

Introduction of Low-Floor Light Rail Vehicles to North America: History and Status of the Portland Type 2 Vehicle

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Modern low-floor light rail vehicles (LFLRVs) first entered revenue service in Europe during the mid-1980s, and since then, numerous transit agencies in Europe have ordered or are operating LFLRVs in various configurations. In 1991 Tri-County Metropolitan Transportation District of Oregon (Tri-Met), the transit operator in Portland, conducted an extensive study of accessibility to its existing and planned light rail lines and after much deliberation decided in 1992 to pursue the first LFLRV procurement in North America. Of particular concern to Tri-Met was whether LFLRVs could meet requirements for higher carbody strength and higher operating speeds than were common in European designs. After a competitive process, a contract was awarded to Siemens Duewag Corporation in June 1993 at a price of \$86.6 million for 37 LFLRVs and associated equipment. Major features of the LFLRV are full compatibility with Tri-Met's existing high-floor light rail vehicles; a 70 percent low-floor section at a height of 14 in.; four doors per side, all in the low-floor section, with a bridgeplate in the center doors; an unpowered center truck with independently braked full-sized wheels on stub axles and with an articulation on each end of the truck; standard motor trucks; and a roof-mounted, microprocessor-controlled, AC propulsion system. Design of the LFLRV was substantially complete by the end of 1994, and proof-of-design tests for all major systems were completed or

under way in mid-1995. Carbody strength tests were successfully conducted in March 1995. Assembly of the first vehicle began in May 1995, and it is estimated that the first vehicle will be delivered to Portland in December 1995.

Low-floor light rail vehicles (LFLRVs) were first introduced into Switzerland and France in the mid-1980s, and within a decade nearly three-fourths of all light rail vehicles on order or put into service in Western Europe have been LFLRVs. However, by the early 1990s no North American transit agency had placed an order for LFLRVs, and only a handful of studies and literature was even available about the subject. This paper describes the background, decision-making process, procurement process, technical characteristics, and current status of the first LFLRV to be introduced into North America.

LIGHT RAIL TRANSIT IN THE PORTLAND AREA

In 1986 Tri-County Metropolitan Transportation District of Oregon (Tri-Met), the public transit authority in Portland, completed construction and opened for rev-

enue service its first light rail line, known as the Banfield line. This new system represented a blend of European and North American transit practices, with low-platform stations, traditional high-floor light rail vehicles, self-service proof-of-payment fare collection, and a wide variety of right-of-way (ROW) conditions ranging from city streets to high-speed, grade-separated sections. Accessibility for mobility-impaired persons was provided by wayside lifts located at the far end of each platform.

The early success of the Banfield line rekindled interest in light rail transit throughout the Portland area. In 1988 Tri-Met began environmental and preliminary engineering studies associated with a major extension of the Banfield line to the western part of the Portland area, known as the Westside Light Rail Project. A Full Funding Grant Agreement, or contract between the Federal Transit Administration (FTA) and Tri-Met, was signed in 1992 for a Westside line approximately 11.4 mi long with 11 passenger stations. Construction started in mid-1993, and revenue service is planned to commence in 1998. In addition to the initial Westside Light Rail Project, funding approval for a further 6-mi extension of the Westside line to the community of Hillsboro was received in late 1994. Characteristics of the Westside-Hillsboro ROW are as varied as those on the Banfield line and also include a 3-mi-long twin bore tunnel with a deep underground station and extensive lengths of 5 percent and 6 percent grades. Planning is also actively under way for a 25-mi line, in a south/north orientation, in the Portland area.

LOW-FLOOR LIGHT RAIL VEHICLE DECISION-MAKING PROCESS

In 1991 Tri-Met was completing its environmental and preliminary engineering studies for the Westside Light Rail Project. During the local decision-making process on the project, community groups requested that Tri-Met consider "universal level boarding" for all passengers as an alternative to wayside lifts or "mini-high" platforms located at the ends of the normal station platform.

In summer 1991 Tri-Met conducted an internal study comparing the mini-high platform approach with LFLRVs. At that time it was concluded that, although LFLRVs were an emerging and attractive technology, their development was still too incipient and their costs likely too high to warrant incorporation into the project. No LFLRVs were on order or in service at that time in North America, and only the Massachusetts Bay Transportation Authority in Boston was known to be seriously investigating their implementation. Consequently Tri-Met recommended proceeding with mini-

high platforms as a design basis for the Westside Light Rail Project and a moderate improvement in provision of accessibility over the wayside lifts on the Banfield line.

At about the same time that the initial report was released, the U.S. Department of Transportation issued its final regulations implementing the Americans with Disabilities Act (ADA), sweeping legislation passed by the U.S. Congress in 1990 that set standards and guidelines for accommodation of persons with disabilities. The ADA regulations thus focused attention on accessibility issues, and various community groups vociferously questioned Tri-Met's plan to proceed with mini-high platforms.

In fall 1991, in response to community concerns, Tri-Met decided to undertake a comprehensive study of accessibility to light rail vehicles and assembled a staff and consultant team to conduct the study. The charter was to investigate thoroughly all feasible means for providing accessibility to the existing and proposed light rail system for all persons, whether the general population or persons with disabilities. After some initial screening three main options were carried forward: mini-high platforms, full-length high platforms, and varying configurations of low-floor light rail vehicles. Vehicle considerations, station platform factors, other wayside elements, costs, urban impacts, service levels, and operations were all delineated.

North American transit properties in Sacramento, Los Angeles, Boston, and Calgary were visited to discuss their accessibility approaches and plans. A literature search of magazines and publications concerning LFLRVs was conducted. A study team visited several cities in six European countries, rode and inspected eight different LFLRVs, and met with several transit authorities and eight manufacturers to discuss LFLRV technology and operating experience. The study team included a wheelchair user, who was able to add an invaluable perspective on the extent of accessibility, or lack thereof, of European transit systems.

An important finding from the European trip was that LFLRVs were being introduced in most places in Europe to improve boarding for the general public but not necessarily for wheelchair users. Most European transit systems were still not accessible to wheelchair users after introduction of LFLRVs because the systems typically had wayside conditions (e.g., inaccessible platforms, street-level boarding, large vertical gaps, etc.) prohibitive for entry into even a low-floor vehicle. Some systems were incrementally raising or modifying their platforms and boarding areas to improve the situation.

The study team found that, at the time, only Grenoble, France, provided a truly accessible system because it was a completely new system constructed in the 1980s with wheelchair accessibility as a guideline. The

Grenoble system built all station platforms at approximately 10 in. above top of rail (TOR) and used bridgeplates on the FLRVs to bridge the remaining gaps between the vehicles and platform.

Progress of the accessibility study was closely monitored by an ad hoc committee chaired by Tri-Met's general manager and composed of representatives from various citizen interest groups, including the mobility-impaired community. This forum, and the commitment of Tri-Met's top management to an objective study, permitted a free exchange of opinions during the process and careful examination of the attributes of the options.

As the consultant team and Tri-Met learned of the extent to which LFLRV technology was permeating the European market, initial hesitations and technical uncertainties began to diminish. In effect, the team became converts. A report was published in early 1992, and the committee recommended that Tri-Met pursue an LFLRV procurement and develop the necessary specifications. This recommendation was approved by the Tri-Met board of directors, the agency's policy body, in April 1992.

The LFLRV approach was chosen in Portland for a number of reasons. In effect, LFLRVs offer the level boarding or near-level boarding capabilities of high-platform systems but do so with low station platforms more suitable for surface operations and cost-effective integration into compact urban environments. Accessibility for mobility-impaired persons and boarding for the general population are improved compared with traditional high-floor/low-platform systems, dwell times at stations are shorter, and schedule reliability is enhanced through elimination of wayside accessibility devices such as the lift in Portland. Wheelchair users can be mainstreamed or nearly mainstreamed into the system, and every LFLRV in a multiple-unit train will be accessible, not just the front end of the first car, as is currently the case in Portland.

A very important and much-debated set of considerations in deciding to proceed with LFLRVs involved the need for, the details of, and the impacts associated with bridgeplates on board the vehicles. Tri-Met's interpretation of pertinent regulations implementing the ADA was that the new vehicles had to be level-entry with the vertical gap between vehicle floor and platform surface within $\frac{3}{8}$ in. or else some sort of bridging device would be necessary. Level entry could be achieved only if an air suspension system equipped with automatic leveling valves were incorporated into the LFLRV to guarantee a relatively constant floor height and if the platform height could match the vehicle floor height. The European experience in 1991 indicated that air suspension appeared to be anomalous but not impossible with LFLRVs. During the accessibility study the study team found one example of an LFLRV with air suspen-

sion—in Turino, Italy. But the real constraint in Tri-Met's system was permissible platform height. Because Tri-Met's existing Type 1 vehicles have swing plug doors, which extend over the platform edge, platform height was limited to 10 in. above TOR to provide clearance. Even if it had been practical to retrofit the Type 1 doors, raising the platform height from 8 in. above TOR to approximately 14 in. above TOR would have had major unworkable impacts throughout the existing Banfield line and also on the Westside-Hillsboro design and was dropped from consideration.

Thus, Tri-Met accepted that, to comply with ADA, in the Portland context a bridgeplate was required. The question then became one of details, in particular, whether the ADA requirements for ramp slope could be met without changing the existing 8-in. platforms. Obviously ramp slope had a direct relation with bridgeplate (transverse) width and impact on carbody structure. Discussions with vehicle manufacturers indicated that the cutout necessary in the underframe to accommodate a bridgeplate mechanism was significant and could not be tolerated on all doors without major impact on the carbody strength. Therefore, a compromise solution was accepted under which the four center doors (two per side) would have bridgeplates. After much investigation and some actual tests by wheelchair users of different ramp slopes, it was also determined that 10-in. platforms would become the design standard for Tri-Met, necessitating a platform retrofit program for the 48 existing 8-in. Banfield platforms.

PROCUREMENT PROCESS

In July 1992 a request for proposal was issued to interested manufacturers. Tri-Met elected a competitive negotiation process, whereby technical proposal and price were evaluated separately, then combined into a single score for each proposal.

Proposals were received in November 1992. After evaluation of technical proposals and price a competitive range was established consisting of two proposers, Bombardier Corporation of Montreal, Canada, and Siemens Duewag Corporation (SDC) of Sacramento, California. Through negotiations with the manufacturers, Tri-Met was able to refine specification requirements, allowing a wider range of established components and manufacturing methods without reducing the reliability or safety of the vehicles. In February 1993 Tri-Met issued the request for best and final offer, and best and final offers were received at the end of March 1993. After evaluation, the contract was awarded in May 1993 to SDC for a total of \$86.6 million for 37 LFLRVs, to be known as the Type 2 vehicles, including spare parts and system support. The contract also in-

cludes an escalation clause, which requires Tri-Met to compensate the contractor for cost increases due to inflation.

Since contract award, Tri-Met has exercised options for nine additional LFLRVs, and the contract as of mid-1995 is for 46 vehicles at a total cost of \$107.2 million plus escalation.

LOW-FLOOR LIGHT RAIL VEHICLE DESIGN

LFLRV development in Europe has progressed along two major paths: partial low-floor vehicles and 100 percent low-floor vehicles. At the time of Tri-Met's accessibility study, several cities in Europe had fleets of partial LFLRVs in revenue service, some for several years, but 100 percent LFLRVs were basically in the prototype stage or in operation in only a very limited fashion. Several concerns came to the fore during the study relating to the transfer of European LFLRV experience to a North American context in general, and a Portland context in particular.

General Arrangement

Three main technical challenges were identified, including a high buff strength (170,000 lbf) for the carbody structure compatible with Tri-Met's existing vehicles, a high-performance requirement with a maximum speed of 55 mph, and good ride quality and noise performance. The study team concluded that the most prudent course for introducing LFLRVs into the Tri-Met system would be to utilize a partial low-floor vehicle with standard powered trucks and a high-floor section at each end. Thus the general vehicle type that emerged was an articulated vehicle, approximately the size of the existing Banfield Type 1 vehicles, with a low-floor center section approximately two-thirds of the total floor area, a low-floor height of 14 in. above TOR, internal steps to the high-floor section (38 in. above TOR) at each end, and bridging plates in the center doorways similar to those in Grenoble to provide accessibility for all combinations of vertical and horizontal gaps with the station platform.

The new Type 2 LFLRV is 92 ft long and 8 ft 8 in. wide, with an empty vehicle weight estimated to be approximately 103,000 lb. There are three body sections: the two main sections (A and B) each approximately 40 ft long and a short center section (C) approximately 10 ft long. Approximately 70 percent of the passenger area is at a floor height of only 14 in. above TOR and all eight sliding plug doors (four per side) are in the low-floor area (see Figure 1). The four center doors are

equipped with bridgeplates, which can be deployed by the driver or by passengers to allow smooth boarding of wheelchairs. Each vehicle has 72 seats and is capable of carrying 189 people at design load. At least four wheelchair spaces are provided.

The LFLRVs are fully bidirectional, with a driver's cab at each end, and are mechanically and electrically compatible with the Type 1 vehicles. Maximum speed is 55 mph, with service acceleration and braking rates of 3.0 mph/sec and an emergency brake rate of over 5.0 mph/sec. The vehicles are specified to climb grades of up to 7 percent and negotiate curves of 82-ft radius. Up to four vehicles can be coupled together, even though block lengths in downtown Portland restrict operation to two-vehicle trains. The new LFLRVs will couple with Tri-Met's existing high-floor vehicles, allowing operation of two-vehicle trains with at least one accessible low-floor vehicle in each train. Pursuant to successful performance of the new LFLRVs, Tri-Met intends to remove all wayside lifts from the Banfield line and provide accessibility exclusively with the LFLRVs.

The major structural elements, including the carbody shells and truck frames, are of welded steel construction and are designed and manufactured at Duewag's facility in Düsseldorf, Germany. The design of these elements, while unique to the Portland vehicle, generally derive from designs and practices found in other Duewag light rail vehicles.

Trucks

Most modern light rail vehicles in North America are articulated, and all such modern articulated vehicles have been single articulated with unpowered center trucks. The Portland low-floor center truck will also be unpowered but represents a significant departure from practices found in North America to date, owing to the requirement by Tri-Met that the low-floor section be continuous throughout the center of the vehicle. Basically, geometry precludes the use of typical wheels (26 to 28 in. in diameter) pressed on typical axles (6 to 8 in. in diameter) in a low-floor section with a 14-in. passenger floor height. Some low-floor truck designs have utilized small wheels (10 to 14 in. in diameter); the more common approach is to use independently mounted wheels without through axles. The Portland center truck is based on the latter approach. Individual, 26-in.-diameter wheels are mounted on bearings on stub axles connected to each other by two U-shaped drop axle pieces (see Figure 2). Thus the stub axles do not rotate during vehicle translation.

The center truck is mounted under a short intermediate body section, which in turn is connected by an articulation on each end to the two main body sections.

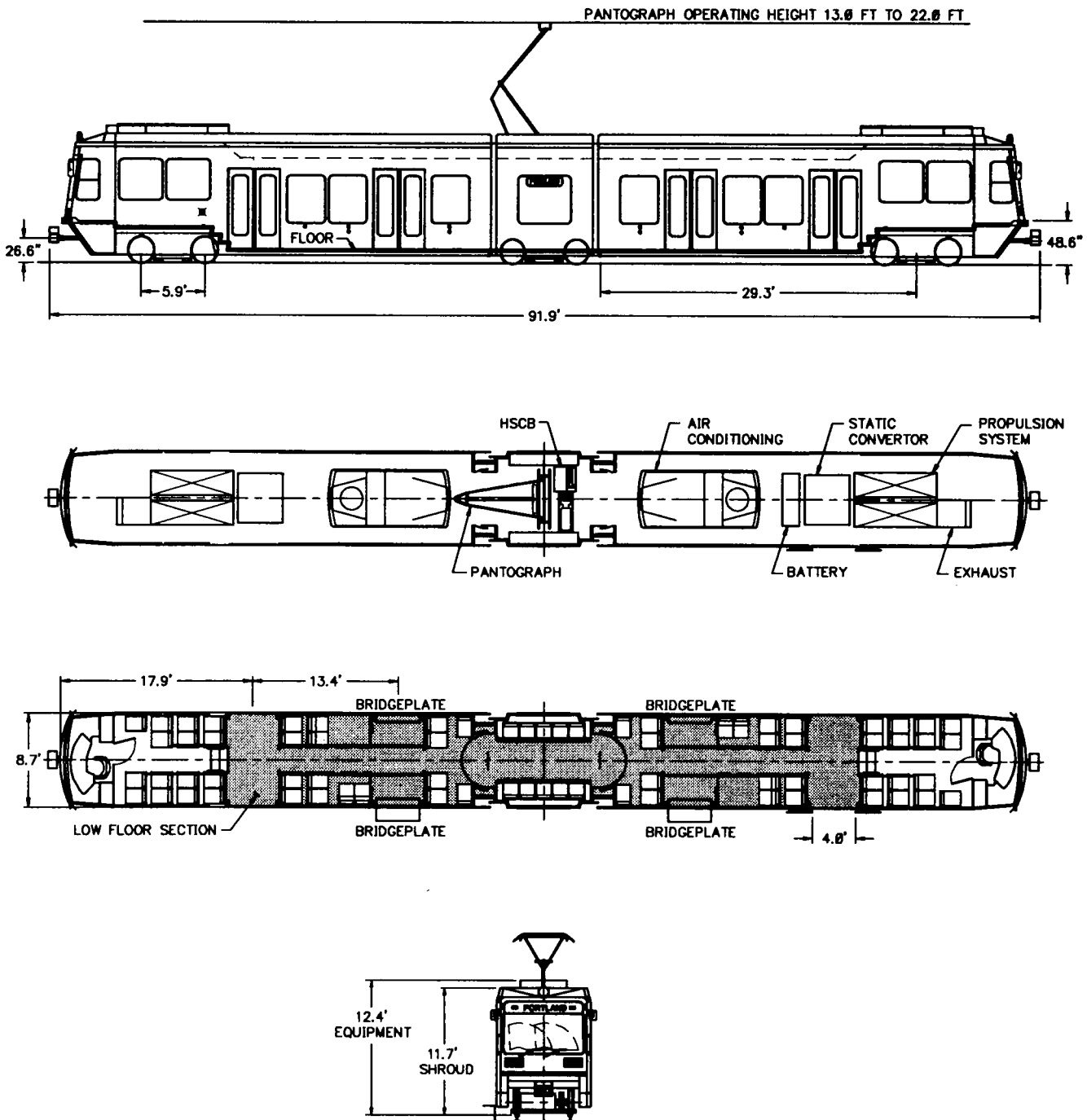


FIGURE 1 General arrangement.

Elastomeric elements will provide a primary suspension system, and coil springs are used for the secondary suspension. The design of the center truck and center body section not only permits the low floor to carry through the center of the vehicle but also permits longitudinal passenger seats in the center section and maintains a similar truck center dimension to that of the Type 1 vehicles and thus similar clearance geometry.

The powered trucks are of conventional Duewag design. Primary suspension is provided by chevrons, and secondary suspension by coil springs. Each end truck is powered by two self-ventilated, fully encapsulated six-pole AC induction motors, each rated at 140 kW. Motors will be truck frame mounted parallel to the axle, and a helical gear drive and flexible coupling transmit the torque to the wheels.

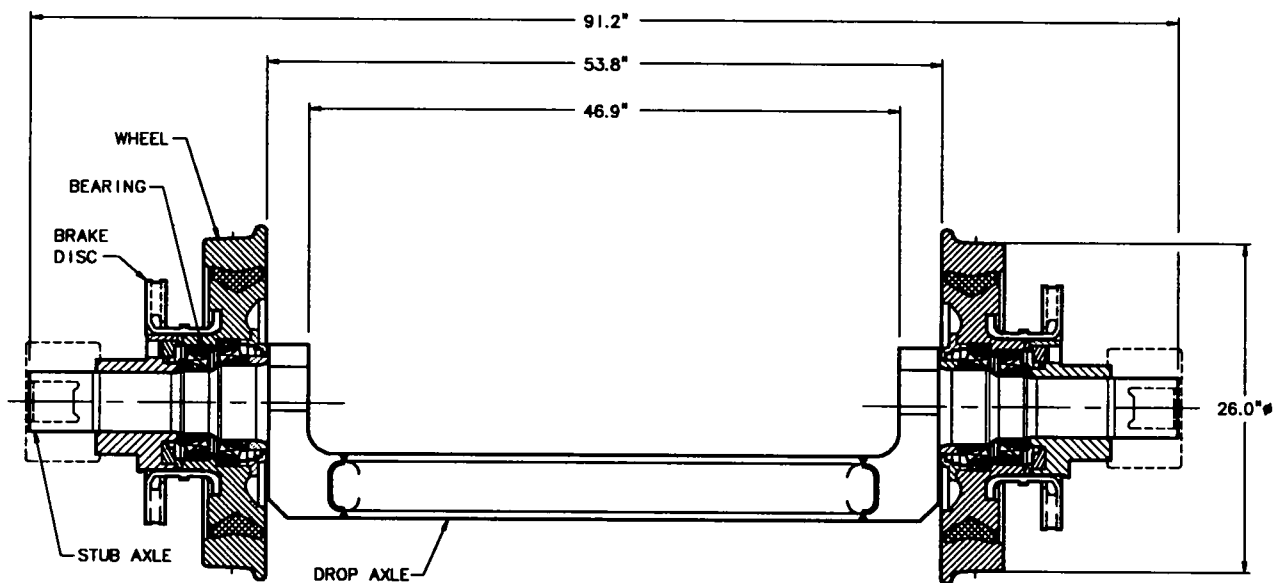


FIGURE 2 Trailer truck drop axle assembly.

Bridgeplate

As discussed above, Tri-Met determined that bridgeplates were necessary for ADA and platform reasons and elected to require them on the four center doors of the vehicle, similar to the arrangement in Grenoble. Since well less than 1 percent of the passenger boardings are forecast to be by wheelchair users requiring the bridgeplate, Tri-Met decided that, for reliability and speed-of-operation reasons, the bridgeplate should not be deployed with every door opening. Accordingly, bridgeplates will be deployed by the train operator or upon request by a passenger. Train operators will be trained to look for wheelchair passengers on the platforms and will then automatically deploy all bridgeplates as part of the normal door opening sequence. Similarly, bridgeplate request buttons inside the vehicle will allow passengers to request and train operators to initiate bridgeplate deployment only at requested doors as part of the normal door opening cycle. If there are no internal bridgeplate requests and the train operator does not see a wheelchair user on the platform, doors will be released or opened as normal without bridgeplate deployment. Should there be a subsequent (late arrival) external bridgeplate request and the door in question is already open, the train operator will close all doors and the requested bridgeplate/door will recycle and deploy.

The bridgeplate will be approximately 48 in. wide, the width of the doorway, and will generally be of a two-piece configuration (see Figure 3). Transverse width will total approximately 21 in. One piece, about 9 in.

in transverse width, will be part of the passenger floor. The other piece, about 12 in. in transverse width, will be stored underneath the floor. When deploying, the undercar portion will extend outward from the vehicle to form a smooth surface with the floor portion, and the whole assembly will pivot or drop to contact the platform approximately 9 to 10 in. from platform edge. An electric motor will drive the bridgeplate kinematics, and the entire assembly will be made of stainless steel and aluminum components.

The bridgeplate assembly will undergo 250,000 cycles of testing prior to installation on the first vehicle. Reliability of the bridgeplate will be important to the successful implementation of the Type 2 concept and will be monitored closely through the acceptance test phase of the contract.

Propulsion and Braking

Traction power is controlled by two voltage source, pulse width modulated inverters, one per motor truck, which are mounted on the roof. The traction inverters employ insulated gate bipolar transistor (IGBT) technology, which allows higher switching frequencies and results in reduced power loss in the motors. The propulsion inverters are force ventilated, and the electronic control units are microprocessor based. Dynamic brake resistors are also force ventilated and mounted on the roof.

A fully blended braking system makes maximum use of regenerative/rheostatic braking, supported by hydraulically operated disc brakes on all axles of the pow-

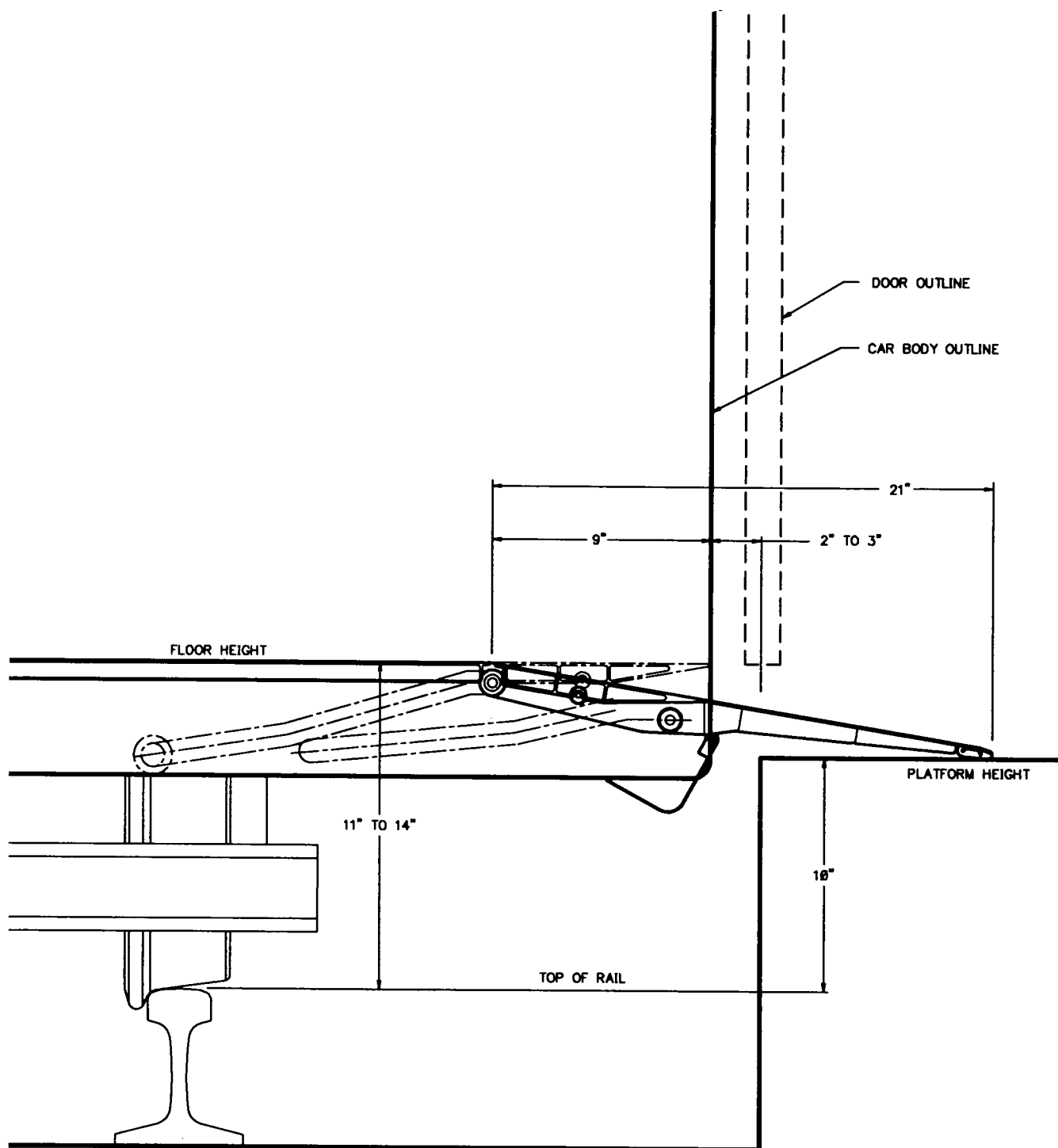


FIGURE 3 Bridgeplate assembly and platform interface.

ered trucks and on all wheels of the trailer truck. The brake control units are of a special design to fit into the minimal undercar space. Track brakes on all trucks provide additional safety and reduced stopping distances in case of emergency.

CARBODY STRENGTH AND CRASHWORTHINESS CONSIDERATIONS

A fundamental concern of Tri-Met during the LFLRV deliberations of 1991 and 1992 was whether the

LFLRV carbody could meet Tri-Met's carbody strength and crashworthiness requirements. Unlike a new start transit system with no prior transit equipment constraints, Tri-Met had decided that the LFLRVs would be completely integrated into its existing operations and would entrain with the existing Type 1 vehicles. Thus it was determined that the LFLRVs would need to meet at least the same carbody compression strength, or buff load, requirements as the Type 1, that is, 170,000 lbf on the anticlimber and 100,000 lbf on the coupler pivot. The 170,000 lbf figure was an early "two-times-the-empty-weight" value, or "2 g" approximation, for the Type 1 vehicles and would prove to be a 1.65 g requirement for the (estimated) 103,000-lb Type 2 vehicles.

In contrast to a buff load requirement of 170,000 lbf, Tri-Met learned in 1991 that most European LFLRVs were designed to withstand buff loads of only 50,000 lbf to 90,000 lbf, roughly half or less than half that required. Apparently a parallel development with LFLRV technology in Europe during the 1980s and early 1990s was a trend toward vehicle weight reduction owing to the relatively high energy costs there. Compounding the concern of meeting higher buff loads was the particular geometry of the Tri-Met LFLRV, which required a relatively high anticlimber height to mate with the existing Type 1 anticlimber and thus demanded even greater structural integrity to provide successful transmission of force from the high-floor section to the low-floor section without failure. In addition, from a crashworthiness perspective, Tri-Met required progressive buckling of the carbody from the end of the car toward the center in the event of an impact in order to prevent telescoping of the body and catastrophic damage in the passenger sections.

The first finite element analysis by SDC indicated some high stresses in the area of the transition from high floor to low floor. Design modifications introduced some reinforcements in this transition area to ensure that progressive buckling, or deformation of the carbody structure on impact, would generally occur from the end of the car towards the center in order to protect the passenger area. Since demonstration of progressive buckling would be a destructive test, Tri-Met only required analysis of the crashworthiness of the vehicle.

An extensive carbody strength test was conducted on one of the first carbody shells at the Duewag facility in Düsseldorf in February and March 1995. In addition to various compressive loads applied to the ends of the carbody, the test included vertical loads to confirm door operation and torsional loads to simulate diagonal jacking or rerailling.

The carbody tested included the three complete but bare carshell sections (A, B, and C) with no flooring, no internal or external appurtenances or equipment, no

paint, and dummy trucks for support (see Figure 4). For just the vertical load test, two complete door assemblies and one bridgeplate assembly were installed and required to operate under maximum load conditions. Approximately 270 strain gauges were mounted on the carbody in critical locations to monitor movement under load and translate readings to stress values in the various structural elements. All readings were recorded and analyzed electronically. In addition, physical deflections were measured using mechanical devices such as plumb bobs and specialized gauges. During the course of the tests, as required, various weights were added to the carbody to simulate actual conditions under passenger loads. Tri-Met's specifications generally required that no permanent deformation of metal occur, no failure of welds occur, and no stress readings exceed the yield strength of the material in question. By contract, SDC was allowed to conduct pretests to ascertain compliance prior to official tests, which would be formally witnessed and recorded.

Initial pretests by SDC of the end compressive load on the anticlimber (the buff load) in February 1995 resulted in a failure at about 70 percent of design load of the floor and roof areas of the center (C) section. SDC responded with the addition of various stiffener plates and gussets to improve weak areas. Similarly, diagonal jacking pretests revealed weak areas in the portals around the interface between the A and C and between the B and C sections, and SDC identified appropriate modifications. When official tests were conducted in March with structural modifications in place, specification requirements were met to Tri-Met's satisfaction.

In summary the carbody strength tests required approximately 3 weeks of setup and 5 weeks to complete in a successful manner. As a result of these tests, ap-

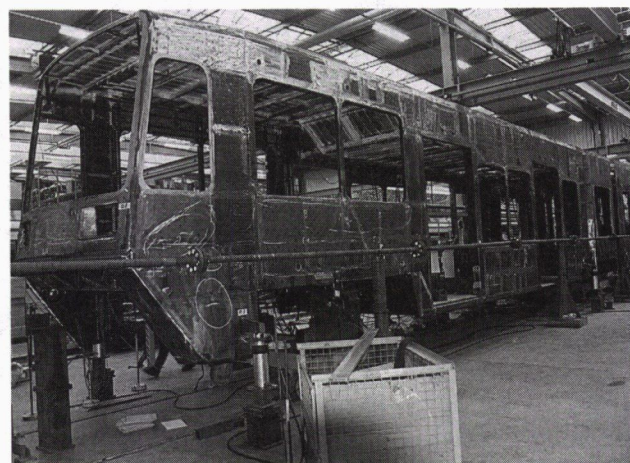


FIGURE 4 Carshell during compression test at Duewag AG plant in Germany.

proximately 120 pieces were added to the carbody structure, most being relatively small plates and gussets, for a total weight of approximately 500 lb, or roughly 2 percent of the three carshell sections and 1/2 percent of the total estimated car weight.

SCHEDULE

Vehicle carbody construction and truck frame fabrication started at the Duewag plant in Germany in mid-1994. Fatigue tests of the motor truck frame, trailer truck frame, trailer truck drop axle, and bolster were started in late 1994 and successfully completed in early 1995. As discussed above, the critical test of the carbody structure was completed in March 1995. Propulsion system tests, motor tests, braking system tests, low voltage power supply tests, and HVAC tests were all conducted from late 1994 to mid-1995. Extensive testing of the various systems and components has been and will be performed throughout the manufacturing process to ensure a safe and reliable vehicle.

Final assembly of the first vehicle began at the SDC plant in Sacramento, California, in May 1995. The first vehicle is currently scheduled to arrive in Portland in December 1995 for operational and compatibility testing with the Type 1 vehicles. Production vehicles will be delivered beginning in early 1996, with the last of the 46 vehicles to be accepted for operation by fall 1997.

CONCLUSIONS

In 1991, as part of a major light rail extension project, Tri-Met began seriously studying LFLRVs in order to

meet ADA requirements and to improve light rail operations and service. Initial concerns were the extent of technical risk and cost in adapting European designs and practices to Tri-Met's requirements and standards, particularly in the areas of carbody strength and high-speed ride quality and center truck stability. These concerns were balanced with perceived advantages of LFLRVs, and a decision was reached in 1992 to proceed with an LFLRV procurement. To minimize technical risks, Tri-Met specified a partial LFLRV with standard motor trucks and required an extensive proof-of-design test program.

Imposition of typical North American requirements for carbody strength has placed a difficult burden on Tri-Met's vehicle manufacturer; yet Tri-Met considered the requirements carefully and determined they were necessary for the natural progression of its system expansion. SDC has demonstrated that North American carbody strength requirements can be successfully met with LFLRVs. This capability, coupled with the stringent requirements of the ADA, likely portend expanded consideration of the LFLRV in major transit capital investment decisions of the future. Demonstration of ability to meet Tri-Met's other technical concern, acceptable ride quality during high-speed operation, will be undertaken in Portland in 1996.

The decision to procure LFLRVs has created much interest locally in Portland. Although validation of this decision cannot be fully realized until completion of all necessary testing, placement of the vehicles into revenue service, and public acceptance, it is Tri-Met's opinion that LFLRVs are exactly the correct approach for the light rail expansion program in Portland and their deployment will likely become widespread in North America, as has been the case in Europe.