Light-Rail Transit: Less Can Mean More

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Perhaps the single most appealing and most useful characteristic of light-rail transit (LRT) is its inherent flexibility. Yet engineers and planners have sometimes overlooked the opportunities that accrue from this flexibility and have tried to use LRT to create a system as much like conventional rapid transit as possible at less than rapid transit's cost. This paper explores LRT's flexibility to operate in a conventional rapid transit environment, as well as its ability to not operate in a rapid transit environment. LRT is also at home in contexts more typical of the bus mode. This provides for a broad range of designs between these two extremes and allows optimal design choices to be accommodated. Design options considered in this paper include right-of-way treatment, approaches to fare collection, grade and curvature alignments, high- versus low-level platforms, signal and vehicle-protection requirements, and trade-offs between speed and capacity.

Every conference or meeting concerned with light-rail transit (LRT) in the few years since it once again became respectable seems to have included several papers that attempt to define what this reborn creation—LRT—really is. But between the definitions and the applications, transit professionals have sometimes demonstrated a reluctance to forsake the full-scale rapid transit on which many of us were nurtured in favor of the full potential that LRT actually holds. We have frequently tended to shoot for the moon. Fortunately or unfortunately, that is not where our potential patrons wish to go.

When the early advocates—or more properly the defenders—of LRT sought to retain and improve the remnants of the nation's streetcar empires in the 1950s and 1960s, this attitude was understandable and necessary. It was essential that some of the attributes commonly associated with conventional rapid transit be introduced to upgrade streetcars into what is now known as LRT, but it is equally important to stress today that LRT still stands for "light-rail transit" and not necessarily for "light rapid transit."

It is a difficult distinction to draw; certainly LRT service should be as rapid as possible. But the connotations of what we know as rapid transit go somewhat further. The term "rapid transit" is associated with multiple-unit operation, high-level platforms, and completely grade-separated rights-of-way. Although LRT is flexible enough to operate in such an environment, the point is that LRT is flexible enough not to operate in this environment as well, and that is perhaps what distinguishes it.

LRT is often defined as an intermediate-capacity mode appropriate for 5000 to 20 000 passengers/h. It can be that, but it can offer much more. The flexibility of LRT gives it a chameleonlike ability to blend with its surroundings.

Until the resurgence of interest in LRT, the workhorses of domestic public transit service were two: heavy-rail transit (either commuter rail or conventional rapid transit) and the local-service bus. These modes define two extremes; when either one satisfies local needs and requirements fully and cost-effectively, LRT has relatively little to offer as an alternative.

However, the situations we face as planners are frequently not so simple. In considering transit improvements in an urban corridor or region, particularly on the microlevel of analysis, there will typically be a segment in which the characteristics of high-speed, high-density, grade-separated rapid transit will appear very attractive, while relatively low-density, single-vehicle service is all that is called for elsewhere, and only a minimal capital investment seems justified. Planners, like everyone else, seek the best of both worlds and struggle to avoid such choices.

What are the choices? One is to provide a trunk rapid transit facility with extensive feeder bus networks connecting to it. But LRT offers another alternative when the capacity of full-scale rapid transit is not called for: It can serve both the rapid transit line-haul and local feeder functions with a single vehicle, reduce the need for transfers between modes, and reduce the need for compromise. On a systemic basis, LRT may offer a greater number of network trips with fewer transfers.

Cannot express buses serve that function equally well and at lower cost? Costs of course are deceptive, since capacities differ and a light-rail vehicle (LRV) can be expected to remain serviceable two to three times as long as the average motor coach—20 to 30 years versus 10 to 15 years—and so on. On the basis of amortized costs, buses may remain less expensive, but the gap narrows. Buses remain unable to achieve such benefits of rapid transit trunk-line operation as high capacity and its corollary, high operator productivity; the speed and safety of operation afforded by signaling, automatic speed protection or full automatic train operation; or high-level, and hence high-speed short-dwell (and fully accessible), boarding and alighting of passengers.

Again, for LRT these are design choices rather than design requirements. The options for different levels of service and different levels of cost (1, 2, 3, 4, 5, 6) are shown in Table 1. The potential range of alignments is represented in Figures 1 to 5, which show various portions of San Francisco's Municipal Railway (Muni) system. Other major design options offered by LRT in virtually any permutation that suits a given context include:

1. Four-axle nonarticulated, six-axle two-section articulated, eight-axle three-section articulated, or larger units;
2. Single-unit, coupled-train, or fully train-lined multiple-unit (usually up to four-car) operation;
3. Fully manual operation, manual operation with wayside signaling, manual operation with automatic speed protection, or automatic train operation;
4. On-board, station, or self-service fare collection;
5. High-level or low-level platforms or street loading;
6. Single-ended or bidirectional vehicles; and
7. Urban, interurban, or suburban passenger operation or mixed passenger and railroad freight service.

Almost without exception, these choices are nonbinding: Any combination can be made compatible with almost any other combination elsewhere in an integrated system and usually even elsewhere on a single line. LRT allows high-speed, fully grade-separated facilities to be built and used to advantage where they are desirable, feasible, and affordable. But on other portions of a line, where geography, cost, politics, or service considerations suggest or require a simpler facility, semiexclusive or even mixed-traffic route segments can readily be taken in stride. There is even a location in Cologne in which a short single-track segment is used to advantage to ingeniously provide the simplest of turn-back facilities in the center of a narrow street on a relatively low-density branch. Double-ended cars can stop, wait, and reverse without blocking either traffic stream (Figure 6).

Table 1. Capacities and costs of six options for LRT alignments (1976-1977).

Option	Passengers per Hour (000s)	Cost of Two-Track Right-of-Way ($000 000s/km)	Station Cost ($000 000s)
Exclusive subway right-of-way	20 to 30	12 to 22	5 to 15
Exclusive aerial right-of-way	20 to 30	2.5 to 11	1 to 5
Exclusive grade-separated surface right-of-way	20 to 30	0.6 to 3.1	0.5 to 4.0
Semiexclusive surface right-of-way in median or at side of road with grade crossings	10 to 20	0.4 to 0.6	0.2 to 1.0
Separated but in-street (or mall) surface right-of-way (incremental expense)	10 to 20	0.6 to 0.9	0.2 to 1.0
Mixed-traffic surface operation	5 to 10	0.6	0 to 0.5

Note: 1 km = 0.6 mile.

Figure 1. Exclusive subway right-of-way: Muni's Castro Street Metro Station during tests.

Figure 2. Exclusive surface right-of-way: J Line in Mission Dolores Park.

SIX ASPECTS OF LRT SYSTEM DESIGN

Automated Versus Manual Control

In most contexts, manual operation or manual operation with automatic speed protection can provide the same level of service as more automated systems but at lower capital and maintenance-related labor costs and with less potential for operating problems. The benefits of full automation accrue only when it is applied to a full line, which must then be fully grade separated; this is usually not the case for LRT. Advanced technology is unnecessary unless the benefits can be clearly demonstrated.

Figure 3. Semiexclusive surface right-of-way: Junipero Serra Boulevard on K Line.

Figure 4. Separated in-street surface right-of-way: raised median on Judah Street along N Line.

Figure 5. Mixed-traffic surface operation (with boarding islands): Ocean Avenue on K Line.

Railroad, Rapid Transit, and Streetcar

It seems to be necessary to make a conscious effort to fulfill LRT's potential for maximal service from minimal facilities and to avoid inadvertantly achieving minimal service by overbuilding the facilities. Building to railroad or rapid transit standards of speed, grades, and signals may produce designs geared to needlessly overbuilt rights-of-way and needlessly limited capacity. Safe LRT operation can be maintained with minimal train-protection features. Line-of-sight operation, supplemented by cab or wayside signals, is fully adequate in most situations. For most surface applications, those not familiar with LRT should be encouraged, when considering signaling and vehicle and right-of-way protection, to think more in terms of what bus operation entails than of the usual conventional rapid transit or railroad practice. This concerns not only engineers and planners but also legislators and regulators, who are beginning to express an interest in the establishment of regulations and standards for design, construction, and operation of LRT systems. If LRT's principal utility derives from its flexibility, it is crucial that this flexibility not be needlessly circumscribed by the regulatory pen.

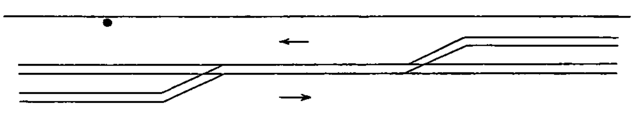
Fare Collection

Off-vehicle, station fare collection is very attractive in concept, but even in a center-city context it may carry with it needlessly high labor costs. For nine stations, Muni will require nearly 70 station agents, as well as supervisory personnel, at a cost that may exceed $1 million/year. If the expected passenger volumes will permit on-vehicle collection, at least at certain hours, a system might be planned to allow an option that does not require fully manned stations at all times. San Francisco's LRVs will not readily accommodate on-board collection at high-level station platforms. The key in this case lies in system planning: Station fare collection costs can be controlled by car design, station design, or fare-structure design.

In high-volume transit operations, boarding time frequently becomes a major source of delay. In San Francisco it was found that on several central-area trunk bus-route segments, boarding accounts for an average of about 14 percent, and sometimes as much as 33 percent, of vehicle running times (7). Typically, the percentages are far more significant than those associated with the traffic delays planners habitually lament. As Table 2 indicates, "general backup" was never either a primary or secondary cause of delay. The usual rail transit solution, based on station fare collection with agent-staffed stations, is excessively labor intensive for most LRT and even some rapid transit applications. One LRT alternative that has emerged from European experience has been the use of prepaid, self-service fares. This system, developed for LRT to permit multi-section high-capacity cars and multiple-unit train operation on surface lines without conductors or operators on each unit, typically requires each passenger to purchase a valid ticket or pass before boarding. All doors are then available for boarding or alighting, even at simple street-level stops, and there are no delays at the fare box. Inspectors check that all passengers have valid tickets or passes on a random basis; fines cover most (or potentially all) of the combined costs of cheating and inspection.

The self-service fare system has proved so successful in reducing costs and increasing labor productivity—not to mention improving service—that it has been applied to conventional buses, rapid transit, and railroad trains as well.

Figure 6. Diagram of single-track segment on Dürener Strasse in Cologne.



Grades and Curvature

Since they had their origins in streetcars, LRT systems in existence, when implementing system improvements, have continued to exploit the fact that there are fewer limitations on gradients and curvatures for LRT than for conventional rapid transit (8, 9). These limitations are typically as shown below (1 m = 3.3 ft):

Type of Vehicle	Maximum Gradient (degrees)	Minimum Radius of Curvature (m)
Boeing Vertol LRV	9.0	13
Conventional rapid transit	5.0	75 to 180

As in the case of other items, these are not rigid limits. Conventional rapid transit can be designed to less demanding standards, and some LRT equipment cannot achieve the limits described above, although historically ordinary streetcars have frequently operated over tighter curves and steeper grades, too. But these figures indicate that LRT can be comfortably designed (and components are readily available) to operate on alignments far less restrictive than those necessary for a conventional rapid transit design.

The grade and curve alignments typical of LRT obviously allow it to be brought to where the customers are far more readily and at far less cost. Conventional rapid

Table 2. Major and secondary causes of delay on selected San Francisco street segments.

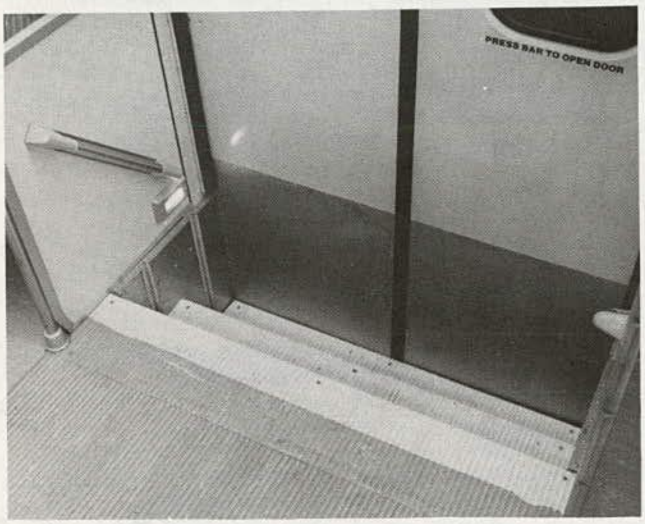
Street	Segment Length (km)	Major Cause of Delay	Percentage of Running Time	Secondary Cause of Delay[a]	Percentage of Running Time
Sacramento	1.16	Loading	33.5	Signal	9.9
Third	0.97	Loading	27.0	Signal	13.9
Columbus	1.77	Loading	24.2	Signal	15.9
Kearny	1.03	Signal	26.0	Loading	24.0
Mission	2.26	Loading	23.0	Signal	11.1
Clay	1.18	Loading	22.4	Signal	15.0
Geary	1.87	Loading	21.6	Signal	10.9
Van Ness	2.89	Loading	20.7	Signal	14.8
Union	1.21	Loading	20.5	Signal	11.1
Carl and Irving	1.77	Loading	16.7	Signal	6.0
Chestnut	0.56	Loading	15.4	—	—
Castro	0.24	Loading	14.8	Signal	9.1
Sutter	0.56	Signal	16.5	Loading	12.3
Post	0.85	Signal	21.8	Loading	11.8
Divisadero	2.26	Loading	10.5	Signal	9.0
Stockton	1.63	Loading	10.4	—	—
Clement	1.16	Loading	7.5	—	—
O'Farrell	1.60	Signal	9.7	Loading	6.3
Polk	1.11	Signal	4.0	Loading	4.0

Note: 1 km = 0.6 mile.

[a] If greater than 5 percent of running time.

Figure 7. High-low step on Boeing Vertol LRV in raised position for high-level platform loading.

Figure 8. High-low step on Boeing Vertol LRV in lowered position for surface operation.

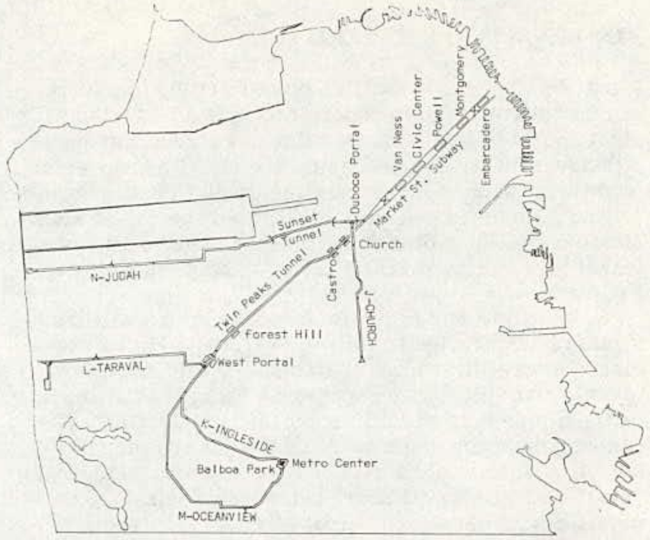


transit usually requires a compromise among fewer feasible alternative alignments; its final design is likely to be more costly than that of LRT, yet it still may not be able to achieve the station designs and locations that are feasible for LRT.

Speed

High operating speed can become an elusive goal. Earlier this year, the Bay Area Rapid Transit system reduced its normal maximum operating speed from 129 to 113 km/h (80 to 70 mph) because it was found that the lower speed would result in improved reliability and performance of traction motors, which in turn would result in a slightly slower but more reliable and less breakdown-prone operation. Reliability is generally more important in attracting and maintaining patronage than speed per se. Also, higher speed operation re-

Figure 9. Muni Metro system's existing and committed facilities (not to scale).



quires greater distance between trains, which in turn can mean lower capacity as measured by the number of trains that can be safely operated past any particular stop. In a system with close stop spacing, even the difference between 56 and 81 km/h (35 and 50 mph) in maximum speed operation can become insignificant. On Muni's system, LRV trains will be able to run from Van Ness Avenue to the Embarcadero Station, including 15-s station stops, in about 4.3 min with a top speed of 81 km/h; at a top speed of 56 km/h, it would take about 5.2 min (10). In percentage terms this would appear to be significant, but it is still only 1 min.

Station Platforms

High-level platforms will speed boarding and be more convenient for passengers but, unless all stops are at high-level platforms, will require a car with a high-low step device, such as that shown in Figures 7 and 8. San Francisco, like a number of West German LRT systems, has opted to accept this combination—high-level subway platforms and low-level surface loading. We do not regret this decision, but it is unfortunate that our car's design does not allow a high-low step to be provided at the front door, which effectively prevents on-board fare collection in the subway. This restriction is vehicle specific, however, and is in no way a general characteristic of LRV design.

Neither Boston, Toronto, nor other present North American LRT operators, however, have chosen to convert their LRT systems to high- or mixed-level boarding, and the Boston and Toronto cars on order do not provide for movable steps. The existing domestic operators, other than Muni, have for the moment at least chosen to avoid the cost of even limited conversion. Although new systems will not be faced with this constraint, high platforms (or a car design that requires off-vehicle fare collection) are still features a new system may not wish to include in an initial operation, e.g., upgrading an existing rail line. Another point to consider is that high-level platforms, particularly for typical American LRT car widths of 2.60 to 2.75 m (8.5 to 9.0 ft), would interfere with normal railroad clearances; mixed passenger and freight use of a rail line would therefore require either low-level platforms or gauntlet or bypass tracks. Again, LRT has the flexibility to allow (but not require) the simpler construction of surface loading, if only initially.

SAN FRANCISCO'S EXPERIENCE

It may be appropriate at this point to cite some further examples from Muni's experience in San Francisco. Muni operates five streetcar lines, currently using Presidents' Conference Committee (PCC) cars, which feed into a Market Street surface trunk line at present. As San Francisco phases into what will be called Muni Metro operation with LRVs, the five surface routes will funnel into a Market Street trunk subway instead (see Figure 9).

Neither now nor in the foreseeable future will the system be converted to full rapid transit. San Francisco, even with federal assistance, could not afford to build five fully grade-separated rapid transit lines on the alignments of all five present lines. The expected passenger volumes could not justify such construction, nor would a reduced system with additional transfers and several short rides be a desirable option in an area as physically small as San Francisco. It may also be crucial that none of these alternatives would be acceptable to San Francisco's residents.

And so, as was illustrated in Figures 1 to 5, San Francisco is now reconstructing its lines for LRT operation in private rights-of-way, in semiexclusive rights-of-way, and in streets for mixed-traffic operation. Is there a price—in longer running times, less reliable schedules, and so forth? Of course there is, but there are also the benefits of better coverage, fewer transfers, more convenient neighborhood access, fewer undesirable impacts as perceived by residents, and a far lower capital cost.

Another example is provided by the subway facilities into which San Francisco's five surface branches will run. This facility has been built to full rapid transit standards. Indeed, it was originally intended to function as such, although now it is extremely unlikely that any such full-scale conversion will ever take place.

High platforms in the subway, unlike those used by similar LRVs in Boston, will make boarding quicker and easier. But they will also increase our labor costs appreciably because of the probable need to provide station agents at all hours of subway operation. This is not to suggest the subway should necessarily have been built with low platforms, which would have allowed front-door entry and on-board fare collection. Once again, however, future systems would do well to ensure that, by virtue of station design, vehicle design, and fare-system design itself, conventional rapid transit fare collection at stations is not required when less costly options available to LRT may be preferable, at least at certain hours.

BUILDING BLOCKS: PRE-METRO AND SEMI-METRO

The varied system components that have been discussed can be assembled to form two generic types of LRT systems. Under one approach, called pre-metro by our European colleagues, LRT represents an incremental strategy in which the ultimate goal is seen as conventional rapid transit and LRT is introduced initially to hold down investment until full rapid transit capabilities are actually required. Two examples of pre-metro systems are the Brussels and the German Rhein-Ruhr systems; the closest domestic example may be the Ashmont-Mattapan portion of Boston's Red Line. The other approach is to build LRT simply as LRT, without viewing upgrading to full metro rapid transit standards as an ultimate goal at all. In Europe the term semi-metro is used to describe such a system.

In practice, planners have sometimes preached the latter approach but followed the former. Needlessly designing to pre-metro standards can be both extremely wasteful and limiting.

It should be noted that even some of the European pre-metro systems are having second thoughts as to the necessity for that approach. With the successful development of several designs of high-low step devices (which allow LRT vehicles to use high-level platforms in a subway) and similar features, there is no need for a clean break between LRT and full metro status. Instead, lines can be improved and upgraded on a systemwide incremental basis, with no need to focus on a single line to elevate it from pre-metro status. Brussels, the best known example of a pre-metro operation, built a first line it intended to later upgrade from pre-metro low platforms to a high-platform metro line. Although this is being completed, subsequent lines will probably follow a semi-metro design with incremental upgrading. Similarly, the Rhein-Ruhr system is being established as a high-grade LRT system, and the original concept of formal upgrading to conventional rapid transit will probably be abandoned. Other systems that initially considered a pre-metro or metro orientation and switched to a commitment to simply high-quality LRT include Hannover and, for that matter, Muni.

CONCLUDING COMMENT

LRT can offer solutions for many of our cities' transit needs. When considering LRT, planners need to examine both ends of the LRT spectrum. The point is that less can mean more, that LRT offers low-capital and low-operating-cost choices, and that it is frequently in scaling down that the opportunities offered by LRT are found.

LRT is attractive because it is a workable, flexible, proven system. New technology and sophistication are not ends in themselves. The goal is simply good, reliable, affordable transit service, and LRT can help provide it.

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Effect of Varying Light-Rail Design Standards

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Light-rail transit (LRT) is a flexible transit mode that can be implemented in a variety of ways. This complicates the task of comparing it with other modes when carrying out the alternatives analysis required by the Urban Mass Transportation Administration to secure federal funding for fixed-guideway transit projects. A recent study for Santa Clara County, California, dealt with this problem by evaluating four possible variations in LRT design standards. This paper draws on the results of that study. It features a description of the study area and site conditions, a definition of the four LRT design standards considered, analysis of the different capital costs associated with each design standard, a discussion of the range of estimates of expected patronage, and a review of the resulting operating requirements and costs. The paper then presents a detailed comparison of the cumulative impact of these design differences on the cost-effectiveness measures for the bus alternatives that were also analyzed in the Santa Clara County study. It was found that, while capital costs for LRT can vary significantly according to the assumed design standard, the cost-effectiveness is primarily dependent on other factors. It is therefore concluded that alternatives analysis requires the study of only one LRT design standard to establish the relative advantages and disadvantages of transit mode alternatives for a given metropolitan area.

Santa Clara County is a dynamic urban area located at the southern end of San Francisco Bay. Once known for its famous fruit orchards, today the county is one of the world's foremost centers of advanced technology. As a result of expected continued growth in the computer, laser, electronics, and space satellite industries, Santa Clara County is projected to grow to about 1 500 000 people and 725 000 jobs by 1990, the design year for which the current transportation studies are being undertaken. The urbanized area of the county encompasses some 712 km^2 (275 $miles^2$), most of which are contained in a broad, flat valley with relatively few topographical restrictions.

The county developed very rapidly in the years following World War II and followed a leap-frog pattern of single-family subdivision development that was fostered by an abundant supply of cheap land and an ever-expanding highway system. No strong downtown area exists today, but the largest city, San Jose, has a population of almost 600 000. Commerce and industry developed principally in a linear form along the main-line railroad and freeway that connect San Jose with San Francisco, 80 km (50 miles) to the north.

The county's existing transportation system consists of an excellent system of freeways, expressways, and arterial streets on which more than 800 000 motor vehicles operate, a fledgling transit system consisting of 234 buses, and a commuter railroad line to San Francisco. Plans and funding exist to expand the transit system to 516 buses by 1980, and recent studies have recommended the upgrading and expansion of the service offered by the commuter railroad line.

The county has adopted a long-range goal of serving 30 percent of the region's daily trips by public transportation (1). Seeking to move toward this goal, the Santa Clara County Transit District in 1976 undertook a study of the engineering and economic feasibility of implementing a light-rail transit (LRT) system within five designated study corridors representative of typical conditions encountered in Santa Clara County. In addition, an alternatives analysis was undertaken as part of this study; it included consideration of a number of different bus alternatives (2).

The five corridors designated for study by the county totaled 56 km (35 miles) in length. They were selected for a variety of reasons, including ready availability of right-of-way, the need to provide service to portions of the county that lacked major highway links, and expected relief of traffic congestion. The right-of-way conditions encountered in these corridors generally fell into three major categories that had distinctly different design conditions. The first type of right-of-way consisted of land that was originally purchased for major freeway facilities that may never be built. These rights-of-way are quite wide; they vary from 46 to 76 m (150 to 250 ft) in width. The second category involved the use of excess land adjacent to existing rail lines. These rights-of-way were generally narrow—23 to 30 m (75 to 100 ft)—and had a single freight track down the center of the right-of-way. The third right-of-way category involved the use of the medians of arterial streets. These median strips either already exist or could be readily created by reconstruction and widening of the streets. Many arterial streets in Santa Clara County have sufficiently wide rights-of-way to permit a raised median of 7.6 to 9.1 m (25 to 30 ft) for two LRT tracks. In most cases, however, this would also require closing a number of minor cross streets and eliminating most left-turn lanes, which would affect local traffic circulation.

In order to minimize the capital cost, as well as for other considerations, it was decided that the study should focus principally on at-grade construction, with no underground facilities at all; aerial construction would be used only where it would be clearly advantageous to do so.

DESIGN STANDARDS CONSIDERED

The first LRT design standard to be considered was based on a review of modern European LRT design practices. It was termed the base-case design alternative and represents a workable solution that could be implemented with a high degree of safety. It may not, however, be completely in conformance with the existing regulations of the California Public Utilities Commission (PUC) and is not completely consistent with the stated requirements