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TCRP Report 2

Applicability of Low-Floor Light Rail Vehicles in North America

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TRANSIT COOPERATIVE RESEARCH PROGRAM

Report 2

Applicability of Low-Floor Light Rail Vehicles in North America

BOOZ • ALLEN & HAMILTON INC.
McLean, VA

Subject Area

Public Transit

Research Sponsored by the Federal Transit Administration in Cooperation with the Transit Development Corporation

TRANSPORTATION RESEARCH BOARD
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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academy of Sciences, acting through the Transportation Research Board (TRB), and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended endusers of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

TCRP REPORT 2

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the Transit Development Corporation, the National Research Council, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Special Notice

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to transit managers, engineers, and policy makers considering the introduction of low-floor light rail vehicles in existing or planned light rail systems. The report investigates the state of the art of low-floor light rail vehicles and assesses the applicability of their use in North America. Low-floor light rail vehicle categories have been developed to facilitate the understanding of the different types of vehicles and their applications. The report describes the growing trend toward low-floor light rail vehicles and the reasons for this growth. It provides an extensive compilation of data on low-floor light rail vehicles, information on North American light rail system characteristics, and an analytical perspective on key issues relevant to the applicability of this technology in North America. The report also develops example applications to demonstrate the cost-effectiveness of using low-floor light rail vehicles, the source of risk, and the trade-offs regarding the use of low-floor versus high-floor light rail vehicles.

In Europe, significant progress is being made on the development and deployment of low-floor light rail vehicles. Interest in low-floor light rail vehicles in the United States began in the 1960s but gained support more recently because of the need to be responsive to regulations implementing the Americans with Disabilities Act (ADA). Moreover, transit operators have come to recognize that improved system-performance benefits can potentially be achieved under certain conditions by using low-floor design concepts. For example, reduced boarding times mean faster service and shorter trip times for all passengers. This enables transit operators to use equipment more efficiently, thereby potentially reducing operating, maintenance, and capital costs.

Under TCRP Project C-2, research was undertaken by Booz • Allen & Hamilton, Inc. to assess the potential applicability of low-floor light rail vehicle technology in North America.

To achieve the project objectives, a comprehensive review of existing information on the state of the art in low-floor light rail vehicles was conducted. As part of this process, transit agencies using and considering low-floor light rail vehicles and the suppliers of these vehicles were contacted to obtain information and operating experience on vehicles both in revenue service and in research and development. The research focused heavily on current European experience with low-floor light rail vehicle technology. Upon collecting this information, a framework for assessing the application of low-floor light rail vehicles in North America was developed focusing on the critical factors that should be considered. Thus, the report is a valuable resource for transit professionals considering the use of low-floor light rail vehicles in existing or planned light rail systems.

Material from this report was considered by the Santa Clara County Transportation Agency (SCCTA) in conjunction with its 1994 assessment of the technological risk of low-floor light rail vehicles. The relatively low risk of Category-2 low-floor light rail vehicles coupled with developments in ADA compliance and noncost issues resulted in a decision to plan for low-floor light rail vehicles as the fleet of the future for the SCCTA.

CONTENTS

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James R. Zebarth of Booz • Allen & Hamilton Inc. was the Principal Investigator for the report. Valuable assistance was provided by R. Alex Curmi, Stelian "Stan" Canjea, Matthew W. Pollack, Yonel Grant, and Sue Mason of Booz • Allen & Hamilton; and Joachim von Rohr and Thomas Kuchler of Light Rail Transit Consultants GmbH in the collection of data and preparation of the report.

Valuable assistance in reviewing the progress and quality of the report was provided by the TCRP Project Panel C-2 listed above. The TCRP Senior Program Officer responsible for report preparation was Christopher W. Jenks. His help and guidance were invaluable.

Information on vehicles, system characteristics, and current practices was provided by many transit agencies and manufacturers. Their cooperation and assistance were most helpful and greatly appreciated.

APPLICABILITY OF LOW-FLOOR LIGHT RAIL VEHICLES IN NORTH AMERICA

SUMMARY

There is a dramatic trend to the increased use of low-floor light rail vehicles (LF-LRVs) in Europe. The study investigates state-of-the-art low-floor vehicle development and assesses the applicability of LF-LRVs for use in North America.

For the purposes of describing LF-LRVs in this report, a classification system has been developed that splits all LF-LRVs into one of three categories. The classification system used is based primarily on type of running gear. This system was selected because the proposed categories represent increasing application complexity and change, the three categories correspond to the proportion of low-floor area, and the three categories represent increasing levels of technological innovation. The categories are described as follows:

- **Category-1** vehicles use conventional motor and trailer trucks throughout and generally have 9 to 15 percent low-floor area but may have up to 48 percent low-floor area.
- **Category-2** vehicles use conventional motor trucks at each end and innovative trailer trucks in between them, with generally 50 percent to 75 percent uninterrupted low-floor area between the motor trucks.
- **Category-3** vehicles use innovative motored and trailing running gear throughout to provide 100 percent low-floor areas.

While there have been a substantial number of Category-1 and Category-2 orders in the past, the trend in Europe is toward refinement and implementation of Category-3 vehicles.

An Applicability Framework Assessment Model has been developed to assist in the evaluation of LF-LRV applicability. LF-LRVs offer a number of possible advantages over conventional vehicles. Platforms to allow level boarding of LF-LRVs can be much smaller in scale and less expensive than corresponding platforms for high-floor systems. Therefore, it is more likely that level boarding can be implemented. Improved vehicle accessibility and faster boarding can result in reduced round-trip times and savings in fleet requirements in some cases. As a result, LF-LRVs provide a more economical transportation solution than conventional LRVs in some circumstances. Even where cost savings do not accrue, the improved accessibility provided by LF-LRVs can be a powerful incentive to the selection of a LF-LRV solution. The Applicability Framework Assessment Model presented in this report provides a mechanism to assess analytically the cost-effectiveness of using LF-LRVs, the sources of risk, and the trade-offs regarding the use of low-floor versus high-floor light rail vehicles. Specific applicability will depend on the results produced by exercising this model for the proposed application.

CHAPTER 1

INTRODUCTION

BACKGROUND AND RESEARCH OBJECTIVES

This report documents research undertaken through the Transit Cooperative Research Program to examine the applicability of low-floor light rail vehicles (LF-LRVs) to North American light rail transit (LRT) systems and thereby analyze the perceived advantages and other key applicability issues. The research problem statement required compilation of existing information on LF-LRVs, including engineering, operating, maintenance, economic, and institutional factors that are relevant to running LF-LRVs on existing and planned LRT systems in North America. The research findings were intended to serve transportation professionals and policy makers.

After submittal of an interim report and discussions by the project advisory panel, the following were defined as the specific outputs and results sought from the research:

- A comprehensive review of existing information on the state of the art and operating experience;
- Development of a generic classification system for LF-LRVs;
- Compilation of a vehicle characteristics database;
- Identification of the critical factors that should be considered in evaluating applicability;
- A generic grouping of North American LRT systems, in relation to the identified evaluation factors;
- A framework for assessing the application of a generic class of LF-LRV in a generic LRT system group; and
- Use of the framework in two case studies.

Advent of LF-LRVs

During the last 10 years, LF-LRVs have been put into service at several major transit systems. Although some early examples appeared as far back as 1925 (shown in Figures 1 and 2), the first modern vehicle—now commonly accepted as a low-floor tram[1]—was put into service in Geneva in 1984. The vehicle, developed by Duewag and ACM Vevey, provided approximately 60 percent of the floor area at a height of 480 mm (19 in) above the top of rail (TOR).(*1*)

Prior to 1984, light rail vehicles (LRVs) evolved steadily, and, while there are many variations in the design and configuration of these conventional LRVs, they are usually supported on four-wheel swiveling trucks that sweep a considerable area below the underframe when the vehicles go around horizontal turns. Conventional LRVs have both motored and trailer trucks equipped with flanged wheels that have a tread diameter range between 560 mm (22 in) and 710 mm (28 in). Therefore, conventional LRVs usually have floors at one level, which must be at a sufficient height to clear the truck under the most adverse suspension deflections. Consequently the floor height range is between 830 mm (32.7 in) and 1,050 mm (41.3 in) above TOR.

Although the conventional LRV design has been optimized in many ways, it has retained a significant disadvantage when passengers must board from low platforms or from street level. In these situations, passengers must climb steps to reach the floor. This makes access difficult for the elderly and practically impossible for persons in wheelchairs. Transit operators recognized several reasons for demanding vehicles with a floor at, or only slightly above, the street curb or low-platform level. Some of the reasons included recognition that climbing steps increases station dwell time, especially if a wheelchair lift is used to circumvent the steps, and access would be easier for the elderly and other mobility-impaired individuals. In the United States, the passage of the Americans with Disabilities Act

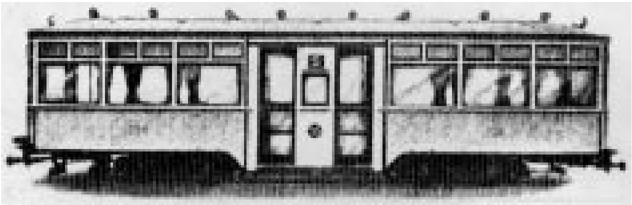

Figure 1. Early example of a LF-LRV—1925 vintage car.

Figure 2. Early example of a low-floor trailer from the 1920s—built by Allan for Amsterdam.

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[1] The term "tram" is the European equivalent of "streetcar" in North America.

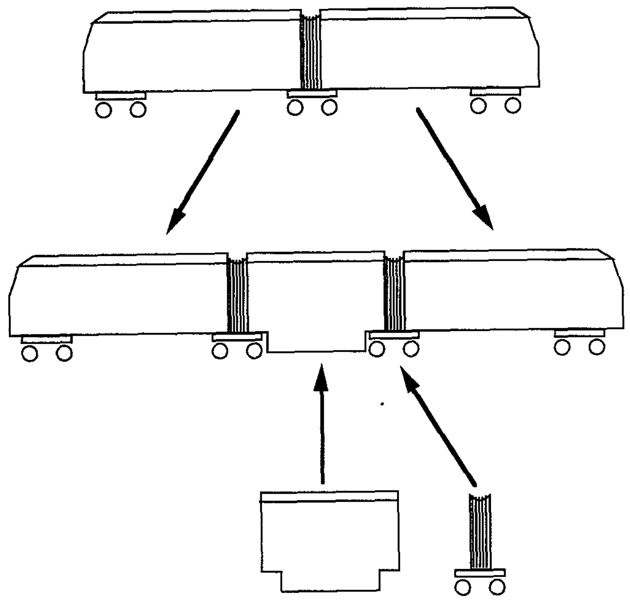


Figure 3. LF-LRV concept—achieved by converting a conventional six-axle, single articulation LRV into an eight-axle, double articulation vehicle.

(ADA) prompted transit operators to look more closely at what European transit systems were using.

The simplest way to create an LRV with a low-floor section is to convert a conventional six-axle, single articulation LRV into an eight-axle, double articulation vehicle. The conversion involves the addition of a fourth truck, a second articulation, and a center-body section. The conversion (Figure 3) provides a low-floor car section in the center of the car with a low-level entrance on one or both sides. An example is a vehicle produced for Amsterdam (Figure 4). While it provides an economical solution, it does have some drawbacks. The low-floor area is small and interior steps are required in the aisles between the low and high floors. Another variation appeared (Figure 5) that provides low-floor space in the end carbody sections but high-floor areas above the standard trucks. This required a shift of equipment from under the car to above the car.

The popularity of LF-LRVs increased substantially when the Grenoble car was introduced into revenue service in 1987 (Figure 6). It has conventional design motor trucks at the ends, requiring a high floor above them. The center section is supported by a single-trailer truck with independently rotating wheels joined by a cranked axle. Although the wheels are normal size, the gangway drops between them (Figure 7), thereby providing a continuous 18-m (59-ft) low floor that is 65 percent of the total passenger area. Floor height is only 345 mm (13.6 in) above TOR, which has become the standard to surpass.

There has been significant growth in the number and design variations of LF-LRVs since 1987. This growth occurred because of a combination of the following factors:

- A strong demand for new vehicles by several European transit agencies—by the end of the 1980s, several LRV fleets were due for replacement;
- The perceived advantages of LF-LRVs; and
- Manufacturers vying to use more ingenious methods to increase the low-floor area and taking advantage of high technology equipment.

By mid-1994, European LRT operators had placed orders for 1,876 LF-LRVs (including 30 trailers) with low-floor heights ranging from 197 mm (7.8 in) to 530 mm (20.9 in) above TOR. Between 1983 and 1993, approximately 600 conventional high-floor LRVs were ordered.

Every major European car builder (and almost every minor car builder) has manufactured at least one type of low-floor

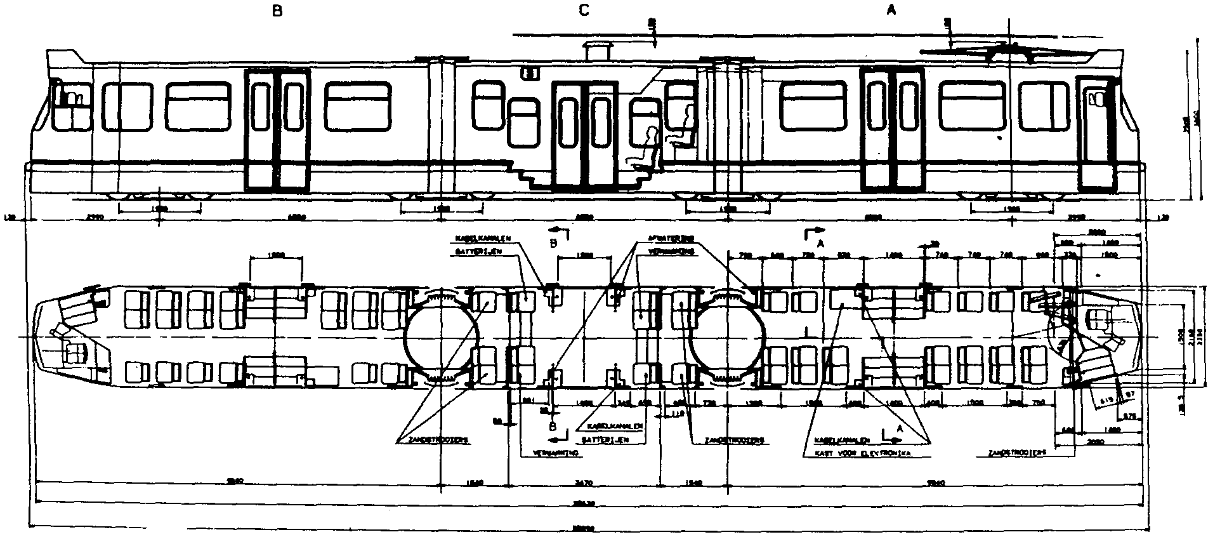


Figure 4. LF-LRV produced for Amsterdam.

vehicle design. Some of these are so revolutionary that they would have been unthinkable in the early 1980s. No single design concept has emerged as distinctly superior, and development of more variants has not yet abated.

The North American debut of LF-LRVs is scheduled for September 1995. The Tri-County Metropolitan Transportation District of Oregon (TRI-MET) in Portland, Oregon, expects delivery of a pilot vehicle that was ordered from Siemens-Duewag Corporation in May 1993. The pilot vehicle will be used for operational and compatibility testing, and the remaining 45 vehicles will be delivered beginning in early 1996.

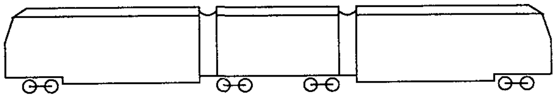
At the time this report was prepared, several other cities were also considering LF-LRVs. The City of Chicago's Central Area Circulator Project had received seven proposals in response to its Request For Proposal (RFP) for 38 vehicles. The Central Area Circulator Project RFP specified vehicles with 70 percent or more low floor; and a contract award is anticipated in mid-1995. In addition, the Massachusetts Bay Transportation Authority (MBTA) in Boston, Massachusetts, was expecting responses to its RFP for 100 LF-LRVs. The Toronto Transit Commission (TTC) in Toronto, Ontario, has developed specifications and is ready to issue an RFP to procure similar vehicles.

Perceived Advantages of LF-LRVs

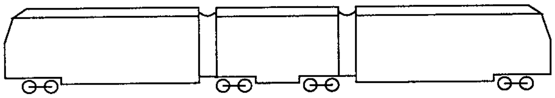
Low-floor vehicles bring a number of benefits to LRT systems with low-platform or street-level boarding(*2*):

- Accessible and comfortable transportation for all passengers, especially persons using wheelchairs or other mobility devices;
- Easier access for the elderly who previously had difficulty boarding conventional trams(*3*);
- Popularity among other passengers (especially those pushing strollers or carrying heavy shopping bags);
- Reduced station dwell times, which is especially useful on lines with close station spacing (Tests in Rotterdam, using the Grenoble LF-LRV, demonstrated a 10 percent reduction in round-trip time [*2*]); and
- Increased patronage (resulting from the previously listed advantages) and greater productivity.

Notice that the advantages are the same as those that are already inherent in existing LRT systems that exclusively have high-platform stations.



The Sheffield configuration has low floors in the outer sections



The Freiburg configuration has a low floor in the center section as well as in the outer sections

Figure 5. LF-LRV variations—Sheffield and Freiburg configurations.

Figure 6. Grenoble LF-LRV.

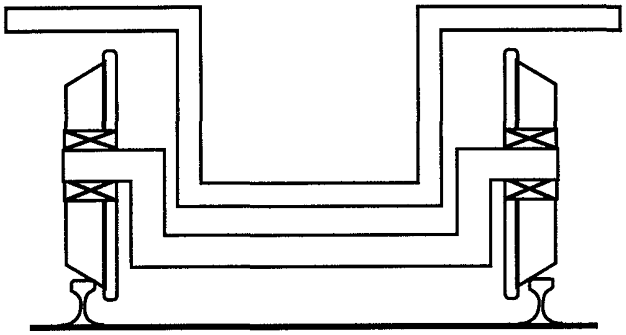


Figure 7. Cutaway view of Grenoble LF-LRV center section.

Key Applicability Issues

U.S. transit operators are also interested in LF-LRVs as a means of complying with the ADA, which requires at least one vehicle in every train to be accessible to persons with disabilities, beginning in 1995. However, several questions arise in evaluating the application of existing European LF-LRVs in North American service:

- Is there a price premium for LF-LRVs, and if so, what is it?

- What are the maintenance implications (resulting from increased complexity and departure from proven and familiar technology)?
- Are the presumed higher life-cycle costs offset by the increased productivity (as is generally perceived to be true in Europe)?
- Is a particular LF-LRV physically compatible with the transit system's current vehicles, infrastructure, and other subsystems? For example, can the LF-LRVs couple with existing cars (that may have considerable operating life remaining)?
- Are the currently available LF-LRVs, which are predominantly European, capable of meeting North American safety standards and the usually more stringent design criteria without costly redesign?
- Do the performance capabilities of LF-LRVs match requirements of the exclusive right-of-way routes frequently found in North American LRT systems?

In addition, several specific technical issues will need to be considered by North American transit operators before selecting a LF-LRV. For example, is the use of the following components acceptable:

- Small wheels?—The technical issue is limited wear life and increased contact stress.
- Unsprung motors and gearboxes?—The technical issue is the high shocks they experience and generate.

Applicability and technical issues are addressed in detail in Chapter 3.

ATTRIBUTES AND DISTINGUISHING FEATURES OF LF-LRVS

As the name implies, LF-LRVs have some portion of the floor at a significantly lower level than conventional LRVs. In practice, the low-floor area can extend from 9 percent to 100 percent of the car length. LF-LRVs have evolved substantially over the past 10 years. Many of the newer vehicles provide an increased proportion of low-floor area than their predecessors, which is why it has become customary to refer to LF-LRVs by the percentage of low-floor area.

For the purposes of describing LF-LRVs in this report, a classification system has been developed that splits all LF-LRVs into one of three categories—Category 1 with all conventional trucks; Category 2 with conventional motor trucks; and Category 3 with innovative motor and running gear throughout. The categories are described below and explored in more detail in Chapter 2.

LF-LRVs with All Conventional Trucks (Category-1 LF-LRVs)

LF-LRVs with all conventional trucks usually have a 9 percent to 15 percent low-floor area in a center section inserted between two articulation joints, each of which is supported by a truck (Figure 8). A variation from this basic concept is the addition of a low floor in the outer carbody sections (Figure 5), providing a 34 percent low floor in the Sheffield configuration, or in all three carbody sections, achieving a 48 percent low floor in the Duewag GT8D built for Freiburg. The last two examples feature "floating" articulations that are not directly supported by a truck.

The low-floor height ranges from 270 mm (10.6 in) to 480 mm (18.9 in); the high-floor height range is 560 mm (22 in) to 910 mm (35.8 in). A step or slope is required between the two levels.

As the percentage of low-floor area increases, it becomes necessary to shift equipment (usually mounted below the underframe) to above the roof or within the vehicle body. Because the underframes are discontinuous, the buff load path is less direct and somewhat more difficult to distribute.

An important innovation on some LF-LRVs with all conven-

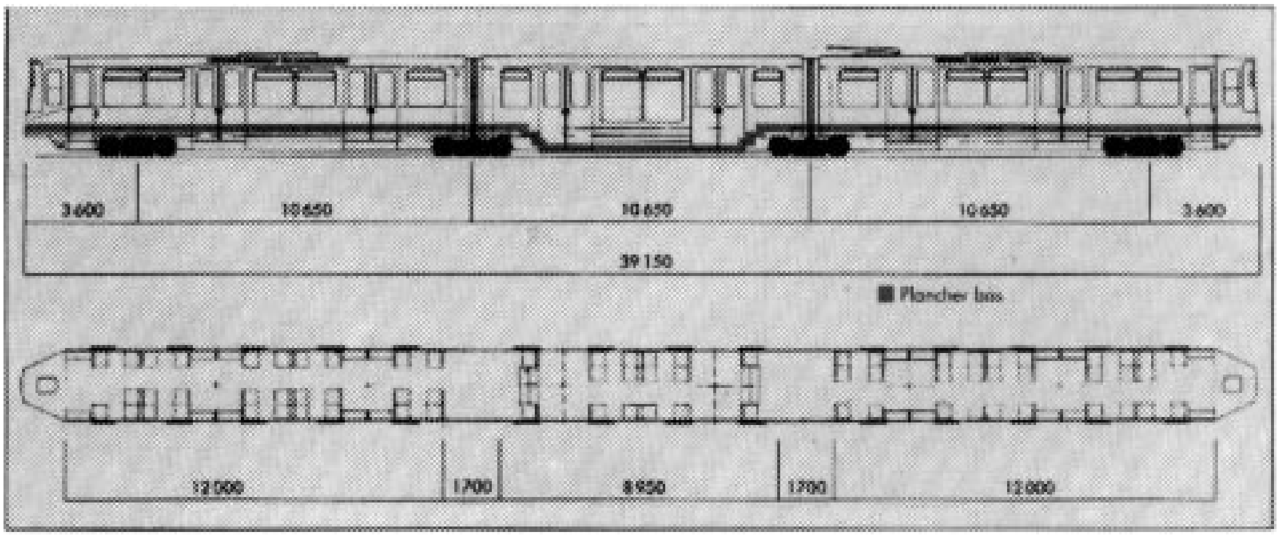


Figure 8. Category-1 LF-LRV—side- and top-view schematic.

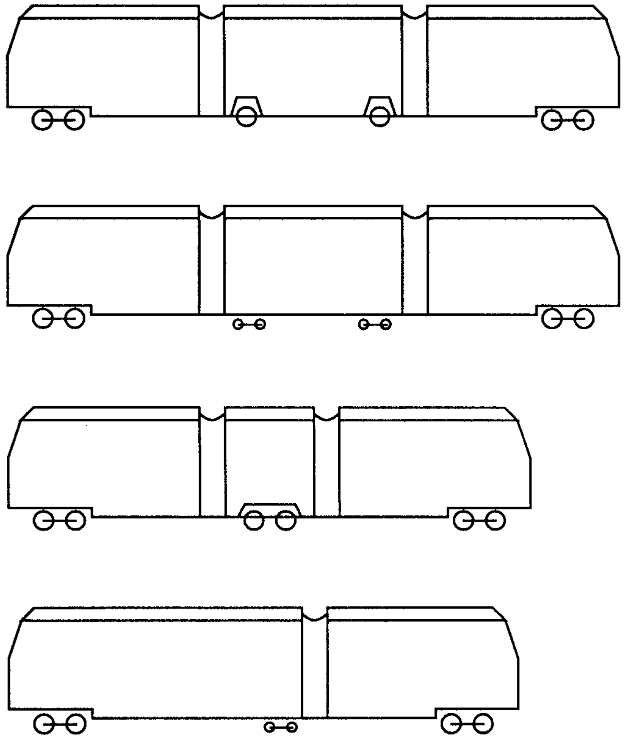
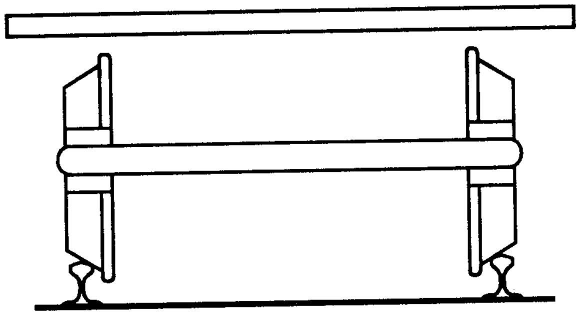
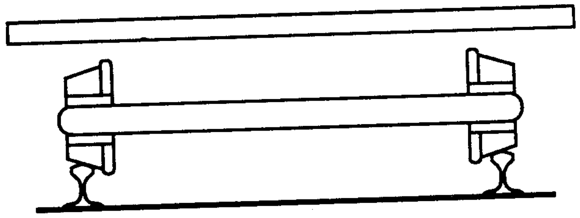


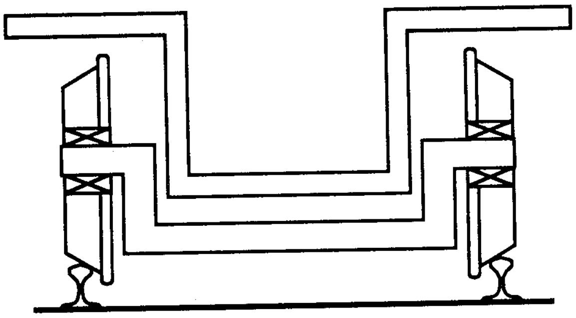
Figure 9. Various configurations of Category-2 LF-LRVs with conventional motor trucks.



Single Axle Conventional Wheelset



Small Diameter Wheels



Independently Rotating Wheels–Cranked Axle

Figure 10. Cutaway view of trailer truck configurations for Category-2 LF-LRVs.

tional trucks was the introduction of "floating" articulations. A floating articulation is one that is not directly supported by a truck. In all other ways, vehicles that make use of floating articulations are a close derivative of the conventional, double-articulated, eight-axle trams—such as the Duewag N8 and M8 families. These vehicles are supported by conventional monomotor or bimotor power trucks and ordinary trailer trucks with slew ring center bearings, two-stage suspensions, and two conventional wheel-axle assemblies that use normal size wheels with diameters of 590 mm (23.2 in) to 690 mm (27.2 in). All four trucks can be powered to provide 100 percent adhesion and high acceleration, but because they are normally used on street lines, maximum speed is usually between 70 and 80 km/h (44 to 50 mph).

LF-LRVs with Conventional Motor Trucks (Category-2 LF-LRVs)

LF-LRVs with conventional motor trucks (Category-2 LF-LRVs) retain the use of conventional power trucks at either end (Figure 9), but feature a continuous low floor between the trucks (between 50% and 73%). This precludes the use of conventional trucks in the center of the vehicle. Instead, the continuous low-floor gangway is achieved with innovative trailer trucks. Trailer trucks may use either small wheels with diameters between 375 mm and 410 mm (14.8 in and 16.1 in) or independently rotating wheels of normal size (Figure 10).

When small wheels are used, they are connected by a rigid axle and have profiled treads, thus retaining the conventional self-centering wheelset principle. Wheel diameters may be small enough for the top of the axles to allow the floor to be lowered to 300 mm (11.8 in) above TOR over the axles. However, 350 mm (13.8 in) to 480 mm (18.9 in) above TOR is more typical. The small wheelsets are connected in pairs by a compact truck frame. Vehicles can have either one or two center trucks and either standard or floating articulations.

In cases where independently rotating wheels are used, they are mounted in pairs (transversely connected by a cranked axle), on special truck frames with very low cross transoms, or on small "single-axle" or wheelset truck frames. The independent wheels may be unsteered, self-steered, or force steered, as described in Chapter 2.

The confined space below the low floor requires the use of compact equipment; therefore, hydraulically actuated calipers and discs are generally used for braking.

Central running gear wheels in Category-2 vehicles are not powered. Maximum speeds typically range between 60 and 70 km/h (38 to 40 mph). However, when TRI-MET (Portland) specified that its LF-LRVs should have comparable performance to its existing conventional LRVs, the evaluation indicated that Siemens-Duewag Corporation could comply with the specified higher speed of 90 km/h (55 mph).

LF-LRVs with Innovative Motor and Running Gear (Category-3 LF-LRVs)

The newest type of LF-LRVs (Category 3) features the following common attributes (typical configurations are shown in Figure 11):

- 100 percent low floor;
- Floor heights less than or equal to 360 mm (14.2 in), the lowest being 197 mm (7.8 in), and with entrance thresholds as low as 152 mm (6 in);
- Novel and sometimes revolutionary running gear;
- State-of-the-art propulsion equipment—in some cases using motors mounted directly on, or forming, the wheel hubs;
- Independently rotating wheels, either driven or free wheeling, usually with some form of steering; and
- No underframe-mounted equipment, except running gear or motors.

The running gear designs vary radically from vehicle to vehicle, and none has emerged as superior. These vehicles have little in common with conventional LRVs. Indeed, being state-of-the-art vehicles, they embody several innovations, including flexible modular designs, use of lightweight materials, bolted construction, and modern streamlining.

Category-3 LF-LRVs provide maximum utility because floors are low throughout their length, thereby avoiding internal stairs and allowing low-level boarding from every doorway. This makes for more efficient on-board fare collection, which has been cited as one of the motivations for developing them.

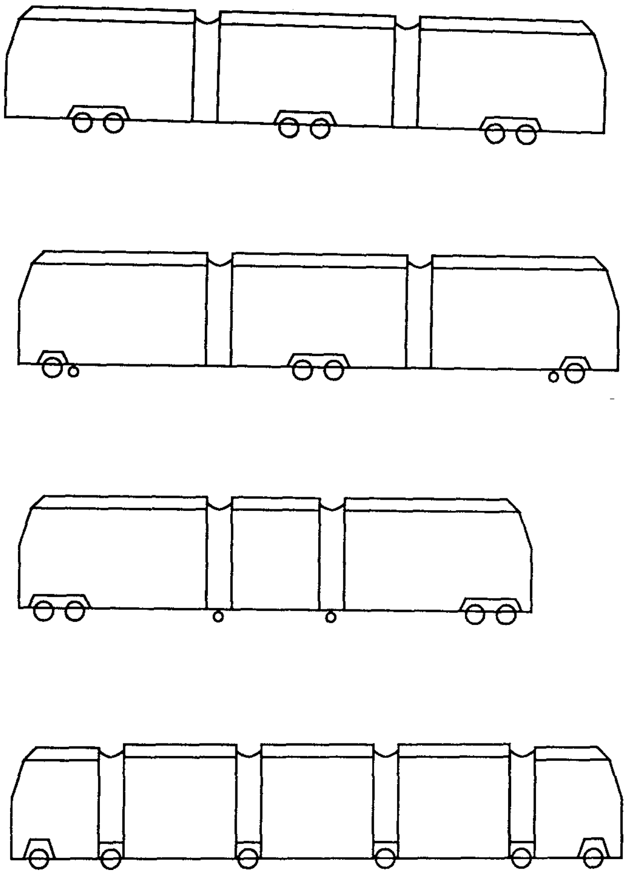


Figure 11. Typical configurations of Category-3 LF-LRVs.

LF-LRV DEVELOPMENT HISTORY

The development of Category-1 and Category-2 LF-LRVs, during the early and mid 1980s respectively, was driven by social and political pressures to provide improved access to transportation systems. Most of the LF-LRV concepts developed during the early-to-mid 1980s had the following common disadvantages:

- There were steps or ramps between the low- and high-floor areas.
- A low platform was needed at approximately the same level as the low floor, which cannot be provided on some city street routes.
- The driver's cab must be located in a high-floor area. Therefore, LRT systems that use on-board fare collection adjacent to the operator must use vehicles with steps that passengers must climb in order to pass the farebox and driver.

Recognizing these shortcomings and wanting to give its domestic manufacturers a competitive edge, the German Association of Public Transport Operations, VDV (formerly VÖV), decided that a new standard tram with a low floor throughout its length was needed. In 1986, VDV set up a consortium of German suppliers and three transit operators to develop the most radical streetcar design since the PCC car. The DM 45 million "Stadtbahn 2000" project was partially funded by the

TABLE 1Stadtbahn 2000 project prototype characteristics

Characteristics	Prototype I	Prototype II	Prototype III
Gauge	1,435 mm	1,435 mm	1,000 mm
Wheel Arrangement*	A'A'1	A'A'1	A'A'A'1
Number of Wheels/Car	6	6	8
Carbody Material	Steel	Aluminum	Steel
Carbody Length/Width	20 19/2 4 m	20 19/2 4 m	26 69/2 3 m
Seat Arrangement	2+1 transverse	2+2 transverse	2+1 transverse
Wheel Diameter	560 mm	560 mm	560 mm
Maximum Vehicle Speed	70 km/h	70 km/h	80 km/h
Vehicle Mass (empty)	17,750 kg	18,560 kg	23,980 kg
Specific Mass (kg/sq m)	366	383	391
Floor Height (from TOR to door/passenger areas)	290/350 mm	290/350 mm	290/350 mm
Originally Proposed Test Locations	Dusseldorf	Bonn	Mannheim

* See the Glossary for descriptions of wheel arrangements.

German Federal Ministry of Research and Technology. Some of the Stadtbahn 2000 objectives were to

- Develop a new standard tram with a 100 percent low floor;
- Minimize specific mass (i.e., mass floor area) and therefore energy consumption;
- Reduce the number of wheels and drives to lower both mass and price;
- Exploit the self-steering, independently rotating wheel, Einzelrad-Einzel-Fahrverk (EEF) wheelset patent, invented by Professor Friedrich of Aachen University (EEF wheelset technology is described in detail in Chapter 2); and
- Achieve a production price on the order of DM 2.2 million (approximately $1.5 million at that time).

Although this is not a comprehensive list of Stadtbahn 2000 objectives, it illustrates the wide range of objectives.

Three prototypes, with the characteristics shown in Table 1, were supposed to be built by 1989 and operationally tested by 1991. However, because of technical difficulties in motorizing the EEF wheelsets and obtaining acceptable ride quality, the prototypes were delayed and could not be built in production within the targeted price. Subsequently, the Stadtbahn 2000 project was terminated and none of the prototypes entered production.

In the meantime, several manufacturers collaborated with specific German cities to develop independently their own 100 percent low-floor vehicle, which would fulfill some of the Stadtbahn 2000 objectives. In 1986, the suppliers—MAN (now part of AEG) and Kiepe—began work with the city of Bremen on a 100 percent low-floor design. Successful prototypes were developed for Bremen in 1990 and Munich in 1991. The prototypes have evolved into production vehicles, and the six-axle GT6N and eight-axle GT8N trams have been ordered by eight cities, including Augsburg, Bremen, and Munich. Orders totaled 200 vehicles by 1993, with options for 204 more.(*4*)

TABLE 2 Other 100% low-floor prototype manufacturers/ locations

City	Model	Builder	Year of Delivery
Turin		Firema	1989
Milan	S350	Socimi	1989
	LRV 2000	BN	1990
Rome	VLC	Breda	1990
Rome		Socimi	1992
Chemintz	6NGT	ABB Henschel (Waggon Union)	1993
Vienna	ULF 197	SGP/Elin	1994

Other manufacturers and cities also experimented with 100 percent low-floor prototypes (Table 2). Some 100 percent low-floor vehicles (Table 3) have been produced directly from design, without the benefit of prototype development.

Production orders that have resulted from 100 percent low-floor prototypes include the following:

- Lille ordered 24 Breda VLCs for delivery in 1993.
- Strasbourg ordered 26 Eurotrams from ABB (Socimi), based on the Rome prototype.
- Chemintz has ordered 53 Variotrams based on the 6NGT.
- Wurzburg has ordered twenty, 100 percent low-floor ve-

TABLE 3 Other 100% low-floor vehicles produced directly from design (without prototypes)

City	Model	Builder	Quantity	Year of Delivery
Frankfurt	R3.1	Duewag	20	1993
Brussels	TRAM 2000	Bombardier (BN)	51	1993-1994

hicles from Linke-Hofmann-Busch (LHB) using the running gear from the Variotram.

- Vienna is expected to order 150 ultra low-floor (ULF) cars from SGP/Elin for delivery in 1996 through 2005, if the ULF prototype performance proves satisfactory.

LF-LRV MARKET STATISTICS

LF-LRV market statistics are useful for understanding trends in the demand for vehicles and the distribution among manufacturers. Data used in this report come from an extensive survey and investigation conducted by Booz • Allen & Hamilton specifically for this study. Information on propulsion and electrical equipment is cited from a 1993 article by Harry Hondius in *Developing Metros* magazine.(*5*) The distribution of LF-LRVs among manufacturers is shown in Figures 12, 13, and 14 and among propulsion and electrical equipment suppliers in Figure 15.

As described earlier in the report, approximately 75 percent of European orders for new vehicles in the 10 years preceding 1993 were for LF-LRVs. Many of the early procurements were predominantly for Category-1 and Category-2 vehicles. However, for deliveries expected in 1993 or later, Category-3 vehicles nearly match the demand for Category-1 and Category-2 vehicles combined (Tables 4 and 5). The trend in Europe is certainly toward 100 percent low-floor Category-3 vehicles. Additional information on LF-LRVs is provided in Appendix A, which served as the basis for development of Table 4.

The vast majority (97%) of the LF-LRVs have been ordered by European LRT agencies. Figure 16 shows the distribution of LF-LRV orders throughout Europe. A majority of the European orders (88%) have been placed with manufacturers within the transit agency's country of origin. For example, of the 35 orders placed by German transit agencies, one order was placed with a manufacturer outside Germany—Cologne ordered Vienna T-type vehicles from Bombardier (Rotax). French transit agencies have ordered vehicles from Italy (Breda) and Germany (ABB), as well as France (GEC Alsthom). Table 6 shows the vehicle manufacturers and their orders for out-of-country transit systems.

The two companies with the majority of orders for Category-3 vehicles are AEG (MAN) with 37 percent of the total orders and SGP with 28 percent of the total orders. As indicated by their absence from Table 6, neither of these two companies has had an order placed by a transit system outside its country. On the other hand, the company with the majority of orders

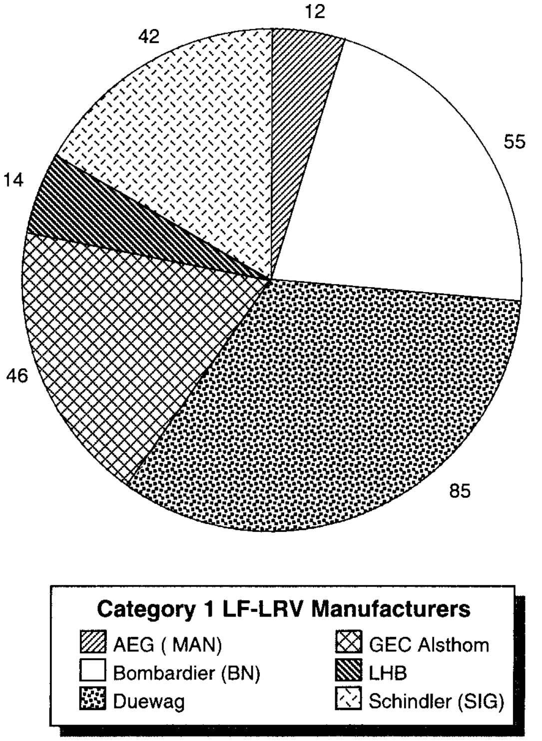


Figure 12. Distribution of Category-1 LF-LRVs by manufacturer.

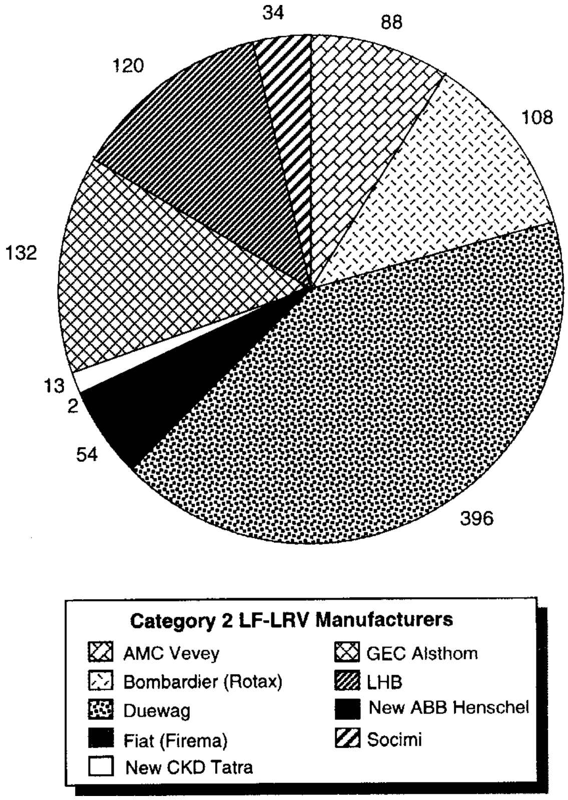


Figure 13. Distribution of Category-2 LF-LRVs by manufacturer.

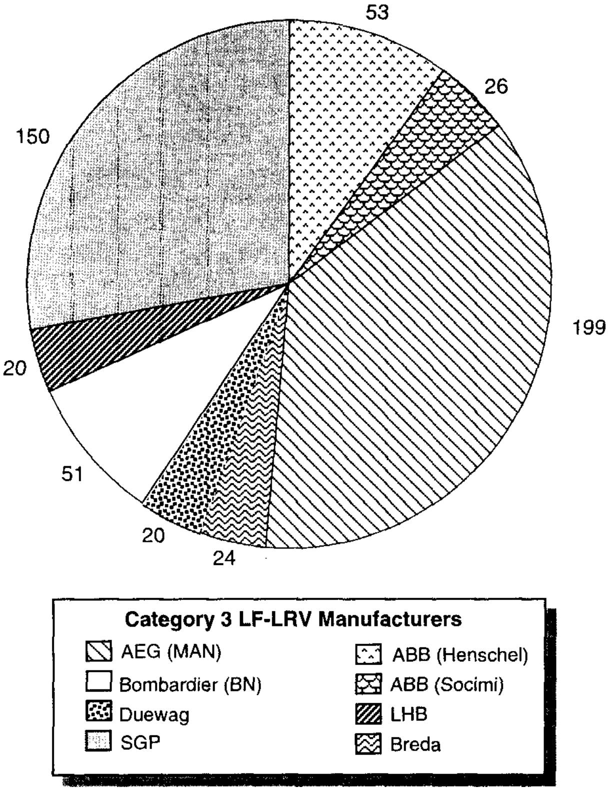


Figure 14. Distribution of Category-3 LF-LRVs by manufacturer.

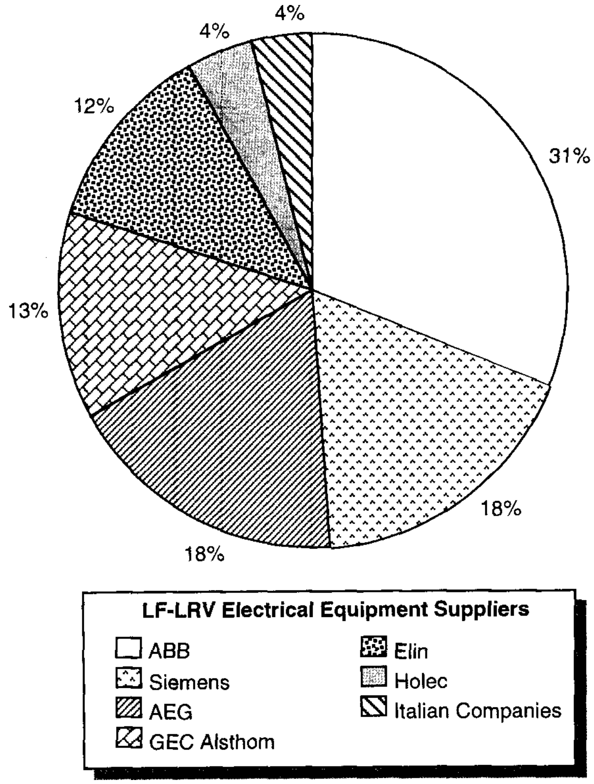


Figure 15. Distribution of LF-LRV market by propulsion and electrical equipment suppliers.

for Category-2 vehicles, Duewag received 20 percent of its orders from outside Germany.

The near-term North American orders are most likely to come from TRI-MET in Portland (order placed with Siemens-Duewag Corporation), the Central Area Circulator Project in Chicago, MBTA in Boston, and TTC in Toronto.

ORGANIZATION OF REPORT

The remainder of this report includes the following:

- Chapter 2, State-of-the-Art Review, defines a classification system that can be easily used to evaluate the state-of-the-art technologies; describes some of the new technologies; and discusses some maintenance and operating experience.
- Chapter 3, Application Considerations, identifies and discusses the significant critical factors that should be examined before considering LF-LRVs. These factors include dimensional compatibility, operating issues, and compliance with North American specifications.
- Chapter 4, Grouping and Characteristics of North American Light Rail Systems, discusses the issues, opportunities, and constraints regarding possible deployment of LF-LRVs at North American LRT systems.
- Chapter 5, Applicability Assessment Framework, defines an applicability assessment model, which demonstrates a process that can be used to define a range of options; then narrows the options to those best suited to a particular transit agency. As a complement to the model, comments in this chapter advise what are the major LF-LRV versus conventional LRV issues, what trade-offs will arise, and what are the most important discriminators between conventional LRVs and LF-LRVs.
- Chapter 6, Case Studies, presents two illustrative examples to show, in a realistic North American context, issues and trade-offs relevant to the choice of LF-LRVs versus conventional LRVs. The first case study is an extension to an existing low-platform LRT system. The second case study is a new LRT system.
- Chapter 7, Conclusions, summarizes the findings of the report and recommends areas for further study.
- Appendix A presents the LF-LRV characteristics database.
- Appendix B presents LRT systems database for 14 North American cities.
- Appendix C, glossary of acronyms and list of transit authorities mentioned in this report.
- Appendix D, bibliography.

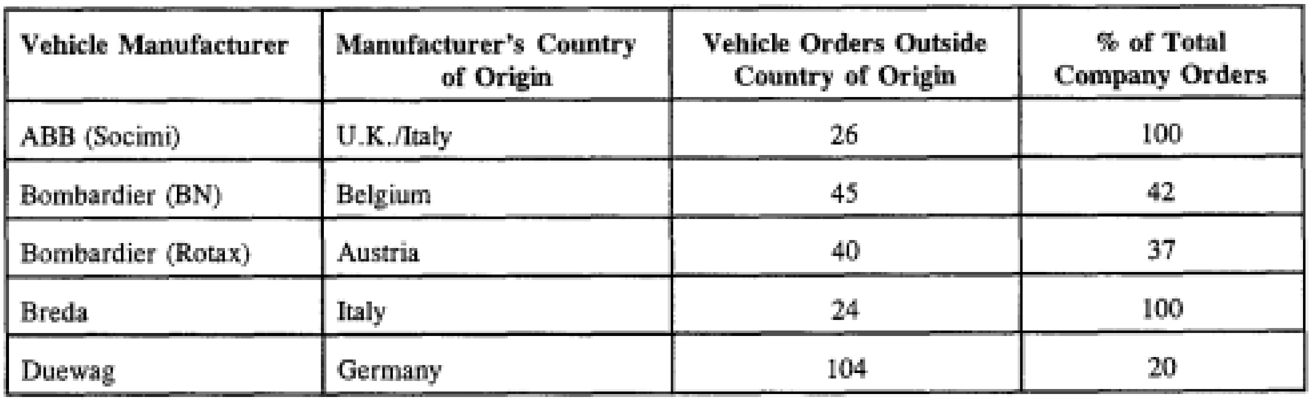
TABLE 4 Total number of LF-LRVs produced or on order world-wide (mid-1994), including prototypes

	No. of Vehicles	% of Total
Category 1	254	13%
Category 2	954	52%
Category 3	675	36%
Total	1,883	

TABLE 5 Total number of LF-LRVs produced or on order worldwide (mid-1994), by expected delivery date

	Expected Delivery Prior to 1993			Expected Delivery 1993 or Later		
	No. of Vehicles	% of Total	Average Order	No. of Vehicles	% of Total	Average Order
Category 1	158	27	23	73	6	18
Category 2	394	68	33	583	44	23
Category 3	29	5	11	646	50	38
Total	581			1,302		

TABLE 6 Low-floor vehicle manufacturers with export sales



Vehicle Manufacturer	Manufacturer's Country of Origin	Vehicle Orders Outside Country of Origin	% of Total Company Orders
ABB (Socimi)	U.K./Italy	26	100
Bombardier (BN)	Belgium	45	42
Bombardier (Rotax)	Austria	40	37
Breda	Italy	24	100
Duewag	Germany	104	20

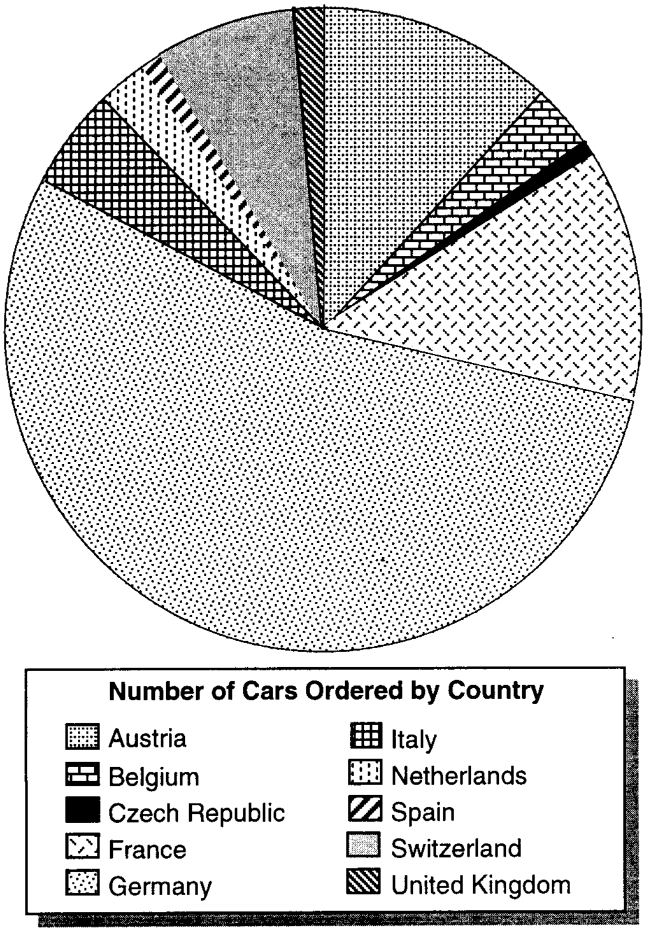


Figure 16. Distribution of Category-3 LF-LRV orders in Europe by country.

CHAPTER 2

STATE-OF-THE-ART REVIEW

To describe the applicability of low-floor light rail vehicles (LF-LRVs) to North American transit systems, it is necessary to develop a classification system and a vernacular to facilitate discussion of state-of-the-art technologies. This chapter begins by defining a classification system, first introduced in Chapter 1, that covers LF-LRVs manufactured or ordered to date. Representative models in each category are described. A detailed list of characteristics (if known) is provided for each vehicle in Appendix A.

As stated previously, Category-2 and Category-3 LF-LRVs have increased the proportion of low-floor area through the use of innovative running gear design and high technology propulsion equipment, particularly motors and gearboxes. These and other new technologies are described in detail in this chapter.

Because LF-LRVs have a short service history, it has been difficult to obtain objective data on reliability, maintainability, and operating cost. Some anecdotal evidence has been collected and is presented in the last section of this chapter.

CLASSIFICATION SYSTEM

The classification system used is based primarily on type of running gear:

Category 1—Vehicles with conventional motor and trailer trucks throughout.

Category 2—Vehicles with conventional motor trucks at each end; and in between them either:

- Small wheel trailer trucks; or
- Independently rotating wheel trailer running gear arranged as:
  - Four independent wheel trucks (with or without cranked axles), or
  - Self-steering wheelsets (including EEF wheelsets described in detail later in Chapter 2); or
- Single-axle conventional wheelsets.

Category 3—Vehicles with innovative motored and trailing running gear throughout.

Figure 17 shows the various wheelset and drive arrangements for both conventional LRVs and the three categories of LF-LRVs. More detail on the use of these wheelset and drive arrangements for each of the three categories of LF-LRVs is provided in the vehicle characteristics compendium section.

The classification system was selected for the following reasons:

- The majority of LRT systems that may be considering LF-LRVs are existing systems, with existing vehicles and facilities. For these systems, the proposed categories represent increasing application complexity and change from existing practices.
- The three categories correspond to the proportion of low-floor area, which is an important characteristic from an operational viewpoint:
  - **Category 1**—generally 9 percent to 15 percent low floor, but up to 48 percent low-floor area;
  - **Category 2**—generally 50 percent to 75 percent uninterrupted low-floor area between motor trucks; and
  - **Category 3**—100 percent low-floor areas and low-level entrances throughout the vehicle (the one exception is the Breda VLC).
- The three categories represent increasing levels of technological innovation and, therefore, application risk.

CHARACTERISTICS COMPENDIUM

Research for this project identified 42 vehicle designs, including 8 prototypes. The known characteristics of each vehicle were entered into a computer database (see Appendix A).

Table 7 shows a summary of vehicle characteristics for vehicles in service or on order. The vehicles are sorted by category. The table should be read in conjunction with Figure 17 regarding detailed running gear arrangements. Axle arrangement terminology is described in the glossary.

It was not possible to ascertain all the characteristics for every vehicle during this research effort. In particular, price information was not always available. However, Table 7 and Appendix A provide a significant level of information regarding the characteristics of LF-LRVs. In addition, a discussion of published and reported prices is provided in this chapter.

DETAILED DESCRIPTIONS OF LF-LRVS

This section describes in greater detail the configuration and attributes of representative vehicles in each of the three previously defined categories. More than one vehicle is described

Trailing Gear Code	Trailing Gear Type
I1	Conventional two-axle
I2	Independent wheels on two cranked axle trailer truck
I3	Four independent wheel trailer truck
I4	Single wheelset with small independent wheels built into articulation
I6	Small wheel trailer truck
I5	Single-axle conventional wheelset steered by articulation
I7	Single wheelset steered by the articulation
I8	EEF wheelset

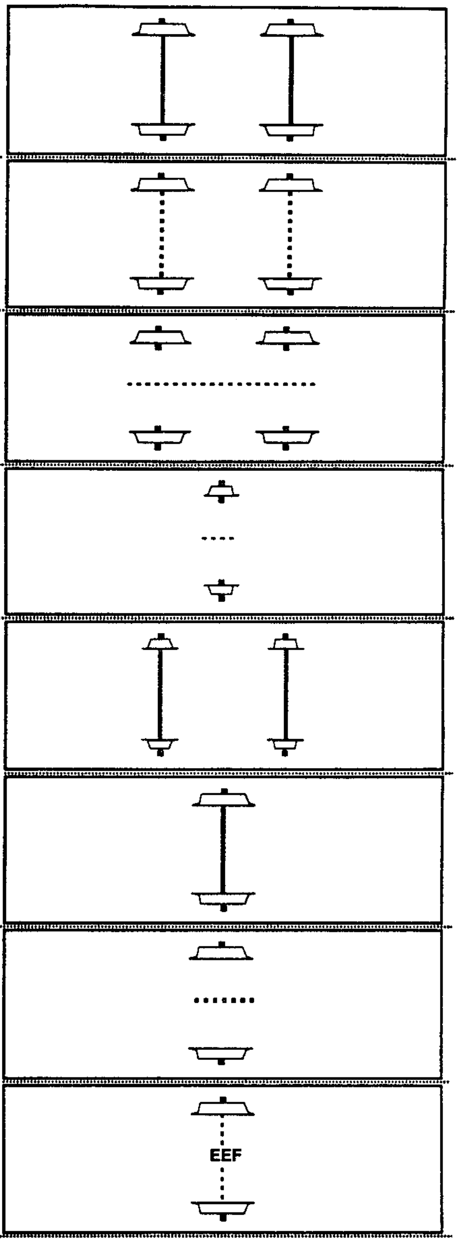


Figure 17. Conventional and LF-LRV wheelset and drive arrangements.

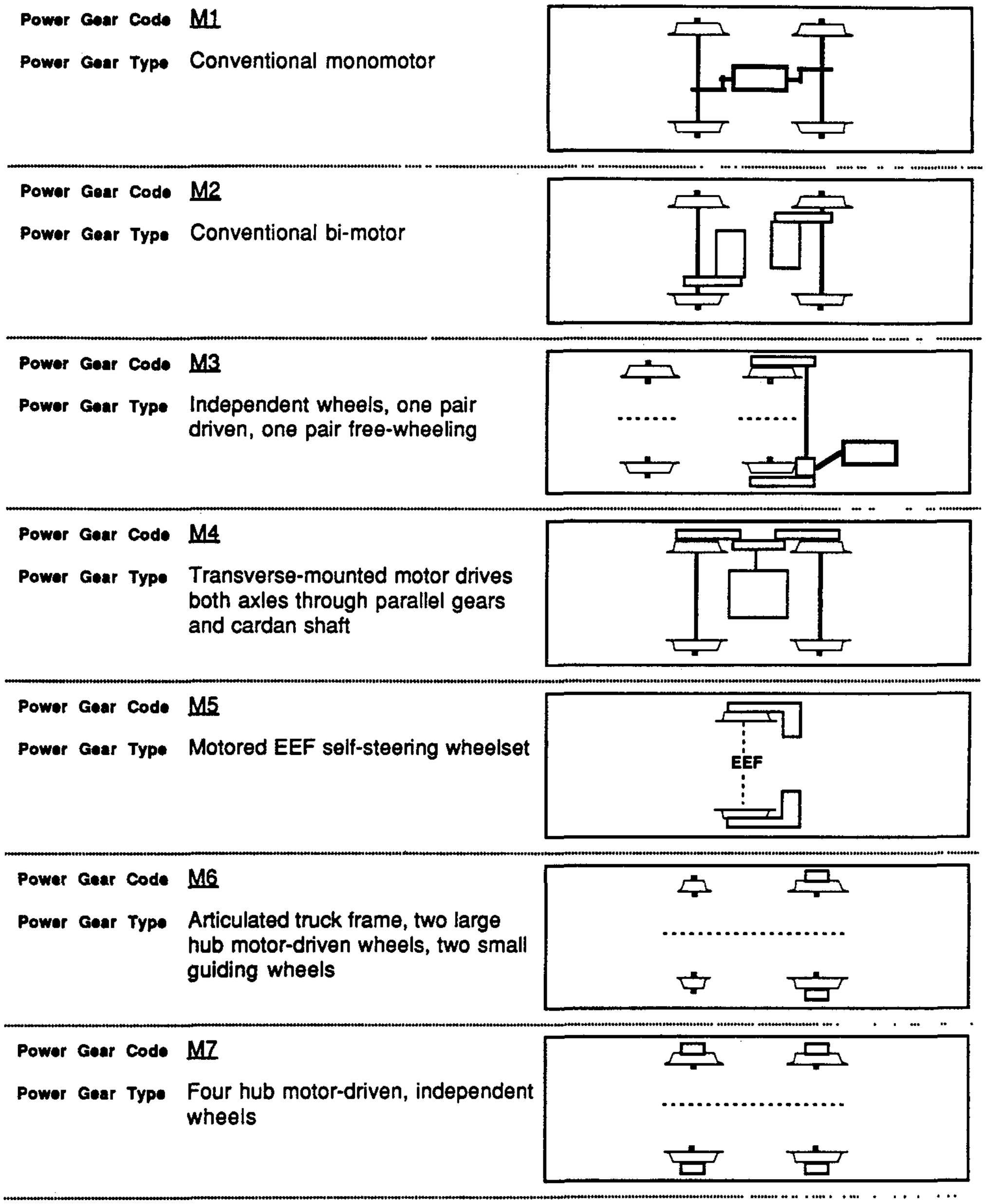
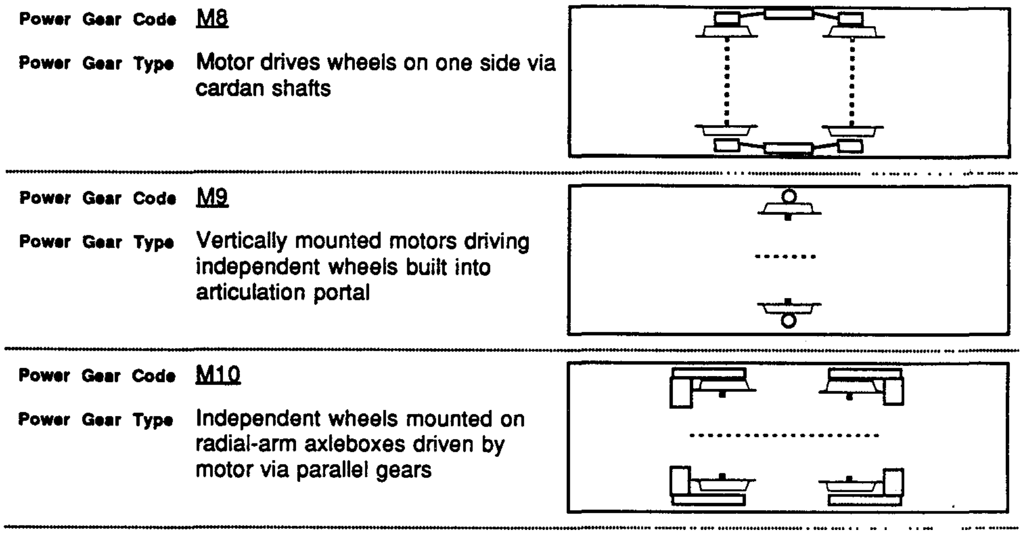


Figure 17. Conventional and LF-LRV wheelset and drive arrangements (continued).



Power Gear Code M8

Power Gear Type Motor drives wheels on one side via cardan shafts

Power Gear Code M9

Power Gear Type Vertically mounted motors driving independent wheels built into articulation portal

Power Gear Code M10

Power Gear Type Independent wheels mounted on radial-arm axleboxes driven by motor via parallel gears

Figure 17. Conventional and LF-LRV wheelset and drive arrangements (continued).

in each category in order to examine the differences in technology. This is especially relevant for Category-2 vehicles, because a number of different wheel/axle technologies are used, and for Category-3 vehicles, because various traction motor technologies are used.

Category-1 Vehicles

Category-1 vehicles have conventional motor and trailer trucks throughout the vehicle. Category-1 vehicles generally have 9 to 15 percent low-floor area but can have up to 48 percent. Two representative vehicles from Category 1 are described in the following.

Wurzburg-Type GT8/8C. The city of Wurzburg, Germany, operates 14 eight-axle LF-LRVs. These vehicles were supplied in 1989 by Linke-Hofmann-Busch of Germany and use Siemens electrical equipment. This vehicle is shown in Figure 18. The design philosophy follows the basic approach of inserting an intermediate section between the two halves of a conventional LRV. The extended vehicle has four trucks instead of the original three trucks, and two articulations instead of the original one articulation. However, the articulations are not directly supported by a truck. All four monomotor trucks are of conventional monomotor design—driven by a single, three-phase, AC, asynchronous induction motor.

All vehicle equipment is fitted to the underside of the two outer sections of the vehicle. The low floor in the intermediate section comprises 9 percent of the total floor area. The vehicle is unidirectional. Five entrance doorways are provided on one side of the vehicle only. The center door provides direct access to the low-floor area, which provides sufficient space for one or two wheelchairs. Internal access to the remainder of the vehicle is provided by steps at either end of the low-floor area.

Similar vehicles of this type are running in Freiburg and Mannheim, Germany, and Basel, Switzerland. The advantages of this design are

- Proven and familiar technology;
- Underfloor equipment mounting, which allows use of existing maintenance workshop layout and equipment;
- Existing six-axle vehicles, which may be converted to this design, thereby cost-effectively achieving increased capacity and accessibility; and
- Maximum use of adhesion to provide high acceleration, even on steep grades, when all axles are powered.

Disadvantages are as follows:

- The low-floor area is small (15% maximum).
- There are internal steps or ramps between the high- and low-floor areas.
- Vehicle length may exceed maintenance shops or existing low platforms or block road intersections.
- Lower performance can result if not all trucks are powered.
- Vehicles are unidirectional.

Sheffield "Supertram." The city of Sheffield, England, operates 25 eight-axle LF-LRVs. These vehicles were supplied between 1992 and 1993 by Duewag of Germany and use Siemens electrical equipment. This vehicle is shown in Figure 19. The design has three articulated sections and four motored trucks. The vehicle differs from the Wurzburg design in that the low floor is in the outer carbody sections and the center section has a high floor. All four trucks are of the conventional Siemens monomotor design, driven by a chopper-controlled DC traction motor. Vehicle equipment is fitted to the underside of the center section. This arrangement achieves a 34 percent low-floor area.

There are four entrance doors on one side. Each door leads

TABLE 7 Summary of Category-1, Category-2, and Category-3 LF-LRVs

Category–1 Low Floor LRVs

City	Builder	Type	Axle Arrangement*	Number of Cars	% Low Floor	Car Length (m *ft*)	Car Width (m *ft*)	Floor Height		Weight (tonne *lbs*)	Max Speed (km/h *mph*)	Min Curve Radius (m, *ft*)	Running Gear Type		First Car
								Max (mm *in*)	Min (mm *in*)				Power	Trailer	
Mannheim	Duewag	N/A	B'2'2'B'	23	9%	25.7 *84.2*	2.2 *7.2*	889 *35*	353 *13.9*	26 *57,320*	60 *37*	25 *82*	M1	T1	1991
Amsterdam/ GVBA	Bombardier (BN)	11G & 12G	Bo'Bo'Bo'Bo'	45	9%	25.6 *84.1*	2.4 *7.7*	870 *34.3*	280 *11*	36.9 *81,351*	70 *44*	25 *82*	M2		1989
Freiburg/ VAG	Duewag	GT 8C	B'B'B'B'	11	9%	32.8 *107.7*	2.3 *7.5*	910 *35.8*	270 *10.6*	38.5 *84,878*	70 *44*	25 *82*	M1		1990
Nurnberg	AEG (MAN)	N82	B'2'2'B'	12	9%	26.1 *85.6*	2.3 *7.5*	880 *34.6*	284 *11.2*	32.8 *72,312*	70 *44*	25 *82*	M1	T1	1992
Wurzburg	LHB	GT 8/8C	B'B'B'B'	14	10%	32.6 *107*	2.4 *7.9*	910 *35.8*	310 *12.2*	42.5 *93,697*	70 *44*	25 *82*	M1		1989
Antwerp/ De Lijn	Bombardier (BN)	N/A	B'2'2'B'	10	10%	29.3 *96.1*	2.3 *7.5*	860 *33.9*	350 *13.8*	42 *92,594*	80 *50*	N/A	M1	T1	1993
Basle/ BVB	Schindler (SIG)	Be 4/4	B'2'2'B'	19	15%	25.4 *83.3*	2.2 *7.2*	855 *33.7*	325 *12.8*	31 *68,343*	65 *40*	12 *39.4*	M1	T1	1987
Nantes/ SEMITAN	GEC Alsthom	N/A	B'2'2'B'	34	16%	39.2 *128.4*	2.3 *7.5*	873 *34.4*	353 *13.9*	51.9 *114,420*	70 *44*	25 *82*	M1	T1	1992
Nantes/ SEMITAN	GEC Alsthom	N/A	B'2'2'B'	12	18%	39.2 *128.4*	2.3 *7.5*	850 *33.5*	350 *13.8*	51.6 *113,759*	70 *44*	N/A	M1	T1	1993
Sheffield/ SYST	Duewag	GT 8	B'B'B'B'	25	34%	34.8 *114*	2.7 *8.7*	880 *34.6*	480 *18.9*	46 *101,413*	80 *50*	25 *82*	M1		1993
Freiburg	Duewag	GT8D-MNZ	Bo'Bo'Bo'Bo'	26	48%	33.1 *108.6*	2.3 *7.5*	560 *22*	290 *11.4*	38.5 *84,878*	70 *44*	19 *62.3*	M2		1993
RBS	Schindler (SIG)	ABe4/8	Bo'2'2'Bo'	23	50%	39.3 *128.9*	2.7 *8.7*	830 *32.7*	390 *15.4*	51 *112,436*	90 *56*	N/A	M2	T1	1992

Sum of Category 1 Cars Ordered 254

* See glossary for definitions

TABLE 7 Summary of Category-1, Category-2, and Category-3 LF-LRVs (continued)

Category–2 Low Floor LRVs

City	Builder	Type	Axle Arrangement*	Number of Cars	% Low Floor	Car Length (m *ft*)	Car Width (m *ft*)	Floor Height Max (mm *in*)	Floor Height Min (mm *in*)	Weight (tonne *lbs*)	Max Speed (km/h *mph*)	Min Curve Radius (m, *ft*)	Running Gear Type Power	Running Gear Type Trailer	First Car
Trailing Gear: Independent wheels on two cranked axle trailer truck															
Portland	Siemens-Duewag	N/A	Bo'2Bo'	46	66%	28.0 *92*	2.7 *8.7*	980 *38.6*	355 *14*	44 *97,003*	88 *55*	25 *82*	M2	T2	1995
Grenoble/ SEMITAG	GEC Alsthom	ZR 2000	B'2'B'	38	65%	29.4 *96.5*	2.3 *7.5*	875 *34.4*	345 *13.6*	43.9 *96,783*	70 *44*	25 *82*	M1	T2	1987
Grenoble/ SEMITAG	GEC Alsthom	ZR 2000	B'2'B'	7	65%	29.4 *96.5*	2.3 *7.5*	875 *34.4*	345 *13.6*	43.9 *96,783*	70 *44*	25 *82*	M2	T2	1995
Paris/ SEMITAG	GEC Alsthom	ZR 2000	B'2'B'	17	65%	29.4 *96.5*	2.3 *7.5*	875 *34.4*	345 *13.6*	43.9 *96,783*	70 *44*	25 *82*	M1	T2	N/A
Rouen/ SEMITAG	GEC Alsthom	ZR 2000	B'2'B'	28	65%	29.4 *96.5*	2.3 *7.5*	875 *34.4*	345 *13.6*	43.9 *96,783*	70 *44*	25 *82*	M1	T2	1993
Val de Seine/ SEMITAG	GEC Alsthom	ZR 2000	B'2'B'	17	65%	29.4 *96.5*	2.3 *7.5*	875 *34.4*	345 *13.6*	43.9 *96,783*	70 *44*	25 *82*	M1	T2	N/A
Trailing Gear: Four independent wheel trailer truck															
Turin/ ATM	Fiat (Firema)	5000	B'2'B	54	56%	22.2 *72.8*	2.3 *7.5*	870 *34.3*	350 *13.8*	30 *66,139*	60 *37*	16 *52.5*	M1	T3	1989
Dresden	Duewag	6MGT	Bo'22Bo'	20	64%	40.5 *132.9*	2.4 *7.9*	600 *23.6*	350 *13.8*	42 *92,594*	70 *44*	15 *49.2*	M2	T3	N/A
Mannheim	Duewag	6MGT	Bo'2Bo'	64	64%	29.9 *98.1*	2.4 *7.9*	600 *23.6*	350 *13.8*	33 *72,753*	70 *44*	15 *49.2*	M2	T3	1994
Mannheim	Duewag	6MGT	Bo'22Bo'	5	64%	40.5 *132.9*	2.4 *7.9*	600 *23.6*	350 *13.8*	42 *92,594*	70 *44*	15 *49.2*	M2	T3	1994
Mannheim	ABB Henschel	6NGT/ Variotram	N/A	2	70%	N/A	N/A	N/A	290 *11.4*	N/A	N/A	N/A	M2	T3	1996
Karlsruhe	Duewag	70D/N	Bo'2Bo'	20	61%	28.8 *94.6*	2.7 *8.7*	580 *22.8*	390 *15.4*	34.5 *76,060*	80 *50*	N/A	M2	T3	1994
Buenos Aires	Duewag	N/A	Bo'2Bo'	9	62%	23.8 *78*	2.4 *7.9*	560 *22*	350 *13.8*	29.7 *65,477*	70 *44*	25 *82*	M2	T3	1994
Valencia	Duewag	N/A	Bo'2Bo'	24	62%	23.8 *78*	2.4 *7.9*	560 *22*	350 *13.8*	29.7 *65,477*	65 *40*	20 *65.6*	M2	T3	1994
Brno City Transport	CKD Tatra	RT6-N1	Bo'2Bo'	12	63%	26.3 *86.2*	2.4 *8*	900 *35.4*	350 *13.8*	32 *70,548*	80 *50*	25 *82*	M2	T3	N/A
Prototype	CKD Tatra	RT6-N1	Bo'2Bo'	1	63%	26.3 *86.2*	2.4 *8*	900 *35.4*	350 *13.8*	32 *70,548*	80 *50*	25 *82*	M2	T3	1993
Rome/ ATAC	Socimi	T8000	Bo'2Bo'	34	54%	21.2 *69.6*	2.3 *7.5*	835 *32.9*	350 *13.8*	29.7 *65,477*	70 *44*	15 *49.2*	M2	T3	1990
Trailing Gear: Single-axle conventional wheelset steered by articulation															
Cologne	Bombardier (Rotax)	T	Bo'1'1'Bo'	40	60%	26.8 *87.9*	2.7 *8.7*	530 *20.9*	440 *17.3*	34.7 *76,500*	80 *50*	20 *65.6*	M2	T5	N/A
Vienna U-Bahn	Bombardier (Rotax)	T	Bo'1'1'Bo'	68	60%	26.8 *87.9*	2.7 *8.7*	530 *20.9*	440 *17.3*	34.7 *76,500*	80 *50*	20 *65.6*	M2	T5	1992

* See glossary for definitions

TABLE 7 Summary of Category-1, Category-2, and Category-3 LF-LRVs (continued)

Category–2 Low Floor LRVs

City	Builder	Type	Axle Arrangement*	Number of Cars	% Low Floor	Car Length (m *ft*)	Car Width (m *ft*)	Floor Height Max (mm *in*)	Floor Height Min (mm *in*)	Weight (tonne *lbs*)	Max Speed (km/h *mph*)	Min Curve Radius (m,*ft*)	Running Gear Type Power	Running Gear Type Trailer	First Car
Trailing Gear: Small wheel trailer truck															
Leipzig	Duewag	8NGT	Bo'2'2'Bo'	25	61%	27.8 *91.2*	2.2 *7.2*	560 *22*	300 *11.8*	32 *70,548*	70 *44*	N/A	M2	T6	1994
Swiss-Italian Railway/ FART	ACM Vevey	ABe4/6	Bo'2'Bo'	12	60%	30.3 *99.4*	2.7 *8.7*	900 *35.4*	530 *20.9*	42.5 *93,697*	80 *50*	N/A	M2	T6	1992
Geneva/ TPG	ACM Vevey	Be4/6	B'2'B'	46	60%	21.0 *68.9*	2.3 *7.5*	870 *34.3*	480 *18.9*	27 *59,525*	60 *37*	17.5 *57.4*	M1	T6	1984
St. Etienne/ STAS	GEC Alsthom	Be4/6	B'2'B'	25	59%	23.2 *76.2*	2.1 *6.9*	710 *28*	350 *13.8*	27 4 *60,407*	70 *44*	18 *59.1*	M1	T6	1991
Bern/ SVB	ACM Vevey	Be4/8	B'2'2'B'	12	73%	31.0 *101.7*	2.2 *7.2*	710 *28*	350 *13.8*	34 *74,957*	60 *37*	15 *49.2*	M1	T6	1989
Geneva	ACM Vevey	Be4/8 Intermediate	N/A	18	N/A	N/A	N/A	N/A	350 *13.8*	N/A	N/A	N/A	M1	T6	1995
Magdeburg	LHB	NGT 8D	Bo'2'2'Bo'	120	60%	29.0 *95.1*	2.3 *7.5*	570 *22.4*	350 *13.8*	34 *74,957*	70 *44*	N/A	M2	T6	1995
Trailing Gear: EEF wheelset															
Rostock	Duewag	6NGTWDE	Bo'1'1'Bo'	50	50%	30.4 *99.7*	2.3 *7.5*	560 *22*	350 *13.8*	30.4 *67,021*	70 *44*	15 *49.2*	M2	T8	1994
Bogestra/ Bochum	Duewag	MGT6D	Bo'1'1'Bo'	43	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	32 *70,548*	70 *44*	15 *49.2*	M2	T8	1992
Brandenburg	Duewag	MGT6D	Bo'1'1'Bo'	4	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	32 *70,548*	70 *44*	15 *49.2*	M2	T8	N/A
Erfurt	Duewag	MGT6D	Bo'1'1'Bo'	4	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	32 *70,548*	70 *44*	15 *49.2*	M2	T8	N/A
Halle	Duewag	MGT6D	Bo'1'1'Bo'	14	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	32 *70,548*	70 *44*	15 *49.2*	M2	T8	1992
Heidelberg	Duewag	MGT6D	Bo'1'1'Bo'	12	63%	28.9 *94.9*	2.3 *7.5*	540 *21.3*	350 *13.8*	31.5 *69,446*	70 *44*	15 *49.2*	M2	T8	1994
Mulheim	Duewag	MGT6D	Bo'1'1'Bo'	4	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	32 *70,548*	70 *44*	15 *49.2*	M2	T8	N/A
Kassel/ KVG	Duewag	NGT6C	B'1'1'B'	25	70%	28.8 *94.3*	2.3 *7.5*	700 *27.6*	350 *13.8*	30.2 *66,580*	70 *44*	15 *49.2*	M1	T8	1990
Bonn	Duewag	NGT6D	Bo'1'1'Bo'	24	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	31.5 *69,446*	70 *44*	15 *49.2*	M2	T8	1994
Dusseldorf	Duewag	NGT6D	Bo'1'1'Bo'	10	65%	28.6 *93.9*	2.3 *7.5*	560 *22*	350 *13.8*	31.5 *69,446*	70 *44*	15 *49.2*	M2	T8	N/A

Sum of Category 2 Cars Ordered 954

* See glossary for definitions

TABLE 7 Summary of Category-1, Category-2, and Category-3 LF-LRVs (continued)

Category–3 Low Floor LRVs

City	Builder	Type	Axle Arrangement*	Number of Cars	% Low Floor	Car Length (m *ft*)	Car Width (m *ft*)	Floor Height Max (mm *in*)	Floor Height Min (mm *in*)	Weight (tonne *lbs*)	Max Speed (km/h *mph*)	Min Curve Radius (m, *ft*)	Running Gear Type Power	Running Gear Type Trailer	First Car
Power Gear: Unknown															
Prototype (Turin)	Firema	Prototype	Bo'2'Bo'	1	100%	22.2 *72.8*	2.3 *7.5*	350 *13.8*	350 *13.8*	24 *52,911*	90 *56*	N/A		T3	N/A
Power Gear: Independent wheels mounted on radial-arm axleboxes driven by motor via parallel gears															
Strasbourg	ABB (Socimi)	Eurotram	BoBoBo2	26	100%	32.5 *106.6*	2.4 *7.9*	350 *13.8*	350 *13.8*	29 *63,934*	60 *37*	N/A	M10	T3	1994
Prototype (Rome)	Socimi	N/A	BoBoBo	1	100%	22.0 *72.2*	2.4 *7.9*	350 *13.8*	350 *13.8*	25 *55,116*	60 *37*	25 *82*	M10		1992
Prototype (Milan)	Socimi	S-350LRV	Bo'Bo'	1	100%	14.0 *45.9*	2.4 *7.9*	350 *13.8*	350 *13.8*	10.5 *23,149*	70 *44*	15 *49.2*	M10		1989
Power Gear: Independent wheels, one pair driven, one pair free-wheeling															
Augsburg	AEG (MAN)	GT6M	1A'A1'A1'	1	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	29.6 *65,257*	70 *44*	15 *49.2*	M3		1993
Berlin	AEG (MAN)	GT6N	1A'A1'A1'	120	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		1994
Braunschweig	AEG (MAN)	GT6N	1A'A1'A1'	11	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		N/A
Bremen	AEG (MAN)	GT6N	1A'A1'A1'	18	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		1990
Frankfurt-an-der-Oder	AEG (MAN)	GT6N	1A'A1'A1'	13	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		N/A
Halle	AEG (MAN)	GT6N	1A'A1'A1'	1	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		N/A
Munich	AEG (MAN)	GT6N	1A'A1'A1'	70	100%	27.3 *89.6*	2.3 *7.5*	350 *13.8*	300 *11.8*	29.4 *64,816*	70 *44*	15 *49.2*	M3		1994
Zwickau	AEG (MAN)	GT6N	1A'A1'A1'	12	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	26.8 *59,084*	70 *44*	15 *49.2*	M3		N/A
Munich	AEG (MAN)	GT6N/ R1.1	1A'A1'A1'	3	100%	26.5 *86.9*	2.3 *7.5*	350 *13.8*	300 *11.8*	29.5 *65,036*	70 *44*	15 *49.2*	M3		1990
Bremen	AEG (MAN)	GT8N	1A'1A'1A'1A'	61	100%	35.0 *114.8*	2.3 *7.5*	350 *13.8*	300 *11.8*	34 *74,957*	70 *44*	15 *49.2*	M3		1993
Jena	AEG (MAN)	GT8N	1A'1A'1A'1A'	10	100%	35.0 *114.8*	2.3 *7.5*	350 *13.8*	300 *11.8*	34 *74,957*	70 *44*	15 *49.2*	M3		N/A
Power Gear: Transverse-mounted motor drives both axles through parallel gears and cardan shaft															
Lille	Breda	VLC	B'1 1 1 B'	24	80%	29.9 *98.1*	2.4 *7.9*	950 *37.4*	350 *13.8*	40 *88,185*	70 *44*	25 *82*	M4	T4	1993
Prototype (Rome)	Breda	VLC	B'1 1 B'	1	75%	22.0 *72.2*	2.5 *8.2*	950 *37 4*	350 *13.8*	22 *48,502*	70 *44*	20 *65.6*	M4	T4	1990

* See glossary for definitions

TABLE 7 Summary of Category-1, Category-2, and Category-3 LF-LRVs (continued)

Category–3 Low Floor LRVs

City	Builder	Type	Axle Arrangement*	Number of Cars	% Low Floor	Car Length (m *ft*)	Car Width (m *ft*)	Floor Height Max (mm *in*)	Floor Height Min (mm *in*)	Weight (tonne *lbs*)	Max Speed (km/h *mph*)	Min Curve Radius (m,*ft*)	Running Gear Type Power	Running Gear Type Trailer	First Car
Power Gear: Motored EEF self-steering wheelset															
Mannheim/ MVG	German Consortium	dGTW-ER	A'A'A'1'	1	100%	26.7 *87.6*	2.3 *7.5*	350 *13.8*	290 *11.4*	23.98 *52,867*	70 *44*	15 *49.2*	M5	T8	1991
Dusseldorf/ RBG	German Consortium	GTW-ER	A'A'1'	1	100%	20.2 *66.2*	2.4 *7.9*	350 *13.8*	290 *11.4*	17.75 *39,132*	70 *44*	18 *59.1*	M5	T8	1991
Bonn/SWB	German Consortium	GTW-ZR	A'A'1'	1	100%	20.2 *66.2*	2.4 *7.9*	350 *13.8*	290 *11.4*	18.56 *40,918*	70 *44*	18 *59.1*	M5	T8	1991
Power Gear: Articulated truck frame, two large hub motor-driven wheels, two small guiding wheels															
Prototype	Bombardier (BN)	LRV2000	A'1'1'A'1'A'	1	100%	20.2 *66.3*	2.5 *8.1*	350 *13.8*	350 *13.8*	24 *52,911*	70 *44*	N/A	M6		1990
Brussels	Bombardier (BN)	TRAM2000	A'1'Bo1'A'	51	100%	22.8 *74.8*	2.3 *7.5*	350 *13.8*	350 *13.8*	31.9 *70,328*	70 *44*	17.5 *57.4*	M6		1994
Power Gear: Four hub motor-driven, independent wheels															
Chemnitz	ABB Henschel	6NGT/ Variotram	Bo'2'Bo'	53	100%	30.9 *101.4*	2.7 *8.7*	350 *13.8*	290 *11.4*	28.3 *62,391*	70 *44*	18 *59.1*	M7	T3	1993
Wurzburg	LHB	GTW	Bo'Bo'Bo'	20	100%	29.1 *95.5*	2.4 *7.9*	350 *13.8*	300 *11.8*	35 *77,162*	80 *50*	N/A	M7		N/A
Frankfurt am Main	Duewag	R3.1	Bo'2'Bo'	20	100%	27.2 *89.2*	2.4 *7.7*	350 *13.8*	300 *11.8*	33 *72,753*	70 *44*	18 *59.1*	M7	T3	1993
Power Gear: Motor drives wheels on one side via cardan shafts															
Prototype	Schindler (SIG)	Cobra 370	A'A'A'A'	1	100%	24.5 *80.4*	2.3 *7.5*	370 *14.6*	320 *12.6*	25 *55,116*	65 *40*	11.8 *38.7*	M8		1993
Power Gear: Vertically mounted motors driving independent wheels built into articulation portal															
Vienna "A"	SGP	ULF197-4	1A'A'A'1	100	100%	23.6 *77.5*	2.4 *7.9*	197 *7.8*	197 *7.8*	23 *50,706*	70 *44*	18 *59.1*	M9	T7	1995
Vienna "A" Prototype	SGP	ULF197-4	1'A'A'A'1	1	100%	23.6 *77.5*	2.4 *7.9*	197 *7.8*	197 *7.8*	23 *50,706*	70 *44*	18 *59.1*	M9	T7	1994
Vienna "B"	SGP	ULF197-6	1'A'A'A'A'1'	50	100%	34.9 *114.4*	2.4 *7.9*	197 *7.8*	197 *7.8*	32.5 *71,650*	70 *44*	18 *59.1*	M9	T7	1995
Vienna "B" Prototype	SGP	ULF197-6	1'A'A'A'A'1	1	100%	34.9 *114.4*	2.4 *7.9*	197 *7.8*	197 *7.8*	32.5 *71,650*	70 *44*	18 *59.1*	M9	T7	1994

Sum of Category 3 Cars Ordered 675

* See glossary for definitions

to a low-floor area. The high-floor areas at the outer ends and center of the vehicle are accessed by interior steps. The advantage of this vehicle over the Wurzburg-type is increased low-floor area that can be accessed at every entrance door. The disadvantages are that the low-floor area is still small (compared to Category-2 and Category-3 vehicles) and discontinuous, being separated by the central high-floor section.

Category-2 Vehicles

Category-2 vehicles have conventional motor trucks at each end with either small wheel trailer trucks or independently rotating wheel running gear between motor trucks. Generally, Category-2 vehicles have 50 to 75 percent uninterrupted low-floor area between motor trucks. Unlike some of the vehicles in Category 1, it is not possible to have all axles motored. Consequently, the vehicles may have somewhat lower specific power. Three types of Category-2 vehicles are described in the following paragraphs.

Geneva/Bern-Type Be4/6 and Be 4/8 LF-LRVs. The city of Geneva, Switzerland, operates a total of 46 six-axle (Be 4/6) LF-LRVs, supplied between 1984 and 1990 by Duewag of Germany (Figures 20 through 24). The vehicles have two sections with conventional Duewag monomotor trucks, driven by DC traction motors at the outer ends. The articulation joint connecting them rides on a compact, two-axle trailer truck, using small wheel technology supplied by Vevey. The small diameter of the wheels permits the floor of the intermediate section to be completely at low level and the vehicle has a 60 percent low-floor area. The advantage of this design is a much greater and continuous low-floor area. The disadvantage is that internal steps are still necessary to reach the high-floor area at the car ends. All vehicle equipment is located at roof level.

The city of Bern, Switzerland, operates a fleet of 12 similar vehicles—designated Be 4/8. These vehicles, delivered between 1989 and 1990, are 31 m (102 ft) long. The difference between the Be4/6 and Be4/8 vehicles is that the Be4/8 has a longer intermediate section that rides on two, two-axle small wheel trucks. This longer intermediate section provides additional low-floor area, increasing the proportion of low-floor area to 73 percent.

Grenoble, Rouen, and Paris. The cities of Grenoble, Rouen, and Paris in France operate a total of 75 six-axle LF-LRVs. These vehicles are shown in Figures 25 through 31. The vehicles were supplied by GEC-Alsthom and were delivered between 1987 and 1993. The vehicles have three sections and are 29.4 m (96.5 ft) long. The two outer motor trucks are conventional monomotor design, driven by chopper-controlled DC traction motors. The short middle section rides on a low-transom trailer truck with two cranked axles, giving a cavity between the independently rotating wheels and thereby enabling the low-floor gangway to run in between them. The wheels on the trailer axles are the same size as those on the motored trucks. Longitudinal seats are placed along the sides of the middle section to provide space under them for the trailer wheels, which are higher than the low floor. Most vehicle equipment is located at roof level. The proportion of low-floor area achieved is 65 percent. The advantage of this design is the increased, uninterrupted floor area. However, it is still necessary to have a high-floor area above the motored trucks. The vehicle is equipped with small powered ramps (Figure 32). When deployed, the ramps bridge the gap between the vehicle's low floor, which is 345 mm (13.6 in) above TOR, and the lowstation platforms.

Kassel Transit Authority Type NGT 6C. The city of Kassel, Germany, operates 25 LF-LRVs (Figures 33 through 37). The vehicles were supplied by Duewag with Siemens and AEG-Westinghouse electrical equipment and were delivered beginning in 1990. The vehicles are 28.75 m (94 ft) long and comprise three sections. The outer sections ride on conventional two-axle monomotor trucks with DC traction motors. The intermediate section rides on two independent self-steering EEF

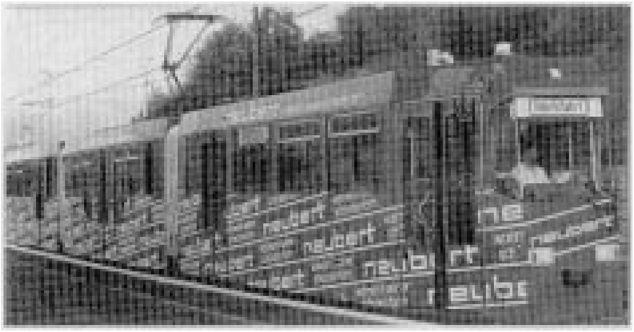


Figure 18. Wurzburg-type GT8/8C LF-LRV.

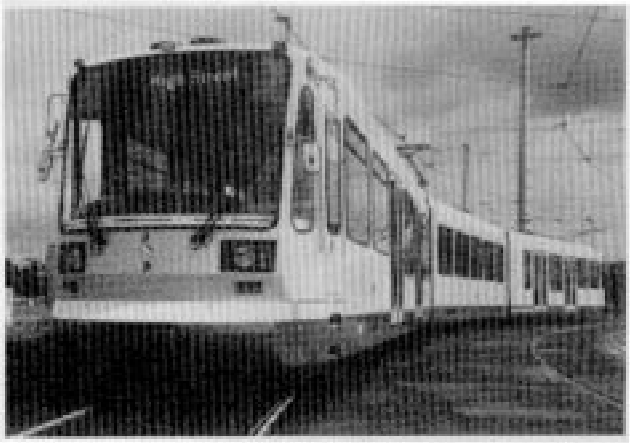


Figure 19. Sheffield "Supertram" LF-LRV (photo).

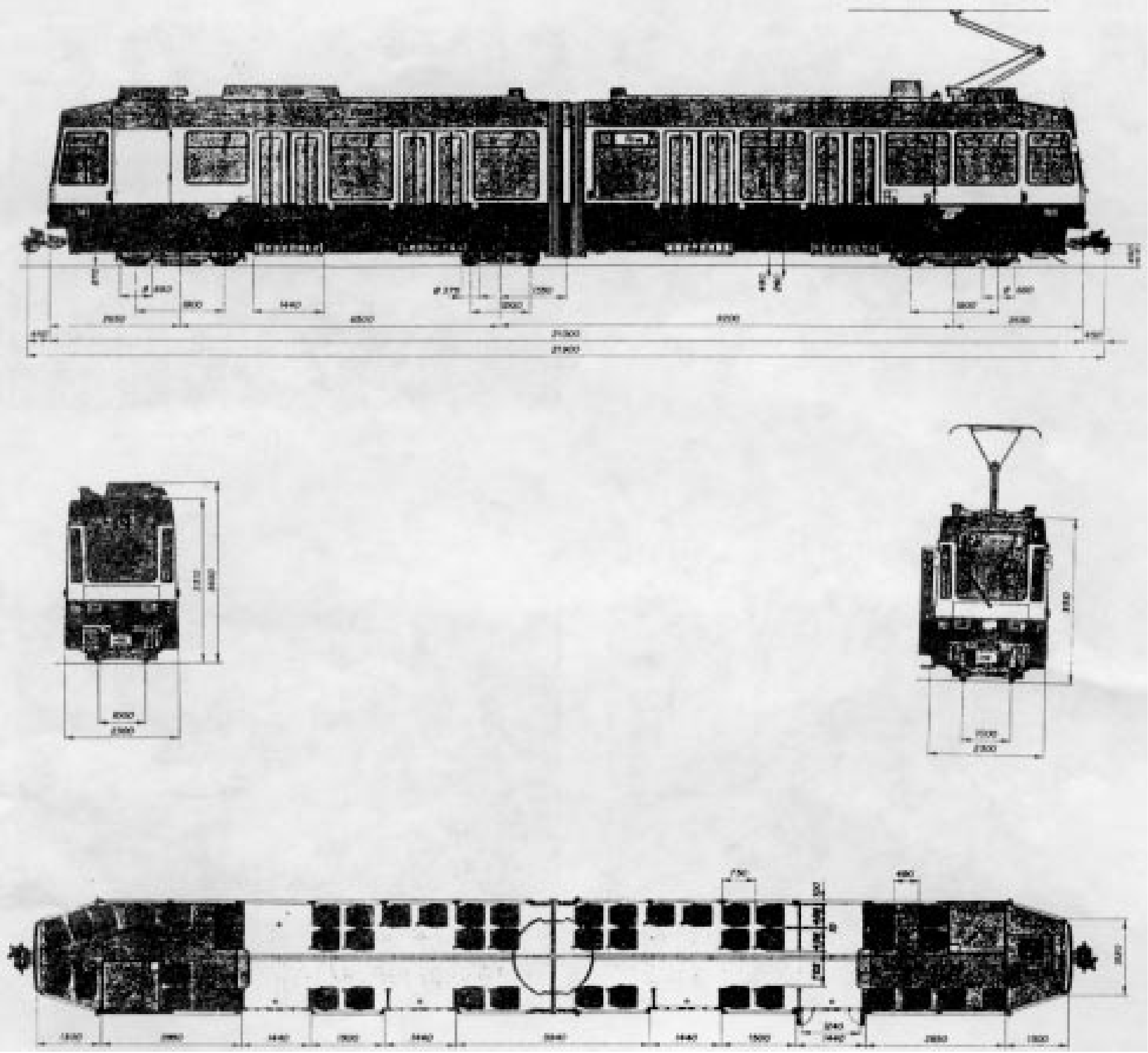


Figure 20. Geneva-type Be4/6 LF-LRV (schematic).

wheelsets. This arrangement minimizes the intrusion of the EEF wheels into the passenger compartment, providing a continuous low-floor area of 70 percent that is 350 mm (13.8 in) above TOR, with entrance thresholds at 290 mm (11.4 in) above TOR. The high floor above the motor trucks is 720 mm (28.3 in) above TOR. All equipment is located at roof level.

The EEF wheelsets are manufactured by BSI and equipped with resilient wheels (Figures 38, 39, and 40). These were developed from experimental prototypes, which were tested in service, and provide very good ride quality with improved reliability.

Duewag has also built a bidirectional variant of the NGT 6C for the city of Bochum, which is driven by smaller AC motors fitted in very compact, meter-gauge, bimotor trucks (Figure 41). The floor over these end motor trucks is only 590 mm (23.3 in) above TOR.

Category-3 Vehicles

Category-3 vehicles have innovative motored and trailing running gear, up to 100 percent low-floor areas, and low-level entrances throughout the vehicle. Five types of Category-3 vehicles are described in the following paragraphs.

Bremen GT8N. The city of Bremen, Germany, has ordered 61, eight-axle LF-LRVs from AEG (MAN), which are currently being delivered (Figures 42 and 43). The vehicles are 35 m (115 ft) long and comprise four sections. Each section rides on a centrally located truck—which has four independently rotating wheels —although one pair is torsionally connected by the drive train that powers two of the wheels in each truck (Figure 44). The trucks have neither bolsters nor axles, with

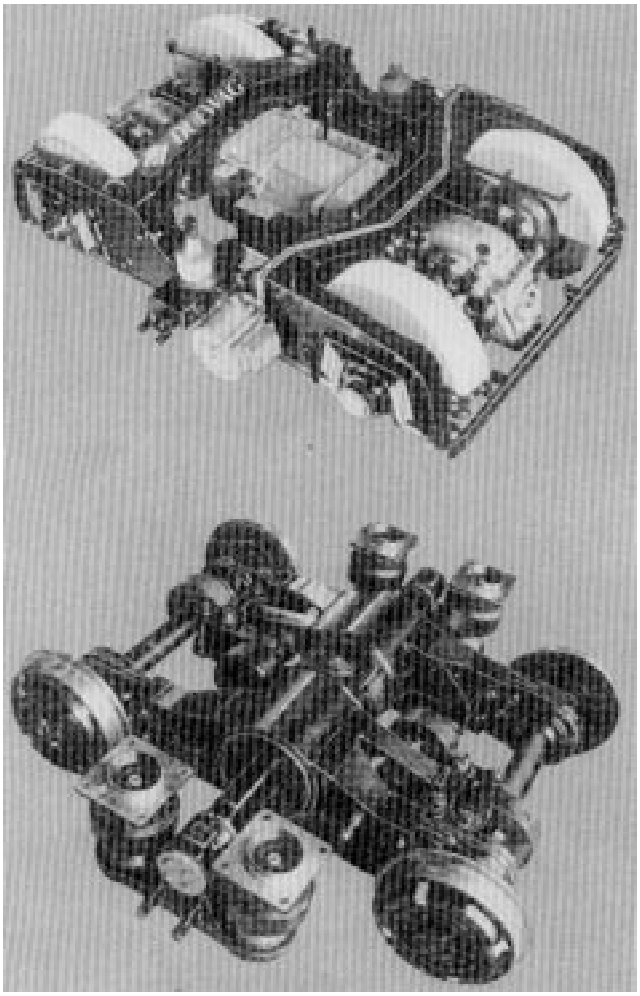


Figure 21. *Geneva-type Be4/6 LF-LRV trucks.*

Figure 22. *Bern-type Be4/6 LF-LRV (photo).*

Figure 23. *Bern-type Be4/6 LF-LRV (interior view).*

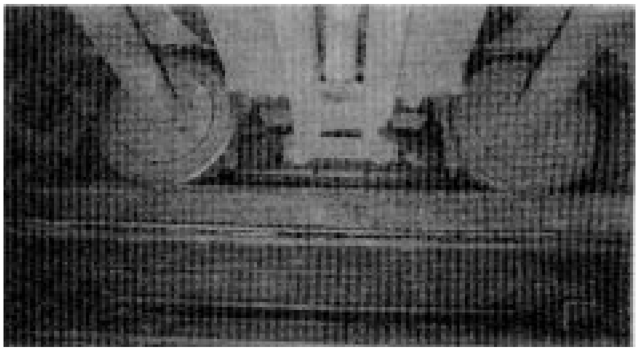


Figure 24. *Bern-type Be4/8 LF-LRV (view of small wheels trailer truck).*

the space between the wheels accommodating low-floor aisles. Although this is a 100 percent LF-LRV, the aisles may be too narrow to permit wheelchairs to pass from end to end.

The trucks have two-stage suspensions with air springs providing the secondary stage. Truck yaw relative to the carbody is enabled by the shearing flexibility of the air springs, but this has limits. It is not a constraint on ordinary curves down to 15-m (62-ft) minimum radius, because the truck swivel is small. However, the ability of this type of vehicle to negotiate short radius reverse curves needs careful analysis.

A single water-cooled AC traction motor, longitudinally and resiliently mounted below each carbody section, propels a pair of wheels on each truck via a cardan shaft, two gearboxes, and a cross-shaft (Figure 44).

A three-truck, three-section version designated GT6N, which is otherwise identical, has been ordered by eight German cities, including Munich. The total number of GT6N and GT8N currently in service or on order is 226, making this type the most popular Category-3 vehicle.

Figure 25. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV (photo—view at station); (photo—view outside city).

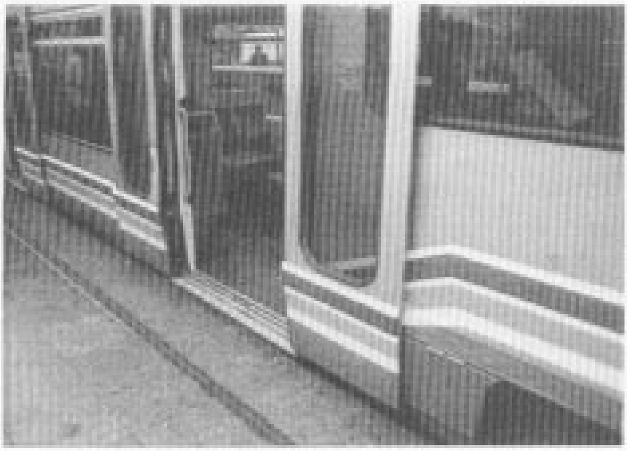


Figure 26. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV interface with station platform.

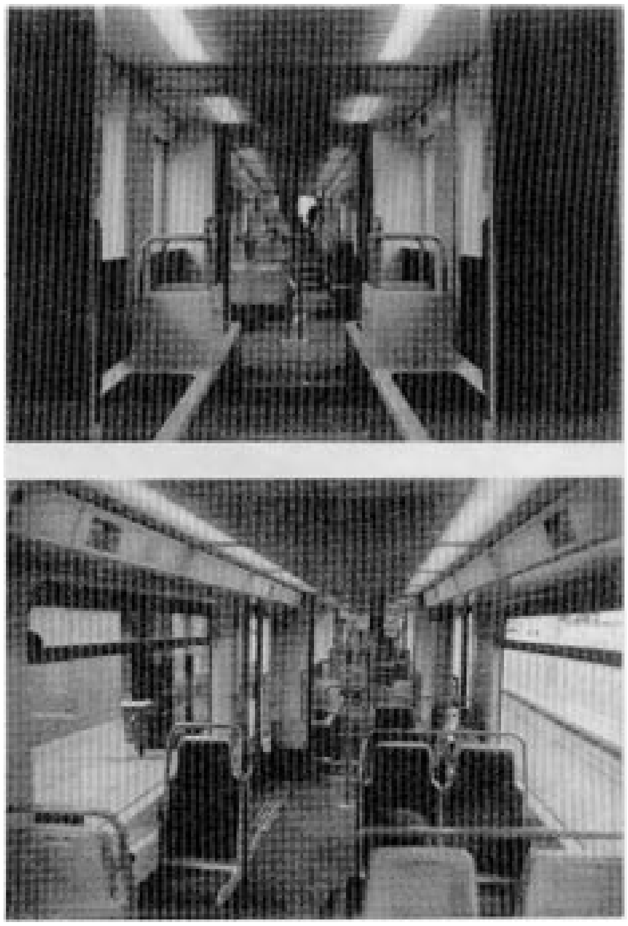


Figure 27. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV (photo—interior view).

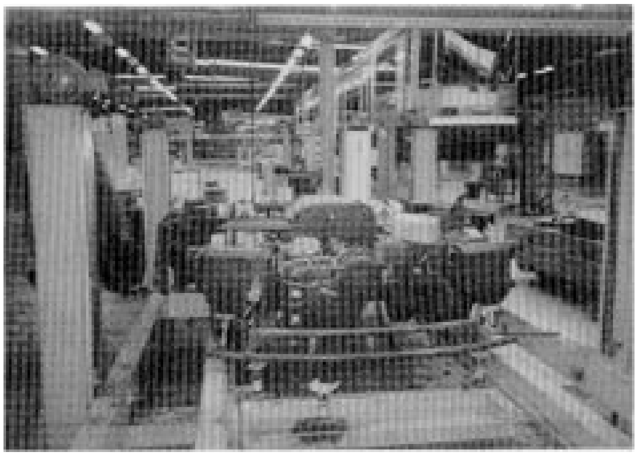


Figure 28. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV trucks (photo).

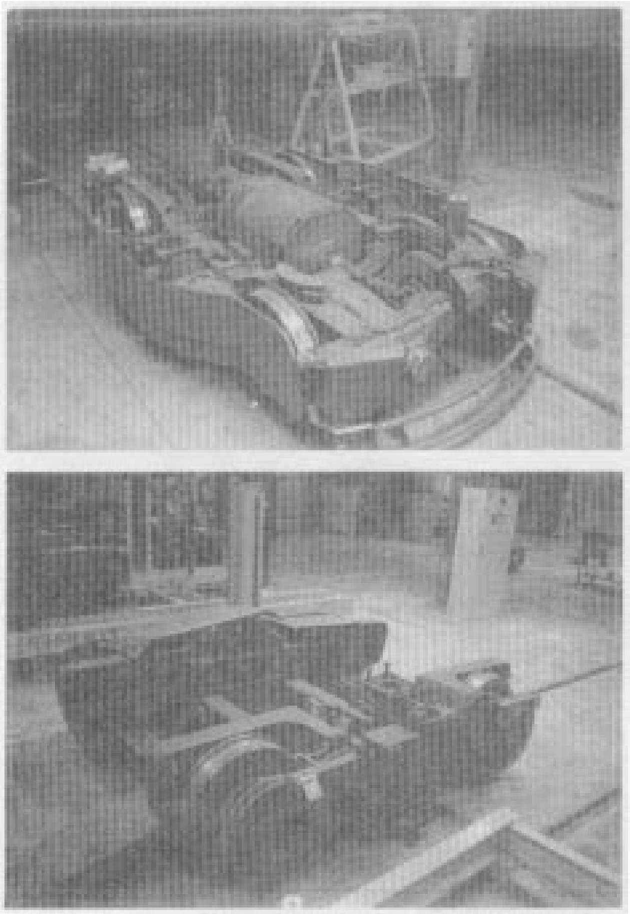


Figure 29. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV power and center truck (photo).

Figure 30. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV access to truck components from shop pit (photo).

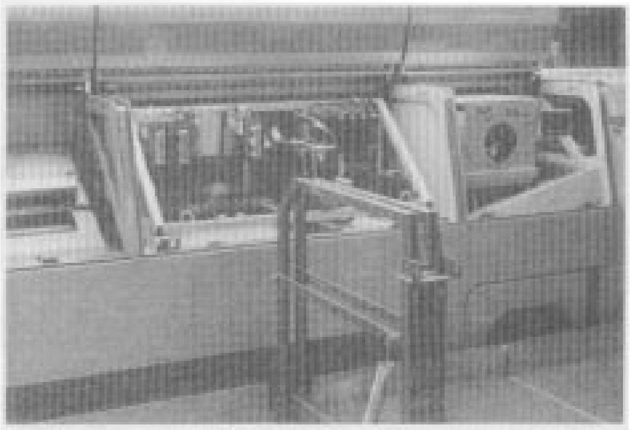


Figure 31. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV access to truck components (photo).

Figure 32. Grenoble/Rouen/Paris GEC-Alsthom LF-LRV powered ramp (photo).

Figure 33. Kassel Transit Authority type NGT 6C (photo—at station).

Figure 34. Kassel Transit Authority type NGT 6C (photo — interior view).

Figure 35. Kassel Transit Authority type NGT 6C (photo—doors open at station).

Vienna Type ULF 197. The city of Vienna, Austria, has ordered 150 "ultra" LF-LRVs from a consortium of SGP Verkehrstechnik, Elin, and Siemens of Austria. The prototype is shown in Figure 45. The vehicles are designed on a modular basis and do not use conventional trucks but locate the drive and wheel guidance equipment in the sidewalls of the vehicle articulation (Figure 46). Each independent wheelset is driven by a vertically mounted, water-cooled AC motor on each side of the articulation. This unique design concept has been called Ultra Low Floor because it provides 100 percent low-floor area at a height of 197 mm (7.8 in), with entrance thresholds at 152 mm (6 in) above TOR.

The advantage of this extremely low-floor vehicle is its easier access from street level. However, there is risk inherent in the extremely innovative technology, which includes

- An active motor torque control to electrically couple the independently rotating wheels, for guidance on straight track;
- A system of linkages connecting the articulation portals for steering on curved track; and
- A pendulum suspension with hydraulic leveling.

Variotram. The Variotram (Figures 47 and 48), manufactured by ABB (Henschel-Waggon Union) has just entered service in the city of Chemnitz, which has ordered 53 of these 100 percent LF-LRVs. It has a low-floor level of 350 mm (13.8 in), with entrance thresholds at 290 mm (11.4 in) above TOR. Like many Category-3 LF-LRVs, the Variotram is a flexible modular concept intended to provide different capacities to suit any application. It can be produced in lengths from 20 m (66 ft) to 60 m (200 ft); widths of 2.3 m (7.5 ft) to 2.65 m (8.7 ft); with either meter gauge or standard (4 ft 8.5 in) gauge trucks, which can all be powered if required; and with air conditioning.

The Variotram has also been engineered to fit within approximately the same dynamic envelope as PCC cars and can negotiate horizontal curves down to 16 m (52.6 ft) radius. The Variotram's powered trucks are propelled by four water-cooled AC hub motors, directly driving each of the independently rotating wheels. The advantages and disadvantages of this direct drive are discussed later in this chapter.

Duewag has manufactured 20 LF-LRVs of similar design, the R3.1 for Frankfurt, which has a truck in the middle of each of three carbody sections (Figure 49).

Figure 36. Kassel Transit Authority type NGT 6C (photo—fare collection).

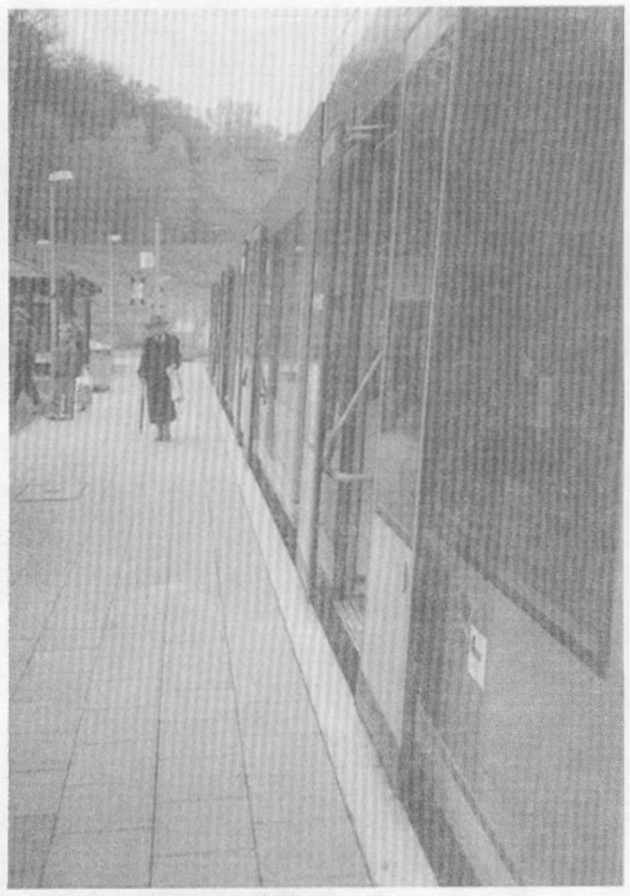


Figure 37. Kassel Transit Authority type NGT 6C (photo—at station).

Eurotram. The Eurotram (Figures 50 and 51) is assembled by ABB Transportation, Ltd., in the U.K., with ABB Trazione SPA in Italy supplying various parts. It was derived from the Socimi prototypes (see Chapter 1) and 26 of these 100 percent LF-LRVs have been ordered by Strasbourg for delivery in 1994. Eurotram is another flexible modular concept. For example, the Strasbourg vehicle is assembled as follows:

- two each, 2,575-mm (8.4-ft) long cab modules at each end;
- three each, 7,550-mm (24.8-ft) long passenger compartments; and
- two each, 2,350-mm (7.7-ft) long articulation sections between the passenger compartments.

The total length is 33.1 m (108.6 ft). The Eurotram is designed to interface with 240-mm (9.5-in) high platforms, with a 110-mm (4.3-in) step up to its 350-mm (13.8-in) low-floor level. The center doors are equipped with powered wheelchair ramps.

The Eurotram has large side windows and a huge compound curved windshield. All roof-mounted equipment is covered by glass reinforced plastic (GRP) panels to maintain a sleek appearance. The carbody frame is made of welded aluminum extrusions covered with removable GRP panels.

The Eurotram's motored and trailer trucks have four independently rotating wheels mounted on a rigid frame truck. The motored wheels are driven by water-cooled, truck frame-mounted, AC squirrel cage motors via parallel drive gearboxes. The truck features air spring secondary and radial arm wheel suspension, using rubber primary springs. The design permits a small wheel base, which the manufacturer claims has good curving characteristics.

VLC. The VLC (Figure 52) manufactured by Breda in Italy, is another modular concept vehicle. However, it is not strictly a 100 percent low-floor vehicle. The end modules ride on a compact, but unconventional monomotor truck, and have a high-floor cab and electric locker compartments 950 mm (37.4 in) above TOR. The passenger compartment floor is continuous at a low level of 350 mm (13.8 in) above TOR. The city of Lille, France, has ordered 24 four-module, triple-articulated, 29.9-m (98.1-ft) long vehicles of this type. The low floor in the Lille configuration comprises 80 percent of the total length.

The powered trucks are unique. Each is driven by a single,

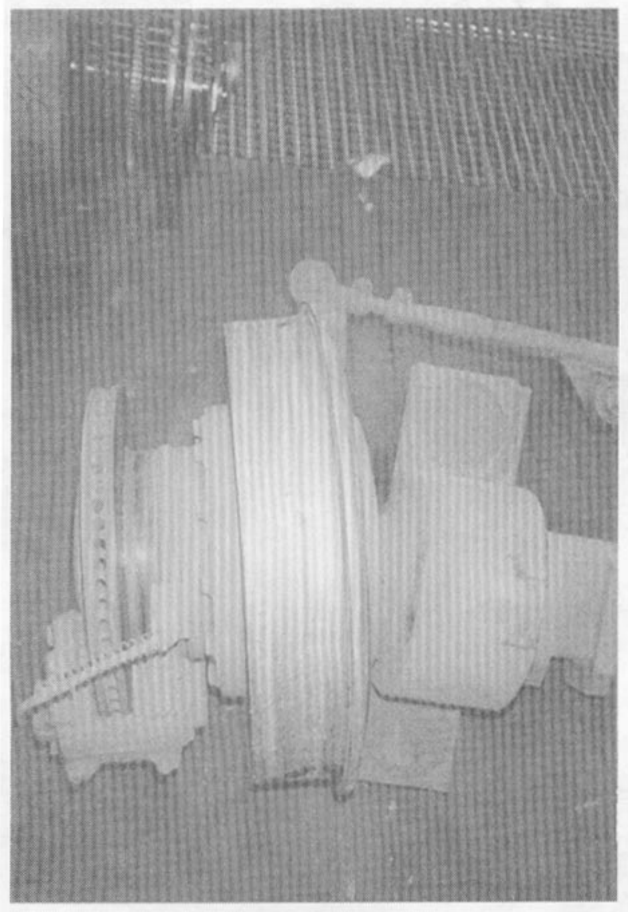


Figure 38. Kassel Transit Authority type NGT 6C LF-LRV with EEF wheelsets manufactured by BSI.

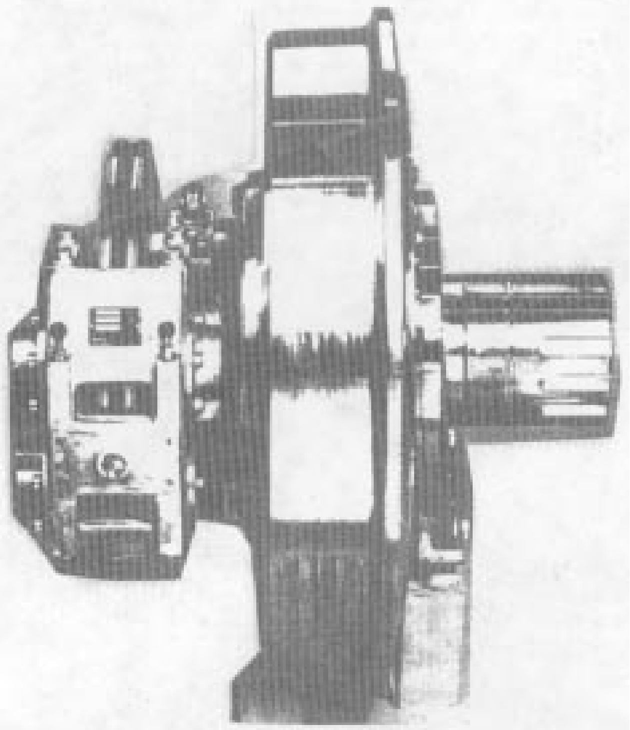


Figure 39. Kassel Transit Authority type NGT 6C LF-LRV with EEF wheelsets and resilient wheels.

transversely mounted, AC asynchronous monomotor driving two conventional wheel-axle assemblies (Figure 53). The single wheelset trailer running gear (Figure 54) supports each articulation section and comprises two independently rotating wheels that are set tangential to the rail on curved track. The trailer running gear is effectively steered by the articulation and, together with the very short wheel base of the power trucks, gives good curving ability down to a minimum horizontal radius of 25 m (82 ft).

The welded aluminum framed carbody is covered by boltedon aluminum side panel extrusions. The ends are made of structural composite material. The structure is capable of withstanding an unusually high buff load (for a European LRV) of 50 tonnes (110,000 lb).

NEW TECHNOLOGY DESCRIPTION AND ASSESSMENT

Low-floor areas in excess of 48 percent have been achieved in Category-2 and Category-3 vehicles by using innovative running gear based on either small wheels or independently rotating wheels. The state of the art has advanced to a point where independently rotating wheels can be motored and/or arranged to be self-steering or forced steered by a variety of methods.

This section briefly describes and assesses the different running gear designs and constructions currently being used in Category-2 and Category-3 vehicles, with particular emphasis on wheelsets and guidance; propulsion, motors, and gearboxes; suspensions; ramps and lifts; and carbody construction and materials.

Since most of this technology is in its infancy, the research found limited, objective reliability and maintainability records that could be used to quantify operating costs. Anecdotal information is cited, when available; otherwise, the assessment is based on fundamental principles.

Small Wheels

The simplest way to achieve a low floor is to reduce the wheel diameter and thereby lower the height of the straight axle that connects the wheels. The advantages of this approach include the following:

- The self-steering characteristics of the conventional wheelset are maintained. It can be shown theoretically that the centering action is more powerful. (*7*)
- Unsprung mass, which determines the vertical wheel/rail interaction dynamic forces, is dramatically reduced; thereby significantly decreasing the vibrations and shocks experienced by both running gear and rail.
- Small wheelsets are cheaper.
- A mini-conventional trailer truck can be made (Figure

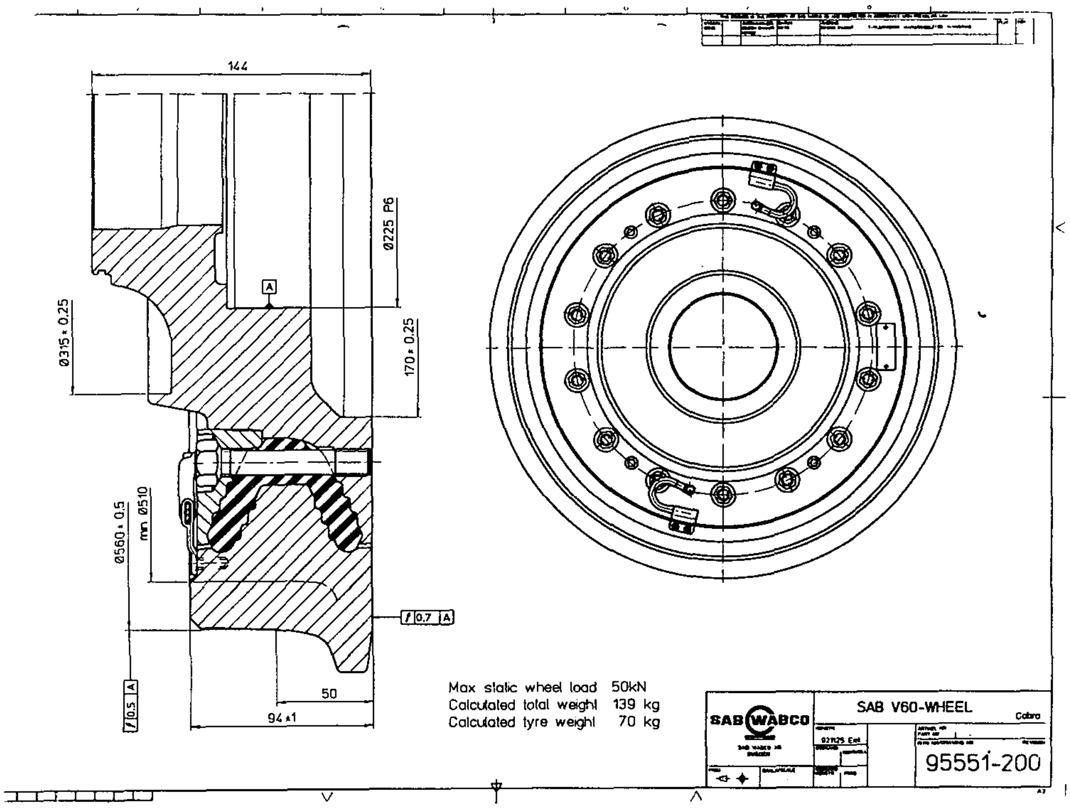
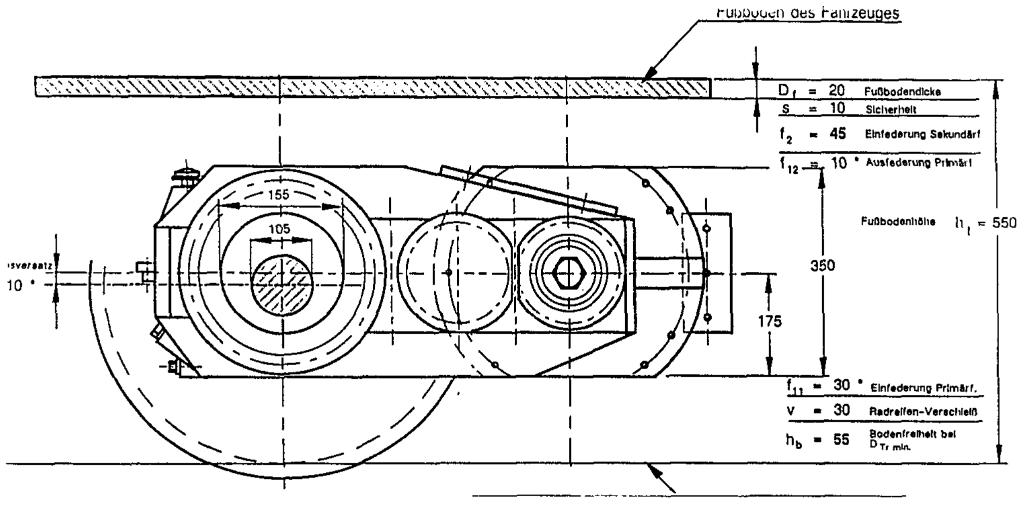


Figure 40. Kassel Transit Authority type NGT 6C LF-LRV with EEF wheelsets and resilient wheels.



LOW PROFILE POWER TRUCK- BOCHUM SOLUTION-

Car floor height, new	**550 mm**	**(21.65 inches)**
Wheel dia. new/worn	**560/500 mm**	**(22/20 inches)**
Fully suspended motor/gear/disc brake		

Figure 41. City of Bochum type NGT 6C LF-LRV with bimotor truck.

Figure 42. Bremen GT8N LF-LRV from AEG (MAN)—photo at station.

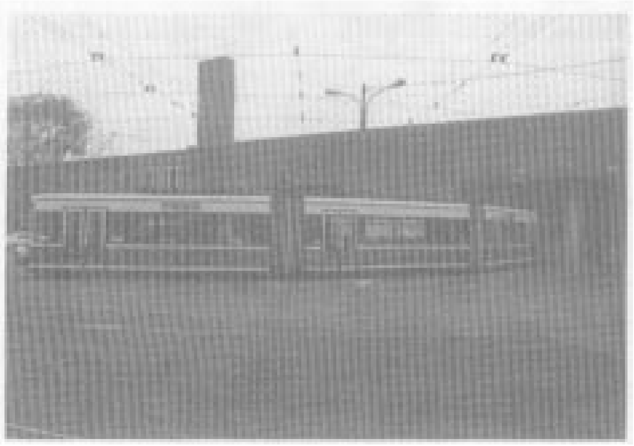


Figure 43. Bremen GT8N LF-LRV from AEG (MAN)—photo.

55) with both primary and secondary suspensions, similar to conventional trucks.

In addition, theoretical analysis done by Vevey (*8*), the principal exponent of this technology, demonstrates that small wheels have the same or slightly less risk of derailment than conventional wheels.

The main concern with small wheels was perceived to be reduced wear life (and therefore increased maintenance costs) as a result of

- Higher contact stresses;
- A greater number of revolutions turned in a given distance; and
- The small radial material depth available for wear and truing to correct flat spots and other tread damage.

In practice, however, the wear rates have not been significantly different from those obtained with standard wheels:

- Vevey reports (*9*) 4-mm (5/32-in) radial wear after 83,000 km (52,000 miles) running in Bern.
- Re-profiling of small wheels is done at intervals of 100,000 km (62,500 miles) in Geneva and 120,000 km (75,000 miles) in Bern.
- Wheel replacement is reported (*9*) to be required after 250,000 km (156,000 miles) in Bern, and 120,000 km (75,000 miles) in Geneva; however, Vevey indicates that machining techniques are likely responsible for the latter.

Furthermore, it can be argued that

- The increased static contact stress experienced by small wheels is offset by the reduced dynamic wheel/rail forces.
- The smaller wheel base of the trucks and the somewhat more powerful steering action of the smaller wheels, should reduce flange contact and lateral slip during curve negotiation.
- The composition of the steel used in the wheels can be adjusted to improve wear properties, further mitigating the effect of higher contact stress. Vevey has done this with evidently satisfactory results.
- Optimizing the longitudinal primary suspension and using wheel flange lubricators can further improve curve negotiation behavior.

Therefore, it appears that the use of small wheels on trailer trucks or on single-axle trailers should give satisfactory operation. Maintenance costs should be lower than conventional trailer trucks because, as Figures 56 and 57 demonstrate, the removal and replacement of the small wheelset is easy to accomplish by lifting the carbody 560 mm (22 in). The wheelset can then be removed for machining on an ordinary lathe in approximately 20 min.

Small wheels that are driven have not been used on any low-floor vehicle. They are too small for the hub motor, and propulsion via a gearbox does not appear to be feasible.

Independently Rotating Four-Wheel Trailer Trucks

The best known vehicle that uses this type of trailer truck is the Grenoble Car. On this vehicle, the independently rotating wheels are mounted on a cranked axle, which provides the following advantages:

- Accurately fixes the back-to-back dimension of the wheels;
- Allows the use of a primary suspension between the cranked axle and the truck frame, similar to conventional trucks; and
- Maintains the left wheel parallel to the right wheel—if one wheel runs tangent to the rail, so will its mate.

On other types of vehicles that use independently rotating wheels—for example the Fiat (Firema) LF-LRV in Turin—the wheels are mounted directly to the truck frame. On other types of vehicles (e.g., the Eurotram), a stub axle is used. In

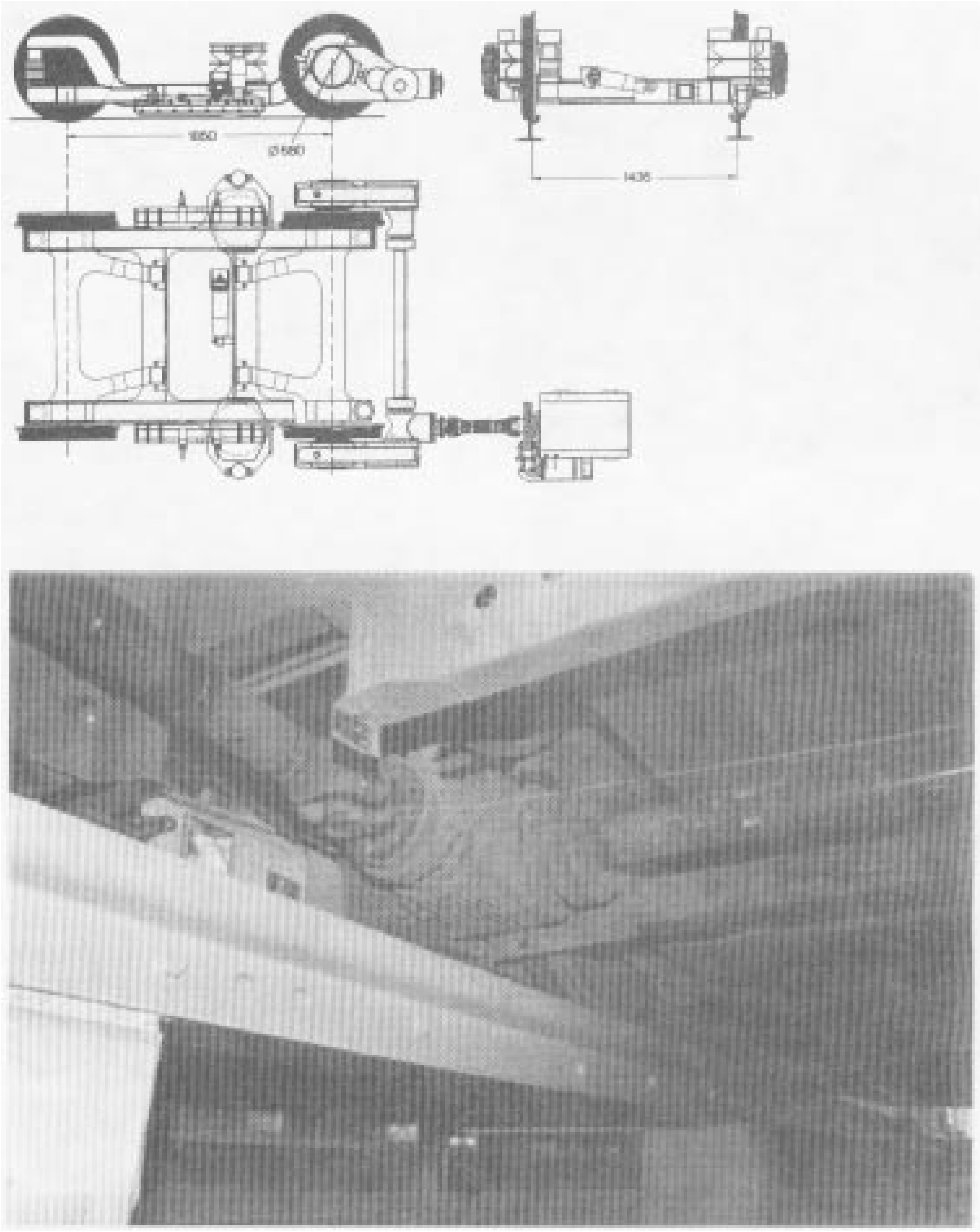


Figure 44. Bremen GT8N LF-LRV from AEG (MAN) truck and wheels.

all cases, a bearing is required in the wheel hub or the truck frame to permit the wheel to rotate freely.

If the treads of the four independently rotating wheels are curved or sharply profiled (such that the diameter increases towards the wheel flange) and they are maintained in good alignment, they will provide a small restoring moment to center the truck on straight track—as conventional wheels do. The wheels generally run on an angle of attack to the rail in curves, which designers attempt to minimize by reducing the truck wheel base as much as possible. The angle of attack causes the wheel to slip laterally across the rail, which generates lateral forces that are greater than in conventional (coupled) wheelsets, thereby exacerbating wheel and rail wear.

Another disadvantage of independently rotating wheels is that there is no possibility for tractive effort-sharing between the left and right wheels. Independently rotating wheels are more prone to spin when driven and slide when braked because of the high variability in adhesion, which is "averaged" in conventional coupled wheels by the axle that connects them. Therefore, it is essential to equip vehicles that use independently rotating wheels with efficient, quick-response, spin-slide controls.

The use of independently rotating wheels on the Grenoble Car since 1987 has been satisfactory (*5*), with a reported (*7*) wheel life of 250,000 km (156,000 miles). Since this type of truck retains most of the advantages of conventional trailer

Figure 45. Vienna type ULF 197 prototype LF-LRV.

Figure 46. Vienna type ULF 197 LF-LRV power portal.

trucks (with two conventional wheelsets), it will continue to be used in both Category-2 and Category-3 vehicles for the foreseeable future.

Force-Steered Single-Axle (Conventional Wheelset) Trailer Trucks

The force-steered single-axle trailer truck concept is shown in Figure 58. It consists of a single, conventional wheelset that is assembled from two, 590-mm (23.2-in) diameter profiled wheels, press-fitted on a solid straight axle with outboard axle bearings and brake discs. In addition, it has the following characteristics:

- A hollow-section, welded-steel truck frame;
- Chevron primary suspension;
- Coil-spring secondary suspension; and
- A steering linkage that connects the truck frame to the adjacent floating articulation and causes the axle to adopt a radial alignment on curved track.

Figure 47. Variotram LF-LRV manufactured by ABB (Henschel-Waggon Union)—at station.

The Bombardier (Rotax)-Duewag, Type T, LF-LRV uses this approach. Beginning in 1993/1994, 68 vehicles were delivered and are now operating on the Vienna U-Bahn. Bombardier states (*10*) that the pressure to produce this vehicle in a short time, without the benefit of extensive operational testing, is the reason they chose the force-steered single-axle trailer truck concept instead of the self-steering independently rotating wheel technology. Service experience with the Type T has been satisfactory, but the cars have not been in service for very long. Therefore, it is not possible to evaluate long-term performance. The steered axle concept is derived from the Talgo intercity train, which originated in Spain and has had a successful inservice history. The very limited application of this concept to date suggests that it may be a "custom" design, unlikely to find widespread use elsewhere.

Self-Steering (EEF) Wheelsets

The principle behind the EEF wheelset has been well-documented (*5*), (*7*), (*11*) and is shown in Figure 59. The independently rotating wheels of this wheelset are allowed to rotate around a vertical axis that is located outboard of the wheel. The wheel tread is tapered or profiled; therefore, the normal

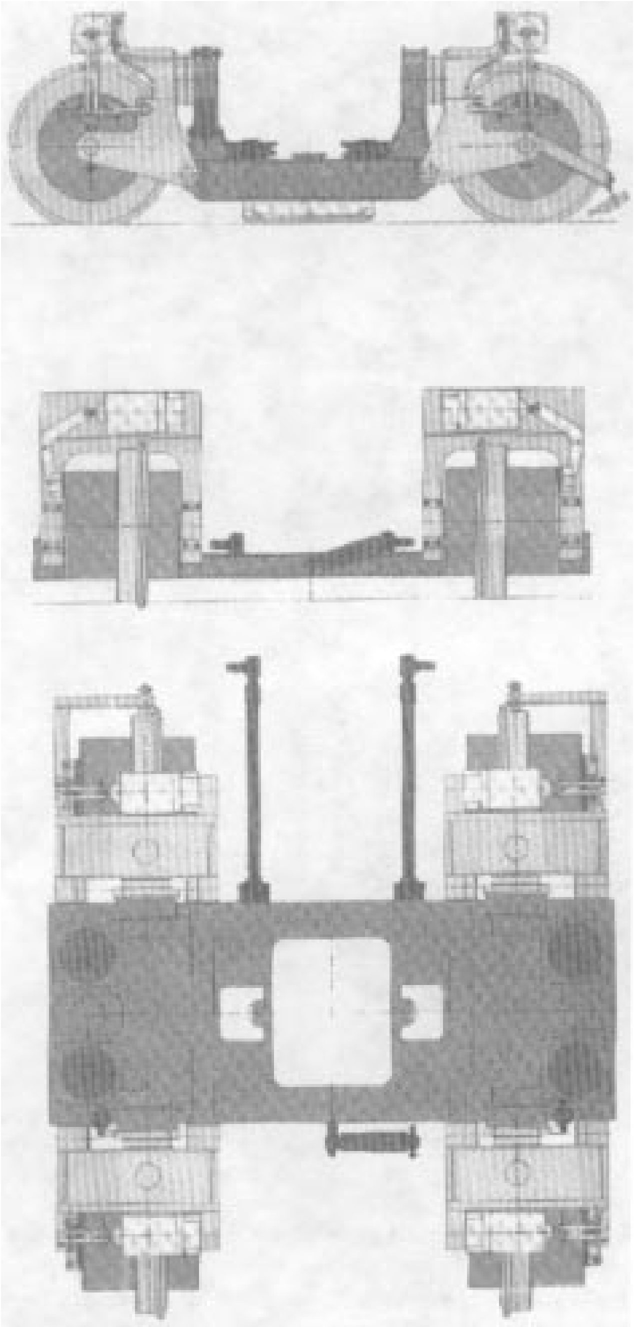


Figure 48. Variotram LF-LRV manufactured by ABB (Henschel-Waggon Union)—running gear and hub motors.

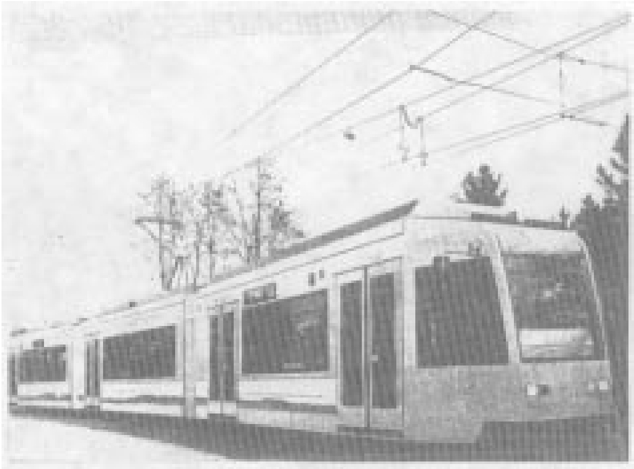


Figure 49. Frankfurt R3.1 LF-LRV manufactured by Duewag.

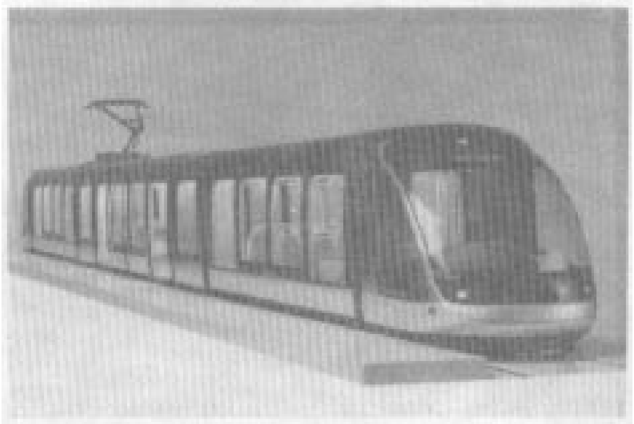


Figure 50. Eurotram LF-LRV assembled by ABB (U.K./Italy).

force at the point of wheel/rail contact is inclined with a horizontal component that always acts in the direction of the track centerline. If the wheel develops an angle of attack with the rail, the horizontal force component provides a couple around the vertical axis of rotation to restore the wheel to run tangentially to the rail.

The complete EEF wheelset assembly (Figure 60) comprises the following:

- Two independently rotating, resilient wheels with integral disc brakes and calipers (Figure 61),
- A type of cranked axle (Figure 62),
- A truck frame,
- Rubber primary suspension,
- Four coil springs for the secondary suspension, and
- A steering linkage that interconnects the two wheels so they steer in unison.

The principle was thoroughly tested on the VDV Stadtbahn prototypes and first used in revenue service in 1990 on the Duewag vehicles for Kassel. Since then, nine other Category-2 Duewag LF-LRVs (for Bochum, Heidelberg, Rostock, Bonn, Halle, Brandenburg, Mulheim, Dusseldorf, and Erfurt) have used EEF trailer wheelsets—a total of 165 vehicles.

EEF wheelsets have performed adequately on the Kassel cars after some initial problems. However, like all independently rotating wheel running gear, quick-response slide controls are needed to avoid formation of wheel flats during braking. In

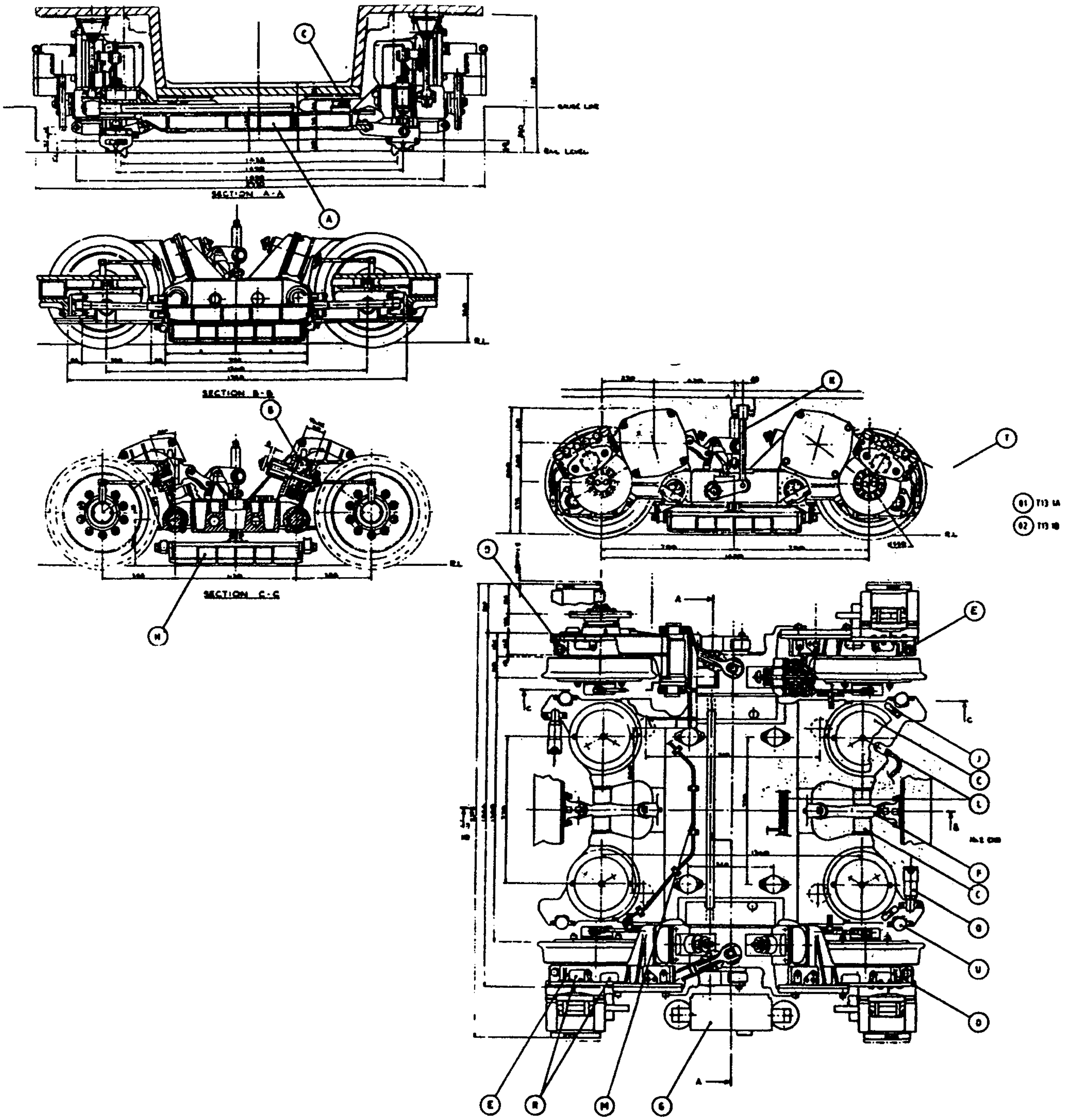


Figure 51. Eurotram LF-LRV assembled by ABB (U.K./Italy)—schematic.

Figure 52. VLC LF-LRV manufactured by Breda (photo—on street).

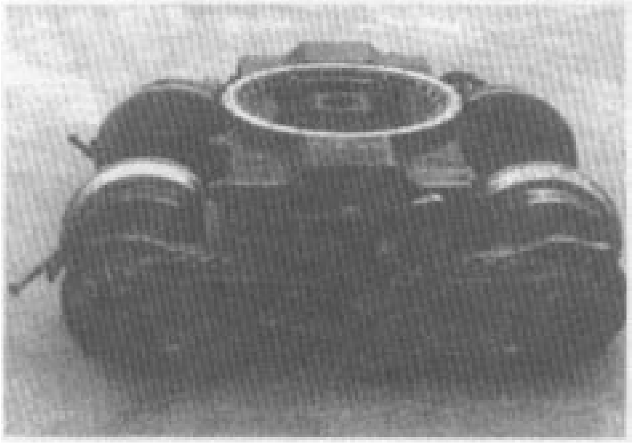


Figure 53. VLC LF-LRV wheel-axle assemblies.

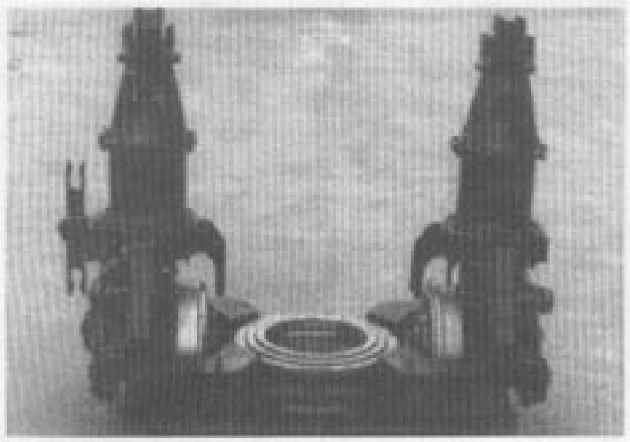


Figure 54. VLC LF-LRV single wheelset trailer running gear.

addition, the maximum speed for vehicles using this technology is currently 70 km/h (44 mph).

The self-guiding principle only works in practice if the wheel develops a substantial angle of attack—otherwise the restoring moment is insufficient to overcome the friction in the pivot bearing. For best results, the nominally vertical axis around which the wheel steers should be slightly inclined in the direction of travel (*7*). This can work on unidirectional vehicles but cannot be done on bidirectional vehicles.

In addition, since the wheelset assembly must be manufactured to very precise tolerances, it will probably continue to be expensive to produce. It is anticipated that EEF trailer wheelsets will undergo considerable refinement during future in-service experience. North American application will probably be limited to low-speed operations.

As noted in Chapter 1, the VDV Stadtbahn prototype program failed to produce a satisfactory motored EEF wheelset. Therefore, EEF technology should currently only be considered practical in trailer running gear applications.

Articulation-Steered Independently Rotating Wheelsets

The articulation-steered, independently rotating wheelset approach has been used in two vehicles—the Breda VLC for Lille and the SGP ULF 197 prototype for Vienna. In both vehicles (*12*, *13*), the two independently rotating wheels support, and are part of, the articulation joint. A system of linkages is used to ensure that the articulation portal splits the angle between adjacent carbodies when the entire vehicle is on a curve. The wheelset turns with the portal and lies on a radius to the curve, thus making the wheels tangential to the rail.

The ULF 197 vehicles operating in Vienna use a system of linkages that interconnect each articulation portal to the one in front and behind (Figure 63). This mechanism is intended to improve steering during curve entry and exit—the leading wheelset follows the rails by wheel flange contact and turns the trailing wheelsets via the linkages.

This type of forced steering works well on curved track and enables the vehicles to negotiate small radius curves quietly and with less wear. However, it does not help guidance on tangent track. The Breda VLC relies on flange guidance on straight alignments. The ULF 197 vehicle can actively control the torque of the motors driving the wheels to "electrically couple" them, thereby simulating a conventional wheelset axle. This state-of-the-art guidance technology is still in its infancy and therefore difficult to assess. Vienna's order for 150 ULF 197 vehicles is reported (*6*) to be contingent on satisfactory performance of the prototypes.

It should again be noted that the articulation-steered running gear has only been used on the VLC and ULF197 vehicles, which are basically trams intended for city street operation where maximum speeds of 70 km/h (44 mph) are sufficient. This form of running gear may not be stable for operation at higher speeds.

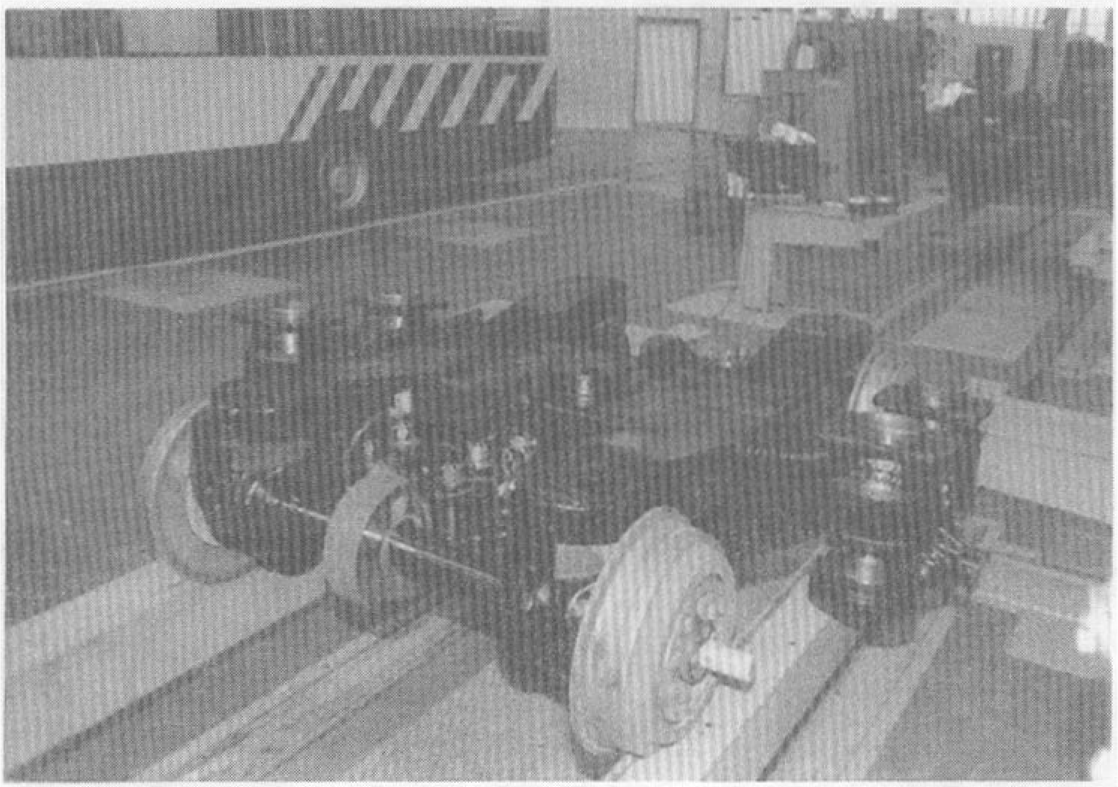


Figure 55. Mini conventional trailer truck.

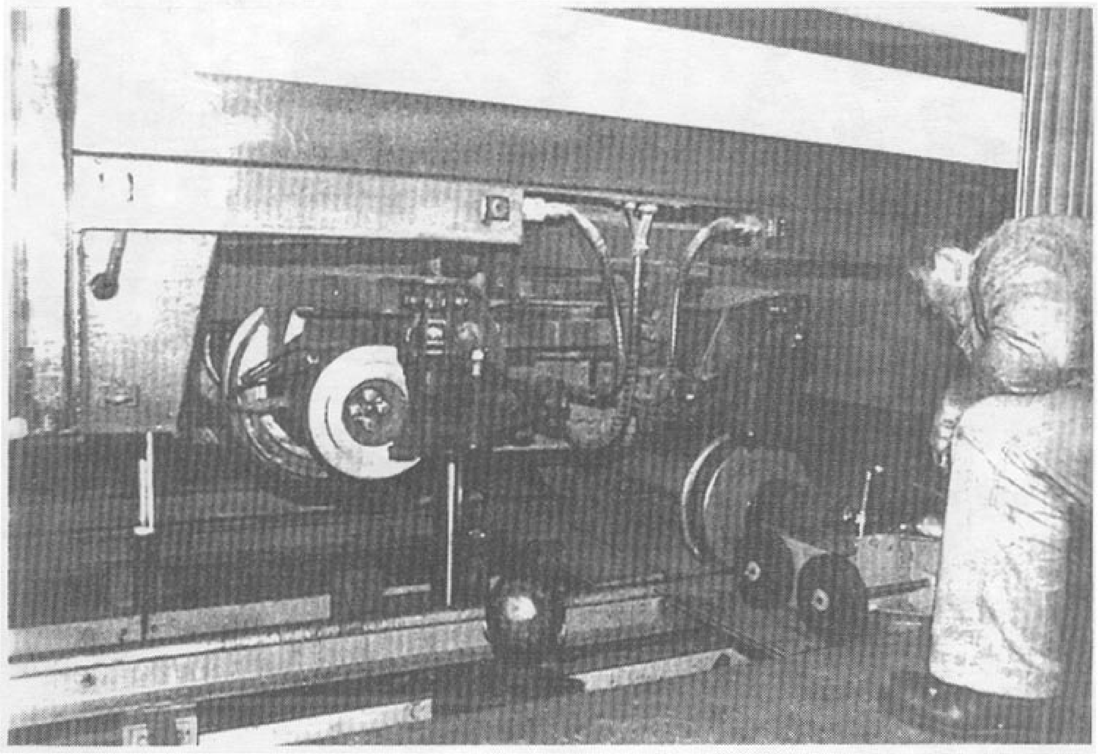


Figure 56. Removal and replacement of small wheelsets (photo).

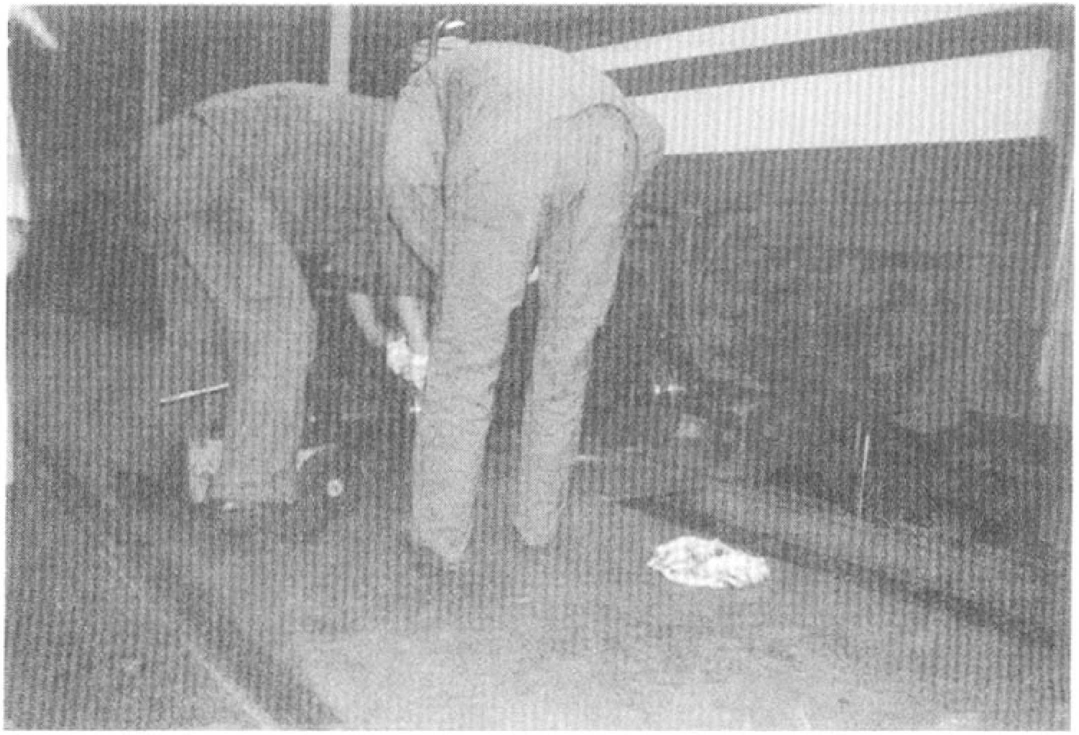


Figure 57. Removal and replacement of small wheelsets (photo).

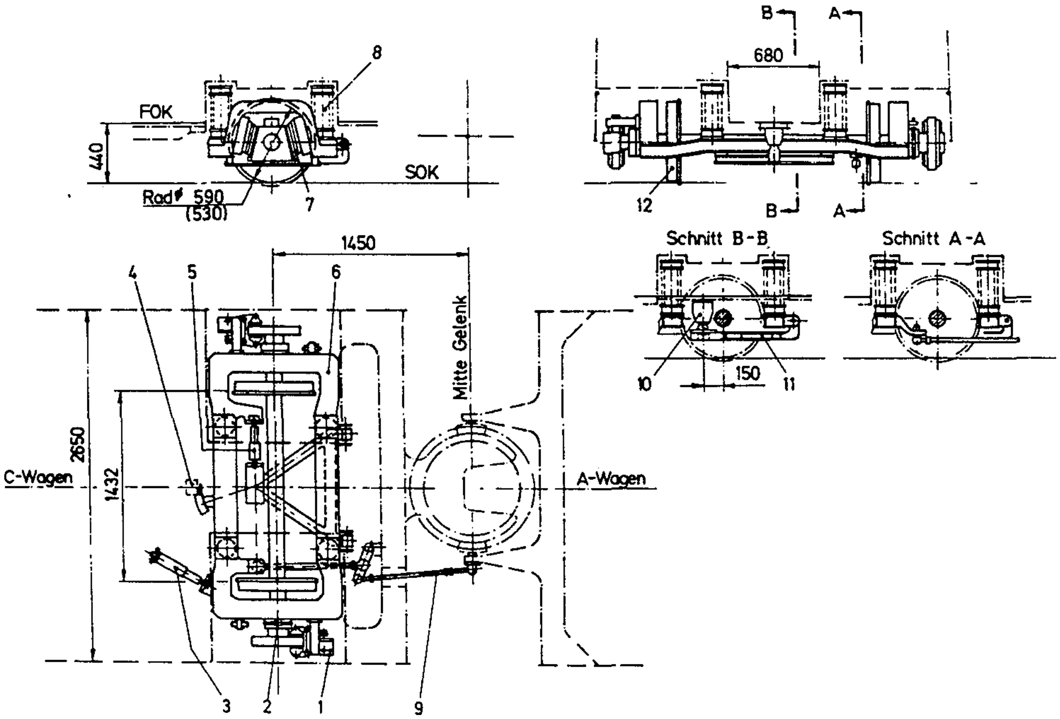


Figure 58. Forced-steered single-axle trailer truck concept (schematic).

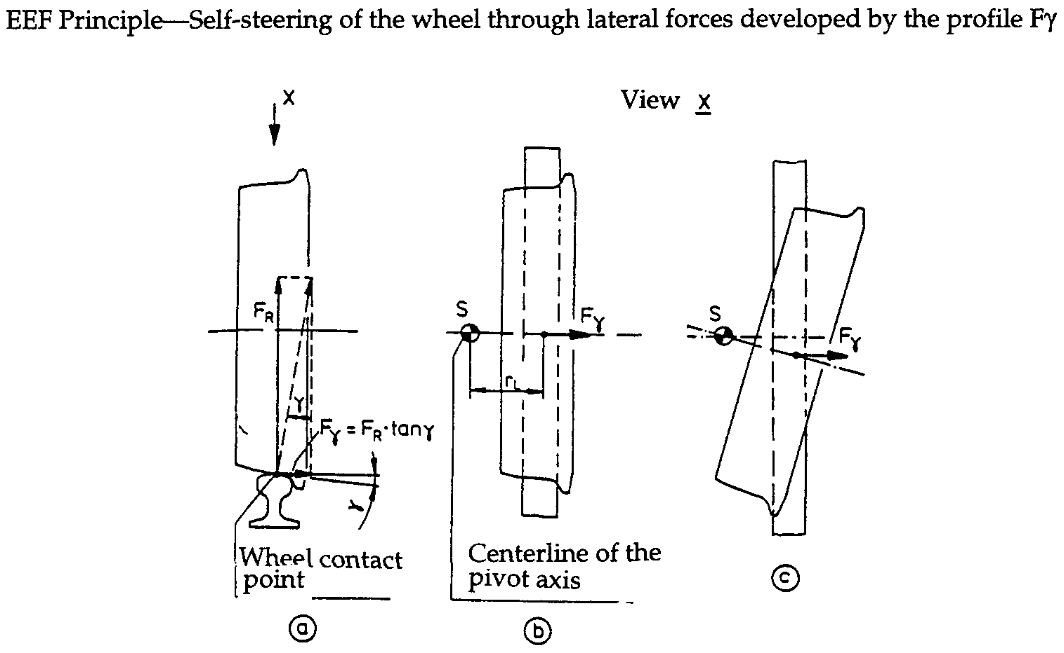


Figure 59. Self-centering EEF wheelset design principle (schematic).

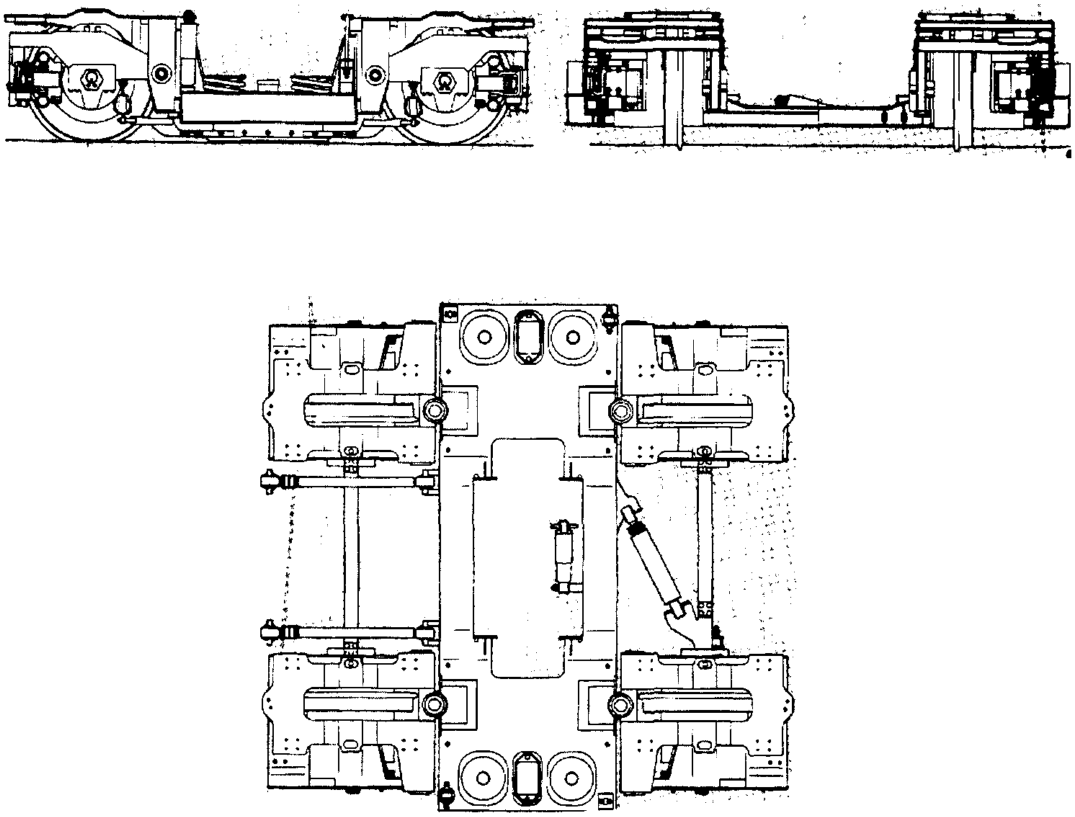


Figure 60. Complete EEF wheelset assembly.

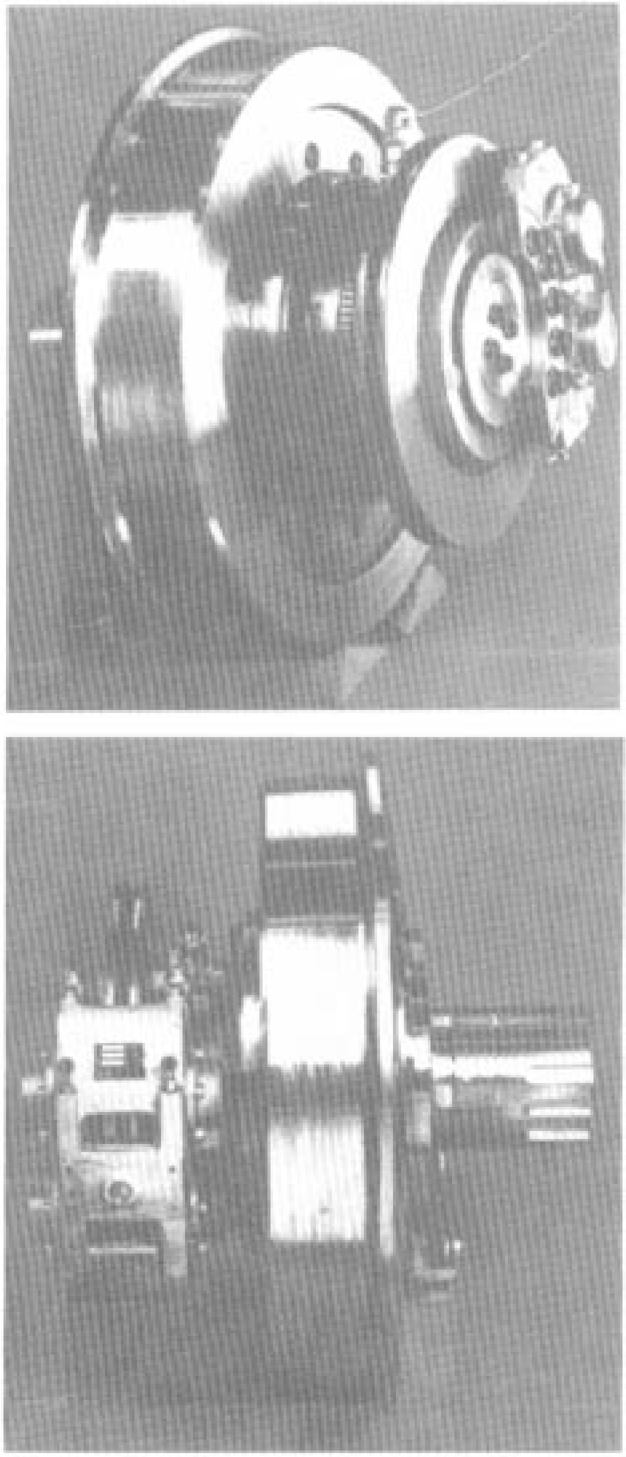


Figure 61. BSI independent wheel (for Kassel).

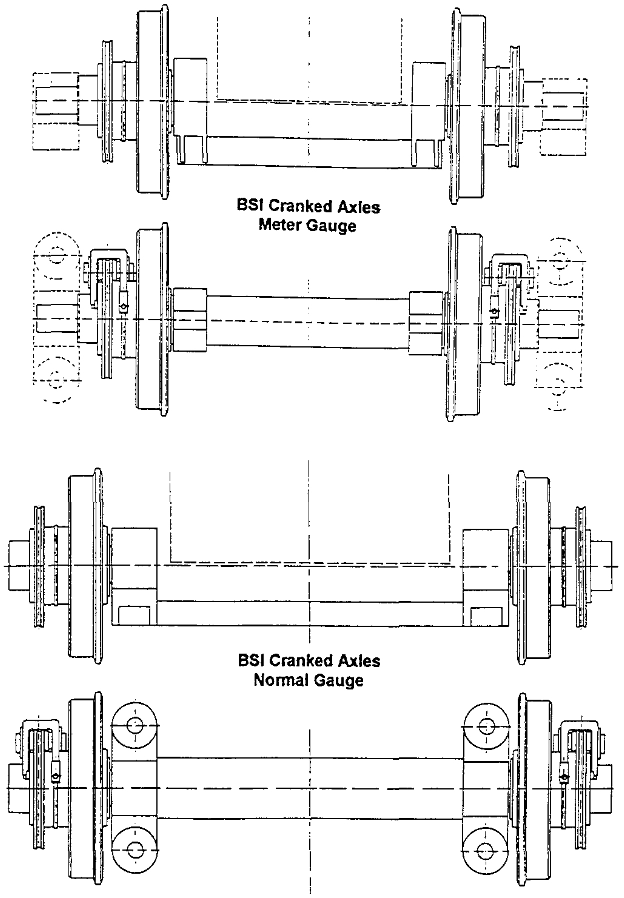


Figure 62. BSI cranked axle (schematic).

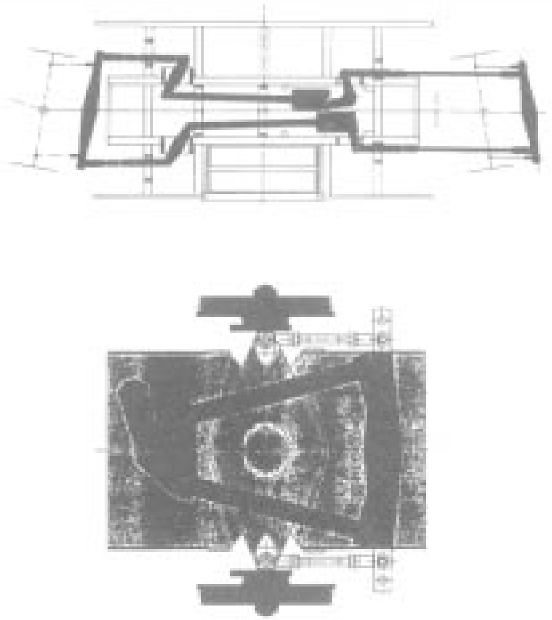


Figure 63. ULF 197 steering linkages interconnecting articulation portals.

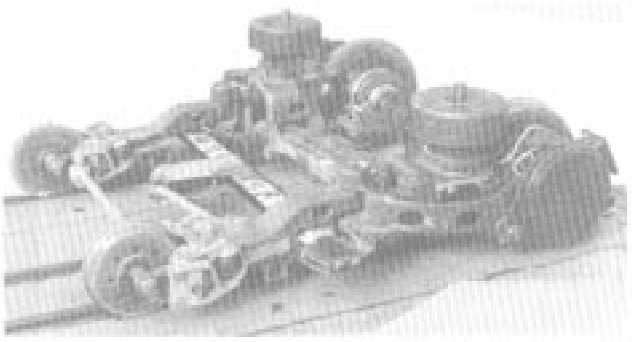


Figure 64. Running gear used on Bombardier (BN) Tram 2000.

Figure 65. Tram 2000 wheels.

Rail-Steered Articulated Trucks

The final example of a state-of-the-art running gear is rail-steered articulated trucks (Figures 64 and 65). Brussels ordered 51 Bombardier (BN) Tram 2000s with this type of running gear.

The running gear consists of two very small, 375-m (14.8-in) diameter rollers that follow the rails. Through a complex system of linkages and an articulating frame, these rollers steer the standard size, independently rotating (hub motor-driven) load-carrying wheels. One truck is located at each end of the vehicle, with the large driven-wheels in the lead. Accordingly, the trucks are suitable for use on unidirectional vehicles only. This arrangement was tested extensively on a roller rig, and for one year in Amsterdam.

The vehicle's ride quality was judged excellent based on a subjective evaluation during this project. The vehicle has entered service, and its manufacturer is pleased with the reliability obtained from the running gear (*21*). If this reliability is sustained, the running gear of Tram 2000 should save on track maintenance cost because of its excellent curving ability. It is again noted, however, that the maximum speed of Tram 2000 is stated as 70 km/h (44 mph). It is not known whether its running gear will be dynamically stable at higher speeds.

Motors and Gearboxes

Design and construction of 100 percent LF-LRVs has been accomplished by using new and innovative drive arrangements to propel the independently rotating wheels, which are intrinsic in the running gear of most Category-3 vehicles. Since space under these 100 percent LF-LRVs is limited, motors and gear-boxes must also be compact—thus requiring the use of three-phase AC traction motors controlled by variable frequency inverters. This form of propulsion is possible because of the development of cheap and reliable power electronics, most notably insulated gate bipolar (IGB) transistors.

Several drive configurations exist—each specifically designed for a particular running gear arrangement. These various drive configurations are described in detail in Figure 66. These designs are very new; therefore, their longevity is difficult to assess.

The AEG (MAN) GT6N/GT8N uses a fully sprung motor, mounted below the carbody, which is isolated by both primary and pneumatic secondary suspensions. On the other hand, hub motor drives, because they increase unsprung mass, are considered a higher risk—particularly when the wheel is not resilient (such as in the Variotram). This increases the shock and vibration experienced by the running gear, motor, and gearboxes, as well as the rail.

In addition, all of these drive configurations are used in vehicles intended to operate on city streets where the maximum speed is limited to 70 km/h (44 mph). It is not known whether the thermal capacity of the water-cooled motor is sufficient for interurban duty cycles typical in North American LRT systems.

Suspensions

After experimenting with prototypes that had only one-stage suspensions, most manufacturers of all three categories of LF-LRVs have reverted to building the running gear with both primary and secondary suspensions.

Rubber primary suspension springs are used on most vehicles. On two of the Category-3 vehicles (the ABB [Socimi] Eurotram and the ABB [Henschel] Variotram), the trucks have a "radial-arm" primary suspension. In these vehicles, the wheel bearing pivots around the truck frame and the primary spring is either horizontal (Variotram) or inclined (Eurotram).

Two vehicles, the Breda VLC and the SGP ULF 197, do not have primary springs. Both vehicles have single wheelsets with independently rotating wheels that support the articulation portal frames, but the wheels are resilient (as are the majority of Category-3 vehicle running gear wheels).

Most secondary suspensions are provided by air springs or coil springs. The advantage of air springs is that stiffness can be adjusted by leveling valves to maintain constant height and secondary-suspension natural frequency, regardless of passenger load. Two of the Category-3 vehicles that have coil spring

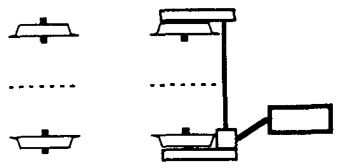
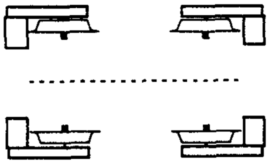
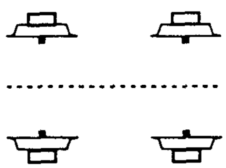
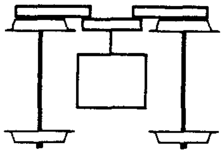
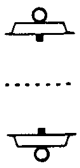
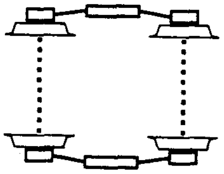
Configuration	Description	Application
	Longitudinal, 3-phase AC, air-cooled, motor suspended under each carbody section. Drives 2 of 4 independently rotating wheels via cardan shaft, right angle gear, cross shaft and two parallel spur gear boxes mounted outboard of each wheel.	All trucks of AEG (MAN) GT6N/GT8N; Augsburg, Bremen, Munich
	Each of 4 independently rotating wheels of the truck is driven by its own 3-phase asynchronous, water-cooled, truck frame-mounted motor, via a parallel gearbox	Power trucks of ABB Eurotram for Strasbourg
	Water-cooled, AC motor mounted in the hub of each independently rotating wheel and driving via an in-line planetary gear set housed in the motor casing or without any gears.	Duewag R3 1 for Frankfurt; ABB (Henschell) Variotram for Chemintz; BN Tram 2000 for Brussels
	Transverse monomotor driving two conventional wheelsets via cardan shaft and two parallel gear boxes.	Power (end) trucks of Breda VLC for Lille
	Each independently rotating wheel of the wheelset is driven by a right angle gearbox and an asynchronous water-cooled motor, vertically-mounted inside the articulation portal.	SGP ULF 197 for Vienna
	One AC asynchronous traction motor, suspended from the carbody (underfloor), drives a pair of independently rotating wheels on one side, via a cardan shaft and right angle gearbox for each wheel.	Schindler COBRA prototype

Figure 66. New drive configurations for Category-3 LF-LRVs.

suspensions use hydraulic cylinders to provide passenger load weight compensation.

The most radical suspension is on the SGP ULF 197 vehicles operating in Vienna. The carbody sections are suspended from the articulation portals by pendulum links and coil springs.

Ramps and Lifts

Although Category-3 LF-LRVs have entrances as low as 152 mm (6 in) above TOR, some type of ramp or lift is needed to enable persons in wheelchairs to enter if there is no platform (i.e., boarding from street level). Some examples of ramps and lifts used on Category-2 and Category-3 vehicles include the following:

- Power ramps on the GEC Alsthom cars (Category-2 vehicle) for Grenoble, Rouen, and Paris. When deployed, this ramp (shown previously in Figure 32) bridges the gap between the vehicle's low floor, which is 345 mm (13.6 in) above TOR, and the low-station platform.
- A 3.1 m (10.2 ft) sliding, extendable ramp used on the Duewag R3.1 in Frankfurt. This ramp can be deployed in under 2 min, which is comparable to the time it takes for a conventional wheelchair lift.
- A sliding ramp and lifting bridge on the AEG (MAN) GT6N vehicle in Munich (Figure 67). This device requires up to 4 min to deploy.
- Powered platform bridgeplates on the ABB (Socimi) Eurotram (Strasbourg) are installed in all four doorways (two per side) at the center carbody sections. These devices

Figure 67. Sliding ramp and lifting bridge used on the AEG (MAN) GT6N LF-LRV in Munich.

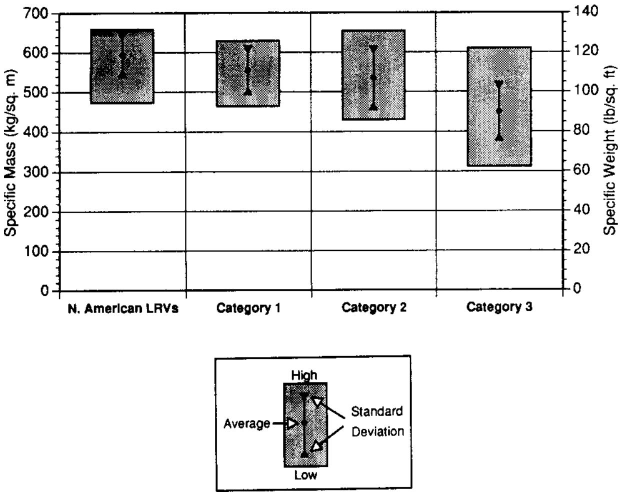


Figure 68. Comparison of specific mass for LF-LRVs and conventional North American LRVs.

are controlled from the cab by the driver, who can monitor boarding and alighting by means of closed-circuit television (CCTV).

Carbody Construction and Materials

An important goal that has guided the development of all Category-3 vehicles has been weight reduction. In addition to the weight savings from the use of innovative running gear and drive arrangements, manufacturers have tried various new materials and construction technologies. Examples of these state-of-the-art materials and construction technologies include the following:

- Breda VLC (Lille)
  - The primary structural frame is fabricated from aluminum extrusions.
  - Extruded aluminum side panels are bolted on to the frame—making them easy to replace.
  - The cab is made from structural composite material.
  - Specific mass is 557 kg/m^2 (114 lb/ft^2).

- ABB (Socimi) Eurotram (Strasbourg)
  - The structure is built from wide aluminum extrusions.
  - Bending stiffness is provided by a deep center sill in the roof frame.
  - Windows are bonded to the structure (similar to automobile windshields).
  - Interior and exterior panels are formed from GRP.
  - Trim panels are secured by Velcro®-type fasteners, making graffiti control and color scheme changes easier.
  - Floors are made from aluminum skin foam-core sandwich bonded to the structure (but its fire resistance is unknown).
  - Specific mass is 372 kg/m^2 (76 lb/ft^2).

- Bombardier (BN) Tram 2000 (Brussels)
  - A rigid steel underframe incorporates an energy-absorbing bumper—capable of absorbing a 6-km/h (3.75-mph) impact.
  - Aluminum extrusion sidewalls are bolted to the steel frame and each other.
  - GRP is used for ends and interior panels—the interior panels are attached with Velcro®.
  - Specific mass is 608 kg/m^2 (125 lb/ft^2).

Although these are departures from conventional LRV construction, the mass reduction benefits are not obvious in terms of achieved specific mass (tare weight ÷ [length × width]). In addition, the corrosion risk associated with the use of dissimilar metals and/or aluminum as the primary structural material must be carefully considered—especially in cities where salt is essential for snow and ice clearing.

By comparison, the AEG (MAN) GT6N/GT8N vehicles, which are fabricated from stainless steel, have specific mass between 422 kg/m^2 (87 lb/ft^2) and 486 kg/m^2 (100 lb/ft^2), respectively. Figure 68 shows a comparison of specific mass for LF-LRVs and conventional North American LRVs. It will require more in-service time to determine if new innovations in construction and materials technologies will result in any life-cycle cost reductions compared to the continued use of steel.

MAINTENANCE EXPERIENCE WITH LF-LRVs

Maintenance on Category-1 LF-LRVs will not differ substantially from conventional high-floor vehicles since they use the same technologies. Most of the Category-3 vehicles have

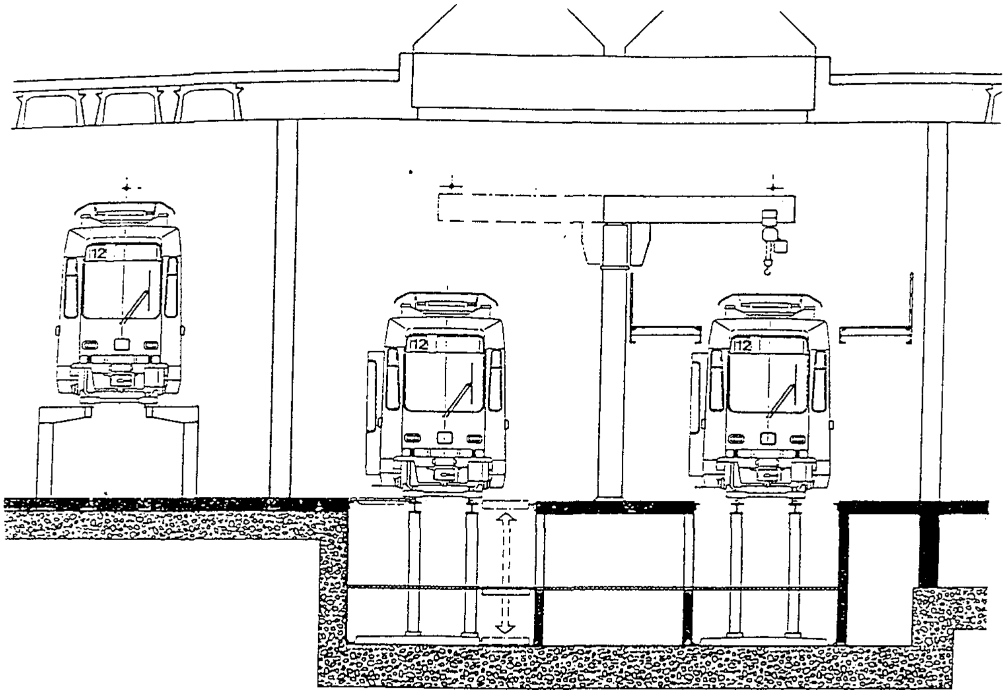


Figure 69. Geneva maintenance shop layout (schematic).

just started service, or will enter service shortly; therefore, there is no maintenance history to report. The purpose of this section is to summarize discussions with operators of Category-2 vehicles, as well as the transit agency in Munich, which has operated the AEG (MAN) GT6N prototypes since 1991.

It is standard practice for European transit operators to cooperate and work with a selected carbuilder to develop vehicles that are suited to their specific needs. Therefore, the transit operators have a vested interest in the vehicle design that they helped define and refine.

Maintenance Experience in Bern and Geneva, Switzerland

Both Bern and Geneva in Switzerland operate the ACM Vevey, Category-2 vehicles with small-wheeled trailer trucks. Both transit operators claim that maintenance is easier and consumes less time compared to the standard LRVs in their fleets. The main reasons cited were ease and speed of wheelset removal, which can be done in 15 min (conversation with Mr. Berger, Chief of Maintenance; Bern, Switzerland).

Maintenance is simplified because the shops were modified to provide good accessibility to all parts of the vehicle (Figure 69), by means of the following:

- Lifts to raise the cars up to 1,700 mm (6 ft 7 in), which enables each truck to be exchanged individually;
- A pit track with space for three vehicles, where a mobile lift table has proven convenient for underfloor equipment and power truck maintenance;
- A track with secure platforms at roof level on either side of the vehicle, which provides easy access to the roof-mounted equipment; and
- A jib crane for lifting and lowering roof-mounted equipment.

Maintenance Experience in Kassel, Germany

The transit agency in Kassel operates the Duewag-built Category-2 vehicles that use EEF trailer wheelset technology. After some refinements, reliability of the self-steering wheelsets has reached an acceptable level (conversation with Mr. Rebitzer, Rolling Stock Engineer; Kassel, Germany). The wheelsets are considered easier to maintain because the disc brake calipers are mounted outboard of the wheels, where they are more accessible. Kassel did not perceive a difference in maintenance costs between their LF-LRVs and conventional LRVs.

Kassel also modified their maintenance shops by installing high platforms for roof-mounted equipment maintenance (Figure 70). They use CCTV to perform daily pantograph and above-roof equipment inspections more efficiently.

Maintenance Experience in Grenoble, France

Grenoble operates the first fleet of Category-2 vehicles that entered revenue service. Built by GEC-Alsthom, these vehicles have four independently rotating wheel trailer trucks. The only maintenance problem has been the resilient wheels, which are heavily loaded and have more frequent replacement rates because of wear caused by the numerous track curves in Greno-ble. Otherwise, Grenoble considers the reliability of these vehicles

Figure 70. Kassel maintenance shop (photo—showing access to roof equipment).

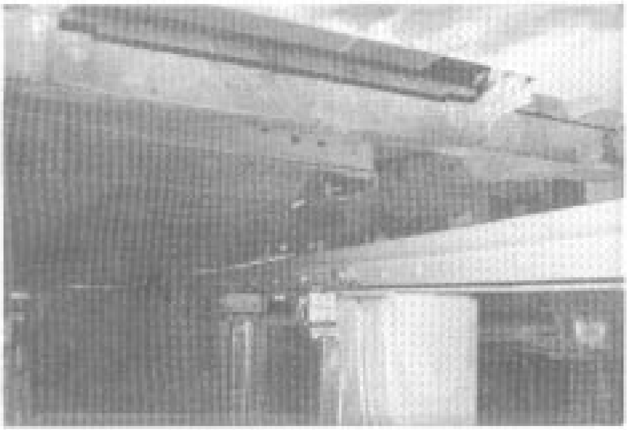


Figure 71. Munich maintenance shop (photo—showing traction motor and shop pit with sliding rail for traction motor drop).

to be acceptable (conversation with Mr. Abatista, Chief of Maintenance; Grenoble, France).

Maintenance Experience in Munich, Germany

Maintenance officials in Munich hope to achieve a 33-percent reduction in maintenance effort after all the new GT6N Category-3 LF-LRVs are commissioned and have replaced the older, conventional LRV fleet. Munich's chief of maintenance attributed this expectation partly to the development and improvement resulting from service trials with the three prototypes and partly to maintenance personnel training (conversation with Mr. Geisl, Chief of Maintenance; Munich Transportation Authority, Munich, Germany). Since the GT6N is made of stainless steel, carbody finish maintenance is expected to be reduced.

One special maintenance shop modification that the GT6N vehicles require is the provision of sliding rails on the pit track to enable dropping the underfloor-mounted traction motors that are installed above one rail (Figure 71).

All of the transit operators interviewed supported the benefits of the maintenance shop modifications in Geneva. In addition, they also saw a need to provide shop power supplies to reach equipment mounted above the roof, since the overhead traction power supply has to be discontinued in the maintenance bays to avoid electrocution of repair personnel.

PUBLISHED AND REPORTED PRICES

The first price information was originally published in *Railway Gazette* (*14*). However, these prices were quoted in German DM per unit floor area. The conversion of these figures to US $ can be misleading, depending on the exchange rate originally used by the author and the current exchange rate. Moreover, it was not clear whether some of these published prices are for the prototype or the production order. A more recent article by the same author (*15*) gives prices for Category-2 vehicles ordered between 1993 and 1994 (the conversion to US $ used is: $ = DM 1.7 and $ = FF 5.7). In addition, some prices for Category-2 vehicles were obtained directly from three transit operators. Table 8 shows prices for Category-2 vehicles.

The price of the Portland order is subject to escalation based on a formula that accounts for increases in labor indices between 1993 and the approximate date of delivery.

The manufacturers of the Brussels Tram 2000, the BN division of Bombardier Eurorail, stated that the price for each of the 51 Category-3 vehicles now being delivered was BF 63 million (conversation with engineers at the BN Division of Bombardier Eurorail). At present exchange rates of about US $ = BF 33 (the US $ is currently losing value), this corresponds to about $1,900,000.

The article (*15*) also quotes a price of $2,060,000 for the ABB (Henschel) Variotram ordered by Chemnitz; 53 of these 100 percent low-floor Category-3 vehicles were ordered for 1993 delivery.

It is difficult to discern any trends from these prices or to

TABLE 8 Category-2 vehicle prices

City	Builder	Length	Width	Year of Delivery	Number of Vehicles	US $ Equivalent
Paris[1]	GEC-Alsthom	29 4 m (96 ft 5 5 in)	2.3 m (7 ft 6 in)	1991	34	2,400,000
Geneva[1]	ACM Vevey	21 0 m (68 ft 11 in)	2 3 m (7 ft 6 in)	1990	46	2,350,000
Portland (Tri-Met)[1]	Siemens-Duewag Corp.	28 0 m (92 ft)	2.65 m (8 ft 8 in)	1995	46	2,319,000
Grenoble[2]	GEC- Alsthom/	29 4 m (96 ft 5.5 in)	2.3 m (7 ft 6 in)	1987	38	2,363,000
Mannheim[2]	Duewag	29.9 m (98 ft 1 in)	2 4 m (7 ft 11 in)	1994	64	2,010,000
Dusseldorf[2]	Duewag	28.6 m (93 ft 8 in)	2 3 m (7 ft 6 in)	—	10	1,635,000

1 Information obtained through interviews
2 Information obtained from *Railway Gazette International Year Book, Developing Metros 1994,* "German Cities Dominate Deliveries of Novel Low- and Middle-Floor Cars."

deduce from this information alone what (if any) is the price premium for LF-LRVs as a function of vehicle category or size of low-floor area. There are simply too many factors that influence prices to make comparisons between vehicles. Some of these factors, which vary from operator to operator, include different specified equipment and interior furnishings, order size, commercial terms, type of procurement process, subsidies, and exchange rates.

Other anecdotal evidence recorded during this research suggests that the premium is quite small:

- TRI-MET reported that Siemens-Duewag Corporation quoted a 10 percent increment above the price of a conventional high-floor LRV built to the same specification. This 10 percent premium was due to the redesign work needed to change from European specifications to North American specifications, as part of the initial transfer of technology.
- Bombardier Eurorail's division stated that their policy is to produce and sell their 100 percent low-floor Tram 2000s for the same price as a comparable, conventional high-floor LRV. This presumably is possible now that the development costs of the sophisticated running gear have been either recovered from the first order or have been written off (conversation with engineers of BN Division of Bombardier Eurorail).