CHAPTER 3

APPLICATION CONSIDERATIONS

There are several significant issues that North American LRT systems should examine when considering low-floor light rail vehicles (LF-LRVs). This chapter introduces these applicability issues as a precursor to the categorization of the North American LRT systems (Chapter 4) and the application assessment framework (Chapter 5), where the issues are more fully developed.

The applicability issues fall into three broad categories:

- **Dimensional Compatibility.** Will the proposed LF-LRV physically fit in an existing infrastructure? What modifications will be required to the existing infrastructure, the vehicle, or both? A new LRT system will probably be free of such physical constraints; nevertheless, the factors discussed in this area should help LRT system planners understand the issues related to integrating LF-LRVs with a future system.
- **Operating Issues.** What are the benefits and disadvantages that LF-LRVs will bring to an existing or planned LRT system (as viewed from an operator's perspective)?
- **Compliance with North American Specifications.** What are the factors unique to North America that will impose requirements that European LF-LRVs may not have been designed to meet?

DIMENSIONAL COMPATIBILITY

The critical factors in assessing dimensional compatibility are concerned with the physical interfaces between a particular vehicle design and an existing or proposed new LRT system infrastructure and include the following:

- Vehicle/station platform interface;
- Vehicle and train length;
- Maintenance facility and equipment interfaces;
- Clearance; and
- Ability to negotiate curves.

Each critical application factor in this category is discussed in the following sections.

Vehicle/Station Platform Interface

There are three areas discussed under vehicle/station platform interface—high-platform interface, low-platform interface, and street-level boarding.

High-Platform Interface. A vehicle with all low-floor entrances cannot be used at stations with high platforms. The only way that a LF-LRV can be used on routes with high platforms is to build the vehicle with at least one high-floor door and entrance. This restriction clearly rules out the use of Category-3 vehicles (100% LF-LRVs).

Low-Platform Interface. Although LF-LRVs can be boarded from TOR level by most passengers, the entrance floors are still high enough to preclude unassisted boarding by persons using wheelchairs or other mobility devices and to make boarding difficult for others with mobility problems. In order to solve this interface problem and obtain the maximum benefits in terms of reduced boarding and alighting times, it has become standard practice to build a low platform or raised curb at station stops whenever possible.

The most efficient design (from the point of view of entry/egress) can be achieved if the low platform is at the same level as the vehicle floor. However, the following potential interface problems and requirements must be addressed:

- Existing high-floor LRVs may be required to stop at the same station, in which case the platform height should ideally be below the level of the bottom step of the conventional vehicle.
- If the conventional high-floor LRVs have outward folding passenger doors, the platform must be below the bottom edge of the doors, otherwise the doors cannot open.
- The door threshold height will vary because of
  - — Suspension deflection under fluctuating passenger load;
  - — Leveling control tolerance or malfunction;
  - — Emergency operation with failed springs;
  - — Uncompensated wheel and rail wear; and
  - — Vehicle manufacturing tolerances.

The allowances recommended by the German Association of Public Transport Operators (VDV) for each of these movements are shown in Table 9. The VDV recommends that the platform should nominally be designed to be 50 mm (2 in) below the door entrance threshold, when the vehicle is at tare weight.

The ADA imposes a stringent requirement of no more than a ±16-mm (0.625-in) height mismatch between the entrance threshold and platform (Figure 72). This makes it extremely likely that some form of floor-height control

TABLE 9 VDV-recommended vertical and horizontal tolerances and suspension movements

	Vertical Tolerances and Suspension Movements	
	mm	in
Primary suspension deflection	10	0 39
Uncompensated wheel wear	10	0 39
Rail wear	15	0 59
Vehicle manufacturing tolerance	5	0 20
Platform build tolerance	10	0 39
Total Vertical Level Difference	50	1.97
Additional allowance for emergency operation with failed secondary suspension	30	1 18
TOTAL WORST CASE	80	3.15

Note: VDV recommends that platforms should be 50 mm (2 in) below the threshold level of an empty vehicle to allow for these tolerances and movements

	Horizontal Tolerances and Suspension Movements	
	mm	in
Flangeway clearance	5 0	0.20
Wheel flange wear	10 0	0 39
Rail head (gauge side) wear	10 0	0 39
Track alignment error	5 0	0 20
Primary suspension deflection	2 5	0 10
Secondary suspension deflection	10 0	0 39
Vehicle manufacturing tolerance	5 0	0 20
Car yaw relative to platform	35 0	1 38
Platform build tolerance	5.0	0.20
TOTAL LATERAL GAP	87.5	3.44

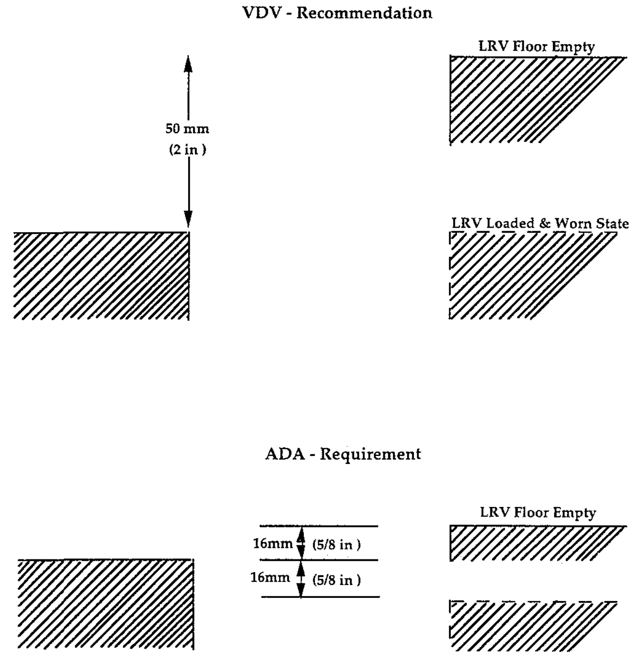

Figure 72. Vehicle/platform interface.

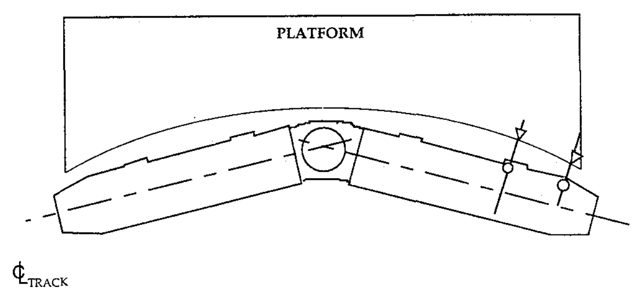

Figure 73. Stations on curved track/platform interface.

system, such as automatic load leveling, will be needed to compensate for deflections in the suspension system. Platform construction tolerances will exacerbate the height mismatch.

- Stations located on curved track may pose an additional problem because the carbody will be parallel to a chord line connecting the running gear (Figure 73). Therefore, a significant lateral gap may exist between the entrance threshold and the low platform. The gap must be limited to 76 mm (3 in) to comply with the ADA.

Some vehicle/platform interface problems can be solved by providing the LF-LRV with a bridgeplate or ramp at the entrances intended for wheelchair boarding. A variety of solutions have been developed that use powered or manually deployed mechanisms.

Street-Level Boarding. In the case where vehicles run in the outer lanes on city streets and it is not practical to have platforms of any height, the only way to provide access to persons with disabilities is by means of a vehicle-borne lift or telescoping ramp. Unfortunately, the deployment time of these devices is currently almost the same as for a wheelchair lift on a high-floor LRV.

Vehicle and Train Length

LF-LRVs can be designed and built to almost any length, depending on required capacity and infrastructure constraints. Category-1 vehicles are usually longer, in the range of 25.4 m (83 ft 4 in) to 39.15 m (128 ft 5 in). If they are created from a six-axle conventional LRV (by adding a low-floor center section), the original length will typically increase by at least 6 m (20 ft). If LF-LRVs are longer than the LRT system was originally designed for, the following will need to be considered:

- Stations will need to be modified to increase the length of platforms, rain shelters, etc.
- Signs and signals will need to be relocated.
- Stations will need to be moved away from street intersections to avoid blocking them.

Another consideration is whether the new LF-LRVs will be coupled with existing conventional LRVs of a different length. This is operationally undesirable because the train may enter the station with either the short or the long car leading, necessitating changes to wayside equipment and two sets of berthing indicators on the wayside. These may confuse drivers, and will cost more. Both MBTA and TRI-MET have specified LF-LRVs that are the same length as their existing vehicles in order to avoid problems like these.

Maintenance Facility and Equipment Interfaces

A third issue regarding dimensional compatibility is whether the vehicle will fit in maintenance workshops, the car wash facility, storage tracks, and paint booths. In addition, vehicle length must be compatible with equipment such as floor hoists (the corresponding underframe jacking pads must also match) and underfloor wheel truing lathes.

These factors will favor selecting a vehicle that is approximately the same length as the existing maintenance facilities were originally designed to accommodate. However, some modifications to shop equipment may still be required. Category 2- and Category-3 vehicles have predominantly roof-mounted equipment. Therefore, if Category-2 and Category-3 LF-LRVs are considered, modifications will be needed to install secure, roof-level servicing platforms and overhead lifting cranes (if they do not already exist). The approach that European LRT systems have taken was discussed in Chapter 2. TRI-MET has decided to build an entirely new maintenance facility to service its new LF-LRVs.

Clearance

The application of any rail vehicle to an existing infrastructure requires careful study to ensure that it will not encroach on the specified dynamic outline, under both normal and emergency operating conditions. Similarly, the clearance between the running gear and the vehicle underbody must also be ensured. LF-LRVs present some concern because the undercar space is smaller, however

- In most cases, the low floor is at approximately the same height as the bottom step of a conventional high-floor LRV.
- The low gangway takes up space normally occupied by the underframe-mounted equipment in conventional high-floor LRVs.

Nevertheless, it is essential to verify that clearance is adequate on the particular track geometry of the proposed application, taking into account the following:

- Small radius vertical curves combined with a large truck center distance (or single wheelset spacing) may significantly diminish the undercar clearance. This may be particularly problematic on designs like the Sheffield and Freiburg GT8D LF-LRVs that have low-floor outer body sections.
- Category-3 LF-LRVs (such as the AEG[MAN] GT6N/8N and Duewag R3.1), which are carried on a single truck in the center of each body section, have large overhangs and will require greater clearance at the entry to and exit from horizontal curves. The overhang may cause even greater difficulties on reverse curves.
- Operation of the ultra low-floor vehicles (such as the SGP ULF 197) in cities that get substantial amounts of snow may require the tracks to be plowed before service starts. This was found to be necessary in Vienna.
- The clearance between the overhead catenary and the roof, especially in maintenance shops, may have to be increased to permit removal and installation of roof-mounted equipment.
- Traversing vertical curves will cause trucks and their wheels to pitch up relative to the carbody, therefore, four-wheel trucks require more underfloor clearance than single wheelsets.

Ability to Negotiate Curves (Curving Ability)

According to the published data collected during this research, all three categories of LF-LRVs contain vehicles that can negotiate horizontal curves down to a 20-m (66-ft) radius and this can be achieved by most types of running gear. The curving ability of LF-LRVs appears to be as good or better than most conventional LRVs. Category-1 LF-LRVs, which are defined as having conventional motored and trailer trucks, are generally less capable than Category-2 and Category-3 vehicles in this context.

In fact, it will probably be possible to modify most Category-2 and Category-3 vehicles to enable them to traverse tight curves. An issue to be considered is which design can do this with the least wheel and rail wear and noise. In theory, the best performance should be obtained from self-steering or force-steered running gear, but there are insufficient data to quantify the benefit.

Small radius reverse curves, with very short or no tangent sections in between (such as on the MBTA's Green Line), will require very careful analysis to determine whether certain types of LF-LRVs can negotiate them. This is especially true for the AEG (MAN) GT6N/8N (Bremen and Munich) and the Duewag R3.1 (Frankfurt) type vehicles. These vehicles have a single truck in the middle of each carbody section and floating articulations. The yaw angle of the truck, with respect to the carbody and between adjacent body sections, may be exaggerated on such severe reverse curve geometry. Moreover, the GT6N/8N accommodates truck yaw by virtue of the shearing flexibility of the air springs, which may be insufficient for the extreme movements resulting in such circumstances.

OPERATING ISSUES

There are six critical operating issues that need to be considered:

- ADA compliance (for agencies in the United States),
- Boarding and alighting times,
- Mixed-fleet operation,
- Fare collection,
- Performance, and
- Maintenance.

ADA Compliance

Public Law 101-366 (July 26, 1990), the Americans with Disabilities Act of 1990 (ADA), is a major institutional factor in the United States. It imposes particular demands on the operation of light rail vehicles. The following sections are excerpts from Title II, Part 1 of the Act.

Section 222. PUBLIC ENTITIES OPERATING FIXED ROUTE SYSTEMS.

(a) Purchase and Lease of New Vehicles.—It shall be considered discrimination for purposes of section 202 of this Act and section 504 of the Rehabilitation Act of 1973 (29 U.S.C. 794) for a public entity which operates a fixed route system to purchase or lease a new bus, a new rapid rail vehicle, a new light rail vehicle, or any other new vehicle to be used on such system, if the solicitation of such purchase or lease is made after the 30th day following the effective date of this subsection and if such bus, rail vehicle, or other vehicle is not readily accessible to and usable by individuals with disabilities, including individuals who use wheelchairs.

(b) Purchase and Lease of Used Vehicles.—Subject to subsection (c)(1), it shall be considered discrimination for purposes of section 202 of this Act and section 504 of the Rehabilitation Act of 1973 (29 U.S.C. 794) for a public entity which operates a fixed route system to purchase or lease, after the 30th day following the effective date of this subsection, a used vehicle for use on such system unless such entity makes demonstrated good faith efforts to purchase or lease a used vehicle for use on such system that is readily accessible to and usable by individuals with disabilities, including individuals who use wheelchairs.

(c) Remanufactured Vehicles. —

(1) GENERAL RULE.— Except as provided in paragraph (2), it shall be considered discrimination for purposes of section 202 of this Act and section 504 of the Rehabilitation Act of 1973 (29 U.S.C. 794) for a public entity which operates a fixed route system -

(A) to remanufacture a vehicle for use on such system so as to extend its usable life for 5 years or more, which remanufacture begins (or for which the solicitation is made) after the 30th day following the effective date of this subsection; or

(B) to purchase or lease for use on such system a remanufactured vehicle which has been remanufactured so as to extend its useful life for 5 years or more, which purchase or lease occurs after such 30th day and during the period in which the usable life is extended; unless, after remanufacture, the vehicle is, to the maximum extent feasible, readily accessible to and usable by individuals with disabilities, including individuals who use wheelchairs.

Section 228. PUBLIC TRANSPORTATION PROGRAMS AND ACTIVITIES IN EXISTING FACILITIES AND ONE CAR PER TRAIN RULE.

(b) One Car Per Train Rule. —

(1) GENERAL RULE.—Subject to paragraph (2), with respect to 2 or more vehicles operated as a train by a light or rapid rail system, for purposes of section 202 of this Act and section 504 of the Rehabilitation Act of 1973 (29 U.S.C. 794), it shall be considered discrimination for a public entity to fail to have at least 1 vehicle per train that is accessible to individuals with disabilities, including individuals who utilize wheelchairs, as soon as practicable but in no event later than the last day of the 5-year period beginning on the effective date of this section.

[The reader is directed to the Federal Register, Part IV Department of Transportation, 49 CFR Part 37 for discussions and interpretation regarding ADA.]

The impact of these clauses on planned and existing LRT systems is discussed in the subsequent section.

Planned LRT System. Policy makers at planned LRT systems have two procurement options:

- Purchase LF-LRVs and make them accessible by means of low platforms and/or lifts.
- Purchase conventional LRVs and make them accessible by means of one or an appropriate combination of the following options:
  - — Wayside lifts providing access to high-floor entrance(s);
  - — High platforms, long enough to berth a train;
  - — Short length, high platforms to match one high-floor entrance;
  - — Vehicle-borne wheelchair lifts; and
  - — Manually deployed vehicle fold-down platforms.

Existing LRT System. The issues facing existing LRT systems are more complex and depend on whether:

- The existing system has exclusively high-platform loading, in which case compliance with the accessibility requirements may not be an issue.

- The acquisition of LF-LRVs is contemplated solely to meet the one car per train rule.
- New vehicles must be procured anyway to replace rolling stock that has reached the end of its useful life and/or to cope with ridership growth.

If LF-LRVs are only being procured to meet the one car per train rule, it must be recognized that some inefficiencies may accrue, e.g., extra LF-LRVs may be required to match existing numbers, or some of the existing vehicles may be used less frequently or become surplus before reaching the end of their useful lives. Under these circumstances, the trade-off will be among

- Buying the minimum number of LF-LRVs required to meet the one car per train rule;
- Equipping some of the existing vehicles with wheelchair lifts or high/low steps, or vehicle fold-down platforms in conjunction with mini-high platforms, to meet the one car per train rule; and
- Providing wayside lifts.

If vehicles are procured to replace rolling stock that has exceeded its useful life or to keep up with increased ridership growth, the number of vehicles to be procured will be dictated by service frequency requirements and the problem of surplus vehicles should not arise. The preferred option for meeting the ADA accessibility requirements will depend on the size of the new vehicle order relative to the number of existing vehicles to be retained.

Boarding and Alighting Times

One potential benefit of operating LF-LRVs is reduced station dwell time because of more efficient boarding, movement through, and alighting from the vehicle. The benefit has two components:

- Quicker entry and egress by passengers who do not need to ascend or descend steps, especially if they are carrying bags or pushing strollers. The full value of this benefit will only be realized if the train is composed entirely of LF-LRVs. If the train is made up of a mix of LF-LRVs and conventional LRVs, the boarding and alighting times will improve depending on the ratio of level to nonlevel entrances.
- Elimination of the time required to use a wheelchair lift or manual fold-down platform to cover the stepwell. This is the main benefit for LRT systems with low-platform stations to consider. It reduces the unreliability of the schedule caused by lift/fold-down platform operation.

The tangible benefits that accrue can be quantified (see Chapter 5) in terms of capital and operating costs saved by the transit system, and the value of time saved by passengers as follows:

- Capital cost reduction occurs if the reduction in the round-trip time is equivalent to or exceeds the operating headway, then one less train is required to provide a given service level.
- Operating cost reduction comes from the savings in labor no longer required to operate and maintain the eliminated train(s).
- The value of time saved by passengers is currently assessed by the FTA as

  — $4.80 per hour for commuting trips and
  — $2.40 per hour for all other trips.

Mixed-Fleet Operation

Many of the North American LRT systems have been built within the last 20 years. They are operating conventional LRVs that have not yet reached the end of their useful life. Older LRT systems that purchased vehicles in the same period also have this situation. In most cases, it will be economically necessary to be able to operate multiple unit trains composed of existing vehicles and new LF-LRVs. This should be feasible with Category-1 and Category-2 vehicles but would be difficult with Category-3 LF-LRVs, as presently designed, because of differences in coupler height.

For example, the Bombardier (BN) Tram 2000 for Brussels was supplied for single vehicle operations only. For future orders, the vehicle has been designed so that an automatic coupler can be installed. This will enable Tram 2000s to be operated in trains but not to be coupled to different vehicles. The situation with the other Category-3 vehicles was not fully explored during this research.

On the other hand, the experiences of TRI-MET and MBTA demonstrate that Category-2 LF-LRVs can readily be designed to operate with existing vehicles. The same is true for Category-1 LF-LRVs, especially if they are created by adding a center section to a six-axle conventional LRV, in which case the coupling interface is inherently provided. It should be realized, however, that the ability to compose mixed trains may require modifications to the existing cars to enable control from any cab. For example, remote activation of a powered ramp from the cab of an existing vehicle requires the addition of controls, trainlines, and coupler contacts (unless spares already exist).

In addition, it is appropriate to specify that LF-LRV characteristics be matched with those of the existing vehicles with respect to

- Performance—to avoid uncomfortable jerk and obtain equal tractive effort from every vehicle in the train; and
- Crashworthiness—to minimize the risk of the stronger vehicle penetrating the weaker in a collision.

The LF-LRV ends must also be designed to allow for the relative movements between coupled cars when negotiating vertical and horizontal curves. This may preclude use of an existing LF-LRV design unless its ends are suitably modified.

While these requirements are not particularly difficult to accomplish, they will entail additional engineering costs, which may be significant on a per car basis if only a small number of LF-LRVs are ordered.

Fare Collection

The dwell time reduction obtained from using LF-LRVs, compared to boarding high-floor LRVs with steps, is achieved only if passengers can board the vehicle via the low-level entrances. This will not be the case in those Category-1 and Category-2 vehicles that have on-board fare collection adjacent to the driver's cab in the high-floor part of the vehicle.

There are three alternatives to resolve this problem—change to a proof-of-payment fare collection scheme, collect fares at stations, or utilize 100 percent low-floor vehicles. While the third alternative will improve the boarding rate it still requires all passengers to enter at one entrance, whereas dispensing with on-board fare collection permits all low-floor entrances to be used for maximum efficiency.

If on-board fare collection is deemed essential, it is important to select a LF-LRV that is operationally compatible with the station platform layout. On some LRT systems, boarding at the front of the vehicle from a right-hand door at one station may be followed by a requirement to exit from a rear door on the left-hand side of the vehicle (e.g., MBTA). This may preclude the use of some Category-3 vehicles, which have narrow low-floor aisles over their trucks that are not sufficiently wide to permit the passage of a person in a wheelchair.

Performance

To benefit from the trip-time reductions that accrue from shorter station dwell times, LF-LRVs must be adequately powered to deliver performance similar to conventional high-floor LRVs. Depending on route profile, this factor could favor one category of LF-LRV over another, but it is unlikely to negate a decision to use LF-LRVs instead of conventional ones.

LRT routes that have closely spaced stations, especially on city streets, require vehicles that can accelerate and brake at the maximum rates consistent with passenger comfort criteria. This will favor LF-LRVs that power all their wheels (all wheels are usually braked anyway), especially if wheel/rail adhesion can be marginal in inclement weather or the route contains steep grades. However, in practice, perfectly adequate performance can be obtained from cars by motoring four out of six wheelsets. Eight-axle, Category-1 vehicles that have only four axles motored may not have adequate performance in some applications. Similarly, some of the Category-3 LF-LRVs may be underpowered.

The trip time on LRT routes with longer distances between stations is more sensitive to maximum speed. The top speed of many existing LF-LRVs, especially in Category 3, is often 70 km/h (44 mph). This is significantly less than the 80 to 90 km/h (50 to 56 mph) maximum speed capability of most conventional LRVs currently operating in North America.

TRI-MET's experience appears to demonstrate that a Category-2 vehicle, which typically has the same amount of specific power as conventional six-axle LRVs, can easily achieve the same maximum speed. Category-1 LF-LRVs can be provided with all motored trucks to give very high specific power and maximize the use of adhesion.

The maximum speed of Category-3 vehicles appears to be design limited rather than power limited. It is unclear whether the compact water-cooled hub motors, which have found widespread application on Category-3 running gear, have sufficient thermal capacity to cope with the duty cycle of some North American LRT systems. The concern is more acute in the case of a direct drive hub motor configuration.

Maintenance

Maintenance is a function of reliability and maintainability. Reliability is a measure of the frequency of equipment failure and the consequential need for corrective maintenance action. It is measured and specified in terms of time or distance between failures. It indicates the level of inspection and preventive maintenance effort, because highly reliable hardware need not be checked and adjusted often. Maintainability is a measure of the time and, therefore, labor required to repair and restore a failed function or component.

Unfortunately, objective data have not been collected to quantify these characteristics. Manufacturers claim, and European transit operators expect, a reduction in maintenance effort, but only time will tell whether this is a realistic expectation. In the meantime, several important factors should be considered in assessing the applicability of LF-LRVs.

Category-1 vehicles will have substantially the same, if not identical, trucks to the conventional LRVs from which they may have been derived, as well as the same subsystems and equipment. On many Category-1 vehicles, subsystems and other equipment are mounted below the floor of the outer carbody sections using the original installation methods. Therefore, Category-1 vehicles will be familiar to maintenance personnel and will likely require about the same level of effort per passenger-mile.

Category-2 and Category-3 vehicles have roof-mounted equipment, which is easier and more accessible to inspect, repair in place, and remove and replace. The installation hardware is also simpler because there is no need to avoid bolts in tension or special brackets that prevent equipment from falling on the track. In addition, running gear and propulsion machinery components on Category-3 vehicles are smaller and lighter, and therefore, easier to handle. Installation is also outboard of the wheels, which provides good access. The same is true for small wheel trucks and brake parts on Category-2 vehicles.

There are several disadvantages that will tend to increase maintenance efforts. These disadvantages were mentioned in Chapter 2 and are restated as follows:

- More numerous components that can fail and require repair. (For example, four motors, gearboxes, discs, and brake mechanisms on some independently rotating four-wheel trucks compared to one or two motors and two each of the other parts on a classical power truck);
- Additional equipment, which is required for LF-LRVs (such as door threshold ramps);

- Unsprung components that endure higher shock and vibration;
- Use of hydraulic actuation, instead of pneumatic, owing to space limitations (hydraulic systems require greater care and cleanliness during maintenance);
- Higher precision and more complex assemblies, such as steering linkages, which require more care and checking after rebuild.

It is difficult to generalize these advantages and disadvantages. A systematic reliability and maintainability evaluation needs to be carried out for the specific new LF-LRV technology. Even then it may be difficult to come to a definite conclusion. For example, in the absence of service experience, it will be difficult to quantify the difference between maintenance of a traction motor water-cooling system and a forced air ventilation system. The water-cooled system has the added burden of air/water heat exchanger maintenance but does not experience filtration and snow ingestion problems.

One way to try to solve this problem is to turn it back to the vehicle builder and suppliers by specifying performance-based, minimum reliability and maintainability developed from experience with existing vehicles. However, the problem then shifts to assessing the credibility of the proposals received and the risk that the purchaser will only get as much as demanded.

In conclusion, at this time Category-1 and Category-2 vehicles represent a lower risk of escalating maintenance effort. Conversely, they do not provide as many of the potential maintenance improvements designed into Category-3 vehicles.

COMPLIANCE WITH NORTH AMERICAN SPECIFICATIONS

European and other foreign car builders have been supplying rail vehicles to North American transit agencies for the past 30 years, managing to comply with the generally more stringent specifications. TRI-MET's experience demonstrates that North American specifications are achievable in Category-2 LF-LRVs. This section discusses the following North American specifications, which are considered most difficult and expensive to meet, particularly in Category-3 vehicles:

- Buff load and compression strength, and
- Fire resistance.

Buff Load and Compression Strength

Buff load is the static longitudinal force that a rail vehicle must be capable of withstanding without permanent deformation to its primary structure. It is intended to ensure that the vehicle body will not collapse and the driver or passengers will not be crushed in the event of a collision with other vehicles. Therefore, it is specified to act on the anticlimber, which logically must be at the same level as other vehicles sharing the tracks. The magnitude of the buff load varies from transit operator to transit operator (usually 150% to 200% of the vehicle's tare weight for North American systems) and appears to be

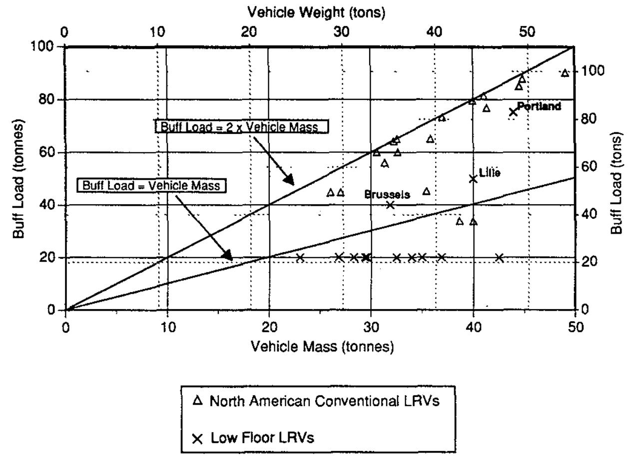

Figure 74. Comparison of buff load.

determined mainly by historical precedent and the exclusivity of the right of way. Figure 74 shows a comparison of typical North American buff load specifications.

It seems logical and legally prudent for vehicles that run on an exclusive right of way to have the same compression strength as any existing LRV using that right of way. This is the philosophy adopted by TRI-MET and MBTA and will likely be typical of other LRT systems. Where the LRVs share tracks used by other rail vehicles, as in San Diego, Cleveland, and Baltimore, local and national regulations will have to be satisfied. In either case, this tends to result in higher buff load requirements than European LF-LRVs, which are typically 20 or 40 tonnes (44,000 to 88,000 lb). The Breda VLC for Lille is an exception—it was designed to withstand 50 tonnes (110,000 lb).

Theoretically, new exclusive right-of-way LRT systems are free to specify lower buff loads, but in practice, they are unlikely to accept the liability risk that a radical decrease may bring. Similarly, there is no technical reason for LRVs to be stronger than buses or trucks, but operators will probably not want to degrade the compression strength standard of previous vehicle specifications for fear of legal repercussions in the event of an accident that causes injury.

Clearly, the majority of existing LF-LRVs must be strengthened to be applicable to North American LRT systems. This is entirely feasible and should not be particularly difficult to achieve on Category-1 and Category-2 LF-LRVs. Category-3 vehicles, however, appear to require extensive design modifications because

- They are more likely to be made of aluminum extrusions or material combinations that do not readily lend themselves to local reinforcing, and
- The end structures are unlikely to match the end sill and anticlimber of an existing vehicle with which they may be required to operate.

Fire Resistance

North American specifications contain more stringent flammability, smoke emission, toxicity, and fire resistance standards than European LRVs are usually designed to meet. In the past, car builders have successfully fire hardened their designs to meet North American criteria, but the task has been more difficult in the case of the floor fire resistance of cars made from aluminum, because of its lower melting point. The pertinent requirement in this context is for a crush loaded floor sample to survive the American Society for Testing Materials (ASTM) E-119 test for at least 15 min.

Cars with steel floor crossings or corrugated floor sheets have successfully passed this test, but those made of aluminum typically require the protection of a stainless steel sheet and a significant thickness of insulation. Consequently, there is a weight and cost penalty associated with fire hardening, which may obviate the weight savings achieved in the first place. In some cases, the floor construction may not be suitable at all. For example, the ABB (Socimi) Eurotram floor is made from an aluminum sheet-foam core sandwich reminiscent of the first BART cars built by Rohr in the early 1970s. In 1979, a fire in the Transbay tube destroyed seven cars. The entire fleet was subsequently retrofitted with fire hardened material.

CHAPTER 4

NORTH AMERICAN LIGHT RAIL TRANSIT SYSTEMS CHARACTERISTICS

A study of representative North American LRT systems was conducted to assess the applicability of low-floor light rail vehicles (LF-LRVs). Relevant data were collected from a survey and a review of published information. A comprehensive data summary is provided in Appendix B.

A discussion of issues, opportunities, and constraints regarding possible deployment of LF-LRVs is provided herein. For ease of understanding, we have organized data and information into five categories, as follows:

- Platform Characteristics,
- Right-of-Way Characteristics,
- System Characteristics,
- Operations Characteristics, and
- Vehicle Characteristics.

Discussion of opportunities and examples are provided to enhance the reader's understanding of issues and to place findings in a North American context. Given the level of detail provided in this report, it is not possible to assess which transit agencies should or should not add LF-LRVs to their fleets. Each transit agency seriously considering the use of LF-LRVs will need to conduct its own in-depth study of the issues.

PLATFORM CHARACTERISTICS

Platforms are one of the most important elements affecting the potential use of LF-LRVs on an existing LRT system. There are two key questions that must be answered—will the existing platforms accommodate the use of LF-LRVs, and are the platforms easily adaptable? Our review and analysis of North American LRT data has shown that existing LRT systems can be split into three basic groups:

- Low Platform—this group comprises LRT systems that have stations without platforms, with low platforms, with mini-platforms for boarding wheelchair users only, or with street curbs of a height up to 360 mm (14 in) above TOR. These systems are considered good candidates for LF-LRV application.
- Low/High Platform—this group comprises LRT systems that have a combination of low- and high-station platforms (e.g., high-level boarding in stations within a tunnel and low-platform boarding outside). These systems are considered possible candidates for LF-LRV application.
- High Platform—this group comprises LRT systems that have exclusively high-platform stations with the platform being equal to or greater than the train length, and at a nominally constant elevation in the range 910 mm to 1,020 mm (36 in to 40 in) above TOR. These systems are considered unlikely candidates for LF-LRV application on existing lines and extensions to existing lines.

A survey of North American LRT systems was conducted (Table 10). The agencies shown in bold type are either in the process of procuring LF-LRVs or are actively pursuing the

TABLE 10 List of North American agencies included in the survey of LRT systems

City	Agency	Type of Platform
Baltimore	MTA	Low
Boston	**MBTA**	**Low**
Buffalo	NFTA	Low/High
Calgary	CT	High
Chicago	**City of Chicago**	**Low**
Cleveland	GCRTA	Low
Edmonton	ET	High
Los Angeles	LACMTA	High
Newark	**NJT**	**Low**
Philadelphia	SEPTA	Low
Philadelphia (Norristown)	SEPTA	High
Pittsburgh	PAT	Low/High
Portland	**TRI-MET**	**Low**
Sacramento	RT	Low
San Diego	MTD	Low
San Francisco	MUNI	Low/High
Santa Clara	SCCTA	Low
St. Louis	BSDA	High
Toronto	**TTC**	**Low**

idea. Note that any of these agencies could decide to construct a new LF-LRV line to complement existing LRT service. All new LRT systems are considered good candidates for LF-LRV application. Four platform characteristics are discussed in greater detail—platform height, platforms in tunnels, level boarding, and door encroachment.

Platform Height

In order to obtain level boarding without the use of telescoping ramps, station platforms must match the LF-LRV floor height. For some transit agencies, this would mean raising the level of an existing curb or platform. These agencies would also have to consider the height of the lowest step on their existing conventional vehicles, architectural restrictions, existing structures, and boarding points (e.g., whether there is boarding directly from the street). The following systems exhibit some boarding directly from street level: Boston, Philadelphia, Sacramento, Toronto, and Buffalo.

Raising a platform to allow level boarding may result in a need to modify the step height of the conventional vehicles to ensure that the step is not lower than the platform height.

Platforms in Tunnels

Where existing high-platform LRT stations have been constructed within tunnels, platform modifications to accommodate low-floor vehicles would be technically difficult, disruptive to service, and consequently costly to implement. LRT systems that fit this criterion include Buffalo, Edmonton, Los Angeles, Pittsburgh, San Francisco, and St. Louis.

Level Boarding

Many transit agencies have invested in equipment or infrastructure improvements to enable level boarding at all stops, while other agencies provide alternative solutions. Level boarding can be provided by combining high-floor cars with high platforms, or low-floor cars with low platforms. All North American systems that provide level boarding currently use high-floor cars. Figure 75 lists the principal access features currently in place at North American LRT systems.

Door Encroachment

Some LRVs are equipped with doors that open or fold outward. If these LRT systems install raised platforms to allow level boarding of vehicles, it is imperative that the top of platform elevation be set lower than vehicle door bottoms to facilitate door opening. A vehicle load-leveling system retains the LRVs floor height at a constant level, regardless of the vehicle load. The following systems have outward opening or folding doors:

- Baltimore (load leveling),
- Boston (load leveling),
- Cleveland (no load leveling),
- Portland (no load leveling),
- Sacramento (no load leveling),
- San Diego (no load leveling), and
- Santa Clara (load leveling).

RIGHT-OF-WAY CHARACTERISTICS

Two right-of-way characteristics of North American LRT systems are discussed in detail—minimum horizontal curve radius and steep grades.

Minimum Horizontal Curve Radius

Existing track horizontal curve radii may restrict the use of some LF-LRVs or at least have an impact on their cost. The data presented in Chapter 2 and Appendix A indicate that the three categories of LF-LRVs, as presently designed, can meet the following minimum horizontal curve requirements:

- Category 1: 20 m (66 ft)
- Category 2:
  - Small wheel trailer trucks 18 m (59 ft)
  - Independently rotating four-wheel trucks 18 m (59 ft)
  - EEF wheelsets 15 m (49 ft)
- Category 3: 15 m (49 ft)

LRT systems on which the existing minimum curve radius falls below 15 meters include:

- Boston—10 m (33 ft) and 13 m (43 ft) for the Green and Mattapan lines, respectively;
- Newark—10 m (33 ft);
- San Francisco—13 m (43 ft); and
- Toronto—11 m (36 ft).

Although this does not rule out any of the three vehicle categories on any of the candidate systems, LF-LRV builders would have to adapt existing designs to meet tight radius requirements.

Steep Grades

Some of the existing LF-LRVs have only half of their wheels motored. This places a high demand on adhesion and would prevent the use of such LRVs on systems with steep grades (8% or greater). LRT systems that experience a significant number of days of inclement weather would have similar concerns about adhesion capabilities. Accordingly, Category-1 vehicles created by adding a low-floor center section and a second trailer truck to a six-axle conventional LRV, and Category-2 and Category-3 vehicles that only have half their wheels motored, may not be readily acceptable in Baltimore, Boston, Cleveland, Pittsburgh, San Francisco, and Toronto.

		Level Boarding	Wayside Ramp	Fold-down Platform	Wayside Lift	Car-borne Lift	Steps on Car
Low Platform	Baltimore		✓	✓			✓
	Boston						✓
	Cleveland						✓
	Newark						✓
	Philadelphia						✓
	Pittsburgh						✓
	Portland				✓		
	Sacramento		✓	✓			
	San Diego					✓	
	Santa Clara				✓		
	Toronto						✓
Low/ High	Buffalo		✓				
	Pittsburgh	✓					
	San Francisco	✓	✓				✓
High Platform	Calgary	✓					
	Edmonton	✓					
	Los Angeles (Blue)	✓					
	Philadelphia (Norristown)	✓					
	St. Louis	✓					

Figure 75. Existing North American LRT accessibility features.

SYSTEM CHARACTERISTICS

Fare Collection

An advantage of LF-LRVs is that boarding (from platforms and from street level) is at least as fast, and in some cases significantly faster, than for conventional LRVs. The use of a proof-of-payment (POP) fare collection system will support more rapid boarding since loading can take place through all open vehicle doors.

On the other hand, if fares are collected on-board, the boarding process will take longer. The station dwell time must include the time passengers take to pay fares (usually at a single location at the front of the vehicle adjacent to the operator). This arrangement would reduce some of the benefit that a LF-LRV could provide.

On-board farebox payment systems are currently in place on the following LRT systems:

- Boston (gates in the tunnel),
- Cleveland (gates in downtown terminal),
- Philadelphia,
- Pittsburgh (gates in the tunnel),
- San Francisco (gates in the tunnel), and
- Toronto (also POP).

OPERATIONS CHARACTERISTICS

There are four operations characteristics discussed in detail—consist length, fleet size and system size, station spacing and system size, and operation in mixed traffic on city streets.

Consist Length

Systems that currently operate multiple car consists have the option of mixing LF-LRVs and conventional high-floor LRVs, or even creating married low-floor/high-floor pairs. Systems designed exclusively for single car consist operation may have more limited options and system constraints.

If an existing fleet that uses only single car consists is modified to include Category-1 vehicles, the increase in train length may require platform, signal, and other infrastructure modifications. Alternatively, the existing fleet could be retired in favor of LF-LRVs of the same dimensions.

The following systems currently run single car consists exclusively: Boston (Mattapan), Newark, Philadelphia (City Transit, Norristown), Pittsburgh (PCC routes), and Toronto.

Some systems currently running single car consists can operate with multiple car consists. Actual infrastructure modification requirements must be assessed on a case-by-case basis.

Fleet Size and System Size

LRT fleet and system sizes are also factors to consider in the applicability of low-floor vehicles. Systems that have large fleets operating on numerous lines will have more opportunities to implement LF-LRVs as part of an overall fleet replacement strategy. For example, such an agency could replace retired conventional LRVs with LF-LRVs on one line of its network and consolidate the balance of its conventional LRVs on other lines. A gradual strategy could be used to replace the entire fleet a portion at a time.

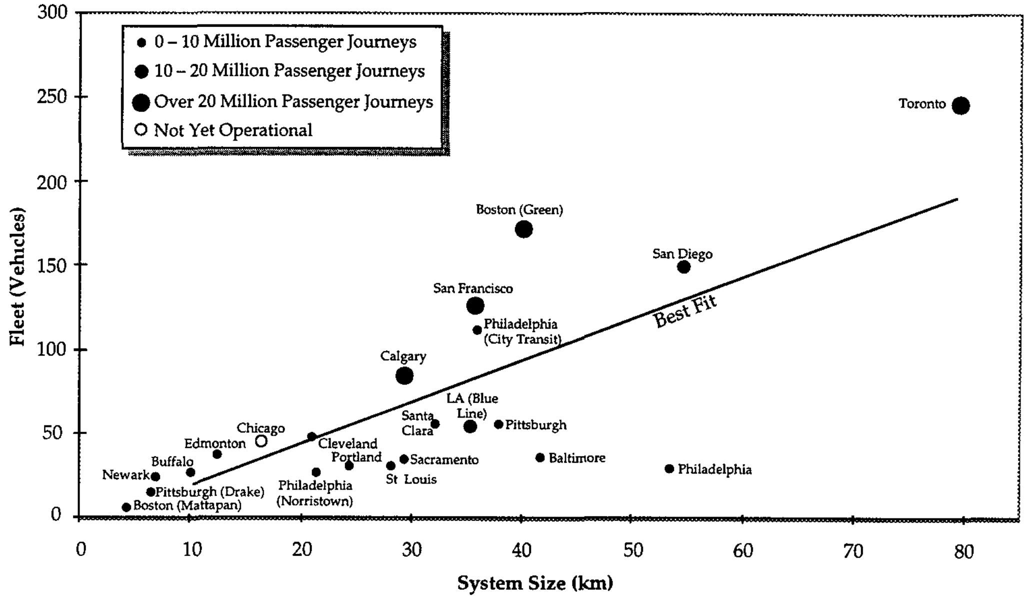

Figure 76. Fleet, system size, and ridership comparisons.

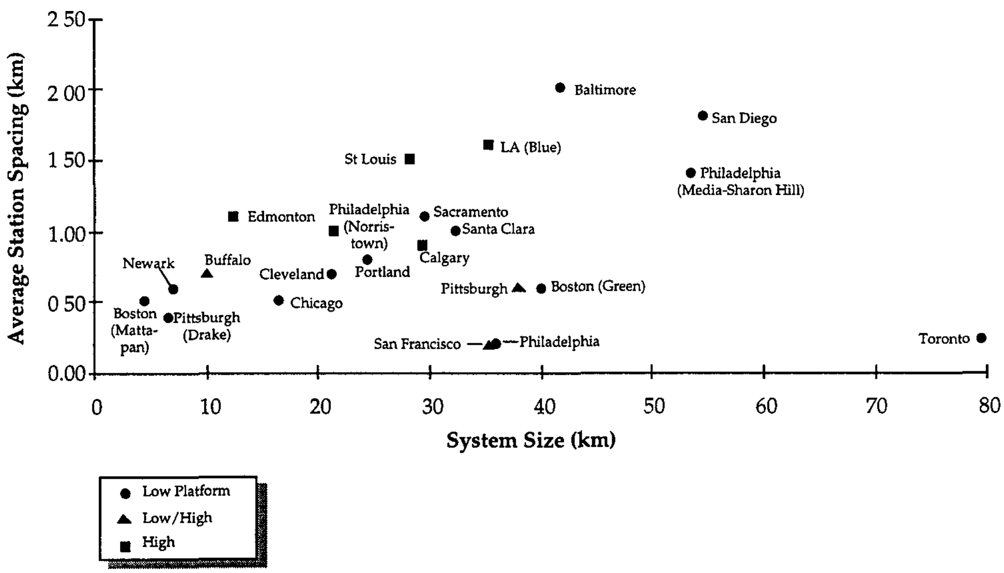

Figure 77. Station spacing and system size comparisons.

Figure 76 shows fleet size, system size, and annual ridership levels for the LRT systems in our survey.

Station Spacing and System Size

Systems with close station spacings save a larger proportion of their round-trip time by reducing station dwell times. Also, longer systems have longer round-trip times. If a train round-trip time can be reduced by the equivalent of a headway, the same level of service can be provided with one less train.

Figure 77 shows the LRT systems classified by average station spacing and system size. Note that the systems at the bottom of the graph are better positioned to take advantage of round-trip time savings.

The following systems have an average station spacing of less than one kilometer (0.6 miles), where application of LF-LRVs has potential for significant round-trip time savings:

- Boston,
- Buffalo,
- Calgary,
- Chicago,
- Cleveland,
- Newark,
- Philadelphia,
- Pittsburgh,
- Portland,
- San Francisco, and
- Toronto.

Current European LF-LRVs are usually powered for a maximum speed of 70 km/h (44 mph), compared to North American systems with maximum speeds usually between 80 and 100 km/h (50 and 62 mph). Where station spacing is small, top speed is of minor importance because vehicles may never attain top speed. Where stations are spaced further apart, maximum speed is more important, and improvements to vehicles to increase top speed may be warranted.

Operation in Mixed Traffic on City Streets

Unless precluded by clearance constraints or track geometry, LF-LRVs will be attractive to North American LRT systems that currently operate streetcars and have a significant proportion of their route shared with automobile traffic. Such systems will usually have locations at which there are no curbs or low curbs that cannot be raised. To meet ADA compliance requirements, telescoping ramps or lifts will be necessary. Systems that fit these criteria are in Philadelphia and Toronto.

VEHICLE CHARACTERISTICS

Axles

The basic unit for creating a Category-1 LF-LRV is a six-axle articulated conventional LRV. A Category-1 vehicle is created by adding a body section and an articulation unit to the basic unit. The following agencies use four-axle non-articulated LRVs that cannot be adapted to Category-1 vehicles: Buffalo, Boston (Mattapan), Newark, Philadelphia, Pittsburgh (PCC routes), Toronto (CLRV), and Toronto (Harbourfront LRT).

CHAPTER 5

APPLICABILITY FRAMEWORK ASSESSMENT MODEL

The recent availability of reliable and cost-effective low-floor light rail vehicles (LF-LRVs) presents a new range of system development options to North American LRT agencies. In some applications, there may be significant advantages in implementing a LF-LRV strategy. However, the addition of new options also makes the selection of the best strategy much more complex.

In order to aid in the selection of the best strategy, we have defined an applicability framework assessment model (Figure 78). The model demonstrates a process that can be used to define a range of options, then narrow the options to those best suited to a particular transit agency. As a complement to the model, comments in this chapter advise what are the major LF-LRV versus conventional LRV issues, what trade-offs will arise, and what are the most important discriminators between conventional LRVs and LF-LRVs. Information on LF-LRVs (Chapter 2), vehicle application issues (Chapter 3) and North American LRT system characteristics (Chapter 4) are discussed both individually and collectively.

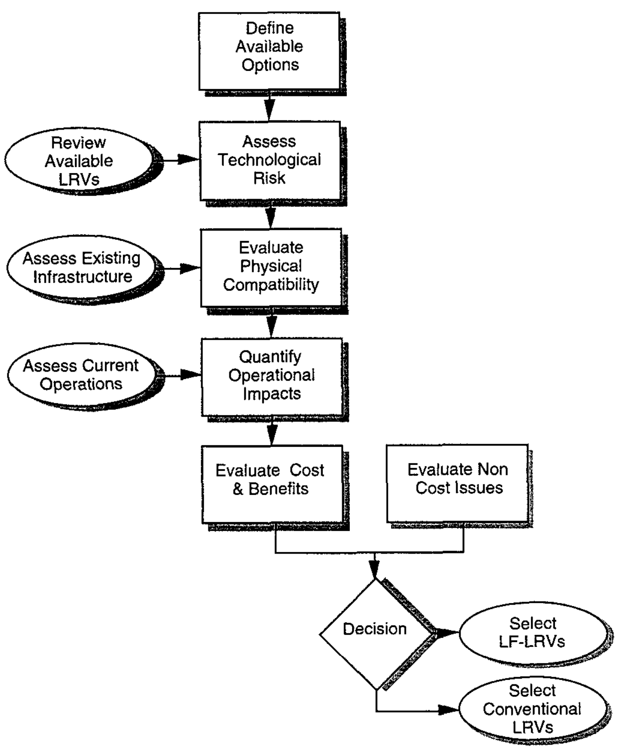

Figure 78. Applicability assessment model.

While we can highlight issues that will be of importance in assessing the applicability of conventional LRV versus LF-LRV solutions, each agency will have to look at the specific detailed requirements of its own system in determining its optimal course of action. Research conducted for this assignment has shown that North American transit agencies operate quite differently from each other and have widely varying system characteristics. Best solutions for each transit agency will also vary significantly.

LF-LRV designs are still evolving in Europe and North America. Because of differences in expectations of the traveling public, legislated requirements, and transit agency characteristics, it is possible and even likely that LF-LRVs in North America will look significantly different than their counterparts elsewhere. Many of the shortcomings of foreign LF-LRVs can be engineered out to provide a vehicle that is much better suited to North American practices and requirements.

The next sections of this chapter discuss the seven steps shown in the applicability assessment model:

- Define available options,
- Assess technological risk,
- Evaluate physical compatibility,
- Quantify operational impacts,
- Evaluate costs and benefits,
- Evaluate noncost issues, and
- Make a decision.

DEFINE AVAILABLE OPTIONS

A first step in selecting the best available options is to define the full range of feasible options. Once the feasible options have been established, a process of elimination can be used to short-list competitive options.

It is important to note that the LRT system option that scores highest from a cost/benefit perspective may not necessarily be the best option. Therefore, it is important to define a range of options that will find competitive solutions, not a single solution. Noncost issues often play a determining factor in the final selection process.

The key issues to be considered by a transit agency in evaluating options will vary, depending on the transit agency's situation and circumstances. For example, issues relating to development of a new line will differ substantially from issues relating to fleet replacement on an existing line. In general terms, an agency will be considering LF-LRVs from one of four perspectives:

- A new line is being developed;

- An existing line is being extended;
- Additional vehicles are being procured to add to fleet size or to replace retired vehicles; or
- The present system does not provide a satisfactory degree of barrier-free access to the traveling public (ADA compliance).

For each of these situations, a strategy and key issues are described in the following paragraphs. Within each of these situations, all existing systems are assumed to be operating conventional LRVs because presently no North American LRT system is operating LF-LRVs.

New Line

Situation. Construction of the first LRT line in a municipality, or construction of a separate (possibly overlapping) line as a complement to an existing LRT line(s).

Strategy. Consider LF-LRV solutions versus conventional LRV solutions, each with appropriate platform, maintenance shops, right of way, systems, and other interfaces developed to match the vehicle selection.

Key Issues. Key issues to consider include

- Reduced cost to install platforms for LF-LRVs compared to conventional LRVs;
- Improved ADA access may increase schedule reliability;
- Possible reduced fleet requirements with LF-LRVs (if boarding is faster); and
- Acceptance of the new system by the communities served and the traveling public (accessibility and aesthetics).

Line Extension

Situation. Extension of an existing LRT line.

Strategy. Add conventional LRVs to the fleet, modify existing fleet (i.e., Category-1 vehicles), or add LF-LRVs to the fleet.

Key Issues. Key issues to consider include

- Fleet uniformity versus mixed-fleet operations and maintenance;
- Lead time to modify existing fleet (with Category-1 LF-LRVs);
- ADA compliance and possible increased schedule reliability;
- Cost to retrofit existing infrastructure versus cost of new construction;
- Possible reduced fleet requirements with LF-LRVs (if boarding is faster); and
- Acceptance of the new extension by the communities served and the traveling public (accessibility and aesthetics).

Fleet Procurement

Situation. Increased fleet requirements necessitate procurement of additional vehicles, or some or all of the existing LRT fleet is aging and must be replaced.

Strategy. Procure replacement vehicles similar to existing vehicles to match infrastructure versus procurement of compatible or replacement LF-LRVs.

Key Issues. Key issues to consider include

- Fleet modification versus fleet replacement and/or addition to fleet;
- Lead time to modify existing fleet (with Category-1 LF-LRVs);
- Fleet uniformity versus mixed-fleet operations and maintenance;
- ADA compliance and possible increased schedule reliability with LF-LRVs;
- Possible reduced fleet requirements with LF-LRVs (if boarding is faster);
- Cost to retrofit existing infrastructure if LF-LRVs are used; and
- Acceptance of the new fleet and service by the traveling public (accessibility and aesthetics).

Barrier-Free Accessibility

Situation. The existing fleet and physical infrastructure are performing satisfactorily except that accessibility to the public is not barrier free and/or does not meet ADA compliance requirements.

Strategy. Modification of existing infrastructure or vehicles, or addition/replacement of conventional LRVs with LF-LRVs.

Key Issues. Key issues to consider include

- Cost to retrofit or modify existing fleet versus modification of infrastructure and/or addition of LF-LRVs to fleet;
- Fleet uniformity versus mixed-fleet operations and maintenance;
- Possible increased schedule reliability with LF-LRVs;
- Possible reduced fleet requirements with LF-LRVs (if boarding is faster); and
- Acceptance of the service by the traveling public (accessibility).

ASSESS TECHNOLOGICAL RISK

North American transit agencies have traditionally preferred using revenue service-proven equipment. This preference provides a basis for narrowing the choice of applicable LF-LRVs by eliminating some of the higher risk technologies that have emerged.

TABLE 11 Summary of LF-LRV Orders To Date

Category	Orders Greater than One Car	Fleet Order Range	Avg. Order (cars)	First Car Delivery
1	12	10-45	21	1987-93
2	33	4-120	28	1984-95
3	16	3-100	34	1990-95

Risk Evaluation

A proven and reliable operating history is a key consideration in assessing the risk associated with vehicle selection. Actual fleet performance during a number of years demonstrates what operating costs, maintenance costs, and fleet reliability should be achievable. While considerable data are available for conventional LRVs, the data for LF-LRVs are relatively limited. Table 11 summarizes the history of LF-LRV orders to date. In all cases, the mode average year (the year in which most orders were made) was 1993. This reflects the recent trend towards low-floor technology in the industry for all categories of LF-LRVs. For illustrative purposes, we have adopted a "proven equipment" criterion based on equipment that has been in service for more than 3 years and in fleets of 15 or more vehicles.

Category-1 vehicles make use of existing, proven technology and only include the addition of a center section, additional truck, and additional articulation. The Basel, Switzerland system has been in operation since 1987. Category-2 vehicles have now been in operation for as many as 10 years, and there have been six large orders placed prior to 1991. For Category-3 vehicles, the situation is somewhat different. There are only two Category-3 LF-LRV orders prior to 1991, one to Bremen and one to Munich in Germany. The remainder of the orders are for 1993, 1994, and beyond.

Category-1 and Category-2 vehicles make use of technology that has already been largely proven on similar high-floor vehicles. There are some innovations, such as small wheel trucks, that are substantially different than on conventional LRVs. Most of these innovations have also proved to be reliable, based on experience at a number of transit agencies. Therefore, the use of Category-1 and Category-2 technologies has little associated risk:

- All Category-1 vehicles could be applicable if they are found to be physically compatible.
- Within Category 2, all three types of running gear technology meet the defined proven equipment criterion and should be considered applicable:
  - — Small wheel trailer truck technology (Geneva, St. Etienne)
  - — Four independently rotating wheel truck technology, with or without cranked axles (Grenoble, Turin, Rome)
  - — EEF wheelsets (Kassel).

For Category-3 vehicles, the technology is still evolving. Vehicles incorporate unusual technological innovations, such as wheels that steer independently, and suspension systems with significantly reduced damping. Extremely limited service history is available for Category-3 vehicles. Using the illustrative "proven equipment criterion" defined above, the only vehicle applicable for use is the AEG (MAN) GT6N/8N. This vehicle operates in Bremen and Munich. In addition to price and other criteria used in selecting the best vehicle, risk should be considered carefully if Category-3 vehicles are being considered.

Mitigating Factors

While risk is an important factor, there are other factors that might make an agency accept higher levels of risk. For example, these issues might include

- More effective fleet use, thereby reducing fleet requirements and cost (i.e., a longer Category-3 vehicle might serve in place of two conventional-length Category-2 vehicles);
- Added passenger benefits (all entry doors are at a low-floor level);
- Participation in the development of cutting-edge solutions; and
- Local incentives such as employment or factors tied to vehicle supply.

EVALUATE PHYSICAL COMPATIBILITY

Relevant issues include the compatibility of new LF-LRVs to existing LRVs, to platforms, to maintenance shops and yards, to right-of-way elements, and to LRT systems elements.

LRV-to-LRV Compatibility

Vehicle-to-vehicle compatibility is especially important when new and existing vehicles operate in mixed consists. Approximately two-thirds of North American transit systems use multiple-car consists. Category-1 and Category-2 LF-LRVs have, by definition, conventional motored trucks. Accordingly, couplers (and anticlimbers) on these vehicles can match those on conventional LRVs. Acceleration, speed control, and braking rates will have to be matched for both types of vehicles. These issues are also relevant to coupling old and new LRVs together.

With respect to buff load and safety in case of a collision, vehicle compatibility is also important even if vehicles never couple but merely operate on the same line. Given that the floor of a Category-3 vehicle is lower than that on a conventional LRV, the natural location for the coupler, and the longitudinal load path through the vehicle (in case of collision), will be at a lower level. At present, no Category-3 LF-LRVs have been manufactured to operate as part of a mixed consist or to meet North American buff load requirements. To do so, would require redesign and additional manufacturing costs.

LRV-to-Platform Compatibility

Improved accessibility is a major reason for selecting LF-LRVs. Careful attention to the platform/LRV interface is necessary to ensure that accessibility is not lost.

ADA compliance requirements are described in Chapter 3. If platforms are to be installed to facilitate level boarding, it will be important that close attention be paid to design and construction tolerances. It is also likely that load leveling will be required on cars to compensate for changing load conditions. Horizontal separation between the car and platform will also have to be monitored closely. Fold-down bridgeplates have been used successfully to reduce or close the gap between cars and platforms. Placement of platforms on curves will be problematic because the in-swing and out-swing of vehicles will affect platform placement. While bridgeplates can accommodate small vertical gaps and horizontal gaps of up to 100 mm (4 in), larger gaps would likely require more sophisticated solutions such as the use of extendable ramps. This will create additional problems. While fold-down bridgeplates can deploy in a second, extendable ramps might easily take several seconds or longer.

If high platforms already exist, it would be necessary to remove the platforms to allow boarding of LF-LRVs. Alternatively, in some cases it may be possible to locate high- and low-stop locations in tandem. This would be a feasible solution where complementary conventional and LF-LRV service is provided, for example, from different lines.

If low platforms are added to an LRT system where conventional high-floor LRVs are presently boarded from street level, care should be taken to ensure that it is not necessary to step down to the first step of conventional high-floor cars. This can be achieved by careful selection of the platform height or modification of the steps on the high-floor cars.

Other means by which wheelchair boarding of LF-LRVs can be provided for is through the use of carborne lifts, wayside lifts, and extendable ramps.

LRV-to-Maintenance Shops and Yard Compatibility

Most LRT systems use vehicles that can operate interchangeably. If mixed fleets are used, adequacy of the yard to support storage and accessibility of both conventional and LF-LRVs should be checked. If LF-LRVs and conventional LRVs are to operate within the same consists, consideration must also be given to make-up and breakdown of consists, storage of ready spare consists, and the ability to make and store consists in the correct car order.

Maintenance shop requirements for LF-LRVs will differ slightly from those for conventional LRVs. On conventional LRVs, many of the components are located under the vehicle; on LF-LRVs, many of these components are located on the roof. Therefore, the need for underfloor pits is reduced, but in place of that there is a need for roof-level platforms. This difference will affect crane access to the sides of the cars, and introduce new safety elements as a result of work taking place adjacent to the power distribution system and increased risk of maintenance staff falling (from the top of vehicles).

Other things to consider in the maintenance shop include lengths of work areas, such as pits and paint booths. Category-1 vehicles are typically longer than conventional LRVs. In-floor jacks, installed for work on conventional LRVs, will likely be in the wrong place for LF-LRVs. Jacking vehicles and raising LF-LRVs by crane will also be complicated if the vehicles have extra body and articulation sections.

LRV-to-Right-of-Way Compatibility

The new train consist (single or multiple car) must clear all civil elements in the right of way. For example, there must be clearance for the running gear and the vehicle underbody along the entire LRT system length. Projection of any equipment above TOR elevation should be carefully assessed.

The LF-LRV must be able to negotiate all curves along the right of way and have sufficient power and traction to climb the steepest grades. (See more discussion of this in Chapter 3 and Chapter 4.)

The specific mass of LF-LRVs is usually equal to or slightly less than that for conventional LRVs. Accordingly, no changes should be required to existing structures or support elements.

LRV-to-LRT Systems Compatibility

LRT systems include signals, communications (wayside), traction power, and fare collection.

Signals (train control) will normally only be an issue if train lengths have changed. If train lengths do change, this might require that stopping locations of trains be changed or even that different station stop locations be used.

Except in the case of relocation of stations or other necessary changes in infrastructure, communications will not usually pose compatibility problems.

Traction power will be only slightly affected by the use of LF-LRVs. Acceleration and performance of conventional and LF-LRVs is similar. On average, Category-1 and Category-2 LF-LRVs have a slightly lower specific mass than conventional LRVs, so a marginal savings in power costs should be anticipated. Category-3 LF-LRVs, on average, will provide even greater savings.

QUANTIFY OPERATIONAL IMPACTS

LF-LRVs were developed with the objective of enhancing passenger accessibility. As a direct consequence of this, the efficiency of LRT operations has been improved because of more rapid boarding of vehicles. Enhanced accessibility also means that the system can serve a broader range of customers and could gain new riders.

On new lines, LRT infrastructure can be developed to fully complement the use of LF-LRVs. In other situations (such as the extension of existing lines, the procurement of additional fleet vehicles, and conversions to meet ADA compliance requirements) it may be difficult to implement LF-LRV solutions. Problems may arise with compatibility between new vehicles and existing infrastructure and operations. Where LF-LRV solutions are implemented, the full benefit of the use of LF-LRVs may or may not be realized.

Issues relevant to the operation of LF-LRVs include the following:

- ADA compliance,
- Schedule reliability,
- Fleet requirements,
- Passenger demand,
- Vehicle performance,
- Mixed-fleet operations,
- Fleet maintenance, and
- Adverse climatic conditions.

ADA Compliance

In addition to the fact that it is desirable that LRT systems provide barrier-free accessibility to passengers, it is necessary that American LRT systems comply with ADA requirements. Most accessibility options are the same for LF-LRVs and conventional LRVs. These include the installation of platforms (to allow level boarding), carborne lifts, and wayside lifts. Another option available for use with LF-LRVs is the use of extendable ramps to allow boarding from curb-level stops.

Where the same method of wheelchair boarding is used on conventional LRVs and LF-LRVs, there is negligible difference in boarding times. For example, whether boarding a conventional high-floor LRV or a LF-LRV using a carborne lift, the time impact on operations will be nearly the same.

Schedule Reliability

A significant gain in operational reliability and reduced dwell time can be achieved through the use of LF-LRVs. Typical dwells at an LRT station where there is level boarding from a platform may vary from approximately 8 sec in very light load situations to 20+ sec in very heavy load situations. In contrast, a single wheelchair boarding or alighting via a wayside or carborne lift usually takes 2 to 4 min—depending on the mechanical system and procedure used and assuming that no problems arise. The use of extendable ramps takes approximately the same length of time.

On some LRT systems, train headways are small and many persons in wheelchairs ride the system. In a case where a single train has two wheelchair boardings and alightings in each direction of its round trip (assuming 3 min per boarding or alighting), its round-trip travel time would increase by 12 min. Peak-hour headways of 10 min or less are common. On a system with a peak-period train headway of 10 min, if no built-in allowance is made for wheelchair boarding, service delays will result in a complete train being lost from the schedule. If an allowance is made for boarding persons in wheelchairs, an extra train would have to be inserted in the schedule in case wheelchair boarding did take place. Even in the case where an allowance is made for one wheelchair boarding and alighting per trip, a second or third wheelchair boarding would result in delays to schedule. If this situation occurred frequently, riders may perceive the service to be unreliable.

The use of LF-LRVs makes it significantly easier to install platforms to allow level boarding of LRVs. If level boarding can be provided, persons in wheelchairs could board unassisted within normal dwell times. This would have an extremely positive impact on schedule and fleet efficiency.

Fleet Requirements

Fleet requirements are a function of round-trip times, consist size, and required train headway. (Spares requirements have been ignored for simplicity.) Round-trip times include vehicle travel time, dwell time, layover time at the end of the line to allow the operator to switch vehicle ends, and schedule adherence time to allow for recovery from delays.

Cars required = (consist size X round-trip time) / train headway

and

Round-trip time = travel time + dwell time + layover time + schedule adherence.

Travel time is affected by vehicle performance (acceleration, braking, and maximum speed). European LF-LRVs often are specified with lower top speeds than North American vehicles. On systems with close station spacing and in-street running, this is not important. Where station spacing is larger, it would be prudent to increase motor power to provide improved performance. At a certain point, performance for any vehicle type will be limited by passenger comfort during acceleration and deceleration. In most cases, however, the difference between LF-LRV and conventional LRV travel times will be negligible.

Dwell times are significantly affected by car accessibility. We have already discussed the potential benefits of using LF-LRVs from the perspective of wheelchair boarding. While a wheelchair passenger can board from a level platform within a normal station stop time, an additional 2 to 4 min is required for each entry and exit using lifts. Gains can also be achieved for boarding of other passengers. It takes longer for a passenger boarding a train to climb 3 steps (conventional high-floor LRV) than to climb 1 step (LF-LRV). Observations indicate that equivalent dwell times of 24 sec, 14 sec and 10 sec would apply to boardings with 3 steps, 1 step, and level boarding, respectively. Similar proportions would apply for lighter and heavier boardings.

Layover time is unrelated to the use of conventional LRVs or LF-LRVs. Schedule adherence may be an issue if the LRT operation is prone to passenger-boarding delays, as is potentially the case with boardings by persons in wheelchairs. This issue has been discussed previously in the section on schedule reliability.

Passenger Demand

There are a number of reasons to anticipate some increases in ridership as a result of deployment of LF-LRVs. It is much easier to mount a single step to board a vehicle than to climb several steps. This is an important matter for many passengers including the aged or mobility impaired (those who can walk but with some difficulty or who use mobility devices). The provision of level boarding would be even better. It would facilitate easy boarding of wheelchairs, baby strollers, and passengers carrying bags. It is common in European cities to see public transportation systems heavily used by passengers with children and shoppers during off-peak periods. The potential for increases in ridership will vary tremendously depending on the land-use characteristics of the area served by the LRT system (e.g., shopping areas, dense residential areas).

A secondary benefit of the use of LF-LRVs can accrue from the limited impact of low platforms on the environment compared to high platforms. The area around the station can be used to improve the appeal and aesthetics of the destination, rather than merely serving as the area on which a platform is located.

Mixed-Fleet Operations

From an operations perspective, it is easiest to deal with a fleet in which all cars are similar. Any single failed car could then be replaced by any other available car. The mixing of LF-LRVs and conventional LRVs complicates operations.

If consists are mixed, as might be required to meet ADA compliance (one car per train rule), then the order of vehicles in the consist could become important, and/or the stopping location of the first car will vary depending on the car type. Failure of the only ADA-compliant car in a consist would require replacement with a like car. This will have an impact on the fleet's vehicle spare ratio requirements.

If the fleet is mixed, but consists are not, this will have a significantly smaller impact on operations. Additional effort will be required in scheduling and deployment of vehicles to ensure that vehicles start and end service each day at appropriate locations.

Fleet Maintenance

Experience to date suggests that there is no significant premium or savings in the maintenance of (Category 1 or Category 2) LF-LRVs versus conventional LRVs. Due to the use of novel technology in Category-3 vehicles, maintenance of those vehicles is expected to cost more, but there are presently insufficient data to quantify the cost premium.

The maintenance of a mixed LF-LRV and conventional LRV fleet will require additional inventory, staff training, and other inputs to ensure that staff can deal with the two different types of cars. This requirement will be similar to the situation where existing and replacement conventional LRVs are slightly different. Accordingly, this issue appears to be of minor importance.

A more serious matter relates to the maintenance facilities to be used. Major issues to be addressed include the following:

- Are the new vehicles longer than existing vehicles? If so, are pits, paint booths, and work areas large enough to accommodate the longer vehicles?
- If there are in-floor jacks in the facility, can they accommodate the new vehicles or be easily modified to do so? The additional articulations on Category-1 and Category-3 vehicles complicate jacking procedures.
- If large overhead cranes are used to lift car bodies for truck removal, is there sufficient crane capacity to allow lifting of the LF-LRV car bodies (particularly if there are more body sections)?

There are also some minor issues that should be considered. Many of the components found under conventional LRVs are placed on the roof of LF-LRVs. Therefore, raised (roof-level) platforms will be required to support the maintenance of LF-LRVs. This will complicate crane access to the car sides. Also, with work being conducted at car roof levels, work must be conducted in close proximity to the traction power distribution system. Extra precautions must be taken to prevent accidental injury of workers both from the power system and from falls.

Facilities can be established to support efficiently the maintenance of LF-LRVs and to support conventional LRVs. The requirement for a facility to support maintenance of both types of vehicles may result in some losses in efficiency. Individual assessment of facilities and maintenance strategies would be required to quantify impacts.

Adverse Climatic Conditions

LF-LRVs have lower underbody sections than conventional high-floor LRVs. In areas with heavy snow accumulation, clearing of snow from the right of way may be necessary to prevent snow from compacting under cars. With conventional LRVs, snow clearing is not necessary except in the most extreme circumstances.

EVALUATE COSTS AND BENEFITS

A cost/benefit analysis can be applied to each feasible option to determine the merit of that option relative to others and to assess the financial practicality of any option. Our analysis and discussion concentrates on the relative merit of LF-LRV versus conventional LRV solutions. Capital and operating costs are considered.

Capital Costs

Platforms for LF-LRVs will usually cost significantly less than high platforms for conventional LRVs. In many cases a low platform could be constructed as a raised sidewalk with a high curb. Because of the significantly reduced scale of LF-LRV platforms, landscaping and other aesthetic treatments sometimes necessary with high platforms can be reduced or eliminated. One of the most significant benefits regarding the use of LF-LRVs is that it is much easier to install low platforms to allow level boarding than it is to install high platforms for conventional LRVs. Costs of low platforms are less, and impacts and intrusion of the platform on the surroundings are also significantly reduced. Accordingly, low platforms can be installed in at least some areas where high platforms cannot.

Representative vehicle costs are shown in Chapter 2. Recent conventional LRV procurement costs for DART in Dallas and MUNI in San Francisco are $2.1 million and $2.2 million, respectively. Category-2 vehicle costs are expected to range from approximately +0 percent to +10 percent more than comparable conventional LRV prices. As the number of LF-LRV orders increases, it is anticipated that no premium cost will apply to LF-LRVs. Conversion costs to turn a conventional LRV into a Category-1 LF-LRV are estimated to be 30 percent of the cost of a new vehicle. Category-3 vehicles typically cost more than Category-2 vehicles. Because the technology and size of Category-3 vehicles vary widely, there will be a correspondingly wide range in prices.

Retrofit of existing infrastructure and systems may be necessary if LF-LRVs are applied to a system originally constructed to operate conventional LRVs. Platforms may have to be modified to match low door-sill heights. Yards and maintenance shops will likely require modification to accommodate roof-mounted equipment. In some cases, it may also be necessary to revise elements of the right of way, such as curve radii, although this would usually not be necessary. Retrofit will probably be unnecessary or of minor consequence for fare collection, traction power, and signaling systems. An exception would be the case where consist lengths increased, thereby necessitating revisions to stop locations and signal systems.

Opportunity cost should also be considered, although in some cases costs or benefits may not directly affect the agency. For example, consider the development of a new LRT system through a central business district (CBD) within a four-lane roadway with wide sidewalks. A high-platform solution would require use of two lanes for trains, two lanes for platforms, and sidewalks to allow passage by the platforms. Conversely, a LF-LRV solution could entail the use of raised sidewalks, thereby leaving two unobstructed traffic lanes. The cost associated with the loss (or retention) of the two lanes will depend on the use of the lanes and other access through the CBD. Opportunity cost also relates to the loss of utility of LRVs during retrofit in the case of development of Category-1 LF-LRVs.

As a general comment, note that conventional high-floor LRV platforms and vehicles are well suited to line-haul operation where much of the LRT right of way is separated from other land uses. Station spacing will be relatively large on a line of this type, so the cost of platform development relative to other costs will be small. On the other hand, where station spacing is close, where stops are located in streets or in close proximity to residential or commercial uses, and where aesthetics are important, there are considerable benefits to be gained in using LF-LRVs.

Operating Costs

Maintenance and operating costs for conventional LRVs versus LF-LRVs will vary depending on the low-floor vehicle technology used. In the event that a smaller LF-LRV fleet can be used because of faster boarding and therefore faster round-trip times, savings may be realized as a result of the reduced number of operations and maintenance staff required. Savings may also be available in energy consumption because LF-LRVs often weigh less than equivalent conventional LRVs.

EVALUATE NONCOST ISSUES

A number of LF-LRV benefits are difficult to quantify in dollar terms. Improved accessibility of the system will better serve the elderly and mobility-impaired. Use of low platforms instead of high platforms can significantly reduce the impact of an LRT system on the streetscape, making the street more friendly to commercial and pedestrian uses. Relevant issues may include the following:

- Vitality of the CBD core and other areas served by the LRT system,
- Quality of service,
- Aesthetics,
- Acceptance of the LRT system by the public and passengers,
- Time savings by users, and
- Safety (easier egress from vehicles stopped on the wayside in case of emergency).

SELECT THE BEST OPTION

Final selection of the best option will require the careful evaluation and assessment of cost and noncost issues. While on one hand it is extremely important that transportation agencies operate efficiently, it is also important that the agencies meet the expectations of the public and municipalities they serve. Weighing cost versus noncost issues is never easy. LF-LRV options provide new opportunities to meet multiple objectives that, in the past, might have been considered to be mutually exclusive.

A process that can be used to select competitive options has been described in Figure 78. In the next chapter, two examples are provided to demonstrate and clarify issues to be addressed.

CHAPTER 6

CASE STUDIES

Two illustrative examples have been developed to show, in a realistic North American context, issues and trade-offs relevant to the choice of low-floor light rail vehicles (LF-LRVs) versus conventional LRV options:

- Case Study 1—An extension to an existing low-platform LRT system; and
- Case Study 2—A new LRT system.

Minor changes in assumptions or LRT system characteristics will have a significant impact on which technology is most cost-effective. Furthermore, in Europe the move to LF-LRV implementation has been driven not by cost, but by service to the public. Whether or not costs indicate a LF-LRV or conventional LRV solution is best, other issues probably will have a major impact on the decision-making process.

CASE STUDY 1

The transit authority owns a fleet of conventional LRVs that meet present demand on the existing line. Characteristics for the existing line and fleet are defined in Table 12 and Table 13. An extension is planned that will increase the line length from 12.9 km (8 mi) to 32.2 km (20 mi). It is estimated that 69 LRVs will be required for the extended line. The extended line characteristics are defined in Table 14.

One major operating concern is that delays occur because of the frequent but randomly occurring boarding of persons in wheelchairs. The stations are equipped with lifts that bring persons in wheelchairs onto the vehicle via the side door, located just behind the operator. Loading wheelchairs involves stopping the vehicle so the appropriate side door properly aligns with the wayside lift; enabling, then raising the lift; and finally lowering and storing the lift. In many cases, passengers need assistance entering and exiting the lift because the lift is only slightly larger than the wheelchair. This process extends normal station dwell by 2 to 4 min. Usually there are no more than two wheelchair loadings and unloadings per round trip. With two boardings and alightings, trains can be delayed approximately 10 min per round trip on average.

The transit authority now wants to evaluate the costs and benefits of conventional LRV and LF-LRV procurement options. In both circumstances, new vehicles should closely match specifications for the existing vehicles.

OPTIONS AVAILABLE FOR CONSIDERATION

The transit authority has selected four options for consideration:

1. Purchase additional conventional LRVs, build appropriate and compatible infrastructure on the new extension;
2. Purchase additional conventional LRVs, retrofit all vehicles to make low-floor (Category-1 vehicles), retrofit existing line infrastructure;
3. Purchase LF-LRVs, retire existing fleet, retrofit existing line infrastructure; and

TABLE 12 Low-platform LRT system extension case study—characteristics of existing line

One-way line length	12 9 km (7.8 miles)
Stations	
• Number	14
• Average spacing	0.92 km (0 57 miles)
• Platform height above TOR (with LRVs)	152 mm (6 in)
• Platform length	61 m (200 ft)
• Wheelchair access	Wayside lift
Track parameters	
• Gauge	1,435 mm (4 ft 8 5 in)
• Minimum horizontal curve radius	25 m (82 ft)
• Maximum grade	6%
Performance using existing conventional LRVs	
• Average station dwell (no wheelchair)	18 sec
• Average round-trip speed	22 5 km/h (14 mph)
• Round-trip time	1 hr 9 min
Design peak-service headway	5 min
Design line capacity (crush)	3,500 pax/h/direction
No of trains required to maintain headway	14
Vehicles/train	2
Number of conventional LRVs required, including 15% spares	33
Required vehicle crush capacity	145
Expected frequency of wheelchair patrons boarding each vehicle in peak-service hours	2 per round trip

TABLE 13 Low-platform LRT system extension case study—existing conventional LRV characteristics

Type: six-axle, single articulation, double ended	
Dimensions	
• Length (over couplers)	25 m (82 ft)
• Width	2.64 m (8 ft 8 in)
• Height	3.35 m (11 ft)
• Floor height	965 mm (38 in)
• Number of steps	2 (on vehicle)
• Step height	267 mm (10.5 in)
• Coupler height	559 mm (22 in)
Buff strength	2 x vehicle weigh
Performance	
• Maximum speed	80 km/h (50 mph)
• Initial acceleration	1.3 m/s^2 (2.9 mph/sec)
• Service brake rate	1.3 m/s^2 (2.9 mph/sec)
Wheelchair access	Wayside lift
Air comfort system	Roof-mounted HVAC
Year of acquisition	1987
Unit purchase price	$1,092, 000

4. Purchase LF-LRVs to operate in mixed consists with existing fleet, retrofit existing line infrastructure.

In this example, the applicability assessment model is used to assist in finding the best option. In an actual analysis, suboptions such as high platforms versus ramps or lifts, would also need to be examined.

TABLE 14 Low-platform LRT system extension case study—characteristics of new line

One-way line length	32 2 km (20 miles)
Stations	
• Number	28
• Average spacing	1.1 km (0.7 miles)
Track parameters	
• Gauge	1435 mm (4 ft 8 5 in)
• Minimum horizontal curve radius	25 m (82 ft)
• Maximum grade	6%
Performance using existing conventional LRVs	
• Average station dwell (no wheelchair)	18 sec
• Average round-trip speed	25 8 km/h (16 mph)
• Round-trip time	2 hr 30 min
Design peak service headway	5 min
Design line capacity (crush)	5,000 pax/h/direction
No. of trains required to maintain headway	30
Vehicles/train	2
Number of LRVs required, including 15% spares	69
Required vehicle crush capacity	208
Expected frequency of wheel-chair patrons boarding each vehicle in peak service hours	2 per round trip

TECHNOLOGICAL RISK ASSESSMENT

New vehicles are required in as short a time as possible. The transit authority is therefore strongly inclined to choose proven equipment that has a history of satisfactory service performance. It has decided to impose proven equipment criteria, which require any major subsystem to have been operating in revenue service for at least 3 years (by mid-1995 when the contract will be signed) demonstrated with a fleet of 20 or more vehicles. Consequently, the list of acceptable designs is narrowed down to the vehicles/technologies listed in Table 15. The table shows that several low-floor designs meet the "proven equipment" criteria; however, all of these utilize conventional power trucks. The transit authority will not consider any Category-3 LF-LRVs.

PHYSICAL COMPATIBILITY EVALUATION

The transit authority must now evaluate five areas of physical compatibility—vehicle-to-vehicle, vehicle-to-right of way, vehicle-to-platform, vehicle-to-maintenance facility, and vehicle-to-systems.

Vehicle-to-Vehicle Compatibility

Coupling. To maximize operating flexibility, comply with ADA requirements, and provide maximum access to the disabled on both the existing line and new extension, the new LRVs must be capable of coupling with existing vehicles.

Except for the original vehicle manufacturer, all suppliers would require design modifications to ensure coupler and train-line compatibility with the existing vehicles. The engineering required would be greater for any vehicle type that has not previously coupled at the conventional 559 mm (22 in) height.

Buff Load. If the chosen LRV has not been in service in North America, then the manufacturer will have to re-engineer

TABLE 15 Low-platform LRT system extension case study—low-floor vehicles; proven equipment criteria

Category	City	Manufacturer	Type	% LF	No. in Order	Year	Power Truck	Trailing Truck
1	Mannheim	Duewag		8.9%	23	1991	Monomotor	Conventional two-axle
1	Amsterdam	Bombardier (BN)	11/12G	9%	45	1989	Bimotor	None
2	Rome	Socimi	T8000	54%	34	1990	Bimotor	Four independent wheels
2	Turin	Fiat (Firema)	5000	56%	54	1989	Monomotor	Four independent wheels
2	St. Etienne	GEC Alsthom	Be4/6	59%	25	1991	Monomotor	Small wheel
2	Geneva	ACM Vevey	Be4/6	60%	46	1984	Monomotor	Small wheel
2	Grenoble	GEC Alsthom	ZR 2000	65%	38	1987	Monomotor	Independent wheels on two cranked axles
2	Kassel	Duewag	NGT6C	70%	25	1990	Monomotor	EEF wheelset

the vehicle to meet the authority's required buff load strength (2 times the vehicle weight).

Vehicle-to-Right-of-Way Compatibility

The track structure, gauge, and horizontal and vertical alignment present no compatibility problems for any vehicle being considered. The maximum grade along the new and existing line is less than 6 percent; therefore, adhesion capability of LF-LRVs is not an issue.

Vehicle-to-Platform Compatibility

Platform Height. The transit authority paid particular attention to the aesthetics of existing line stations and installed pleasing curb-level platforms. Raising station platforms to allow level boarding of conventional LRVs is considered infeasible. In fact, the authority considered and rejected the idea of using high platforms in construction of the original line. The authority is considering two options for the stations, depending on the vehicle type purchased:

- **Conventional LRV.** Construct curb-level platforms at the new stations with wayside lifts to allow boarding for those with mobility restrictions.
- **LF-LRV.** Construct low-level platforms, essentially a raised curb, at the new stations. The existing vehicles have two steps, the bottom one being 432 mm (17 in) above TOR, when the vehicle is empty. All stations are on tangent track. The station platforms can therefore be constructed to 350 mm (14 in) above TOR to allow level boarding onto LF-LRVs. Passengers boarding the conventional vehicles would have an initial step, onto the LRV, of 82 mm (3 in). The existing stations would have a new top course placed on top of the existing platforms, and rails and architectural features would be adjusted.

Platform Length. The platforms on the existing route, and those proposed for the extension, are 61 m (200 ft) long. Conventional LRVs and Category-2 LF-LRVs will be specified so that existing platform lengths are not exceeded. If the transit authority chooses to convert the existing six-axle LRV fleet to achieve a 10 percent to 15 percent low-floor area (i.e., develop Category-1 vehicles), this would increase each LRV's length by approximately 6 m (20 ft). This would require lengthening existing platforms. The stations are not near street intersections, so extensions are possible.

Vehicle-to-Maintenance Facility Compatibility

The transit authority's yard has surplus capacity that can handle the increased fleet size, but the existing maintenance facility will require expansion. Facility requirements for extra conventional LRVs will be different from those for LF-LRVs, but the facility cost is expected to be approximately the same for conventional and Category-2 vehicles. If Category-1 LRVs are used, some modification of the existing facility will be required to handle the increased car length.

Vehicle-to-Systems Compatibility

Signaling. Preliminary work by the transit authority's engineering department regarding safe braking distances suggests that Category-1 vehicles will not pose a safety problem, and changes to track circuits and signals will not be needed. However, more detailed tests will be required to verify this. There are no problems anticipated with the use of additional conventional LRVs or Category-2 LF-LRVs.

Power Consumption (as a function of mass). Some power savings should accrue from the use of LF-LRVs. European LF-LRVs have a specific mass approximately 10 percent lower than conventional LRVs, on average. Bringing the vehicles to North American buff load specification will increase the vehicle specific mass by approximately 3 percent (based on Portland's experience). Therefore, the transit authority estimates a 7 percent mass reduction can be achieved. Taking into account system passenger loading and operating characteristics, a savings of 2.7 percent of traction power energy costs is expected.

Alternatively, the authority estimates that converting its entire fleet to Category-1 vehicles will result in a running fleet mass that is 18 percent higher (25% longer, 10% lighter, 3% buff load penalty) but with increased vehicle capacity. Premium energy costs are estimated at 7 percent.

Fare Collection. The existing POP system will not be affected by the vehicle type.

OPERATIONAL IMPACT QUANTIFICATION

Vehicle Performance

The new vehicle must match existing performance standards. If a European LRV is selected, improvements to the propulsion system will be required.

Round-Trip Time

The authority currently uses 14 trains on a 5-min headway during peak hours. Wheelchair boardings are common, and the boarding and alighting of two wheelchairs per train per round trip often results in service delays of 10 min. This is considered unacceptable by Operations. To accommodate this, an extra 10 min for schedule adherence will have to be built into the extended line schedule, if conventional LRVs are purchased. As a result, an additional two conventional LRV trains will be required to provide service during peak hours.

The authority expects that selection of LF-LRVs will result in reduced round-trip times and vehicle savings for the following reasons:

- Wheelchair boarding time can take place within normal station dwells since level boarding will be provided for; therefore, no additional vehicles will be needed to compensate for this.
- Boarding time onto the LF-LRV for all other passengers (especially the elderly and passengers with packages or pushing strollers) will be reduced. The peak consist will be a coupled conventional/low-floor train, so some passengers will still be boarding via the conventional LRV. The authority expects that the average station dwell time will drop from 18 sec to 16 sec. The 2-sec reduction in station dwell times will add a buffer of approximately 2 min (over 56 station stops) to the running schedule.

Fleet Mix

The authority is counting on rapid wheelchair boarding and alighting of LF-LRVs. After careful consideration, Operations decided that low-floor boarding locations be clearly marked, and that trains consistently stop in the same location. Accordingly, vehicles will always operate with the LF-LRV in front on the inbound trip, and the conventional LRV in front on the outbound trip. When passenger demand drops off, LF-LRVs can be operated as single car consists. Cars will stop at LF-LRV boarding locations at these times.

Given that yard capacity is not a problem, the need to store both conventional LRV and LF-LRV operating spares on separate tracks and the need to break and make mixed consists is of minor significance.

Training

The transit authority will be hiring additional operations and maintenance staff for the line extension. Therefore, operations and maintenance training will be required regardless of the vehicle procured. The introduction of LF-LRVs would require more extensive training requirements.

COST ESTIMATION

Because the existing fleet was acquired 7 years ago and the procurement specification required a 25-year design life, the present LRVs should be operable for another 18 years. The cost of purchasing identical additional vehicles is estimated to be $1,900,000 to $2,200,000, so the retained value is high, but no potential buyer could be found who was willing to pay anything near that price for used vehicles. The service and reliability performance of the vehicles has been satisfactory and maintenance costs are about average for the industry. The authority therefore eliminates Option 3 from consideration, which was based on retirement of the existing fleet.

A first-cut estimate for the remaining three options is shown in Table 16. Note that the costs are provided for illustrative purposes only, and that the only price elements shown are those in which prices will vary by option.

NONCOST ISSUES

The line extension will serve an outlying suburban area. Residents and passengers have been vocal in expressing their expectations for the extension.

Aesthetics

Low- or no-platform stations are favored. Strong objections to the visual impact of high-platform stations adjacent to resi-

TABLE 16 First-cut cost estimate for remaining options

	CONVENTIONAL FLEET		CATEGORY-1 FLEET		MIXED HIGH/LOW FLEET	
Vehicles						
Per Vehicle Cost	$2,200,000		$2,200,000		$2,200,000	
Low-Floor Design Premium	$0		$220,000		$220,000	
Number of Vehicles	36		36		36	
Subtotal		$79,200,000		$87,120,000		$87,120,000
Modify Existing Vehicles	$0					
Per Vehicle Cost	0		$550,000		$0	
Number of Vehicles			33		0	
Subtotal		$0		$18,150,000		$0
New Stations						
Curb-Level Platform	$75,000		$0		$0	
Low-Level Platform	$0		$150,000		$150,000	
Wayside Lift	$50,000		$0		$0	
Number of New Stations	14		14		14	
Subtotal		$1,750,000		$2,100,000		$2,100,000
Existing Stations Modification						
Raise Platform/Remove Lifts	$0		$100,000		$100,000	
Adapt Platform to Longer Vehicles	$0		$50,000		$0	
Number of Existing Stations	14		14		14	
Subtotal		$0		$2,100,000		$1,400,000
Existing Maintenance Facility Modification	$0	$0	$100,000	$100,000	$0	$0
Safety Distance Testing Over Alignment	$0	$0	$100,000	$100,000	$0	$0
Training						
Operations	$50,000		$75,000		$75,000	
Maintenance	$50,000		$100,000		$100,000	
Subtotal		$100,000		$175,000		$175,000
Additional Recurring Cost						
Power Consumption	$0		$0		($40,500)	
Minimum Vehicle Life (yr)	15		15		15	
Net Present Value (4%)		$0		$0		($450,295)
Schedule Reliability Capital Cost						
Four Additional Vehicles	$8,800,000	$8,800,000	$0	$0	$0	$0
Schedule Reliability Recurring Cost						
Operations (2 consists, 2 shifts)	$160,000		$0		$0	
Maintenance ($2 00 per mile)	$83,200		$0		$0	
Expected Vehicle Life (yr.)	15		15		15	
Net Present Value (4%)		$2,703,992		$0		$0
TOTAL ESTIMATED COST		$92,553,992		$110,745,000		$90,344,705

dential areas were heard. A request for input on the possibility of raising existing platforms in the CBD area by 200 mm (8 in) was met with indifference. The general population was not bothered by the wayside lifts; most nonriders were unable to identify the lifts as such.

Meeting the Needs of Persons in Wheelchairs and Other Passengers

Persons in wheelchairs have expressed extreme concern about the use of wayside lifts for boarding. It takes 2.5 min on average for one person in a wheelchair to board a train, while other passengers can board in seconds. Persons in wheelchairs feel self-conscious when using the system and say that it is unfair that their use of the system is often resented by other passengers.

Positive responses on the possibility of level boarding were also received from focus groups representing the elderly and those with limited ambulatory abilities (such as those with heart conditions, hip problems, etc.). The possibility of introducing level boarding was regarded as a tremendous step forward by all focus groups.

Impact on Businesses Along the Route

There are many businesses located near stations in the CBD area. While extremely concerned and resistant to the installation of high platforms, they had no objection to installing low platforms. The possibility of increased ridership was seen as a plus. The only remaining concern was that signage and shelters adjacent to stops should be located so that business signs and display windows remained clearly visible to passersby.

Project Objectives

There is an expectation of new ridership originating from the existing segment since new origin/destination pairs will be created. Current passenger complaints regarding schedule unreliability (as a result of delays from boarding persons in wheelchairs) are a serious concern. The authority wants improved schedule reliability.

THE NEXT STEPS

The next steps will include refinement of options and costs, participative involvement with stakeholders to obtain feedback, then weighing of cost and other considerations to make the best decision.

CASE STUDY 2

The transit authority is taking advantage of an existing dedicated right-of-way corridor to build a new LRT line to connect an outlying business district to the CBD. Ridership forecasts were developed during early planning stages, and alignment design development has just recently been completed. The route characteristics are shown in Table 17. Members of the authority are familiar with LRT systems in North America and Europe. The authority was impressed with the use of Category-3 LF-LRVs in Europe and might be willing to accept increased technological risk in the interest of obtaining a 100 percent low-floor solution. The authority sees itself as an industry leader and is accustomed to implementing new technology solutions and careful risk management. The authority now wishes to evaluate the costs and benefits of purchasing conventional LRVs and LF-LRVs.

TABLE 17 New LRT system case study—characteristics of new line

One-way line length	24 1 km (15 miles)
Stations	
• Number	30
• Average spacing	0 8 km (0 5 miles)
• Vehicle entrance	Level—*Steps*
• Wheelchair access	Direct—*Ramp/Lift*
Track parameters	
• Gauge	1,435 mm (4 ft 8.5 in)
• Minimum horizontal curve radius	18.3 m (60 ft)
• Maximum grade	5%
Estimated system performance	
• Average station dwell (no wheelchairs)	13 sec—*18 sec*
• Average round-trip speed	25 km/h (15 5 mph)—*23.5 km/h (14.5 mph)*
• Round-trip time	1 hr 55 min—*2 hr*
Design peak service headway	5 min
Design line capacity (crush)	4,500 pax/h/direction
No of trains required to maintain headway	23—*24*
Vehicles/train	2
Number of vehicle required, including 15% spares	53—*56*
Required vehicle crush capacity	188
Expected frequency of wheelchair patrons boarding each vehicle in peak service hours	2 per round trip

OPTIONS AVAILABLE FOR CONSIDERATION

The authority has narrowed down the options to be considered to three:

1. Purchase conventional LRVs; build curb-level station platforms with lifts for ADA compliance.
2. Purchase conventional LRVs; build high-level station platforms to provide level boarding access to vehicles.
3. Purchase LF-LRVs; build low-level station platforms to provide level boarding access.

The applicability assessment model is used to assess these options.

TECHNOLOGICAL RISK ASSESSMENT

The authority expects the new LRT system to begin operation in 3 years. Given this time frame, the authority might accept a vehicle that has limited in-time service, provided reliability assessments are positive. However, it would not accept a completely new vehicle design. Accordingly, proven equipment criteria were established that require any major subsystem to have been operating in revenue service for at least 2 years (by mid-1995, when the contract will be signed) in a fleet of 10 or more vehicles. The list of acceptable designs is narrowed down to the vehicles/technologies listed in Table 18. The table shows that the authority will consider a wide variety of designs, including four Category-3 solutions, three with novel power trucks.

PHYSICAL COMPATIBILITY EVALUATION

Vehicle-to-Vehicle Compatibility

Coupling. Coupling is not expected to be an issue. If a manufacturer's designed vehicles do not couple, then the design would have to be modified to accommodate coupling.

Buff Load. If it does not already meet North American buff load conventions and authority requirements (1.5 to 2 times the vehicle weight), LRVs would have to be modified to achieve compliance. The authority does not want to take on possible additional risk from accepting a lower buff load capability; thus, it has specified a requirement of 1.5 times the vehicle weight.

Vehicle-to-Right-of-Way Compatibility

The existing alignment and maximum grade of 5 percent pose no problems to any vehicles under consideration.

Vehicle-to-Platform Compatibility

The authority has decided that while it might prefer a low-platform solution, cost is a major issue. Low platforms are seen to be nothing more than raised curbs. High platforms would require carefully applied architectural treatment to ensure the platforms did not become eyesores. Vehicles will require load-leveling capabilities.

Vehicle-to-Maintenance Facility Compatibility

Facility design will not start until a vehicle type is selected. The cost of facility development is expected to be the same regardless of the vehicle selected.

Vehicle-to-Systems Compatibility

Signaling. Selection of vehicle technology will not influence the signaling system.

Power Consumption. The authority estimates that a Category-2 LF-LRV will weigh approximately 7 percent less than an equivalent conventional vehicle, and a Category-3 LF-LRV will weigh 12 percent less. Corresponding savings of 5.5 percent and 10.5 percent of energy costs are expected. The savings of 5.5 percent is used for the cost estimate.

Fare Collection. The authority has decided to implement a proof-of-payment fare collection system and is carefully looking at ways to improve transfers to and from other modes of transportation. Selection of vehicle type will not affect fare collection decisions.

OPERATIONAL IMPACT QUANTIFICATION

Vehicle Performance

The authority requires that the new vehicles must perform to usual North American standards. A top speed of 80 km/h (50 mph) is desirable, particularly in case the line is extended. Competing European LRVs will require enhanced propulsion systems.

Round-Trip Time

According to the preliminary system characteristics (see Table 16), if the authority purchases conventional LRVs with steps, 24 trains would be utilized during peak hours. These 24 trains maintain their 5-min headway as long as no wheelchairs need to be lifted onto any of the trains. The authority's Operations Department has determined that the peak fleet (for the option using LRVs with steps) would have to be increased by two trains during peak hours to compensate for delays because of wheelchair boarding.

The authority expects that the time savings resulting from the purchase of level-boarding vehicles for the fleet will be two-fold:

1. The boarding of persons in wheelchairs can take place within normal station dwells because level boarding will be provided. Therefore, no additional vehicles will be needed to compensate for this.
2. Boarding time for all other passengers (especially the elderly and passengers carrying packages or pushing strollers) will be reduced at all entrances so that the average station dwell time will be 13 sec, as opposed to 18 sec for LRVs with steps.

A 5-sec reduction in station dwell time would mean a reduction in the round-trip time on the line of 5 min.

Taking into consideration the reduced round-trip time, if the authority incorporates level boarding, 23 trains would be utilized during peak hours (as shown in Table 17). These 23 trains maintain their 5-min headway whether or not wheelchair boardings occur.

Training

Training costs are expected to be the same regardless of the type of vehicle selected.

TABLE 18 New LRT system case study—low-floor vehicles; proven equipment criteria

Category	Manufacturer	Type	Power Truck	Trailing Truck
1	AEG (MAN)	N82	Monomotor	Conventional 2-axle
1	Bombardier (BN)	11/12G	Bimotor	None
1	Bombardier (BN)		Monomotor	Conventional 2-axle
1	Duewag	GT 8C	Monomotor	None
1	Duewag	GT8D	Bimotor	None
1	Duewag	GT 8	Monomotor	None
1	Duewag		Monomotor	Conventional 2-axle
1	GEC Alsthom		Monomotor	Conventional 2-axle
1	LHB	GT 8/8C	Monomotor	None
1	Schindler (SIG)	Be 4/4	Monomotor	Conventional 2-axle
1	Schindler (SIG)	ABe4/8	Bimotor	Conventional two-axle
2	ACM Vevey	Be4/6(8)	Monomotor	Small wheel
2	ACM Vevey	ABe4/6	Bimotor	Small wheel
2	Bombardier (Rotax)	T	Bimotor	Single-axle conventional wheelset steered by articulation
2	Duewag	NGT6C	Monomotor	EEF wheelset
2	Duewag	MGT6D	Bimotor	EEF wheelset
2	Fiat (Firema)	5000	Monomotor	Four independent wheels
2	GEC Alsthom	Be4/6	Monomotor	Small wheel
2	GEC Alsthom	ZR 2000	Monomotor	Independent wheels on two cranked axle
2	Socimi	T8000	Bimotor	Four independent wheels
3	ABB Henschel	Vario-tram	Four hub motor-driven, independent wheels	Four independent wheels
3	AEG (MAN)	GT6(8)N	Independent wheels, one pair driven, one pair free-wheeling	None
3	Breda	VLC	Transverse-mounted motor drives both axles through parallel gears and cardan shaft	Single wheelset with small independent wheels built into articulation
3	Duewag	R3.1	Four hub motor-driven, independent wheels	Four independent wheels

TABLE 19 Preliminary cost estimate for case-2 options

	CONVENTIONAL WITH STEPS		CONVENTIONAL WITH HIGH PLATFORM		LOW WITH LOW PLATFORM	
Vehicles						
Per Vehicle Cost	$2,200,000		$2,200,000		$2,200,000	
Low-Floor Design Premium	$0		$0		$220,000	
Number of Vehicles	55		53		53	
Subtotal		$121,000,000		$116,600,000		$128,260,000
New Stations						
Curb-Level Platform	$75,000		$0		$0	
Low-Level Platform	$0		$0		$150,000	
High-Level Platform	$0		$1,200,000			
Wayside Lift	$50,000		$0		$0	
Number of New Stations	30		30		30	
Subtotal		$3,750,000		$36,000,000		$4,500,000
Additional Recurring Cost						
Operations (1 consist, 2 shifts)	$80,000		$0		$0	
Power Consumption	$0		$0		($68,750)	
Maintenance ($2.00 per mile)	$31,200		$0		$0	
Minimum Vehicle Life (yr)	15		15		15	
Net Present Value (4%)		$1,236,365		$0		($764,389)
Schedule Reliability Capital Cost						
Four Additional Vehicles	$8,800,000	$8,800,000	$0	$0	$0	$0
Schedule Reliability Recurring Cost						
Operations (2 consists, 2 shifts)	$160,000		$0		$0	
Maintenance ($2 00 per mile)	$62,400		$0		$0	
Minimum Vehicle Life (yr)	15		15		15	
Net Present Value (4%)		$2,472,729		$0		$0
TOTAL ESTIMATED COST		$137,259,094		$152,600,000		$131,995,611

COST ESTIMATION

A preliminary cost estimate for the three options is provided in Table 19. Note that costs are provided for illustration only, and that only elements in which prices vary by option are shown.

NONCOST ISSUES

The authority, through focus group meetings, passenger surveys, and feedback from businesses and elected officials, has found that there are a number of issues that cannot be assessed purely in terms of costs.

Aesthetics

The public has resisted some transportation projects in the past. Some transportation improvements have been seen as disruptive and adversely affecting the areas they were intended to serve. Naturally, low platforms are preferred, but high platforms would be considered acceptable provided they are carefully blended into the existing environment.

Meeting the Needs of Persons in Wheelchairs and Other Passengers

Lobbying groups prefer low-floor, level-boarding solutions. The installation of high platforms still requires passengers to get from sidewalk level to top-of-platform level.

Impact on the City

Some areas along the line are prime candidates for redevelopment. The city has expressed two concerns over the potential installation of high platforms:

- High platforms are utilitarian but detract from the look of the line. Installation of high platforms alongside historic buildings on the route would completely change the feel of the area. Minimalist platforms are seen to be much

more friendly to rejuvenation of the once vibrant commercial areas.
- The installation of high platforms will take up two extra lanes in the existing roadway. Aging utilities in the area will require replacement in the near future. If widened sidewalks are also used to double as low-platform areas, some room will be available along the alignment to establish a utility corridor. Alternatively, utilities would have to be relocated under the sidewalks in close proximity to shallow building foundations. Use of high platforms would preclude the establishment of a utility corridor.

System Growth Capability

The authority is optimistic regarding future expansion of the line. Therefore, long-term implications of present decisions are being carefully evaluated. The dramatic trend to use of 100 percent LF-LRVs in Europe will have at least some impact on future policy decisions here. A decision to install a high-platform system in the face of this knowledge might be unpopular, so adequate justification for a conventional LRV solution would be required.

Acceptance by the Public

The authority has limited budgets and sees a well-used LRT system as the next step in developing an integrated public transportation system that the public will want to use. Traffic congestion and delays in bus service have been the cause for numerous complaints indicating that schedule reliability will be an issue. City council members have stated a preference for LF-LRV solutions since this would do more to prompt revitalization along the line thereby increasing the city's tax base. Given that a LF-LRV seems feasible, focus groups have stated their strong preference for LF-LRVs and the improved accessibility these vehicles provide.

THE NEXT STEPS

The next steps will include refining options and costs, obtaining feedback from stakeholders, and then weighing cost and other considerations to make the best decision.

CHAPTER 7

CONCLUSIONS

INTRODUCTION

There is a growing trend toward the use of low-floor light rail vehicles (LF-LRVs)—as of early 1994, over 1,700 LF-LRVs had been delivered to or ordered by operators in Europe and North America. Since the introduction of LF-LRVs in Europe over 10 years ago, approximately 75 percent of new LRV orders in Europe have been for LF-LRVs.

LF-LRVs provide improved accessibility and are more easily integrated into the existing environment than conventional LRVs. Low floors are typically 350 mm (13.8 in) or less above TOR compared to 910 mm (35.8 in) or more for high floors. Only a single step is needed to board LF-LRVs from curb level compared to three or four steps for conventional high-floor LRVs. Installation of platforms, which might be something as simple as a raised curb, can provide level boarding of the LF-LRV. In contrast, the higher platforms necessary to match high-floor vehicles extend high above the adjacent sidewalk.

Accessibility is becoming a much more important issue in North America. Transit agencies see the increasing need to provide barrier-free service. In the United States, the Americans with Disabilities Act of 1990 requires that rail transportation "... be readily accessible to and usable by individuals with disabilities, including individuals who use wheelchairs ..."

There are problems with making conventional LRVs accessible. High platforms can be provided (or high mini-platforms) to provide level boarding, but these take up considerable space and require a wider right of way. Carborne or wayside lifts can be used to raise wheelchairs from street level to the level of the car floor, but lifts are slow and not failproof. While a person in a wheelchair can board or exit a car during a normal station dwell time where level boarding is provided, it takes 2 to 4 min for this passenger to board or to exit a vehicle when a lift is used. On systems with tight peak-period headways, one person in a wheelchair boarding and exiting a car could potentially cause a delay significant enough that a train could be lost from the peak-period schedule. Also, cars served by lifts or mini-platforms can usually only accommodate two wheelchairs per train. LF-LRVs offer new solutions to these problems.

CLASSIFICATION OF LF-LRVS

There is a wide variety LF-LRVs available, and many of them have a great deal of similarity to each other. An extensive database record of available vehicles is provided in Appendix A. We have developed three categories to simplify discussion and understanding of LF-LRVs:

- *Category 1.* Vehicles use conventional powered and trailing trucks. Vehicles are usually created by adding a body section, articulation, and an additional truck into a conventional LRV. The new body section contains the low-floor section (typically 9% to 15% of the floor area). The vehicles make extensive use of proven technology. Maintenance and operating costs are comparable to those for conventional high-floor vehicles.
- *Category 2.* Conventional motored trucks are used on these vehicles, so vehicle propulsion is not affected. To increase the amount of low-floor area in the vehicle (typically 50% to 70% of the floor area), modified trailer trucks are used. The trailing trucks might use smaller wheels, cranked axles, or independent wheels to accommodate the low-floor area above. The Portland vehicle is an example of a Category-2 vehicle. As in the case of Category-1 vehicles, Category-2 vehicles make extensive use of proven technology. The modified trailer trucks have also proven to be very cost-effective and reliable, so vehicle operating and maintenance costs are comparable to conventional LRVs.
- *Category 3.* Innovative motored and trailing trucks and other novel technologies are used to create vehicles with a 100 percent low-floor area. Unlike conventional LRVs, standard modules are used to create vehicles with multiple articulations, and running gear and drive technologies are substantially different than those used on conventional vehicles. Designs vary widely, and the technology is still rapidly evolving. Category-3 vehicles have not been in service long enough to allow assessment of long-term reliability, maintainability, or cost-effectiveness.

COMPARISON OF CONVENTIONAL AND LF-LRVS

The price of conventional LRVs ranges from $2 million to $2.2 million (1994 dollars) per car for orders of 30 or more cars based on recent procurement information from MUNI and DART. The premium cost for LF-LRVs compared to a similar conventional vehicle is between 0 percent and 30 percent. In the case of the Portland Category-2 vehicle, the premium was approximately 10 percent. With the increasing number of low-floor vehicle orders, the premium is expected to disappear completely over the next 5 years.

Virtually all experience with LF-LRVs to date comes from Europe. European practices differ in some ways from those in North America, and the following issues warrant attention in the adaptation of European vehicles:

- *Buff Loads.* European LRVs are designed to withstand buff loads of 20 to 40 tonnes, while North American vehicles are usually required to withstand loads equal to two times the car weight. The significant increase in longitudinal load-carrying capacity requires strengthening of European vehicles and will result in an increase to the vehicle's mass. In the case of mixed consist operation, particularly with conventional and Category-3 vehicles, this problem would be exacerbated.
- *Coupling.* Category-1 and Category-2 vehicles use conventional power trucks; therefore, coupling to conventional vehicles can be accommodated. Category-3 vehicles are often lengthened through the addition of a body section and articulation rather than by coupling to a second vehicle. Because of the different floor heights, coupling Category-3 LF-LRVs with Category-1 or Category-2 LF-LRVs would be problematic.
- *Operating Speed.* Many European LF-LRVs have a top speed of 70 km/h (44 mph), which is substantially slower than some North American transit systems. With operation in city streets and close station spacing, common in Europe, higher top speeds are unimportant. Propulsion systems can be enhanced to provide vehicles that meet North American criteria.
- *Maintenance Facilities.* With the reduced availability of space under the car to support equipment, LF-LRVs make use of space above the roof of the car. As a result, less work is performed in pits, and more work is performed at the car roof level. Raised platforms are needed to support these efforts. Also, many LF-LRVs are longer and have more body sections than conventional LRVs. Requirements for jacks, cranes, and pit and paint booth lengths may vary from those for existing fleets.
- *Fire Resistance.* In order to reduce vehicle weights and improve energy consumption, European vehicles often use lightweight materials. Fire resistance of the carbody, and fire hardening of vehicle roofs are issues that need to be considered.

APPLICABILITY OF LF-LRVS IN NORTH AMERICA

There is a great deal of variety in the fleets operated by North American transit agencies and the accompanying right of way, systems, and station infrastructure. Also, depending on whether the agency is procuring vehicles or improving accessibility of an existing line, building a line extension, or constructing a brand new line, the key issues to be addressed will vary. An applicability framework assessment model was developed to assist agencies in the evaluation of LF-LRV applicability. Steps defined in the model are as follows:

- *Define Options.* The availability of LF-LRV solutions provides a new range of options to be considered. These include mixed consist operation (conventional LRVs and LF-LRVs), and the construction of low platforms to allow level boarding at the low-floor level. Other options relating to LF-LRVs are similar to high-floor options.
- *Assess Technological Risk.* While Category-1 and Category-2 LF-LRVs make extensive use of proven technology with a history of reliability and performance, Category-3 LF-LRVs incorporate many technological innovations never previously tried. Agencies should select a vehicle consistent with the degree of risk they are willing to accept.
- *Evaluate Physical Compatibility.* Compatibility of LF-LRVs to the existing infrastructure must be assessed. If a new system is being constructed, the physical infrastructure and the vehicles can be designed to complement each other. If it is an existing system, the ability of cars to run in mixed consists and the potential need for retrofits of platforms, shops, right of way, and systems must be considered. Where the existing line has a number of existing high platforms to provide level boarding of conventional LRVs, use of LF-LRVs is likely inappropriate.
- *Quantify Operational Impacts.* The operation and maintenance of a mixed fleet complicates work practices. At the same time, LF-LRVs offer many advantages. Improved accessibility is an important consideration. If level boarding of LF-LRVs can be provided where level boarding of conventional LRVs cannot, there is the opportunity for a significant improvement in service reliability and reduction in round-trip time. Reduced round-trip times may allow reductions in fleet requirements. For example, with wayside lift loading and unloading of two persons in wheelchairs, a system delay of 10 min or more is possible. Delays of 10 min per trip will manifest either as reduced service reliability or increased vehicles needed to compensate for the delays. With 10-min headways, one additional train would be required. Level boarding of LF-LRVs effectively removes boarding delays and the need for additional vehicles.
- *Evaluate Costs and Benefits.* LF-LRVs currently cost approximately 0 percent to 10 percent more than similar conventional vehicles. It is anticipated that in the near future the cost premium for LF-LRVs will disappear. In addition, loading platforms can be constructed much more cheaply for LF-LRVs, and operating efficiencies may result in fleet requirement savings.
- *Evaluate Noncost Issues.* Transit agencies should weigh a number of noncost considerations. The public increasingly expects barrier-free accessibility to public transportation. The degree of visibility and intrusion of system infrastructure into the existing environment around an LRT line are directly affected by the type of vehicle used. LF-LRVs provide superior solutions with respect to both concerns.

SUGGESTED RESEARCH

The move to LF-LRVs in Europe is driven by the desire to increase system accessibility. Quantitative data on maintenance costs and cost comparisons of LF-LRVs to conventional LRVs were not recorded by the European transit agencies surveyed, and thus were not available for comparative analyses to be performed.

Additional information on the following would be of use to North American transit agencies:

- Quantitative review of maintenance types and costs for maintenance of LF-LRVs versus conventional LRVs,
- Qualitative and quantitative review of reliability and maintainability performance of LF-LRVs versus conventional LRVs,
- Investigation of maintenance procedures developed to meet the unique characteristics of LF-LRVs,
- Investigation of maintenance facility features and requirements to serve the differing needs of LF-LRVs,
- Public acceptance of LF-LRVs,
- Investigation of LF-LRV buff strength and the difficulty in achieving current North American conventions,
- Performance of LF-LRVs in heavy snow conditions, and
- Category-3 LF-LRV technology.

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