Application of Light-Rail Transit Vehicles

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Flexibility is the primary concept associated with light-rail transit (LRT). This flexibility includes its application, implementation, operation, and capacity and has clear implications for light-rail vehicle (LRV) design, since the capabilities of a vehicle selected for a specific system must meet the requirements of that system. The thesis of this paper is that all such LRT requirements can be met by a family of vehicle designs based on standardized subsystem componentry. System requirements are dealt with in four categories—capacity, geometry, performance, and impact; the vehicle components include the car-body, propulsion, suspension, and command and control subsystems. The alternatives and options within each category are identified, and the matching process is examined. Particular attention is devoted to car-body alternatives; it is shown that the use of single-ended LRVs is desirable whenever system characteristics permit and that articulation is properly used to solve clearance rather than capacity problems. The Toronto Transit Commission's ordering of new LRVs is used to illustrate the process of selecting vehicle attributes that meet the system requirements and the process of moving from a definition of desirable vehicle characteristics through development and testing to car delivery. The ability to derive several vehicle designs from the basic design is discussed in the context of ongoing development activities in order to prove the feasibility of the family-of-vehicles idea.

Numerous definitions of light-rail transit (LRT) have been advanced in recent years to describe the electrically powered, medium-capacity, steel-wheel-on-steel-rail transit mode that is in the midst of a renaissance in North America. At the TRB conference on LRT held in Philadelphia in 1975, LRT was defined as "an urban electric railway having a largely segregated but not necessarily grade-separated right-of-way . . . that provides a medium-speed service for a medium volume of passengers" (1) and as "[encompassing] a wide range of electrically propelled, steel-wheel vehicles" (2). In these and most other descriptions, the key concept is the mode's inherent flexibility with respect to

1. Application—a wide variety of appropriate rights-of-way in urban environments;
2. Implementation—staged upgrading of a minimum system in conjunction with the development of passenger demand;
3. Operation—a range of services, passenger handling techniques, and operating policies; and
4. Capacity—ability to handle passenger volumes ranging from a few thousand to approximately 20 000 passengers/h/direction.

This flexibility also has implications for system costs, since it enables LRT planners to choose from a range of design standards and a variety of techniques for coping with right-of-way and operations problems and thereby to match their system costs to the economic objectives of the transit facility. This discussion is concerned with the implications of this flexibility for LRT equipment and infrastructure, in particular for light-rail vehicles (LRVs).

The thesis of this paper is that the flexibility that is inherent in the LRV concept demands a degree of vehicle flexibility that can best be provided through a family of complementary designs offering a range of capacity and performance but commonality in major components. Producing such a family of vehicle designs depends on major componentry—propulsion, suspension, car body, command and control—that can be efficiently integrated to form the specific vehicles required to meet differing operating requirements. This thesis is in many respects an extension of the approach to vehicle design embodied in the Presidents' Conference Committee (PCC) car. Thousands of streetcars, including many in Europe, were produced by using the same basic PCC body design with modifications, such as increased width and double ending, to suit individual operator's needs. In this paper, commonality is extended beyond vehicle body design to include the major subsystems.

For LRT to be most effective, the specific componentry combination and the resulting vehicle characteristics selected for any application must correspond closely to the characteristics of the LRT right-of-way: stations, geometrics, desired type and level of service, and planned operation. To the extent that operators are able to define similar requirements for transit applications, vehicle standardization is possible. However, if operational circumstances vary, as has occurred in the past and will apparently continue in the future, then a family of vehicles will be required to provide the necessary service. An examination of the nature of operating requirements typically prescribed for LRT systems is instructive in defining the requirements for rolling stock.

OPERATING REQUIREMENTS

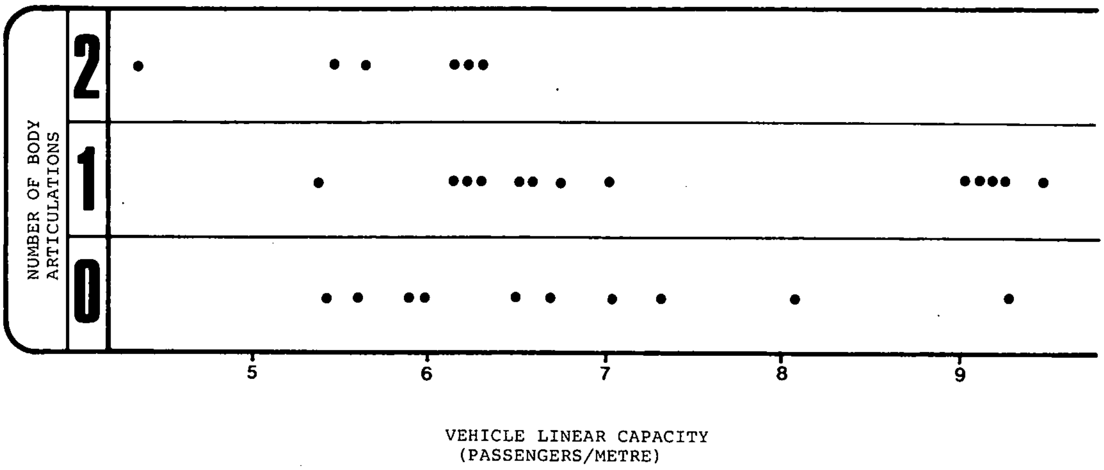
A set of operating requirements or desired characteristics must be established to describe the various circumstances in which LRT systems might operate. The factors that affect the basic LRV design and componentry may be divided into four areas: capacity, geometry, performance, and impact.

The importance of the capacity requirement is clear. Typically, LRT facilities, particularly those with a large percentage of separated right-of-way, are installed to assist the development of economic corridors that have a forecast passenger demand of 5000 to 20 000 passengers/h/direction. Traffic volumes below 5000 passengers/h/direction are usually more economically served in the long run by mixed-traffic modes. Conversely, concentrated loadings above 20 000 passengers/h/direction that cannot be distributed over two or more transit facilities are sufficiently great to require and justify full-scale heavy-rail transit (HRT) systems. A major difference between LRT and HRT may be found in the issue of flexibility; HRT can be thought of as an ultimate development of LRT—a very high-capacity rail system employing large-capacity vehicles, prepaid passenger and high-platform station design, fully exclusive rights-of-way, and high performance standards. By definition, rail systems designed to serve 5000 to 20 000 passengers/h/direction fall within the LRT range. The breadth of this service range is indicative of the flexibility of the concept and technology. The capacity requirements of individual applications affect the selection of car-body size and configuration and the command and control vehicle equipment options.

System geometry requirements include the right-of-way characteristics that distinguish each application—the available right-of-way width, the length and severity of grades, the minimum radii of curves on the line and in yard and storage areas, the permissible overhang and clearances, the design of terminal and turnback areas, and the degree of right-of-way separation and protection from other traffic and pedestrians. These influence car-body, command and control, and propulsion componentry.

The performance requirements of interest are the

Figure 1. Relationship of linear LRV capacity to body articulation.



rates of acceleration and deceleration, cruise speed, limitations on ride comfort, and the ability of the vehicle to maintain prescribed levels of service under a variety of conditions. These performance requirements define the capabilities demanded of the vehicle's suspension, propulsion, and command and control systems.

Environmental and community impacts are important elements of transit system design, particularly at a time when citizen involvement in the planning process is common. Control of noise, vibration, visual impact, community disruption, and intrusion are facets of this problem. Requirements associated with alleviation of impacts can affect all four categories of vehicle componentry.

VEHICLE COMPONENTS

Selection of vehicle configuration, performance standards, and component subsystems depends on the operating requirements of the system in which the vehicle will be used. In addition, the selection process must include consideration of the cost associated with each potential design. Cost trade-offs occur both in the areas of capital and operating costs and in the determination of overall life-cycle cost. In most circumstances, costs accurately reflect the suitability of the match between system requirements and vehicle characteristics; they are thus excellent arbiters of vehicle design. With this type of selection process in mind, it is instructive to examine the design options within each component group. This will illustrate the process of matching vehicle attributes to system requirements.

Car-Body Configuration

The selection of a car body includes decisions about dimensions, frame configuration, directionality, and passenger access and egress. In general, the vehicle dimensions in both length and width will be as large as possible in order to increase the productivity of equipment and labor. Upper limits on vehicle width depend on the available clearances in tunnels and other constricted zones and the distances required between vehicles on curves and in normal roadway traffic lanes. With respect to minimum width, the North American habit has been to strive for a vehicle width that will permit 2 + 2 transverse seating with an appropriate aisle space. This leads to minimum exterior car-body widths of slightly more than 2.5 m. By comparison, many European LRVs have been designed for 2 + 1 transverse seating with a side aisle for circulation and standees; this leads to a vehicle width of 2.1 to 2.3 m. Maximum car-body length is determined by clearances on curves and by vehicle structure limitations. Truck centers on the order of 7.5 to 12.0 m, corresponding to rigid body lengths of 15 to 20 m, have proved to be acceptable for the clearances found in most applications.

If greater vehicle capacity is desired for a given system than that available in the longest permissible single-unit rigid car, then a third truck and articulation joint can be added to effectively reduce the spacing of truck centers. Articulation arose in Europe, where the narrow streets and tight corners precluded the use of long, wide, rigid cars. In most instances, the additional capacity (primarily standee space) offered by articulated body designs is only marginally greater than that of the longest rigid car designs; the complexity of articulation therefore need only be added to overcome clearance constraints rather than to increase capacity. This characteristic is illustrated in Figure 1, which plots LRV passenger capacity per unit of car length. The graph, based on 29 European and North American LRV designs (3), indicates that linear capacity does not depend on the addition of body articulations.

Car directionality is determined by the availability of right-of-way for construction of turnback facilities. In most LRT applications, it is desirable to use single-ended vehicles, since the loss of capacity associated with double-ended cars is substantial. There is typically a 10 to 20 percent increase in fleet capital cost for equal capacity operations. Double-ended vehicles are economical only for applications in which the amortized cost of loops at all regular service and emergency turnback points exceeds the annualized equivalent of the substantial capital and operating costs for the vehicles. The table below presents the results of a comparison of costs for an LRT operation designed to provide service for 10 000 passengers/h/direction over a 16-km reserved right-of-way line.

Item	Single-Ended LRVs	Double-Ended LRVs
Vehicle capacity	157	150
Fleet size	88	93
Annual vehicle kilometers	8 190 000	9 720 000
Annual vehicle hours	250 000	300 000
Annual fleet operating cost, $	4 090 000	4 690 000
Annualized fleet capital cost, $	6 520 000	7 150 000
Total annual cost, $	10 610 000	11 840 000

The annual difference in costs associated with the purchase and operation of single-ended and double-ended versions of the same articulated LRV under identical operating rules, including schedule speed of 32 km/h and station fare collection, in this example is $1 230 000. The capital cost equivalent of this sum (at 8 percent/year over 20 years) is $13 000 000. This is the value of the capital expenditure that could be devoted to loops for a single-ended LRT facility, over and above the value of turnbacks and crossovers, at no additional total expense over that for a double-ended system. Each LRT facility will have a substantial cost penalty of this type associated with double-ended cars; in many cases loops will offer an attractive financial alternative.

The car-body options for passenger access relate to doorway design, height of stepwells, and fare-collection procedures. The selection of alternatives here must take into account the station infrastructure (platform heights throughout the system and the fare-collection procedures) and the passenger volumes expected. To reduce dwell times, it is always desirable to use honor-system, self-service, or station fare collection in conjunction with high-level platform loading. However, this is not always practical for on-street operations, and the reduction in dwell times (and thus operating cost) then can be realized from reducing the service time per passenger is so small that the capital cost of such options can usually only be justified for systems that have passenger volumes at the upper end of the LRT range. Provision of mixed-height platforms to meet special circumstances, e.g., high-low loading, will add to vehicle and station costs and will undoubtedly create operational and maintenance complexity.

Propulsion

The primary propulsion componentry choices that are sensitive to system operating requirements relate to the motor and control package, braking techniques, and power collection. The direct-current rotary electric motor with mechanically driven wheels has been the standard propulsion system in the LRT industry. Recently, alternative motor control hardware that provides a choice among mechanical, partially electronic, or totally electronic technology has become widely available. The primary differences among these systems are found in the potential energy savings possible with the totally electronic system. As a result of both reduced power draw during acceleration and the ability to return power to a receptive line during deceleration, energy savings as large as 30 percent (in comparison with PCC technology) may be realized. The opportunities for savings of this magnitude occur where there is a dense network, frequent service, and downtown street operations equipped with appropriate power distribution facilities, such as in Toronto. Smaller savings would be achieved on isolated individual LRT lines, especially during off-peak hours.

Braking requirements are much more sensitive to system performance requirements than is the propulsion package. Electrodynamic motor braking, friction shoe and disc braking, and magnetic track brakes are among the alternatives. In general, brake reliability and power must increase with increasing vehicle frequency. This relationship arises from the need for greater braking confidence when operating at close vehicle spacings and is manifested in the increased use of backup systems. Furthermore, braking power requirements increase as the degree of right-of-way protection decreases, particularly if such decreases result in mixed-traffic operation. These requirements typically lead to the provision of simple, reliable emergency service brakes.

The power collection technique is directly related to the right-of-way characteristics. Third-rail power collection eliminates the need for trolley-wire support structures and reduces the visual impact, but it is usually only feasible when the entire system right-of-way is fully exclusive and protected. Otherwise, overhead collection by trolley or pantograph must be employed. Generally, pantographs have superior tracking and current characteristics and are suitable for most new systems. The overheads of existing systems may be designed around the trolley shoe and may therefore have to retain this equipment.

Suspension

Suspension options relate primarily to truck design and, while most suspension design decisions are based on ride comfort, stability, maintenance, and propulsion integration factors, measures are available to minimize interior and exterior noise and vibration. In response to increasing concerns about environmental noise, urban rail vehicles are now being fitted with wheels, axles, and trucks that are designed to reduce noise and emissions. In particularly restrictive situations, further improvements are necessary in the suspension design and in its interface with the guideway. These improvements include superior wheel and rail standards and, potentially, the use of steerable trucks to reduce wear and squeal in curves. The choice of hardware for specific applications is clearly dependent on the acceptable impact level in the environment in which the vehicles are to be used.

Command and Control

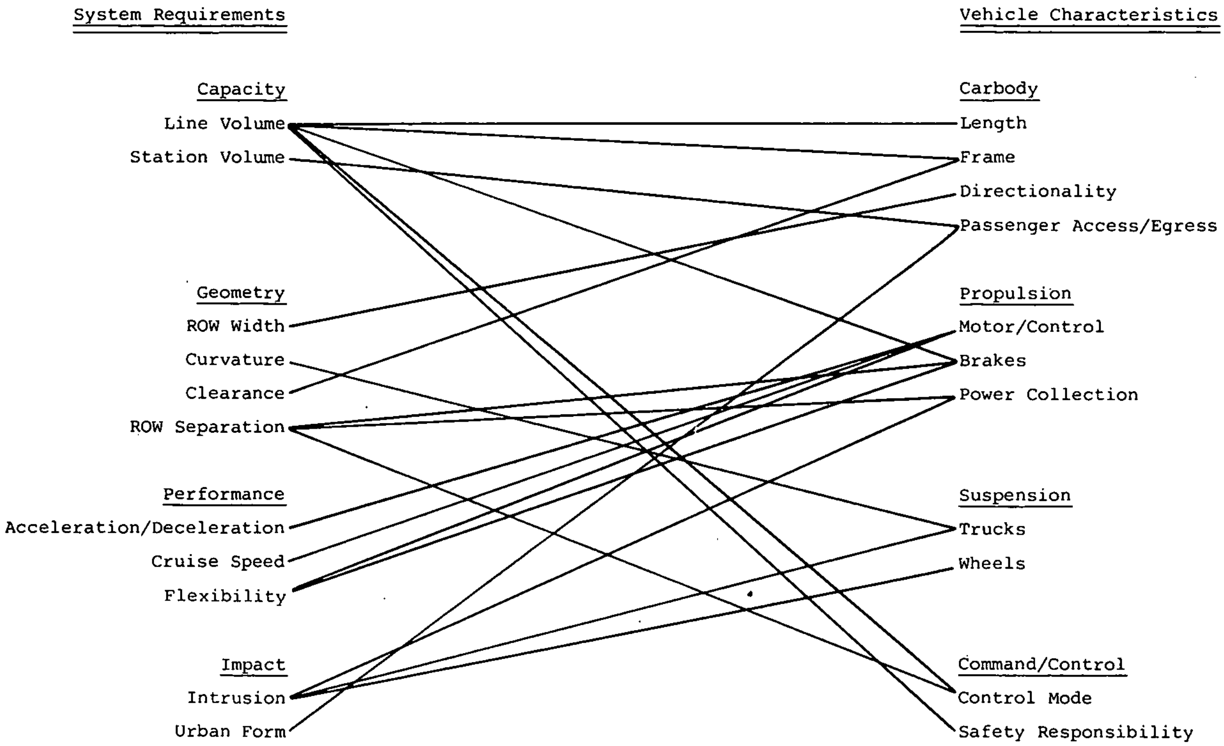
Vehicle or train control alternatives range between fully manual and fully automatic vehicle operation and protection. If the right-of-way is not protected from pedestrians and vehicular traffic, then a manual control capability must be provided. If sight lines are poor or headways are sufficiently short to raise safety concerns, then automatic train protection may be needed. If headways are shorter than human operators can deal with, then automatic train operation may also be necessary. Conversely, if the required capacity is low so that headways may be relatively long, there is generally no need for more than strictly manual command and control. A command and control choice that appears to be finding increasing use in unprotected rights-of-way designed for operations at moderate headways is the use of cab-signal command displays with manual vehicle control, complemented by automatic train protection vested in the system. For most LRT facilities, command and control and safety requirements are fixed by the nature of the application and are not subject to cost trade-offs.

Summary

The major elements of LRT system requirements and vehicle characteristics are shown in Figure 2. Several of the important interactions are indicated on this chart; many more occur at the more detailed levels of vehicle design and selection.

The above overview is representative of the range of LRT options within which LRV designs must be formulated. One effective technique for achieving a range of vehicle designs responsive to varying requirements is to develop a family of designs based on common componentry. The process required to implement this technique, moving from the definition of system requirements to hardware development and testing, illustrates

Figure 2. Interactions between system requirements and vehicle characteristics.



the matching of requirements and equipment. The process entails several sequential steps:

1. Define system characteristics and resulting vehicle requirements;
2. Formalize design criteria and specifications;
3. Evaluate and procure subsystem componentry consistent with the specifications;
4. Finalize the design and produce and test prototypes; and
5. Manufacture, test, and deliver production vehicles.

Each of these steps must be pursued for each vehicle design, but obvious economies can be realized through component commonality and design flexibility. Separation of the steps permits selection and application of skills and resources in the most effective and efficient manner.

TORONTO'S NEW LRV

In November 1972, the Toronto Transit Commission (TTC) decided to retain, and possibly expand, its streetcar and LRT operation. This decision created a requirement for a new fleet of LRVs to provide the base service on TTC's system through the 1980s and 1990s. System characteristics that affect vehicle design were well defined by the features of the existing Toronto operation. Thus the baseline clearances, geometrics, passenger capacities, performance capabilities, comfort levels, maintenance standards, and noise requirements were determined for the new fleet. In addition, it was considered desirable to improve on the performance of the existing PCC cars wherever possible, particularly in the key areas of energy use, passenger amenities, and maintenance and reliability standards, as well as to build into the fleet sufficient performance flexibility to be able to operate over any new territory and to new service standards that might arise as a result of system expansion into the metropolitan Toronto suburbs. These concerns resulted in a clearly defined set of requirements for a fleet of new LRVs.

Formalization of the vehicle requirements into a technical performance specification was a key element of the process. It was essential that the specifications be an effective marriage between the requirements of the system and the operator and the capabilities of proven state-of-the-art transit technology. In a year-long undertaking similar in many ways to the Urban Mass Transportation Administration's LRV design process of the early 1970s, design criteria were established to reflect the evolution of expectations and technologies that has occurred since production of the PCC cars. On the basis of these criteria and in close cooperation with the TTC, initial vehicle and component specifications were developed and reviewed.

When the required vehicle capabilities and performance levels were well defined, component manufacturers were asked to indicate their ability to supply the necessary vehicle equipment. This was done before the detailed design was established, in order that the widest selection and greatest flexibility of componentry would be possible. This equipment flexibility is essential to the concept of a family of vehicles. Equipment that meets the Toronto fleet requirements has been selected and will be furnished as free issue to the car builders.

The process of converting general specifications and subcomponent characteristics into the specific details of vehicle design with all its interfaces was identified as a separate task from the actual production of the vehicle. An experienced European LRV designer was selected in competitive bidding to assist in design, detailed specification, and proving of prototypes. The design has now been finalized, and the first vehicles are in the testing stage. Six prototypes are scheduled to have completed European testing and to be delivered to Toronto in late 1977 and early 1978. These six prototypes are the forerunners of 190 cars to be produced by a Canadian car builder. The car builder's responsibility will be to fabricate the body and trucks and to integrate the subsystem componentry by using production tooling designs developed for the prototypes wherever possible. Production and delivery of the 190 cars will be effected from 1978 to 1980.

The LRV that is emerging from this process is 15.4 m long and 2.6 m wide over the rub rails. The interior layout selected by TTC provides 47 seats, with standee space sufficient for 43 to 78 additional passengers, depending on comfort level. The maximum number of seats that can be provided is 58. It is a rigid, four-axle single-ended car geared in the TTC configuration for a maximum speed of 80 km/h. In private right-of-way operation, the propulsion system is capable of higher speeds. Acceleration levels allow the car to reach 80 km/h in 30 s, while deceleration is 1.5 m/s^2 in service and twice that in the emergency mode. In order to conserve energy and reduce the vehicle's life-cycle cost, the car is equipped with an electronic chopper motor control and a regenerative braking system. Regenerative and rheostatic electrodynamic braking is supplemented by a friction disc system that is capable of handling all braking requirements on a continuing basis. The propulsion and brake systems have plug-in diagnostic features to aid preventive and line maintenance.

Passenger comfort is enhanced by an outboard frame truck that has steel and rubber primary suspension and load weighing. A forced-air ventilation system provides interior comfort with or without a full air-conditioning package. Interior noise reduction is accomplished by the use of extensive acoustical insulation throughout the car, and both interior and exterior noise are controlled through the use of resilient wheels.

The vehicle represents an improvement in light-rail safety standards. Specific safety features to benefit both the driver and the passengers include system indicator displays, a raised control platform, provision for cab signaling, a bottom step 25 cm high, emergency escape windows, and obstruction-sensing doors.

FAMILY OF LRVS

An awareness of possible future LRV needs has resulted in the inherent flexibility and potential for growth that were built into the design. The additional propulsion capability, for example, can be used to increase either the maximum service speed or the vehicle weight and payload. The greatest flexibility is that afforded by modular design and fabrication of the car shell. Because the entire body structure is formed by joining a set of door, end, and body shell modules, the vehicle can be lengthened, widened, or otherwise reconfigured very easily. This flexibility permitted the design and construction of two six-axle articulated cars based on the shells, trucks, motors, and other components of the basic Toronto car.

These articulated prototypes will be 23.5 m long and single ended, and they will carry, in an interior layout similar to that of the TTC car, 63 seated passengers and 78 to 141 standees. They will be delivered to the Transit Test and Development Centre near Kingston for testing and analysis in the third quarter of 1978. The design capability being demonstrated in this prototyping program is the ability to provide vehicles, based on the same set of components, that are suited to different operating requirements. These particular prototypes represent vehicles that would find application on LRT systems that are required to carry substantial passenger volumes but are subject to restrictive horizontal clearances (e.g., older systems originally designed for short cars or new facilities constrained by existing urban infrastructure).

For LRT systems in which relatively large volumes of passengers must be carried but clearance is not a problem, a long rigid car presents the most economical alternative. Based again on the car-body modularity and the propulsion capabilities of the 164-MW monomotor truck, it is possible to stretch the vehicle length to approximately 20 m. This obviously enhances capacity and productivity in a high-density application. Apart from different under-floor equipment layouts and minor changes associated with the details of specific operator and operating requirements, there are few hardware differences among the vehicles developed in this family concept. They can all make use of the same shell components and truck, suspension, propulsion, door, and ventilation subsystem componentry. In different configurations these components yield a variety of designs, each suited for a different specific subset of LRT operating conditions. While it is not realistic to expect operators to abandon the operational and maintenance advantages of a single-vehicle fleet in favor of fleets of different vehicles corresponding to each different route circumstance, it is possible with a family of designs to provide alternatives from which the operators can select the one or two vehicles best suited to their needs.

It is the ability to design and deliver a variety of vehicles such as these, based on the same components and each responsive to a specific need, that leads to the conclusion that a family of complementary LRV designs is feasible and provides the flexibility necessary to meet the varied requirements of LRT without incurring diseconomies of small production scale. The family-of-vehicles design approach can provide a high standard of vehicle types for a variety of LRT applications.

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