

Center Truck Performance on Low-Floor Light Rail Vehicles

DETAILS

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 114

**Center Truck Performance on
Low-Floor Light Rail Vehicles**

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DERBY, UNITED KINGDOM

Subject Areas
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 Transportation 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 Academies, 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.

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- Massachusetts Bay Transportation Authority
- Metropolitan Transit Authority, Houston, Texas
- New Jersey Transit
- San Diego Trolley, California
- Santa Clara Valley Transit Authority, California
- Southeastern Pennsylvania Transportation Authority
- Toronto Transit Commission
- TriMet, Portland, Oregon

FOREWORD

By Christopher W. Jenks

TCRP Manager

Transportation Research Board

This report should be of interest to engineers, manufacturers, maintainers, and others interested in low-floor light rail vehicle (LFLRV) center truck performance issues and their potential solutions for center trucks with unpowered, independently rotating wheels (IRWs). The report describes performance issues observed in the operation of LFLRV center trucks (focusing on 70-percent low-floor vehicles), such as excessive wheel wear and noise and occasional derailments, and provides guidance on how to minimize or avoid these issues. The report also includes guidance on LFLRV specifications, maintenance, and design, as well as on related infrastructure design and maintenance, to maximize performance of these LFLRV center trucks.

Low-floor light rail vehicles (LFLRVs) are used by many transit systems with increasing popularity. The typical design includes a three-section articulated vehicle body with the center section connected to a center truck with unpowered, independently rotating wheels (IRWs). The leading and trailing sections of the vehicle are each supported by a motored truck at one end and by the common non-powered center truck at the other. The low-floor height prevents the use of wheel sets with solid axle connections between right and left wheels of the center truck.

In acceleration and braking modes during curving, because there are two articulations connecting the center section, the center section and truck may rotate excessively, thereby causing a high angle-of-attack and flanging. Also, the IRWs of the center truck do not promote self-steering through the curve, increasing the angle-of-attack and flange forces. This condition leads to increased flange wear, gauge face wear, stick/slip noise, and the potential for derailment at curves and special trackwork. Wheel life of the low-floor center truck can be significantly less than that of motored trucks.

Research was needed to better understand the performance of the center trucks of LFLRVs, compile lessons learned to date, and provide guidance to transit agencies and light-rail vehicle (LRV) manufacturers on how to mitigate performance problems.

Under TCRP Project C-16, Interfleet Technology was asked to develop guidance to transit agencies and LFLRV manufacturers for mitigating the issues associated with the design and operation of unpowered center trucks on a three-section, articulated vehicle body with the center section fixed to a center truck with IRWs. To accomplish the project objective, the research team reviewed relevant domestic and international literature; collected design and performance data from transit systems operating LFLRVs and their vehicle manufacturers; and identified the factors that can contribute to events such as derailments, excessive noise, excessive wheel and rail wear, and reduced ride quality (e.g., hunting and excessive curving). Based on these factors, the research team conducted extensive computer modeling using ADAMS/Rail for various LFLRV and track infrastructure combinations. As a result of these analyses, the research team developed guidance related to vehicle and infrastructure design and maintenance.

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S U M M A R Y

Center Truck Performance on Low-Floor Light Rail Vehicles

The purpose of this research was to help introduce low-floor light rail vehicles (LFLRVs) to the United States and Canada. Some LFLRVs that use unpowered wheels on stub axles on the articulated center section experience problems with excessive wheel wear and derailments. Vehicles of this type operate in transit systems in several cities in the United States, Europe and Australia; the success of these vehicles has been varied.

The research was commissioned in order to better understand the performance of these center trucks, to compile lessons learned to date and to provide guidance to transit agencies and LFLRV manufacturers in mitigating problems associated with this type of vehicle. This report concentrates on these objectives and provides the associated guidance.

The work involved a literature review, consultation with transit systems (via a questionnaire and visits), the identification of contributory factors, and modeling to assess their relative importance. The guidance produced was structured so as to facilitate its use by different sectors of industry, for different applications over a long time. The topic is complex and the guidance sets the research findings in the context within which they will be used.

Although performance problems including derailment, excessive wheel and rail wear, and noise and poor ride quality have arisen with these vehicles in the United States, corrective action has been taken and performance has improved. Despite this, the solutions adopted to date may not be the optimum ones for a “new start” system. The guidance presented in this report is based on the results of the previous corrective action, wider experience, and the work carried out during the research project.

Performance problems are more likely to occur when these vehicles are introduced to a long-established transit system, where the track geometry and other conditions may be more challenging for innovative vehicle designs. The guidance suggests that it may be necessary to modify the infrastructure and change maintenance practices when LFLRVs are introduced to existing systems. It is suggested that new systems that intend using them should adopt infrastructure standards and practices similar to the type of system for which these types of cars were originally designed.

The use of independent rotating wheels on the center trucks, more than any other feature, contributes to the performance issues. The research identified the main contributory factors and the guidance makes recommendations to enable the problems to be avoided.

In Europe the application of LFLRV designs of different types has been more extensive than in the United States and Canada where only two designs have been applied and those not extensively. It may be worthwhile tackling the reasons for this situation.

The research has noted the diversity of wheel profiles used on the light rail transit systems of the United States and Canada. The wheel-rail interface is key to solving the problems with LFLRVs and so the report proposes that further work be done to attempt to standardize on profiles that may have wider benefits.

CHAPTER 1

Introduction

1.1 Background and Research Objectives

The purpose of this research was to help introduce low-floor light rail vehicles (LFLRVs) into the United States and Canada. LFLRVs offer significant advantages, especially in terms of easier accessibility and the ability to use less-intrusive low platforms at stops. LFLRVs are especially attractive for new systems and have become the “standard” design solution offered by all the major suppliers.

Unfortunately, some LFLRVs that use unpowered wheels on stub axles on the articulated center section experience issues with excessive wheel wear and derailments. Vehicles of this type operate in transit systems in several cities in the United States, Europe, and Australia—some for more than a decade—and the success of these vehicles has varied.

The typical design for a 70-percent low-floor vehicle on a U.S. light rail transit system comprises a three-section articulated vehicle body with the center section mounted on a truck with non-powered, independently rotating wheels. The leading and trailing sections of the vehicle are each supported by a motored truck at one end and by the common non-powered center truck, via the articulation, at the other. The low-floor height precludes the use of conventional wheel sets with solid axle connections between right and left wheels of the center truck. Figure 1-1 shows a vehicle of this type used at Santa Clara Valley Transit Association (VTA) in Santa Clara, California.

Unlike a conventional wheelset, the independently rotating wheels (IRWs) of such a center truck cannot steer the wheelset through the curve. This inability leads to increased flange wear, gauge face wear, stick/slip noise, and the potential for derailment at curves and on lateral discontinuities in alignment. External factors related to the configuration of the overall vehicle design have a stronger influence on the dynamics of the truck than with conventional running gear. Wheel life of the low-floor center truck can be significantly

less than that of the conventional motored trucks at the outer ends of the vehicle.

The research was commissioned in order to better understand the performance of these center trucks, to compile lessons learned to date, and to provide guidance to transit agencies and LFLRV manufacturers in mitigating issues with this type of vehicle. This report concentrates on these objectives and provides the associated guidance.

1.2 Research Activity

The research contract was conducted by Interfleet Inc. who formed a team that as well as their own experts in this field, included researchers from the following firms:

- Raul V. Bravo and Associates;
- ZETA-TECH Associates;
- PROSE AG (Switzerland);
- Transport Technologie Consult Karlsruhe (TTK) (Germany); and
- Institut für Bahntechnik (IFB) (Germany).

Appendix A describes the activities carried out.

1.3 Worldwide LFLRV Developments

To date, LFLRVs have been introduced in eight U.S. transit systems. Given that roughly 22 systems in the United States and 4 in Canada might use them, this means that 31 percent of systems have applied this solution. Table 1-1 compares these figures for the United States and Canada and other parts of the world. This table suggests that in the United States use of this technical solution is more cautious than other countries.

Figure 1-2 shows the cumulative supply of light rail vehicles worldwide since 1967. The numbers of low-floor cars now

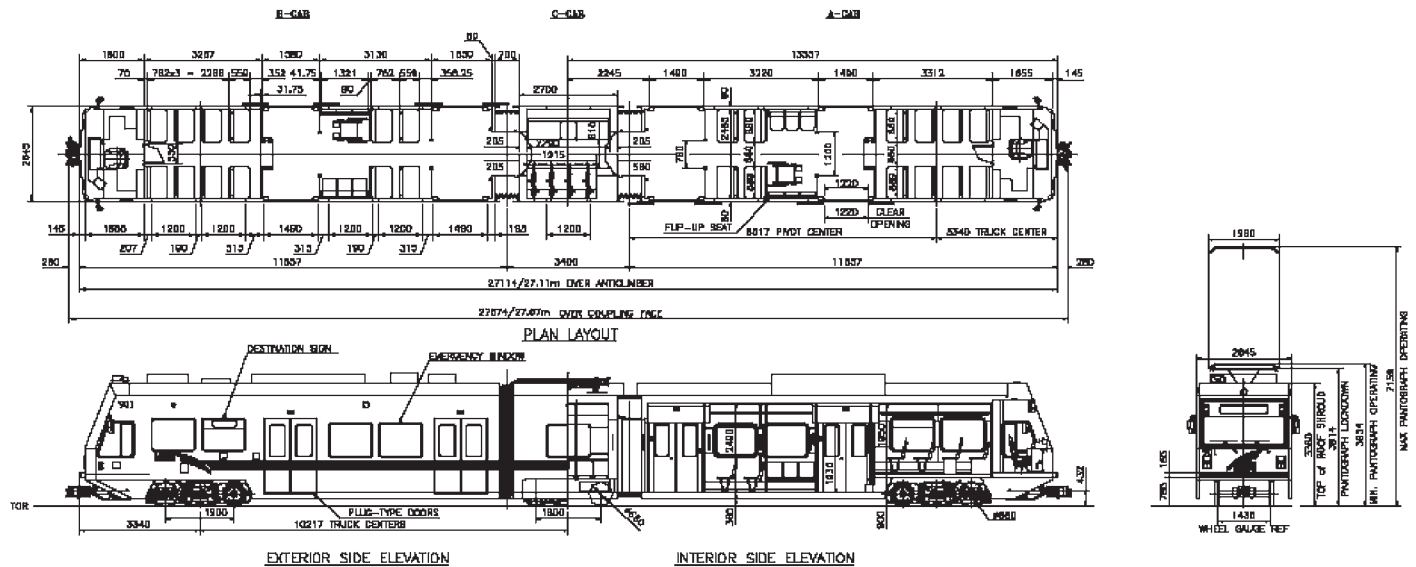


Figure 1-1. LFLRV, Santa Clara Valley Transit Authority.

approximately matches the number of high-floor cars. Figure 1-2 also shows that, within the low-floor sector, the total number of 100-percent low-floor cars matches the total number of partial low-floor cars and that these proportions have changed in the past 10 years. All new orders for light rail vehicles (LRVs) in Europe since 2000 have been low-floor types, except where the systems needed to have high-floor vehicles because they have high platforms. Few European systems have high platforms. Given the prevalence and popularity of these designs, solutions to any issues are needed urgently.

Chapter 2 of this report discusses low-floor developments and applications in detail.

1.4 Potential Issues

The performance issues identified in the research project statement issued by TCRP (1) that have been considered specifically within this study are

- Derailments, especially those of the center trucks;
- Asymmetric wheel flange wear and grooving of treads;

- Excessive rail wear;
- Reduced ride quality, including hunting and excessive curving; and
- Noise and vibration.

These issues will vary with the type of infrastructure (i.e., on different types of embedded and ballasted track, on tangent track, curves and special trackwork). Solutions may vary according to this context and all have been considered.

The research has been undertaken on the basis that, although sometimes unsatisfactory performance has a single cause, it often has multiple causes. The issues being observed may well be concurrent manifestations of multiple failure phenomena and, therefore, even more difficult to isolate and identify. Examples of this would include design issues aggravated by operating practice, infrastructure characteristics, or even something as highly variable as dynamic passenger loading.

Chapter 3 discusses performance issues and their possible causes based on the research carried out, which consisted both of original research and reviews of earlier published material on the same topics.

Table 1-1. Examples of the worldwide application of LFLRVs.

Region	No. of systems that could use LFLRVs	No. of systems using LFLRVs	Percentage Application	Note
USA and Canada	26	8	31%	Some old and many new LRT systems
UK and Ireland	7	5	71%	Mostly new systems
France	12	12	100%	Some old and many new LRT systems
Germany	59	42	71%	Many old systems, very few new ones
Benelux	9	8	89%	Mostly old systems
Australia	3	3	100%	Mostly old systems

LRT, light rail transit.

CUMULATIVE LRV ORDERS

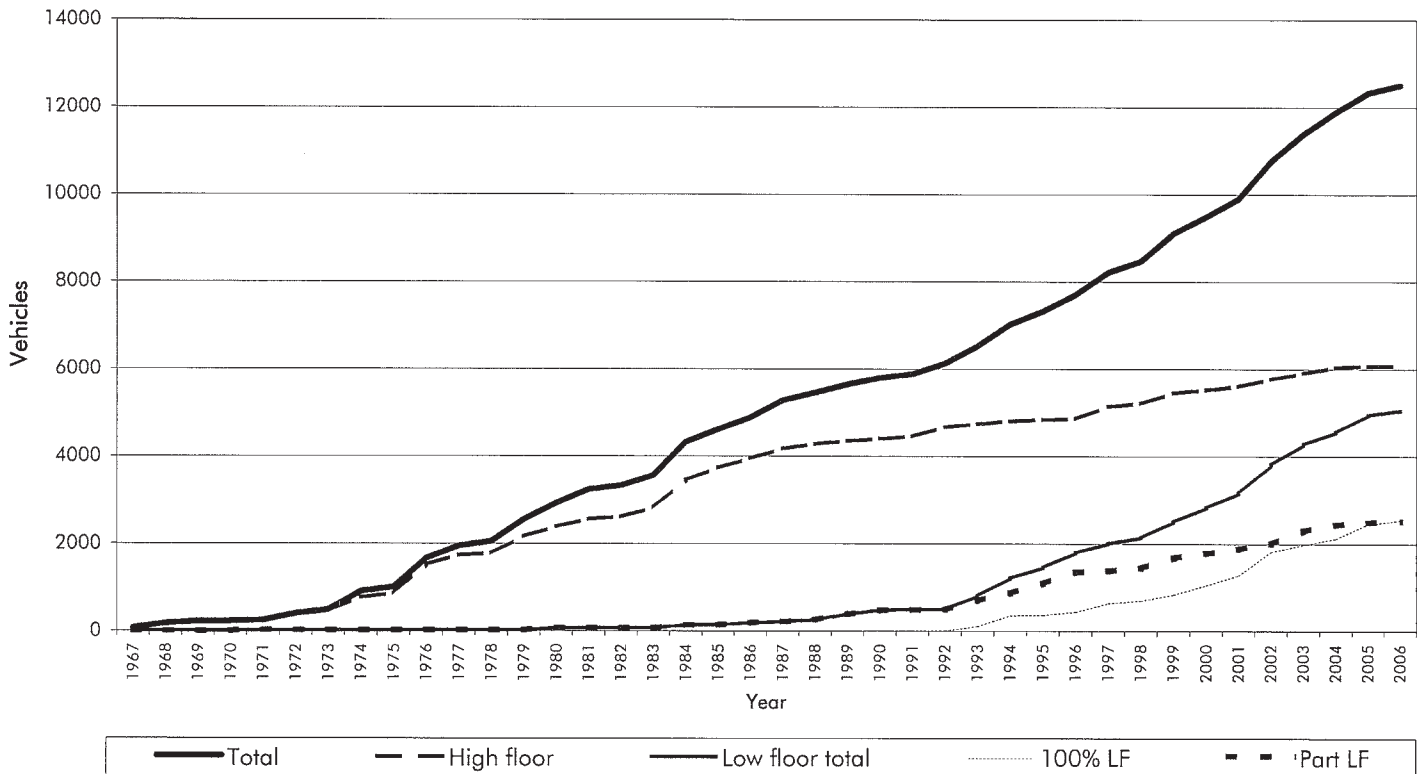


Figure 1-2. Cumulative worldwide pattern of LRV vehicle orders since 1967.

1.5 Organization of the Report

Chapter 2 describes (1) LFLRV technology and its application worldwide, (2) how it has developed and the issues that have emerged worldwide, (3) how these issues have been mitigated against, and (4) how the industry has reacted. Chapter 2 also looks at trends resulting from this experience.

Chapter 3 covers each of the identified performance issues. For each issue, generic examples that have occurred in the United States are given with explanations of what type of vehicles and conditions were involved. Chapter 3 also explains potential causes of performance issues, including contributory factors and justifications for the research findings.

Chapter 4 is practical guidance on dealing with the performance issues, with sections that apply to specific stages in application and to the interests of different users. Chapter 4 includes advice on best practices for system design so as to avoid future issues.

Chapter 5 identifies future research that might be carried out either to examine these issues in more detail or to generally facilitate the introduction of LFLRVs in the United States and Canada.

Chapter 6 summarizes the conclusions of the research.

Appendixes provide more detail on the research carried out, a glossary of the terms used, vehicle data and track data

for the systems studied in most detail and a comparison of track maintenance standards between the United States and Germany, and a bibliography.

1.6 Dimensions

The U.S. and Canadian transit systems use U.S. system measurements but some of the suppliers will have used the metric system in order to design equipment and products. In addition the research has compared U.S. and European standards where the latter have also used the metric system. The convention that has been adopted in this report is as follows:

- **U.S. system measurement only**—All distances, speeds, mass and weight. Also length, where there is no value in showing a metric equivalent (e.g., the route length of a system).
- **U.S. system measurements with metric system equivalents**—Lengths where it is useful to show a metric equivalent to facilitate comparison with other metric figures. An example of this would be 3 inches (76.2 mm).
- **Metric system measurements with U.S. equivalents**—Lengths originally specified in the metric system, including manufacturer's designs and European standards, may also

be expressed in the metric system when referred to by some U.S. transit systems. An example of this would be 75 mm (2.95 inches).

- **Track gauge**—This is generally referred to as 1,435 mm, without showing the conversion to U.S. standards (56.5 inches), so as to avoid repetition. Other dimensions

associated with track gauge are also shown in millimeters so as to facilitate comparison.

- **Fractions**—These are used for length dimensions in units of one-half, one-third, one-quarter, one-eighth, and one-sixteenth of an inch; in all other cases, length dimensions are expressed in decimals.
-

CHAPTER 2

LFLRV Technology and Applications

2.1 Conceptual Development

TCRP Report 2 (2) described the development and application of LFLRV technology in the United States and Canada; however, it was published in 1995 and much has happened in the intervening 10 years. The first modern low-floor streetcar was introduced into service in Geneva, Switzerland, in 1984. Sixty percent of the floor level was at 480 mm (19 inches) above rail. It was built by Duewag and ACM Vevey. Vehicles of this type are known as “partial low floor.” Before this, the typical streetcar or LRV had an even floor height sufficient to clear the wheels on all trucks. The partial low-floor concept was based on the fact that, if a significant proportion of the floor height was lowered, most users would benefit from easier access, including those most likely to need it. The partial low-floor concept did mean, however, that steps or ramps had to be included in the interior to provide access to the remaining high-floor areas. Steps and ramps might introduce safety and space issues.

Two innovations have facilitated the development of various low-floor concepts: independent rotating wheels (IRWs) and Einzelrad-Einzelfahrwerk (EEF) wheelsets. IRWs are wheels that rotate on the stub axle or an equivalent bearing medium; they may be steered as a pair by the vehicle articulation or built into a truck in accord with normal practice. EEF wheelsets have IRWs that are self steering. The yawing moment caused by the high angle of attack is used to steer the wheels, control being provided by a pivoting axlebar and a low-level linkage, which ensures that the wheels remain parallel. They are used as single wheelsets. Zurich cars with EEF wheelsets also have car-body-controlled steering.

Partial low-floor vehicles have been achieved in several ways. *TCRP Report 2* used a categorization which can be usefully applied:

- Category 1—Vehicles with conventional motor and trailer trucks throughout;

- Category 2—Vehicles with conventional motor trucks at each end but non-conventional center trailer trucks or wheelsets; and
- Category 3—Vehicles with innovative motored and trailing running gear throughout.

TCRP Report 2 also introduced a classification system for trailer trucks:

- T1 Four conventional wheels, two conventional axles;
- T2 Four IRWs, two cranked axles;
- T3 Four IRWs;
- T4 Two small IRWs built into articulation;
- T5 Two conventional wheels, one conventional axle, steered by articulation;
- T6 Four small wheels, two conventional axles;
- T7 Two IRWs steered by the articulation; and
- T8 EEF wheelset.

Category 1 vehicles have low-floor areas between the trucks, so the trucks are not of the low-floor type. The proportion of low-floor area will be restricted by this approach. Since *TCRP Report 2* was written, the Skoda Astra Streetcar has been introduced in the United States; this is a three-section articulated LRV with a low-floor center section. It is a Category 1 vehicle because the center section has no wheels suspended from the end sections through the articulation and is, therefore, outside the scope of this study.

Category 2 is of interest because it includes the low-floor vehicles with a center truck having IRWs that are the subject of the current study. Table 2-1 provides data on the main types of vehicle produced in this category. Table 2-1 uses a notation to describe the wheel arrangement, which is described in the Glossary (Appendix B). The vehicle designs marked with an asterisk were first introduced in the United States.

The table shows how much various manufacturers have been involved in these developments and the varieties of

Table 2-1. Category 2 LFLRVs.

Year introduced	Builder	Model	Number built	Center truck type	Wheel arrangement	Sections	Where used
1984	Vevey	Be4/6	39	T6	B' 2' B'	2	Geneva, St. Etienne
1987	GEC Alstom	TSF	136	T2	B' 2' B'	3	Grenoble, Paris, Rouen, St. Etienne
1989	Vevey	Be4/8	34	T6	B' 2' 2' B'	3	Bern, Geneva
1990	Socimi	T8000	33	T3	Bo' 2 Bo'	3	Rome
1990	Duewag	NGT6C/ NGT6D/ MGT6D/ 6NGTWDE	283	T8	B'1'1'B'	3	Bochum, Bonn, Brandenburg, Dusseldorf, Erfurt, Halle, Heidelberg, Kassel, Muelheim, Oberhausen, Rostock
1993	Bombardier	T	78	T5	Bo'1'1'Bo'	3	Vienna
1994	Duewag/ Siemens	Valencia type	31	T3	Bo' 2 Bo'	3	Lisbon, Valencia
1994	Duewag	6MGT	64	T3	Bo 2 Bo	5	Ludwigshafen Mannheim
1994	Duewag	8MGT	5	T3	Bo 2 2 Bo	7	Ludwigshafen Mannheim
1994	DWA/ Alstom	NGT8D	25	T6	Bo' 2' 2' Bo'	3	Magdeburg
1995	Duewag	NGT8	56	T6	Bo' 2 '2' Bo'	3	Leipzig
1995	Adtranz/ Bombardier	GT6-70DN	45	T2	Bo' 2 Bo'	3	Karlsruhe
1995	DWA Bautzen	Flexity Classic NGT6DD	47	T2	Bo 2 Bo	5	Dresden
1995	Bombardier	Flexity Swift K4000	276	T2	Bo' 2 Bo'	3	Alphen, Cologne, Croydon, Istanbul, Minneapolis, Rotterdam, Stockholm
*1996	Siemens/ Duewag	SD- 600A/660A	79	T2	Bo' 2 Bo'	2	Portland
1996	ABB- Henschel	Variotram 6MGT-LDZ	58	T3	Bo 2 Bo	5	Heidelberg, Ludwigshafen, Mannheim
1997	Tatra	RT6N1	19	T3	Bo' 2' Bo'	3	Brno, Poznan, Prague
1997	Tatra	KTNF6	36	T2/T3	B' 1' 1' B'	3	Brandenburg, Cottbus
1998	FIAT	Cityway	28	T2/T3	Bo' 2 2 Bo'	5	Rome
1999	FIAT/Stanga	T5000	54	T2/T3	Bo' 2 Bo'	3	Turin
1999	Alstom	Citadis 401	68	T2	Bo' Bo 2 Bo'	5	Dublin, Montpellier
1999	Bombardier	Flexity Classic 8NGTW	40	T2	Bo' 2' 2'Bo'	3	Kassel
*1999	Breda	Type 8	100	T2	Bo' 2 Bo'	2	Boston

(continued on next page)

product that have been developed, partly because of the “modular” or “platform” approach that adapts a basic design to meet various specifications. The history of some of these developments is described in Section 2.2.

The table also shows the extent to which the various center truck configurations have been applied. The types used

have been T2, T3, T5, T6, and T8. The more recent developments have not used the T8 and the T5 option only appears once.

Use of the T2 and T3 categories of independent wheel center trucks is widespread and has been a sales success for various manufacturers. This type is generally regarded as having lower

Table 2-1. (Continued).

Year introduced	Builder	Model	Number built	Center truck type	Wheel arrangement	Sections	Where used
*2000	Kinki Sharyo		187	T2	Bo' 2 Bo'	2	Hudson-Bergen, Newark, Santa Clara
2000	Ansaldo-breda	T69	16	T3	B' 2' B'	3	Birmingham
2000	Alstom	Citadis 301	69	T2	Bo' 2 Bo'	3	Dublin, Orleans, Valenciennes
2000	Bombardier	Flexity Classic M8DNF	34	T2	Bo' 2' 2' Bo'	3	Essen
2002	Bombardier	Flexity Classic NF2000 NGT6	40	T2	Bo' 2' Bo'	2	Dessau, Halle
2002	CAF		8	T2/T3	B' 2 B'	3	Bilbao
2003	Bombardier	Flexity Classic NGT6	26	T2	Bo' 2' Bo'	3	Krakow
2003	Bombardier	Flexity Classic NGTD12DD	32	T2	Bo' Bo' 2' 2' Bo' Bo'	5	Dresden
2003	Bombardier	Flexity Classic NGT8'S'	60	T2	Bo' 2' 2' Bo'	3	Frankfurt
2003	Bombardier	Flexity Classic SN2001	30	T2	Bo' 2' 2' Bo'	3	Schwerin
2003	Alstom	Citadis 500	28	T2	Bo' 2' 2' Bo'	3	Kassel
2003	Leipzig Works	Leoliner	37	T2/T3	Bo' 2' Bo'	2	Leipzig
*2003	Siemens	Avanto S70	44	T2	Bo' 2 2 Bo'	5	Houston, Paris, San Diego
2005	Siemens	NGT6D	45	T2/T3	Bo' 2 Bo'	3	Ghent
2006	Bombardier	Flexity Classic NGTD8DD	50	T2	Bo' Bo' 2' Bo'	5	Dresden
2006	Alstom	Citadis 500	50	T2	Bo' 2 Bo'	3	Den Haag

technical risk than a 100-percent low-floor (Category 3) LRV but issues of high wheel wear on the center trucks are widespread.

Some designs are more successful than others, and the inherent sensitivity of the arrangement allows minor adjustments to vehicle and truck design parameters to give significant benefits in running behavior. This has been borne out by the research undertaken.

Vehicles with the T6 type of conventional, small-wheel truck have reportedly performed well. The small-wheel truck is always located fully underneath a body section and not mounted under a short "center section." The truck is free to pivot and is not attached to the other body section. This may influence performance positively.

Single wheelsets designs (T5 and T8 categories) have not been perpetuated beyond the early orders documented in *TCRP Report 2*. In particular the EEF wheelset-equipped cars have reportedly not performed as well as anticipated in all cases because of the high cost of maintaining the relatively complex steering system.

Section 1.3 demonstrated that 100-percent low-floor cars are now achieving a high level of successful applications in Europe and have taken a significant proportion of the market from the partial low-floor concept. One-hundred-percent low-floor cars offer the advantage of a uniform floor level as well as easier access, but often a uniform floor level can only be achieved with some restriction on available floor space. There have been no applications of this type, which falls in Category 3, to date in the United States and Canada.

The issue of adopting 100-percent low-floor cars was considered in *TCRP Report 2* (Chapter 3). The study concluded that introduction into the United States and Canada on entirely new systems might prove difficult because

- New systems might not wish to assume the potential liability for specifying lower buff loads, even though no technical reason was identified why this cannot be done.

- One-hundred-percent low-floor designs might not meet stringent U.S. and Canadian fire standards (ASTM E-119 was specifically cited).

Ten years since the publication of *TCRP Report 2*, the greater availability and worldwide experience of 100-percent low-floor operation may now outweigh the liability issue. These issues are considered in Chapter 4 under “Best Practice for System Design,” and recommendations for research into how this type of vehicle might be introduced in the United States and Canada are included in Chapter 5.

A notable development is the appearance of a significant number of 100-percent low-floor cars (Category 3 in *TCRP Report 2*) having conventional small-wheeled trucks throughout. The low floor is achieved by the use of 560-mm-diameter wheels and 5-percent ramps to allow the floor to clear the trucks, without introducing steps. These cars have been successful in sales terms and the researchers are not aware of any major dynamic/wear-related issues with them. This tends to support the conclusion of *TCRP Report 2*, which expressed optimism in regard to this particular concept. However, wheel contact stresses are higher with small wheels for a given axle load.

One source (3) has suggested that the optimum arrangement for future LFLRVs would be to employ conventional motor bogies and a conventional small-wheeled trailer bogie in the center, based on experience with the existing car designs.

2.2 Product Development

This section gives a brief overview of the products of the major suppliers that fall into the Type 2 LFLRV category. These products were known to the researchers when the research was completed and any omissions are accidental. TCRP does not endorse any particular product described here.

2.2.1 ALSTOM

GEC Alsthom developed some of the earliest LFLRVs, the French Standard Type (TSF), which first entered service in 1987 in Grenoble. These vehicles are a three-section design with a short center section fixed to a truck with cranked axles and IRWs (Type T2).

This company is now part of ALSTOM, which has developed this technology into the modular “Citadis” range. The Citadis is available in three configurations. Three of these are Category 2, the basic 301, 401, and 500 models having conventional motor trucks and an independent wheel center truck. The “Regio Citadis” 500 model is designed for longer distance and higher speed routes and has an extra center truck. These are designed for use in shared running applications.

ALSTOM also produces a version of the Citadis that is a Category 3 vehicle with IRW trucks throughout.

The center truck of the Category 2 Citadis cars is the “Arpege” type, a design that has no primary suspension, relying instead on a flexible truck frame, resilient wheels, and coil spring secondary suspension at the corners of the frame. The design of the wheelsets incorporates a low-level driveshaft linking the wheels together. As such they are not truly IRWs. Table 2-2 summarizes some of the main deliveries made of these vehicles.

2.2.2 Kinki Sharyo

Kinki Sharyo is the manufacturing arm of the Kintetsu Group of companies. They have worked with ALSTOM and have only supplied LFLRVs within the United States and Canada. The center trucks were developed by Fiat-SIG with assistance from PROSE AG. The truck design is conventional, employing cranked axles, chevron rubber primary suspension and air bag secondary suspension.

Kinki Sharyo has a large part of the U.S. market; this has been a significant development in recent years. They introduced LFLRVs into the United States which now have millions of miles of operating experience. One hundred and forty-five vehicles have been delivered and more are on order. The vehicles were supplied to NJ TRANSIT and Santa Clara Valley Transportation Authority (VTA). They are supplying low-floor center sections to convert existing LRVs in Dallas to LFLRVs.

2.2.3 AnsaldoBreda

This company was formed by the merger of two Italian firms Ansaldo and Breda; the latter had been a vehicle (e.g., locomotives, coaches, multiple units, metro cars, and streetcars) builder. The company has supplied many LRVs, including cars for the Cleveland Transit Authority and San Francisco Muni, but until recently had built relatively few LFLRVs. The early designs for AnsaldoBreda LFLRVs were delivered to the Massachusetts Bay Transportation Authority (MBTA) in Boston, Midland Metro (UK), Oslo Tramways (Norway) and Lille Transpole (France). The Oslo car is a Category 1 with all conventional trucks while the Lille cars are virtually Category 3 cars with a large low-floor area and a very different running gear system that incorporates

Table 2-2. ALSTOM (and predecessor) Type 2 LFLRVs.

Product	Main cities	Approx. numbers built
Citadis 301	Dublin, Orleans, Valenciennes,	69
Citadis 401	Dublin, Montpellier	68
Citadis 500	Den Haag, Kassel	78
TSF (French Standard)	Grenoble, Paris, Rouen	116
TOTAL		331

conventional motor trucks fitted under a high-floor area containing the cab and other electrical equipment. The Boston MBTA and Midland Metro cars are classic Category 2 configurations, but the center trucks differ in their design.

Sixteen Category 2 LFLRV vehicles are in use on the Midland Metro and 100 have been ordered and some introduced into service by Boston MBTA.

Ansaldobreda also offers a modular range known as Sirio, but it is a Category 3 100-percent low-floor design not relevant to this study.

2.2.4 Bombardier

The “Flexity Swift” LFLRV cars that run on the Minneapolis Metro Transit are part of a range of similar products. Bombardier developed the standard Flexity Swift range with the first examples appearing in Cologne in 1995. Very similar vehicles have also been built for Istanbul, Croydon, Rotterdam and Stockholm. This product is a classic Category 2 design with three sections, and an IRW truck under the short center section. It is intended for light rail systems with a mix of street track and segregated running.

Through mergers and takeovers, Bombardier has also inherited a range of other Category 1, 2, and 3 designs, which it now sells under the same “Flexity” brand. Of relevance to this study is the “Flexity Classic” design, originally developed by DWA as the “LF2000.” This is a Category 2 design similar in concept to the Flexity Swift but with a different configuration of vehicle bodies. There is no small center section, with IRW trucks with freedom to yaw instead being placed under full-length body sections. This design has been very popular in Germany, notably with Frankfurt am Main where an option for more Category 3 cars was abandoned in favor of this more traditional type of vehicle.

Bombardier offers a Category 3 product, Flexity Outlook, which uses these trucks to obtain a 100-percent low floor. The company claims that these trucks give much better running performance than IRW alternatives and, as such, no longer markets its inherited IRW Category 3 designs. Table 2-3 summarizes some of the main deliveries of these vehicles.

Table 2-3. Bombardier (and predecessor) Type 2 LFLRVs.

Product	Main cities	Approx. numbers built
Flexity Classic	Adelaide, Bremen, Dessau, Dresden, Essen, Frankfurt-am-Main, Halle, Kassel, Krakow, Schwerin	389
Flexity Swift	Alphen, Cologne, Croydon, Istanbul, Minneapolis, Stockholm	255
GT6-70DN	Karlsruhe	70
T	Vienna	3
Variotram	Heidelberg, Ludwigshafen, Mannheim	42
TOTAL		759

2.2.5 Siemens/Duewag

Siemens (formerly Duewag) based its first Category 2 design on the EEF self-steering wheelset concept. Many of these vehicles were constructed, but Siemens stopped developing this design in the 1990s. The company produced some more typical Category 2 vehicles and the center trucks for the Siemens Duewag/Adtranz (later Siemens/Bombardier) GT6-70DN cars introduced in Karlsruhe, Germany, beginning in 1995.

Most relevant to the U.S. market are the SD-600 and SD-660 types. These are a Category 2 design of which there are 79 on the TriMet system in Portland, Oregon. Siemens’ second product is the “Avanto” type, a Category 2 design having a short center section with cranked axles and IRWs. These operate in Houston, on new infrastructure. Table 2-4 summarizes some of the main deliveries of these vehicles. Siemens offers the “Combino” range as its standard product. This is a Category 3 100-percent low-floor design that has all IRWs.

2.2.6 Summary

Table 2-5 summarizes the statistics of the vehicles considered in this review and indicates the scale of U.S.

Table 2-4. Siemens (including Duewag) Type 2 LFLRVs.

Product	Main cities	Approx. numbers built
6MGT	Ludwigshafen, Mannheim	64
8MGT	Ludwigshafen, Mannheim	5
Avanto S70	Houston, Paris, San Diego	34
Buenos Aires	Buenos Aires	9
Lisbon	Lisbon	10
MGT6D	Bochum, Brandenburg, Erfurt, Halle, Heidelberg, Muelheim, Oberhausen	146
NGT6C	Kassel	25
NGT6D	Bonn, Dusseldorf	72
6NGTWDE	Rostock	40
NGT8	Leipzig	56
NGT8D	Magdeburg	71
SD-600A	Portland	52
SD-660A	Portland	2
Valencia	Valencia	25
TOTAL		611

Table 2-5. Summary of vehicle numbers for Category 2 type LFLRVs.

Supplier group	Cars	% of total	Cars US	US % of supplier group	% of US total
ALSTOM	331	15	0	0	0
Bombardier	759	34	24	3	7
Breda	116	5	100	86	27
Kinki Sharyo	145	7	145	100	39
Siemens	636	29	98	15	27
Other	238	10	0	0	0
TOTAL	2225	100	367	17	100

applications and how the products used differ from experience generally.

2.3 Application in the United States

Table 2-6 summarizes the deliveries of the Category 2 LFLRVs in the United States with center trucks having IRWs. There are six basic car types, originating from three separate supply strands (i.e., [1]Siemens/Duewag; [2] Breda; and [3] Kinki Sharyo and Bombardier). Combining these car types with the eight transit systems with differing characteristics provides varied experience.

Appendix C provides more detailed information about most of these cars.

Appendix D provides details of the systems over which these vehicles operate. The systems are grouped as old or new as follows:

- Old—traditional streetcar systems opened before 1950, including those that have been modernized and extended but not reconstructed to modern LRT standards; and
- New—modern LRT systems opened since 1970.

All seven transit agencies were surveyed for specific information about these cars, track standards, experience with the use of the center trucks, and any mitigation they may have introduced for overcoming issues.

The following sections describe the experience in each U.S. city, concentrating on those that have the most vehicles or the most experience of performance issues. The information is taken from a literature search, a questionnaire, visits to some of the systems, and correspondence as explained in Appendix A.

2.3.1 Portland TriMet

Infrastructure

The Tri-County Metropolitan Transportation District of Oregon (TriMet) operates a 33-mile-long light rail system in

Portland. The first section opened in 1986. There is also a short streetcar line and a vintage trolley service.

LFLRV Fleet

The first batch of Portland cars were on order when *TCRP Report 2* was published. There were 46 cars and 6 more of this type (SD-600A) were added later. Portland also took delivery of 27 cars of type SD-660A later, bringing the total fleet of LFLRVs to 79. TriMet has pointed out that the SD-600A and SD-660A are virtually identical, so these are considered as one type from here on.

Details of the Center Trucks

The center truck frames are rigid and have independent resilient 26-inch (660-mm) Bochum wheels on a cranked drop axle. The primary suspension is provided by conical rubber chevron springs; the secondary suspension is provided by coil springs controlled by lateral and vertical dampers. Resilient traction links control yaw. The center truck is braked. No vehicle-mounted lubrication is used.

Measures Undertaken When These Vehicles Were Introduced

A computer model simulation of the routes was used when the vehicles were selected in order to check that the vehicles would be suitable. Vehicles were also test run on the routes before being accepted. The supplier provided operation and maintenance manuals as well as training.

Experience Using These Vehicles

TriMet's experience in using these vehicles has generally been good. Wheel wear has been higher than for other types of car, but passengers have not raised issues about noise and ride comfort, and there have been no derailments. There would be no issue about introducing further cars of this type or other types of LFLRV.

TriMet is required to comply with the FTA *Guidelines for Design of Rapid Transit Facilities* in which interior noise should not exceed 78 dBA at 55 mph except in tunnels. TriMet has exceeded these standards with wheels that are rough or with flat spots and on corrugated rail.

Measures To Reduce Issues

Wheel flange wear on the center truck occurs at a higher rate than on the motor trucks as TriMet expected. The LFLRV center truck tends to produce more squeal than motor trucks. About 20 wayside lubricators have been installed at sharp

Table 2-6. Category 2 LFLRV deliveries, North America.

City/system	LFLRVs	Years supplied
Portland MAX	Siemens/Duewag SD-600A and SD660A	1996-2004
Boston MBTA	Breda Type 8	1999-2003
NJ Transit Hudson-Bergen and Newark Subway	Kinki Sharyo	2000-4
San Jose, Santa Clara VTA	Kinki Sharyo	2001-4
Minneapolis Metro Transit	Bombardier Flexity Swift	2003-4
Houston METRO	Siemens Avanto S70	2003-4
San Diego SDT	Siemens Avanto S70	2004

curves in embedded track to mitigate wheel squeal from both low- and high-floor LRVs. These lubricators have been used for the past 2 years on girder rail, embedded track, and some open track; they also help reduce wheel and rail wear. They are considered to have been effective. Lubricant is pumped through a 1/4-inch-diameter hole in the rail head at the wheel/rail contact area. On open track, TriMet also has about 10 wayside lubricators. Figure 2-1 illustrates a wayside lubricator.

Residents have complained of noise from vehicles, and readings of 80 dBA have been made. This has been mitigated by rail grinding and keeping wheel profiles in good condition.

2.3.2 Massachusetts Bay Transportation Authority (MBTA)

Infrastructure

MBTA operates 31 miles of streetcar lines in Boston. These lines developed out of a system that had its origins 150 years ago. The 25-mile-long Green Line, where LFLRVs are used, dates in part from 1897. Parts of this line are underground subway. Unlike the Portland Metropolitan Area Express (MAX) system, the Green Line is a long-established streetcar network with many potentially challenging infrastructure features. It is also one of the busiest systems of its kind in the United States and Canada, with relatively intense and complex services. The track used on the Green Line has relatively severe geometry. Curves can be as tight as a 42-ft (12.8-m) radius with no tangent track between reverse curves.

LFLRV Fleet

MBTA ordered 100 cars from AnsaldoBreda, the first of which was delivered in 1998 for testing (4). They were designated Type 8 by MBTA and have been used only on the Green Line. Figure 2-2 shows such a car.

Measures Undertaken When These Vehicles Were Introduced

The supplier ran a computer simulation of the Type 8 design, based on track conditions considered appropriate. Test running before operation in Boston was limited to 10 mph

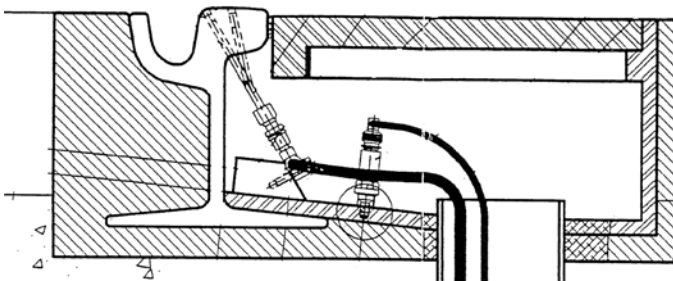


Figure 2-1. Wayside lubricator.



Figure 2-2. MBTA Type 8 LFLRV on the Green Line in Boston.

on a short test track, but trial running was also undertaken on the Green Line. The manufacturer provided specialized operations and maintenance training and operations and maintenance manuals.

Details of the Center Trucks

Figures 2-3 and 2-4 show views of the center truck used on the Type 8 cars. As explained in Section 2.2.3, this car design is unique to Boston. The center truck frame is flexible. In plan view, it has two L-shaped elements with a spherical joint connection at the end of the shorter arm of each element (see Figure 2-5).

The IRWs are mounted on a low-level cranked axle so that they are constrained as if they were on a conventional solid axle. The primary suspension consists of stiff rubber bushings between the truck frame and the axle. These are formed of metal external and internal rings with rubber between them. The rubber element is configured so as to give a variation

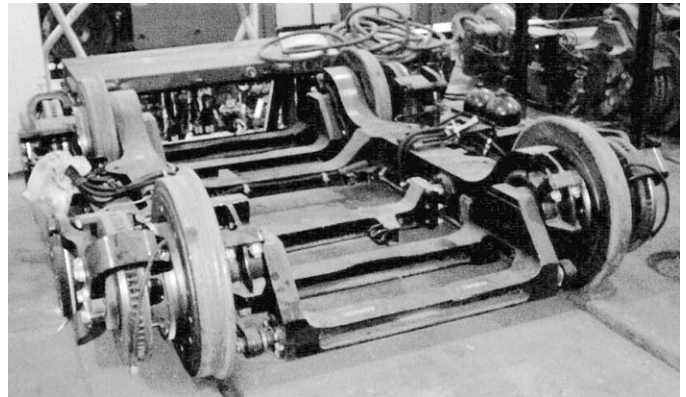


Figure 2-3. Center truck of MBTA Type 8 car (general view).

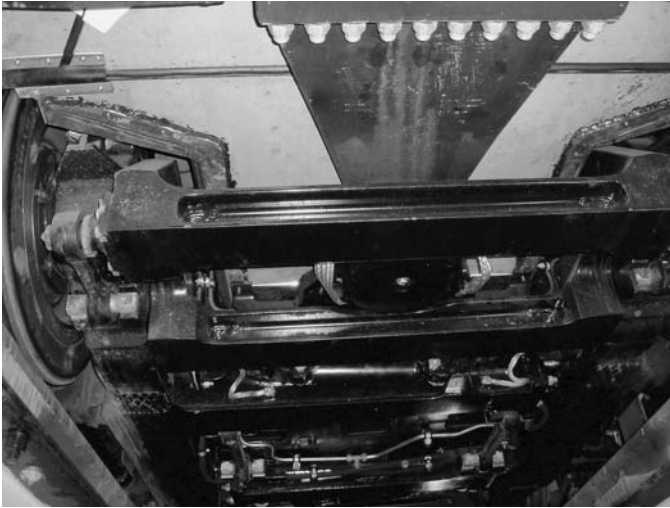


Figure 2-4. Underside view of the center truck (MBTA Type 8).

between vertical and longitudinal stiffness. Figure 2-6 illustrates this arrangement.

Four air springs are used to support the bolster; these are arranged inboard of the axles, and each pair is linked from side to side by a common leveling valve. The two ends are linked through a relay valve, which permits cross feeding. This arrangement is controlled by two lateral dampers. Figure 2-7 illustrates this arrangement. As illustrated in Figure 2-8, the center truck has an anti-pitching system using a torsion rod to provide stiffness. The roll control of the entire vehicle and of the center section is largely performed by transverse rods on the roof; the joints are spherical ball bearings in line with the relative trailing axle. Figure 2-9 illustrates this arrangement. The vertical pitching of the center section is controlled by the air springs and anti-pitching bars; there is no pitch damping.

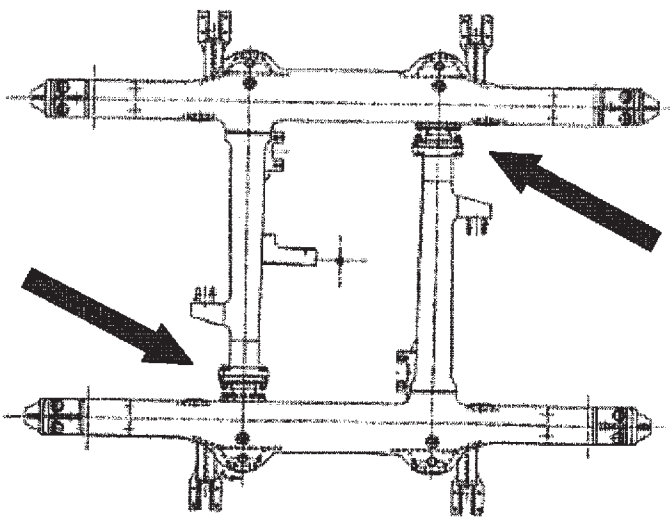


Figure 2-5. Articulated center truck frame (MBTA Type 8).

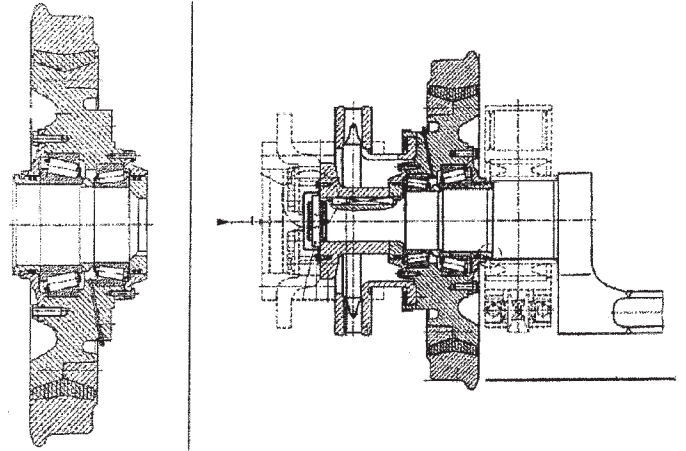


Figure 2-6. Cranked axle arrangement, IRW and primary suspension (MBTA Type 8).

Experience Using These Vehicles

Since the Type 8 cars were introduced in 1999, some derailments have occurred. MBTA has also experienced excessive wheel and rail wear associated with these cars. There have been issues with interior noise resulting from the difficulty of damping the noise coming from the wheel-rail interface within the tight space envelope. Ride comfort requirements are met, although some yaw and pitching movements are noticeable. There have been no complaints from passengers however.

Measures To Reduce Issues

In 2001, investigations began to study the causes of the derailments using simulations and a special test track facility. As a result a new wheel profile was introduced and track maintenance standards were altered (5).

Derailments occurred on tangent track because of lateral disturbances caused by track irregularities. These irregularities were a combination of gauge widening and cross level variation, which created a large angle of attack and caused wheel climbing. Vertical movement of the center truck causes a truck yaw rotation because of the arrangement of the traction links. This is noticeable at speeds above 35 mph, and, at speeds above 40 mph, the lateral-to-vertical-force ratio is exceeded, increasing derailment risk. The manufacturer

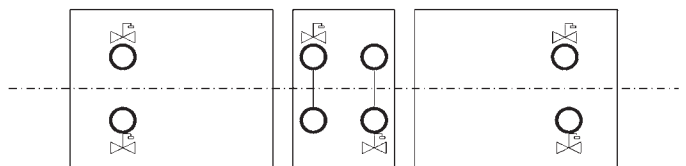


Figure 2-7. Air spring control system (MBTA Type 8).

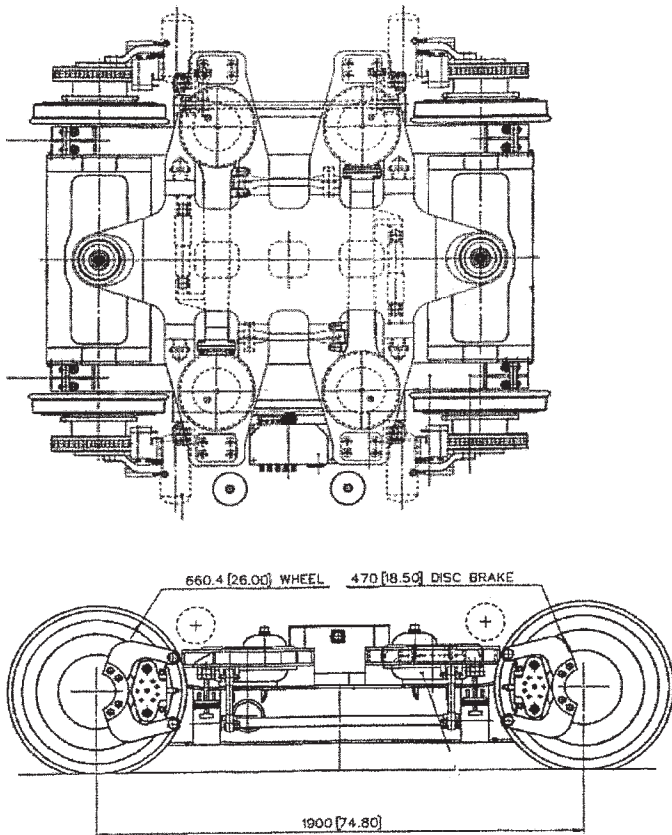


Figure 2-8. Anti-pitching system (original design) (MBTA Type 8).

introduced a modification that allows the cars to operate up to 50 mph without exceeding the limit at which the lateral-to-vertical force ratio might cause derailment.

A modification has improved the control of yaw on the center truck. The modification consists of a virtual pivot with traction rods. An asymmetric arrangement of two traction rods ties the bolster and truck frame together. Smaller “dog bones” are tied to the truck frame to prevent rotation of the wheelsets. The bolster-to-frame arrangement is being changed to a design that provides greater rotational freedom between the truck and car body by introducing a virtual center pivot with limited rotational freedom.

Part of the Green Line (the B Line) was changed to the new track maintenance standard, and the railhead was re-profiled

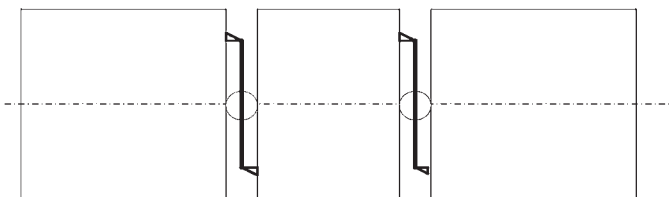


Figure 2-9. Roof-mounted rods to prevent inter-section roll (MBTA Type 8).

to remove the lip that had developed from wear. The maintenance interval was reduced from 6 to 3 months.

Type 8 cars received the new wheel profiles first, followed by the earlier Type 7 high-floor cars. These earlier cars were not modified but are wearing to the new profile. At first wheels had to be re-profiled every 2,000 miles to keep them within limits, but now wheels can be used in excess of 30,000 miles before re-profiling is necessary. No derailments resulting from dynamics have occurred since March 2003.

Excessive wheel wear has been greatest on the motor trucks, with localized wear at the flange tip resulting in the flange angle degrading rapidly. At one time it was necessary to re-profile the wheels as often as every 2,000 miles, as mentioned. This occurred because of changing the flange angle from the older Green Line standard of 63 to 75 degrees to mitigate derailment issues. This was a transition issue and was overcome by seven measures:

- Very close monitoring of wheel profiles,
- Checking maintenance tolerances by use of dynamic modeling,
- Gauge face grinding of the rail,
- Design and grinding of a new railhead profile to promote better steering and reduced contact,
- Changing the profile on other cars in the fleet,
- Grouping cars with the new profile on one line, and
- Tests of a friction modifier.

The early test results of the use of a stick lubricator on the front and back flanges of the wheels on the motor trucks were inconclusive and were based on limited data. As mentioned, the overall result has been to increase the mileage between truing to more than 30,000 miles.

There has also been excessive rail wear from the same cause and re-grinding has reduced this issue. This has, however, shortened the potential life of the running rail. The most severe wear issues occur on tight-radius curves (less than 100-ft radius) and are caused by all vehicles. MBTA believes that IRWs actually may have lower contact forces on these sharp curves.

The addition of sound-deadening panels beneath the floor and inside the articulation bellows reduced the noise level within the vehicles to limits that met the appropriate standards.

2.3.3 Newark Subway

Infrastructure

NJ TRANSIT operates the Newark Subway, which is a short (5-mile-long) remnant of a much larger streetcar network. This route was built in a tunnel in 1935 and has survived as a relatively busy small transit system, with an extension now

under construction. The subway uses traditional streetcar technology, where the wheels have narrow tires, although it does not have any street running sections; it does have tight curves at the city center end of the route.

LFLRV Fleet

NJ TRANSIT introduced 18 Kinki Sharyo LFLRVs in 2000 for use on the Newark system (see Figure 2-10); this fleet is being expanded.

Details of the Center Trucks

The center trucks were supplied by Fiat-SIG (see Figures 2-11 and 2-12). The center truck frames are rigid “H” type and have 26-inch (660-mm) Bochum IRWs on a low-level “cranked” beam referred to as an “idler axle.” The primary suspension is provided by rubber chevron springs; the secondary suspension is provided by air springs. Resilient traction links control yaw. The center truck is linked to the end sections by bearings under the articulation and the relative movement is controlled by a pair of Z-links and two dampers above one of the joints. These Z-links and dampers are roof mounted (see Figure 2-13). The center truck is braked and has track brakes. A REBS grease spray lubrication system has been tried on one car for over a year as an experiment. The REBS grease spray lubrication system has two nozzles for each axle end and sprays REBS friction modifier on the wheel. The vehicles are fitted with a special wheel profile (see Figure 2-14), which is appropriate to the track geometry of the subway.

Measures Undertaken When These Vehicles Were Introduced

A computer model simulation of the routes was used when the vehicles were selected in order to check that they would be



Figure 2-10. NJ TRANSIT Kinki Sharyo LFLRV in Bloomfield workshop.

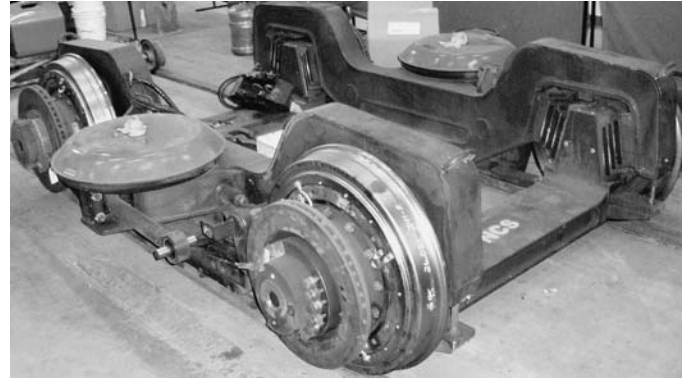


Figure 2-11. Center truck (NJ TRANSIT Kinki Sharyo LFLRV).

suitable. Vehicles were also test run on the subway and elsewhere before being accepted. The supplier provided operations and maintenance manuals and training.

Experience Using These Vehicles

NJ TRANSIT’s experience in using these vehicles has generally been good although issues have occurred.

Wheel wear has been higher than for conventional cars. Center truck wheels wear faster than those on the drive axles. Wheel turning started after 100,000 miles and was repeated at 30,000-mile intervals. This was causing the flange thickness to increase, so profile correction is necessary as part of the wheel turning. Although the subway is small, the depot is equipped with a modern underfloor wheel lathe. NJ TRANSIT staff have observed that the truck’s curving behavior on curved tracks and switches probably causes the excessive wear. The hardness of the tires was designed to give optimum wheel and rail wear rates.

Excessive rail wear generally occurs on curved track and typically on switches and crossings. The highest rate of wear occurs at the reversing loops in Penn Station. These reversing



Figure 2-12. Lateral bump stops on the center truck (NJ TRANSIT Kinki Sharyo LFLRV).

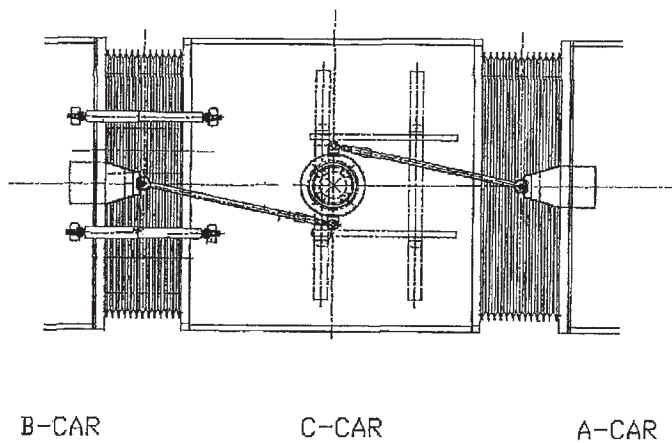


Figure 2-13. Roof-mounted Z-links and dampers (NJ TRANSIT Kinki Sharyo LFLRV).

loops have radii of 60 and 82 feet. All cars pass around them, but they are not carrying passengers at the time.

The inner rail on these curves is more affected. NJ TRANSIT predicts the need to replace the rails on these loops every 10 years but might be able to extend this to 15 by optimizing the performance of the wayside lubricators.

Three derailments have occurred, but these have all happened at slow speed on switches. The cause has been identified as the tendency of the center truck to curve. This side curving can cause derailment because of adjustment of the switch blade under the stock rail, thereby causing a step up and associated with a cross leveling of more than 1/8 in. toward the point of the switch. This has been identified as the cause in all cases.

Noise levels are high on the Penn loop; figures of 109 dBA have been recorded when speed has exceeded 5 mph.

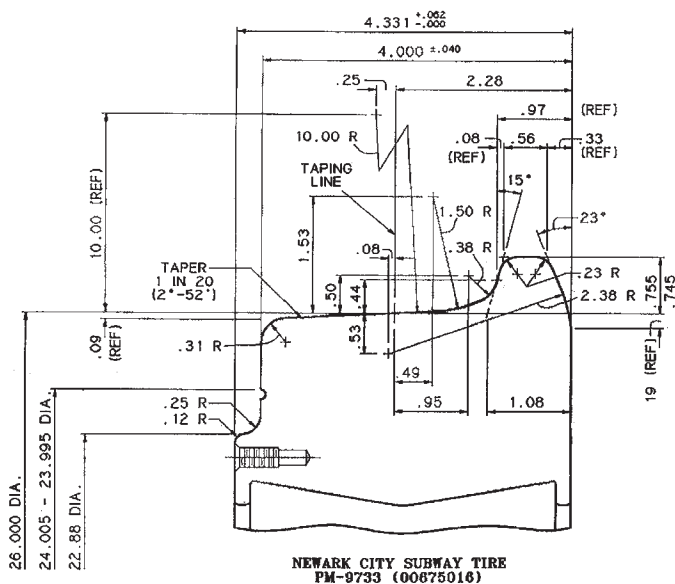


Figure 2-14. Newark city subway wheel profile.

Although passengers are not carried on this section, any excessive noise affects passengers waiting at the adjacent platforms.

Ride comfort has not been an issue.

There would be no issue about introducing further cars of this type or other types of LFLRV on the Newark Subway.

Measures To Reduce Issues

NJ TRANSIT has introduced house tops to stop derailments from occurring. House tops are fitted to all switches, except those operated infrequently.

The noise issue on the Penn loop is being managed by using lubrication, gauge widening, flange way widening and installation of restraining rail at both rails (see Figures 2-15 and 2-16).



Figure 2-15. Fully guarded switch in Penn Station.

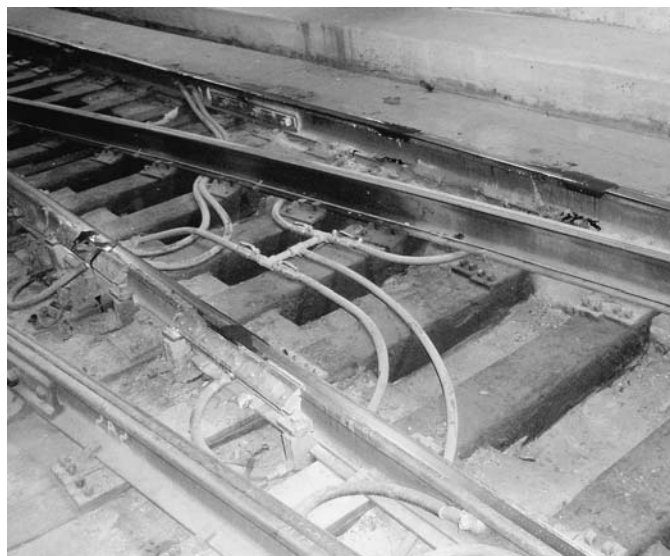


Figure 2-16. Rail surface friction conditioner at Penn Station, showing lubricant on rail surface.



Figure 2-17. Friction conditioners for rail flange and guide rail in the workshop area.

Gauge widening will increase the angle of attack, but in this situation the derailment risk is low.

There are 12 lubricators in the yard to cover all turnouts and sharp curves (see Figure 2-17). Also there are four way-side friction modifiers. Two are on the Penn loop and the others are on a 100-ft-radius curve close to an apartment building.

2.3.4 Hudson-Bergen NJ TRANSIT

NJ TRANSIT also introduced 29 LFLRVs of the same type as used on the Newark Subway onto the new Hudson-Bergen line in 2000. A further order is pending.

The Hudson-Bergen uses the AAR1B wheel profile (5¼ inches wide) and a different wheel back-to-back dimension (53⅜ inches compared with 54⅞ inches on the Newark Subway). No specific issues have been reported by NJ TRANSIT. Such issues as have been encountered with these cars on the Newark Subway are mainly associated with the more extreme geometry of older streetcar track. Hudson-Bergen is re-profiling all wheels at 30,000 miles, so wear may not have been identified as an issue. The maintenance of the cars is not carried out directly by NJ TRANSIT, but by the car builder under the Design, Build, Operate, and Maintain (DBOM) contract.

2.3.5 Santa Clara Valley Transit Authority (VTA)

Infrastructure

The Santa Clara VTA system of San Jose is a newly built light rail; it was inaugurated in 1987. The route is 30 miles long. The

route uses both girder (Ri59) and standard (115 RE) rail. The minimum curves are 30 m (98 feet) on the route and 25 m (82 feet) in the depot.

LFLRV Fleet

Kinki Sharyo has supplied a fleet of 100 LFLRVs to the Santa Clara VTA; these have an ALSTOM traction system (see Figure 2-18). Thirty were supplied in 2001-2 and a further 70 were supplied in 2004. Mileage is 30,000 to 120,000 miles per year per vehicle, with 42 required to provide the service.

Details of the Center Trucks

The center truck frames are rigid and have full independent resilient 26-inch (660-mm) Bochum wheels. The primary suspension is provided by rubber chevron springs, the secondary suspension is provided by air. The center truck cannot yaw because it is integral with the central module. The center truck is braked. No vehicle-mounted lubrication is used. These cars are very similar to those in use by NJ TRANSIT (see Figures 2-19 and 2-20).

Measures Undertaken When These Vehicles Were Introduced

Track is ground to provide uniform wear of the running surface including asymmetric railheads on curves.

Vehicles were test run on the route before being accepted and the fact that NJ TRANSIT were already operating similar vehicles was important. The supplier provided operation and maintenance manuals and training.



Figure 2-18. VTA Kinki Sharyo LFLRV.



Figure 2-19. Cranked axle under the articulation (VTA Kinki Sharyo LFLRV).

Experience Using These Vehicles

VTA's experience in using these vehicles has generally been good. There have been no wheel or track wear issues or derailments and ride comfort has not been an issue. There would be no issue about introducing further cars of this type or other types of LFLRV to the system.

Noise is excessive on sharper curves (less than 600 feet radius), but this occurred with high-floor cars as well.

The fleet has now accumulated more than 4 million miles and the VTA and its customers are very pleased with the performance and ride comfort of these vehicles. No hunting, noticeable resonance in the suspension, or other unpleasant side effect is attributable to the low-floor technology. Both interior and exterior noise emissions and vibration are within specification.

Measures To Reduce Issues

The wheel profile is being changed so as to provide an extended transition between the conical part of the running surface and the flange. This is being done in order to reduce

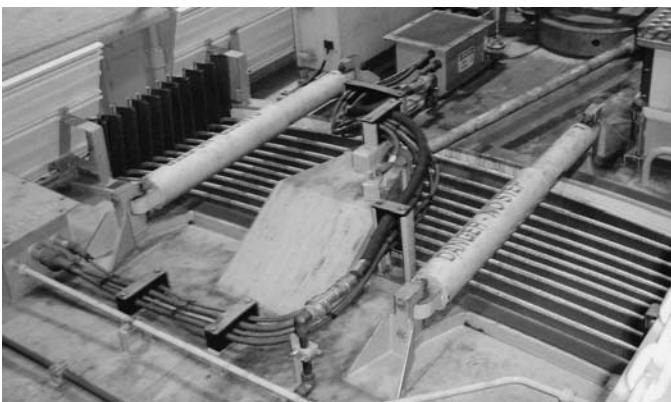


Figure 2-20. Roof-mounted articulation dampers and Z-link.

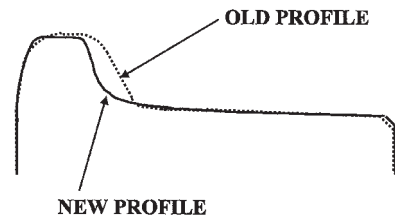


Figure 2-21. Alteration to the VTA wheel profile.

the truing interval and hence extend the life of wheels. Figure 2-21 illustrates this measure.

There have been issues with railhead corrugation on embedded track since the system was opened and this has continued with the introduction of LFLRVs.

Also anticipating issues, VTA installed wayside flange lubricators in order to reduce wheel squeal on sharp curves. The system is also experimenting with surface friction conditioners (see Figure 2-22). These measures are provided in order to reduce wheel squeal for all types of car.

All vehicles are fitted with the supports and holders for flange, surface, and wheel back conditioning (see Figures 2-23 through 2-25). All the sticks have, however, been removed because of concern about extending braking distances.

Because of the high deceleration rate, the friction brake on the center trucks is heavily used. The brake discs are close to the wheel and the wheel bearings, causing the grease to warm up. The bearings have to be overhauled regularly because the properties of the grease change from this heat.

Center trucks are showing slightly more flange wear than motor trucks and these trucks are noisier than motor trucks or older conventional cars.

Lubricators have been installed and these solve noise issues most of the time.

Deraillments have occurred, but these have all been because of operator error and, in one case, an automobile collision. The moments transferred through the car bodies caused a high angle of attack of the wheels of the center truck (see Figure 2-26)



Figure 2-22. Surface friction conditioner, Santa Clara.

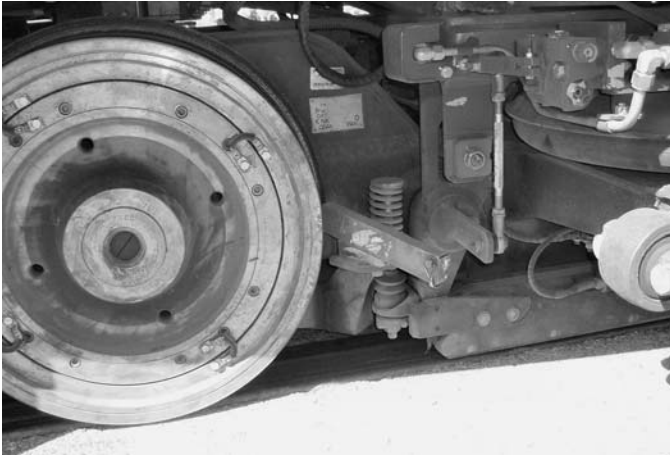


Figure 2-23. Holder for the wheel flange friction conditioner.



Figure 2-24. Holder for the wheel tread friction conditioner.

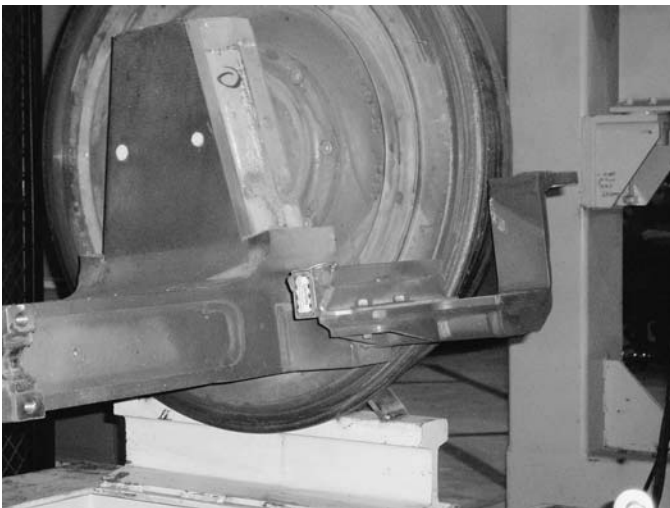


Figure 2-25. Holder for the wheel back face friction conditioner.

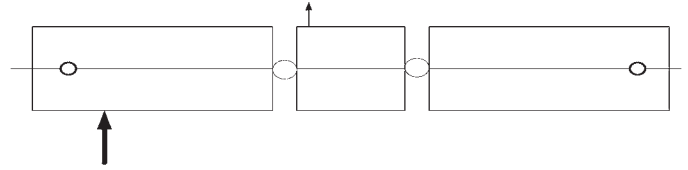


Figure 2-26. Side collision—the center truck derails because of the reaction of lateral loads.

2.3.6 Minneapolis Metro Transit

Infrastructure

The Minneapolis Metro Transit “Hiawatha Line,” a new light rail system opened partly in June 2004 and fully in December 2004, is 12 miles long (6).

LFLRV Fleet

The Hiawatha Line fleet consists of 24 Bombardier Flexity Swift type LFLRVs. These vehicles are based on the K4000 cars used in Cologne.

Details of the Center Trucks

The center trucks have IRWs. These trucks have radial arm suspension with the arms linked by a horizontal rod. The primary springs are rubber and the secondary suspension is provided by coil springs.

Experience Using These Vehicles

Operating experience is limited, although test running began in March 2003. A low-speed derailment occurred in a maintenance yard in March 2005 (7). This was caused in part by excessive wheel wear, and the system instituted more regular inspections as a result. The curve was said to be tighter than on the service route. Also, varying wheel wear had been found on the wheels of the center trucks on 22 of the LFLRVs, and they were still under warranty.

2.3.7 Houston MetroRail

Infrastructure

The MetroRail Red Line is a light rail system that began operation in Houston, Texas, in January 2004. It is 7½ miles long and part of the Metropolitan Transit Authority of Harris County. Track geometry is not severe—the minimum curve being a 125-ft (38.1-m) radius. Most of the track is conventional 115 RE rail, although 80 percent of the route is embedded.

LFLRV Fleet

Eighteen Siemens Avanto S70 LFLRV cars have been supplied—delivery began in 2003. There has been over 2 years’ of experience of operating this type of LFLRV; these are the only type of vehicles used on the system. Speeds have been limited to 40 mph (see below) although the cars can reach higher speeds.

Details of the Center Trucks

The Avanto vehicles have IRWs on the center trucks. The design uses cranked axles and a rigid center truck frame. The primary suspension consists of eight conical chevron rubber springs mounted on the inboard side of each wheel on the axle flange. The secondary suspension uses high-pressure hydraulic springs that maintain the car-body floor to platform height by means of six level sensors. Lateral damping is used, and yaw is controlled by means of resilient traction links. Three stabilizing links are used across the center section. Resilient wheels are used; Figure 2-27 shows the wheel profile.

Measures Undertaken When These Vehicles Were Introduced

Siemens undertook a computer model simulation of the route to check that the Avanto would be suitable. Speeds were restricted to 40 mph.

Experience Using These Vehicles

Wheel wear has been double the expected rate and has been occurring on both the tread and the flange. Some localized track wear, associated with sharp curves in the yard, has

been experienced, but generally track wear has not been an issue.

The system uses jointed track—noise has been experienced on rail joints, expansion joints, and sharp curves. There have also been noise issues arising from flat spots on wheels. Vehicle ride is adversely affected by the uneven wheel wear; it is more apparent on tangent track. Noise and uneven ride are more noticeable on the center truck.

Measures To Reduce Issues

To overcome noise issues, MetroRail is providing continuous welded rail, top of rail friction modifiers, and lubrication of the flange ways within curves. These measures significantly reduce squeal, vibration, and crabbing and, therefore, reduced noise both inside and outside the cars. MetroRail does not see the vehicle ride issue as requiring mitigation at present.

2.3.8 San Diego Metropolitan Transit System (SDT)

Eleven more Siemens Avanto S70 cars have been supplied to San Diego for use on the Green Line, which opened July 10th 2005. This is an extension of a much larger system, which has been using high-floor cars and which opened its first route in 1981. When investigations were made for this report, only one car on the system was under test, so there was no experience from which to draw conclusions.

2.4 Summary of Experience

Table 2-7 summarizes performance issues in the United States to date based on the questionnaire results. The table expresses how the transit systems themselves see their issues and the extent to which they have been able to manage them “in house.” Only those systems that provided questionnaire responses are included.

The more serious issues (in terms of safety and cost) are occurring on the older systems, so application of this new technology to an established network can be expected to be more problematic. This seems to be mainly a function of the track geometry associated with such systems. Older systems may also need to adapt maintenance practices to suit the new types of car.

Issues similar to those experienced with this type of vehicle in the United States have occurred in other parts of the world. Where these are known, they appear very similar. In examining the performance issues, the researchers considered possible differences in practices and standards between Europe and the United States to see if there was any evidence that this might have had an influence.

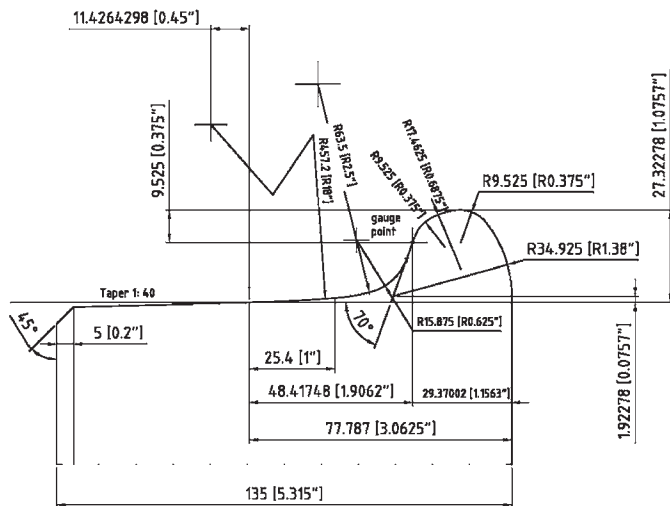


Figure 2-27. Wheel profile.

Table 2-7. Questionnaire view of the extent and seriousness of problems.

System	Portland	Boston	Newark	Santa Clara	Houston	San Diego
Derailements	No	Yes	Yes	No	No	Too early to say
Excessive wheel wear	No	Yes	Yes	No	No	
Excessive track wear	No	Yes	Yes	No	No	
Excessive trackside noise	No	Neutral	No	Yes	Neutral	
Excessive interior noise	No	Yes	No	No	Yes	
Excessive poor riding	No	Neutral	No	No	No	
Mitigation introduced	Yes	Yes	Yes	No	Yes	
Mitigation successful	Yes	Partly	Partly	N.A.	Partly	

No significant differences were seen. This is discussed more in Chapter 3.

2.5 European Experience with This Type of Vehicle

As indicated in Table 2-1, numerous LFLRVs with a center truck of this type and IRWs operate in Europe. The experience of the European team members working on this research project was that, although similar issues had emerged in Europe, such issues tended to be less serious and were now being effectively managed.

One German system that has been using a relatively large fleet of cars of this type for 10 years has had the following experience:

- There was more wear on IRWs than other wheels.
- Trailer truck wheel wear was roughly the same as motor truck wear, whereas it would normally be expected that wheels on motor trucks wear faster.
- Noise levels had been expected to reduce with IRWs because of their improved curving performance, but the noise levels remained the same.
- Performance issues were found to be worse on badly aligned or maintained track sections.

Re-profiling of wheels tends to be in the range 10,000 to 40,000 miles, but IRWs typically are at the lower end of this range.

Small-diameter wheels have been used as an alternative to IRWs, but these have their own issues, so it is an issue of balancing the overall performance of these options in the specific application.

Derailements occurred on another system where 10-percent low-floor cars are being used. These vehicles have IRWs but combine these with a more complicated body configuration, allowing more degrees of freedom. There has been a tendency to revert to partial low-floor vehicle solutions to avoid the increased wear and other issues associated with 100-percent low-floor cars of this type.

2.6 Trends

The U.S. systems studied are not proposing to replace their LFLRVs with high-floor cars and will probably expand the use of LFLRVs. Sometimes this will be in situations where they have not been used before (e.g., a planned street running extension of the Newark Subway). Other cities will introduce them, although the possibility of introducing other configurations of partial low-floor vehicle or 100-percent low-floor vehicles may eliminate the need to do this.

Given that older systems may have more difficulty introducing these cars than systems that can be designed to accommodate them, it is interesting to consider what other cities with “traditional streetcar” systems are planning.

In June 2005, the Toronto Transit Commission initiated a procurement process for low-floor vehicles to replace 96 existing streetcars. Four issues may make this process difficult:

- The use of single-point track switches that may cause issues for IRWs,
- Curve radii of 36 feet (inside rail),
- Low axle load requirements, and
- Prolonged 8-percent and some 7.5-percent grades that favor vehicles with all axles powered (8).

The Southeastern Pennsylvania Transportation Authority (SEPTA) started a procurement for LFLRVs in 1998, but the process was cancelled because of the significant costs. The cost-driving factors included

- Curve radii of 35.5 feet;
- Non-standard (5 feet 2¼ inch) gauge, which means that vehicles have to be designed specially;
- Clearance requirements limiting the length and width of cars; and
- The small size of the order (12 vehicles).

SEPTA plans to replace 141 cars eventually and will re-evaluate the use of LFLRVs then (9).

Another trend is the increase in sales of “standardized” designs, permitting comparison of almost identical models on different systems worldwide.

Global standardization has only a limited relevance to the U.S. and Canadian market because of the different standards that apply compared with the European light rail market, which is much larger. Despite this, two products in use in the United States and Canada may be directly comparable with experience elsewhere. The Minneapolis vehicle belongs to the Bombardier Flexity Swift family and is

similar to vehicles operating in Cologne (Germany), Alphen an der Rijn (Netherlands), Stockholm (Sweden), Istanbul (Turkey), and Croydon (UK). The Houston/San Diego Siemens “Avanto S70” design, also now on order for the Charlotte Area Transit System, has also been ordered by Paris RATP—although this latter order has not entered service yet. This is suitable for the U.S. and Canadian market because the European design was intended for shared operation of LRVs on heavy rail routes and, therefore, meets U.S. buff load requirements.

CHAPTER 3

Performance Issues and Causes

3.1 Overview

Generally, performance issues will result from several causes rather than one particular cause. Possible solutions can be broadly divided into design or maintenance parameters and other measures. Solutions may relieve one performance issue but may create or worsen another—the inter-relationships between issues and solutions are very important. Which solutions will work or are appropriate will depend on specific vehicle and track design features and other characteristics of the transit system concerned. Solving performance issues is complex, and general solutions will not always be effective.

Table 3-1 summarizes the measures identified in this research as appropriate for solving the main performance issues specified. The table distinguishes between types of solution in both the “parameters or other” classification and by type (i.e., vehicle, wheel profile, track and switches). This table illustrates the complexity of the inter-relationships involved.

Sections 3.2 through 3.5 of this chapter discuss each of the main performance issues in turn. Information is given about the extent to which these issues have actually occurred in the United States and the types of vehicle and conditions involved. The causes and potential solutions are summarized. Section 3.6 gives more background on each of the contributory factors, based on the findings of this research.

3.2 Derailment

3.2.1 Basic Causes

The two principal causes of derailment that can be managed through the design and maintenance of vehicles and track are flange climbing and track discontinuity.

Flange climbing derailments occur when the wheel flange climbs up out of the rails (i.e., when the vertical

forces holding the wheel down on the rail are exceeded by the lateral forces, causing the flange to climb for a long enough period for the wheel to clear the rail). This is expressed as the L/V (lateral load divided by vertical load) ratio. As will be explained, this situation can be caused by many factors.

Track discontinuity derailments occur where the wheel flanges are insufficiently constrained by the track. Under normal conditions, this might only occur on switches and crossings where there are gaps in the rails or irregularities in the rail contact surfaces or where moving parts may not be in their proper positions.

The flange climbing derailment risk of IRWs will be slightly higher than for conventional wheelsets because of the increased lateral forces, the possibility of a higher angle of attack generated by IRWs, and the configuration of LFLRV being studied. Trucks with IRW center trucks are, therefore, fundamentally more susceptible to derailment and, as a result, their behavior can be strongly influenced by other factors, which would normally be of only secondary importance for trucks with solid axles.

Vehicle suppliers should allow for this behavior. Increased “sensitivity” may also mean that track standards have to be tighter than might be acceptable with more conventional vehicles. It is also generally recognized that the management of the wheel/rail interface is even more critical.

3.2.2. Experience with Derailments

Of the derailments that have occurred in the United States since this type of LFLRV was introduced and which were noted in questionnaire responses, only the following resulted from these interface issues:

- NJ TRANSIT Newark
Subway 3 derailments All on switches.
- MBTA Boston 11 derailments 4 on switches.

Table 3-1. Summary of measures.

Performance problem	Derailment	Wheel wear	Rail wear	Noise	Ride
Vehicle parameters					
Trailing truck wheelbase (Variations within limited space available on the center truck)	Minimal effect	Minimal effect	Minimal effect	No effect	No effect
Smaller wheel diameter/ wheel flange length	Avoidable effect	Increases	Increases	Increases	No effect
Variation in wheel diameter	Minimal effect	Minimal effect	Minimal effect	No effect	Minimal effect
Wheel parallelism	Effects	Effects	Minimal effect	Minimal effect	No effect
Wheel profile parameters					
Flange angle	Effects	Effects	Minimal effect	Minimal effect	No effect
Toe radius	Effects	No effect	No effect	No effect	No effect
Flange height	Extra safety	No effect	No effect	No effect	No effect
Tread width	Avoidable effect	Minimal effect	Minimal effect	Minimal effect	No effect
Blend radius	Effects	No effect	No effect	No effect	No effect
Flange thickness	Indirect effect	No effect	No effect	No effect	No effect
Tread radius/taper	Effect	Effect	Effect	Effect	Effect
Other vehicle features					
Center section fixing to truck	Possibly minimal effect	Possibly minimal effect	Possibly minimal effect	No effect	No effect
Position of secondary suspension	Minimal effect	No effect	No effect	No effect	No effect
Inter-body damping	Effect	Improves	Improves	Improves	Improves
Primary suspension stiffness	Effect	No effect	No effect	No effect	Effect
Use of flange tip running	Reduces risk	Effect	Effect	Effect	No effect
Lubrication	Minimal effect	Effect	Effect	Effect	No effect
Track parameters					
Gauge tolerances	Effect	Effect	Effect	Effect	Effect
Flangeway clearance	Effect	Effect	Effect	Effect	No effect
Other track features					
Use of tighter tangent track	Effect	Effect	Effect	Effect	Effect
Sharp curves	Possibly	Impact	Impact	Impact	Possibly
Gauge widening on curves	Possibly	Impact	Impact	Impact	Possibly
Tangent track between curves	Possibly	Possibly	Possibly	No effect	No effect
Use of restraining rail	Effect	Effect	Effect	Effect	No effect
Undercut switches	Effect	No effect	Local effect	Local effect	Local effect
Extra guard rails and house tops	Extra safety	No effect	No effect	No effect	No effect
Embedding rails	No effect	No effect	No effect	Effect	No effect
Flexible switches	Effect	No effect	No effect	No effect	No effect
Switch rail tip design	Effect	No effect	No effect	No effect	No effect

There has also been one derailment in Minneapolis (see section 2.3.6).

3.2.3 Solutions

Strategies to manage the wheel-rail interface (e.g., optimizing the flange angle in combination with the rail profile in use) are essential to preventing flange climbing derailment. In addition it is necessary to manage other features of the vehicle that might increase the angle of attack. The wheel-rail interface is also the key to preventing track discontinuity derailments, but here the prevention of track discontinuity is clearly also critical.

3.3 Excessive Wheel and Rail Wear

3.3.1 Basic Causes

For any type of LRV, wear will occur because localized high points on the wheel or rail profiles cause high contact stresses, because the rail is softer than the wheel material or vice versa,

or because the loads on the contact area are extremely high. It is also possible for wear to occur as corrugations or for it to propagate more quickly because of wheel flats or localized track irregularities. High points will be eliminated if the wheel-rail interfaces match under all conditions. Relative hardness of wheel and rail can be managed so as to keep wear from this cause within acceptable limits. Certain conditions can increase contact area loads, including sharp curves. It is possible to reduce the conditions that create rail corrugations and wheel flats and to eliminate the track irregularities that cause most wear. The LFLRVs considered in this study may be more susceptible to wear because IRWs and the center truck configuration make it more difficult to manage the relative aspects of the wheel and rail at the interface.

3.3.2 Experience with Excessive Wheel and Rail Wear

Excessive wheel and rail wear is a major issue for many light rail systems, and many new systems worldwide seem to have experienced this, regardless of the type of vehicles used.

Portland MAX has experienced higher LFLRV wheel flange wear on the center truck than on the motor trucks (Section 2.3.1). MBTA's Green Line experienced rapid wheel wear on all trucks of the Type 8 cars, and experienced excessive rail wear on its very sharp curves from all cars (Section 2.3.2). The Newark Subway has had higher wheel wear on the center trucks of its LFLRV fleet than on the wheels of the motor trucks and has very high rail wear on sharp curves (Section 2.3.3). NJ TRANSIT's Hudson-Bergen line, Santa Clara VTA, Houston Metro, and San Diego did not report issues in the questionnaire responses but, in some cases, it was too early to have observed this issue.

3.3.3 Solutions

On the type of LFLRV being studied, the use of IRWs on a short articulated section introduces the risk of increased angle of attack. The wheel-rail interface is critical for all LRVs, but for these types of vehicle it is also necessary to control the relative position of wheel and rail more closely so as to overcome this "flexibility."

Measures that reduce wheel and rail vehicle wear (e.g., lubrication) are more likely to be required if this type of vehicle is used, and this may increase costs. For new systems, it is possible to avoid the extremes of track geometry that have caused these issues on older systems.

3.4 Noise

3.4.1 Basic Causes

IRWs generate more noise on tangent track because their lack of any intrinsic steering ability allows rubbing flange contact to occur. The noise generated by this is likely to be particularly noticeable in the vehicle because of the proximity of the floor to the noise source and the difficulty of producing a successfully noise-inhibiting design within the constraints of an LFLRV. The more complex body shape, with two floor heights, makes noise suppression more difficult, but this effect is hard to quantify.

Noise can result from wheel-rail roughness and, therefore, can be a secondary effect of wheel-rail wear (see above); wheel-rail roughness includes track corrugations and the extreme condition of wheel flats. Rail roughness tends to dominate over wheel roughness. IRWs are more sensitive than conventional wheelsets to wheel flat development because adhesion during braking cannot be shared across an axle and because of the low rotational inertia of the wheels.

For all rail vehicles, rolling noise (the inevitable but not significant base level noise) can be worsened by periodic grinding if such grinding does not achieve an adequately smooth rail surface. Rolling noise will also be affected by the support stiffness of the rails. If the rail head and wheel profile vary

significantly, this will worsen rolling noise, but conformity can cause corrugations, generating noise issues as noted above.

There is a relationship between the wheel-rail contact area and noise because of "contact stiffness," but noise does not vary significantly over a large range of contact stiffness variation. Frequent truing of wheels will avoid issues in this area (10).

In general, rails and wheels radiate noise. The ties tend to dominate at low frequencies, rail at mid-frequencies, and wheels at high frequencies. Resilient wheels will radiate less noise. The reflectivity of a surface is also important, so although ballasted track tends to radiate more noise because of the exposure of the rail web, the ballast tends to absorb this better than a smooth road surface.

Corrugations may be more likely on light rail because of light contact patch loads and lack of variation in wheel diameter (but experience is that variation in wheel diameter worsens wear issues generally). Where corrugations occur, the ability of the wheel to follow the rail profile is critical in terms of noise, so suspension/truck stiffness becomes a contributory factor.

All noise is significantly increased by resonance effects, so whatever can be done to reduce these will be important.

Noise occurs on curved track because of the lateral slip of the wheel tread across the railhead and by contact between the wheel flange and the gauge face of the rail. Squeal or howl will be the only noticeable wheel-rail noise on sharply curved track because cars will be moving slowly. Such noise is likely to be an issue on older systems with curves, which are sharper than modern LRVs are usually designed for, and LFLRVs are the first modern cars to be introduced.

Flange contact is important with IRWs because their lack of self-steering ability leads to the generation of high angles of attack, which in turn leads to higher noise levels being generated.

Squeal is sustained non-linear wheel oscillation and will only occur if the damping capabilities of the wheel are poor. This is unlikely with modern designs of LFLRVs which, in common with other modern LRVs, are likely to use resilient wheels.

Noise emanating from special trackwork can be significant, even though obviously localized. LFLRVs may be worse in this respect if they use significantly stiffer suspension than conventional vehicles.

3.4.2 Experience with Noise

Traditional streetcar lines were characterized by noise; unfortunately, many new light rail systems have experienced noise issues, despite technical advances and effort at the design stage. The U.S. transit systems using LFLRVs, however, have not generally experienced any significant issues that can be directly related to the use of this type of car.

MBTA and Houston Metro have experienced a noisy environment in the vehicles but have either found solutions or

consider it to be within acceptable limits. Santa Clara VTA noted issues with wheel squeal on both high-floor and low-floor cars but consider that, in both cases, the noise does not exceed limits.

In general, systems may have issues, perhaps only at certain locations, but they have been able to manage them effectively.

3.4.3 Solutions

In general, noise can be reduced on tangent track by maintaining rail smoothness. The use of resilient wheels and other forms of damping may reduce squeal on curves but not necessarily eliminate it. Squeal may be controlled by use of lubricants or possibly using different metals for the wheels and rails, although the latter theory has not been fully tested.

The use of special trackwork designed to reduce the risk of derailment with LFLRVs will probably have the added benefit of reducing noise associated with this type of track, assuming that discontinuities are eliminated.

3.5 Reduced Ride Quality

3.5.1 Basic Causes

The increased number of degrees of freedom of the center truck may allow additional dynamic modes to develop that may affect ride quality. The primary suspension is usually stiffer than for conventional cars and is likely to have reduced travel. IRWs have a greater susceptibility to the formation of wheel flats, which, although they may not significantly affect ride, the noise generated can give passengers the impression that the vehicle is riding badly. Similarly, if passengers experience more noise than on other cars, this may cause them to take more notice of ride discomfort.

If rail wear increases, which as stated in Section 3.3 may be the case with LFLRVs, corrugations generated must be dealt with promptly, otherwise the ride will seem very poor and may affect other cars using the system.

3.5.2 Experience with Ride Quality

None of those six transit authorities using LFLRVs that responded to the questionnaire saw ride quality as having caused any serious issues. Where rough riding has been experienced, it has usually not reached the point at which passengers have complained.

3.5.3 Solutions

The design must provide adequate suspension, despite the lack of space. The center section must be linked to the other sections so as to allow the articulation to operate smoothly

without jerks, pitching, or yawing. The wheel tread profile is critical. If uneven wear occurs, the variation in wheel profile will cause a poor ride, so variations in wheel profile need to be kept within tolerance limits. The track quality needs to be high in terms of gauge and other variations.

3.6 Contributing Factors

3.6.1 Vehicle Parameters

Truck Wheelbase

The main effect of varying the center truck wheelbase would be to increase the critical angle of attack on very sharp curves. The angle of attack would typically be 2.5 degrees on a 25-m (82-ft) curve for a 1.9-m (6 ft 2³/₄ in.) truck and would change by about 0.1 degree for each 50-mm (2-in.) longer or shorter wheelbase dimension. Therefore, the effect is very slight. In practice, there is very little variation among vehicle designs.

Wheel Diameter

Small wheels have not been specifically studied in this research project because all the existing U. S. and Canadian systems using this type of LFLRV have used a 26-inch wheel and this is suitable for future applications in the United States.

The use of smaller wheels generates a range of additional issues because of

- Higher tread contact stresses;
- The need to ensure adequate guidance at obtuse crossings;
- The lower available volume of wearable material; and
- Lower wheel inertia, leading to increased risk of wheel slide.

The smallest wheels known to be used in an IRW application are of 550 mm (21⁵/₈ inch) diameter on a design used in Europe.

Smaller wheels (<400 mm/15³/₄ inches) are used on several LFLRV designs, but with wheels of such a small diameter it is possible to create a low-floor design without the need for IRWs.

Variation in Wheel Diameter on the Same Axle

IRWs steer by their wheel profile and the effects of gravity, so variations in wheel diameter on the same axle will not have the effect that might occur with conventional wheelsets.

Axle Parallelism

Guidelines have been adopted in Europe in order to maintain the parallelism of axles within limits (11). Practice there

has suggested that halving the permitted out of parallelism compared with conventional trucks gives an appropriate limit for center trucks with IRWs.

3.6.2 Wheel Profile Parameters

Wheel Profile/Rail Profile Match

To minimize wear, it is necessary to ensure a good match between wheel and rail profiles. The following characteristics are desirable:

- Absence of 2-point contact;
- Smooth progressive movement of contact patch position on rail and wheel through the full range of wheelset lateral displacements;
- Maximum width of contact patch to occur at low wheelset lateral displacement, to minimize contact stresses (and hence wear) at the position where the wheelset will spend most time; and
- Wheel and rail profiles to broadly retain the same shape as they wear.

The need to match wheel and rail profiles makes it undesirable to have a mixture of significantly different wheel profiles operating on the same system. There will usually be slight differences caused by different wear rates on a given new profile, but this is beneficial because it helps avoid rolling contact fatigue caused by uniform wear patterns.

All the above applies to any LRV; however, IRW cars of the type being studied are more sensitive to issues of wheel/rail profile matching because they generate higher lateral forces and possibly higher angles of attack. The results of the modeling carried out as part of this research, described in Appendix A, suggested that, in some cases, conventional LRVs may generate higher angles of attack on the same track than LFLRVs with IRW center trucks.

Although issues are minimized if wheel and rail profiles are compatible, this is not easy to achieve during a “transition” stage (e.g., when new cars with new profiles are introduced to an existing system). It is possible however as has been demonstrated in Zurich (10).

Using more than one wheel profile on a system can affect wheel-rail interaction adversely. Having one wheel profile on a system also facilitates profile maintenance; however, the wheel width and wheel back-to-back dimensions can be varied so that vehicles occupy the same space in the rail groove and in respect of the angle of attack on curves, thereby allowing vehicles with different wheel base dimensions to be used. Table 3-2 shows wheel tapers that have been used with various rail profiles on the U.S. transit systems that use LFLRVs.

Table 3-2. Rail sections and associated wheel tapers.

System	Rail	Wheel taper (1 in)
Portland	115RE	30
Portland	Ri59	30
Newark	115RE	20
Hudson-Bergen	115RE	20
Santa Clara	115RE	32
Santa Clara	Ri59	32
San Diego	115RE	40
Houston	115RE	40
Boston	115RE	Formerly 40 now 20
Boston	149GCR	Formerly 40 now 20

Flange Angle

Traditional European tramway flange angles range from 76 to 78 degrees. More modern designs have reduced this to 70 degrees, while the European heavy rail standard is still lower—typically at 68 degrees. The heavy rail freight standard in the United States is 75 degrees and passenger lines vary from 68 to 75 degrees. The Siemens cars used in Portland and Houston have 70-degree angles. In Boston, the original design on the Type 8 cars was 63 degrees, since modified to 75 degrees. This latter angle is also used on the NJ TRANSIT cars and the Siemens Avanto.

Selection of flange angle is driven by two conflicting criteria:

- Shallow flange angles are better for reducing flange wear.
- Steep flange angles are better for resisting flange climbing derailments.

Shallower flange angles increase the risk of flange climbing derailment caused by the reduced lateral force needed to climb and by reducing the climb out distance once the critical L/V limit is exceeded.

Steeper flange angles can increase the risk of derailment on sharp discontinuities in the gauge side of the rail, although the flange-tip radius is also an important factor. A steeper flange angle also causes more wear.

This conflict explains why heavy rail vehicles, which negotiate much larger radius curves than LRVs, generally have low flange angles (63 degrees typically) whereas LRVs generally have high angles of 70 to 75 degrees. However, a few systems, where wear is considered the critical factor, are actually using relatively shallow angles (e.g., Berlin, 68.2 degrees, and Zurich, 64 degrees). In both cases, these flange angles are used with 100-percent LFLRVs, although in Zurich the wheels are actively steered into the curves by an articulation-controlled linkage, which limits the angle of attack.

IRW cars of the type being studied will generate higher lateral forces and higher angles of attack compared with conventional LRVs. These types of vehicle, therefore, require

relatively high flange angles to ensure safety against derailment.

It would not be appropriate to state a fixed “optimum” flange angle, given that the selection for a particular car design should be based on the angle necessary to provide minimum wear while giving safety against derailment and good matching to the local rail profile.

On systems where a mixture of IRW and non-IRW cars operates, the IRW cars probably will require the highest flange angle. Ensuring that all cars on the system have a consistent profile means that the non-IRW cars will need to adopt the same profile—this is likely to have the following consequences:

- A change to the dynamic behavior/wear characteristics of the non-IRW cars, which will, therefore, require reassessment; and
- Less-than-optimum wear performance from the non-IRW cars.

This issue has been discussed in *TCRP Report 71, Volume 5 (12)*, which noted the same range of angles in use and that recent guidance had proposed a minimum angle of 72 degrees (+3 degrees, –2 degrees). This was proposed by APTA (13). It was associated with a 1 in 20 tread taper and was to be achieved at the gauge point, $\frac{3}{8}$ inch above the standard base line. The basis was to establish a margin of safety above the 70 degrees previously considered sufficient.

Flange Height

In simple terms, the higher the flange, the lower the probability of flange climbing derailment under extreme circumstances. However, it is often not possible to increase flange height on an existing system that uses grooved rail or where flange clearance is limited. Increasing the flange height may affect wheel back-to-back dimensions, flange thickness, and wheel mass. To ensure safety at obtuse crossings, larger flanges are necessary when very small wheel diameters are used.

With higher flanges, the flange-tip width reduces. A narrower flange tip is disadvantageous, if flange-tip running (i.e., where wheels run on the tips of their flanges, rather than the wheel treads) is used on track with flat grooves in crossings and in switches with sharper angles, because the contact stresses are higher and, hence, wheel and rail wear increases.

The height of the wheel flange determines how long an excessively high L/V ratio must be sustained before the vehicle derails. As such, wheel flange height is the last defense against derailment and, ideally, the vehicle-track interaction should be designed so that excessive L/V conditions do not

occur. It is not a critical parameter but the following considerations apply:

- Higher flanges give some protection against derailment.
- The height of the flange will be limited by the depth of the track groove. This depth is not only determined by the rail section—it is also affected by rail head grinding, which tends to reduce the effective depth of the groove. Flange height selection, therefore, affects infrastructure maintenance costs.
- Higher flanges will tend to have thinner tips, which will be subject to increased wear if flange-tip running is practiced, although wear rate will decrease as the tapered flange gets lower. Modern vehicles, which tend to have higher axle loads, will be particularly affected.

The minimum allowed flange height in Germany is 18 mm ($\frac{3}{4}$ inch). Good practice in that country is to never go below 22 mm (0.87 inches) and to use a maximum of 24 mm (0.95 inches) on newly profiled wheels that will be subject to flange tip running, so as to allow for wear. But if a higher flange has a smaller flange-tip width, it might wear quickly with extensive flange-tip running, losing this advantage. A balance is needed—the figures suggested represent such a compromise. With good track conditions, no flange-tip running, and flange height increasing caused by wheel wear with time, a minimum value of 20 mm (0.9 inches) may be sufficient.

Table 3-3 summarizes the flange heights used on LFLRVs in the United States.

Tread Width

The U.S. systems using LFLRVs use flange-tip running and, therefore, can use thinner wheels. Selection of tread width is not considered to be influenced by whether or not a car has IRW. It is mainly determined by the type of system on which the cars will operate. Streetcars use narrow wheels (4 inches typically) for the following reasons:

- Many large-angle crossings requiring flange running—the outer part of the wheel tread is not used because of the

Table 3-3. Flange heights.

System	Type of car	Flange height	
		inches	mm
MBTA 8	Type 8	0.75	(18)
Portland MAX	Siemens/Duewag	1.063	(27)
NJT	Kinki-Sharyo	0.75 (1)	(18) (1)
San Jose, Santa Clara VTA	Kinki-Sharyo/Alstom	(1.063)	27
Houston/San Diego	Siemens Avanto S70	(1.08)	27.3

Notes:

1. To be changed to 1 inch (25.4 mm)

For explanation of the use of brackets in this table see Section 1.6.

typical switch design where sharp curves require flange running (so there is no tread contact).

- Wider wheels may damage the surface of the adjacent highway.

LRVs use wider wheels (5 inches or more) for the following reasons:

- Where there are limited or no flange running and small-angle crossings, the outer part of the tread comes into contact with the rail because of the typical switch design for gentle curves where frogs are used in association with check rails.
- Care is needed to avoid development of hollow tread wear and consequent damage to highway by the outer part of the tread.

Table 3-4 shows the width of wheels used on the main systems studied; for explanation of the use of brackets in this table, see Section 1.6.

Standard AREMA frogs require a 5.25-inch-wide wheel.

These considerations suggest that wheel tread width should be about 5.25 inches, unless flange-tip running is used throughout, in which case, tread width may be reduced to 4 inches. A wider wheel can be accommodated on embedded track, provided the rail head is raised above the surrounding pavement. U.S. and Canadian standards allow this projection.

The width of the wheel has a minimal indirect effect on performance issues and, in the case of derailment, the track can be designed to accommodate wheel width without this issue arising.

Relative Hardness of the Wheel and the Rail

The relative hardness will affect wear rates. A “softer” wheel is generally preferred, because it is easier to re-profile wheels than rails. The work hardening quality of the material is a related factor (e.g., manganese steel performs well because it work hardens when shock loads are applied). But manganese steel may not be the best material for withstanding the more usual sliding loads that arise at the wheel-rail interface. Tests carried out by the German Railways using a roller test

machine to simulate railway wheel/wear conditions produced some interesting results (14):

- Lower strength rail steel wore less than high-strength rail steel when the same wheel material was used.
- Wheel wear was reduced by using softer rail material.
- The increase in rail wear when using higher strength wheel steel was not as great as the wheel wear reduction.
- The reduction in wheel mass decreased with harder wheels.

Therefore, using higher strength wheel material may have advantages and using higher strength rail material may not.

The ratio of the yield strength to the tensile strength of the materials used is also very important. Although the material may not fail (measured by its tensile strength), it may experience plastic deformation (related to yield strength), causing it to crack and wear rapidly.

Rail and wear hardness are part of the much wider consideration of tribology, the science of wheel and rail wear, in which many other factors play a part. Tribology also considers loading conditions, the micro and macro properties of materials, the influence of lubrication and dust at the interface, and environmental conditions (e.g., humidity and contamination). Relationships are complex and non-linear.

3.6.3 Other Vehicle Issues

Configuration Issues

The angle of attack of a wheelset is defined as the angle between the track radial line and the centerline of the wheelset axle. High angle of attack values will magnify many of the wheel-rail interface issues and create issues at switches and crossings. The truck design and the way it is attached to the body sections will affect the angle of attack; details of the suspension system will determine both the rate of change and the probability of extreme angles occurring. The angle of attack will also be influenced by the articulation design and the truck wheelbase.

LFLRVs with center sections have been shown to have a fundamentally poorer dynamic performance than conventional two-section LRVs. In part, poorer performance arises because of the additional degrees of freedom that this type of vehicle possesses. The design of the center section must, therefore, control these extra degrees of freedom, allowing sufficient flexibility while preventing the development of any oscillation modes.

The modeling undertaken as part of the research showed that two very different design solutions can perform almost equally well in practice. Table 3-5 shows how the various modes of the center section are controlled in the two LFLRV cars that were modeled.

Table 3-4. LFLRV wheel widths.

System	Type of car	Tread width	
		inches	mm
MBTA	Type 8	4	(101.6)
Portland MAX	Siemens/Duewag	(4.96)	126
NJT (Newark Subway)	Kinki Sharyo	4	(101.6)
NJT (Hudson-Bergen)	Kinki Sharyo	(5.25)	133
San Jose, Santa Clara VTA	Kinki Sharyo/ALSTOM	(5.51)	140
Houston/San Diego	Siemens Avanto S70	(5.31)	135

Table 3-5. Methods of controlling the movement of the center section.

Mode of center section	Kinki Sharyo LFLRV	Breda Type 8 LFLRV
Bounce	2 air bags	4 air bags
Pitch	Referenced to other sections by Z-link and dampers	Referenced to truck by anti-pitch bar
Roll	Held rigid to other sections by design of articulation joints	Held rigid to other sections by horizontal bars at roof level
Yaw	Not permitted relative to truck (locked)	Some degree of freedom

There is no particular advantage to any specific solution; however, the design must address the issue of truck and wheelset alignment, because the absence of self-steering on the center truck will promote misalignment of the wheels leading to wear, noise, and potentially an increase in derailment risk. The following factors should be considered:

- Parallelism of the IRW wheelsets must be maintained as closely as possible. The effect of tolerance build-up within the truck must be considered in the design. The design ideally should prevent the alignment changing because of service wear or maintenance, but if this is not possible, the maintenance instructions must include a requirement to check the wheelset alignment following overhaul of trucks and propose methods of reclamation.
- The effect of friction or asymmetries in center-section articulation linkages and/or dampers must be accounted for in the design. These can lead to the car sections being out of alignment on straight track.

The conclusion of the modeling exercise was that the choice of articulation design as such has little overall effect on vehicle performance. Performance is mainly influenced by the other factors mentioned in this section. The articulation design should be chosen to suit the selected vehicle configuration.

Position of Secondary Suspension

In the modeling exercise, two arrangements of secondary springs were studied:

- Two springs at a central location on the truck (conventional) and
- Four springs, one at each corner (unconventional).

These arrangements were found to have equivalent dynamic performance within the context of the overall vehicle design.

Primary Suspension Stiffness

IRW cars require better resistance to wheel unloading on twisted track than non-IRW cars, because IRW cars generate

higher lateral loads. Therefore, vertical wheel unloading must be minimized in order to avoid a risk of derailment. The study of this is a standard part of any car design process. There is no evidence of issues in achieving the requirement. Two very different solutions to the issue were studied in this research:

- Conventional rubber/metal primary suspension and
- Minimal primary suspension combined with a torsionally flexible bogie frame (as used on the MBTA Type 8 cars and described in Section 2.3.2).

The solutions were found to perform equally well. Notably, the flexible frame studied did not have significantly higher unsprung mass than the conventional design. Typical stiffnesses will range from 500 N/mm to 1,000 N/mm (1.4 to –2.8 tonf/inch), and lower values cause issues with rolling behavior. Probably, the flexible frame would have poorer noise and vibration isolation and potentially higher maintenance costs. It is a less well-proven solution.

Total Side-To-Side Play Between the Truck Frame and Car Underframe

This is a secondary suspension issue. The horizontal stiffness of the secondary suspension should have a progressively increasing stiffness gradient, and the rotational freedom about the vertical axis needs to be limited. The higher the swiveling angle, the higher the torque moment induced by the longitudinal forces at the articulation.

Maintaining the Vehicle in a Straight Line During Braking

Maintaining the vehicle in a straight line during braking is desirable because it reduces the specific performance issues being studied, keeps the vehicle within the permitted space, and helps minimize the gaps at boarding points. Maintaining the vehicle in a straight line during braking can be achieved by controlling the braking rates on each articulated section.

Braking IRWs is more difficult than braking conventional wheels because each wheel may react to the friction conditions on one rail and will not be affected by the other. A conventional wheelset, which has more total mass, is less likely

to seize. The sections can be kept in a straight line by braking the rear truck harder than the leading truck. At other times, the traction applied to the leading truck can be slightly more than to the trailing truck, so as to achieve the same effect. Conditions that cause the center truck to swivel and cause issues are eliminated if its lateral play is reduced by such methods.

3.6.4 Lubrication

Table 3-6 gives an overall picture. All systems studied use track-mounted lubricators but have not generally provided vehicle-mounted ones. The severity of the issues quoted depends on individual judgment, but wheel wear seems to be the most common issue being mitigated. Table 3-7 gives more detail of the track lubrication methods used.

In some of these applications, in particular San Diego and Boston, track lubrication exists, but has not been used as a primary method of dealing with the issues associated with LFLRVs. In San Diego, only one car has been introduced recently. The other systems gave reports on the effectiveness of trackside lubrication (both gauge face and top of rail friction modifiers) in dealing with issues as described in Chapter 2.

Table 3-6. Use of lubrication to mitigate against performance problems.

System	Lubrication system		Problems experienced			
	Track mounted	Vehicle mounted	Excessive wheel wear	Excessive track wear	Excessive external noise	Excessive internal noise
Newark City Subway	Yes	No	Yes	Yes	No	No
Portland	Yes	No	No	No	Yes	No
Santa Clara	Yes	No	No	No	Yes	No
San Diego	Yes	No	No	No	No	No
Houston	Yes	Yes	Yes	No	No	Yes
Boston	Yes	Testing	Yes	Yes	No	Yes

Table 3-7. Details of lubrication systems used on U.S. transit systems using LFLRVs.

System	Grease applicators	Top friction modifiers	Side friction modifiers	Mitigating		
				Wheel wear	Track wear	Noise
Newark City Subway	Yard turnouts	On Penn Stn. Loop tracks	Sharp curves	No	Yes	Yes
Portland		Sharp curves, Girder rail, embedded track		Yes	Yes	Yes
	Sharp curves, ballasted track			Yes	Yes	Yes
Santa Clara		Sharp curves		No	No	Yes
San Diego		Sharp curves		Existing lubrication, no problems with LFLRV as yet		
Houston		Sharp curves		Yes	Yes	Yes
Boston		Sharp curves		No	No	Yes

The conclusion of this research is that systems mainly see lubrication as a solution to the wheel squeal issue and contributing, alongside other mitigation, to reduced wheel and rail wear.

3.6.5 Track Parameters

Data from the studied systems were collated in order to study the effect of flangeway clearance and track gauge variations. The gap between the railhead and the wheel at gauge measurement height and the equivalent figure between the back of the wheel and the restraint side of the groove in embedded track were considered. The information was assembled for tangent track only, because this will indicate the extent to which the wheels on the center truck might be free to move laterally or rotate about a vertical axis.

The gauge may be narrowed on tangent track in order to reduce angle of attack, but if the gauge is excessively narrow, a light wheelset might rise out of the track and derail, even with a steep flange angle. This has occurred with a vehicle of this type. Tight gauge conditions were caused by a combination of the failure of an axle-end retaining nut on the vehicle and the relatively narrow track gauge at the location.

Adequate flangeway clearance is important in order to allow sufficient lateral wheelset displacement and, hence, allow steering by rolling radius difference for non-IRW rather than flange contact. A minimum clearance of 5 to 7 mm (0.2 to 0.3 inches) is recommended. A nominal 9 mm ($\frac{3}{8}$ inch) would be suitable for ideal track conditions. The higher value is better in continuous track, so that the vehicle can adjust without restraint.

On curves, the gauge may be widened because of the angle of attack, but one needs to avoid the situation where the gap allows a wheel to hit the side of the rail with some force because, in certain situations, this will lead to damage and possibly derailment. Also, care must be taken to avoid wheels being pinched between guards or girders when the gauge is widened.

On IRW, steering by rolling radius difference does not occur. Instead, some limited steering forces are generated because of the different contact angles. Although this effect is small, it is important to ensure that flangeway clearance is not allowed to become too small such that the effect cannot develop at all.

It is possible to exploit the principle of asymmetric wheel profiles. The rail is ground on the running face to give an optimum profile and on curves the profile ground onto on each rail may be different, in order to achieve the same effect. This principle has been used on the Santa Clara VTA system, where LFLRVs are in use.

3.6.6 Other Track Features

Curve Radii

The study considered the minimum curve radii appropriate for the specific type of vehicle being examined in this research (i.e., a three-section articulated vehicle with a center trailing truck with IRW).

IRW cars generate higher levels of lateral force and higher angles of attack, which increase wear rates and the risk of derailment. This issue is made worse as curve radii reduce. Below 25 m, the angle of attack increases sharply—25 m is generally regarded as an advisable minimum for new track alignment (see Figure 3-1).

To minimize wear and noise and to improve ride, transition curves should be provided for IRW cars. This is necessary because the body is rigidly fixed to the center truck and so the effect of changes of curvature will be magnified. A minimum transition length of 6 m (20 feet) is used in Germany and it would be appropriate to use this figure in the United States and Canada for this configuration of LFLRV so as to ensure that this track condition is no worse.

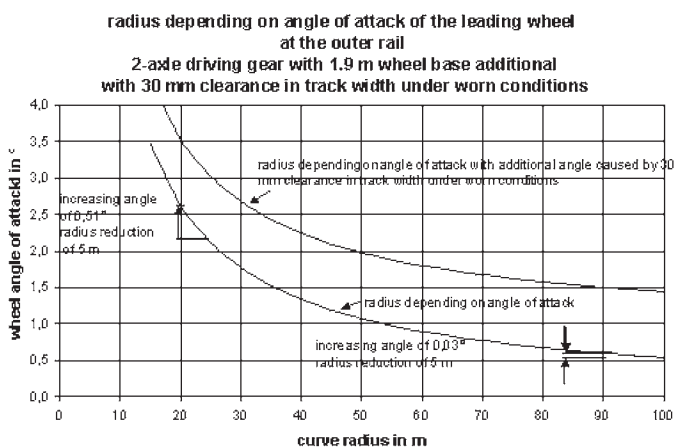


Figure 3-1. Example of angle of attack increasing with reducing curve radius.

The provision of tangent track in reverse curves is not a particularly critical requirement for IRW cars. The tangent track minimizes articulation angles, but three-section IRW cars will generate lower articulation angles than two-section cars for any given curve. Transition curves should be used as well as the tangent track on reverse curves.

Lateral Alignment Specifications for Track

The effects of poor lateral alignment will be more severe for IRW vehicles, but modeling indicates that the issue is probably related to ride, rather than a derailment risk. U.S. specifications are comparable with European practice for low-floor cars; however, the method of application differs from European practice and this probably will lead to a lower standard of track than these cars may have been originally developed for (See Appendix E).

Track Twist

This is not a critical factor for IRW, providing that existing limits continue to be applied.

Issues Associated with Special Trackwork

All the performance issues can arise from issues associated with special trackwork but derailment is the most serious because the risk is potentially increased, whereas issues with noise, wear, and ride can be mitigated, provided the principles discussed elsewhere in this report are applied. In view of this, the only issue that is specifically discussed here is that of derailment.

Table 3-8 summarizes all the identified LFLRV center truck derailments on special trackwork that have taken place in the United States. Table 3-8 shows the circumstances and any mitigation that each system introduced following these incidents.

Where these incidents have been caused by track defects, the mitigation has been either to improve track standards or to add further restraining measures. This is in line with the guidance provided in a previous report (15). In some cases, vehicle modifications occurred as well.

Where the wheels on center trucks wear rapidly, the flanges become very thin and this increases the derailment risk on special trackwork.

It is difficult to close switchblades precisely because of practical reasons; a tolerance of 3 mm (1/8 inch) is normal. IRWs need to be able to cope with this variation in order to ensure safe operation, especially if the design of the switch makes this critical.

The risk of derailment on switches can be minimized or eliminated with various types of restraining and guardrail,

Table 3-8. LFLRV center truck derailments on switches.

System	Vehicle	Description	Mitigation
Newark City Subway	Kinki Sharyo	Both axles of center truck derailed on switches at low speed (three incidents 2001/2/4)	House top protection added to switches
Santa Clara	Kinki Sharyo/ALSTOM	2003. Lead axle of center truck derailed on yard switch 2004. Both axles of center truck derailed on switch at 5 mph.	None (Causes were not vehicle or infrastructure related)
Boston	Breda	2000. Leading axle of center truck derailed on reverse curve switch at 20 mph, running empty.	Vehicle alignment corrections, additional restraining rails.
		2001. Leading axle of center truck derailed on curved switch at low speed.	None

including house tops positioned above rail level to guide the backs of wheels and thereby prevent wheel flanges from splitting the switchblade from the rail (see Figures 3-2 through 3-4). However, fully guarding can easily double the cost of a switch, itself a relatively expensive piece of equipment, so other solutions may be worth considering. For example, there is the possibility of developing moveable frog switches for transit applications—these might prove to be part of an optimum solution when IRWs are in general use (15).

The report referred to above (15) concludes that derailment risks can be minimized by adopting the following practices, which it then ranks, as shown, in order of effectiveness:

- Lubrication,
- Development and implementation of maintenance and inspection standards,

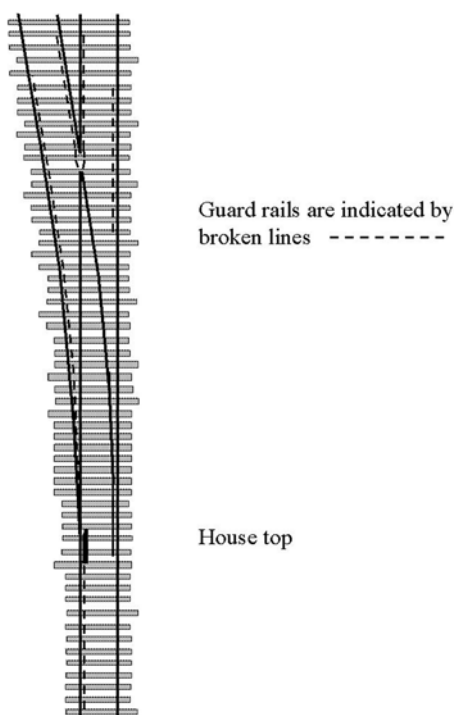


Figure 3-2. Fully guarded switch.

- Adoption of standards for gauge face wear angles on switch and closure rails, and
- Eliminating the mismatch between wheel and rail.

Because IRW trucks may generate high angles of attack and high lateral forces, it is necessary to tightly control the accuracy of positioning of switchblade tips to prevent the risk of climbing.

The possible need to provide more complex switches as a way of overcoming issues with LFLRVs has cost implications, which may significantly affect the business case for introducing them.

3.6.7 Maintenance Standards

None of the maintenance standards of transit systems are subject to the Federal Railroad Administration processes, but are determined by the regulations that apply in each individual state of the United States. Also, Federal regulations (including the new requirement [49 CFR Part 659]) will come into effect in 2006 that each state must designate an independent oversight agency. This will affect the application of maintenance standards because Section 19 is a requirement for a system safety plan that shall include maintenance plans with inspection periods and so forth.

APTA published a *Manual for Safety System Program Plans* in 1991, significant parts of which will now be incorporated

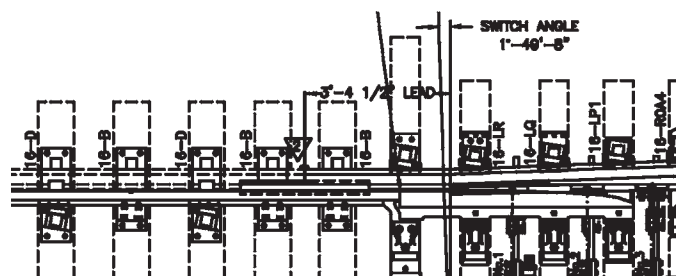


Figure 3-3. Enlargement of the house top area showing guard rails either side.

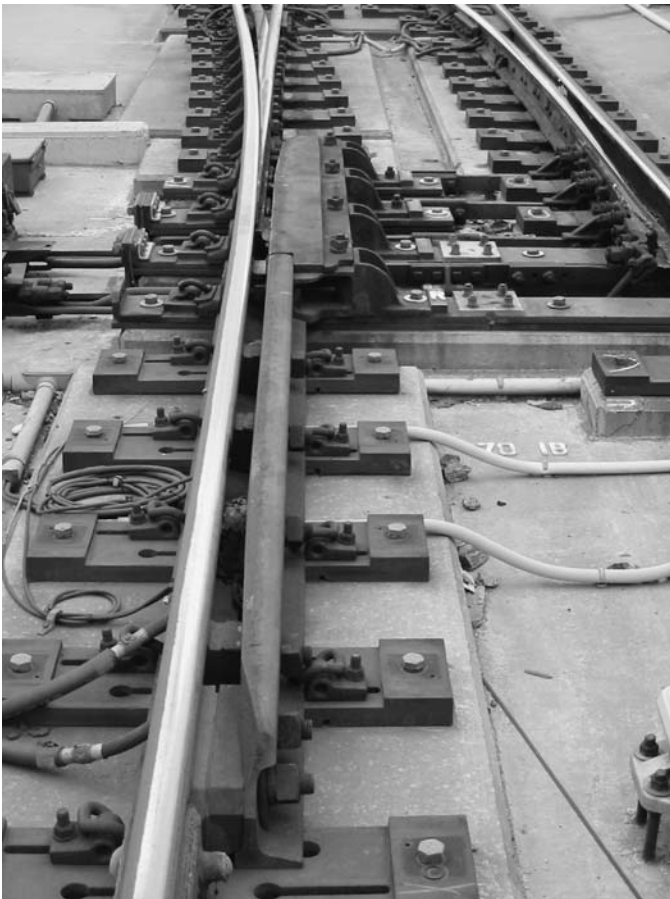


Figure 3-4. A house top with the guard rail on the approach.

in the regulations. The manual proposed that each transit system should develop and manage its own maintenance plans. Also APTA published its *Standard for Rail Transit Track Inspection and Maintenance* in 2002. This is a detailed document, but is only an advisory guideline. It covers embedded streetcar track as well as ballasted track, but significantly makes no mention of LFLRVs or vehicles with IRWs. In many areas, it recommends that transit systems create their own standards for the vehicle types used.

Table 3-9 summarizes what the various transit systems consulted as part of this study have said about the maintenance standards issue.

Table 3-9. Maintenance standards used by transit systems that have LFLRVs.

System	Notes
NJT	Has its own manual ("MW 4").
Portland	Own specific requirements. Track is maintained to the suggested limits of the FTA guidance manual "Design Criteria" published in August 2002.
Santa Clara	Issued own procedures MTN-PR-6405.
San Diego	Applies FRA class 6 requirements—most of the initial route was part of the FRA-controlled general railway system of the United States.
Houston	Uses a maintenance manual.
Boston	Published its own track maintenance and safety standards for the Green Line in 2002.

There does not appear to have been any standardization of maintenance relevant to LFLRVs—each system that has introduced them has had to develop its own requirements.

Maintenance procedures will generally be followed if the instructions provided are clear and easy-to-follow. Table 3-9 shows which systems have their own standards and those published by one of these systems is a good example of this. The system's standards present the information in separate sections applicable to different situations and provide introductory material that assists understanding and application and that can be the basis of staff training exercises.

TCRP Report 71, Volume 5 (12) also notes the diversity of maintenance practices among transit operators and the consequent difficulty in establishing uniform guidelines.

Track maintenance standards are likely to affect the following contributing factors to performance issues identified in this study:

- **Rail Profile.** Certain wear patterns will cause the rail profile to change. If the profile is not checked and corrected regularly, this will cause issues.
- **Track Tolerances.** If the track geometry is not maintained within tolerances, derailment and possibly other performance issues will result.
- **Lubrication.** Wayside track lubrication systems need to be maintained so that they function properly to reduce noise and wear issues and to prevent excessive lubrication, which creates excessive contamination of the roadbed and top of rail, potentially leading to extended braking distances.

CHAPTER 4

Guidance

4.1 Purpose and Structure

This guidance applies to the introduction, operation, and maintenance of LFLRVs of a specific type (i.e., three-section cars with the short center section carried on an unpowered truck having IRWs). This guidance covers infrastructure as well as the vehicles themselves and is state of the art, subject to the limitations of this and earlier research programs. This guidance is confined to measures identified in this research as a means of mitigating specific performance issues (i.e., derailment, wheel and rail wear, noise and poor ride). This guidance has been designed to be clear, applicable, and easy to refer to by the intended users:

- Transit agencies that operate or plan to operate LFLRVs,
- Rail vehicle and infrastructure maintenance organizations,
- Rail vehicle manufacturers,
- Rail vehicle sub-suppliers,
- State regulatory and oversight authorities, and
- National bodies.

The application of the guidance will differ for existing and planned new systems. On existing systems, decisions requiring changes must allow for the costs of modifying infrastructure and vehicles, whereas on new systems best practice may be designed in from the start. Recommendations for modifying vehicle designs for future orders will not be implemented immediately by suppliers, implying a tiered approach. Table 4-1 shows the range of possibilities in terms of time frame.

“Existing vehicles” refers to LFLRVs operating on transit systems in the United States and Canada and remaining in use on those specific systems. “Vehicles currently available” refers to vehicles that might be transferred to another system or new vehicles built to the same design or a design in use on other systems worldwide.

It has been assumed that a “new” system will start with total freedom to specify and use whatever vehicles and infrastructure

it chooses, subject only to U.S. and Canadian legislation and regulation. This may not always be the case, even with a totally new system, in that the system may be using some existing infrastructure or be constrained in other ways. The guidance only covers those elements of specifications that directly influence the performance of LFLRVs; other elements must not conflict with these. Users of the guidance need to bear these points in mind.

Existing systems also may be able to make infrastructure modifications over time and to introduce new standards for extensions and new projects. Existing systems also may procure new vehicles in the near future (e.g., if a market elsewhere can be found for the LFLRVs they are currently using). Most issues are likely to be “system issues” (i.e., resulting from the combination of vehicles and track), so moving vehicles between systems may either solve or worsen these issues.

Guidance is split into section headings to facilitate this tiered approach. The sequence is based on the timescale associated with introducing vehicles now adopting best practice in future, as follows:

- Vehicle standards,
- Vehicle selection issues,
- Vehicle maintenance,
- Vehicle modification,
- Future vehicle design,
- Infrastructure standards,
- Operation of LFLRVs,
- Infrastructure maintenance,
- Infrastructure modification, and
- Best practice for system design.

Each of these sections is further divided into specific component areas, organized and presented to be easily accessed and referenced. Cross references are supplied to other chapters of this report to indicate why the guidance is given so that users can gain a full understanding by making use of these

Table 4-1. Situations where the guidance will apply.

Ref	Time period	Situation covered
A	Short term	Existing system with existing vehicles
B	Short/	New system with vehicle designs currently available
C	medium term	Existing system, replacing vehicles with vehicle designs currently available
D	Medium /long term	Existing system, replacing vehicles with ones of a new design
E	Long term	New system with new designs of vehicle

links. In many cases, however, information has been repeated from other sections of the report so that this chapter can be more easily used as a stand-alone document.

4.2 Performance Issues Addressed by the Guidance

The following notes explain what the more detailed measures described in this guidance are attempting to achieve in overall terms.

4.2.1 Derailment Protection

The main causes of derailment covered here are flange climbing derailment and derailment on switches and crossings. These can cause any LRV to derail, but the specific type of LFLRV covered by the guidance is more vulnerable.

4.2.2 Wheel and Rail Wear

The main causes of wear, associated with this type of vehicle, are

- High guiding forces caused by poor steering capability,
- Constant flange contact on straight track caused by lack of self-centering capability,
- Incompatible wheel and rail profiles, and
- Misaligned track.

LFLRVs using IRWs are intrinsically more prone to wear because of their dynamic performance and sensitivity to external factors.

4.2.3 Ride Quality

The vehicle configuration may cause the end sections to pitch. Pitching can be eliminated by design of the articulation and linkages between the sections. There is little room on this design of center truck for extra suspension equipment.

4.2.4 Noise

The various sources of noise can be aggravated by the use of center trucks with IRWs. Rubbing flange contact will occur

on tangent track. Wheel and rail roughness, caused by wear and so forth can generate a rumbling noise. Rolling noise can be created if the bearing surfaces are not properly maintained. Light contact of the unpowered IRWs on the track may cause corrugations, which create very noisy conditions. On sharp curves, both flange contact and lateral slip of the wheel can occur creating wheel squeal and flanging noise. Noise may also result from poor quality special trackwork. There is less space on this configuration of vehicle to install damping material.

These issues can be managed within acceptable limits by a combination of measures, some of which may also relieve the other issues already noted and by solutions that might only be applied locally, such as wayside lubricators on sharp curves or vehicleborne friction conditioners.

4.3 Fundamental Guidance

Some issues apply generally or in more than one of the main areas into which the guidance has been split. These are fundamental to the situation being studied (i.e., the introduction of a technology to the United States and Canada that has largely been developed elsewhere). The transit systems of other countries have adopted different standards and operate in a different regulatory environment than those of the United States and Canada. As a result, new systems in those countries do not follow the same practice. These basic facts give rise to potential risks that can be mitigated by applying these fundamental principles:

- **Guideline 1:** The vehicle supplier must fully understand the requirements of the transit system and the operating context and modify designs accordingly. The transit system must facilitate this by providing all relevant information.
- **Guideline 2:** The transit system must fully understand the effect of anything it specifies and not make requirements that are inappropriate for LFLRV operation (e.g., the system has put forward “historical” requirements).
- **Guideline 3:** The infrastructure must be suitable for the type of LFLRV to be used, taking into account features that may not appear in a written specification and may need to be modified to suit.

Successful implementation and operation will ultimately depend on all guidelines being followed in all areas. The overriding guidance is to emphasize the importance of achieving compatible solutions to solve issues where the interface issues are crucial.

As mentioned above, this guidance is limited by the scope and resources available for this research program and the comprehensiveness of earlier studies that have been assimilated into it. This means that full and accurate application of the guidance would not necessarily mitigate all issues likely to

arise. Application of the guidance will require further work in order to develop optimum vehicle/track performance on specific transit systems.

4.4 Vehicle Specifications

4.4.1 Who Applies These?

Technical requirements for vehicles will be specified by the transit system and followed by the vehicle supplier, either based on those provided by the transit system or on their own engineering and commercial strategy. The extent to which the transit system specifies and the supplier designs will vary, according to the type of specification process used, but the overall vehicle standards should not be affected by this as Figure 4-1 shows.

Where a performance specification is used, Guideline 1 is particularly important, whereas where a technical specification is issued, Guideline 2 becomes more significant.

4.4.2 Where Do They Apply?

Table 4-2, an extract from Table 4-1, shows the situations in which consideration of vehicle specifications applies (i.e., C, D and E). Situation C will only apply if the existing vehicles exactly match, or can be modified to match, the vehicle requirements. In the guidelines that follow in this section, a distinction is made between vehicles being supplied to existing systems and vehicles being supplied to new systems.

4.4.3 Basic Vehicle Configuration

The vehicles described here are LRVs with three-section articulated bodies as shown in Figure 4-2. The center section is mounted on its own truck, the “center truck,” which is an unpowered trailer truck. The end sections are mounted on individually powered trucks, but part of their mass is also carried by the center truck via the articulations. The floor height

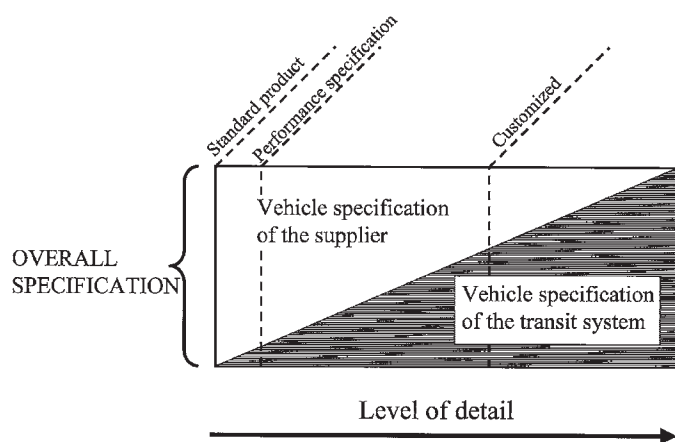


Figure 4-1. Variation in procurement methods.

Table 4-2. Situations where considerations of vehicle specifications apply.

Ref	Situation covered
C	Existing system, replacing vehicles with vehicle designs currently available
D	Existing system, replacing vehicles with ones of a new design
E	New system with new designs of vehicle

in the central area of the vehicle is relatively low, so the wheelsets on the center truck do not have solid axle connections but use IRWs. The researchers are therefore assuming that this configuration is included in the vehicle specifications. The remaining guidance in this subsection describes how key elements of this configuration can be specified so as to minimize performance issues. Any basic vehicle configuration must be tested, initially by modeling, to check that it performs satisfactorily on the system(s) that might use it.

4.4.4 Wheel Profile

Table 4-3 lists the main features of a typical wheel profile (Figure 4-3) and shows how each one influences the key performance criteria. The profile must be designed to give running stability at speed and must be optimized for the conditions of the system, including speeds and ratio of sharp curves to tangent track.

Using the same profiles on all vehicles on a system is desirable; introducing new profiles, either on new or existing vehicles, needs to be carefully programmed in order to allow a smooth transition.

“Railway” type profiles may be used but this choice rules out any flange tip running and it may prove difficult to maintain the rail sections in the street, whereas transit wheel profiles can use grooved rail, which is simple to maintain in that it only requires grinding horizontally.

The use of wheel profiles that match the rail profile minimizes wear (however, see Section 4.9.4. as well).

Continuously evolving contact points and contact angles reduce noise and wear and are preferable to two-point contact, which should be avoided. Contact in the flange root area should minimize noise and wear. The use of a large flange root radius between the tread and the flange can avoid the need for steep tread slopes (such as 1 in 20), which may be less suitable for light transit, but at the same time reduce flange contact. The profile should not encourage a rapid change of contact points, which will create jolts and damage wearing surfaces.

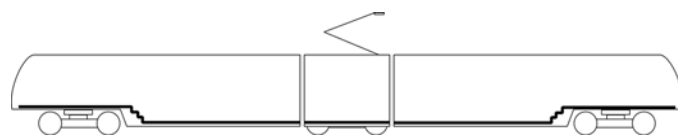


Figure 4-2. Configuration of the LFLRVs used in the United States and Canada.

Table 4-3. The purpose of the features of a wheel profile.

Profile feature	Influences
Tread slope and shape	Ride, guidance, wear, and noise
Flange angle	Derailment protection, passage through S&C
Toe radius	Switch safety
Toe shape	Flange running ability
Flange height	Derailment/depth of grooves
Blend radius	Guard rail effectiveness
Flange root radius	Flange wear (especially on IRW)
Flange thickness	Toe radius/blend radius, wear allowance.

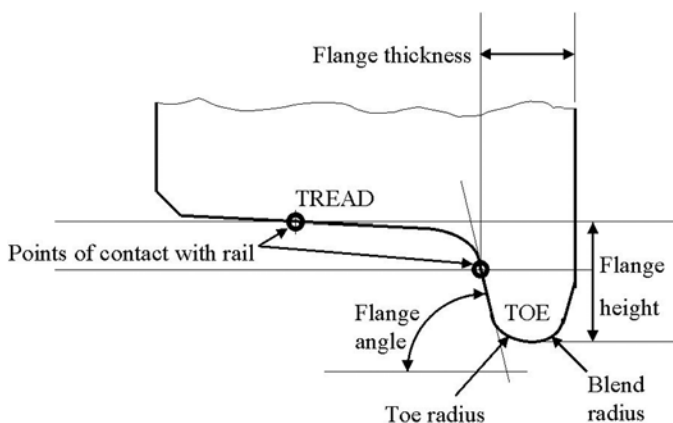
On sharp curves, the wheel profile “footprint,” (i.e., a horizontal section through the flange at rail level) needs to be considered. Clearance needs to be considered in three dimensions, rather than just the two associated with a vertical cross section.

Developing a suitable wheel profile for a vehicle is an issue of balancing the following main requirements:

- Satisfactory guidance on all types of track,
- Safety against derailment,
- Ride quality,
- Minimizing contact stress and avoiding rolling contact fatigue,
- Minimizing wear, and
- Minimizing the requirement for changes to rail profiles and wheel profiles on existing vehicles.

Flange-tip running is a standard practice on street running transit systems. The tip of the flange is flat so that the wheels can run on a flat surface in the frog casting rather than relying on the tread, which will drop significantly in the gap required on sharp switches. The angle of switch at which flange-tip running becomes necessary depends on wheel width.

Because flange-tip running tends to cause more wear and noise, it should only be used when essential, especially where

**Figure 4-3. Main features of a wheel profile.**

LFLRVs are in use, where the noise will be more apparent. The need for flange-tip running can be avoided if sharp angle switches and crossings are not used, but the use of sharp angle crossings may be unduly restrictive on light rail transit (LRT) system design in some cases.

4.4.5 Lubrication

Table 4-4 summarizes the types of lubrication system available. The choice of lubrication system depends on local conditions (e.g., a system that is largely straight with one sharp curve may use a track-based solution at that location only, whereas a system characterized by many sharp curves may equip some or all the fleet with vehicle-mounted lubrication systems). LFLRVs require flange lubrication for the center truck because of the increased incidence of flange contact and higher lateral forces compared with high-floor cars.

4.4.6 Wheel Parallelism

The design of the center truck must specify sufficiently close tolerances to ensure that the parallelism of the IRWs is maintained within close limits. In Germany, the parallelism of the axles in a truck should be within 1.2 mm (0.05 inches) measured at the wheel. One German system that has been using LFLRVs for some years found that halving this figure to 0.6 mm (0.025 inches) for the “theoretical” axles of IRWs gave a satisfactory performance.

4.4.7 Vertical Suspension Stiffness

The limited space available for primary suspension within the design of a low-floor truck creates a challenge for the designer in achieving sufficient flexibility to accommodate track twist. Despite this, most solutions successfully use a conventional arrangement of a rigid frame and primary suspension. It is possible to save space by reducing the flexibility of the suspension and providing a truck frame that is articulated in the twisting sense. Any such arrangement must, however, ensure that parallelism of the wheelsets is maintained.

4.4.8 Vehicle Articulation Design

The articulation design encompasses the mechanical arrangement by which the end sections, the center truck, and the center section are attached together. Various designs are possible with no intrinsic advantage of one arrangement over another. However, all designs must address the following basic requirements:

- **Safety Against Derailment.** The design must not generate excessive lateral forces between the wheel and rail and must

Table 4-4. Types of lubrication.

Location to lubricate	Vehicle mounted	Track mounted
Flange/gauge face of rail	Grease spray sticks	Grease application by hand or an automatic system
Wheel back/restraining rails	Grease spray sticks	Grease application by hand
Tread-rail head	Friction modifier sticks	Friction modifier application by automatic system

be capable of negotiating all track features without leading to wheel unloading. Lateral forces are typically controlled using a pair of dampers at roof level to control center section yaw. These only need be provided at one end of the center section.

- **Wheel Wear And Noise Generation.** The design must ensure that the alignment of the center section is maintained as close to tangential to the rails as possible, in order to minimize noise and wear generated by flange contact. To achieve this, the alignment tolerances must be maintained as closely as possible, and parasitic noises (e.g., such as those arising from dampers) must be minimized.
- **Ride.** Pitching of the short center section must be controlled. Typically, this requires the use of roof linkages. Alternatively, the center section can be fixed relative to one end-section and only allowed to pitch relative to the

other. A single damper on the center line, which only reacts to sharp accelerations or decelerations, may be sufficient. Relative roll between sections must also be controlled, either by linkages or by the design of the articulation pivots.

4.4.9 Summary of the Proposed Guidelines for Basic Vehicle Parameters

Table 4-5 summarizes the guidelines proposed for vehicle parameters by heading. The final column gives the reference for background information on why the suggestion is made. It is only possible to give some limiting values; actual values need to be determined for each design by the use of modeling techniques. These guidelines cover the main parameters identified

Table 4-5. Summary of proposed guidelines.

Parameter	Existing systems	New systems	Cross reference
Floor height above rail above the center truck.	About 350/355 mm (13 ³ / ₄ -14 inches) unless there are good reasons for using another height and never less than 290 mm (11 ¹ / ₂ inches)	About 350/355 mm (13 ³ / ₄ -14 inches) and not less than 290 mm (11 1/2 inches)	
Center truck wheel diameter (Minimum)	26 inches (660 mm)	550 mm (21 ⁵ / ₈ inches)	Section 3.6.1
Center truck wheelbase	1800-1900 mm (71-75 inches)		Section 3.6.1
Wheel gauge (see note 1)	To be determined based on giving a minimum clearance of 5 to 7 mm (0.2-0.3 inches) to the existing track under all conditions	Nominal track gauge less 9 mm (³ / ₈ inch)	Section 3.6.5
Wheel width	To be determined based on track geometry	Preferably 5.25 inches (133 mm) or 4 inches (102 mm) if flange tip running is used throughout	Section 3.6.2
Wheel taper	See note 2	See note 2	Section 3.6.2
Wheel flange height	24 mm (0.95 inches) with flange tip running, 20 mm (0.8 inches) otherwise	22 mm (0.87 inches) with flange tip running, 20 mm (0.8 inches) otherwise	Section 3.6.2
Flange angle	To suit rail profile and similar to other cars that will continue in use on the system	72° minimum. 75° maximum (the latter for lines with sharper curves and switches)	Section 3.6.2
Back-to-back wheel dimension	To be determined from preceding figures and based on track geometry and an appropriate flange width	Wheel gauge less twice the appropriate flange thickness	

in this research as influencing LFLRV performance significantly. The guidelines all apply to the center truck.

Note 1: Wheel gauge is the distance between the contact areas on the rail sides of the flanges on a pair of wheels. It is measured at a defined gauge line height for new wheels “wheelset.” The figures shown apply to the center truck.

Note 2: The wheel taper should be between 1 in 20 and 1 in 40. The actual value should be determined by analysis and will relate to the type of rail used and its inclination. A variable taper will reduce the risk of two-point contact and provide better steering and possibly give better results. The objective is to keep contact at the rail center.

The selection of actual parameters can be based on a “decision tree” approach in order to develop an optimized solution.

4.5 Vehicle Selection Issues

The transit system must check that the vehicles being supplied meet the requirements stated in Section 4.4 as part of a structured vehicle acceptance process. The following steps are envisaged:

- The supplier provides a response to the request for a proposal that included the transit system’s specification. The supplier’s response should include the supplier’s own specifications, drawings, and other data. The transit system’s assessor should scrutinize this information and carry out any necessary calculations and investigations to ensure that the requirements are met. This should involve requests for further information from the supplier as necessary. The process should also involve modeling vehicle performance, using an appropriate software package, and replicating the actual track conditions as closely as possible, although there may not always be sufficient data available to do this thoroughly. The modeling should either be carried out by the transit authority or by the supplier or the supplier’s agent. In the latter case, the results should be certified or checked by an independent body acting on behalf of the transit authority.
- During the design and construction process, the supplier may wish to modify the vehicle design. In this case, each modification should be acceptance-tested by the transit authority according to the guidance in Section 4.4 and using the dynamic modeling package if appropriate.
- When the first vehicle is ready to be delivered, the supplier should certify that it now meets the agreed specifications and vehicle acceptance tests should take place. These tests should take place at either the supplier’s own premises or elsewhere as appropriate. The main stages, in relation to the issues described in Section 4.4, will be
 - A visual check to see that the vehicle has all the features expected and that they are correctly assembled;

- A static measurement check, including use of wheel profile measuring gauges;
- A static loading test to check that the suspension characteristics are as expected;
- Dynamic running tests to ensure that the vehicle ride meets the performance requirements under a range of loading conditions, including noise measurements both inside and outside of the vehicle; and
- Checks on the condition of the wheel running surface and on the track at vulnerable locations (e.g., sharp curves and switches) to ensure that excessive wear is not occurring. Such checks will be made throughout an extended period of testing in service before the vehicles are finally accepted.

This process constitutes “type testing.” Acceptance tests shall also be arranged for subsequent deliveries of the same type and, as a minimum, the supplier should certify that each vehicle has been checked to ensure that the key parameters comply with those of the vehicle that was thoroughly tested.

4.6 Vehicle Maintenance Guidelines

4.6.1 Who Applies These?

Maintenance of vehicles is often carried out by the transit system, although it is quite common for it to be performed under a maintenance contract by the supplier or another agency. It is also usual for vehicle maintenance to be the responsibility of the supplier until the completion of an acceptance process.

In these circumstances, either the transit system must fully understand the issues associated with maintaining what may be a vehicle type that has not operated on the system before, or the contracted supplier or agency must be fully familiar with the “peculiarities” of the system and the way it is operated.

Part of the process involves the supply of information by the supplier so that staff are aware of maintenance requirements. Part of the responsibility will, therefore, rest with the supplier, even where they are not involved in subsequent maintenance activity. It is vital that suppliers provide information as part of their contract, in the form of manuals, training, and so forth, that take into account the level of familiarity of the maintenance staff with their vehicles. This will avoid the serious issues that can arise when a supplier delivers a vehicle to a new market that is unfamiliar with the technology.

4.6.2 Where Do They Apply?

Vehicle maintenance guidelines will apply in the situations (A to E) described in Section 4.1. In Situation A, it may be necessary to implement some of these suggestions retroactively.

4.6.3 Process

It is suggested that vehicle maintenance is based on the following principles:

- Provision of high-quality technical manuals,
- Training of staff,
- Scheduled preventive maintenance,
- Timely corrective action, and
- Good-quality maintenance records.

These principles will apply generally, but are even more important in ensuring that performance issues associated with LFLRVs are minimized.

Provision of High-Quality Technical Manuals

There have been cases where suppliers have provided inadequate technical manuals with incomprehensible drawings, incomplete sections, text in foreign languages, text lifted from subcontractor manuals without editing, and so forth. The contract for vehicle supply should include the provision of adequate technical manuals, with procedures for fault finding, preventative and corrective maintenance, overhaul, and so forth. The manuals should also include illustrated parts lists. The format of the manuals should include photographs, diagrams and other material to readily identify components, and how testing, dismantling and re-assembly takes place. They should be divided into sections to cover different types of maintenance (e.g., electrical, mechanical, and diagnostic). Manuals should be supplied in both printed and digital format.

The manuals only need be provided where the suppliers are not carrying out maintenance; this applies to components as well as vehicles as a whole. So for example if the center trucks are to be maintained by the supplier, the manual should only cover how they are removed, replaced, and tested.

The maintainer should check and approve the manuals as part of the vehicle acceptance process and the supplier's contract should ensure that the maintainer makes any appropriate changes.

The maintainer, where this is not the supplier, should consider incorporating the manuals into its own maintenance documentation. This has several advantages:

- The manuals can be simplified to cover only the requirements of the transit system.
- Any special requirements of the system can be highlighted.
- The maintenance schedules (see below) can be incorporated.
- Experience can be incorporated.

- The user should normally only refer to one document, which is more convenient, saves time, and avoids potentially serious confusion.

Training of Staff

Maintenance staff require training to maintain LFLRVs. Where the maintenance is not to be carried out by the supplier, the training should also be a part of the vehicle supply contract and its successful completion should be part of the vehicle acceptance process. The training needs to be such that it will allow some of the staff trained to train other new staff subsequently. The maintainer has a responsibility to ensure that training is ongoing.

Training will normally be based on the material in the manuals and include both classroom and on-vehicle training with fault finding and other exercises. At the conclusion of any training, trainees should be tested so as to ensure that they meet the required standard and their ongoing performance should be monitored. If any maintenance procedures change because of experience, new components, and so forth, refresher courses will be necessary.

Scheduled Preventive Maintenance

LFLRV performance will partly depend on maintaining key center truck parameters within relatively tight tolerances; therefore, vehicles must be monitored as part of a scheduled preventive maintenance program. Tolerances and other requirements, as listed in Table 4-6 and included in the supplier's manuals, need to be checked. Initially, checking should be performed relatively frequently until "patterns" are discerned and the supplier's recommendations for periodic inspection can either then be adopted or modified. The equipment and techniques used for taking critical measurements must do so accurately and properly gage tolerances.

Timely Corrective Action

Where an issue is identified or emerges it is essential that the vehicle does not remain in service if this might cause damage, be dangerous or initiate performance issues.

Good-Quality Maintenance Records

Records need to be kept for each vehicle, each truck, and each component on the center truck and for other key components associated with LFLRV technology (e.g., roof-mounted linkages and dampers). The records should show measurements taken during programmed inspections and after major maintenance work and overhaul has taken place.

Table 4-6. Features to be included in maintenance manuals.

Parameter	Tolerance	Cross reference
Difference in wheel diameter between wheels on the truck	Within 1/16 inch (1.6mm)	Section 3.6.1
Wheel wear on tread before scrapping	Depends on wheel and rail profiles	
Wheel wear on flange before scrapping	Depends on wheel and rail profiles	
Wheel gauge	+0.04 inches (± 1 mm)	
Wheel taper	$\pm 0.5^\circ$	
Flange height	Minimum 0.75 inches (18 mm)	Section 3.6.2
Flange angle	+3°, -2°	Section 3.6.2
Wheel back-to-back dimension	+0.04 inches (± 1 mm)	
Axle parallelism	0.6 mm (0.025 inches)	Section 3.6.1

4.6.4 Maintenance Tolerances

Vehicles are designed to manufacturing tolerances but may be maintained to different tolerances. Also, dimensions will be allowed to vary within operating tolerances before maintenance or corrective action occurs.

The maintenance manuals should include tolerances for all the features shown in Table 4-6 that are associated with the performance of the center trucks on LFLRVs; these are derived from the standards mentioned in Section 4.4, or are typical of tolerances in use in the industry. They are not exhaustive. Where actual tolerances are shown, these will only apply for vehicles that also conform to the recommendations for new systems specified in Section 4.4. In all other cases, tolerances must be developed based on the principles outlined in this guidance and described elsewhere in the report.

Avoid creating rough wheel surfaces because of wheel truing—rough wheel surfaces increase derailment risks, especially on LFLRV center trucks. A surface finish of N8 (125 μ inch) should be achieved.

4.7 Vehicle Modification

Circumstances can arise where either the supplier or the transit system undertakes modifications to vehicles. Where vehicles are transferred between systems, it may be necessary to make modifications because of different track geometry or other reasons. In all these cases the modification must be seen as a design change and both the modification itself and any other features of the vehicle that may be altered as a result must go through the same processes as would be associated with a new design, including

- Application of the fundamental guidance Guidelines 1 and 2 (see Section 4.3);
- Application of the proposed specifications (see Section 4.4);
- Acceptance process (see Section 4.5); and
- Revised maintenance standards with new manuals, training and tolerances (see Section 4.6).

4.8 Future Vehicle Design

This chapter can also be used as guidance on the overall design of LFLRV most likely to give trouble-free performance on U.S. and Canadian transit systems. This assumes that the design is limited to the scope of the research (i.e., LFLRVs having an unpowered center truck with IRWs), but it needs to be re-emphasized that other types of LFLRV may also be a possibility.

The guidance will apply to the two “long-term” situations D and E of Table 4-1 (Table 4-7). In these cases, the guidance shown in Table 4-5 will apply, but it is possible to identify a standard set of parameters that may well have a ready market, especially for Situation E, that would have the following features. Option A is suitable where flange tip running exists on most switches and crossings on the system and Option B where it does not. The suggested parameters are

Floor height:	350 mm (133/4 inches)
Center truck wheel diameter:	660 mm (26 inches)
Center truck wheelbase:	1800 mm (5 feet 11 inches)
Wheel gauge:	1,426 mm (56.14 inches)
Wheel width:	Option A 4 inches (102 mm) Option B 5.25 inches (133 mm)
Wheel taper:	Variable taper.
Wheel flange height:	Option A 22 mm (0.87 inches) Option B 20 mm (0.79 inches)
Flange angle:	Variable between 72° and 75°
Back-to-back wheel dimension:	Depends on flange thickness

These key critical interface parameters are associated with center truck design based on the research carried out and assume that the equivalent infrastructure standards also apply.

Table 4-7. Situations where future vehicle design will apply.

Ref	Situation covered
D	Existing system, replacing vehicles with ones to a new design
E	New system with new designs of vehicle

4.9 Infrastructure Guidelines

4.9.1 Application

One of three situations will apply as shown in Table 4-8. The third situation is quite common on older European systems where, although LFLRVs have been introduced, LFLRVs are often confined to certain routes until other routes are modified. The split in the level of detail in the specification between the transit system and the infrastructure supplier, in Situations 2 and 3, will vary in a similar way to that for vehicle specifications as discussed in Section 4.4. The fundamental Guidelines 2 and 3 (see Section 4.3) apply to infrastructure and are essential to ensure trouble-free performance. Infrastructure standards will apply in all the scenarios described in Table 4-1.

4.9.2 Track Geometry Standards

Table 4-9 shows the track geometry guidelines suggested for existing and new systems using LFLRVs. It is very important to get the gauge and position of restraining rail correct on curves.

4.9.3 Track Guidelines

New systems should consider using 115 RE rail. For embedded track, the matching rail is either Ri59/13 or Ri59N grooved rail or 115 RE with a formed groove alongside. 115 RE rail should be inclined at 1 in 40—this will match the profile of RI59 where the latter is laid without any inclination. In some cases, these sections will not be appropriate, but care needs to be taken to select a rail section that matches these sufficiently well so that wheel profiles can be modified if necessary.

Older systems should replace their rail with these sections when rail becomes due for renewal and should replace it when introducing LFLRVs if the business case makes sense. Otherwise they should continue with the rail sections in use.

The track base must remain as level and twist free as possible so the specifications for new lines should include features to make the track maintain its alignment. Older track should be upgraded to this guideline or operated at reduced speed. Where ballast is used, ballast shoulders should be created so

as to hold the track against lateral movement. Heavier grade ballast will help maintain track alignment.

4.9.4 Wheel-Rail Interface Guidelines

The wheel-rail interface must be compatible in all situations. The wheel and rail profile should be such that there is contact over the designed contact area on the wheel tread and the wheel flange. At the same time, contact bands must not be too wide because such bands might be a cause of rolling contact fatigue (see Section 3.6.2).

4.9.5 Switches and Crossings

One of the main objectives of specifying features of switches and crossings when LFLRVs are operated is to minimize derailment risks associated with IRWs on the types of center truck used. This can be achieved by a smooth passage and reducing the freedom for wheels to take a wrong path.

The following guidance is based on the research findings and an earlier TCRP report (1). In this case we need to reconsider Table 4-1. In Situations A, C, and D, the switches and crossings will already exist and they may or may not be suitable. As a minimum, they should be modified so as to allow LFLRVs to operate safely. It is difficult to generalize what will be required to do this because of the possible variations in track geometry and vehicle, but one might

- Change the type of switch,
- Change the “number” of the switch to give a less acute switch angle,
- Provide more guard rails,
- Improve the embedding of the switchblades into the running rails, and/or
- Provide cover guards (house tops).

Table 4-10 shows guidance for switches and crossings in Situations B and E. In Situation B it is still difficult to generalize in all areas because of variations in vehicle parameters. In Situation E, however, one can assume that the vehicles and track will conform to the guidance given so far in these guidance notes.

Table 4-8. Situations where infrastructure standards will apply.

Situation	Description	Who sets and applies the standards
1	An existing system that is introducing LFLRVs.	Transit system
2	A new system that will use LFLRVs.	Transit system/infrastructure supplier
3	An existing system that will have new extensions that will use LFLRVs but where the standards need to allow for compatibility with existing routes.	Transit system/infrastructure supplier

Table 4-9. Suggested track geometry guidelines.

Feature	Existing systems	New systems	Note
Nominal track gauge	As existing unless a business case can be made for conversion to 56.5 inches (1,435 mm.)	56.5 inches/1435 mm (or close equivalent).	Use of standard gauge gives maximum choice of supplier.
Tangent track gauge	As existing but modify if appropriate.	Based on nominal track gauge, wheel profile, and new build tolerances.	See Section 3.6.5.
Minimum curve radius	As existing but try to avoid regular use of unusually sharp curves if possible.	82 feet (25 m).	For each curve use as large a radius as practical, especially on frequently used track.
Gauge widening on tight radius curves	As existing but modify if appropriate.	None.	See Section 3.6.5.
Minimum tangent track between curves	As existing but modify if appropriate.	Length = 0.35V where V = operating speed (mph), or 66 yards, whichever is greater.	Transition curves should be used wherever possible.
Vertical curvature	As existing.	Appropriate for vehicle geometry.	Combinations of sharp horizontal and vertical curves are to be avoided.
Rail inclination	As existing.	Depends on rail type.	
Flangeway clearance	As existing.	Minimum 0.2 inches (5 mm), ideally 0.28-0.31 inches (7-9 mm)	See Section 3.6.5.
Where should restraining rail be provided?	Conform to existing practice.	Apply U.S. Standard.	
Flangeway width	Existing.	1 ¹¹ / ₁₆ inch (42 mm) preferred unless unsuitable.	Flangeway dimensions correspond to those of RI59 rail.
Flangeway depth	Existing.	1 ⁷ / ₈ inch (47 mm) preferred unless unsuitable.	

Table 4-10. Guidance on switches and crossings.

Feature	Situation B (Existing vehicles)	Situation E (New vehicles)
Type of switch operation	Flexible switch rails rather than pivoting switchblades; swing nose frogs are ideal.	
Stock rail contact	Make use of undercut blades (e.g. Samson switches)	
Embedment	Make use of elastomer to reduce noise	
Guard rails	Adjustable so that they can be set accurately.	
Switch rail tip design	Adapt to suit vehicles	Design to avoid flange angle issues
Fully guarded switches	Provide if necessary at vulnerable locations	Avoid need by good overall system design
House tops	Provide if necessary at vulnerable locations	Avoid need by good overall system design
Flangeway	As constant as possible, acting like the plain line situation.	
Flangeway clearances	Minimum 1 ¹ / ₂ inches (38 mm) wide. 1 ³ / ₈ - 1 ¹ / ₂ inches (35-38 mm) deep (U.S. Standard)	
Minimum size	As existing but improve if possible.	#10. #8 in crossovers, #6 in yards.

4.9.6 Lubrication

Trackside lubrication is an appropriate way to reduce noise and wear on curves and help minimize the risk of derailment on switches and crossings; however, it should only be used on sections of track where such issues arise.

4.10 Operation of LFLRVs

The following guidelines are for any U.S. or Canadian system introducing LFLRVs to minimize performance issues:

- Staff training should include issues peculiar to LFLRV operation, including an appreciation of the risks of not adopting changed practices. This training should include operators, vehicle and track maintenance staff, and supervisory staff.
- Procedures should be in place in order to recognize and deal with the early symptoms of performance issues, (e.g., wheel and rail wear and noise), and to allow management to take early corrective action while minimizing disruption.
- Operators should avoid vehicle jerking and maintain constant speed on curves, only accelerating when the curve has passed. This is particularly important as a means of achieving ride comfort on LFLRVs.
- If LFLRVs need to operate at slower speeds than other vehicles in the fleet, the operators need to be fully aware of this.

4.11 Infrastructure Maintenance Standards

4.11.1 Who Applies These?

Maintenance of track is often carried out by the transit system, although it is quite common for it to be performed under a maintenance contract or, in the case of new infrastructure, by the supplier. In these circumstances, the maintainer must fully understand the issues associated with maintaining track in a suitable condition for the LFLRVs operated on it. Track standards assumed by the vehicle supplier when vehicles were supplied need to be followed subsequently or problems will occur. A process for managing the interface between vehicles and track at the contract stage should cover this.

4.11.2 Where Do They Apply?

Infrastructure maintenance guidelines will apply in the situations (A to E) described in Section 4.1. In Situations A, C, and D, it may be necessary to implement some of these recommendations retroactively.

4.11.3 Process

The researchers recommend that infrastructure maintenance be based on the following principles:

- Provision of maintenance manuals,
- Training of staff,
- Use of adequate tools and equipment,
- Scheduled preventive maintenance,
- Timely corrective action,
- Good-quality maintenance records, and
- Maintenance tolerances.

These principles apply generally but are even more important in minimizing performance issues associated with LFLRVs.

Provision of Maintenance Manuals

Using good-quality infrastructure maintenance manuals can overcome many issues. Each system needs to provide such manuals so as to address system-specific situations. For example, even though track workers may have all the information and training needed to determine what needs to be done and to calculate the tolerances that apply, workers are much more likely to do the work properly if all requirements are set down in one place in an easy-to-use document. A consistent approach, so that everyone involved in track maintenance understands their roles and responsibilities, is also needed. The act of creating an infrastructure maintenance manual ensures that the transit authority anticipates issues that might cause issues and manages them.

Where the maintainer is not the transit authority, the latter should monitor the process sufficiently so as to ensure that the performance requirements are being met in an optimized way (e.g., the transit system has not observed the guidelines and, as a result, its vehicles are suffering excessive wheel wear). An independent body may perform this audit.

Manuals should be updated periodically as experience is gained and should incorporate clear schedules for periodic maintenance and procedures for dealing with different levels of issues that might require corrective action.

Training of Staff

Maintenance staff need training to maintain infrastructure to the new guidelines that might be required for LFLRVs. Such training should be part of the training normally provided to maintenance staff, rather than as a separate course. Any maintenance contract should require the maintainer to provide this training both for existing staff and for new staff.

Training will generally be based on the material in the manuals and include both classroom and on-track training. At the end of any training, trainees should be tested to ensure

that they meet the required standard and their ongoing performance should be monitored. If any maintenance procedures change because of experience, new practice, and so forth, refresher courses will be necessary.

Operators should be trained to report faults that they detect when driving vehicles in regular service, because this an important source of feedback on condition.

Tools and Test Equipment

The tools and test equipment needed to meet the minimum requirements of this guidance are as follows:

- Profile measurement systems,
- Track measurement cars, and
- “Mine sweepers” to detect track anomalies.

Scheduled Preventive Maintenance

LFLRV performance will depend partly on maintaining key track parameters within relatively tight tolerances; therefore, these tolerances must be monitored as part of a scheduled preventive maintenance program. The key parameters to be checked include rail profile and alignment, switches and crossings dimensions (including gauge face wear), and availability of trackside lubrication. The periodicity and methods of inspection should be determined and incorporated in the

infrastructure maintenance manual. Also, faults should be detected during the course of scheduled service running.

Timely Corrective Action

Where an issue is identified or emerges, action must be taken to avoid accidents, damage, or objectionable performance issues. The seriousness of the issue should be determined and then graded on a scale of action that might range from no action but correct by the next periodic inspection to situations that might require operational restrictions to a complete stoppage.

Good-Quality Maintenance Records

Records need to be kept for the maintenance work carried out on the track and should consist of a linear record of each section of the route and for each infrastructure item (e.g., switches), showing details of components, measurements taken, inspections made, and work carried out. These records should be revised whenever work takes place and be available to everyone who needs access to them.

Maintenance Tolerances

The maintenance manual should include maintenance tolerances for all the features of the infrastructure where LFLRVs are operated. Some possible tolerances are shown in Table 4-11 as

Table 4-11. Suggested maintenance tolerances.

Parameter	Tolerance	Note
Track gauge	+ $\frac{3}{8}$ inch, - $\frac{1}{4}$ inch (+9.5 mm, -6 mm) from design	Example of a standard that has been used in the U.S. where LFLRVs are in use.
Track wear	Top wear 25 mm (0.975 inch), side wear 20 mm ($\frac{13}{16}$ inch).	German standard, which accommodates IRWs but is not unduly harsh in the U.S.
Horizontal alignment	APTA 8.3 Table 5	See Section 3.6.6
Lateral alignment	APTA 8.4 Table 6	A check is needed that the lateral alignment variations provide sufficient clearances for LFLRVs.
Track twist	APTA 8.4 Table 6	
Super-elevation	APTA 8.4 Table 6	
Cross level	Not more than $1\frac{1}{4}$ inches (32 mm) variation in 62 ft (8.9 m) length.	Tighter than APTA 8.4 Table 6
Track structure	APTA 9 and 13.5	Standards must be developed so that the requirements listed above are met.
Rail-end mismatch	None should exist.	Welded rail should always be used.
Restraining rail guard face gage	5 mm (0.2 inch) variation	Tighter than APTA 11.2 Table 12.
Minimum flangeway in S&C	This may be less than the $1\frac{1}{4}$ inches (38mm) in APTA 12.1.2	IRWs are an "exception," see APTA 1.3
Flangeway depth	APTA 12.3.1 and 13.4.2 apply.	
Condition of S&C	It may be necessary to adopt tighter standards than APTA recommends.	See also APTA 13.7
Gauge face wear angle	+3° to match wheel limits	

an indication of how tight they may need to be, but each system should derive tolerances for its own conditions. This is not a list of all the features that should be included, but concentrates on those features especially important for operating the type of LFLRV being studied. These are derived from the guidelines mentioned in Sections 4.9.2 through 4.9.5. Where actual tolerances are shown, these will only apply to vehicles that also conform to the guidelines for new track specified in those sections. The researchers assume that the basis for the system's maintenance standards are APTA's *Standard for Rail Transit Track Inspection and Maintenance*, referred to as "APTA" in the table.

4.12 Infrastructure Modification

Circumstances can arise where the transit system modifies track. Modifications might include removing redundant features to allow easing of curves, eliminating problematic features, and so forth. Modifications should never "worsen" the standards described in the preceding paragraphs. Modification may require the addition of requirements that may appear "worse" (e.g., tighter radii because of introducing street running to a system previously confined to reserved track). In all these cases, the modification must go through the following processes:

- Application of the fundamental guidance provided in Guidelines 2 and 3 (see Section 4.3);
- Application of the proposed guidelines (see Section 4.9);
- Acceptance; and
- Revised maintenance guidelines with new manuals, training, and tolerances (see Section 4.11).

4.13 Best Practice for System Design

4.13.1 Basics

This section considers the situation likely to arise in the future where a totally new system is planned that is not constrained by any existing design decisions or technology and will not need to link with an existing one. It will only be constrained by federal, state, and other regulations.

Basically, four types of transit system might use LFLRVs:

1. Street running using embedded rail;
2. Reserved track (e.g., using flat bottom rail, cross ties, and ballast or direct fixation);
3. Transit sharing railroad tracks; and
4. Combinations of these.

LFLRVs can operate on all these, and this will probably continue. There is no "right" solution for transit system types;

the choice depends on local circumstances. For an entirely new system, the choice of LFLRV and guidelines to be followed will be influenced by the type of system. It is not necessary to have an "optimum" solution that will suit any type of system—doing this may add unnecessary cost and inflexibility to new transit networks.

The next fundamental issue is the choice of floor height. In the future, most entirely new transit systems may want to use low-floor vehicles in order to meet ADA requirements. An exception may be Type 2 systems that might economically use high platforms with high-floor vehicles and gain level access throughout. If low-floor vehicles are selected, basically, two choices exist—partial low-floor (PLF), which includes the type of vehicle being considered in this study, and 100-percent low-floor vehicles.

The issue of adopting 100-percent low-floor cars was considered in *TCRP Report 2* (Chapter 3). The study concluded that introduction into the United States and Canada on entirely new systems might prove difficult because

- New systems might not wish to assume liability for specifying lower buff loads, even though no technical reason was identified why this cannot be done.
- 100-percent low-floor designs might not meet stringent U.S. and Canadian fire standards (ASTM E-119 was specifically cited).

The buff loads traditionally applied in the United States are derived from the "2 g" formula (i.e., the vehicle should sustain an end loading equivalent to twice its own mass). This has not been the practice in Europe and, as a result, U.S. and Canadian LRVs tend to have heavier structures than their European counterparts. This is not always the case—New Jersey has used a 1-1.1 g formula. On the other hand, some states (e.g., California) have regulated to the 2 g formula (2). *TCRP Report 2* observed that U.S. systems tended to use higher speeds but many European systems are now operating at equivalent and higher speeds without the higher buff loads. The buff load issue is a definite restriction for Type 3 systems, or Type 4 systems that include any Type 3 track. However, an initiative is taking place to reconsider the FRA position about buff load requirements for joint use tracks.

Ten years on from the publication of *TCRP Report 2*, greater availability and worldwide experience of 100-percent low-floor operation will begin to outweigh the liability issue. The researchers also suggest that the fire issue be considered as a possible future TCRP research activity, taking into account, among other features,

- The environment of transit operations using 100-percent low-floor cars, including the extent of tunnels;

- The sources of fire under a low floor compared with a high floor; and
- Recent standards developed in Europe for fire safety on all types of rail systems, including streetcar and light rail systems.

Although the guidance that follows refers only to PLF cars, some of these types may also be affected by the issues mentioned above that have stopped the introduction of 100-percent low-floor cars.

4.13.2 Who Should Apply This Guidance?

This section of guidance is important to all the organizations and individuals noted in Section 4.1. In particular modifications to track should be of interest to their long-term strategies. Modifications to track will strongly influence

- Plans for future transit systems,
- Product development for the U.S. and Canadian market, and
- Changes in the regulatory framework.

4.13.3 Where Will It Apply?

By definition it can only apply to Situation E in Table 4-1 (i.e., long-term new system applications with new designs of vehicle).

4.13.4 Basic Vehicle Configuration

The earlier guidance in this document has assumed the specific type of PLF LRV being studied in this research [i.e., one that has three sections, the center section mounted on a center truck with IRWs (see Section 4.4.3)]. However, other types are possible:

- A two-section vehicle with floating articulation and an independent wheel bogie under one of the body sections. Because this arrangement has fewer degrees of freedom, it may offer better dynamic performance than the three-section type under study. Examples are the Leipzig Leoliner design and the LF2000 in Dessau.
- As above but small-wheel solid axle trailer bogie under one of the sections. Examples are the Geneva and St. Etienne Be4/6 designs.
- Cars with all-conventional bogies, floating articulations, and low-floor areas between bogies. Examples are the Sheffield GT8 and Zurich Forchbahn cars.

- Cars with all-conventional Jakobs bogies and lowered floor areas between. A European example with low-floor center sections is the Basel Be4/8.
- Low-floor trailer cars using small wheels and IRW trucks. This appears to be an outdated concept. Examples exist in Rostock and Leipzig.

Some vehicles have been built using EEF wheelsets but, following the difficulties experienced with this type, no products are available based on this concept.

Given that the researchers did not consider these types of vehicle, no guidance specific to them is given in the notes that follow. It is assumed that systems will be using the center truck type. One area of future research could be to see if using these other types would offer advantages in the U.S. and Canadian context. If the issues listed in Section 4.13.1 concerning the introduction of 100-percent low-floor vehicles were addressed, this might influence future configurations and design of PLF types as well.

4.13.5 Infrastructure Guidelines

The track geometry standards listed under “new systems” in Section 4.9.2 would apply. New systems should consider using 115 RE rail. For embedded track, a matching grooved rail is RI59/13 or RI59N, although it is also possible to use 115 RE with a formed groove alongside. Specifications for new lines should include features to make the track as rigid as practical. The wheel-rail interface issues discussed in Section 4.9.4 will apply. The table column, Situation E (New vehicles), in Table 4-10 will apply.

4.13.6 Vehicle Specifications

Section 4.8 will apply, but will need to be reviewed for a Type 3 (Joint transit/railroad) application and may only apply if Section 4.13.5 is fully applied.

4.13.7 Other Guidelines

The following sections will also apply in full to this situation:

- 4.5 Vehicle selection issues,
- 4.6. Vehicle maintenance guidelines,
- 4.7. Vehicle modification,
- 4.10. Operation of LFLRVs,
- 4.11. Infrastructure maintenance standards, and
- 4.12. Infrastructure modification.

Although these are not system design issues as such, the system design needs to consider that they should be in place.

CHAPTER 5

Recommendations for Further Research

1. Extension of the research to other types of LFLRV, including 100-percent low-floor and steering single-axle trucks with IRWs. Linked to this is the issue of the validity of the “2 g” crashworthiness approach, which may be inhibiting the implementation of other types of LFLRV in the United States and Canada.
 2. Detailed analysis of the operation of IRWs through different types of U.S. and Canadian designs of switches and crossings, including single-point switches. This would include the design of switches to accommodate optimized wheel and rail profiles suitable for IRWs.
 3. Development of a set of standardized wheel profiles and matched rail profiles. These might have a fixed flange contour with adjustments for flange height and the presence or absence of flange tip running. A recommended flange-to-tread transition should be specified, as well as the end of the tread contour. Wheel width would be variable, based on requirements. Compatibility of such a standardized wheel profile would be studied in relation to the rail profiles of existing systems and the performance requirements of existing vehicles.
 4. Development of a “total” optimum solution for a “fresh start” system.
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CHAPTER 6

Conclusions

The principal objective of this research was to provide guidance on this topic. Complete understanding of all the issues associated with the dynamics and performance of center trucks on this type of LFLRV would be a considerable task; therefore, these conclusions should be seen as observations that have arisen during the course of this research.

1. Performance issues have arisen during the introduction of LFLRVs in the United States; however, in all cases they are now being managed reasonably effectively and, as a result, performance has improved. The solutions adopted may not be the optimum ones and are certainly not optimum for application in all cases. The issues that have arisen do not appear to be significantly worse than those that have arisen in other parts of the world during the introduction of this type of vehicle.
 2. The issues associated with introducing these cars to older systems, where the track conditions may not be ideal, and new ones where the infrastructure can be built to accommodate them differ markedly. There are also issues associated with introducing new vehicle types into an established operating and maintenance culture, and compatibility with earlier, different car types.
 3. In terms of the vehicle, most performance issues are influenced by the use of IRWs, rather than the configuration and attachment of the center truck. The issues are, therefore, mainly those associated with the use of that type of wheel and with the design of the wheel profile.
 4. Track standards must be appropriate for this type of vehicle. This may mean modifications to existing systems that introduce them and will mean that appropriate maintenance standards must be applied.
 5. The introduction of LFLRVs to the United States and Canada has not had the same effect as in other parts of the world where this concept now dominates. Only two low-floor vehicle concepts have been applied, whereas other concepts might give better overall performance if they could be introduced.
 6. There does not seem to be any significant difference in the standards used in the United States and those used in Germany that is affecting LFLRV performance. The comparison with Germany is appropriate because that country has a history of continuous large-scale streetcar and light rail development and a substantial body of accepted standards. There are, however, different philosophies in how standards are applied.
 7. Each system in the United States and Canada has tended to adopt its own specifications and solutions to emerging problems. For example, nearly every system has its own wheel profile. This lack of standardization makes introducing new technology and effective solutions to issues much more difficult.
 8. The general advice to ensure that the wheel-rail interface is both compatible and managed properly is even more important for this type of vehicle.
 9. New systems that intend on using LFLRV should avoid the extreme track geometry that characterized older streetcar lines and adopt standards appropriate to the type of system for which these cars were originally developed.
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References

1. Transit Cooperative Research Program, "Center Trucks of Low-Floor Light Rail Vehicles," Research Project Statement, Project C-16, FY 2004.
 2. Booz, Allen, and Hamilton, Inc. *TCRP Report 2: Applicability of Low-Floor Light Rail Vehicles in North America* Transportation Research Board, National Research Council, Washington, DC (1995).
 3. Hüber, B., "Laufruhe von Niederflurbahnen: Möglichkeiten der Optimierung," (Running smoothness of low-floor vehicles: Potential for optimization.) *Der Nahverkehr* (September 2004).
 4. Aprile, A.; Bandinelli, A.; and Marianeschi, M. "Integrating Low-Floor Technology into a Pre-Existing Infrastructure: Partial Low-Floor Light Rail Vehicle In A Mixed Environment: Lessons Learned from the Manufacture of Boston's Partial Low-Floor Light Rail Vehicle," TRC E-C058, 8th National Rail Transit Conference. TRB (2000).
 5. Fraser, G. R.; Leary, R. J.; Marianeschi, M.; and Pellegrini, C., "Integrating new light rail vehicle technology into mature infrastructure," TRC E-C058, 9th National Rail Transit Conference. TRB (2003).
 6. Marie, J., "Hiawatha Joins the Light Rail Family," *Railway Gazette Metro Report* (2004).
 7. Minneapolis Star Tribune, "Light-Rail Car Derailment Caused by Wheel Wear," April 22nd 2005.
 8. Letter from TTC, July 11th 2005.
 9. Letter from SEPTA, July 19th 2005.
 10. Lehna/Theiler/Imhof. "Radprofiloptimierung bei den Verkehrsbetrieben Zürich" ("Wheel Profile optimization on the Zurich Transport System"), Presentation prepared by the Institut für Bahntechnik GmbH (In German).
 11. "Richtlinien für die Spurführung von Schienenbahnen nach der Verordnung über den Bau und Betrieb der Straßenbahnen (BOStrab), Spurführungs-Richtlinien (SpR)," (Regulations on the Guidance of Rail Vehicles in accordance with the German Federal Regulations on the Construction and Operation of Light Rail Transit Systems (BOStrab), Guidance Regulations (SpR). March 2004.
 12. Wu, H.; Shu, X.; and Wilson, N. *TCRP Report 71, Volume 5: Flange Climb Derailment Criteria and Wheel/Rail Profile Management and Maintenance Guidelines for Transit Operations*. Transportation Research Board, National Research Council, Washington, DC 2005.
 13. APTA, "Passenger Rail Equipment Safety Standards Task Force Technical Bulletin 1998-1, part 1 on Commuter Car Safety Regarding: Wheel Running Surface Manufacturing And Reprofileing Contour," Prepared by the Wheel/rail Interface Working Group of the Passenger Rail Equipment Safety Standards (PRESS) Task Force, November 3rd. 1998.
 14. Herbst, B.; Patzelt, B.; and Heyder, R. "Tribologische und werkstoffkundliche Untersuchungen an Rad- und Schienenstählen." (Tribology and material investigations of wheels and rail steels). *Tribologie+Schmierungstechnik* 47/2000 (In German).
 15. Zarembski, A., "Derailment of Transit Vehicles in Special Trackwork," TCRP Final Draft Report, July 1996. Zeta-Tech.
 16. Zarembski, A., "Derailment of Transit Vehicles in Special Trackwork," TCRP Final Draft Report, July 1996. Zeta-Tech.
 17. Sarunac, R., and Zeolla, N. "Structural and Crashworthiness Requirements of Light Rail Vehicles with Low-Floor Extension," Transportation Research Board E-Circular E-C058, pp 89-103, November 2003.
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APPENDIX A

TCRP Research Project C-16 Scope of Work

The research was organized into 11 tasks as follows:

Phase 1—

- Task 1. Review of domestic and international literature.
- Task 2. Collection of information from suppliers and transit systems.
- Task 3. Identification of the factors contributing to performance issues.
- Task 4. A working paper covering Tasks 1 through 3.
- Task 5. Identification and planning of the research needed in Phase 2.
- Task 6. Production of the interim report covering Tasks 1 through 5.

Phase 2—

- Task 7. Execution of the approved research plan.
- Task 8. Production of a working paper summarizing the results of Task 7.
- Task 9. Development of the guidance required to mitigate performance issues.
- Task 10. Development of recommendations for further research.
- Task 11. Development of the final report.

The notes that follow describe the work carried out on each task. Conclusions and results are summarized; text in the body of the report is not duplicated.

Task 1. Literature Review

The review focused on locating information as early as possible that illuminated the following issues:

- The principles applied in designing vehicles.
- The extent to which the designs of center trucks and vehicle articulation have taken into account the environment

within which they will be used, especially conditions that apply on U.S. and Canadian light rail systems.

- The extent to which issues have arisen internationally, how they have been dealt with, and how successful any corrective measures have been.
- Comparing conditions that may have caused issues internationally with those that exist in the United States and Canada.
- Finding data on wheel and rail wear where center trucks of this type have been used.
- Finding out how vehicle manufacturers have responded to these issues and seeing if they have modified their designs.
- Establishing if standards in the United States differ from other countries using these vehicles, and whether such differences might contribute to any known issues or might limit the potential for corrective action.
- Obtaining details of the history of performance issues in order to identify any patterns.
- Reviewing the documentation of vehicle and/or track modifications implemented by transit systems in order to address the issues.

It was thought that the best material would be that produced by the transit authorities and vehicle manufacturers themselves. Documents that report on these organizations' activities will tend to be prone to error, and previous research and periodical articles based on second-hand reports will, in turn, be even more likely to be inaccurate. A "hierarchy" of documents in terms of their reliability was created in order to avoid this issue.

The literature review was carried out by a team of engineers and technical specialists in this area working internationally and sharing information continually via email.

Interfleet assessed literature using a form developed for this purpose. The form was used to record the essential information, providing a summary in English that could easily be referred to at any stage in the project. The form was

also designed so that the data could be recorded in data base format.

The overall view was that the amount of literature that is directly relevant and of high value to this research was fairly limited and that the main pieces of literature had probably been identified and reviewed.

During Phase 2 further literature was identified—some of which was seen as being especially relevant, including the reports issued by TCRP Projects D-2 and D-7, which were now available. Only the MBTA and TriMet Portland appeared to have written up their experience in the United States and Canada and so experience elsewhere could not be determined by a literature search when the research was undertaken. Some European systems had reported on their experience in operating vehicles of this type. Berlin and Duisburg had reported on experience with 100-percent low-floor vehicles and Essen had reported on experience of a 70-percent low-floor vehicle with four trucks. These cities had experienced issues different from those seen in the United States and the vehicles were not of the generic type under investigation. Despite this, their findings about the principles involved helped to inform Task 3. Some of the lessons learned were expected to be applicable to the U.S. and Canadian vehicle types being studied. Some publications covering appropriate areas of theory were identified but, in an area where the key developments are both novel and recent and where commercial secrecy remains, these were not significant except as a means of identifying the key factors. The main exception to this was the work carried on for TCRP Research Project D-7 and reported in *TCRP Report 71, Volume 5*, which considered performance issues with IRWs. All the literature reviewed is listed in Appendix F, together with a short summary of the content and its value.

Although the literature review was useful and was performed as planned, the amount of published information directly relevant to this research project was very small. Although a more exhaustive search might identify further material, the costs of doing this would probably not justify the small benefit. The value, therefore, was in confirming that this research was the first to examine these issues in this particular way and, therefore, could provide useful guidance for the transit industry.

Task 2. Transit Agency and Manufacturer's Experience

Priority was given to understanding the issues that have arisen in the United States and the operating environment within which LFLRVs operate in this country. To this end, a targeted questionnaire was produced for the transit agencies operating LFLRVs. This questionnaire was scheduled after significant progress had been made with Task 3, so that pertinent questions could be asked.

Some design and performance data were obtained from other sources, including internal libraries and files and

telephone and email contacts. Although this and the preceding tasks targeted partial low-floor vehicles of a specific design, where appropriate, the experience of operators of 100-percent low-floor cars was also taken into account. This was done to estimate whether there were lessons to be learned from these vehicles that were applicable to center trucks on partial low-floor cars.

As in the case of the literature review, the review of design and performance data was prioritized to first consider information with the highest potential utility. This was to maximize the effectiveness of the task within resource constraints and in light of potential availability issues resulting from the sensitive nature of some of the relevant information.

All seven transit agencies that operate this type of car were asked in the questionnaire for some specific information about these vehicles, track standards, experience associated with the use of the center trucks, and any mitigation the agencies might have introduced for overcoming issues. Six of the seven agencies provided detailed responses, along with supporting information such as drawings and maintenance procedures. This information proved to be of great value to this project. The responses covered all the systems that had the most experience of operating this vehicle type and that had experienced performance issues with this vehicle type before 2005.

Further information was collected during Phase 2 by direct inquiry and as part of Tasks 7.2, 7.3, 7.7., and 7.12.

Task 3. Contributing Factors

The project scope identified the following potential performance issues:

- Derailments,
- Excessive wheel and rail wear, and
- Reduced ride quality.

The issues being observed were thought to be concurrent manifestations of multiple failure phenomena and, therefore, even more difficult to isolate and identify. Effort in Task 3 was concentrated on identifying those factors that appeared to adversely affect LFLRV dynamic performance. This identification was done by circulating ideas internally in a table; these ideas were then discussed and refined by experts based on their collective experience. This analysis was used both as the basis of the questionnaire designed to obtain key feedback from U.S. and Canadian transit agencies (Task 2) and, combined with these results, to formulate preliminary guidance. The initial findings proved sufficiently robust so as to at least indicate situations likely to cause issues that might easily be avoided, especially with new systems.

The contributing factors were assessed iteratively in discussions between the groups of technical experts. The results

provided the basis for investigations in Phase 2 that were then combined in order to produce Chapter 3 of this report.

The initial assessment indicated that certain features of LFLRV design are likely to have a greater effect on the performance issue areas being investigated than would be the case with a traditional high-floor LRV. Based on the questionnaire returns, this appeared to have led to significant divergence in the performance of different U.S. LFLRV designs. In Phase 2, the researchers proposed investigating these divergences in order to establish the optimum combination of parameters to minimize issues. At this stage, the following features appeared critical:

- Wheel profile, in relation to rail profile;
- Flange angle;
- Flange height;
- Truck and truck-to-body attachment detail design and tolerances; and
- LRV articulation design, including stabilizing links and dampers.

Because lubrication was seen as beneficial, it was proposed to study this as well in Phase 2.

Some of the more serious issues were clearly associated with track geometry. Four issues were apparent from Phase 1 work:

- Wheel and rail profiles must be compatible.
- Sharp curves (under 25 m/80 ft radius) should be avoided. Where they exist, special measures such as low speed restrictions, track lubrication, and restraining rail may be necessary.
- Switches and crossings need to provide as smooth as possible transit for LFLRV wheels and wheels need to be adequately checked by restraining rail.
- The maintenance standards need to keep the track parameters within the tighter tolerances that may be necessary for LFLRVs.

Task 4. Working Paper

A working paper was prepared to bring together the principal data collected during the performance of Tasks 1 through 3 that was likely to influence subsequent work. It was used to develop the Phase 1 report, including discussions on the research needed in Phase 2 (Task 5 of Phase 1).

Task 5. Identification and Planning of the Research Needed in Phase 2

The conclusions of Phase 1 were that Phase 2 should concentrate on modeling the features identified as critical for

LFLRV performance in combinations appropriate to U.S. applications. This was seen as giving most value from the resources available. As part of this modeling activity it was seen to be necessary to obtain further data and background information so that the results were truly representative.

The modeling activity involved creating vehicle and track models that would cover the main combinations of design features. This assessment was checked against what could be seen happening in practice by visits to representative U.S. transit systems using LFLRVs.

Task 6. The Interim Report Covering Tasks 1 through 5

The report was prepared and some comments were received from the Panel. Interfleet presented the report for discussion at the TCRP Project Panel C-16 meeting. The panel requested further information on the proposed Phase 2 Research Plan. A supplement was produced in order to provide this information and replacing section 5 of the Interim Report and the associated appendices 8.7 and 8.8. The supplement included more detail about why ADAMS/Rail was selected as the modeling tool.

Task 7. Execution of the Approved Research Plan

Phase 2 concentrated on modeling the features identified as critical for LFLRV performance in combinations appropriate to U.S. applications. Vehicle and track models were created to cover the main combinations of design features found on the generic LFLRV type under consideration. This activity formed the core of Task 7, which was divided into 14 subtasks.

ADAMS/Rail was used to undertake detailed analysis of track and vehicle conditions. Rail vehicle models were created by entering the required assembly data into forms. ADAMS/Rail then used the data to automatically construct the subsystem models and full-system assemblies building a complete, parametric model of each light rail vehicle being studied.

Tracks were also modeled in ADAMS/Rail, defining the track centerline by specifying the analytic layout parameters: curvature, cant, and gauge. Track-measured data was specified as irregularity parameters: alignment, cross level, and gauge variation. The virtual vehicles were run through a series of kinematic, static, and dynamic tests to determine the vehicle's stability and derailment safety.

Information was requested and obtained from two other major U.S. and Canadian transit systems to determine why

they had not introduced this type of vehicle onto their systems.

Task 7.1 Identification of the Parameters Required for the Vehicle Models

Models were created of the following vehicle types:

- A high-floor LRV closely based on the MBTA Type 7 car.
- An LFLRV closely based on the MBTA Type 8 car, and
- An LFLRV closely based on the Kinki Sharyo New Jersey, Newark Subway car.

These represented a traditional high-floor articulated vehicle, a low-floor vehicle that has experienced some issues, and a low-floor vehicle that is reportedly successful. The design of all three vehicles conforms to the generic vehicle type outlined in the Research Project Statement but the detail designs of the three cars are known to differ substantially from one another. These basic models were subjected to a range of detail variations during the modeling work in order to increase the breadth of the results. These variations are discussed in Task 7.3.

A list of all the information required to cover all the options to be modeled was prepared; this took into account the capability and structure of the model being used. A technical memo was prepared with 3 parameter list documents and circulated among the team. These parameter lists were eventually completed following the visits to transit systems (Task 7.12); in the meantime estimated values were used.

Task 7.2 Collect Data on U.S. Vehicles

The lists created in Task 7.1 identified missing parameters that were required by using a color code. Red indicated information definitely required; yellow indicated where it was possible to make assumptions or use available unconfirmed data without serious effect on the results. Sensitivity analyses were performed to quantify the possible errors of the output.

Before the visit to transit systems (see Task 7.12) a memo was produced that identified the most important questions to be answered. During the visit some new insights were gained and more accurate parameter values were obtained, mainly for the MBTA Type 7 cars.

Task 7.3 Collect Data on Alternative Vehicle Designs

The key parameters of the models were varied in order to gauge the effects of introducing different design features. The purpose of this task was to gather information on alternative components or arrangements that exist in order to be able to

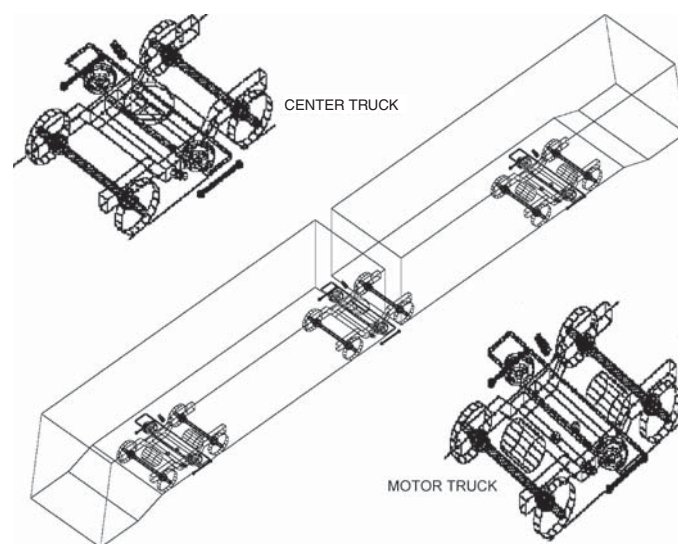
create representative models of them. These design modifications included

- Articulation roll stiffness,
- Pitch damping of articulation,
- Different solutions for stabilizing the pitching mode of the body section above the center truck,
- Variation in the lateral secondary suspension stiffness, and
- Different wheel and rail profiles.

These variations, which were easily implemented in the parameterized model, allowed study of the effect of design changes on the behavior of the vehicle. Although these are comparative rather than absolute analyses, they gave the basis to fulfill the project objectives.

Task 7.4 Develop Vehicle Models

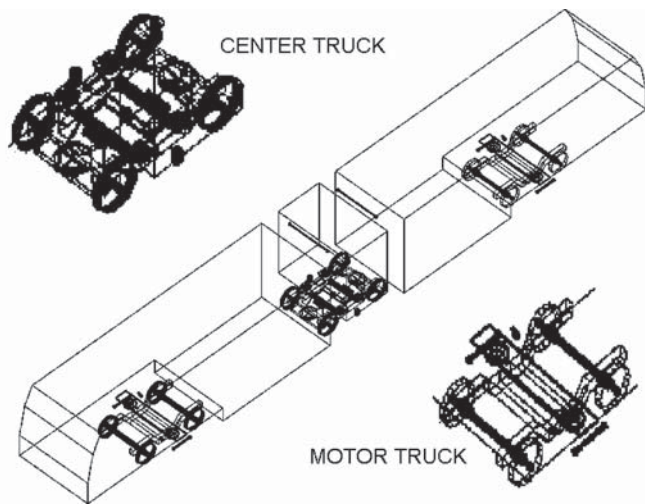
Vehicle models were created for the vehicle types listed above. This work included coordination of data collection in Tasks 7.2 and 7.3 so as to achieve compatible treatment of each one. Figures A-1 through A-3 are representations of the three models.



The MBTA Type 7 vehicle produced by Kinki Sharyo is a standard vehicle (not low-floor) with normal trucks and wheelsets. The main vehicle parameters are:

Overall length	21.95 m
Overall mass	35,500 kg empty, 48,670 kg full
Axle load	9.3 t motor truck, 7.7 t trailer truck (max. load, from model)
Pivot distance	7 m
Wheel base	1.905 m
Number of sections	2
Motor trucks (2)	2 standard wheelsets
Trailer truck (1)	2 standard wheelsets, arranged between the car bodies, selfsteering, independent of car bodies
Inter-car connection	Common crown bearings, no dampers

Figure A-1. MBTA Type 7.



The MBTA Type 8 produced by Breda has a low-floor area in the central part including the center section (C-car) which is therefore equipped with independently rotating wheels. The pitching stability of the center section is achieved by anti-pitch spring elements. This vehicle type has experienced derailment problems and high wheel wear on the center section (C-car). The main vehicle parameters are:

Overall length	21.95 m
Overall mass	38,460 kg empty, 47,360 kg full
Axle load	9.3 t motor truck, 6.8 t trailer truck (max. load, from model)
Pivot distance	7.14 m
Wheel base	1.905 m
Number of sections	2 end sections, 1 short central section rigidly connected (in yaw) to the central truck
Motor trucks (2)	2 standard wheelsets
Trailer truck (1)	4 single wheels on 2 rigid cranked axles, pitching stabilized by a spring system
Inter-car connection	2 spherical bearings at either end of the central truck, no dampers, roll inhibited by lateral bars at roof level

Figure A-2. MBTA Type 8.

Task 7.5 Creation of the Vehicle/Track Options Matrix

The purpose of this sub-task was to define combinations of vehicle features and track layouts that gave a wide range of possibilities in order to identify those parameters that are crucial in terms of derailment prevention. Table A-1 shows which basic runs were undertaken using the existing vehicle designs:

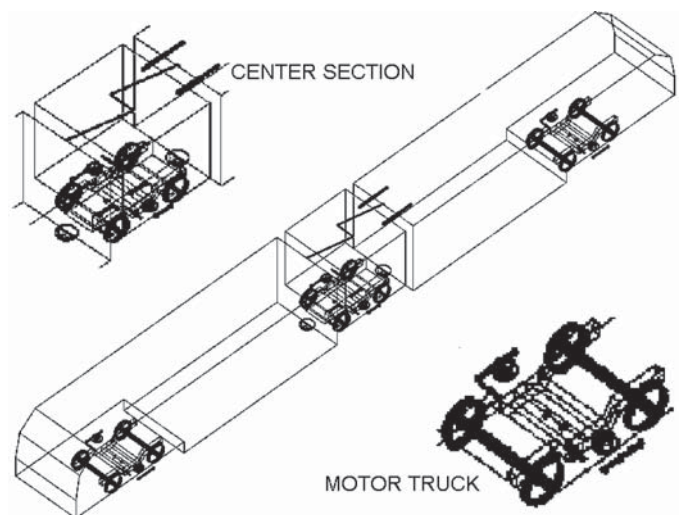
Both empty and fully laden vehicles were modeled; this is because although from the point of view of safety against derailment the empty vehicle is most critical, it is possible that other factors (like wheel/rail forces) might get critical at full load.

Parameter variations were defined based on the assessment of possible alternative design options used in other vehicles (see Sub-task 7.3) and in order to cover uncertainties in the model inputs. Table A-2 provides an overview of all the analysis cases considered. Cases S1 to S3 were performed in the first

loop of analyses described under Sub-tasks 7.10 and 7.11 (initial assessment). The others were performed following the visits to transit systems, which permitted the models to be refined.

Task 7.6 Create the Equivalent Model Modifications

The model and parameter options described in Sub-task 7.5 were implemented in the ADAMS/Rail template based vehicle models. Modifications concerning the structure of the vehicle (adding or removing elements) resulted in a new version of the model whereas parameter variations were covered by different sets of parameter files. For every option, an ADAMS solver input file was generated and the collection of input files was run as a batch queue.



The Kinki NJT LFLRV has a low-floor area in the central part of the vehicle including the center section (C-car) which is therefore equipped with independent rotating wheels. The pitching stability of the center section is achieved by a system of bars (Z-link) arranged on the roof of the vehicle. This vehicle is reported to perform satisfactorily. The main vehicle parameters are:

Overall length	26.7 m.
Overall mass	45,790 kg empty, 59,440 kg full.
Axle load	10.2 t motor truck, 9.4 t trailer truck (max. load, from model).
Pivot distance	10.15 m.
Wheel base	1.9 m on motor truck, 1.8 m on trailer truck.
Number of sections	2 end sections, 1 short central section rigidly connected (in yaw) to the central truck.
Motor trucks (2)	2 standard wheelsets.
Trailer truck (1)	4 single wheels on 2 rigid cranked axles.
Inter-car connection	2 crown bearings with pitch hinge on either side of the central truck, a pair of dampers between central and end section, pitch stabilization of the central section by a system of bars at roof level (Z-link) connecting all three sections.

Figure A-3. NJT.

Table A-1. The basic modeling runs.

No.	Vehicle/Condition	Track				
		TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
1	KS New Jersey LFLRV - empty	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
2	KS New Jersey LFLRV - full (fully laden)	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
3	MBTA No. 7 - empty	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
4	MBTA No. 7 - full (fully laden)	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
5	MBTA No. 8 - empty	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)
6	MBTA No. 8 - full (fully laden)	TCRP D-7 reference	New Jersey new	MBTA "worst case"	High speed track	High speed track (worn)

Notes:

"TCRP D-7 reference" means the track parameters identified in *TCRP Report 71, Volume 5* (Wu, Shu, Wilson), in the work on the investigation of wheel flange climb criteria for transit vehicles.

"New Jersey new" refers to a track of the Hudson-Bergen line as defined in the track design manual.

"MBTA "worst case"" refers to track parameters assuming extreme MBTA track geometry and track at the limits accepted in current MBTA maintenance standards. MBTA track was chosen because this is a long-established system in contrast with a typical new build.

"High speed track" means a synthetic track definition defined specifically to study derailment at high speed on (nearly) straight track sections. "High speed track worn" is a variation with significant rail wear following the information obtained during the visit to transit systems.

Task 7.7 Collect specific U.S. Track Data

Tables were produced to compare the track standards used on seven of the eight transit systems LFLRVs identified in Phase 1. Data for another modern light rail system was also included, because comprehensive information was in hand. The tables also showed equivalent U.S. national standards and the equivalent German standards. Notes were made of where practice varies from the U.S. standards, e.g. where tighter tolerances are being applied. A table was produced for each of the following issues:

- Wheel and rail profiles,
- Sharp curves,
- Switch and crossing transitions,
- Track standard tolerances,
- Gauge tolerance on tangent track,
- Tangent track between curves,
- Parallelism of rails,
- Flangeway clearance on special trackwork, and
- Track twist.

The purpose was not to create comprehensive tables of data but more to identify where any notable discrepancies likely to have an effect on LFLRV operation might exist and allow recommendations to be made where necessary.

As part of this work a detailed comparison of typical U.S. practices with the equivalent German standard was also

carried out. This showed that the German Standards and guidance (BOStrab/VDV) were not prescriptive in general terms but deal with a process that trained engineers need to apply to their systems, based on their own knowledge of them and of standards that have been adopted in the past. One reason for this is that most systems in Central Europe have existed for a long while and parameters vary as a consequence. It was, therefore, decided that it would be useful to give the MBTA track standards to engineers in the research team who had experience of accepting LFLRVs on a representative German system to determine if they would make changes based on BOStrab/VDV practice. This exercise highlighted some specific differences that may be having an effect:

- Smaller ballast not taking up forces as well,
- Gauge variation,
- Check rail clearances, and
- Permitted number of defective ties.

The detailed comparison is included in this report as Appendix E.

Task 7.8 Track Model Features

Decisions were made on what track conditions would be representative to model and what specific features should be included. Table A-3 shows the parameters of the first three track options.

Table A-2. Analysis cases.

No.	Vehicle / Condition	Track(s)
S1	KS New Jersey LFLRV Reduced roll stiffness (1/10) of the inter-car articulations	MBTA “worst case” New Jersey new TCRP D-7 reference
S2	KS New Jersey LFLRV Z-link (inter-car stabilizing mechanism) removed	MBTA “worst case”
S3	MBTA No. 8 Increased roll stiffness (x10) of the inter-car articulations	MBTA “worst case”
S11	KS New Jersey LFLRV - empty Wheel profile with 63° flange angle	High speed track High speed track worn MBTA “worst case”
S12	KS New Jersey LFLRV – empty Inter-car dampers removed	TCRP D-7 reference MBTA “worst case”
S13	KS New Jersey LFLRV - empty Inter-car dampers between all cars (2 sets of 2)	TCRP D-7 reference MBTA “worst case”
S14	KS New Jersey LFLRV – empty Z-link replaced by a pitch stabilizer spring	TCRP D-7 reference MBTA “worst case”
S15	KS New Jersey LFLRV - empty Wheel profile with 63° flange angle plus inter-car dampers between all cars (2 sets of 2)	High speed track
S16	KS New Jersey LFLRV – empty Wheel profile with 63° flange angle plus Z-link replaced by a pitch stabilizer spring	High speed track
S21	MBTA No. 8 - empty Wheel profile with 63° flange angle	High speed track High speed track worn MBTA “worst case”
S22	MBTA No. 8 - empty Inter-car damper analogue to KS New Jersey LFLRV	TCRP D-7 reference MBTA “worst case”
S23	MBTA No. 8 - empty Wheel profile with 63° flange angle plus inter-car damper analogue to KS New Jersey LFLRV	High speed track
S24	MBTA No. 8 - empty Two sets of inter-car dampers	TCRP D-7 reference MBTA “worst case”
S25	MBTA No. 8 - empty Wheel profile with 63° flange angle plus two sets of inter-car dampers	High speed track
S31	MBTA No. 7 - empty Wheel profile with 63° flange angle	High speed track High speed track worn MBTA “worst case”

Data extracted from the *TCRP Report 71, Volume 5*, reference (Exhibits 41-6) as model input. The curvature was transformed so as to consist of circular curve sections joined by spiral sections. The original curvature data was assumed to correspond to the formula: $\text{degree} = 5729.578/R$ for R in feet. The super-elevation was transformed so as to consist of constant sections and linearly varying sections. Lateral and vertical track excitations for both rails were set to zero at $X = 30$ m (98 ft).

Some of the reported derailment issues involving MBTA type 8 cars occurred on straight track sections at high speed at a time when wheel profiles with a flange angle of 63° were in use. In order to assess the influence of other system

parameters on this behavior, a pair of track layouts was defined as follows:

- Curve radius 2000 m allowing high speed but imposing a flange contact on one side
- Lateral track irregularity of amplitude 3/4 inch over a length of 20 feet in order to see separately the effect for every truck
- 115 RE rail profile (new rail) and a worn shape as described by the transit system engineers during the US visit. The wear shape and original rail profile are compared in Figure A-4.

Table A-3. Track option parameters.

Model	NJT New Track	TCRP Report 71, Volume 5 Reference	MBTA worst case
Track type	Ballasted	Ballasted	Ballasted , Note A
Rail profile	115RE	115RE	115RE, Note A
Rail inclination	1:40	1:40	1:40
Track gauge	56.5in	56.5in	56.5in straight, 57.5in curve
Where measured	5/8 in below rail head		
Curve radius	300ft	See below	44ft
Vertical curve (combined)		See below	400ft
Spiral length	130ft (2 of)	See below	20ft (2 of)
Circular length	180ft	See below	46ft
Superelevation	4in	See below	Note B
Track irregularity		See below	Note C
Design speed	23mph	38mph	4.5mph

Note A. Although some of the worst conditions occur on embedded track the application of the same rail sections in all these cases allows the separation of rail profile issues from other track quality issues.

Note B. Negative elevation 1.25 in (32 mm), starting at 36 m, fully established 40m to 50m, removed with end of curve spiral (based on MBTA limits for track maintenance).

Note C. Track irregularity 1.25 in (32 mm) lateral on outer rail in inward direction, on a length of 31.5 feet (based on MBTA limits for track maintenance).

Task 7.9 Develop Track Models

Three track models were created using the material from Sub-tasks 7.7 and 7.8 covering the basic options defined under Sub-task 7.5. Details of the track features are given in 7.8. After the visit to transit systems, a fourth track was added. This track contained a curve with large radius and a single lateral inward track irregularity on the outer rail. It allowed comparison of the vehicle models with respect to the derailment at high speed on straight tracks observed for the MBTA Type 8 central truck.

The track models are defined in ADAMS/Rail as a sequence of straight and curved sections joined by spiral transitions. The software versions used in this project require a straight section between two curved sections of different radius. This is an acceptable restriction for most practical purposes but it required some adaptation for the TCRP Report D-7 reference

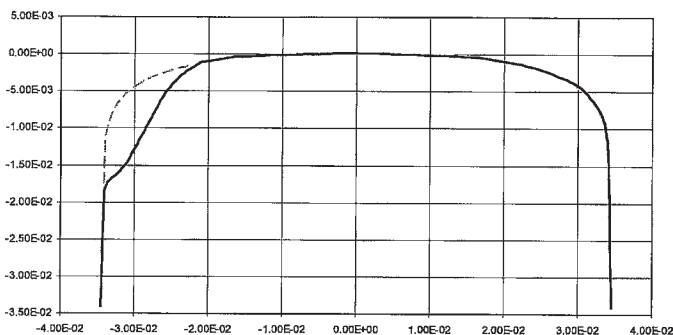


Figure A-4. Comparison of wear shape and original rail profile.

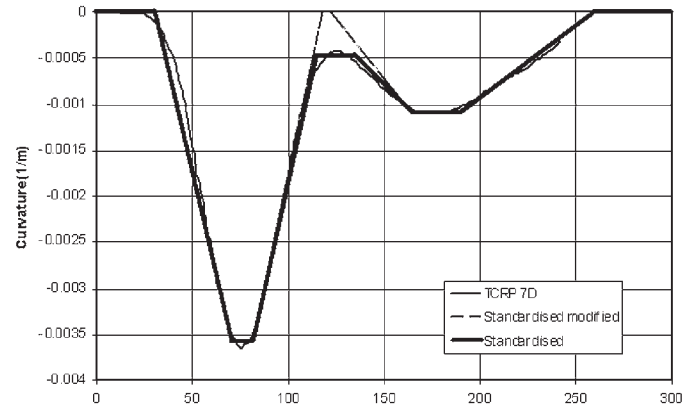


Figure A-5. Continuously varying curvature in sections.

track model. The continuously varying curvature was transformed into a sequence of sections with constant curvature and transition spirals (named “Standardized” in Figure A-5) and slightly modified to include a straight section around $t=120$ (“Standardized modified”).

Task 7.10 Simulation Runs

The basic simulation options given in Table A-2 and sensitivity cases S1 through S3 identified in Task 7.5 were run using ADAMS/Rail. A selection of typical results is shown in Tables A-4 through A-9. These results were obtained with preliminary model and track parameters. Wheels are numbered in the form w_{ij} , where i is the axle index and $j=1$ is for right and $j=2$ for left wheels respectively (Figure A-6). Forces are shown in Newtons (N) (1 lbf = 4.45 N). Lateral forces are negative if the wheel is pushed inward (this is usually the case for an outer wheel in a curve). The curves modeled are right curves; therefore the leading outer wheel of the center truck is w_{32} .

Table A-4. Wheel-rail lateral force (N), NJT new track.

Vehicle	w_{32}	w_{41}
NJT_Full	-23 kN	2.5 kN
Type 7_Full	-27 kN	-2.5kN
Type 8_Full	-17 kN	1.5kN

Table A-5. Wheel-rail lateral force (N), TCRP Report 71, Volume 5 track.

Vehicle	w_{32}	w_{41}
NJT_Full	-23kN	3kN
Type 7_Full	-10kN	3kN
Type 8_Full	-18kN	2kN

Table A-6. Wheel-rail typical lateral force (N), MBTA worst-case track.

Vehicle	W ₁₂	W ₂₁	W ₃₂	W ₄₁
NJT_Full	-42kN	-19.5kN	-32kN	-27kN *
Type 7_Full	-37kN	-19kN	-34kN	-20kN
Type 8_Full	-37kN	-20kN	-15kN	-14kN

*Unsteady peak value

Table A-7. Maximum L/V, NJT new track.

Vehicle	W ₃₂	W ₄₁
NJT_Empty	0.43	0.05
Type 7_Empty	0.50	0.07
Type 8_Empty	0.45	0.02

Table A-8. Maximum L/V, TCRP Report 71, Volume 5, track.

Vehicle	W ₃₂	W ₄₁
NJT_Empty	0.93	0.22
Type7_Empty	0.51	0.10
Type 8_Empty	0.80	0.30

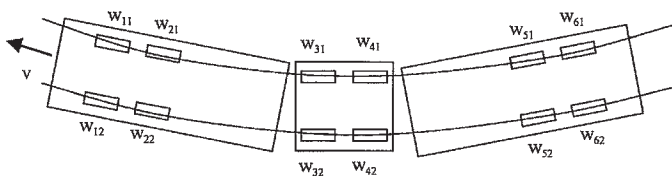
Table A-9. Maximum L/V, MBTA worst-case track.

Vehicle	W ₃₂	W ₄₁
NJT_Empty	0.60	0.72
Type 7_Empty	0.62	0.50
Type 8_Empty	0.47	0.42

Task 7.11 Initial Assessment

The analysis results obtained with the preliminary vehicle models showed a similar behavior of the vehicles. Although some observations may have depended on preliminary data, the following general tendencies were observed:

- The MBTA worst-case track had the smallest curve radius and may therefore have produced the largest steady lateral forces caused by a large angle of attack. The maximum forces were obtained for the NJT LFLRV.

**Figure A-6. Simulation run numbering.**

- The highest peak lateral forces occur in the perturbed zone of the *TCRP Report 71, Volume 5*, track and again the maximum was found for the NJT LFLRV.
- The maximum L/V ratios are found in the perturbed zone of the *TCRP Report 71, Volume 5*, track and the vehicles with single wheels (MBTA Type 8 and NJT) were most affected.

The MBTA Type 8 vehicle, which has reportedly encountered various difficulties in service (e.g., derailment and excessive wear), behaved quite satisfactorily in the simulation.

The analysis results obtained for the sensitivity cases S1 to S3 showed only minor effects:

- The modification of the roll stiffness of the articulations between the end sections and the central section with single wheels has no significant effect on the wheel unloading. This meant that the vehicle could be considered to be rigid in torsion for all the cases considered.
- The removal of the Z-link did not affect wheel/rail forces. However it did lead to a progressive pitch deformation, which was however developing slowly caused by the high damping factor of the inter-car dampers. A means of pitch stabilization is required (Z-link or an alternative solution).

Task 7.12 Visits to Transit Systems

Visits were made to discuss four transit systems with leading engineers involved in their operation and maintenance. Questions and agendas were prepared in advance.

The team was able to have other discussions to discuss results, exchange and obtain information, and see and experience the systems, vehicles, and maintenance facilities.

Task 7.13 Simulation Runs

The information gathered during the visit to the transit systems allowed finalization of the vehicle models and completion of the model options as described in Subtask 7.5. An overview of the simulation output is provided

in Tables A-10 to A-22 and Figures A-7 through A-9. The main outcome can be summarized as follows:

- The overall behavior of the three vehicle types was found to be very similar. All the vehicles were able to negotiate small radius curves without excessive L/V ratios.
- The vehicles with single wheel trucks (NJT LFLRV and MBTA Type 8) produce higher lateral forces in narrow curves as expected. This was expected to increase noise and wheel-rail wear.
- The pitch stabilization of the cars with a center truck was solved in two different ways: The NJT vehicle had a link mechanism (Z-link) connecting the three car bodies at the roof level whereas the MBTA Type 8 had a torsion spring system located in the truck. The Z-link introduced some asymmetry, which resulted in the vehicle running eccentrically close to one rail even on straight tracks. Similar effects would be produced by manufacturing tolerances with any vehicle design. The MBTA Type 8 solution is prone to dynamic pitching modes caused by the damper design.
- Inter-car dampers tended to reduce the pitching mode of the center section. The MBTA Type 8 cars did not have dampers but by adding them into the model they were found to be especially beneficial. The disadvantage was a limited increase in the lateral forces and therefore the L/V ratio. The best behavior was obtained with two pairs of dampers (both articulations damped). However the improvement was not significant. The modeling suggested that only one pair of dampers was required for the NJT LFLRV in order to limit the lateral wheel-rail forces.
- The use of wheel profiles with low flange angles (63°) increased the tendency for derailment on all vehicles. There was a marked difference between the solutions with independent wheels and the standard wheelset truck of MBTA Type 7. The effect was accentuated when combined with worn rail profiles.

The MBTA Type 8 vehicle, which was reported to have derailment issues, had a very similar behavior to the NJT LFLRV. In general, the lateral forces and L/V ratio were found to be even less critical.

Table A-10. Wheel-rail lateral force (N), NJT new track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	-20kN	-2.6kN
Type 8/empty	-12.8kN	-6.1kN
NJT/empty	-17.6kN	2.7kN
Type 7/full	-30kN	-6.45kN
Type 8/full	-14.3 kN	-6.95kN
NJT/full	-19.8kN	-3.68kN

Table A-11. Wheel-rail lateral force (N), TCRP Report 71, Volume 5, track.

Vehicle/Condition	W ₃₂	W ₄₁
Type7/empty	-4.5kN	+8.2kN
Type8/empty	-30.8kN	-12.2kN
NJT/empty	-20.8kN	-13.3kN
Type7/full	-6.4kN	-10.8kN
Type 8/full	-28kN	-13.5kN
NJT/full	-32.8kN	-20.1kN
NJT/empty S12	-47.2kN	-37kN
NJT/empty S13	-28.6kN	-10kN
NJT/empty S14	-50.6kN	-12.5kN
Type 8/empty S22	41.2kN	11.3kN
Type 8/empty S24	41.2kN	12.2kN

Table A-12. Wheel-rail lateral force (N), MBTA worst-case track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	-27.3kN	-12.3kN
Type 8/empty	-10.8kN	-10.5kN
NJT/empty	-21.8kN	-31.2kN
Type 7/full	-44.7kN	-18.35kN
Type 8/full	-17.6kN	12.9kN
NJT/full	-37.5kN	-38.4kN
NJT/empty S11	-28.5kN	30.1kN
NJT/empty S12	-32.6kN	31.7kN
NJT/empty S13	-34.8kN	32.3kN
NJT/empty S14	-23.8kN	28.3kN
Type 8/empty S22	22.5kN	24.5kN
Type 8/empty S24	21.5kN	20.8kN

Table A-13. Wheel-rail lateral force (N), high-speed track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty S31	-14.9kN	-8.6kN
Type 8/empty S21	-21.1kN	-16.8kN
NJT/empty S11	-27.1kN	-10.6kN
Type 8/empty S23	-20.6kN	-6.8kN
Type 8/empty S25	-19.6kN	-6.8kN
NJT/empty S15	-28.3kN	-12.5kN
NJT/empty S16	-25.3kN	-12.5kN

Table A-14. Wheel-rail lateral force (N), high-speed worn track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty S31	-11.1kN	-3.8kN
Type 8/empty S21	-24.2kN	-8.8kN
NJT/empty S11	-27.1kN	-10.3kN

Table A-15. L/V ratio, NJT new track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	-0.56	-0.1
Type 8/empty	-0.44	-0.25
NJT/empty	-0.49	-0.37
Type 7/full	-0.56	-0.094
Type 8/full	-0.44	-0.22
NJT/full	-0.44	-0.13

Table A-16. L/V ratio, TCRP D-7 track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	-0.2	-0.15
Type 8/empty	-0.72	-0.42
NJT/empty	-0.61	-0.33
Type 7/full	-0.2	-0.24
Type 8/full	-0.63	-0.39
NJT/full	-0.56	-0.41
NJT/empty S12	-1.25	-0.95
NJT/empty S13	-0.7	-0.21
NJT/empty S14	-1.0	-0.3
Type 8/empty S22	-1.32	-0.44
Type 8/empty S24	-1.32	-0.38

Table A-17. L/V ratio, MBTA worst-case track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	-0.84	-0.48
Type 8/empty	-0.49	-0.44
NJT/empty	-0.78	-0.87
Type 7/full	-0.75	-0.50
Type 8/full	-0.48	-0.44
NJT/full	-0.68	-0.78
NJT/empty S11	-0.82	-0.83
NJT/empty S12	-1.0	-0.94
NJT/empty S13	-0.85	-0.94
NJT/empty S14	-0.72	-0.75
Type 8/empty S22	-0.78	-0.85
Type 8/empty S24	-0.75	-0.78

Table A-18. L/V ratio, high-speed track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty S31	-0.47	-0.13
Type 8/empty S21	-0.67	-0.28
NJT/empty S11	-0.74	-0.36
NJT/empty S15	-0.76	-0.42
NJT/empty S16	-0.74	-0.40
Type 8/empty S23	-0.67	-0.28
Type 8/empty S25	-0.63	-0.28

Table A-19. Wheel lift (mm), high-speed track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty S31	none	none
Type 8/empty S21	none	none
NJT/empty S11	none	none
NJT/empty S15	2 (short duration)	none
NJT/empty S16	none	none
Type 8/empty S23	none	none
Type 8/empty S25	none	none

Table A-20. Wheel lift (mm), high-speed worn track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	1.4 (short duration)	none
Type 8/empty	none	1.5 (short duration)
NJT/empty	none	1.5 (short duration)

Table A-21. Angle of attack (degrees), NJT new track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	1.1	0.07
Type 8/empty	1.0	0.15
NJT/empty	1.1	0.2
Type 7/full	1.0	0.07
Type 8/full	1.0	0.15
NJT/full	1.0	0.1

Table A-22. Angle of attack (degrees), MBTA worst-case track.

Vehicle/Condition	W ₃₂	W ₄₁
Type 7/empty	4.5	2.4
Type 8/empty	4.1	2.8
NJT/empty	4.3	2.8
Type 7/full	4.6	2.3
Type 8/full	4.1	2.8
NJT/full	4.3	2.6
NJT/empty S12	3.8	2.9
NJT/empty S13	4.3	2.5
NJT/empty S14	4.6	2.2
Type 8/empty S21	4.2	2.7
Type 8/empty S22	4.2	2.7
Type 8/empty S24	4.2	2.7

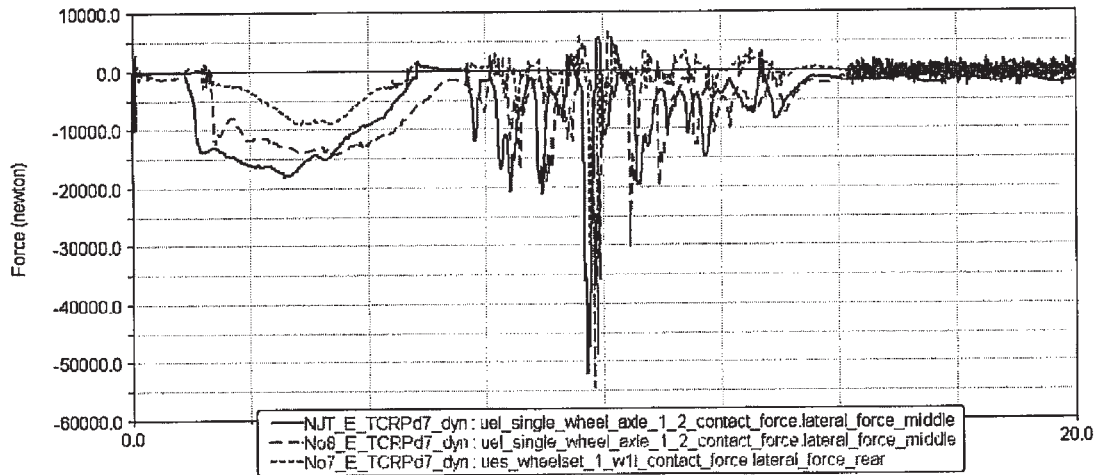


Figure A-7. Simulation Output 1.

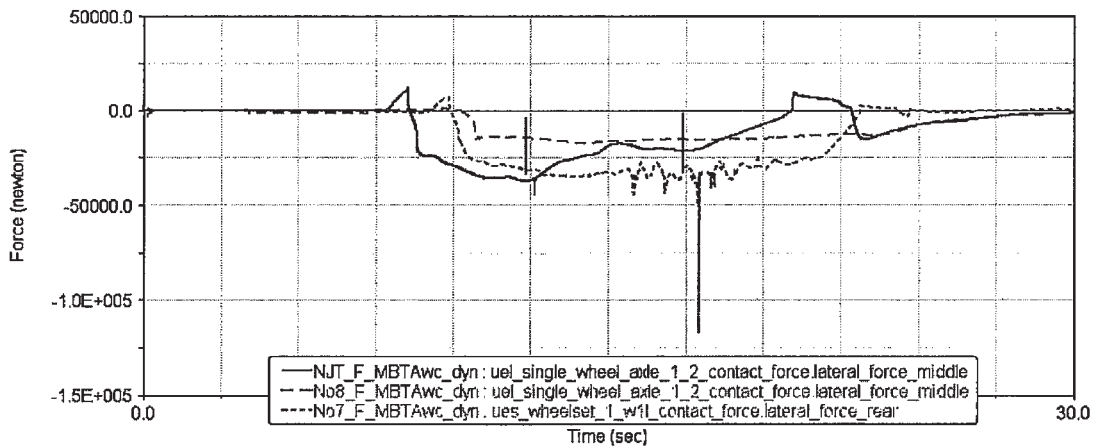


Figure A-8. Simulation Output 2.

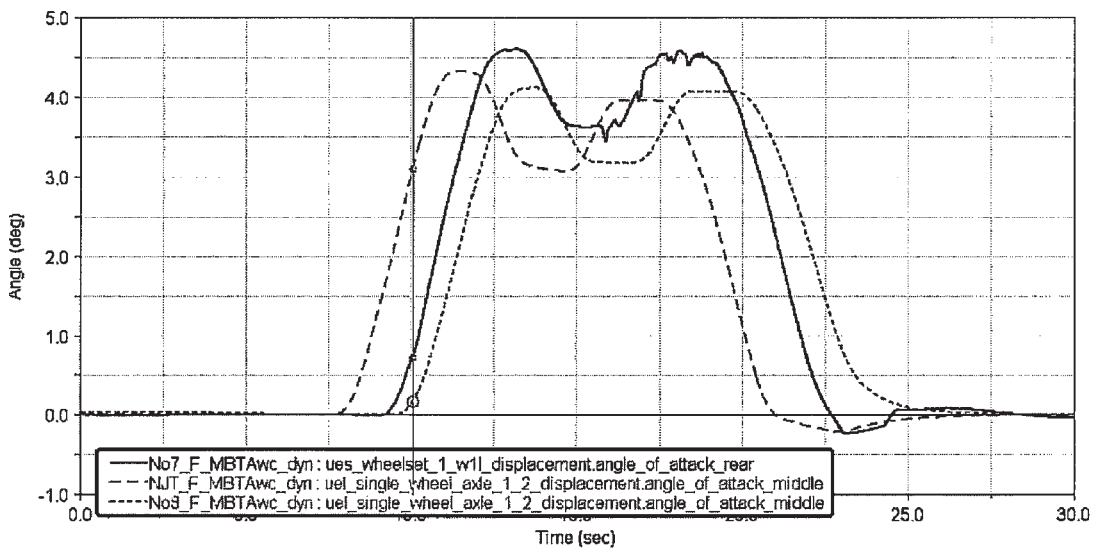


Figure A-9. Simulation Output 3.

Task 7.14 Final Assessment of Results

The results of the modeling, other investigations carried out and conclusions of the visits to transit systems were assessed as a whole in order to produce the input required for Tasks 9 and 10. Chapter 3 of this report incorporates the results.

The assessment process was based on the results of the modeling and other research and the experience and knowledge of individual team members. The discussion material in Chapter 3 is therefore an original collation of some of the latest thinking in this topic area by the experts involved. Drafts of the working paper (Task 8) were circulated and revised and each of the main contributory factors were discussed in depth at the workshop held in Cologne (Task 9).

Task 8. Working Paper Summarizing the Results of Task 7

This was issued for distribution to the panel for comment.

Task 9. Development of the Guidance Required to Mitigate Performance Issues

A structured workshop took place in Cologne, Germany, at which the European experts in the team addressed both the issues associated with Task 9 and with Task 10. They concentrated on two main issues. One was checking that the results

from the modeling and theoretical studies were being correctly interpreted, based on their own experience of theoretical work. The other was to feed in any European experience of solutions that were being recommended where there is limited experience of applying them in the United States and Canada.

The guidance, which forms Chapter 3 of this report, was prepared in draft and discussed by the team as a whole.

Having completed Tasks 7, 8, and 9, all the input required in order to make clear overall recommendations was now available.

Task 10. Develop Recommendations for Further Research

The research work was used as a basis for creating an initial list that was then brainstormed at the Cologne workshop and further discussed by the team. Some issues were identified. These tend to be of two types:

- Issues that could not be fully explored within the limits of the current budget and
- Areas of research in associated areas that are outside of the scope but might provide alternative solutions.

Task 11. Develop the Final Report

The preliminary draft final report was issued with three months allowed for the Panel to review it and for Interfleet to provide the final text.

APPENDIX B

Glossary

AAR	Association of American Railroads.	2	Vehicles with conventional motor and trailer trucks at ends but unconventional center trucks.
ADA	Americans With Disabilities Act 1991. Legislation regarding access to transit by persons with disabilities.	3	Vehicles with innovative motored and trailing running gear throughout
AOA/Angle of Attack	The angle between the track radial line and the centerline of the wheelset's axle. This is the same as the angle between the axis of rotation of the wheelset and a line perpendicular to the track centerline (which is an alternative definition).	Contact angle	Angle of the plane of contact between the wheel and rail relative to the track plane.
APTA	American Public Transportation Association.	Contact stress	The force acting per unit area at the point of contact between wheel and rail.
Axle Arrangements:		Conicity	The self-steering capability of a wheelset resulting from the taper on the wheel treads.
1	Two-wheel axle that is fixed in the truck frame.	dBa	Decibels (Weighted) - Unit of noise measurement, weighted to represent sensitivity of human ear to sound.
1'	Two-wheel axle that can rotate within the truck frame.	DBOM	Design, Build, Operate and Maintain.
B	Monomotor, four-wheel truck with fixed axles.	EEF	Einzelrad-Einzel-Fahrwerk wheelsets, self-steering and independently rotating wheels.
B'	Monomotor, four-wheel truck with axles that can rotate within the truck frame.	Flange angle	The angle between the contact face of the wheel face and a vertical line parallel with the back of the wheel.
Bo	Bimotor, four-wheel truck with fixed axles.	Flangeway	The clearance between the gauge side of a rail and a restraining rail or the equivalent part of a girder rail or switch.
Bo'	Bimotor, four-wheel truck with axles that can rotate within the truck frame.	FTA	Federal Transit Administration.
2	Four-wheeled trailer truck with fixed axles.	IRW	Independently Rotating Wheels. A pair of wheels on a common axle that rotate independently of each other.
2'	Four-wheeled trailer truck with axles that can rotate within the truck frame.	L/V Ratio	The ratio of lateral to vertical wheel/rail contact forces that influence derailment.
Bochum	Proprietary name for a resilient wheel that has a flexible web element between the axle and the rim.	LFLRV	Low-Floor Light Rail Vehicle.
BOStrab	German Transit Standards.	LRT	Light Rail Transit—refers to an operator or system using light rail vehicles.
Buff load	The static longitudinal force that a rail vehicle must be capable of withstanding without permanent deformation to its primary structure.	LRV	Light rail vehicle.
Category—Reference to definitions applied in <i>TCRP Report 2</i> :		Kelsan	Proprietary name of a type of grease applicator.
1	Vehicles with conventional motor and trailer trucks throughout.	KS	Kinki Sharyo (vehicle supplier).
		PCC	President's Conference Committee (type of streetcar).

Penn	Pennsylvania Rail Road Station in Newark, New Jersey.	NJT	New Jersey Transit, Newark, NJ.
PLF	Partial Low Floor.	RATP	Parisian Autonomous Transportation System, Paris, France.
Portec	Proprietary name of a type of wayside grease applicator.	SDT	San Diego Transit, CA.
REBS	Proprietary name of a type of grease manufactured in Germany.	SEPTA	Southeastern Pennsylvania Transportation Authority, Philadelphia, PA.
Rolling Contact Fatigue	The deformation and damage on a wheel or rail caused by the repetitive experience of normal and tangential forces.	SNCF	French National Railways.
S&C	Switches and Crossings (Special Trackwork).	TriMet	Tri-County Metropolitan Transportation District, Portland, OR.
TRIS	Transportation Research Information Service.	TTC	Toronto Transit Commission; Toronto, Ontario, Canada.
TTCI	Transportation Technology Center, Inc.	UITP	International Public Transport Association.
VDV	German Public Transit Operator's Association.	VBZ	Zurich Transportation Authority, Zurich, Switzerland.
Transit Authorities		VDV	German Association of Public Transport Operators.
DART	Dallas Area Rapid Transit.	VTA	Valley Transportation Authority, Santa Clara, CA.
HBL	Hudson Bergen Line (part of NJT).		
MAX	Metropolitan Area Express (part of TriMet).		
MBTA	Massachusetts Bay Transportation Authority, Boston, MA.		

APPENDIX C

Vehicle Data

Supplier	Breda	Kinki Sharyo		Siemens			Units
System	MBTA	NJT HBL and Newark	Santa Clara VTA	Portland MAX	San Diego	Houston	
Type	8			SD	Avanto	Avanto	
Length	72	87.7	87.7	89	96.4	96.4	feet
Center pivot distance	23.4	33.3	33.7	34.8	33.6	33.6	feet
Vehicle mass (empty)	43	49.6	48.7	48.5	49.3	49.5	ton
Maximum speed	55	55	55	55	56	65	mph
Center truck wheelbase	74.8	70.9	70.9	70.9	70.9	70.9	inches
Floor height over center truck	14	13 ³ / ₄	14 ¹ / ₄	14	14	14	inches
Dampers between links	0	2	2 (one end)	3	2 each	2 each	
Center truck primary suspension	Rubber cylindrical springs	Rubber chevron springs	Rubber chevron springs	Conical rubber springs	Rubber chevron springs		
Primary suspension range	+10, -11	11	+30, -20	+15, -20	+29, -17	+25, -20	mm
Center truck secondary suspension	4 Air springs with leveling valves	Air spring with 2 height control valves	Air springs with 6 height control valves	Central coil springs, lateral and vertical dampers	Coil springs, lateral and vertical dampers	Coil springs, lateral and vertical dampers	
Vertical plus	25	22	22	20	No limit	35	mm
Vertical minus	40		10	50	43	45	mm
Lateral plus	34	10	10	25	10	30	mm
Lateral minus	34	10	10	25	20	30	mm
Yaw control on center truck	Resilient traction links	Resilient traction links and stops	Fixed	Resilient traction links	Resilient traction links	Resilient traction links	
Wheel dia. (new)	26	26	26	26	26	26	inches
Wheel tread slope	1 in 40	1 in 20	1 in 32	1 in 30	1 in 40	1 in 40	
Flange angle	75	75	70	70	75	70	degrees
Flange height	0.75	0.75	0.75	1.063	1.063	1.08	inches
Wheel tread width	4	4	5.5	4.96	5.31	5.31	inches
Wheel gauge max.	1427	1423	1415	1427	1415	1422	mm
Wheel gauge min.	1427	1421	1405	1423	1411	1418	mm
Wheel back to back	1376	1372-4 (1)	1363-8	1368.6 1365.46	1352.52- 1355.7	1359-1360	mm

(1) Newark Subway cars, 1,358 mm on Hudson-Bergen

APPENDIX D

Track Data and Standards Applicable to the Transit Systems Studied

Type	"Old"	"Old"	"New"	"New"	"New"	"New"	"New"
City	Boston	Newark	Portland	Hudson-Bergen	Santa Clara	Houston	San Diego
System	MBTA	NJT	MAX	NJT	VTA	Metro	SDT
Routes	Green Line	Penn Station-Grove St.	Blue, Red and Yellow lines	Hoboken-West Side/Bayonne	Mountain View-Baypoint-St.Teresa, Almaden	Downtown-Reliant Park	Blue and Orange lines
Route miles	25	4	33	21	31	8	50
Opened	1889	1934	1986	2000	1987	2004	1981
LFLRVs introduced	1999	2000	1996	2000	2001	2004	2004
Track types used:							
-Ballasted	✓	✓	✓	✓	✓	✓	✓
-Direct fixation		✓	✓		✓		✓
-Embedded	✓		✓	✓	✓	✓	✓
Track gauge (mm):							
-Tangent track	1435.1-1445	1432-1438	1422-1454	1422-1473	1433-1441	1434-1470	1422-1467
-Curved track	1435.1-1445	1432-1438	1422-1454	1422-1473	1433-1441	1435-1437	1422-1467
-Sharp curves	1447.8	1438	1416-1460	1438	1439-1447	1435-1473	1422-1467
Minimum curve radius (feet)	42	60	82	100	82	123.4	150
Minimum length of tangent track between curves:							
-(Feet)	0	150	50	150	0	32.8	50
Min.vertical curve (feet)	300	1500	2000		1660	180	100
Rail inclination:							
-Embedded	0	NA	0	0	0	1 in 40	
-Non-embedded		1 in 40	1 in 40	1 in 40	1 in 40	1 in 40	
Maximum speed (mph)							
-Tangent track	50	50	55	50	55	66	55
-Sharp curve	6	5	5	5	8	5	10
Rail sections used	115 RE 149 GCR	115 RE	115 RE RI 59 RI 60	115 RE	115 RE RI 59	115 RE 132 RE (Test track only)	115 RE 90 ARA-A
Flange tip running	Yes	Yes	Yes		Yes	No	Yes
Swing nose frogs	Yes	No	Yes		No	No	Yes
Track-mounted lubrication	Yes	Yes	Yes	Yes	Yes	No	Yes

APPENDIX E

Track Maintenance Standards

A comparison was made between a maintenance standard issued by a long-established transit system and the standards used in Germany. The purpose was to discover if LFLRVs are being operated in a different maintenance context in Europe than in the United States. It was found that requirements of the U.S. document did not contrast significantly with German regulations in most areas. The U.S. maintenance standard was compared with both the German maintenance requirements for light rail (BOStrab) and short-line railways (NE-Bahnen) because the U.S. standard studied had characteristics of both heavy and light rail systems in some sections. The comparison was based on experience in Karlsruhe with the maintenance of light rail infrastructure and included discussions with the Karlsruhe Transit system.

Approval of railway infrastructure and rolling stock in Germany is carried out by the representative for light rail safety (Technische Aufsichtsbehörde), which is the responsible supervisory authority in each state. The transit systems are responsible for everyday operations and maintenance and one person, the so-called “chief operating superintendent” (Betriebsleiter) is personally responsible for safe operations. The technical authorities will, however, inspect the transit system at regular intervals (typically yearly). Furthermore, there are some special compulsory inspections by the authorities (e.g., inspection of structures every 3 years).

Even though there are numerous legal requirements, the management of each Transit system and especially the “chief operating superintendent” (Betriebsleiter) has substantial freedom as to how and when maintenance is carried out within the legal limits. This becomes apparent when looking at the maintenance levels throughout different German systems. In general, it is the German philosophy not to work to the maximum wear limit but to have shorter maintenance intervals to ensure problem-free operations and high running comfort and also to save cost.

The light rail operator in Karlsruhe generally uses the strategy of “advanced maintenance,” which is linked to the available budget. When sufficient funds are available, a “wear reserve” will be built up, which allows operation with reduced maintenance, using up this reserve, for some years (e.g., 3 to 5 years) on most lines, should a need arise.

In general, no other set of standards is used for operating LFLRVs in comparison with standard, high-floor vehicles. There is one exception in that additional measures have to be taken to ensure safe entry and exit situations at platforms (i.e., fixing the track against the platform to ensure a minimal gap).

Fault and Reaction Values

The U.S. procedure consists of identifying different stages (GREEN, YELLOW, and RED) during maintenance inspections and then stating what specific measures are to be undertaken when specific measurements exceed appropriate limit values. These measures were compared with the German requirements. The regulations were seen to be very demanding in terms of short response times (e.g., with RED meaning a reduction of the speed limit to 10 km/h and defect removal within 72 hours). This means that it may be difficult to organize the work needed within the time available in terms of setting up the site, operational measures during the construction period, organizing subcontractors, and so forth. Work is required on the track at the YELLOW stage as well.

Early detection is practiced in Germany. According to the “BOStrab” (tramway) regulations, every German Light Rail Transit system has to develop a table (Quermaßstabelle), which includes all values relevant to track guidance (e.g., wheel back to back distance), covering vehicles, and track gauge and track geometry, including switches and crossings. This table includes minimum and maximum values outside of which safe operations would be jeopardized. The responsible “chief operating superintendent” (Betriebsleiter), or an

engineer appointed by him, determines the necessary measures to ensure the track always remains within these values.

This table is generally prepared by external experts (typically the firms that design track, switches, crossings, and other infrastructure) and updated when necessary to ensure track and wheel wear are minimized. It must be updated where there is a potential new safety risk, for example because of the introduction of new types of vehicles or the use of different wheel profiles.

Heavy rail values exist which are valid all over Germany, but light rail values vary. This is because wheel/rail guidance geometry differs from light rail system to light rail system. However, many light rail systems use the heavy rail values as guidance.

The analysis showed that the U.S. standards are actually more demanding in terms of quicker response times.

Inspections

In Germany, the responsibility for service reliability lies with the responsible track maintenance engineer and/or the “chief operating superintendent” (Betriebsleiter). This person’s qualifications, in addition to a technical or engineering degree, include specialized training of about 290 hours of experience. Table E-1 compares the inspection intervals used in Germany with those of the U.S. transit system.

In Germany, switches are examined more frequently than required in the U.S. standard. In contrast, in the United States, there are more on foot inspections of the track than in Karlsruhe. Apart from these specified inspections, a further important diagnostic is the use of the normal service vehicles travelling at maximum speed, in order to be able to estimate certain track bed errors (e.g., warping of the track). Detection of track defects while travelling at speeds up to 5 mph is unlikely to be as effective. Minor defects will only be detected when “walking the track,” while track bed errors can sometimes be better detected if travelling at maximum speed. The collection of regular track failure

reports issued by the operators in Germany is considered to be of value.

Specific Standards

The following standard applies to the ballast roadbed in Germany for light and heavy rail (but not high speed heavy rail)

- Ballast ahead of crosstie: 40 cm (15.7 inches)
- Layer thickness under crosstie: 30 cm (12 inches)
- Sub-Ballast: 20 cm (7.9 inches)

The ballast material specified for the U.S. transit system was $\frac{3}{4}$ to $1\frac{1}{2}$ inches (18 mm to 38 mm), which is smaller than the size required in Germany of 22 mm to 63 mm ($\frac{7}{8}$ to $2\frac{1}{2}$ inches). The smaller size of ballast may not take up track forces as well. Although the structure of the ballast was similar, the U.S. system did not require as substantial a shoulder, which may provide reduced stability.

In Germany, gauge is defined as the minimum distance between the rails measured 14 mm (0.55 inches) and for some rail types 10 mm (0.4 inches) below the top of the rail. In the United States, the gauge is measured at $\frac{5}{8}$ inch (16 mm) or $\frac{3}{8}$ inch (9.5 mm) in equivalent situations. The U.S. standards for gauge are similar to those used in Germany for both tangent track and sharper curves.

The U.S. standards for horizontal track alignment and for curves, superelevation, and corresponding speed limits, were found to be very much the same as those used in Germany. As Figures E-1 and E-2 show, the wear limits on rail are very similar too.

Top wear = 25 mm (1 inch), side wear = 20 mm ($\frac{13}{16}$ inch)

In Germany, the guard check gauge dimension for heavy rail is 1,394 mm (54.88 inches) for a 1,435 mm track gauge with grooved guardrail of 41 mm (1.6 inches). For tramways using embedded rail, the guard check gauge is between 1,404 mm

Table E-1. Inspection periods, USA and Germany.

Inspection requirement	USA	Germany
Section patrol		
- Frequency	3 times per week	3 times per year minimum (Note 1)
- Method	On foot or by vehicle at speeds up to 5mph.	On foot and by scheduled trains or trams.
Switch inspection	Once per month.	Visual inspection and grease once per week. 6 inspections per year. 1 geometric inspection per year.

Note 1: Further inspections may occur if operators report faults.

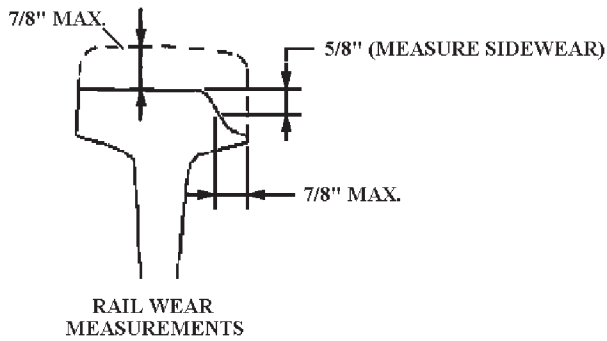


Figure E-1. U.S. maintenance document.

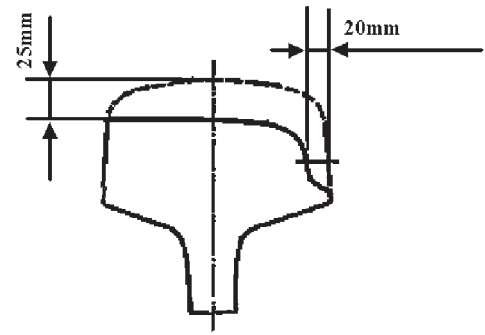


Figure E-2. German standard.

and 1,413 mm (55.28 inches and 55.63 inches). This is a reasonably exact match with the U.S. requirement that was studied (GREEN Maintenance threshold) of between $55\frac{3}{8}$ " (1,406 mm) and $55\frac{5}{8}$ " (1,413 mm). However, for segregated track, Light Rail, the German standard says that the guard check gauge should be in the range >1402 mm to <1407 mm. ($>55\frac{3}{16}$ to $<55\frac{3}{8}$ inches). This is to allow for independent

wheels and narrow flanges. The U.S. requirement did not make this differentiation.

The number of defective ties allowed in a section is more than in Germany. The measurements of the crossties are identical to those used in Germany. The allowed defective crossties per section may be critical. This results in worse track condition and/or increased maintenance cost.

APPENDIX F

Bibliography

Part 1. Most Relevant Sources (including a brief summary)

Anon. “Richtlinien für die Spurführung von Schienenbahnen nach der Verordnung über den Bau und Betrieb der Straßenbahnen (BOStrab), Spurführungs-Richtlinien (SpR),” (Regulations on the Guidance of Rail Vehicles in accordance with the German Federal Regulations on the Construction and Operation of Light Rail Transit Systems (BOStrab), Guidance Regulations (SpR). March 2004.

This document explains the German regulations on the guidance of streetcars. There is considerable detailed information on the wheel and track profiles and other key parameters used in different circumstances.

Anon. “VDV-600 Oberbau Richtlinien und Zusatzrichtlinien,” VDV 1995.

A regulatory document detailing track design parameters for German streetcar systems. Supplementary to the above reference.

Aprile, Bandinelli, Marianeschi, “Integrating Low-Floor Technology into a pre-existing infrastructure: partial low-floor light rail vehicle in a mixed environment: Lessons learned from the manufacture of Boston’s partial low-floor Light Rail Vehicle,” TRC E-C058, 8th National Rail Transit Conference. TRB 2000.

The Breda approach to developing the MBTA Type 8 car, then seen as one of the most difficult operating environments on a U.S. and Canadian transit system. The technical issues, solutions, and risk control measures are discussed.

APTA, “Standard for Rail Transit Track Inspection and Maintenance. Volume 5 - Fixed Structure, RT-S-FS-002-02, Draft- July 26th 2004.

Minimum requirements for inspecting and maintaining rail transit system tracks.

Booz, Allen and Hamilton Inc. *TCRP Report 2: Applicability of Low-Floor Light Rail Vehicles in North America*, 1995.

Review of all LFLRVs in use in the United States and Canada. Discussion of vehicle applicability, compatibility

with existing systems and operations, and two case studies that help define risk assessment and operating compatibility.

Breindl/Hachmann/Risch, “Radverschleiß und polygonale Radabnutzung an Straßenbahnen. Untersuchungen der BVG Berlin und Adtranz Nürnberg,” (Polygonal wheel wear on trams. Research by BVG Berlin and Adtranz Nürnberg.) Der Nahverkehr March 2000.

BVG (Berlin) operates a vehicle pool of 452 Tatra and 105 low-floor vehicles of the GT6 type. After introduction of the vehicles, very high wheel and flange wear and the development of polygons on the wheels was recorded. To counteract this, a catalog of measures was developed that included first a study of the current status of wear and the polygon developments for the low- and high-floor vehicles. To avoid the development of excessive noise, a track-based measuring system was introduced that detects problems when vehicles pass into the depot. As a result of the study, the re-profiling of the wheels was optimized by modifying the wheel lathe. The article concludes that systematic research into the reasons for polygon development would be necessary.

Brickle/Gilchrist, “A re-examination of the proneness to derailment of a railway wheelset.” IMechE 1976.

A theoretical study that looks in detail at derailment theory for conventional wheelsets.

Canjea/Thornes, “NJ Transit Low Floor Light Rail Car - A Modern Design.” TRC E-C058, 8th National Rail Transit Conference, TRB 2000.

This paper gives both technical details of the design of the Kinki Sharyo cars and information regarding the operational experience gained.

Elkins/Wilson, “Wheel/rail interaction: flange climb derailment and effects of IRW,” TTCI Rail Transit ’04, 2004.

This presentation deals with the fundamental theory of wheelset curving and derailment, and then contrasts this with the behavior of independent wheels. The sensitivity of independent wheel center trucks to vehicle design parameters is explored in detail.

Fraser/Leary/Marianeschi/Pellegrini, "Integrating new light rail vehicle technology into mature infrastructure," TRC E-C058, 9th National Rail Transit Conference. TRB 2003.

In 1995, MBTA ordered 100 partial low-floor, double-articulated LRVs from AnsaldoBreda. These vehicles operate in consist with existing high-floor, single articulated LRVs. Some of the challenges faced by the project team are discussed. Derailments of the leading axle of the center truck have been an issue. Several modifications were implemented following a study of vehicle dynamics and an investigation of the effects of track quality.

Frederich/Kraft, "Funktionale Spurführungsgeometrie für Nahverkehrsbahnen," (Functional tracking geometry for commuter type railways) *Der Nahverkehr*, April 1999.

Tracking is the general term for the two functions "track guidance" and "track securing." Track guidance is performed by the geometry of running surface and the railhead. Track securing is acting, if holding the track by the running surface is not sufficient any more. This operating condition has to be avoided as far as possible, because it will create high forces and thus wear, increased running resistance, and noise.

Frederich/Kraft, "Berechnungen zur Spurführung. Wie prüft man die richtige Abstimmung von Fahrwerk und Gleis?" Calculations for wheel-rail guidance. How to evaluate the correct calibration between truck (running gear) and track?, *Der Nahverkehr*, May 1999.

Determination of the common geometric plane (GGE)–outline of the flange–interdependence between rail head and wheel profile–determination of guidance dimensions–geometrical criteria. The goal was the functional determination of guidance dimensions; systematic research into the requirements of the guidance geometry for rapid transit systems, and development of an assessment system for the co-ordination of the transverse dimensions of truck (running gear) and track. Development of the formulae with the example of a fixed-axle truck; the system demonstrated is based on functional track and truck dimensions.

Frederich, "Nullebenen-Konzept der Spurführung," (Applying the zero-level concept to improve the track following capability), *ZEV + DET Glas. Ann 123*, August 1999.

The combination of traditional mechanics and modern electronics is opening new dimensions and possibilities. Advances in automobile engineering and modern mechanical engineering have proved this.

An analysis of the wheel/rail contact conditions of conventional wheelset has led to a new track following principle. The undesirable wave phenomenon is eliminated without impairing the desirable radial self-alignment. The solution is called zero-level concept with power diversion control and electronic wave compensation. The paper describes the principle, the implementation, and the results obtained on two experimental trucks.

Frederich, "Horizonte der Spurführung," (Horizons of wheelset alignment and tracking). *ZEV + DET Glas. Ann 124*, May 2000.

Wheelsets and ideal alignment and tracking are still being considered as inseparable. It is revealed by a closer review that wheelsets do not really lend themselves to high-speed running or curve running. An additional drawback is their high weight.

The systematic search for other rolling and alignment principles has led to new solutions that will open the way to new methods of alignment and tracking. Today, three directions of development are feasible.

Heilig/Porter, "Finally some Operating Experience with Low Floor Light Rail Vehicles (In North America). TRC E-C058, 8th National Rail Transit Conference. TRB 2000.

Experience of operation of the Portland LFLRVs during the first 2 years of revenue service. Reliability parameters are quantified and compared with those for older high-floor vehicles. Topics covered include service reliability, ride quality, and the performance of the center trucks.

Hondius, "Citadis-Straßenbahnen: Entwicklungen seit 1999. Ein Überblick über die Evolution der Niederflur-Baureihe von Alstom," (Citadis trams: Development since 1999. An overview on the evolution of the Alstom low-floor concept.). *Der Nahverkehr*, January/February 2004.

History of the development of the Citadis Models as 6 low-floor versions. Citadis are a hybrid construction, using welded aluminum, steel as well as rivets to combine aluminum and steel. Citadis-Trams have no major mechanical faults and, in general, a good reputation.

Hüber, "Laufruhe von Niederflurbahnen: Möglichkeiten der Optimierung," (Running smoothness of low-floor vehicles: Potential for optimization.). *Der Nahverkehr*, September 2004.

Development of LFLRVs since the end of the 1980s. Description of the development of different types, including 70-percent low floor with single wheel, single axles, and 100-percent single wheel trucks. Description of the problems operating wheelsets without axles on light rail networks because the wheel back-to-back distance cannot be kept constant after longer periods of operation. A description of the high wear resulting from the lack of sinus running when no fixed axles are used. After a description of the possible solutions for low-floor vehicles, the author gives a statement as to the best construction for low-floor vehicles with optimal guidance characteristics.

Int-Veen/Nimphius, "Niederflurbahnen für Essen. Erfahrungen nach drei Jahren Praxiseinsatz," (Low floor streetcars for Essen. Experiences after three years practical application). *Der Nahverkehr*, December 2002.

The article deals with the 70-percent low-floor vehicles introduced to the Essen network between 1999 and 2001. The vehicles were manufactured by Bombardier. Some detail is

provided about the operational experience, such as requirements determined by existing infrastructure and the specifications of the operator. Issues such as introduction to service, experiences with vehicle electrical and mechanical systems, treatment of life-cycle-costs, energy consumption, wheel wear, brakes, doors, bonding, and derailment are covered.

Kramp, Shu, Wilson, "Effects of Independently Rolling Wheels on Flange Climbing Derailment", ASME 2004.

Extended description of the work covered in the report by Elkins and Wilson (see above).

Krettek/Miluczky, "Zum Einfluss der Dachdampfer auf den Lauf von Niederflur-Multigelenkstadtbahnwagen," (About the influence of roof dampers on the running behavior of multi-articulation streetcars) proprietary note, 2002.

The authors are describing the investigations in regard to the optimization of the running behavior of the multi-articulation low-floor vehicle 2000 of the Duisburg transit authorities DVG. This vehicle showed unacceptable lateral and yaw modes.

Modifications on the drive concept, intercar dampers and modifications of the wheel profile contributed to a considerable improvement of the running behavior.

Lenti, "Simulation einer Strassenbahn mit Einzerradaufhängung," (Simulation of a streetcar with single wheels) Stadtverkehr April 2002 (Volume 47).

During the design of the new streetcar for Turin, Italy, ALSTOM Ferroviaria decided to determine the dynamic behavior of the vehicle by means of virtual prototyping. ADAMS/Rail was used to simulate the vehicle, validation of the models were performed, and the dynamic behavior of the first streetcars was as predicted. This tool proved to be well suited for this purpose.

MBTA Internet Homepage 31.10.04. www.mbta.com. Information on Type 8 LRV.

Green Line Fleet List. Status of type 8 cars. Chronology of events involving type 8 cars.

Morgan, "Light Rail Vehicles' Low-Floor Center Section," TRC E-C058, 9th National Rail Transit Conference. TRB 2003.

A report on the assessment by Dallas (DART) for introducing LFLRVs, taking into account all related issues, including infrastructure changes. The LFLRV would be existing cars with an added center section. High speed was an issue, because of lack of experience of high-speed applications of this solution. The decision was mainly based on cost; technical issues were barely discussed.

Nelson, *TCRP Report 23: Wheel/rail Noise Control Manual*, 1997.

A very detailed review of railroad borne noise, including wheel/rail noise generation, noise control treatments, and cost analysis.

Parsons Brinckerhoff Quade and Douglas, Inc., *TCRP Report 57: Track Design Handbook for Light Rail Transit*, 2000.

A detailed review of LRT operations in the United States and Canada. Includes vehicles, track geometry, structural designs, track materials and special trackwork, aerial structures, and signals.

Pearce/Sherratt, "Wheel Profile Shapes." Paper presented at the Wheels and Axles Seminar, Institution of Mechanical Engineers, April 1999.

Basic principles involved in developing wheel profiles, including LRVs for operation both on tramway and railway infrastructure.

Pearson, "Passenger Access Considerations for Low-floor Light Rail Vehicles," TRC E-C058, 8th National Rail Transit Conference. TRB 2000.

This paper considers the relationship between vehicle and platform heights for LFLRVs, taking into account all the main contributory variables (e.g., track bed, truck, and suspension characteristics). Applicable FTA and ADA regulations are discussed.

Schreiber, "Betrachtungen zum Spurkranzverschleiss an den Losraden des Niederflurmittelwagens," (Consideration of the flange wear on the single wheels of the low floor intermediate section) proprietary note, 1997.

The author describes the behavior of the single wheels of the low-floor intermediate sections of streetcars (a popular enhancement of the capacity of existing vehicles in Europe). The pros and cons of the solution are discussed and the theory of the behavior of these running gears is given. Estimates on the life of the wheels are given and procedures to guarantee the standing of the profile between reprofiling are given.

Snowdon, "The Development of Tyre Profiles for Tramway and Light Rail Operation." Paper presented at the Wheels and Axles Seminar, Institution of Mechanical Engineers, April 1999.

Paper by the Chief Engineer, Tramtrack, Croydon, describing how the wheel profiles of the Docklands Light Railway were developed.

Stöhrer, "Leoliner: Neue Niederflurbahn für knappe Beschaffungsbudgets," (Leoliner: New Low-floor tram for tight procurement budgets). *Der Nahverkehr*, November 2003.

In Sept 2003, the prototype of the new six-axle low-floor articulated tram NGTW 6 Leoliner was introduced. Previously (1994), the LVB (public transport operator in Leipzig) had ordered 56 articulated low-floor vehicles. The Leoliner concept is to get new vehicles in "half the time for half the price." It has been designed and manufactured by LFB, a joint venture of LVB and Siemens TS. The vehicles operate on standard bogies for off-street track in the non-modernized parts

of the network. Width of the vehicles is 2,300 mm, 60 percent of the vehicle is low-floor.

Suda, "Dynamic stability and steering ability of steering trucks using unsymmetrical suspension with independently rotating wheels," World Congress on Railway Research, November 1997, Volume D.

This paper presents the dynamic stability and steering ability around curves of a new truck for rail vehicles with IRWs in the trailing axle. From the theoretical analysis using a truck model, the proposed truck has better curving performance than conventional trucks with normal wheelsets.

Swanson, "Evolution, Not Revolution in LRV Design," TRC E-C058, 8th National Rail Transit Conference, TRB 2000.

An overview of some of the commercial considerations that influence LFLRV design. Not particularly relevant other than as a source of some general system parameters.

Wu, Shu, Wilson, *TCRP Report 71, Volume 5: Flange Climb Derailment Criteria and Wheel/Rail Profile Management and Maintenance Guidelines for Transit Operations*. Transportation Technology Center, Inc. TRB 2005.

Results of the research carried out under TCRP Project D-7. It describes flange climb derailment criteria for transit vehicles that include lateral-to-vertical (L/V) ratio limits and a corresponding flange-climb-distance limit and provides guidance for wheel and rail maintenance practices.

Zarembski, "Derailment of Transit Vehicles in Special Trackwork," TCRP Final Draft Report, July 1996. Zeta-Tech.

Results of the research carried out under TCRP Project D-2. The objective was to determine the most cost-effective mitigation devices and techniques to be used by rail rapid transit systems to reduce or eliminate the possibility of special trackwork derailments.

Part 2. Other Sources

Anon, "Niederflur-Straßenbahn-Prototyp für München." (Low floor prototype tram for Munich). Stadtverkehr Sonderdruck 1993.

APTA, "Passenger Rail Equipment Safety Standards Task Force Technical Bulletin 1998-1, part 1 on Commuter Car Safety Regarding: Wheel Running Surface Manufacturing And Reprofilng Contour," Prepared by the Wheel/rail Interface Working Group of the Passenger Rail Equipment Safety Standards (PRESS) Task Force, November 3rd, 1998.

Bombardier Eurorail, "Zweissystemfahrzeug Stadtbahn Saar." (Dual system rail vehicle for the Saar Light Rail system). Supplier literature, 1996/07.

CKD Tatra, "Dreiteiliger Niederflur-Stadtbahnwagen RT6-N1." (Three section low floor tram RT6-N1). Supplier literature.

DeLibero, "MetroRail paves the way towards a comprehensive mobility plan." Railway Gazette Metro Report 2002.

Dillig, "Präsentation der Niederflur-Straßenbahn für Halle." (Presentation of low floor trams for Halle) Stadtverkehr Sonderdruck 1993.

Dillig, "Avanto Tram-Train für die SNCF." (Avanto Tram Train for French National Railways). Der Stadtverkehr 2002/10.

Hondius, "Die Entwicklung der Nieder- und Mittelflur-Straßen- und Stadtbahnen." (The Development of Low floor and Middle floor Trams and Light Rail Vehicles Der Stadtverkehr (Series of articles - still being published). 1989/02, 1990/05, 1992/03, 1992/04, 1993/01, 1993/02, 1993/10, 1993/11-12, 1994/06, 1995/02, 1995/03, 1996/01, 1996/02-03, 1997/09, 1998/09, 1998/10, 1999/11-12, 2000/01, 2000/11-12, 2001/01, 2001/11-12, 2002/01, 2002/11-12, 2003/01, 2003/11-12, 2004/01, 2004/11-12, 2005/01.

Hondius, "Frankfurt/M.: Übergabe des ersten in Serie hergestellten R-Wagens." (Frankfurt-on-Main: Delivery of the first of the R series cars) Stadtverkehr Sonderdruck 1993.

Hondius, "Potsdam: ViP nimmt ersten Serien-Combino in Betrieb." (Potsdam: The first of the Combino series enters service). Der Stadtverkehr 1999/01.

Hondius, "Incentro - die neue Systemstraßenbahn von Adtranz." (Incentro - the new tram concept from Adtranz). Der Stadtverkehr 2000/06.

Hondius, "Die Drehgestell-Niederflurbahnen NF 2000 von Bombardier Transportation." (The low floor light rail truck NF 2000 from Bombardier Transportation), Der Stadtverkehr 2001/05.

Hondius, "Der Bombardier-Cityrunner für die Grazer Verkehrsbetriebe." (The Bombardier Cityrunner for the Graz Transport Company). Der Stadtverkehr 2001/06.

Hondius, "Neue Bahnen für Schwerin." (New rail vehicles for Schwerin). Der Stadtverkehr 2001/09.

Hondius, "System cars dominate falling market." Railway Gazette Metro Report 2002.

Hondius, "Die Combino-Lieferung an M>Tram Melbourne hat begonnen." (Supply of Combinos to the Melbourne Tramway begins). Stadtverkehr 2002/05.

Hondius, "Neuentwicklung: Regiotram-Fahrzeuge für den Raum Kassel." (New developments: Regiotram vehicles for the Kassel region.) Der Stadtverkehr 2002/05.

Hondius, "Avanto, die neue System-Niederflurstadtbahn von Siemens TS." (Avanto the new low floor tram design from Siemens Transportation Systems). Stadtverkehr 2002/06.

Hondius, "Neue Fahrzeuge und Strecken in Linz." (New vehicles and services in Linz) Der Stadtverkehr 2002/07-08.

Hondius, "Big builders face uncertainty as system cars dominate the market." Railway Gazette Metro Report 2004.

Hondius, "Bombardier-Straßenbahn für Eskisehir bei OEG erprobt." (Bombardier tram for Eskisehir (Turkey) is tested by OEG). Der Stadtverkehr 2004/04.

Kunow, "Kassel: Neue Niederflur-Straßenbahn." (Kassel: New low-floor tram). Stadtverkehr Sonderdruck 1993.

Lehna/Theiler, "What is the Advantage of Optimizing the Wheel/Rail Profiles?" Presentation given at InnoTrans 2004.

Lehna/Theiler/Imhof, "Radprofiloptimierung bei den Verkehrsbetrieben Zürich" ("Wheel Profile optimization on the Zurich Transport System"). Presentation prepared by the Institut für Bahntechnik GmbH (In German).

Marie, "Hiawatha joins the light rail family." Railway Gazette Metro Report 2004.

Op de Beeck/Mechelen/Hondius, "Neue Straßenbahnwagen für "De Lijn," (New Tram for the Belgian Coast Light Railway). Der Stadtverkehr 2000/03.

Riechers, "Die Stadtwerke Ulm/Neu-Ulm erneuern ihren Straßenbahnpark," (The public transport systems of Ulm and New Ulm replace their tram fleet) Der Stadtverkehr 2003/06.

Sarunac/Zeolla, "Structural and Crashworthiness Requirements of Light Rail Vehicles with Low-Floor Extension." Transportation Research E-Circular E-C058, pages 89-103, 2003.

STADLER, "Stadler präsentiert Prototyp des Gelenktriebwagens 2/6." (Stadler presents the prototype driving trailer 2/6). Press release 1995/08.

Tuzik, "Examining wheel/rail interaction on rail transit systems." "Interface," November 4th 2004.

Uebel, "Die Entwicklung des Niederflur-Gelenktriebwagens GT 6 N der Bremer Straßenbahn AG." (The development of the low floor driving trailers GT 6 N of Bremen Tramways) Stadtverkehr Sonderdruck 1993.

Abbreviations and acronyms used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation