LOW-FLOOR LIGHT RAIL VEHICLES
This study explores the option of integrating a low-floor extension (LFE) module into the existing light rail vehicle to augment current service with low-floor boarding and simultaneously to increase passenger capacity. In an effort to minimize the overall weight of the LFE, this study examines two feasible approaches for specifying the longitudinal strength of the LFE that are consistent with current industry practice. The two alternatives considered are the “strength-based approach” and the “energy-based approach.” The de facto industry practice is a strength-based approach where the buff strength is specified to meet two times the AWO weight of the vehicle, commonly referred to as the “2-g buff load.” The feasibility of an alternative approach, using crash energy management (CEM) principles to limit the longitudinal loads in a controlled manner, was also examined in detail. In a collision, the CEM zone would generate predetermined peak and average reaction loads, thereby limiting the longitudinal load transmitted to the LFE, while still meeting minimum static strength values. These zones would be designed to deform or crush in a controlled manner, thereby absorbing collision energy and minimizing the potential for deformation and acceleration in the passenger compartment.

Since structural strength is fundamental to passenger safety, the new structure of the LFE module and any modifications made to the existing vehicle must meet the same structural standards used originally or must provide an equivalent level of performance in a collision. For this study, collision performance is being measured only in terms of peak and average accelerations and deformation.

BACKGROUND

Currently, light rail vehicles (LRVs) comply with the federally mandated Americans with Disabilities Act requirements by providing access to disabled patrons through the use of wayside high blocks combined with onboard bridge plates. This set-up has limited access to the leading doors on each train for passengers using the high block, which is typically used by passengers who are disabled or those with luggage or strollers.

The Authority wanted to investigate the possibility of replacing the existing method of providing access and increasing system capacity at a lower cost. The concept under consideration is the addition of an low-floor extension (LFE) to the center of existing LRVs. The driving force for investigating this concept is that the “non-powered LFEs may be added to the entire fleet at a significantly lower cost, as compared to procuring a fleet of new low-floor LRVs.”
LFE CONCEPT

The conceptual LFE modification to the existing LRV may include the insertion of a 30-ft-long low-floor section between the two existing car bodies. The low-floor section is constructed of steel in a similar manner as the existing car. For the purposes of this study, the existing propulsion capacity was assessed only for an LFE constructed from steel similar to that used in existing LRVs. As the propulsion capacity remains unchanged, the heavier steel LFE was used in all calculations. Two articulation joints identical in design to the existing joint are located at each end of the LFE body. Conventional un-powered trucks identical to the existing center truck design support each articulation joint. Doors located on each side of the car body at the middle provide easy entrance and exit from the car at curb level. The LFE section provides 20 seats, standing area for 43 passengers at crush load, and air comfort through an independent heating, ventilation, and air conditioning system.

The LFE concept developed employs the existing propulsion equipment with no changes to the principal physical components such as traction motors, gear units, propulsion inverter, and high-voltage systems. As a consequence, the maximum acceleration rate is reduced.

Among other issues, structural strength and crashworthiness are two performance parameters being reviewed because the available designs for the LFE section do not meet the same structural requirements as those designed for the existing vehicles. Since structural strength is fundamental to passenger safety during a collision—for example, it acts to prevent the collapse and gross penetration of occupied volumes—the new structure of the LFE module and any modifications made to the existing vehicle must, at minimum, meet the same structural standards used in the existing vehicle so that the LFE structure provides an equivalent level of performance in foreseeable collision scenarios. An LFE design with less strength than the existing passenger compartment would be at risk of sustaining a large part of the deformation in a collision, potentially endangering passengers.

LFE STRUCTURAL ISSUES

To determine the technical feasibility of implementing the LFE from a structural perspective, the primary structural characteristics of the LFE LRV, namely the car body compression strength and crush strength, were studied. The key issue is in determining the load values to use in the design of the LFE such that adequate structure strength is provided without excessive weight. One of the main parameters considered in the design of railway structures is the longitudinal yield strength or buff strength of the vehicle. This load requirement is important because when vehicles are properly designed to this load, they are protected against large-scale deformation, penetration, and damage during a variety of collision events ranging from hard couplings to end-to-end collisions with other rail vehicles, and, to some degree, collisions with highway vehicles.

Typical industry practice for LRVs has been to design the vehicle structure to resist a static load equal to two times the empty weight of a ready-to-run vehicle applied at the ends of the vehicle without permanent deformation (yield or buckling), often called the “2-g buff load” criterion.
STRUCTURAL STRENGTH OVERVIEW

As the LFE concept has been popular in Europe exclusively, the structural characteristics and crashworthiness of the LFE need to be reviewed thoroughly to account for the differing design philosophies between Europe and North America. In North America, traditionally a 2-g load (two times vehicle ready-to-run weight) has been required, in some cases by law (California CPUC).

In Europe, the compression strength is typically specified according to the vehicle type, category, or rail service and not necessarily according to the tare or ready-to-run weight only. For instance, in Europe, the typical compression strength of an LFE LRV is in the range of 40,000-100,000 lbs; however, the requirements for North American LRVs are in the range of 140,000-200,000 lbs. Caution must be used when comparing requirements for European LRVs with their North American counterparts, particularly for structures and crashworthiness, because the operating speeds in North America tend to be higher, even though the classification or label of “LRV” is used in both regions.

CRASHWORTHINESS—STANDARDS AND INDUSTRY PRACTICE

In the past, the crashworthiness of LRVs was mostly defined by their buff load. A high buff load was seen as the most straightforward path to ensuring that the vehicle structure did not suffer large-scale collapse in collision, hence providing protection to passengers. Traditionally a 2-g buff load has been required for LRVs in locations such as Baltimore, Maryland; San Francisco, Santa Clara, San Diego, and Los Angeles, California; Denver, Colorado; St. Louis, Missouri; Pittsburgh, Pennsylvania; and Boston, Massachusetts. The exception is New Jersey, where 1.0 to 1.1 g was specified. The Parsons Brinckerhoff study for NJ Transit’s LRV revealed that the working team could not determine the technical rationale behind the 2-g buff load. The 1-g requirement could not be explained convincingly either. Furthermore, specifying a minimum buff load does not necessarily limit the peak loads and accelerations experienced during a collision because the collapse load of the structure is often higher than the static buff load.

Today, the industry is considering an alternative approach. The strength-based crashworthiness approach is augmented with energy-based crashworthiness requirements; the ultimate goal is to reduce passenger deceleration rates during a collision while controlling the absorption of collision energy to minimize loss of space in the occupied volume of the vehicle.

The strength-based philosophy is currently the most widely used approach to ensure some level of rail vehicle crashworthiness. Under this approach, vehicle specifications typically limit the various strength requirements of the structure. The most significant strength requirement is the buff strength. Ultimately, the strength requirement does not consider the energy-absorbing capability of the vehicle structure. If the structure were designed not to crush by utilizing very high strength, then the load and decelerations would also reach very high values during an accident. Depending on the design, collision energy might be dissipated as fracture, derailment, or override—all of which are generally uncontrolled and undesirable outcomes.

The energy-based crashworthiness (or CEM) philosophy is based on providing protection against one or more specific collision scenarios. These scenarios are used to determine, by considering the physics of collisions, an estimate of the energy that must be absorbed and the structural components that must be used to absorb the energy. Selection of specific collision
scenarios is the most difficult step in this approach because there must be a rationale underlying selecting parameters such as speed, consist configuration, and impact angle. The selected parameters must be representative of the most likely collision in a given system. Such a scenario can be derived from the review of accident data or from a careful review of proposed operations and the types and likelihood of various accidents. A common accident scenario for passenger train operations is the collision of a moving train with a stationary train. The moving train is often considered to be traveling at a speed substantially lower than its maximum operating speed because the collision event is envisioned to occur as a train is entering the station or has its brakes applied in anticipation of the collision. Once the accident scenario is selected, it is necessary to decide how the energy will be dissipated between various vehicles in the train and the individual ends of a vehicle. A very conservative approach is to require the impacted ends of the lead vehicles to absorb all of the collision energy in its couplers and end structure. However, optimized designs tend to distribute the collision energy along the entire train consist. Collision dynamics computer models can be used to obtain estimates of the distribution of collision energy in the train consist.

The energy-based approach also requires carefully designed structural features in order to ensure that a survivable volume remains after collision energy is absorbed. Limiting accelerations, which can result in secondary impact injuries to passengers, is also a main goal of this approach. To ensure that passenger areas maintain a survivable volume, the passenger compartment structure should have greater strength than the crushable zones, and the amount of deformation or crush required to absorb specified collision energy must be limited. An equally important consideration is the secondary impact injury to passengers. Secondary impact injuries can be controlled by limiting the strength requirement for the crush zone (the maximum force required to initiate controlled deformation), thereby limiting the maximum passenger accelerations.

The use of CEM principles is also being considered for new standards currently developed by industry committees. The American Society of Mechanical Engineering Rail Transit-1 (ASME RT-1) standards committee is in the process of developing a standard for structural requirements for LRVs, which includes CEM specifications similar to European standards, although important revisions are being made to meet North American standards. The standard will include the same general approach for crashworthiness as that discussed above—absorption of collision energy in a controlled manner at a predefined location on the vehicle structure. Typically, collapsible structural elements are located either at the end(s) of the car or within the end structure. Depending on the type of vehicle and the collision scenario considered, the energy absorption structure could have a static “end” strength lower than the typical buff strength (2-g) value in order to minimize the average deceleration in the passenger compartment. To guard against loss of occupied volume, passenger compartments will be specified to have a higher strength than the crush zone to sustain loads from the collapsing structure.

An example of a crash energy design requirement in the proposed RT-1 standard is that each car end should be designed to absorb 350 kJ of energy with a collapsing distance of 20 to 28 in. for a collision between two LRVs: one moving at 12 mph, the other parked with its brakes off. [Development on the RT-1 standard continues; discussions during the American Society of Mechanical Engineers (ASME) meeting in March 2002 will likely result in further revisions to the requirements.] Another example is New Jersey (Hudson–Bergen) where 308 kJ was required. It should be noted that these requirements are specified for new vehicle procurements.
LRV–LFE DESIGN ALTERNATIVES

This study was focused primarily on the overload conditions resulting from vehicle collisions in order to assess the buff strength requirements for the LFE module. From the structural perspective, the design of LFE can be executed using the following criteria for the longitudinal strength of the vehicle:

- Design the LFE to follow the traditional 2-g criteria based on using the new total weight of a vehicle with an LFE.
- Design the LFE to match the existing LRV buff load and collapse load; for example, use the strength-based LRV design philosophy.
- Design the LFE using a strength-based approach in conjunction with the CEM applied to the existing vehicle structures to definitively limit the longitudinal loads during a collision.

These design approaches are not new to LRV designs and have all been applied on various light rail projects throughout the United States, with the most typical approach being the 2-g criteria. (Examples include San Francisco Municipal Rail LRVII; Pittsburgh Stage II; Boston #8; and Southern New Jersey Light Rail, to name a few.)

Industry Practice—Traditional 2-g Criteria

The most straightforward approach for sizing the buff strength of the LFE would be to maintain the 2-g ratio based on the overall weight of the modified vehicle. This is the strength-based approach, which has the benefit of simplicity and service history. However, when compared with the other approaches, the 2-g criteria could result in added weight from the structure, which is undesirable. If the 2-g ratio is strictly maintained, the empty weight of a vehicle with a 30-foot-long LFE is estimated to be in the range of 145,000 to 147,000 lbs. Therefore, the buff load of the LFE would need to be approximately 294,000 lbs plus some additional factor to ensure that the LFE would not collapse. In addition, the 2-g approach, again if strictly followed, would require some structural modifications to the existing cars, which were designed for a buff load of 200,000 lbs, although some excess capacity might already exist in the structure. The disadvantages of this approach are excessive weight from the LFE and the possible modifications to the existing vehicle. The increased vehicle buff strength, as discussed before, does not necessarily provide for a crashworthy design because the higher longitudinal body stiffness can result in higher passenger decelerations in a collision.

Strength-Based Design: Match the Existing Buff Strength

Another option for the LFE design could be to follow a second strength-based design philosophy—that is, to match the existing buff load (for instance, 200,000 lbs). The main advantage of this approach is that the existing cars remain unchanged or may need fewer modifications than with the 2-g design. The weight of the structures would also be lower as compared with the traditional 2-g approach. Using the LFE AWO weight of 33,000 lbs, the “g” ratio of the LFE LRV would be approximately 1.4 g; the traditional industry practice of 2-g would not be achieved. Therefore, the performance of the structures during a collision must be
carefully examined to ensure that the LFE module will not suffer loss of occupied volume during a collision. Hence, the difference between the buff strength, which is typically specified as a minimum value, and the actual collapse strength of an existing vehicle must also be examined relative to the design of the LFE.

One disadvantage of this approach that must be considered is legality. If some of the revised strength requirements are lower than those traditionally used—for example, lower than the 2-g industry practice without any other reinforcements or changes—there is potential exposure to a legal argument in case of injury or fatality. The inevitable argument would be that, if the LRV had been designed to “industry standards,” then this scenario would have never happened.

**Strength-Based Approach with Crash Energy Design Principles**

This approach is essentially a variation of the strength-based approach as described above. In this case, it is assumed that the existing structure requires modification in order to achieve the desired force level and deformation response during collision. The foundation of the CEM concept is the definition of crush zones where impact energy is absorbed in a controlled manner. The structure in the CEM zone is designed based on vehicle weight, estimated velocity at impact (i.e., kinetic energy), available energy absorption via the coupler, available space, and passenger deceleration limits. By limiting the peak buff load generated during the collision event via the CEM zones, the overall weight of the structures may be reduced as compared with the strength-based (2-g) approach. Deceleration levels could also be lower with CEM, thereby reducing the potential for injury to passengers. The CEM zone must be optimized such that the desired amount of energy absorption is achieved without creating forces that exceed the strength and space limitations of the vehicle structure.

**APPROACH AND METHODOLOGY**

The use of CEM principles includes the important step of defining the collision scenario used to size the energy absorption structures. For typical LRV specifications written to date, the collision scenario is based on LRVs colliding with other LRVs on the system. [Examples of where CEM concepts using pre-defined collisions have been utilized include Southern New Jersey Light Rail, Hudson–Bergen Light Rail, John F. Kennedy (JFK) Airport Access, and the ASME RT-1 Light Rail specification, which is currently under development.] Collision scenarios are typically defined by specifying the following:

- The track geometry and conditions (typically dry, level tangent track);
- The couplers and anticlimbers fully engaged;
- The number of vehicles in the consists involved (typically the maximum consist size for both trains);
- The vehicle weights, including passenger loads; and
- The impact speed, also called closing speed (the maximum value often used is 15 mph for systems with a 55 to 60 mph maximum design speed).
The values noted are examples. These variables must be reviewed for each system when defining a scenario so that the CEM zone is custom-designed for the intended service. When defining the design collision scenario, it is particularly important to consider the system speed (since the collision energy to be absorbed by the structure increases with the square of velocity). Once the collision scenario is defined and the resulting collision energy is determined, the CEM zones can be designed.

Again, the force level and available space must be considered so that the smallest possible deformation is achieved without unduly high accelerations. The desired deceleration rate, location, available space, and strength of the existing structure are all key variables in determining the size and force level of the energy absorption devices. In general, the longer the absorption device, the lower the force level (deceleration rate) can be to absorb a given amount of energy. As part of this study, the use of the energy-based design approach will be considered in an effort to limit the peak longitudinal loading on the vehicle, and hence the LFE.

**Approach**

A variety of collision scenarios were analyzed using dynamic motion analyses to estimate acceleration (or deceleration) levels in each vehicle and overall deformation. The analyses use lumped mass-spring models to estimate the interaction and response of vehicles.

These analyses are first-order approximations of the collision events. The response of the structure on a detailed level is not obtained from this approach. Rather, the global structural characteristics needed to achieve a desired response (such as a limited deceleration rate, limited peak force, etc.) can be ascertained from the results. Collision scenarios similar to those discussed previously will be defined and simulated. The analysis is conducted using the following steps:

- Define the vehicle characteristics to use as model input data;
- Define the collision scenarios;
- Build the model and run the analyses;
- Collect the data generated from the simulation and examine the results; and
- Formulate conclusions.

The simulation is based on the dynamic analysis of mass-spring systems. A commercially available computer program, Working Model 2D, was used to formulate the analysis and solve the resulting system of equations. (Working Model 2D has been used by Booz Allen on the JFK Airport Access project, on the Southern New Jersey Light Rail project, and for the development of the ASME RT-1 standard to simulate vehicle collisions.) Working Model 2D can simulate the static and dynamic (including impulse) response of any combination of masses, springs, dampers, pulleys, and gears under external loads such as forces, friction, and torque. All of the elements and parameters in the program can be customized to simulate any desired scenario, including non-linear or time-varying inputs such as a spring with non-linear stiffness or a pulsating force.

In the simulation, vehicle consists were placed in motion at the envisioned collision velocity and collided with standing vehicles that had their brakes on. Vehicle configurations included in the study were
• Existing vehicle with no LFE;
• Existing vehicle with an LFE and CEM zones (strength-based approach with CEM); and
• Existing vehicle with an LFE both designed to 2-g based on the new total weight.

These configurations were selected because they represent the possible range of vehicle strengths. The strength-based approach was not modeled because it is essentially a variation of the CEM approach.

These configurations were analyzed under four different scenarios, each scenario having three closing speeds. The collision scenarios included single- and multi-vehicle consists, modified vehicles with LFEs, and the existing vehicles.

For each analysis conducted, the vehicles were modeled as a rigid block or series of blocks connected by springs with stiffness values selected to simulate the crush strength of the vehicle structure or couplers. The stiffness and crush strength of the structures were represented as spring elements located between the respective mass elements. Where possible, a single spring was used to represent components that act in series, for example, couplers between vehicles in a train. Couplers at the front of the colliding trains have been modeled individually to explicitly determine deflection at the impact point. Connections such as articulation joints are not modeled directly; sections of a complete vehicle are connected directly by spring elements simulating the stiffness of the structure so that load transfer between sections (the end car and LFE) is properly simulated. A two-step approach was used for this study:

• Simulation 1 included a number of analyses to determine the worst-case combination of speed and number of vehicles in terms of both deformation and accelerations. Particular attention will be given to deformation because the available space on the existing cars is a clear constraint. For this simulation, the mass of the LFE was lumped into the mass of the end cars and the LFE structure was simulated by the springs between the end cars. Hence, acceleration values will be average values since the LFE mass is not discretely modeled.
• Simulation 2 was conducted using refined models so that the worst-case scenario determined from Simulation 1 can be examined in more detail. The refined model included additional mass-spring elements to depict the LFE unit separately.

For this study, the collision performance has been measured only in terms of peak and average accelerations and deformation.

**Methodology and Definition of Vehicle Model**

The vehicle characteristics in the models were selected using data and structural analysis information from the procurement project records. The data collected from previous evaluations or studies of the LFE concept were also used. Where noted, estimates were made for any missing details based on established industry standards and past experience. The main input data for the vehicle model are weight, coupler force data, and structural stiffness (force deformation characteristics).

For the purposes of this study, it is assumed that the collapse load will be higher than the buff load and will remain constant as the end car structure is crushed. Although this assumption is highly dependent on the structural geometry of the under-frame, the intent of the study is not
to evaluate a specific design, but rather to compare vehicle design philosophies and how they might influence the design loads for the LFE. In order to limit the number of permutations in the analysis, the LFE buff strength was selected based on a reasonable maximum value given consideration for weight limitations.

The weight for the LFE using CEM on the existing vehicle was estimated using the unit weight of the existing vehicle: 1,100 lbs/ft. This value is assumed to include the weight from structures added for the CEM zone. The unit weight estimate is somewhat conservative because it includes the weight of subsystems, such as propulsion inverters, that will not be present on the LFE. For this study, it has been assumed that the collapse strength of the LFE is equal to the buff strength, which is a very conservative assumption. In reality, collapse strength or ultimate strength is typically higher than the static buff strength.

Additionally, models with CEM zones require the maximum length of crush to be specifically defined in order to properly simulate the difference between CEM and the passenger compartment collapse. The following lengths were used:

- Crush zone length for Simulation 1 is 21 in. (this value was selected as a base point). The zone is assumed to begin at the back of the anticlimber, extending 21 in. into the cab area.
- Crush zone length for Simulation 2 is 30 in., extending from the back of the anticlimber inwards.

The springs that represent the passenger compartments and the LFE structure have been modeled with sufficient length to capture the full dynamic response of the system; therefore, the maximum crush can be estimated. In other words, a crush length was specified for CEM zones only.

**Generation of Characteristic Force Deflection Curve for the Vehicles**

The individual structural characteristics and the crush zone lengths noted in the previous section were combined in the models to represent the response of the structure under different collision scenarios. The simulation depicts the response of the vehicle as a whole and of the separate “cars” or modules (such as the leading car or LFE). To achieve this, the idealized force-deflection curves were generated using the strength characteristics. The curves represent the average force generated as the coupler and structure collapse over distance. These curves are idealized to simplify the calculation; they are estimations with sufficient accuracy for a preliminary study. In reality, a rail car structure collapsing under dynamic loading displays highly varying force deflection curves with many peaks, although an average level is typically maintained.

The force versus deflection curves used in the simulations represent

- The existing vehicle, including the couplers;
- The end cars of a vehicle with CEM zones designed to 200,000 lbs buff strength;
- The end cars of a vehicle designed to a 2-g (based on total weight of end cars and the LFE) buff strength;
- The LFE module designed to the 200,000 lbs buff strength; and
- The LFE designed to 2-g (based on total weight).
Once all properties (i.e., velocity and static/dynamic frictions) of the mass and spring elements are defined and connected, the model is ready to be analyzed.

**Analysis Assumptions and Collision Scenarios**

The analysis is based on assumptions that are commonly used in recent vehicle specifications (for example, Southern New Jersey Light Rail and JFK Airport Access), which include crashworthiness and CEM requirements. The assumptions are:

- Both consists are on level tangent track;
- The standing vehicle(s) is fully braked and the coefficient of friction between the wheel and the rails is equal to 0.3;
- The couplers fully engage and absorb energy during all collisions;
- The moving vehicle(s) is not in braking mode—for example, it maintains a constant velocity up to impact;
- The maximum number of vehicles in any consist is two; and
- Collisions with vehicles of dissimilar strength may occur.

The following collision scenarios were analyzed as part of Simulation 1:

- Scenario 1: One existing vehicle colliding into two vehicles with an LFE and CEM.
- Scenario 2: One vehicle with an LFE and CEM running into two existing vehicles.
- Scenario 3: Two existing vehicles running into two existing vehicles.
- Scenario 4: Two vehicles with LFEs and CEM running into two identical vehicles.

Each of these scenarios was analyzed at 5, 15, and 17.5 mph closing speeds. The first two speeds were selected based on industry practice. Typical LRV specifications with crashworthiness requirements call for a maximum collision design speed of 15 mph. The 17.5 mph was selected because it is approximately half the estimated average system speed. It has been included for reference only.

**RESULTS**

The following table shows the results obtained for the simulations conducted. In Simulation 1, several different scenarios were analyzed to determine the worst-case scenario. Typically, the scenario with the highest speed and largest consist proves to be the worst case for consists of the same vehicle strength, although this may not always be the case when vehicles of mixed strength are considered.

**Results of Simulation 1: Determining Worst-Case Scenario—Simplified Model**

In Simulation 1, all of the scenarios noted previously were analyzed. The results of these scenarios, shown in Table 1, indicate that, in collision Scenario 4, two modified vehicles (with LFE and CEM zones) colliding with the same two vehicles consist is the worst case, assuming
**TABLE 1  Summary of Results for Collision Scenario 4 (Simplified Model)**

<table>
<thead>
<tr>
<th>SIMULATION 1</th>
</tr>
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<tbody>
<tr>
<td><strong>Scenario 4: Two Vehicles with LFEs and CEM Colliding into Two Similar Vehicles</strong></td>
</tr>
<tr>
<td><strong>A) Speed = 5 mph</strong></td>
</tr>
<tr>
<td>Vehicle</td>
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<tr>
<td>Vehicle 2</td>
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<tr>
<td>Vehicle 1</td>
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<td>Vehicle 3</td>
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<tr>
<td>Vehicle 4</td>
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<tr>
<td><strong>B) Speed = 15 mph</strong></td>
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<tr>
<td>Vehicle</td>
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<tr>
<td>Vehicle 2</td>
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<tr>
<td>Vehicle 1</td>
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<tr>
<td>Vehicle 3</td>
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<tr>
<td>Vehicle 4</td>
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<tr>
<td><strong>C) Speed = 17.5 mph</strong></td>
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<tr>
<td>Vehicle</td>
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<tr>
<td>Vehicle 2</td>
</tr>
<tr>
<td>Vehicle 1</td>
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<td>Vehicle 3</td>
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<tr>
<td>Vehicle 4</td>
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</tbody>
</table>

The entire fleet is fitted with LFEs (mixed scenarios—i.e. vehicles of different strength colliding together—were also considered and will be discussed in a later section).

At 15 mph, the coupler and the CEM zone are expended completely and deformation has begun in the passenger compartment on vehicles 1 and 3, which are at the impact interface. This result indicates that a 21-in. CEM zone at 200,000 lbs does not have sufficient energy absorption to prevent deformation of the passenger compartment at 15 mph. In Simulation 2, the CEM zone was increased to 30 in., but the force level stayed the same. This was examined closer in the refined analysis (Simulation 2) with multi-spring models. The average accelerations are about the same for each of the respective vehicles in the train consists.
The main goal of this simulation was to confirm that the two-cars-into-two-cars scenario is the worst case, which has been proven. Thus, Scenario 4 can be used in the refined analysis without the need to check all other scenarios.

Results of Simulation 2: Refined Analysis for Scenario 4

Using the three-block model refinement and collision Scenario 4, another analysis was conducted for 5, 15, and 17.5 mph speeds. Note that the length of the CEM zone is increased to 30 in. (versus 21 in. from Simulation 1). This was done to allow for sufficient deflection so that the maximum length required in the CEM zone could be determined. As in Simulation 1, the crush force of the CEM zone was 200,000 lbs. All of the parameters and assumptions noted previously were also retained. The impact occurs at the same interface as Simulation 1, between vehicles 1 and 3. The results for this simulation (at 15 mph) are presented below.

Vehicles 1 and 2—Moving Consist

- Coupler stroke is used entirely at both ends of vehicle 1, one end located at the impact interface and the other coupled with vehicle 2.
- The entire coupler stroke is expended on vehicle 2, indicating that the collision energy has been distributed in part along the length of the vehicle through the couplers. Although the deformation-to-crush zones show that the majority of the energy was absorbed at the impact ends.
- The CEM zone crushed on vehicle 1 (at end car 1A only) was over 28 in. No damage occurred in the passenger compartment. This indicates that, in principle, a 30-in. crush zone with an average force of 200,000 lbs is sufficient to absorb the collision energy generated from this scenario.
- The LFE deformed approximately 1 in. in total (the sum of the deflections at both ends). Hence, the LFE had just begun plastic deformation in this model, but extensive collapse (loss of occupied volume) did not occur. Peak deceleration was 1.72 g.
- Since the LFE did not significantly crush, the CEM zone in this model was effective in limiting peak loading.
- Peak deceleration levels occurred in vehicle 1 at 2.21 g. This deceleration level is not excessively high and it occurred over a very short duration. The average accelerations were lower.

Vehicles 3 and 4—Standing Consist (Brakes On)

- The coupler stroke was used entirely at the impact interface of vehicle 3. At the coupling interface, between vehicle 3 and vehicle 4 only, 11.3 in. was used.
- The CEM zone on vehicle 3 was crushed almost 19 in. Peak acceleration was 2.7 g. The length of crush was not the same as vehicle 1 because of the brake force (simulated as a friction force). It is expected that one vehicle would sustain more damage than another when the standing vehicle has its brakes applied.
- As in vehicle 3, the LFE deformed approximately 1 in. in total (the sum of the deformations at both ends). Hence, the LFE has likely just begun plastic deformation, but extensive collapse (loss of occupied volume) did not occur. The maximum deceleration was recorded as 2.47 g.
Comparison of the CEM Versus the 2-g Approach—Scenario 4.1

An additional scenario similar to Scenario 4 was analyzed using vehicles designed to the 2-g approach. As previously noted, the 2-g strength ratio is based on the assumed weight of the LFE and the existing vehicle. The results of this scenario were compared with Scenario 4 to determine the differences between using CEM and the 2-g approach:

- In comparing the 2-g results with the CEM design, it can be seen that the CEM zones limit the peak and average accelerations in passenger compartments significantly.
- The strength-based approach with a CEM zone was successful in limiting the loading transferred to the LFE body because the acceleration levels are lower at the LFE.
- The strength-based approach with a CEM zone also reduces the acceleration levels in the second vehicle in the train consist.
- The deformation is higher in the ends of the vehicle with CEM, although this is expected. The intent of the CEM zone is to deform in a controlled manner (i.e., at a specific force) over a predetermined distance.
- The second vehicle in both consists sustained structural damage, indicating higher energy levels between coupled vehicles. This did not occur in the CEM case due to the lower weight of the vehicles and the energy absorption at the impact interface.
- The deformation level in the LFE is very low for both the CEM and 2-g vehicle. Hence, loss of occupied volume did not occur. However, the overall weight of vehicle with an LFE and CEM is estimated to be less than the 2-g approach. This weight savings may be significant when considering propulsion and braking requirements. Additionally, the lighter LFE may have lower energy and maintenance costs.

To simplify the comparison, Table 2 shows only the maximum values for the deformation and acceleration along the vehicles in the moving consist from Scenarios 4 and 4.1.

**TABLE 2 Comparison of Results between the CEM and 2-g Approach for Collision Scenarios 4 and 4.1 (2 vehicles into 2 vehicles at 15 mph)**

<table>
<thead>
<tr>
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SUMMARY AND CONCLUSION

A number of collision scenarios were analyzed via first-order lumped mass-spring dynamic models to examine the feasibility of implementing an LFE module designed to a longitudinal compression specification not based on the 2-g de facto industry standard. In the strictest interpretation of the 2-g approach, both the existing vehicles and the LFE would need to meet this requirement based on their total combined weight. This would result in a buff-strength value for the LFE and end cars that is higher than that of the existing LRVs. Instead, the use of a strength-based approach with CEM principles to limit peak longitudinal loading in the vehicles, and hence the LFE, was examined with the goal of minimizing the added weight from an LFE. Using available data from the records, estimates were made for the weight and strength values of the LFE and for the size and strength of the CEM zone. The maximum longitudinal strength of the LFE, when fitted to a vehicle with CEM, was assumed to be 200,000 lbs.

The dynamic analysis was conducted to examine the acceleration and deformation of various simulated structural elements in the vehicle under different collision scenarios, with speeds up to 15 miles per hour. Analyses with speeds up to 17.5 miles per hour (half the average system speed) have been included for reference.

Based on the data available, the assumptions noted, and the analysis results presented in this report, the following is concluded:

- There is a risk that an LRV LFE designed to the traditional 2-g criterion would not meet the desired structural weight limits needed to reinforce existing structure due to additional weight of LFE.

- It is technically feasible to implement an LFE designed to a specific longitudinal strength value (i.e., using a strength-based approach), instead of applying the 2-g buff load criteria as calculated from the new total weight. The longitudinal strength value for the LFE could be established in two ways.

  Option 1 is to maintain a minimum static strength (200,000 lbs for instance). Determine the load generated from the existing end car structure in a collision under a rational collision scenario and design the LFE structure to resist this load without loss of occupied volume. However, due to the structural design of the existing end structures, the end sill and center sill could be very stiff and may generate very high loads before collapsing in a vehicle-to-vehicle collision. The end structures must be capable of progressive energy absorption in order to avoid high load fluctuation and excessive or uncontrolled deformation. It is likely that the significant changes in the existing structure would be required to achieve this.

  Option 2 is to augment the end car structure, in accordance with CEM principles, by adding the energy absorption elements designed to mitigate a rational collision scenario. As in Option 1, the minimum static strength must at least match that of the existing structure. The results of the analysis in this study demonstrate how adding CEM can be beneficial in limiting longitudinal loads transferred through a vehicle during the collision scenarios noted. The analysis shows that for a collision of two vehicles into two vehicles at 15 mph, (a) for vehicles with an LFE and CEM zones having an average crush strength of 200,000 lbs, the collision energy could be absorbed with approximately 28 in. of crush at the front of the vehicles involved; (b) as with the CEM zone, the LFE module, having 200,000 lbs of crush strength, sustained approximately 1 in. of total deformation under this scenario; and (c) for vehicles with an LFE designed to the 2-g
approach, approximately 12 to 13 in. of deformation occurs at the ends of each vehicle, which is less than the CEM approach. However, the peak acceleration levels are much higher.

For either option, the collapse strength of the structures must be examined in detail. Passenger compartments of the existing vehicle and the LFE must be capable of sustaining the peak crush loads from either the CEM zones or the existing end structure without collapsing. Both options require a significant engineering effort, including detailed linear and non-linear finite element analyses of the structures in order to determine the loads generated during a collision. The optimum location for the CEM zone would be forward of the cab area, configured with minimal effect on visibility. One possible concept could be two tube-like elements with a plunger arrangement that compresses a crushable element designed to achieve the desired force level. Tubes approximately 25 to 28 in. long could be integrated into the end sill structure.

The CEM concept also has technical risks and difficulties that must be considered:

- There are significant engineering costs and a long lead-time for complex analyses and testing.
- The CEM elements are custom designs that could prove difficult to develop.
- There are significant labor costs to retrofit the existing structure.
- Depending on the design, the weight savings may be lower than anticipated. It is estimated that the weight of the LFE–LRV combination designed using the 2-g approach can be approximately 5,000 lbs greater than the CEM approach.

The use of couplers with the highest possible energy absorption level significantly aid in mitigating a collision, regardless of the design approach selected.

Finally, as part of the specification development for a CEM zone and the LFE, many other structural aspects of the vehicle must be carefully reviewed to determine if strength levels are adequate and consistent with the CEM design.
The issue addressed is how to increase capacity and update passenger accessibility to keep pace with the “low-floor” trend in the transit industry, without making obsolete an existing fleet. The benefits of adding a new, low-floor center section to an existing light rail vehicle is discussed, and various issues and characteristics that must be considered and resolved before proceeding are identified, including, but not limited to: size of vehicle, aesthetic appearance, performance, propulsion and braking systems, all other onboard systems, structural strength, size and length of station platforms, interface with station platforms, and maintenance shop and other wayside facilities.

It is concluded that with good base line conditions, the addition of a low-floor center section to an existing vehicle allows a transit agency to upgrade capacity, facilitate passenger access to the rail vehicles, and transition toward the “low-floor” trend in the transit industry without having to either sell or scrap a relatively new, existing fleet or be faced with operating a mixed fleet of existing high-floor vehicles and new low-floor vehicles.

INTRODUCTION

From their inception, rail transit systems have continually expanded, improved service, enhanced availability, and increased the level of comfort for passengers. One of the latest developments in this continuing evolution is the ability to provide direct, level boarding for light rail vehicles (LRVs). Previously, this type of passenger accessibility was an exclusive characteristic of heavy rail systems using high platforms. High platforms are inherently incompatible in city streets with mixed pedestrian and automobile traffic. The new designs of LRVs address and partially mitigate this problem with floor levels that are approximately 14 in. above the top of rail (TOR). The low-floor rail vehicle, combined with a matching station platform, can be accepted into the streets of a city with relatively minor inconveniences. The low-floor, level boarding mode of operation greatly enhances accessibility for all passengers, reduces station dwell times and facilitates overall operation of the system. Also, level boarding accessibility allows the elimination of the special equipment and facilities, both on the vehicles and at the stations that are required for compliance with Americans with Disabilities Act (ADA).

DEFINITION OF THE PROBLEM

Providing level boarding for all passengers with the low-floor vehicle configuration is a very attractive feature. For a new light rail transit system there is almost no decision to make. The design of the new stations, maintenance facility, and other wayside facilities can be matched to the dimensions and configuration of the rail vehicles and the overall low-floor, level boarding
concept can be readily incorporated into a new system. For an existing light rail system that is either expanding or upgrading, the decision to change to level boarding configuration is much more difficult. For an existing system there are two choices:

- Continue to operate and expand or upgrade the system, “as is;” or
- Convert to low-floor, level boarding configuration and modify all existing stations and facilities as required.

From a maintenance and operations point of view, continuing to operate “as is” is the path of least resistance. The agency simply buys more vehicles with the same dimensions and characteristics and continues to operate them in the same manner, using the same stations and maintenance facilities. However, the general ridership, ADA community, local and federal government agencies, combined with the transit agency’s inherent desire to improve the system may influence the decision to convert to low-floor, level boarding configuration. Regardless of these influences, the transit agency must consider the financial impact of the modifications and changes that will be necessary to convert to level boarding operation and the disruption caused by the implementation of these changes. Converting to low-floor, level boarding configuration is difficult and expensive. Changing an existing, high-floor system to the low-floor, level boarding mode will require

- A new fleet of low-floor rail vehicles;
- Modifications to all existing passenger stations to provide level boarding onto the new low-floor vehicles;
- Modifications to maintenance facilities to provide for full maintenance access to the equipment installed on the roof of the new low-floor cars; and
- Modifications to any other wayside facilities that are affected by the change in characteristics of the low-floor vehicle.

Additionally, the disposition of the existing fleet of rail vehicles has to be determined. If the vehicles have reached the end of their useful or economic life they can be retired (scrapped), and new vehicles can be purchased as part of the upgrade. Selling the existing fleet of vehicles to another property—while sounding like an easy solution—requires a willing buyer with a compatible system and available funds. With other transit systems also considering and trying to convert to low-floor operation, the sale of a used, high-floor vehicle becomes improbable.

Somehow the existing high-floor and new low-floor vehicles have to be integrated together while still providing the desired, full-time, level boarding accessibility for the passengers. The most direct solution is to establish operational procedures for a mixed fleet of vehicles, requiring that all single car trains and at least one car in any multcar train is a low-floor vehicle. Obviously, these operational restrictions can be implemented, but there will be an adjustment period for the passengers and a continuing complication in the operational and maintenance procedures, to maintain the criteria.

If the decision is to continue “as is,” the course of action to expand is clear: follow the general criteria and guidelines that have been previously established and used for construction of the existing system.
The premise addressed in this paper is that an existing transit agency makes a decision to convert to an overall low-floor, level boarding mode of operation as part of an upgrade or expansion of the system.

The apparent course of action is to define and procure a new low-floor vehicle, modify the stations and facilities to match the new vehicle and establish procedures to operate a mixed fleet of high-floor and low-floor vehicles. However, depending on the characteristics of the existing fleet, another option is available for converting to low-floor, level boarding operation. Insert a new, low-floor center section into the existing, articulated LRV.

The following discussion will explore and analyze some of the more significant issues that must be addressed for each aspect of the system that will be affected by the low-floor, level boarding configuration and compare the differences between the low-floor vehicle and insertion of a low-floor section into an existing vehicle.

REAL WORLD SCENARIO

Many agencies have discussed the possibilities of incorporating a new center section into an existing vehicle configuration. Until now in North America, this has been an intellectual exercise. This paper will discuss the design, review, engineering process, and decisions leading up to the implementation of an actual test program of a low-floor center section by the Dallas Area Rapid Transit (DART).

DART is the newest and fastest growing, fully operational, high speed (65 mph), LRT system in the United States:

- Design and construction of the DART Starter System was initiated in 1990.
- DART issued the first contract for the procurement of LRVs in November 1991.
- Revenue service on the Starter System opened in June 1996 with 21 mi of track and 40 LRVs.
- In November 1997, DART issued a contract modification to procure 34 additional LRVs to supplement the existing fleet and prepare for Build-Out Phase I of the North East Corridor.
- In May 1998, DART issued a new contract for the procurement of 21 LRVs to support service on the Build-Out Phase I of the North Central Corridor.
- At the end of 2002, DART completed the 23-mi, Build-Out Phase I expansion and is now operating a 44-mi system with 95 LRVs.

In less than 10 years DART has doubled the size of the system and the fleet of rail vehicles. Continuing this rapid expansion, DART has initiated design and construction for Build-Out Phase II, which is scheduled for completion by 2012. Build-Out Phase II will again double the size of the system by adding approximately 44 mi of double track and increasing the fleet by at least 100 LRVs.

As part of the Phase II expansion, DART has decided to change to the low-floor, level boarding, mode of operation.

The current fleet of DART LRVs consists of “high-floor” vehicles. Passengers board from an 8 in. platform, step up 8 in. to the vehicle, and then there are three more 8 in. steps up to the passenger floor that is 40 in. above TOR. ADA compliance is provided with high blocks located at the end of the platform combined with a trap/bridge arrangement on the vehicle. The
DART LRVs are all relatively new and hence were not considered for retirement (scrapping). Selling the vehicles to another property was recognized as an unrealistic course of action. To convert to level boarding operation DART either has to procure new low-floor cars and operate a mixed fleet of high-floor and low-floor vehicles or insert a low-floor center section into the existing vehicles. (As of August 2003, DART has not made a final decision with respect to the type of vehicle that will be used for future expansion fleets. The following information is a summary of activities to date. DART’s final decision will be based on this information, any new factors that may be identified, discussion with DART member cities, local community and special interest groups, and coordination with FTA.)

The (strong) possibility of a conversion to low-floor, level boarding operation was recognized very early in the Build-Out Phase II program. Preliminary, internal reviews and discussions were initiated to determine if a typical low-floor vehicle could be procured to meet DART’s criteria of appearance, operational requirements and performance characteristics. Alternative courses of action were explored as well. Some of the salient characteristics that DART did not want to lose in the conversion to low-floor, level boarding operation were

- “Signature” appearance of the DART LRV,
- Acceleration and braking performance (3.0 mphs), and
- 65 mph operating speed of the rail vehicles.

**Vehicles**

DART has an existing fleet of 95 high-floor LRVs and is in the process of exercising an option for 20 additional high-floor vehicles, all from the same manufacturer and of the same design. The overall age of the fleet is relatively low. The 40 oldest vehicles started service in 1995–1996. The 55 newer vehicles were put into service in 2000–2001. The 20 additional LRVs are scheduled for delivery in 2005. In general, the fleet is considered to be reliable and is well accepted by the public. The specified design life of the vehicles is 30 years. As discussed previously, the ideas of retiring or selling the fleet were discarded early in the studies. Therefore, the existing fleet of vehicles has to be incorporated into the new level boarding mode of operation, until they reach the end of their economic life. There are two ways of accomplishing this:

- Operate a mixed fleet of vehicles consisting of the existing fleet of DART LRVs combined with new low-floor vehicles; or
- Insert a low-floor center section into the existing vehicles and procure additional vehicles to meet the desired fleet size.

**Low-Floor Light Rail Vehicles**

Low-floor light rail vehicles (LFLRVs) are considered to be established, proven technology. They are in successful operation on numerous properties in Europe and in North America. At the present time there is no LFLRV in service that is designed for 65-mph operation. With the exception of Metro Rail in Houston, Texas, all of the LFLRVs in operation are designed for 55-mph operation. The LFLRV that is being procured for Houston, Texas, is specified to have an operating speed of 66 mph. Dynamic testing of this vehicle is scheduled to begin in 2003.
Because of the established, acceptable, history of operation, a detailed review of the characteristics of a typical LFLRV was not pursued. LFLRVs are considered to be an acceptable alternative for the DART system and Phase II expansion, with the qualification that an operating speed of 65 mph can be achieved in normal revenue operation.

**Low-floor Center Section**

Center section inserts are a newer, less established, technology that have not been employed in North America. DART undertook an in-depth investigation to determine if the use of a center section is a viable alternative that could be used as part of the Phase II expansion to both increase capacity and enhance overall passenger accessibility.

Several transit properties in Europe have inserted center sections into existing vehicles to increase capacity. In general, all of these applications have been low-speed (35 mph to 45 mph) applications. With the exception of the prototype operating in Dallas, Texas, a center section insert has not been used for revenue service in North America. A center section can be installed in any articulated vehicle. The age of the vehicle and the technology of equipment used on the vehicle are the determining factors in the decision for installing a center section. If the vehicle is near the end of its useful life it may not be reasonable to invest a large amount of money in upgrades. If the propulsion, braking, or auxiliary equipment cannot support the weight increase and power requirements of the center section, the vehicle would not be acceptable for operations.

Another factor to be considered with the integration of a center section into an existing articulated vehicle is the overall structural strength. The DART LRV was designed to meet a “2g” requirement. That is, the buff load (end compression strength) of the car-body structure is designed to be twice the empty weight of the completed vehicle in the ready to run configuration.

The value of 2g is an historic value selected to represent a car-body strength high enough to withstand minor to intermediate collisions without basic structural damage, but low enough to minimize the potential for passenger injury. The car body must demonstrate both 2g end strength and the ability to crumple from the ends in a controlled manner when collision energy exceeds the structure’s strength. This “cushions the blow” of the collision, providing a compromise between two factors that cause injury in collisions: 1) loss of passenger volume (crushing of the structure), by providing a reasonable level of static strength; and 2) controlled crush behavior when the car-body strength is exceeded. The ratio of “actual” weight of the DART LRV (107,000 lb) and “actual” structural buff test load (227,000 lb) is 2.12 g. Compared to similar articulated LRVs, the DART LRV is stronger. This characteristic makes the addition of the weight of the center section much more viable.

The DART LRV is both relatively new, and the propulsion, braking, and auxiliary systems are relatively current technology. These characteristics make the introduction of a low-floor center section into an existing vehicle—while still maintaining similar performance, operational characteristics and a top speed of 65 mph—a viable possibility.

The general technical issues of car-body strength, performance, speed, and so forth, related to the incorporation of a low-floor center section into the DART LRV were reviewed and the results were found to be favorable. The concept that was further developed was to maximize the passenger capacity of the low-floor center section while making the minimum number of changes to the existing vehicle. With no increase in propulsion, the additional weight of the center section would reduce overall acceleration of the modified vehicle to approximately 2.3 mph/s. However, the operating speed of 65 mph would be maintained. The addition of a second
trailer truck with 4-disc brakes would compensate for the extra weight and maintain the 3.0
mphps deceleration rate. Basically, the concept was to separate an existing LRV at the
articulation joint and insert a low-floor center section and a second trailer truck between the two
existing sections, creating a 3-section, double-articulated, 4-truck, 8-axle, “super” light rail
vehicle (Super-LRV).

Structure

The structure of the DART low-floor center section is designed to be approximately 5% stronger
than the existing LRV structure. This makes the center section uniform and consistent with the
existing car-body structure and the philosophy of crash worthiness (controlled deformation
starting at the ends of the vehicle) that is included in the basic design. The addition of the center
section with an actual weight of 31,000 lb changes the weight/strength ratio of the DART Super-
LRV to 1.64 g. This is equivalent to the older Type I and the new “Type II” low-floor vehicles
currently in service in Portland, Oregon. The actual structural strength, 227,000 lb, and crash-
worthiness characteristics of the DART car body structure remain unchanged.

Dimensions and Performance

The height, width, and appearance of the low-floor center section were matched to the existing
car. The floor height of the low-floor area was selected to be 16 in. above TOR so that it would
match the first step in the stairwells of the existing car. This is 2 in. higher than the typical 14 in.
floor height of a low-floor car. While the low-floor center section could have been built to 14 in.
above TOR, the 16 in. height was selected to eliminate the trip hazard with 14 in. platforms at
stairwells of the existing doors, which are at 16 in. Truck spacing of 31 ft for the center section
was selected to match the existing truck-to-truck distance to maximize capacity without changing
the static and dynamic envelope, with the exception of the increase in overall length from 92 ft, 8
in. to 123 ft, 8 in. The center section was designed with articulation joint assemblies and
electrical boxes for car line and train line signals that would directly match up with the respective
A and B sections of the DART LRV. The second trailer truck and bolster is the same as the
existing trailer truck.

Using the same articulation and center trucks has several advantages and a disadvantage.
The advantages are that no new equipment is added to the vehicle and the use of a traditional
truck configuration, with continuous, straight axles and full size, inboard, disc brakes (as
compared to a typical low-floor center truck with stub axles and wheel or outboard mounted
brake assemblies). The traditional center truck configuration is considered an essential element
for maintaining a 65-mph operating speed and a 3.0-mphps deceleration rate of the Super-LRV.
The disadvantage is that the area of the low-floor portion is limited to the distance between the
center trucks.

Equipment

The capacity of the existing on-board air supply and friction braking systems was determined to
be sufficient to support operation of the friction brakes and air spring on the additional truck and
the door operators on the center section. The capacity of the low-voltage system was determined
to be sufficient to operate all control functions of the center section and the track brakes on the
additional truck. It was determined that an additional heating, ventilation, and air cooling (HVAC) unit would be required to be installed on the roof of the center section along with a new 10 kW static inverter to provide power for the HVAC unit and interior lightning. To the extent possible, existing components, equipment, and systems were incorporated into the design of the center section. The door operators, door panels, trailer truck, brakes, HVAC unit, interior lights, passenger seats, passenger side windows, portions of the interior lining, and other miscellaneous parts are identical to those used on the existing car. The operator’s cab and all car and train line control functions remain unchanged. The only new or different operating component is a 10 kW static inverter that is used to power the HVAC unit on the center section. Insertion of a completed low-floor center section into a DART LRV was planned to be a simple process of unbolting, disconnecting, and separating a LRV, inserting a center section and trailer truck, and then bolting and connecting everything back together—the ultimate plug and play modification.

Implementation

As with all designs, the Super-LRV met all of the criteria and looked great on paper. The next logical step was to prove the concept in a real world application. As a joint research and development effort DART coordinated with Kinkisharyo International, LLC (manufacturer of the DART LRV), to build a complete, fully operational, low-floor center section, install it in a DART LRV, and test it on the DART system to confirm the results of the studies and reviews that had been performed. The basic agreement was that DART would supply equipment and materials from existing stores for installation on the center section and Kinkisharyo would provide the raw material, coordination, manufacturing, assembly, testing, and transportation of the center section. After inserting the center section into a vehicle, DART and Kinkisharyo would jointly conduct dynamic testing of the Super-LRV to verify the dynamic capabilities and performance. After this, the Super-LRV would be released for revenue service to verify operational acceptability and to gauge the reception by the ridership.

Manufacturing and Testing

The low-floor center section was manufactured at the Kinkisharyo manufacturing facility in Osaka, Japan, in 2001 and delivered to the DART maintenance facility in February 2002. The center section was installed in LRV 170 in May 2002 creating the first, fully-operational, double-articulated, 65-mph, Super-LRV. All of the planned static and dynamic tests have been successfully completed. The initial acceleration rate of the DART Super-LRV is 2.4 mph/s, which is a little higher than expected. The Full Service Braking rate, 3.0 mph/s, is the same as the existing LRV. Operating speed, 65 mph, remains the same. After completion of dynamic testing the Super-LRV was operated extensively on the DART system as an “out of service” train. Unofficial reports from DART Operations and Maintenance staff indicate the vehicle performed well and was well received by all. Currently, Super-LRV 170 is being used in daily revenue service. The only operational restriction is that the Super-LRV cannot operate as part of a 3-car consist because the resulting train (two standard DART LRVs and one Super-LRV) is too long for some of the existing station platforms.
Conclusion

Because of the extensive review that was conducted and actual field-testing of a DART vehicle on the DART system, the addition of a low-floor center section is considered to be a viable alternative for further consideration during the Phase II Expansion plans, without qualifications.

Compatibility with the Rest of the System

Parallel with the review and design of the Super-LRV, the operational issues and interfaces with other systems (electrification, communications, and signals) and wayside facilities (stations and maintenance shop) were also considered. Each of these areas was carefully reviewed to determine what requirements needed to be incorporated into the design of the new line sections in Build-Out Phase II and what modifications needed to be implemented in the existing line sections.

Wayside Facilities

Length of the station platforms was identified as the primary limiting factor for the use of the longer vehicle with the center section. A LFLRV of approximately the same size and length as the current DART LRV will fit into the existing stations and any future plans for capacity increases.

A Super-LRV, with a center section installed is 123 ft, 8 in. overall. This is 31 ft longer than an existing LRV (92 ft, 8 in.). The most critical areas of station length are the 4 stations in the downtown Dallas Central Business District (CBD), because they are constrained by cross streets. The length of the station platforms that are in use in the CBD can accommodate a 2-car consist of Super-LRVs without modification. In terms of passenger seating this is equivalent to the 3-car trains that are being operated during rush hours.

In the future, when increased capacity requires the use of 4-car trains, all of the station platforms will have to be modified to increase platform length by approximately 100 ft. The original design of the Starter System included space for this expansion at all stations, including the four stations in the CBD area. In this event, a 3-car, Super-LRV consist, which has a higher seating capacity, can be used in place of a normal 4-car LRV train.

Wayside Systems: Signal System, Grade Crossings, Traction Electrification System, Overhead Catenary System

If a new LFLRV is selected and specified to have the same operating and performance characteristics as the current LRV, there would be no change in the interfaces with any of the operating wayside systems; Signals, grade crossings, train electrification system (TES) and overhead catenary system (OCS).

Although the Super-LRV has a lower acceleration rate, it has the same braking rate as the current vehicle, so no change would be required for the Signal System block length or the grade crossing approach circuits. With the Super-LRV, each vehicle has the same propulsion system and will have the same maximum current limit as the existing vehicle. However, there will be fewer cars operating for the same number of passenger seats that are in service, resulting in a net reduction in power consumption (cost) and general wear on the OCS.
Operations

A new LFLRV would be specified to have the same level of performance and speed, as the existing DART vehicle, and hence would have no impact on the current operation. Because of the extra weight of the center sections in the Super-LRV, it will have a lower initial acceleration rate. However, it has been determined that the existing schedules could be maintained on the existing system. Simulations using the lower acceleration rate of the Super-LRV indicate that the worst case run from terminal to terminal results in an increase in the running time of approximately 2 min on one of the lines. Detailed review of the simulations indicates that the majority of this time is lost in central areas of the system where station spacing is reduced to approximately 1 mi and even less in the CBD. This run time increase is considered to be acceptable in the overall schedule of operations and is absorbed in the turn times at the end of the lines. As the DART system expands and station spacing increases in the outer areas, the effect of the lower initial acceleration on overall run time is further reduced.

Capacity

A new LFLRV would have equivalent seating capacity as the current vehicle, as shown in Table 1. As part of the modification to insert a center section into a DART LRV, two double-flip seats (four seats) that were removed by DART to enhance ADA accessibility will be reinstalled, and four new single seats will be installed. Combined with the 24 seats in the center section, the seating capacity of a Super-LRV is 104. A 2-car, Super-LRV consist can be directly substituted for a 3-car, LRV consist without modification to platform length and provide nearly equivalent passenger capacity. Table 1 lists a summary comparison of the seating capacity of various train configurations.

Maintenance

A new LFLRV would have a high percentage of new components, equipment, and systems. Operations and Maintenance staff would have to be trained on both a new LFLRV and the existing vehicles. Spare parts would have to be stocked for both types of vehicles. The introduction of a Super-LRV into the DART system has no change in operations and effectively no change to the maintenance procedures, spare parts, and training that are required to keep the Super-LRV in revenue service. With the exception of the new static inverter installed on the roof of the C-car, all of the operating equipment is the same, with complete interchangeability, as the equipment used on the current vehicle.

Service and Inspection Facility

The Service and Inspection (S&I) facility will have to be modified regardless of the type of low-floor vehicle that is selected. For any low-floor vehicle, a second maintenance level would have to be installed at roof height to provide for full maintenance access to the roof mounted equipment. The Super-LRV is 31 ft longer, which requires that the maintenance pits be extended, and the in-floor hoists modified to allow access to the equipment.
TABLE 1  Comparison of Seating Capacity by Car Consist

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<th>LFLRV (# Seats)</th>
<th>Super-LRV (# Seats)</th>
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<tr>
<td>1 Car</td>
<td>72</td>
<td>76</td>
<td>104</td>
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<td>2 Car</td>
<td>144</td>
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<tr>
<td>3 Car</td>
<td>216</td>
<td>228</td>
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<tr>
<td>4 Car</td>
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<td>304</td>
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Note: In some hours of intermediate, off-peak operation, when passenger volume is lower, it will be possible to operate a single Super-LRV in place of a 2-car normal LRV train.

CONCLUSION

A new LFLRV can be incorporated into DART’s plans for system expansion and is considered to be a readily available alternative for the planning and implementation for Phase II expansion and future increases in capacity—with the qualification that a 65-mph operational speed can be provided.

Review of a center section concept and application including actual manufacture and testing of a low-floor center section shows that the Super-LRV concept is also a viable and now proven course of action to support the Phase II expansion and future increases in capacity, without qualification, and has additional benefits when compared to a new LFLRV.

DART BUILD-OUT PHASE II

With the successful completion of the joint development effort of the Super-LRV, DART had two general vehicle designs, LFLRV or Super-LRV, either of which could be used as the basis for conversion to low-floor, level boarding operation, expansion of the system and future increases in capacity for the entire system. Using the two possible vehicle configurations as starting points, DART next began to review the existing lines and the planned expansions to determine what features must be designed into the new extensions and facilities and what modifications would need to be incorporated into the existing lines and facilities in order to convert to low-floor, level boarding operation.

Currently DART operates two lines with 3-car consists during peak hours. The two lines start and end in the Northern and Southern urban areas of Dallas and merge together to go through the CBD creating 4 “branches” (two to the North and two to the South) that feed into the CBD. Build-Out Phase II will add three more branches (two to the North and one to the South), also feeding into the CBD.

All of the existing stations can accommodate 3-car trains. When required to increase capacity the length of all of the existing station platforms can be increased to accommodate 4-car trains. Based on the enthusiastic public acceptance of the DART Light Rail System and a ridership in early 2003 of approximately 66,000 passengers per day, DART expects to increase capacity in the near future. In anticipation of this requirement all of the new stations in Build-Out Phase II will be built to accommodate 4-car trains. Also, in anticipation of the conversion to level
boarding, the new platforms will be built at 16 in. above TOR to be compatible with either of the two low-floor vehicle designs.

The new vehicles that DART will purchase as part of the Phase II expansion will have to be operationally compatible with the existing fleet and will have to serve as the basis for level boarding operation.

The advantages and disadvantages of several different fleet configurations were reviewed to determine the best course of action. The existing DART LRV was used as the base line criteria for comparisons with other fleet configurations. Current plans are that DART will procure 20 LRVs to supplement the existing fleet for a total of 115 LRVs. For Phase II Build-Out an additional 100 LRVs (estimated) will potentially be procured. This will result in a total fleet size of 215 cars (95 + 20 + 100 = 215 cars) with 15,480 passenger seats (215 × 72 = 15,480 seats). The total number of passenger seats is the characteristic that allows direct comparison of the different fleet configurations. Of the various fleet combinations that were reviewed, three stand out as being potentially acceptable:

- **Base Fleet**—Maintain the existing fleet of 115 LRVs (72 seats) and procure 100 additional LRVs (72 seats). Total 215 cars (uniform fleet, high-floor cars) 15,480 seats.
- **Option 1**—Maintain the existing fleet of 115 high-floor LRVs (72 seats) and procure a new fleet of approximately 95 new low-floor LRVs (LFLRV) (76 seats). Total 210 cars (mixed fleet), 15,500 seats.
- **Option 2**—Procure 114 low-floor center sections to be installed in the existing fleet of vehicles (104 seats) and procure approximately 47 new LFLRVs (76 seats). Total 162 cars (mixed fleet), 15,532 seats.
- **Option 3**—Procure 114 low-floor center sections to be installed in the existing fleet of vehicles (104 seats) and procure approximately 34 new Super-LRVs that are the same as the existing fleet with the low-floor center section included (104 seats). Total 149 cars (uniform fleet), 15,496 seats.

All calculations that resulted in a “fraction” of a vehicle were rounded up to the next “whole” vehicle with the corresponding number of seats. It should also be noted that DART has procured one low-floor center section and installed it in LRV 170. In the fleet size calculations above and the cost estimations following, the numbers have been adjusted to reflect that DART already has one fully operational, Super-LRV that is ready for service.

Changes to existing wayside facilities and stations to take full advantage of the low-floor configuration will be required regardless of the course of action. The actual configuration of the vehicles will determine the modifications necessary at all existing facilities and the design and construction of all new facilities. A summary discussion of the various elements that will be affected and a comparison of some of the cost impacts is presented below.

**COST—THE DRIVING FACTOR**

As a starting point for the Build-Out Phase II studies, cost was used as the primary consideration in DART's review and decision-making process. In a special situation another, more important, factor may override cost as the determining factor. These special situations are addressed and resolved on a case-by-case basis.
After the real estate, the primary capital asset of an existing system, and the primary capital cost for expansion of the system, are the rail vehicles. Additionally the manufacturing lead time for the new rail vehicles is approximately two years from award of contract. Decisions with respect to these two major cost drivers, the existing fleet and the new vehicles, must be established as early as possible in the program, because the modification of all existing facilities and systems and design of all new facilities and systems will be driven by the basic decisions in these two areas. The questions addressed were

- What will be done with the fleet of existing vehicles to incorporate them into the low-floor, level boarding mode of operation?
- What type of new vehicles will be procured to provide service on the expansion portion of the system?
- What modifications will be required for existing stations and facilities?

Vehicles

Using the fleet sizes noted above, a rough order of magnitude (ROM) cost for the different fleet configurations with equal passenger seat capacities could be determined. A summary review of recent LRV procurements indicates that a ROM price for a new, LFLRV is $3 million. The ROM cost of a low-floor center section is assigned at $1 million. Using these values the ROM fleet costs for the “base fleet” and the 3 options above are as follows:

- Base Fleet (115 existing LRVs plus 100 new LRVs): $300 million.
- Option 1 (115 existing LRVs plus 95 new LFLRVs): $285 million.
- Option 2 (114 new low-floor center sections plus 47 new LFLRVs): $255 million.
- Option 3 (114 new low-floor center sections plus 34 new Super-LRVs): $250 million.

Station Modifications

To maximize the accessibility benefits of the low-floor vehicles the station platforms must be designed to be directly compatible with the selected vehicle. All new Phase II station platforms will be built so that the entire platform will provide level boarding with the vehicle regardless of the configuration. The configuration of the vehicle determines the extent of the modifications that are necessary for the existing platforms.

If a LFLRV is selected, the entire length of the platform for each of the existing stations must be raised 8 in. to guarantee that a passenger that boards at a new station (with full length, level board, platforms) is not stranded at an existing station. The implications and complications of this kind of modification are a significant cost factor because of the numerous interfaces with other wayside facilities (doors, elevators, escalators, stairways, columns, seating, ticket vending machines, landscaping, etc.). Almost everything on the platform must be removed, the platform must be raised 8 in., and all equipment and facilities must be reinstalled. There would be a significant disruption of service as each station is closed for this type of modification.

If a Super-LRV is selected, special use platforms (SUP) can be used to modify the existing stations. SUPs are essentially “humps” or localized sections of the platforms that are raised 8 in. so that the door of each low-floor center section lines up with the SUPs when the train stops. There would be relatively minor interface issues associated with the installation of
SUPs on each station platform. This greatly reduces the length of the disruption at each of the stations when this modification is made. To minimize conversion time, confusion, and effect on the passengers during the change over to level boarding operation, temporary or semi-permanent segments of the SUPs could be prefabricated off site and then placed into position on the platforms, until the final configuration SUPs have been installed. Regardless of the use of SUPs, some of the existing platforms will be totally raised 8 in. because of site specific complications and restrictions. (If SUPs were installed for each door of an LFLRV they would overlap each other, which is equivalent to raising the entire platform.)

The cost difference between raising all existing platforms 8 in. for use with LFLRVs versus installing two SUPs on each platform for use with the Super-LRV, for each of the existing stations, is estimated to be approximately $15 million.

**Maintenance Facility Modifications**

Regardless of the type of fleet that is selected, modifications to the existing S&I facility will be required.

If a LFLRV is selected, with the majority of equipment installed on the roof, the inspection and maintenance areas will have to be modified to provide for full maintenance access to the roof of the vehicle. Essentially a second floor has to be installed at the roof level of the low-floor vehicles. Estimated costs for this are approximately $1 million.

The equipment location of the Super-LRV is the same as the existing vehicle; however, the Super-LRV is 31 ft longer. The maintenance pits will have to be extended and the in-floor hoists will have to be modified to accommodate the longer vehicles. Estimated costs for modifications to the S&I for the Super-LRV are approximately $4 million.

The new maintenance facility that is included in Phase II expansion will be built to accommodate the type(s) of vehicles that are selected.

**Fleet Operation**

Currently DART operates 1-, 2-, or 3-car consists, depending on the time of day. When system capacity is increased, 4-car consists will be used. If LFLRVs are used to increase the size of the fleet, these configurations will continue without change.

If all Super-LRVs are procured the size of the consists at various times of the day will change. The capacity of two Super-LRVs is equivalent to three LRVs. Therefore, 3-car trains can be replaced with 2-car Super-LRV trains. In the future, 4-car LRV trains can be replaced with 3-car Super-LRV trains. Additionally, a portion of 2-car trains used in intermediate, off-peak hours can be replaced with a single Super-LRV. A single Super-LRV costs the same to operate as a single LRV and costs less to operate than two LRVs. Two Super-LRVs cost less to operate than three LRVs.

Based on the calculated power consumption and the smaller train consists that are possible with the Super-LRV, it is estimated that DART could realize energy savings of approximately $500,000 per year on the existing system if Super-LRVs are used, as compared to the DART LRV. Extending this projection to include the Phase II expansion, which, approximately, doubles the size of the system, it is estimated that a savings of $1 million per year could be realized when Phase II is opened for service.
Fleet Maintenance

Standardization of a fleet of rail vehicles is an intangible but significant benefit to the Maintenance and Operations Department. Operation of a mixed fleet of low-floor and high-floor vehicles with different components and parts will be the source of continuing difficulties for the life of the vehicles. All maintenance staff will be required to be trained on and be familiar with both types of vehicles. The storerooms will have to stock sufficient quantities of separate spare parts for the different types of vehicles.

A standardized fleet of Super-LRVs eliminates these difficulties. Another benefit is having direct interchangeability with all of DART’s existing spare parts, effectively reducing the overall capital value of spare parts in inventory. Additionally, the overall quantity and value of spare parts will be reduced, because a fleet of Super-LRVs is approximately 30% smaller than an equivalent fleet of high and low-floor vehicles. While standardization of the fleet is recognized as a benefit both to Operations and Maintenance, no cost has been estimated to reflect this (real) value.

Another maintenance benefit associated with Super-LRVs is that there will be a net reduction in preventative maintenance costs for the fleet. If Super-LRVs are selected there will be 30% fewer vehicles to be maintained for the same number of passenger seats. Because there is physically more equipment installed on a Super-LRV (1 HVAC unit, 1 center truck, 1 static inverter) it is estimated there will be a 20% reduction of the man hours necessary for normal preventative maintenance activities for the entire fleet of Super-LRVs as compared to an equivalent fleet of mixed high and low-floor vehicles. Based on current procedures, this represents an approximate savings for scheduled, preventative maintenance activities of approximately $680,000 per year. In the longer term there will be a reduction in costs for rebuild or overhaul of equipment because there is less equipment to be maintained.

SUMMARY

To be able to address the continued enthusiastic reception and demands for expansion of service and a desire to continue to enhance overall accessibility of the LRT System, DART is in a unique position. The option of introducing a low-floor vehicle into service, with the associated changes in infrastructure, maintenance, and operations is available to all transit agencies. Inserting a center section into an existing vehicle is also possible for all agencies. Inserting a center section into a modern vehicle and maintaining essentially the same performance and 65-mph operating speed is an option that is only available to DART. The results of the static and dynamic testing that were performed confirm that the insertion of a low-floor center section into the DART LRV is a reasonable method of achieving a low-floor, level boarding configuration and reducing cost, while maintaining

- Schedule performance,
- 65-mph operating speed,
- Standardization of the fleet of vehicles, and
- Signature appearance of the DART rail vehicle.

A summary comparison of the cost impacts of the various aspects of the DART System, equipment, and facilities identified in the body of the report is presented in Table 2.
### TABLE 2 Comparison of Options for DART Fleet Combinations

<table>
<thead>
<tr>
<th></th>
<th>Base Fleet 115 LRV 100 LRV</th>
<th>Option 1 115 LRV 95 LFLRV</th>
<th>Option 2 115 Super-LRV 47 LFLRV</th>
<th>Option 3 149 Super-LRV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Cost</td>
<td>$300 million</td>
<td>$285 million</td>
<td>$255 million</td>
<td>$250 million</td>
</tr>
<tr>
<td>Station Mods</td>
<td>$25 million</td>
<td>$25 million</td>
<td>$25 million</td>
<td>$10 million</td>
</tr>
<tr>
<td>Facilities Mods</td>
<td>$1 million</td>
<td>$5 million</td>
<td>$4 million</td>
<td></td>
</tr>
<tr>
<td>*Savings Fleet Power</td>
<td>No Change</td>
<td>No Change</td>
<td>Slight reduction</td>
<td>*$1 million per year</td>
</tr>
<tr>
<td>*Savings Fleet</td>
<td>No Change</td>
<td>No Change</td>
<td>Slight Reduction</td>
<td>*$680,000 per year</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Uniform (High-floor)</td>
<td>Mixed</td>
<td>Mixed</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

The Base Fleet simply maintains the current configuration with high-floor vehicles. Fleet Options 1 and 2 both result in the incorporation of a new low-floor vehicle, potentially from a different manufacturer, into the DART fleet with the associated changes in operations and maintenance. Option 3 essentially has no changes in the maintenance and operation of the fleet.

All transit systems and applications have different criteria and emphasis on different individual characteristics. In this comparison the selection of the Super-LRV will achieve the desired goal of a low-floor, level boarding mode of operation and has a clear cost advantage both in initial procurement and future operations and maintenance, with no significant operational or interface disadvantages. In another situation with the emphasis on a different aspect or requirement, a similar study may result in a different indication.
The Massachusetts Bay Transportation Authority operates the oldest light rail system in North America, known as the Green Line, with sections dating back more than 100 years. In order to improve accessibility to the Green Line, in 1995, MBTA ordered 100 partial low-floor, double-articulated light rail vehicles (LRVs) from AnsaldoBreda of Italy. These vehicles will operate in consist with existing high-floor, single-articulated LRVs. Some of the challenges faced by the project team are discussed, and some lessons learned that may be of value to other mature light rail operations contemplating such procurements are highlighted.

Derailments of the leading axle of the center truck of the No. 8 Low-Floor Car have been the most challenging aspect of the procurement. Following a comprehensive study of the vehicle dynamics and an investigation of the effects of track quality on derailment performance, several modifications were implemented to correct the problems. While some of the characteristics of the Green Line are unique, the important lessons learned can be usefully applied to other procurements involving the introduction of low-floor LRVs to systems with older infrastructure.

INTRODUCTION

The Massachusetts Bay Transportation Authority (MBTA) operates the most intensive light rail service in the United States, over some of the oldest infrastructure to be found in the world. This position as “grandfather” of the light rail industry means that the MBTA and its predecessor agencies have frequently faced the need to introduce new technology into the existing infrastructure. For the MBTA light rail system (the Green Line), vehicle technology has been an area where there has been frequent technological change. The original streetcar lines were developed for four-wheeled, horse-drawn trolley cars. The MBTA is currently deploying the eleventh generation of electric trolley vehicles to operate over these same lines.

Boston’s transit providers have never been shy of introducing new technology. From the early introduction of the first electric streetcars, through the President’s Conference Committee (PCC) car era, to the (then) advanced Boeing Vertol Standard Light Rail Vehicle (SLRV) in the
1970s, Boston has often been at the leading edge of vehicle technology. This trend continues, with the MBTA becoming the second North American property to order low-floor light rail vehicles (LFLRVs), and the first “mature” U.S. light rail system to procure these vehicles.

Introducing new technology is not always easy, and the introduction of the low-floor car (LFC) to Boston has been no exception. As this project has been covered at length in previous papers (1–4), only a brief summary of the highlights is discussed below.

The procurement of LFCs was driven by two factors: the desire to make the Green Line service accessible to all, in compliance with the Americans with Disabilities Act (ADA) requirements, and the need to replace the aging and unreliable Boeing SLRV fleet. After extensive investigations and reviews of available vehicle designs, the MBTA decided to procure a fleet of partial (70%) LFLRVs. These vehicles were specified to occupy the same physical envelope as those that they will replace in order to avoid the need for infrastructure modifications. The new vehicles were also required to be compatible with the workhorse of the Green Line fleet, the Kinkisharyo-built No. 7 Surface Rail Car (SRC), permitting operation of mixed consists to ensure there is at least one accessible vehicle per train.

In 1995, after a competitive procurement, MBTA awarded a contract to Breda Costruzioni Ferroviarie of Italy (now AnsaldoBreda) for design and supply of 100 LFLRVs, to be known as the No. 8 LFC. The contract also includes requirements for upgrading the 115 No. 7 SRCs to make these cars compatible with the systems installed on the No. 8 LFC.

Unfortunately, technical problems were encountered that required the fleet to be withdrawn from revenue service and which significantly delayed the project. These problems illustrate some of the challenges faced when integrating new vehicle technology into an existing, and aging, light rail system.

**SUMMARY OF THE NO. 8 LFC PROJECT**

**The Vehicle**

The No. 8 LFC is a new design (Figure 1), although its design solutions and systems were proven on other AnsaldoBreda products or on other LFLRVs. The three-section vehicle has an articulated frame motorized truck at each end, with an independent wheel trailer truck (also an articulated frame) beneath the center body section. The majority of equipment is roof mounted, including the IGBT propulsion inverters. Braking is electro-hydraulic, with truck-frame mounted hydraulic pressure control units. Key parameters are listed in Table 1.

**Program Summary**

An extensive prototype and development-testing program followed delivery of the first car to Boston in early 1998. This program focused on areas such as vehicle clearance, dynamic performance, propulsion and braking integration, and car monitoring systems. The first cars entered revenue service in March 1999. In the fall of that year, concerns with poor braking performance under low adhesion conditions forced withdrawal from service, and an intensive slide control system investigation program began. The fleet re-entered service on two further occasions, only to suffer a series of derailments, which caused further withdrawals. After a very extensive investigation and corrective action program, revenue service resumed in March 2003.
FIGURE 1 Prototype No. 8 LFC at riverside carhouse.

### TABLE 1 No. 8 LFC Main Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Bidirectional, double-articulated LRV</td>
</tr>
<tr>
<td>Configuration</td>
<td>Bo’ 2’ Bo (2 motor trucks, 1 trailer truck)</td>
</tr>
<tr>
<td>Low Floor Area</td>
<td>Approx. 70%</td>
</tr>
<tr>
<td>Track Gauge</td>
<td>4 ft 8.5 in. (1435 mm)</td>
</tr>
<tr>
<td>Minimum Curve Radius</td>
<td>42 ft (12.8 m)</td>
</tr>
<tr>
<td>Catenary Voltage</td>
<td>620 Vdc nominal</td>
</tr>
<tr>
<td>Length over Coupler Faces</td>
<td>74 ft (22.6m)</td>
</tr>
<tr>
<td>Max. Overall Car Width</td>
<td>8 ft 8 in. (2.64 m)</td>
</tr>
<tr>
<td>Max. Height, Equipment Included</td>
<td>11 ft 10 in. (3.6 m)</td>
</tr>
<tr>
<td>Wheel Diameter (new)</td>
<td>28 in. (711 mm) motor, 26 in. (660 mm) trailer</td>
</tr>
<tr>
<td>Floor Height from TOR</td>
<td>14 in. (356 mm) Low Floor, 35 in. (889 mm) High Floor</td>
</tr>
<tr>
<td>Side Door Opening Width</td>
<td>50 in. (1270 mm)</td>
</tr>
<tr>
<td>Seated Passengers</td>
<td>44</td>
</tr>
<tr>
<td>Standing Passengers</td>
<td>77 @ AW2, 154 @ AW3</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>86,000 lbs (39,090 kg)</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>55 miles/h (88 km/h)</td>
</tr>
<tr>
<td>Maximum Acceleration</td>
<td>2.8 mphps (1.24 m/s²)</td>
</tr>
<tr>
<td>Full Service Brake Rate</td>
<td>3.5 mphps (1.55 m/s²)</td>
</tr>
<tr>
<td>Emergency Brake Rate</td>
<td>6.0 mphps (2.66 m/s²)</td>
</tr>
</tbody>
</table>
Integration with Existing Vehicles

To operate in compliance with ADA regulations, at least one car per train must be “accessible.” Given the continuing use of the No. 7 SRC fleet on the Green Line, this meant that the No. 8 LFC was to be operationally compatible with the No. 7 SRCs to operate as a two- or three-car consist. For successful consist operation, an important goal is to closely match performance of the two vehicle types in order to avoid uncomfortable and potentially damaging coupler action. The challenge for the No. 8 LFC designers was to match the performance of the AC drive No. 8 LFC, with its fast acting hydraulic brakes, to the performance of the DC drive No. 7 SRC, with its air brakes. The different propulsion characteristics and system reaction times of the two vehicles required extensive fine-tuning of the control systems on the No. 8 LFC.

Slide Control Challenges

The performance demanded of the No. 8 LFC is quite high, particularly in braking. With the streetcar nature of parts of the Green Line, the ability to brake a train rapidly and stop within short distances is vital. The No. 7 SRC is equipped with track brakes on all trucks, but space constraints on the No. 8 LFC prevented installation of track brakes on the center truck, which placed this heavier car at a stopping-performance disadvantage. This situation was complicated by the configuration of the center truck, which has four independently braked low-inertia wheels, the sliding of any one of which could reduce effort on other trucks. By contrast, the No. 7 SRC has a much simpler system, which did not react to some of the slippery conditions detected by the No. 8 LFC and, as a result, stopped in a shorter distance.

Extensive testing and software changes eventually resulted in a design that offered stopping performance equivalent to, or better than, the No. 7 SRC under all foreseeable conditions (naturally occurring friction coefficients of as low as 0.043 were measured during night testing along the tree-lined Highland Branch). Comparative testing with application of a soap solution to the rails was used to confirm the equivalence of the stopping performance under controlled conditions. It is testament to the ability of the control system that it is able to overcome disadvantages of weight, low-inertia wheels, and less track brake effort compared with the No. 7 SRC, and yet still deliver equivalent performance.

DERAILMENT OF INDEPENDENT WHEELED TRUCK

Derailment Incidents

Derailments of the center truck of the No. 8 LFC have been the most challenging aspect of the project to date. The derailments started at a time when basic qualification testing (including ride quality and stability) had been completed, and revenue service had commenced. Significant mileage had been accumulated on the fleet in test and revenue service without incident and deliveries were starting to ramp up following the suspension of service due to braking problems. With the good equalizing properties of the articulated frame trucks, derailments were also unexpected. The derailments started in April 2000, when final preparations were being made for the fleet to return to revenue service. While the first two derailments were under investigation, two further derailments occurred, at different locations and with different vehicles. Following an initial
investigation, three further derailments occurred. All derailments were unusual in that they occurred on main line (rather than yard) track at higher speeds than is expected for derailments on the Green Line. All incidents involved flange-climbing derailment of the leading axle on the independent wheel center truck. In all cases, the vehicle was lightly loaded, resulting in the minimum load on the center truck wheels.

Derailment Investigation Outline

A comprehensive Corrective Action Plan (CAP) was initiated, focusing on three key related system elements:

- The No. 8 LFC and its dynamic performance;
- The Green Line track condition and future maintenance standards (Table 2); and
- The existing No. 7 SRC and its impact on track condition.

The CAP was developed jointly between the MBTA and its consultants—Booz Allen Hamilton (coordination), HNTB (track issues) and Transportation Technology Research Center (TTCI) (vehicle dynamics). The CAP also involved the carbuilder, AnsaldoBreda, supported by vehicle dynamics experts from the Politecnico di Milano (PdM). The MBTA sought confirmation of its CAP process by requesting peer review from a panel assembled through the American Public Transportation Association. Finally, the CAP was submitted to and approved by the MBTA’s State Safety Oversight body, the Massachusetts Department of Telecommunications and Energy (DTE).

As the nature of the derailment problem and the necessary corrective actions became clear, the MBTA decided on a phased approach to restoring the No. 8 LFCs to revenue service on a route-by-route basis. The initial phase, Phase 1, was focused on an interim return to service on one route [the Commonwealth Avenue (B) line]. This line operates at relatively low speed but presents many different track geometry and condition challenges, and thus forms an ideal basis for testing No. 8 LFC operation. Phase 1 was used to establish the baseline requirements for operation of the cars at limited speeds of up to 35 mph (56 km/h) and included work related to wheel profiles, track maintenance standards and upgrades, and validation testing. Subsequent and current work, under Phase 2, will see a return to service on a line-by-line basis and will include the work necessary to validate safe performance up to the maximum required speed of 55 mph (88 km/h).

**TABLE 2 MBTA’s New Track Maintenance Standards**

<table>
<thead>
<tr>
<th>Maximum track gage [tangent and curves greater than 1000-ft (305-m) radius]</th>
<th>56-7/8 inch (1445 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal alignment, 31-ft (9.4-m) chord</td>
<td>⅝ inch (16 mm)</td>
</tr>
<tr>
<td>Runoff over 31 ft (9.4 m) at end of raise</td>
<td>1-⅝ inch (32 mm)</td>
</tr>
<tr>
<td>Deviation from uniform profile–62-ft (18.8 m) chord</td>
<td>1-⅞ inch (41 mm)</td>
</tr>
<tr>
<td>Variation in cross level on spirals over 31-ft (9.4 m) chord</td>
<td>⅜ inch (22 mm)</td>
</tr>
<tr>
<td>Deviation from zero cross-level</td>
<td>1-⅞ inch (28.6 mm)</td>
</tr>
<tr>
<td>Difference in cross-level over 62 ft (18.8 m)</td>
<td>1-⅛ inch (41 mm)</td>
</tr>
</tbody>
</table>

**NOTE:** Maintenance standards for unrestricted speed.
Derailment Investigation Approach

The wheel to rail interface was exhaustively investigated, and complex mathematical models were developed to simulate the behavior of the vehicle on measured Green Line track geometry and irregularities. The aim of this investigation was to isolate the detailed mechanics of the derailment, and to identify appropriate corrective action strategies.

Initial work focused on addressing the derailments using the simple Nadal theory as a safety limit (Figure 2). This limit remains a conservative one; although, for an independent wheel, more accurate approaches can be employed when full details of the wheel-to-rail interface are available. Initial efforts were focused on increasing the Nadal limiting value by addressing the most controllable variable—the effective flange angle. The original wheel profile design employed a 63-degree flange angle, driven by the fact that all other vehicles on the Green Line use such a profile. Analysis quickly showed that a change to a more modern 75° flange angle was feasible and should deliver significant increases in the derailment safety margin by increasing the Nadal limit. Considered simply, for a constant vertical load, the tolerable lateral force between wheel and rail could be increased by 53% by changing the flange angle. In order to confirm the validity of this premise, an extensive investigation was launched.

The conceptual approach followed during the investigation is shown in Figure 3. This approach was followed to develop, refine, and validate an accurate dynamic model of the vehicle.

\[
\text{Nadal's limit:} \quad \frac{L}{V} = \frac{\tan \delta - \mu}{1 + \tan \delta}
\]

Where \( \mu \) is the coefficient of friction between wheel and rail.

**FIGURE 2** Nadal’s derailment theory.
FIGURE 3 Outline of derailment investigation approach.

for use as a predictive tool for derailment performance. Two independent mathematical models were developed (using NUCARS™ by TTCI and ADTracs by PdM). These models used some different approaches and assumptions, but ultimately converged to give comparable results. Both models were also validated by real world testing, building confidence in their accuracy.

The model was used to develop the new wheel profile for use on the No. 8 LFC. This new profile was designed to optimize wheel-to-rail contact and increase the effective contact angle. In conjunction with this investigation, extensive activities were carried out to upgrade the condition of the Green Line track. Modeling showed that a common defect on the Green Line, cyclic side wear, or scalloping, was particularly dangerous for the dynamics of the independent wheel design. In addition, during the investigation of the new profile, some rail wear conditions were identified that would compromise the effectiveness of the new wheel profile. These conditions manifested as side wear, with a “lip” of flowed metal formed immediately beneath the tip of the existing wheel flange. The new wheel profile would interfere with this lip, so an unprecedented rail side-grinding program was initiated, which removed this condition on the entire Green Line.

New, viable, track maintenance standards were identified and implemented by the MBTA. In parallel, through extensive modeling and testing, the maximum line defects (alignment, gauge, and cross level) acceptable to the No. 8 LFC were identified and compared with the new maintenance standards.

Test Track Testing

While all this was good in theory, it was agreed that physical testing was necessary to confirm the true benefits of the wheel profile and track condition changes. The first stage in the process was to construct a test track, into which predetermined perturbations were installed (Figure 4).

This test track was instrumented with strain gages to measure the actual forces in the rails due to wheel-to-rail interaction. In addition, a test vehicle was extensively instrumented to
monitor movements and accelerations at various locations throughout the car. One of the key elements in this was the development by AnsaldoBreda of an instrumented wheelset (Figure 5).

**FIGURE 4** Perturbation in test track.

**FIGURE 5** Instrumented axle.
This innovation used the drop axle arrangement of the center truck as a system for measuring the actual wheel-to-rail forces, in close to real time. This system proved much quicker to produce and more cost effective than a more traditional instrumented wheel and formed an invaluable part of the investigation.

The perturbations introduced into the test track were quite extreme—1 3/16-inch (42-mm) horizontal alignment, 5/8-inch (16-mm) gage, and 3/4-inch (19-mm) cross level, all measured over a 31 ft (9.4 m) chord—to deliberately provoke high L/V ratios at the maximum design speed for the test track of 25 mph (40 km/h). Under the high friction levels encountered in the summer months, L/V levels of 0.95 were reached at speeds of up to 28 mph (45 km/h). No derailments were experienced.

The test track testing program permitted a direct comparison of model predicted, and actual measured, vehicle reactions to the controlled perturbation inputs. Good correlation was found between the predicted and measured wheel-to-rail forces and thus L/V ratios. Good correlation was also achieved with other vehicle parameters such as modes of vibration and acceleration levels. The program thus achieved its primary objective of validating the mathematical model(s) of the vehicle and resulted in a believable predictive tool for derailment behavior.

Main Line Testing

The next step was to use the model to predict vehicle behavior in the real world, represented by the Commonwealth Avenue (B line) of the Green Line. Detailed Track Geometry Measurement System (TGMS) data was collected, using a vehicle mounted non-contact (laser) system, to obtain the most reliable loaded track geometry data. One of the challenges of this process was to filter the data, as the system was originally designed for the relatively large curve radii and smooth transitions found on railroads. The tight curves with short or missing spirals found on the MBTA’s 100-year-old streetcar system often confused the system into reporting major alignment errors rather than actual curvature. Problems were also encountered with the laser system detecting wayside features, such as restraining or girder rail and road crossings as rail positions, and thus reporting gage as tight as 54 in. (1372 mm).

With the TGMS data filtered, the vehicle models were used to predict vehicle performance over the alignment and to identify problem areas of the track. Certain of these problem areas were used as focal points for later dynamic testing. The same test vehicle, with its instrumented axle, was used to conduct tests at various speed increments over the test locations, in addition to a line speed “minesweep” run of the entire line. The results from this test program both confirmed vehicle performance and identified a number of locations where corrective action was required for the track.

Having confirmed that the vehicle performance would be acceptable within the newly defined track maintenance standards, the track on the B line was upgraded to comply with these new standards. As a final step, a repeat TGMS run was performed to confirm that the upgrades had delivered a line that complied with the new standards.
Revenue Service

After a period of test running, and upon receiving CAP approval from the Massachusetts DTE, on March 22, 2003, revenue service resumed with the No. 8 LFC fleet on the B line. Revenue operation of the No. 8 LFCs is currently restricted to this route, pending upgrades of other routes to the new track standards and further investigations and possible changes to raise the current vehicle maximum speed of 35 mph (56 km/h) to 55 mph (88 km/h).

Summary of Findings

Derailment Causes

The fundamental reason for the derailments was found to be the Green Line track conditions (type and severity of irregularities) that proved to be critical for the dynamics of the independently rotating wheel design (Figure 6). In addition, the Green Line fleet original wheel profile, specifically the flange angle of 63º, resulted in a low L/V limit (under high friction levels), preventing any additional derailment safety margin. Vertical truck performance was not found to play a significant role in the derailments, as the articulated frame design provides for excellent load equalization.

The modeling process identified lateral alignment as the predominant critical track condition, particularly short wavelength lateral alignment perturbations—magnitude greater than ⅝ in. on a 31-ft wavelength. The problem of lateral perturbations is compounded when these perturbations are cyclic in nature. Track surveys identified that such cyclic alignment conditions were to be found especially on the higher speed sections of the Green Line, and it has been hypothesized that these are the result of interaction between the track structure and older generations of vehicles. The situation is more severe with combination defects, where perturbations in alignment are compounded with gage and or cross-level defects.

![Comparison of independent and coupled wheel steering.](image)

**FIGURE 6** Comparison of independent and coupled wheel steering.
However, the work to date has confirmed that the No. 8 LFC, with the new wheel profile, has acceptable margins of safety against derailment at speeds of up to 35 mph (56 km/h) when operated over track that is maintained according to the MBTA’s newly developed and implemented track maintenance standards, even in the presence of cyclic alignment defects.

_Friction Levels_

One of the other contributing factors to the derailments was the magnitude of the coefficient of friction between the wheel and the rail present on the Green Line, that was greater than expected in the Northeastern United States. To ensure the correct Nadal limit was used, tribometer measurements were taken. The results showed levels as high as 0.6 under extreme conditions and consistent levels of 0.5 over a prolonged period, including overnight. The effect of the coefficient of friction on the Nadal limit is well known, and the maximum L/V level permissible under Nadal with a 0.5 coefficient of friction is 0.74. This increases to 1.13 with the new, steeper, flange angle of the new wheel profile.

_Corrective Actions_

_Wheel Profile_

The new 75º wheel profile (Figure 7) designed during the investigation has been implemented, to all trucks, on all No. 8 LFCs, and the MBTA is investigating changing its existing fleet to this profile in order to maximize wheel-to-rail compatibility. The MBTA has addressed rail profile compatibility through the initiation of a rail side-grinding program, and there are plans to develop a new rail head-grinding profile to optimize compatibility with the new wheel profile.

![FIGURE 7 New wheel profile for No. 8 LFC.](image-url)
**Track Condition**

Track maintenance standards and procedures were developed and implemented as a result of the investigation. One aspect of these standards is to adopt the current FRA (5) approach for alignment measurement, over a 31-ft (9.4-m) chord (older standards required measurement of alignment only over a 62-ft (18.9-m) chord). Track geometry is therefore now measured over a 31-ft (9.4-m) chord for both curved and tangent track, and new limits have been established for the various irregularity parameters.

The MBTA currently plans to perform TGMS data collection every three months to monitor track condition, supplemented by track walking three times per week. In addition, the rail profile will be optically measured every six months to ensure that an appropriate rail side contact angle is maintained. This aspect is expected to be particularly critical during the transition of the vehicle fleet from the existing to the new profile.

**Future Efforts**

The current derailment investigation (Phase 2) is focused on re-introducing revenue service on other routes, based upon the results from the Phase 1 investigation. The investigation continues to investigate possible methods of increasing the safety margin against derailment at higher speeds. Other efforts under active investigation are the introduction of the new wheel profile to the No. 7 SRC fleet, changes to the rail profile, and adoption of friction management techniques. Although flange lubrication should not be depended upon to prevent derailments, it does have a role as a mitigating method and brings other benefits of reduced wear and noise.

**CONCLUSIONS**

The introduction of new LRV technology into a system built around very different requirements many years ago can cause unexpected problems. Problems have been encountered with matching brake performance with the existing fleet, under extreme rail conditions, and with compatibility of the new independent wheel center truck design, dictated by the low floor requirement, with the existing Green Line track infrastructure.

There are valuable lessons to be learned from this project, which are applicable to older properties that are contemplating introducing new vehicle technology that differs significantly from that currently in use.

In particular, independent wheel truck designs require careful integration of track maintenance standards with the vehicle design since such designs are less forgiving of track irregularities than conventional rigid axle trucks. The track irregularities that appear to cause the most problems are lateral, whether due to wide gage, side wear, rail deformation, or misalignment. Reverse curves with short tangent lengths are also particularly challenging for these trucks, as they are not able to steer themselves correctly through such geometry. It is important to note that these problems have been the experience with trucks that have good vertical equalizing properties. Stiffer trucks may also suffer problems due to vertical alignment and track twist or warp. From the No. 8 LFC experience, the following lessons learned are offered:
• Ensure that all parties are fully aware of exactly what track conditions (geometry and quality) and maintenance standards will be maintained (taking into consideration the inherent characteristics of independent wheel designs). Reliable line geometry and defect measurements should be taken to avoid any misunderstandings. Such information should be included in the specification, and must be used as a design input.
  • Focus on early identification of any track features that may cause derailment potential, so that they can be addressed before the vehicles are delivered.
  • Perform rigorous and truly representative dynamic modeling of the vehicle design over the actual track conditions that will be encountered.
  • Validate the dynamic model by track testing at the earliest opportunity.
  • Recognize that track maintenance standards must be rigorously enforced and may need to be raised to a higher level.

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REFERENCES
