., operating "on sight" as would a bus in traffic). The further implication of this concept is that full interlocking should not be required for portions of the line operating at street speed nor at terminals in the CBD.

* Automatic train control (ATC) is thought necessary by some for high-speed, close headway operations. The California Public Utilities Commission (PUC) requires ATC where LRV speeds may exceed 55 mph. For overall LRT economy, ridership attractiveness, and safety, the advantages of ATC may be debatable. However, ATC may be required for other than "small" operations that typify some new LRT systems now being built or proposed (i.e., systems with high speeds or close headways, or both).

Summary--Signals

LRT system designers are challenged to find the correct level of signaling for each segment of an LRT line. The different needs for signals indicated by the wide variances in LRT ROW types and operating conditions, coupled with the broad catalogue of proven, available signal equipment, should encourage designers to seek the technical solution that will both respond to conditions and conserve total costs.

FARE COLLECTION

Fares traditionally have been collected on board transit vehicles by operators or fare collectors, or in stations using turnstiles and barriers to separate passengers who have paid from those who have not. The former requires an employee on each vehicle. The latter requires servicing and repairing the fare collection equipment and, most often, involves staff in stations to collect fares or assist riders. These costs, if not carefully controlled, may approach the value of fares collected and thus prevent fares from contributing significantly to meeting overall operating and maintenance costs.

Self-Service, Proof-of-Payment Fare Collection

Modern LRT design and operating practice offer a solution to overcome this problem: self-service, proof-of-payment (SSPOP) fare collection. With SSPOP, passengers buy tickets from vending machines at stations, and these tickets (or season passes or bus transfers) are subject to random inspection by roving staff. In San Diego a fairly high rate of inspection (about 25 percent of all riders) and stiff fines have held evasion to 1 percent or less since the system opened in 1981. SSPOP is not an honor system. Riders caught without tickets are punished. Several benefits accrue from SSPOP. Multicar trains need only one operator. This can yield substantial savings

in operating labor, a factor that was significant in justifying the LRT now under construction in Sacramento. Stations need not be staffed, which is another source of operating savings. Finally, station construction is simplified. As a practical matter, it is virtually impossible to build a secure "fare paid" area into an at-grade, low-platform station.

Fare vendors should be connected via dedicated telephone lines, or other simply accessible channels, to audible alarms in the dispatcher's office to inform staff when break-ins are being attempted. These alarms allow the dispatcher to identify the machine affected so that security personnel can be sent promptly to the scene.

Station Monitoring

A dispatcher can monitor unstaffed station platforms using remote television. A full closed-circuit setup will allow "real-time" monitoring and can provide a photographic record of incidents suitable for court use. For substantially less cost a slow scan TV setup will provide dispatchers with some station monitoring capability but will not yield high enough quality for court exhibits. The principal factor that differentiates the cost of the two types of video monitoring is that the real-time system requires broad band communication (i.e., a circuit over coaxial cable). The slow scan system uses a voice band channel (i.e., one that is provided by telephone line). The slowing down of the intelligence rate is physically necessary for the use of voice band transmission. There also is some room for argument about the effectiveness of an individual's capability to monitor a real-time video screen: it appears to have a mesmerizing effect that is counter to the broad band capability.

Experience with slow scan in San Diego has indicated to Sacramento's designers that it probably has greater utility for prevention (patrons and others see the cameras mounted at the stations) than for providing staff with usable information. As a result station monitoring in Sacramento will consist of train operators and fare inspectors passing by and observing, fare inspectors alighting to change trains, roving security patrols, local police patrols, audible alarms on the fare vendors, and emergency lines to the dispatcher and police on the pay telephones. It is believed that this will suffice in that particular socioeconomic environment. In specifying monitoring programs for other new LRT systems, designers must consider local conditions.

Summary--Fare Collection

Buses and multiple-unit train operations with on-board fare collection are labor intensive per unit passenger. SSPOP fare collection and passenger-operated doors practically reduce the rider-to-employee ratio to a level that is economically feasible for LRT. However, security problems (a subjective issue) are not alleviated by a reduction in staff. Nonetheless, security problems (or concepts) should not generate requirements that offset the advantages presented by SSPOP and passenger-controlled doors.

CONCLUSION

A transit agency that wishes to introduce an LRT system with balanced total costs (capital and operating costs versus LRT performance) and aesthetic

acceptability must make a number of significant decisions in determining the final type of system configurations to be used. These issues are addressed during the feasibility and conceptual engineering stages.

The application of technology for the key LRT fixed systems has been summarized. Factors that affect the cost-effective design and specification of track and roadbed, traction power, signals, and fare collection have been stressed. Each is an important element of the overall LRT system, and each can be designed to enhance system economics by controlling capital and operating costs.

An attempt has also been made to show that these total costs must be balanced against LRT system performance for a given induced ridership. For LRT, the balance is bounded on both the lower and the upper ends of its spectrum. An excursion either way removes the LRT right-to-be.

In today's difficult financial environment for rail transit systems, designers are encouraged to seek out and apply balanced cost solutions such as those described in this paper. Only by planning and building cost-effective systems will most American cities be able to afford the benefits of modern rail transit service.