
# Track-Related Research, Volume 7: Guidelines for Guard/Restraining Rail Installation

## DETAILS

26 pages | | PAPERBACK
ISBN 978-0-309-11817-0 | DOI 10.17226/14347

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TRANSIT COOPERATIVE RESEARCH PROGRAM

# TCRP REPORT 71

# Track-Related Research

## *Volume 7:*

## *Guidelines for Guard/Restraining Rail Installation*


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*Subject Areas*
Public Transit • Rail


Research sponsored by the Federal Transit Administration in cooperation with the Transit Development Corporation

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2010
www.TRB.org

## 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.

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

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

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

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

## TCRP REPORT 71: VOLUME 7

Project D-7/Task 16
ISSN 1073-4872
ISBN 978-0-309-11817-0
Library of Congress Control Number 2001135523



*Published reports of the*

**TRANSIT COOPERATIVE RESEARCH PROGRAM**

*are available from:*

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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# FOREWORD

By S. A. Parker
Staff Officer
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This report includes the results of a research task carried out under TCRP Project D-7, "Joint Rail Transit-Related Research with the Association of American Railroads/ Transportation Technology Center, Inc." The report includes comparisons of two guard rail installation philosophies and the effects of vehicle types, wheel flange angle, wheel/rail (W/R) friction coefficient, curve radius, cant deficiency, and track perturbation on flange climb derailments that have been investigated through simulations. It offers guidance that transit agencies can follow in their W/R maintenance practices for both transit rail cars and light rail vehicles. This report should be of interest to engineers involved in the design, construction, maintenance, and operation of rail transit systems.

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Over the years, a number of track-related research problem statements have been submitted for consideration in the TCRP project selection process. In many instances, the research requested has been similar to research currently being performed for the Federal Railroad Administration (FRA) and the freight railroads by the Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado, a subsidiary of the Association of American Railroads (AAR). Transit track, signal, and rail vehicle experts reviewed the research being conducted by TTCI. Based on this effort, a number of research topics were identified where TCRP funding could be used to take advantage of research currently being performed at the TTCI for the benefit of the transit industry. A final report on one of these efforts—*Guidelines for Guard/Restraining Rail Installation*—is presented in this publication.

A railroad train running along a track is one of the most complex dynamic systems in engineering due to the presence of many nonlinear components. Wheel and rail geometries have a significant effect on vehicle dynamic performance and operating safety. The W/R interaction in transit operations has its own special characteristics. Transit systems have adopted different W/R profile standards for different reasons. Older systems with long histories have W/R profile standards that were established many years ago. Newer systems have generally selected W/R profiles based on an increased understanding of W/R interaction in recent years.

Transit systems are typically operated in dense urban areas, which frequently results in systems that contain a large number of curves with small radii that can increase W/R wear and increase the potential for flange climb derailments. Transit systems also operate a wide range of vehicle types, such as those used in commuter rail, light rail, and rapid transit services, with a wide range of suspension designs and performance characteristics. Increasing operating speed and the introduction of new vehicle designs have posed an even greater challenge for transit systems to maintain and improve W/R interaction.

Under TCRP Project D-7 Task 16, TTCI was asked to compare the effects of two guard rail installation philosophies on vehicle performance and to develop guidelines for the application of guard/restraining rails based on vehicle type, track geometry, and operations conditions. Simulations show that Philosophy I (shared contact between the high-rail flange and the guard rail on the low-rail wheel) leads to better vehicle dynamic performance than Philosophy II (no high-rail flange contact with the guard rail contact on the low-rail wheel) in terms of lower lateral forces on rails, lower vehicle rolling resistance, and lower leading axle wear.

The effects of vehicle types, wheel flange angle, W/R friction coefficient, curve radius, cant deficiency, and track perturbations on flange climb derailments have also been investigated through simulations. From this study, TTCI developed guidelines for guard/restraining rail installation in terms of vehicle type and track geometry.

# CONTENTS

SUMMARY

# Guard/Restraining Rail Study—Phase II

This report compares the effects of two guard rail installation philosophies on transit vehicle wheel/rail (W/R) force, wear, rolling resistance, and axle steering capability. The effects of vehicle types, wheel flange angle, W/R friction coefficient, curve radius, cant deficiency, and track perturbation on flange climb derailments were also investigated through NUCARS® simulations. A number of conclusions regarding guard/restraining rail installation in terms of vehicle type and track geometry are drawn from this work including the following:

- Philosophy I (shared contact between the high-rail flange and the guard rail on the low-rail wheel) leads to better vehicle dynamic performance than Philosophy II (no high-rail flange contact and with the guard rail contact on the low-rail wheel) in terms of lower lateral forces on rails, lower vehicle rolling resistance, and lower leading axle wear.
- Both philosophies lead to higher vehicle rolling resistance and leading axle wheel wear compared with the case with no guard rail.
- The axle steering capability difference between these two philosophies is negligible.
- The Nadal limit and the flange climb distance limit are the criteria for flange climb derailment; they are adopted as the guard rail installation criteria in this report.
- There are many factors leading to flange climb derailment. Three factors have the most critical effects: wheel flange angle, W/R friction coefficient, and track perturbation amplitude.
- Flange climb derailment risk decreases as wheel flange angle increases: the larger the wheel flange angle, the smaller the guarded curve radius.
- Flange climb derailment risk decreases as W/R friction coefficient decreases: the lower the friction coefficient, the smaller the guarded curve radius. No guard rail is needed for all simulated vehicles if the friction coefficient can be kept under 0.4.
- Flange climb derailment risk increases as track perturbation increases: the smaller the track perturbation amplitude, the smaller the guarded curve radius.
- Transportation Technology Center, Inc., (TTCI) recommends the adoption of 75° flange angle wheels for both transit cars (Types 1 and 2) and light rail vehicles (Types 1 and 2) to prevent flange climb derailment.
- From a safety point of view, the guard rail installation guidelines for the simulated transit rail cars (Types 1 and 2) and the light rail vehicles (Types 1 and 2) (defined in Table 2 of this report) with the recommended 75° flange angle wheels are the following:
  - For yard curves (15 mph speed limit) with the most severe (Level 3, shown in Figure 21) track perturbations:
    - No guard rails are needed for Type 1 and Type 2 transit rail cars or Type 2 light rail vehicles.
    - Guard rails should be installed on curves with radii less than or equal to 755 ft for the Type 1 light rail vehicle.

- For main-line curves:
  - No guard rails are needed for Type 1 and 2 transit rail cars running at a 7.5 in. cant deficiency speed with Level 2 (shown in Figure 20) track perturbations.
  - No guard rails are needed for Type 1 light rail vehicles running at a 7.5 in. cant deficiency speed with Level 1 (shown in Figure 19 in the report) track perturbations.
  - No guard rails are needed for Type 2 light rail vehicles running at a 4.0 in. cant deficiency speed with Level 1 track perturbations.
  - Guard rails should be installed on curves with radii less than or equal to 500 ft for Type 1 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.
  - Guard rails should be installed on curves with radii greater than or equal to 955 ft for Type 2 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.

- Vehicle curving performance is different from case-to-case due to many factors stemming from vehicle and track aspects. The guidelines listed here as well as the details provided in Tables 7 through 10 of the report could be used as a reference and applied by taking into account the specific vehicle/track features and operating environment.
- These guard rail installation guidelines do not apply to special trackwork, such as the guard rails for switches, crossings, and turnouts.

CHAPTER 1

# Introduction

In 2005, Transportation Technology Center, Inc. (TTCI) conducted research for TCRP Project D-7/Task 12, "Guard/Restraining Rail Study" to develop guidelines for the application of guard/restraining rails in transit systems.

*TCRP Research Results Digest 82: Use of Guard/Girder/Restraining Rails* was published in 2007 (*1*) as a result of this study, and it recommended simultaneous contact between the guard and high rails, which would result in the sharing of lateral forces. The optimal flangeway clearances needed to achieve this were included in the report. A general guideline based on a wheel lateral-to-vertical force (L/V) ratio and flange climb distance criteria was also proposed. Subsequently, TRB Committee AP080, Rail Transit Systems Design, suggested that the two guard rail installation philosophies described in the following sections be compared.

## 1.1 Philosophy I

The "shared contact" methodology will be referred to as guard rail installation Philosophy I (illustrated in Figure 1). The optimization methodology proposed in the previous study (*1*) for optimal flangeway clearance clearly belongs to Philosophy I. With equal rates of wear, it is expected that the high rail and the guard/girder/restraining rail will wear out at the same time and be replaced during the same track maintenance period, minimizing service interruptions.

## 1.2 Philosophy II

There is a different guard rail installation philosophy used by transit systems that will be referred to as Philosophy II (illustrated in Figure 2). The methodology of Philosophy II is to increase the check gage dimension and track gage so that no flange contact with the high rail will occur under any combination of wear and tolerances. As a result, the guard/girder/restraining rail resists all the curving forces and therefore experiences all the gage face wear, while the high rail experiences only rail head wear. Philosophy II can be accomplished by simply widening the track gage.

The following (based on the Research Needs Statement for Optimizing the Check Gauge of Restraining Guard Rail[1]) are reasons for installing guard rails using Philosophy II:

- Because of the variations in the wheel mounting back-to-back dimensions, wheel flange wear, rail gage face wear, and track gage variations, it is impossible to have shared contact with both the high rail and the guard/restraining rail in any reliable manner. This can result in contact that is shared intermittently, and adverse steering forces are introduced into the trucks, resulting in rapid oscillation and in significantly increased nosing forces. These forces can damage the track, such as gouging wear of both the high rail and the guard/restraining rail and breaking the bolts holding the guard/restraining rail. The sudden, adverse steering forces also are likely to result in a lurching and an uncomfortable ride in the vehicles, especially for standing passengers.
- Contacting the back of the flange on only the guard/restraining rail reduces curving noise, since only one rail and one wheel are involved as opposed to two. This results in less bell-ringing and wheel squeal and significantly reduces wear on the high rail so that the high rail has a considerably extended life, roughly equal to that of the low rail.

Even though the wheel/rail (W/R) contact of these two philosophies starts in two significantly different situations, they ultimately end with the same situation as Philosophy I, because the high-rail contact will eventually occur for Philosophy II as the guard/restraining rail gradually wears in.

The obvious question is this: Is Philosophy I or II the correct way of installing a guard rail? It is an important question because it could lead to operating safety issues, premature

[1] Research Needs Statements: Optimizing the Check Gauge of Restraining Guard Rail, http://rns.trb.org/dproject.asp?n=13826.

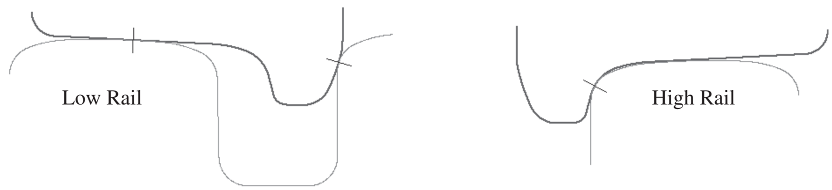


*Figure 1. Guard rail installation Philosophy I.*

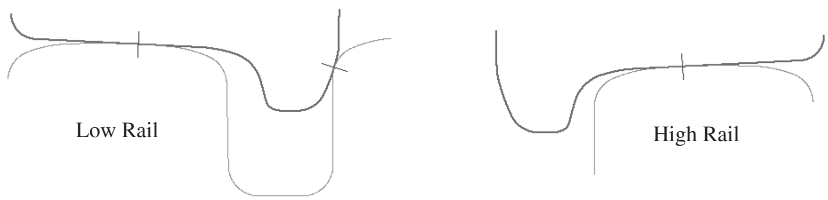


*Figure 2. Guard rail installation Philosophy II.*

wear, or damage to the track that increases the maintenance requirements, poor ride quality, and additional noise.

Consequently, in 2008, TTCI conducted research for TCRP under TCRP Project D-07/Task 16, "Guard/Restraining Rail Study—Phase II" with the following three tasks:

- **Task 1:** Conduct a literature review of guard/restraining rail installation guidelines and the philosophies behind them.
- **Task 2:** Quantify the performance/benefits of both philosophies and recommend a preferred method through modeling using the following key results as a basis for comparison:
  – Lateral forces developed (implying damage on rail and fastening system);
  – Rolling resistance (implying energy consumption);
  – Wear index (including wear of both the flange face and flange back); and
  – Axle angle-of-attack (implying axle steering capability).
- **Task 3:** Develop guard rail installation guidelines based on track curvature, vehicle type, and operation condition.

This report presents the results of the work done in support of these three tasks.

CHAPTER 2

# Literature Review

A guard/restraining rail practice survey was conducted during the Phase I study (*1*) and during TCRP Project D-07/ Task 8 published as *TCRP Report 71, Volume 5: Flange Climb Derailment Criteria and Wheel/Rail Profile Management and Maintenance Guidelines for Transit Operations* (*2*). Radii of curves on which transit systems install guard rails differ from 500 to 1,000 ft. The flangeway clearance differs from 1.5 to 2.5 in. depending on the wheelset and track geometry dimensions. Most of the track standards used on various transit properties are based simply on prior practice without independent verification that the practice is still appropriate or effective.

The Phase I study proposed optimization methodologies for guard rail installation based on the "sharing contact" philosophy (Philosophy I), which need to be justified. This study conducted an additional literature review that focused on the guard rail installation criteria or standards worldwide and the philosophies behind them. However, there is very little literature published on these topics. The following comments are based on the results of the literature review.

One of the main functions of a guard rail is to prevent flange climb derailment. Most flange climb derailments occur under the following conditions:

- Tight curves or small radius switches, mostly in yards;
- Low flange angle wheels;
- High W/R friction coefficient, such as a new trued wheel with a rough surface;
- Independent rotating wheels (IRW); and
- Severe track perturbations.

Table 1 shows that the wheel flange angle used in different transit systems ranges from 63 to 77° (*3*). The effect of the flange angle and the other factors listed above, including vehicle suspensions and the operation environment, on flange climb derailment needs to be investigated in order to create guard/ restraining rail guidelines.

**Table 1. Wheel flange angle.**

| Wheel Flange Angle | Transit System* |
|---|---|
| 63° | BART (Transit Rail Car), Toronto, SEPTA, WMATA (Transit Rail Car) |
| 70° | Santa Clara VTA, Portland MAX, Edmonton, Houston, Baltimore, Dallas, KOLN, SEPTA (Transit Rail Car) |
| 75° | MBTA, NJT HBL and Newark, San Diego, Pittsburgh |
| 77° | BOCHUM, ZURICH |

* The vehicles in this table are Light Rail Vehicles (3), except for those specified as Transit Rail Car.

CHAPTER 3

# Comparisons of Two Guard Rail Installation Philosophies

To compare the two different guard rail installation philosophies, the TTCI NUCARS vehicle-track dynamics computer program was used to conduct steady-state curving simulations on a number of constant radii curves without perturbations to evaluate performance trends. Table 2 lists the parameters of the four types of transit vehicle models used in this project. Figure 3 illustrates their structures and layouts. Since there are no uniform definitions of "heavy rail vehicles," "transit rail cars," or "light rail vehicles," this report adopts the customary definitions used by most transits, which are the following:

- **Heavy Rail Vehicles:** They are also referred to as commuter rail and subject to FRA regulations. They normally have two trucks and examples include Metro North; LIRR; METRA (Chicago); SEPTA (Philadelphia, commuter service); CalTran (California); MARC (Baltimore); and MBTA (Boston). All these cars are designed to interact with freight traffic and are designed with the appropriate "buff load."
- **Transit Rail Cars:** They normally have two trucks and examples include NYC Transit (subway and elevated); SEPTA (Philadelphia, subway); WMATA; MARTA; Baltimore (subway); CTA (Chicago, subway and elevated); Los Angeles; MBTA (Boston, subway); and BART.
- **Light Rail Vehicles:** They normally have two trucks or three trucks with articulation. Examples include MBTA (Boston, green line); NJ Transit; Baltimore; Pittsburgh; Charlotte; MUNI (San Francisco); Denver; San Diego; San Jose (Valley); Portland; St. Louis; and SEPTA. These cars can be high floor, low floor, or a combination of both. They are formerly referred to as street cars or trolley cars.

The Type 1 transit rail cars and Type 1 light rail vehicles were used for the steady-state curving simulations in this section, and all four types of vehicle models were used for the flange climb derailment simulations discussed in Section 4. All four vehicle models were similar to those used in the TCRP Phase I guard rail study (*1*) and the previous TCRP flange climb derailment study (*2*). No simulations or analyses were made for heavy rail vehicles, although the lightest weight heavy rail vehicles can have dimensions and wheel loads that are similar to the Type 2 Transit Rail Car.

The Type 1 light rail vehicle represented a typical high-floor articulated vehicle composed of two car bodies and three trucks, as Figure 3(b) shows. The two car bodies articulated on the middle truck and all three trucks have solid wheel sets.

The Type 2 light rail vehicle model was a typical articulated low-floor light rail transit vehicle. It was composed of three car bodies and three trucks, as Figure 3(c) shows. The end car bodies were each mounted on a single truck at one end and connected to an articulation unit at the other end. The center car body was the articulation unit riding on a single truck equipped with independent rotating wheels.

The track inputs included a number of left hand smooth curves with curve radii from 100 to 955 ft and 1-in. superelevation. The vehicle running speed was 15 mph. The W/R profile combinations used in the simulations were a 63° flange wheel for the Type 1 transit rail car and a 75° flange angle wheel for the Type 1 light rail vehicle on standard American Railway Engineering and Maintenance-of-Way Association (AREMA) 115 lb/yd rail. The W/R friction coefficient used in the simulation was 0.4 to avoid causing flange climb derailments.

## 3.1 Transit Rail Cars (Type 1)

In most cases, guard rails are installed on the inside of the low rail. One function of a guard rail is to reduce excessive lateral force on the high rail by contacting the low-rail side wheel back. The reduction of lateral force on the high rail is mostly controlled by the flangeway clearance between the low rail and the guard rail, as the Phase I study (*1*) of this project showed. The lateral force distributions between the high rail and the guard rail are significantly different for these two guard rail installation philosophies. More than twice the lateral force acts on just the guard rail using Philosophy II, and the lateral

**Table 2. Vehicle modeling parameters.**

| Parameters | Transit Rail Car 1 | Light Rail Vehicle 1 | Transit Rail Car 2 | Light Rail Vehicle 2 |
|---|---|---|---|---|
| Carbody (Numbers) | 1 | 2 | 1 | 3 |
| Truck (Numbers) | 2 | 3 | 2 | 3 (IRW in middle truck) |
| Truck Center Spacing (ft) | 52 | 23 | 47.5 | 24 |
| Axle Spacing (ft) | 7.3 | 6.3 | 6.8 | 6.2 |
| Wheel Load (kips) | 9.45 | Mid truck: 5.2<br>End truck: 8.2 | 13.95 | Mid truck: 5.9<br>End truck: 8.49 |
| Wheel Diameter (in.) | 27 | 27 | 27 | 27 |
| Wheel Flange Angle (degrees) | 63 | 75 | 63 | 75 |

force acts almost equally on both rails using Philosophy I (see Figure 4). The excessive lateral force on the guard rail will result in rail and component damage and will reduce their service life. The flangeway clearance optimization methodology and benefits were investigated in the Phase I report.

Figure 5 shows that installing the guard rail using Philosophy II results in a larger rolling resistance than does that of Philosophy I. Installing the guard rail using Philosophy I with optimal flangeway clearance could decrease the rolling resistance on tight curves with radii less than 250 ft.

In 1982, a transit rail car was tested on TTCI's Tight Turn Loop (TTL) (a 150-ft radius curve with 1.5-in. superelevation) track with and without restraining rails (*4*). The vehicle weighed 97,020 lbs and had truck center spacing of 54 ft, axle spacing of 7.5 ft, and a wheel radius of 15 in.

The restraining rail case represents a condition where the wheel flange back contacts the restraining rail at a 90° angle, as Figure 6 shows. The guard rail case represents a condition where the wheel flange tip contacts the rail with a less than 90° angle, as Figure 7 shows. Even though the restraining rail was installed horizontally on the TTL track, the restraining rail height was only about 0.5 in. above the low-rail top and resulted in the contact with the wheel on the back of the wheel flange tip. Therefore, according to the definition, the TTL horizontally mounted rail with low height, as Figure 7 shows, was modeled as a guard rail because its contact angle (δ) on the wheel flange back was less than 90°.

The tests showed that the traction force required to propel the car with the guard rail was about 30% higher than without the restraining rail, as Table 3 shows. The test result was consistent with the simulation result in Figure 5, which showed about a 10 to 30% traction force increase in the 100 ft and 250 ft radii curves as a result of using Philosophy II.

Figure 8 shows that both philosophies resulted in a larger wear index on leading axle wheels (the sum of the wear index from all contact points on both wheels of the lead axle) than did the case without a guard rail, but there was a smaller wear index with Philosophy I than with Philosophy II.

The axle steering capability was evaluated by using the axle angle of attack (AOA) on curves. Figure 9 shows that the axle

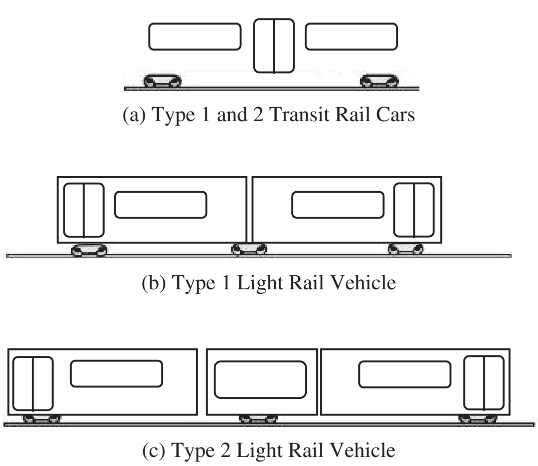


*Figure 3. Transit vehicles structures and layouts.*

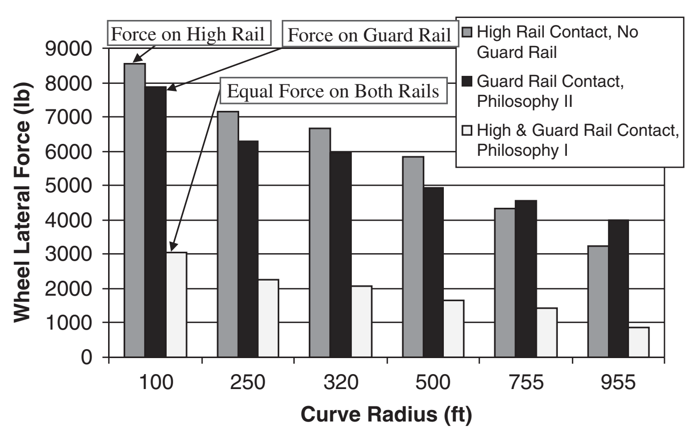


*Figure 4. The wheel lateral force of a Type 1 transit rail car with a guard rail.*

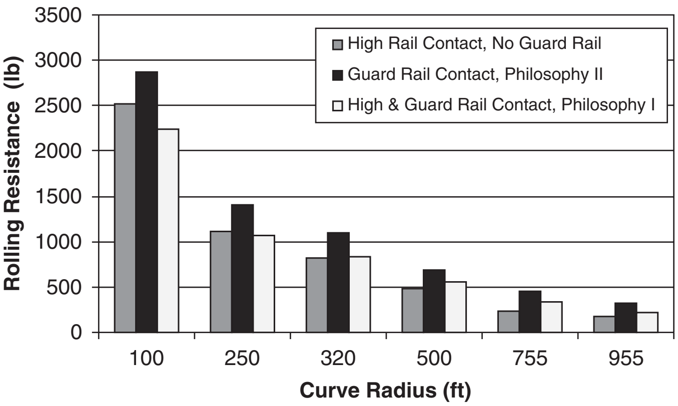


***Figure 5. The vehicle rolling resistance of a Type 1 transit rail car with a guard rail.***

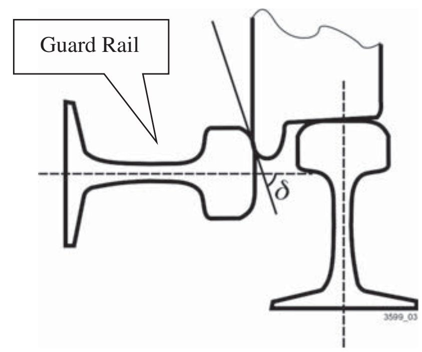


***Figure 7. Wheel and horizontal guard/restraining rail installed at a low position.***

steering capability was not changed significantly by installing a guard/restraining rail, especially on tight curves. Both philosophies resulted in a slightly larger AOA on the leading axle than did the case with no guard rail; Philosophy I generated a smaller AOA than Philosophy II. This conclusion was confirmed by the test results of the transit rail car on TTL track in 1982, as Figure 10 shows.

The differences between the two guard rail installation philosophies on restraining rail applications (with a flange back contact angle of about 90°) were also investigated through simulations. Figure 11 shows that the wheel lateral force of the Type 1 transit rail car with a restraining rail had a similar trend to that of guard rail cases. However, the vehicle rolling resistances with restraining rail were much bigger than those of guard rail cases, except the case of 100 ft radius curves, as Figure 12 shows. Because the vehicle rolling resistance is the sum of the wear index on all wheels, a similar trend was found in the wheel wear index. As expected, Figure 13 shows that the leading axle wear index with a restraining rail was much larger than that of the guard rail cases except for the case of 100 ft radius curves.

The Phase I study of this project (*1*) showed that the wear index increases with the contact angle. The increase of the wear index and the vehicle rolling resistance with a restraining rail is due to the high (90°) contact angle between the wheel back and the restraining rail, compared with a contact angle smaller than 80° between the wheel flange tip and the guard rail. The higher the contact angle is, the higher the spin creepage is, which leads to a higher wear index.

The axle steering capability was compared by using the axle AOA in curves. Figure 14 shows that the axle steering capability was not changed significantly by installing a guard/restraining rail, especially on tight curves. Both philosophies resulted in a slightly larger AOA on the leading axle than did the case with no guard rail, with Philosophy I generating a smaller AOA than Philosophy II. Figure 14 shows that the axle AOA of the Type 1 transit rail car with a restraining rail had trends similar to the trends of the guard rail cases; the AOA change caused by guard/restraining rail installation was negligible compared with the cases with no guard rail, regardless of which philosophy was used.

## 3.2 Light Rail Vehicles (Type 1)

This section compares the two guard rail installation philosophies with applications to the Type 1 light rail vehicle with a 75° flange angle wheel. Simulations were conducted only for a guard rail installation with a back of flange contact angle to the guard rail of less than 80°.

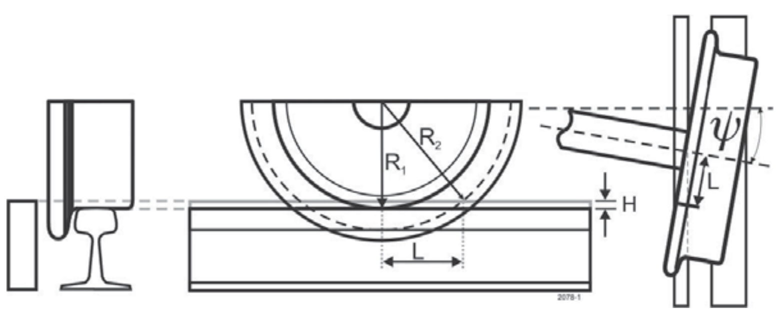


***Figure 6. Wheel back/restraining rail contact.***

**Table 3. Transit vehicle traction force measurement on TTCI's TTL track.**

| Case | Location | Measured Traction Force (lb) | Average Traction Force (lb) | Test Date |
|---|---|---|---|---|
| Without Guard Rail | 119,000 | 3,250 | 2,716 | 5/11/1982 |
| | 118,700 | 2,400 | | |
| | 118,700 | 2,500 | | |
| With Guard Rail | 118,300 | 3,600 | 3,600 | 5/28/1982 |
| | 118,500 | 3,400 | | |
| | 118,700 | 3,400 | | |
| | 118,900 | 3,900 | | |
| | 119,100 | 3,700 | | |

Figure 15 shows that the wheel lateral forces on the guard rail using Philosophy II on most curves except the 100-ft radius curve were larger than those of the cases with no guard rail. This was caused by the wheel flange tip climbing on the guard rail at the 100-ft radius curve. As a result, the high-rail contacts were close to the wheel flange root and shared part of the lateral force, which reduced the lateral force on the guard rail.

Figures 15 through 18 show similar trends compared with Figures 4 through 9 for the transit rail car. The conclusions drawn from the simulations of the Type 1 light rail vehicle with 75° flange angle wheels will be the same as the Type 1 transit rail car with 63° flange angle wheels as discussed in Section 3.1.

The following conclusions can be drawn from the Type 1 transit rail car and the Type 1 light rail vehicle steady-state

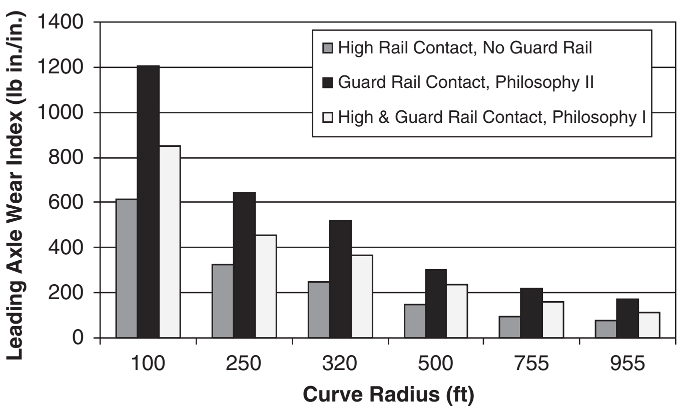


*Figure 8. The wear index of a Type 1 transit rail car with a guard rail.*

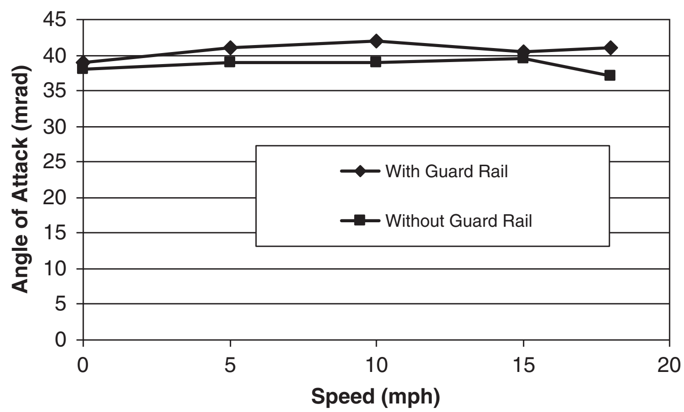


*Figure 10. Measured transit rail car leading axle AOA on TTL track.*

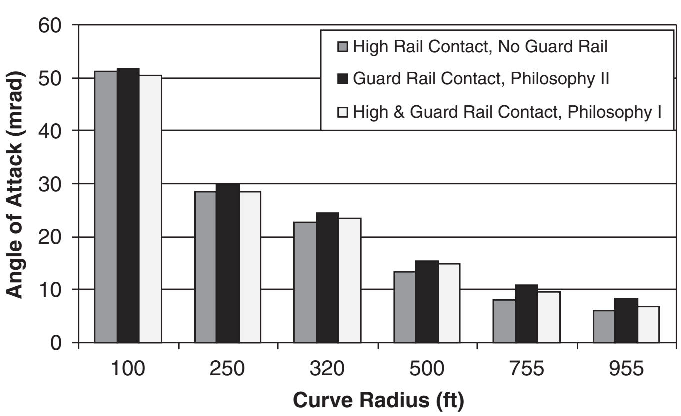


*Figure 9. The axle AOA of a Type 1 transit rail car with a guard rail.*

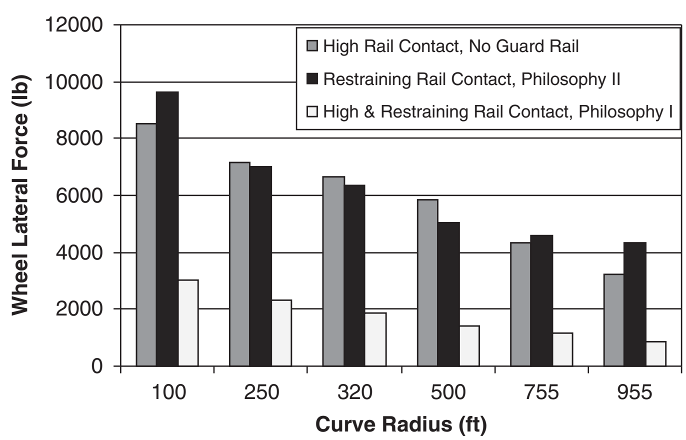


*Figure 11. The wheel lateral force of a Type 1 transit rail car with a restraining rail.*

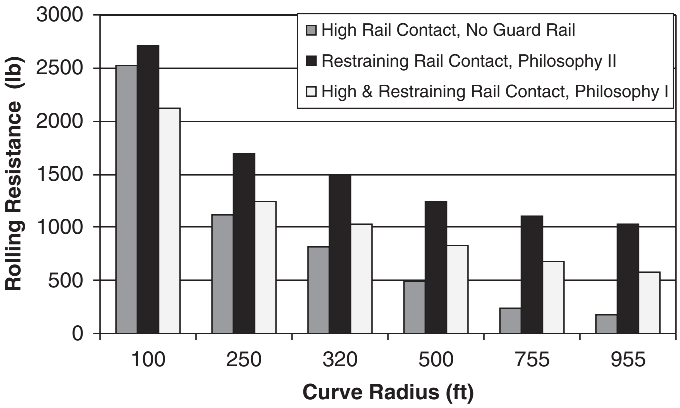


***Figure 12. The vehicle rolling resistance of a Type 1 transit rail car with a restraining rail.***

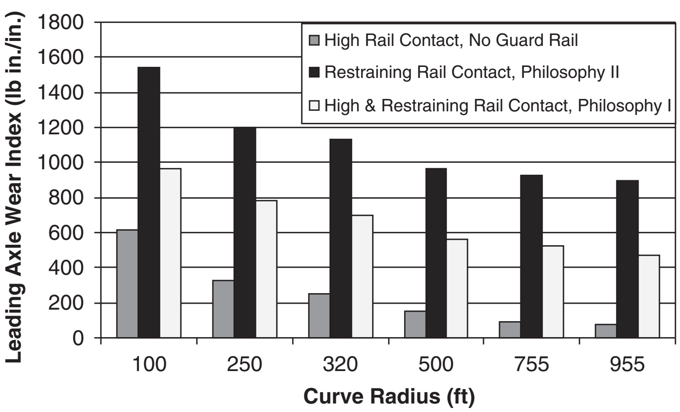


***Figure 13. The wear index of a Type 1 transit rail car with a restraining rail.***

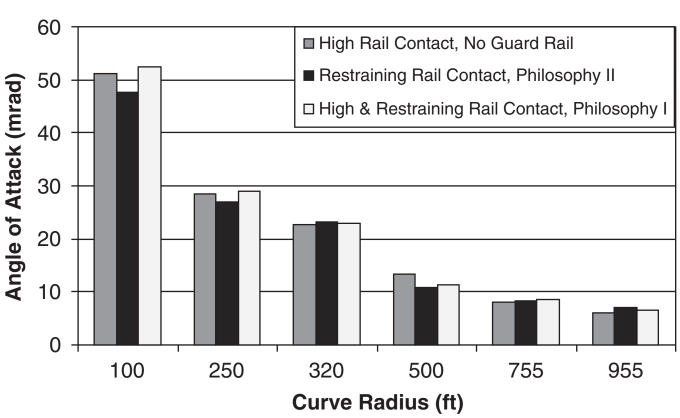


***Figure 14. The axle AOA of a Type 1 transit rail car with a restraining rail.***

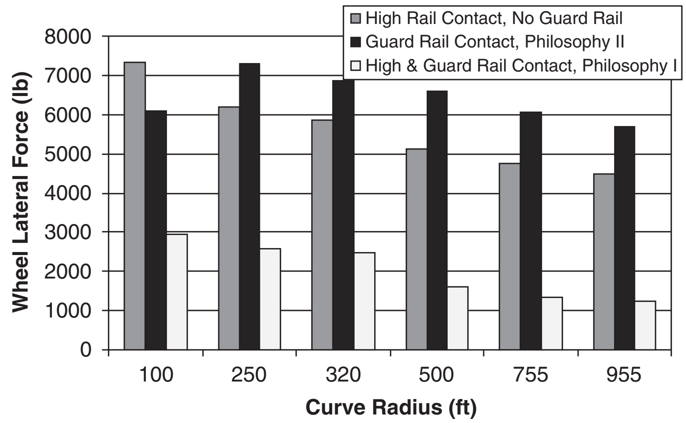


***Figure 15. The wheel lateral force of a Type 1 light rail vehicle with a guard rail.***

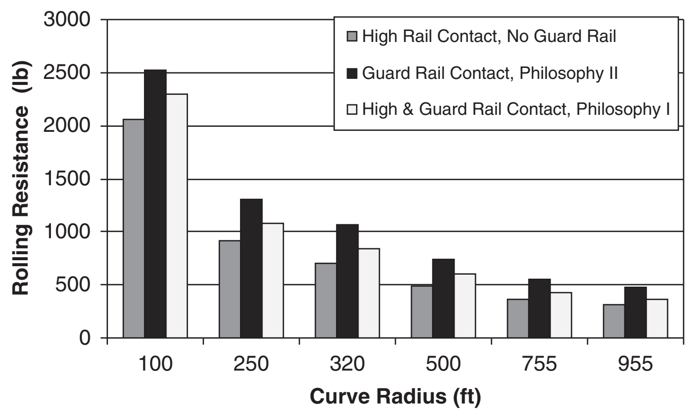


***Figure 16. The vehicle rolling resistance of a Type 1 light rail vehicle with a guard rail.***

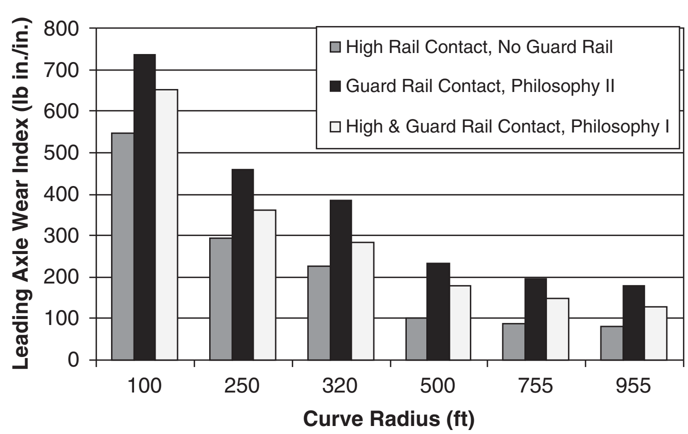


***Figure 17. The wear index of a Type 1 light rail vehicle with a guard rail.***

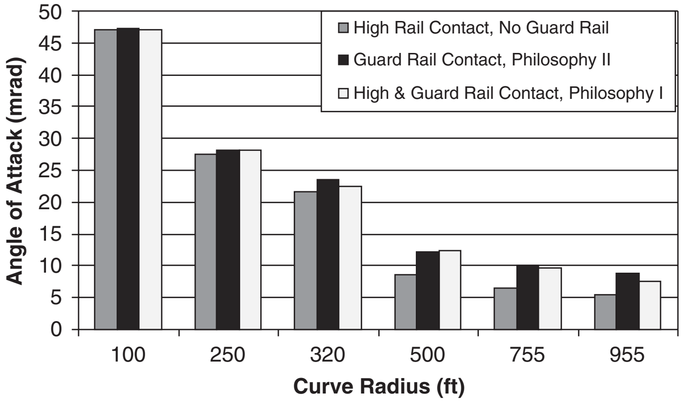


***Figure 18. The axle AOA of a Type 1 light rail vehicle with a guard rail.***

curving simulations, regarding comparisons of the two different guard rail installation philosophies:

- Philosophy I leads to a better vehicle dynamic performance than Philosophy II in terms of lower lateral forces on rails, lower vehicle rolling resistance, and lower leading axle wear.
- Both philosophies lead to higher vehicle rolling resistance and leading axle wheel wear, compared with the case with no guard rail.
- The axle steering capability difference between these two philosophies is negligible.
- Restraining rails (the W/R contact angle is almost 90°) and guard rails (the W/R contact angle is less than 80°) provide similar trends in performance.

CHAPTER 4

# Transit Vehicle Flange Climb Derailment Simulation

Flange climb derailment can occur due to excessive lateral forces acting on the wheel as a vehicle negotiates a curve. A common remedy for flange climb derailment in curves is to install guard rails on curves to provide additional resistance to flange climbing. The fundamental flange climb derailment mechanism was investigated in *TCRP Report 71, Volume 5* (*2*).

In this Chapter, dynamic curving simulations were conducted on four types of transit vehicles by using the NUCARS program. The L/V ratio and flange climb distance criteria proposed in the previous TCRP project (*2*) were applied to the simulation results. Guidelines for guard rail installation were produced based on these analyses.

## 4.1 Simulation Cases

The track geometries were represented both as smooth track without track irregularities (as designed) and also with a "down and out" perturbation in the middle of the curve. The "down and out" perturbations consisted of a combination of track geometry irregularities that were of a magnitude at the limit generated based on the track standards from several transit systems. This consisted of a downward vertical cusp on the high rail combined with an outward lateral alignment cusp on the high rail and an inward cusp on the low rail of a magnitude sufficient to ensure that the maximum permitted gage was not exceeded. These irregularities had a 31-ft wavelength with a cosine shape, with three levels of severity of perturbations, as displayed in Figures 19 through 21. Table 4 lists the amplitudes of the track perturbations.

The most severe perturbation (Level 3) is typical of the maintenance limit for low-speed operation in rail yards. The Level 1 perturbation represents a typical limit for a high speed on a main line. These perturbations were placed in the middle of a number of left hand curves with curve radii from 100 ft to 3,000 ft, and 1-in. superelevation. The vehicle running speed was 15 mph on yard track, and speeds corresponding to 4.0 in. and 7.5 in. cant deficiency overbalance speeds on main-line tracks for different radius curves (see Table 5).

The wheel/rail friction coefficient has a large effect on the potential for derailment; therefore, all simulation cases were carried out for W/R friction coefficients of 0.3, 0.4, 0.5 and 0.6.

## 4.2 Transit Rail Cars

Figure 22 shows the steady-state curving results for a transit rail car (Type 1) on a yard track without perturbations. The wheel L/V ratio on tight curves with a radius less than 500 ft increases when the W/R friction coefficient increases. The vehicle derailed on curves with a radius less than or equal to 250 ft at a friction coefficient of 0.6, which indicates that a guard rail is needed even on a perfect track without perturbations.

As expected, the dynamic curving L/V ratios on a perturbed track without a guard rail increase with the W/R friction coefficient and the amplitude of the perturbations (See Figures 23 and 24). The L/V ratios are generally higher than those in the steady curving conditions. The dynamic L/V ratios approach or exceed the Nadal limit (shown as a solid line) at a friction coefficient of 0.5. The vehicle derailed for all simulated cases (100 to 3,000 ft radii curves) with a friction coefficient of 0.6 and Level 3 perturbations.

There are many factors that lead to flange climb derailment. Three of them have the most critical effects: wheel flange angle, friction coefficient, and perturbation amplitude. As Figure 22 shows, even without perturbations, wheel flange climbing can still occur because of a lower (63°) flange angle and a higher friction coefficient (0.6).

Tests and simulations show that the friction coefficient plays a critical role for derailment. If the W/R friction coefficient can be controlled to remain under 0.4 with reliable lubrication devices, guard rails are not needed for this type of vehicle (Figures 22 through 24). However, many factors lead to the variation of the friction coefficient such as weather conditions, unreliable rail lubrication, new trued wheel surface roughness,

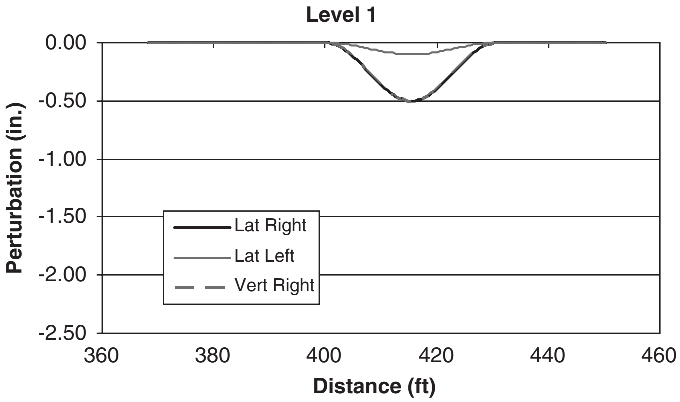


*Figure 19. Track perturbation, Level 1.*

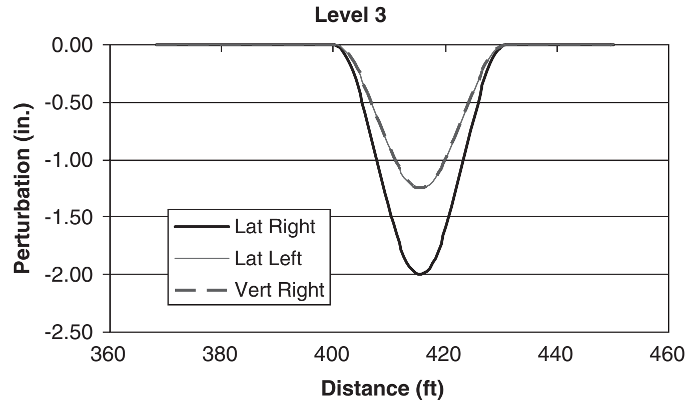


*Figure 21. Track perturbation, Level 3.*

and W/R wear conditions; all of these factors are hard to control.

Table 6 lists the W/R friction coefficients measured on TTCI's track. The measured rail friction coefficient at normal conditions can be higher than 0.55 but are seldom above 0.6.

To ensure a reasonable safety margin, the simulation results with a friction coefficient of 0.6 are used in this study to make judgments about whether guard rail installations are needed. The simulation results with a friction coefficient of 0.55 were also conducted for a less conservative application.

Based on the conclusions and findings in *TCRP Report 71* (*2*), the following criteria were used for making judgments about whether a guard rail is needed:

- For curves with radii less than or equal to 755 ft or for vehicles with independent rotating wheel:
  - The L/V ratio limit equals the Nadal limit. There is no flange climb derailment risk if the L/V ratio is less than the Nadal limit; and
  - The flange climb distance limit equals 3 ft. This criterion is less conservative than the above L/V ratio criterion.

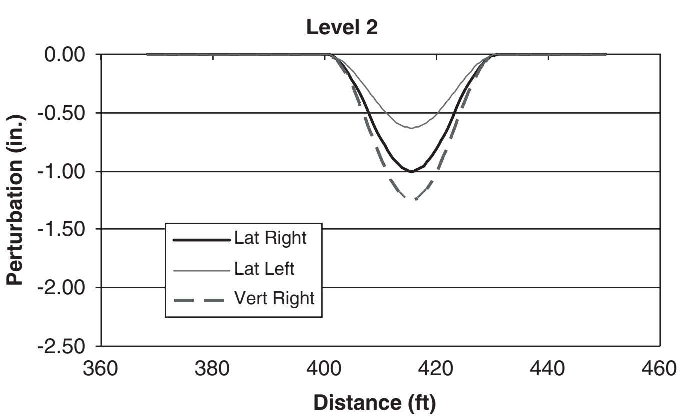


*Figure 20. Track perturbation, Level 2.*

The likelihood of flange climb derailment is rare if the wheel climbs on the rail with distance less than 3 ft.

- For curves with radii greater than 755 ft:
  - The L/V ratio limit equals the Nadal limit; and
  - Flange climb distance limit equals 5 ft.

The reasons for using a longer flange climb distance criteria for curves with radii larger than 755 ft are the following:

- The steady-state axle AOA on curves with radii larger than 755 ft is normally less than 5 milliradians (mrad);
- The L/V ratio limit decreases with the increase of AOA and converges to the Nadal value as the AOA becomes larger than 10 mrad (*2*); and
- The flange climb distance decreases when the AOA increases, and converges to a value (*2*).

Based on these criteria, for the Type 1 transit rail car with a 63° flange angle running on yard track with Level 3 perturbation, the guard rail should be installed on curves with radii less than 3,000 ft to prevent flange climb derailment because the L/V ratios with a 3-ft window (for curves with radii less than or equal to 755 ft) or a 5-ft window exceeded the Nadal value. However, if the track perturbation maintenance improves to the Level 2 standard on yard tracks, only curves with radii less than or equal to 755 ft need to be guarded, as Figure 25 shows.

Maintenance on a main-line track is normally better than maintenance on a yard track. Correspondingly, the allowable running speed on a main-line track is higher than the allowable running speed on a yard track. The Type 1 transit rail car either derailed or the L/V ratio and flange climb distance exceeded the criteria values on all simulated curves at speeds of 4 or 7.5 in. cant deficiency on Level 3 perturbed tracks, which indicates such maintenance levels cannot be tolerated on main-line track for this vehicle. The situation was a little better for Level 2 perturbations where the L/V ratio had less than a limit of 4 in. cant deficiency speed on curves with radii larger

**Table 4. Track perturbation amplitude.**

| Perturbation Level | Left (Low) Rail Lateral Perturbation Amplitude (in.) | Left (Low) Rail Vertical Perturbation Amplitude (in.) | Right (High) Rail Lateral Perturbation Amplitude (in.) | Right (High) Rail Vertical Perturbation Amplitude (in.) |
|---|---|---|---|---|
| 1 | –0.13 | 0 | –0.50 | –0.50 |
| 2 | –0.63 | 0 | –1.00 | –1.25 |
| 3 | –1.25 | 0 | –2.00 | –1.25 |

**Table 5. Overbalance running speed on curves.**

| Curve Radius (ft) | Superelevation (in.) | 4.0 in. Cant Deficiency Speed (mph) | 7.5 in. Cant Deficiency Speed (mph) |
|---|---|---|---|
| 100 | 1.0 | 11.14 | 14.52 |
| 250 | 1.0 | 17.62 | 22.96 |
| 320 | 1.0 | 19.93 | 25.97 |
| 500 | 1.0 | 24.92 | 32.46 |
| 755 | 1.0 | 30.62 | 39.89 |
| 955 | 1.0 | 34.43 | 44.87 |
| 1,145 | 1.0 | 37.70 | 49.13 |
| 2,000 | 1.0 | 49.83 | 64.93 |
| 3,000 | 1.0 | 61.03 | 79.52 |

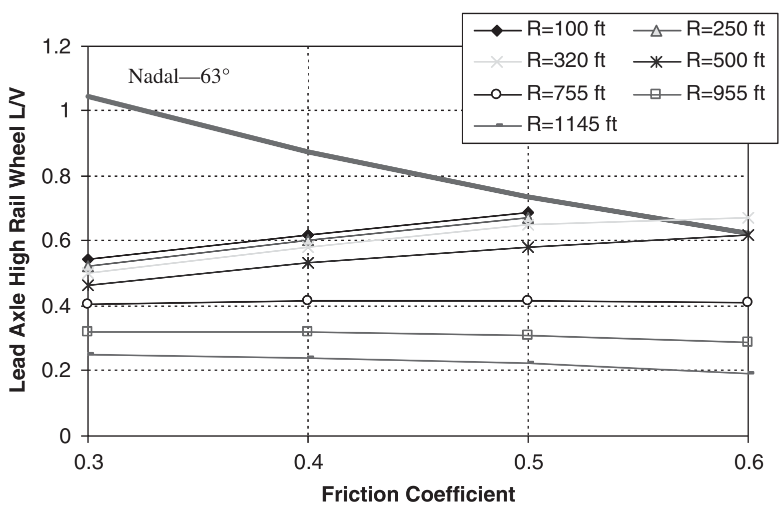


***Figure 22. Wheel L/V ratio of a Type 1 transit rail car with steady-state curving 15 mph, no guard rail.***

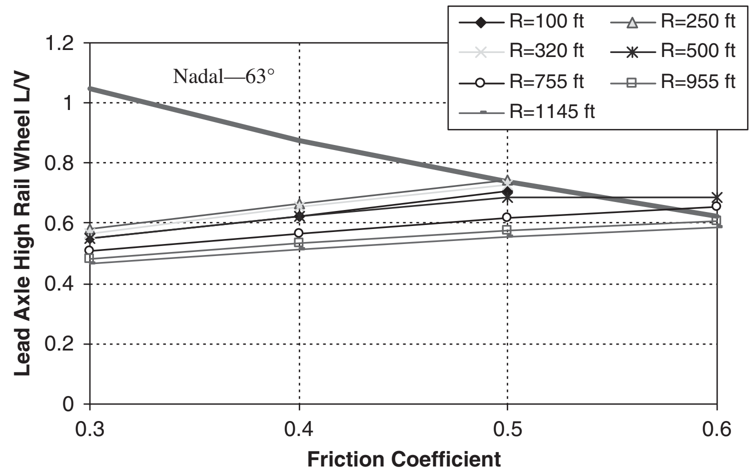


***Figure 23. Wheel L/V ratio, Type 1 transit rail car, Level 2 perturbations 15 mph, no guard rail.***

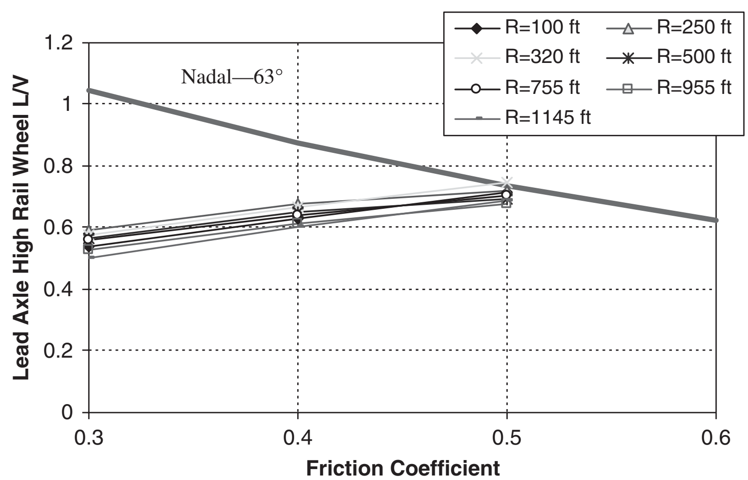


***Figure 24. Wheel L/V ratio, Type 1 transit rail car, Level 3 perturbations 15 mph, no guard rail.***

**Table 6. Measured W/R friction coefficients (tribometer readings) on TTCI track.**

| Track | Location | Inside | Outside | Weather Condition | Date | Time |
|---|---|---|---|---|---|---|
| RTT | R36 Post Marker | 0.43 | 0.52 | Sunny | 2/25/2007 | 10:30 AM |
| | R36 Post Marker | 0.41 | 0.46 | Cloudy | 3/08/2007 | 9:00 AM |
| | R36 Post Marker | 0.40 | 0.44 | Sunny | 3/15/2007 | 9:10 AM |
| | R36 Post Marker | 0.46 | 0.45 | Sunny | 3/16/2007 | 8:40 AM |
| TDT | R165 Post Marker | 0.50 | 0.56 | Sunny | 2/23/2007 | 10:00 AM |
| | R165 Post Marker | 0.32 | 0.37 | Sunny, Soap and Water Spray on Track | 2/23/2007 | 11:00 AM |
| WRM | 7.5° curve | 0.48 | 0.46 | Sunny | 2/19/2007 | 12:20 PM |
| | 12° curve | 0.43 | 0.43 | | | |
| | 10° curve | 0.49 | 0.47 | | | |
| WRM | 10° bypass curve | 0.44 | 0.45 | Sunny | 3/20/2007 | 1:30 PM |
| WRM | 7.5° curve | 0.48 | 0.5 | Cloudy | 3/21/2007 | 10:20 AM |
| | 7.5° curve | 0.43 | 0.44 | | | |
| | 12° curve | 0.46 | 0.5 | | | |

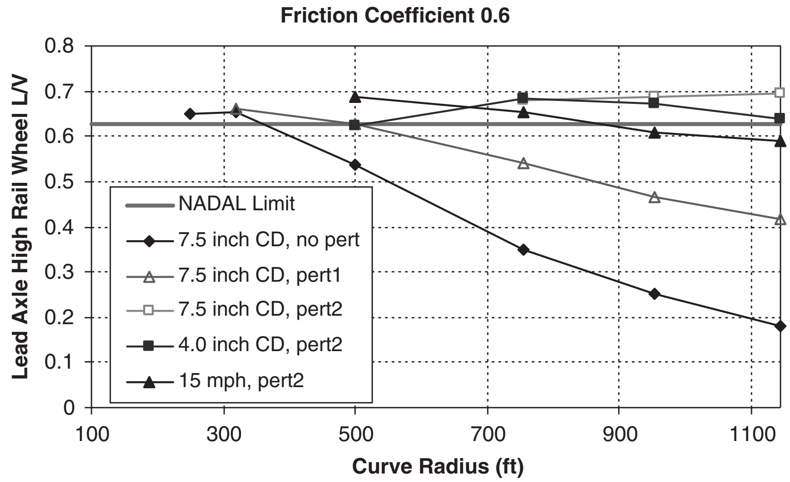


***Figure 25. The wheel L/V ratio of a Type 1 transit rail car with a 0.6 friction coefficient and a 63° flange angle.****

*Refer to Table 5 for the different speeds corresponding to 7.5-in. cant deficiency (CD).

than 2,000 ft. For Level 1 track perturbations, the L/V ratio exceeded the Nadal value on curves with radii less than or equal to 500 ft at 7.5 in. cant deficiency speed, as Figure 25 shows. Under such conditions, no guard rails are needed for curves with radii larger than 500 ft for the Type 1 transit rail car.

Another way to decrease the flange climb derailment risk is to decrease the W/R friction coefficient. As Figure 26 shows, if the friction coefficient is 0.5, for the Type 1 transit rail car, the guard rail should be installed on yard curves with radii less than or equal to 300 ft, and main-line curves with radii less than or equal to 500 ft at a 7.5 in. cant deficiency speed. However, controlling the friction coefficient to less than 0.5 on curves in a consistent and reliable way may be difficult during actual service.

A measured worn rail profile was used in the simulation to investigate the effect of worn rails on flange climb derailment. Figures 27 through 29 show that the L/V ratio for the worn rail case is less than that of the new rail case shown in Figures 22 to 24. These results imply that simulations using new W/R profiles will lead to conservative conclusions. An investigation of worn W/R profiles on freight car flange climb derailment (*5*) also showed a similar phenomena because most wheels and rails wore into a steeper flange contact angle.

Another common practice to decrease flange climb derailment risk in transit systems is to increase the wheel flange angle. As discussed in the previous *TCRP Report 71, Volume 5* (*2*), increasing the flange angle increases the Nadal flange climb limit. Case studies were conducted for the Type 1 transit rail car

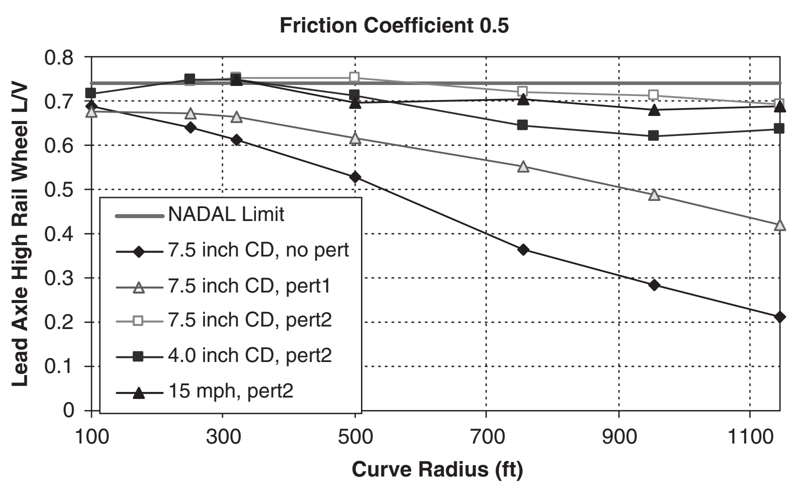


***Figure 26. The wheel L/V ratio of a Type 1 transit rail car with a 0.5 Friction Coefficient and a 63° Flange Angle.****

*Refer to Table 5 for the different speeds corresponding to 7.5-in. cant deficiency (CD).

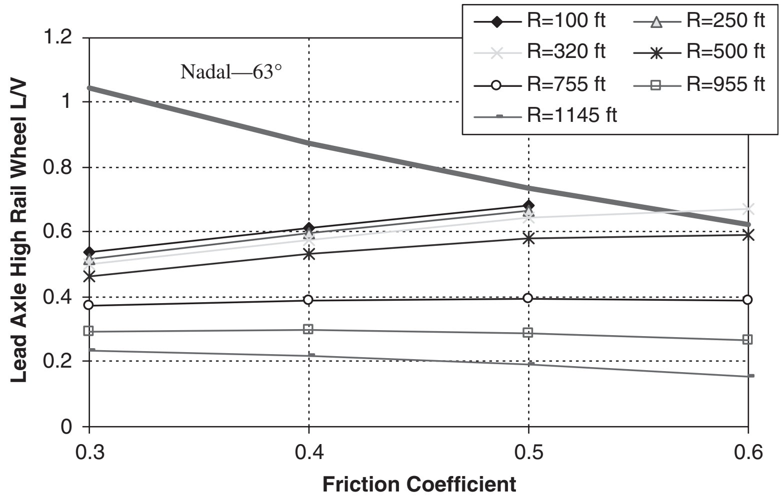


***Figure 27. Wheel L/V ratio, Type 1 transit rail car, steady-state curving, 15 mph, worn rail.***

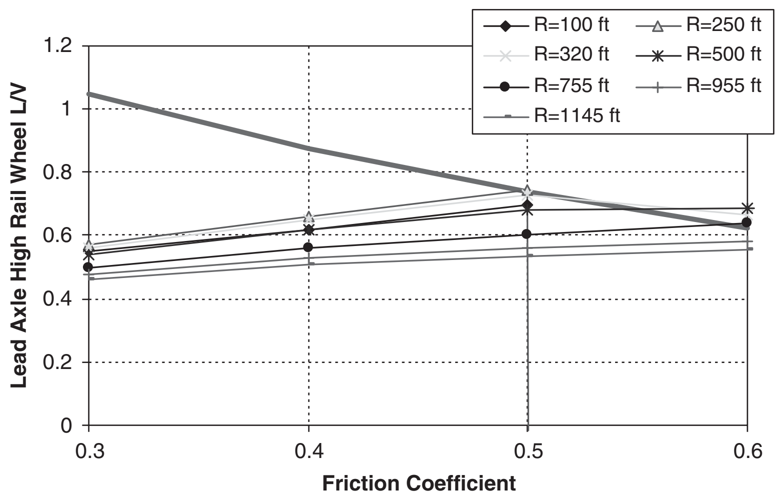


***Figure 28. The wheel L/V ratio, Type 1 transit rail car, perturbation Level 1, 15 mph, worn rail.***

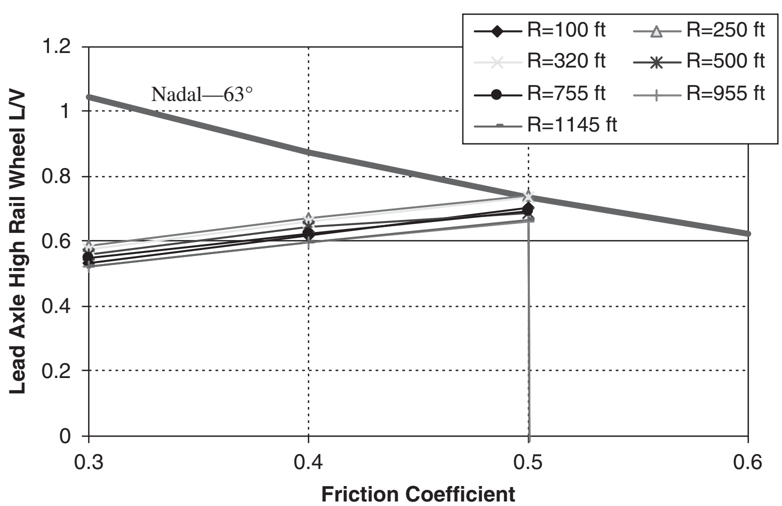


***Figure 29. Wheel L/V ratio, Type 1 transit rail car, perturbation Level 3, 15 mph, worn rail.***

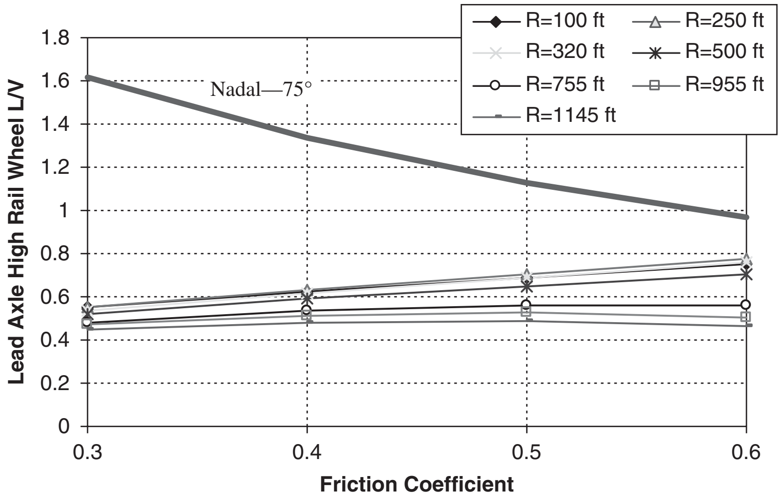


*Figure 30. Wheel L/V ratio, Type 1 transit rail car, 15 mph, 75° flange angle, steady-state curving.*

using the same modeling parameters except for the wheelset dimensions and the 75° angle wheel profiles. Figure 30 shows the significant safety improvements made by using the 75° flange angle wheel compared with the 63° flange wheel (Figure 22), with all simulated steady-state curving L/V ratios far below the Nadal values.

Figures 31 and 32 show that the dynamic curving L/V ratios of the Type 1 transit rail car with 75° flange angle wheels also increase as the perturbation increases. As Figure 30 shows, a steeper flange angle wheel increases the L/V ratio slightly compared with the 63° flange angle wheel. The improvement is because the NADAL value for the 75° flange angle is considerably higher than for the 63° flange angle.

The use of a steep flange angle wheel reduces the flange climb derailment potential. Figure 33 shows that the L/V ratios for all the simulated cases at a speed of 15 mph and with Level 3 perturbations are less than the Nadal value. Therefore, no guard rail is needed on yard curves with radii larger than 100 ft for a vehicle with a 75° flange angle wheel running at a speed of 15 mph. However, the risk of derailment still exists under conditions of higher speeds and a poorly maintained track. As Figure 33 shows, the vehicle with a 75° flange angle wheel still derailed on curves with radii larger than or equal to 1,145 ft at a 7.5 in. cant deficiency speed because of excessive lateral impacts. The track has to be maintained with at least a Level 2 standard to allow a 7.5 in. cant deficiency running speed.

The following conclusions for the Type 1 transit rail car can be drawn from the above analyses:

- The flange climb derailment risk is very high for the Type 1 transit rail car with a 63° flange angle wheel. Guard/restraining rails should be installed on the following:
  - Yard curves with radii less than 755 ft; the speed limit is 15 mph under Level 2 perturbations.

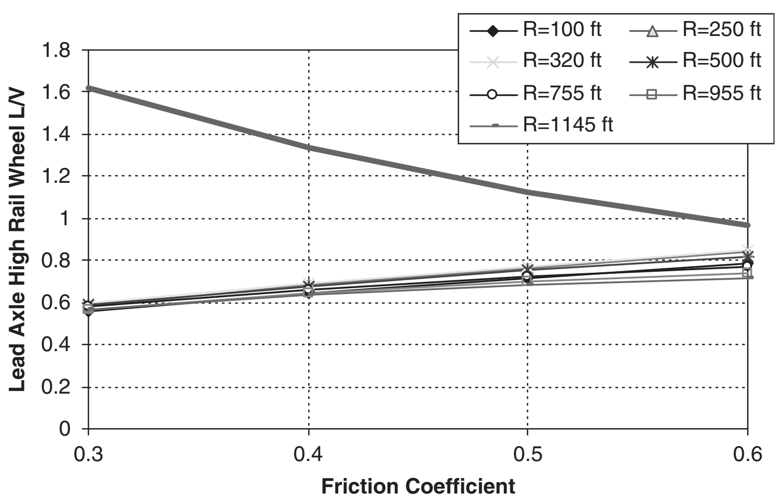


*Figure 31. Wheel L/V ratio, Type 1 transit rail car, 15 mph, 75° flange angle, perturbation Level 2.*

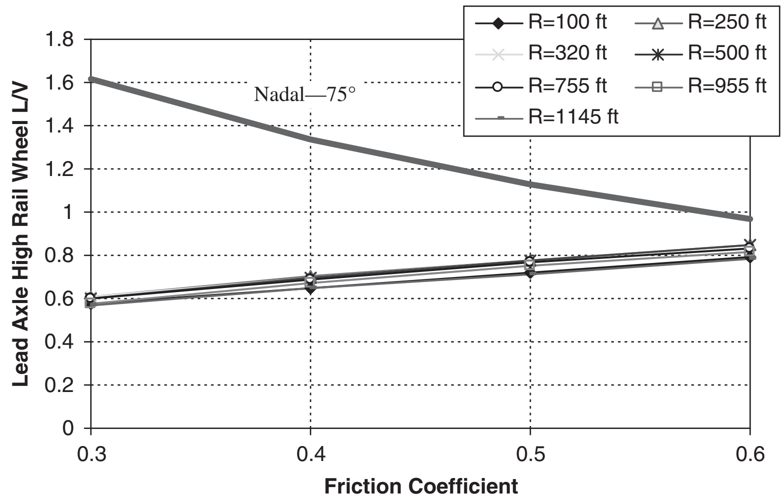


***Figure 32. Wheel L/V ratio, Type 1 transit rail car, 15 mph, 75° flange angle, perturbation Level 3.***

– Main-line curves with radii less than 500 ft; the speed limit is 4 in. cant deficiency under Level 1 perturbations.

- The flange climb derailment risk is significantly reduced by using 75° flange angle wheels. No guard rail is needed in yard, and the main-line speed limit can be 7.5 in. cant deficiency under Level 2 perturbations.
- From a safety point of view, the 75° flange angle wheel is recommended for use in transit vehicles.

## 4.3 Light Rail Vehicles

The light rail vehicle also benefits from the use of a steep flange angle (75°) wheel. As Figures 34 and 35 show, all simulated steady-state curving L/V ratios for the Type 1 light rail vehicle running on yard curves are far below Nadal values; the dynamic L/V ratios under Level 3 perturbations approach or exceed the Nadal value only with a friction coefficient of 0.6.

Figure 36 shows the following for the Type 1 light rail vehicle with a 75° flange angle wheel:

- The dynamic curving L/V ratios for the vehicle running at a speed of 15 mph under Level 3 track perturbations exceeded the Nadal value on curves with radii less than or equal to 755 ft.
- The dynamic curving L/V ratios for the vehicle running at a 7.5 in. cant deficiency speed under Level 1 track perturbations were below the Nadal value on all simulated curves.
- The dynamic curving L/V ratios for the vehicle running at a 4.0 in. cant deficiency speed under Level 2 track perturbations exceeded the Nadal value on curves with radii less than or equal to 500 ft.

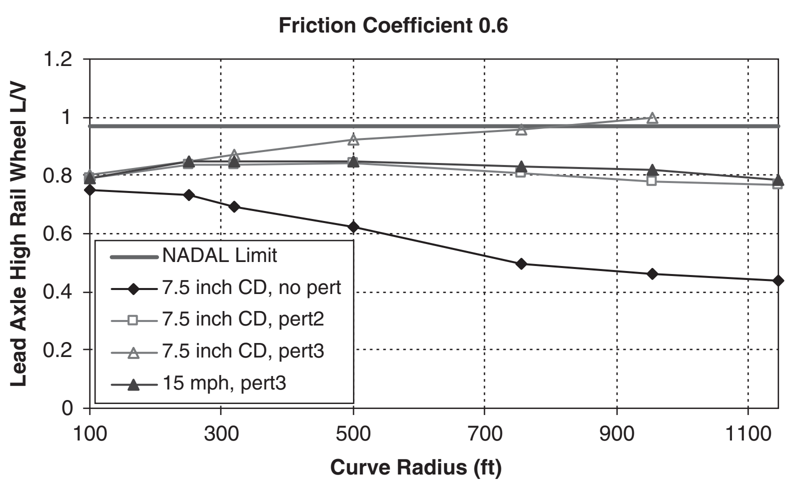


***Figure 33. Wheel L/V ratio, Type 1 transit rail car, 75° flange angle, friction coefficient 0.6.****

*Refer to Table 5 for the different speeds corresponding to 7.5-in. cant deficiency.

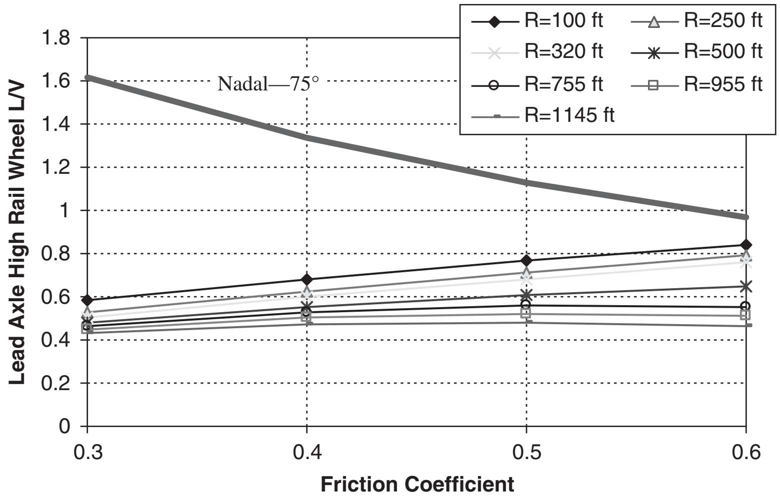


*Figure 34. Wheel L/V ratio, Type 1 light rail vehicle, steady-state curving, 15 mph.*

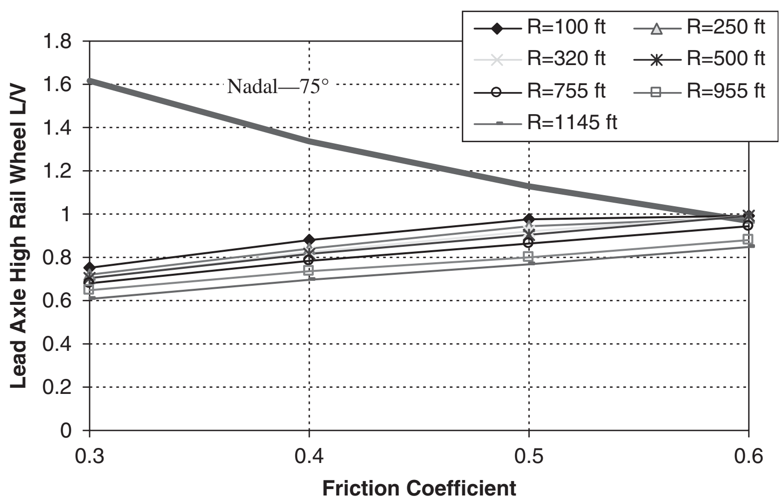


*Figure 35. Wheel L/V ratio, Type 1 light rail vehicle, Level 3 perturbations, 15 mph.*

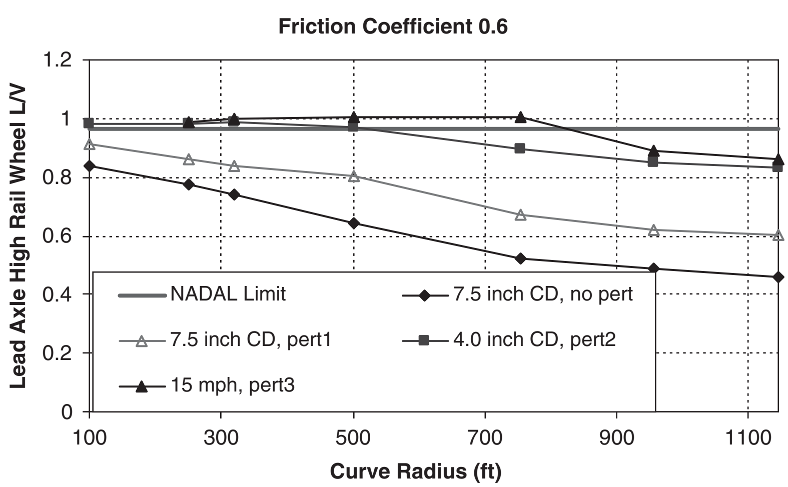


*Figure 36. Wheel L/V ratio, Type 1 light rail vehicle, friction coefficient 0.6.*

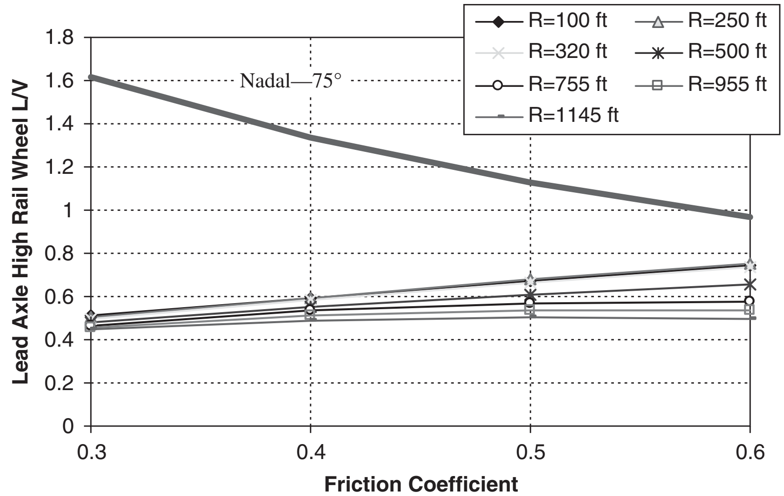


***Figure 37. Wheel L/V ratio, Type 2 light rail vehicle, steady-state curving, 15 mph.***

Correspondingly, for the Type 1 light rail vehicle with a 75° flange angle wheel, the following was determined:

- No guard/restraining rail is needed for the vehicle running at a speed of 7.5 in. cant deficiency on curves with radii larger than or equal to 100 ft if the track is maintained at a Level 1 perturbation standard.
- Guard/restraining rails should be installed on the following:
  - Yard curves with radii less than 755 ft; the speed limit is 15 mph under Level 3 perturbations, and
  - Main-line curves with radii less than 500 ft; the speed limit is 4.0 in. cant deficiency under Level 2 perturbations.

*TCRP Report 71, Volume 5* (*2*) showed that the IRW is prone to flange climb derailment due to the lack of longitudinal creep forces. The simulation of the Type 2 low-floor light rail vehicle with an IRW in the middle truck was conducted to address the safety concerns for this type of vehicle. Figures 37 and 38 show that both steady-state and dynamic curving L/V ratios for all simulated cases are less than the Nadal values. Therefore, the low-speed curving performance on yard curves by the Type 2 light rail vehicle with a 75° flange angle IRW is even better than the performance by the Type 1 light rail vehicle that used solid axles for all trucks. Because the wheelset geometry and wheel profiles used by both types of light rail vehicles are exactly the same, the performance difference must be caused by the different dynamic behavior between the solid axles and the IRWs, different vehicle structures, and the suspension characteristics.

These two types of light rail vehicles behave differently, not only on low-speed curving, but also on high-speed curving. Figure 39 shows that the IRW L/V ratios generally increase with the running speed and result in flange climb derailment on

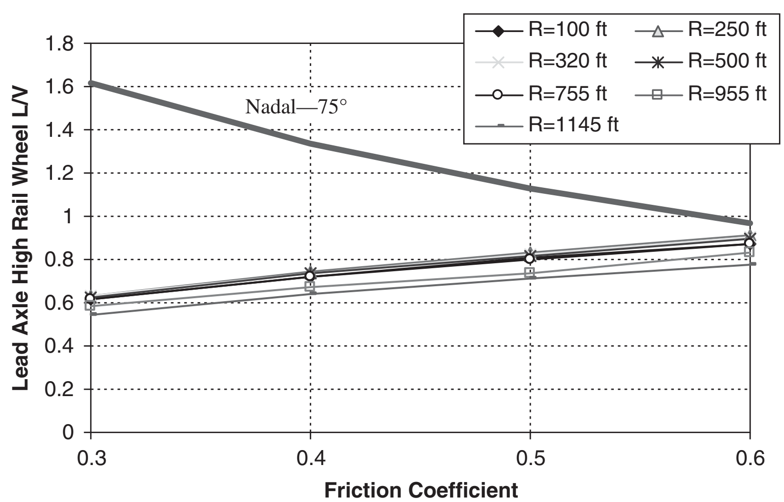


***Figure 38. Wheel L/V ratio, Type 2 light rail vehicle, Level 3 perturbations, 15 mph.***

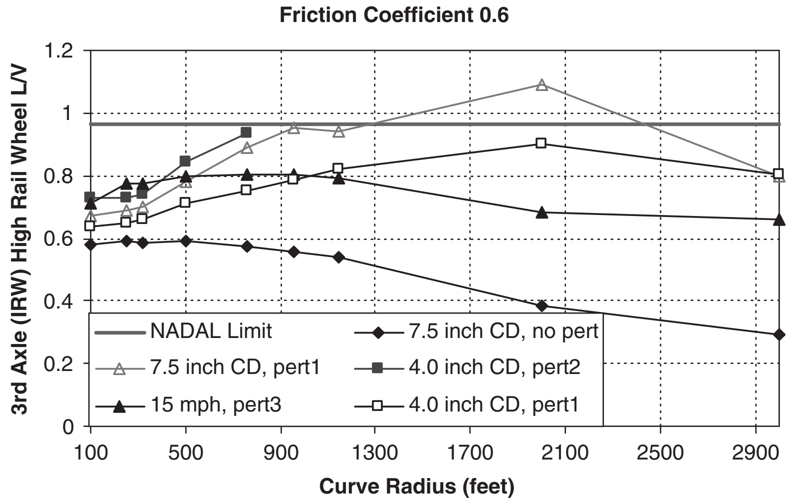


*Figure 39. Wheel L/V ratio, Type 2 light rail vehicle, friction coefficient 0.6.*

curves with radii greater than or equal to 955 ft at a 4.0 in. cant deficiency speed under Level 2 perturbations. The derailment was caused by resonance responses of the Type 2 vehicle at higher speeds. The Type 2 light rail vehicle with a 75° flange angle wheel can run safely at a 4.0 in. cant deficiency speed on curves with radii larger than 100 ft and Level 1 perturbations.

## 4.4 Summary of Flange Climb Derailment Simulations

Dynamic curving simulations of the four types of transit rail cars and light rail vehicles with three different flange angle wheels (IRW for Type 2 light rail vehicles only) at 15 mph on yard track were conducted using the NUCARS program. Table 7 lists the radii of the curves where either the dynamic curving L/V ratio exceeded the Nadal value or the vehicle derailed with a 0.6 W/R friction coefficient. Curves with radii less than those shown in the following tables are recommended for guard rail installation. Table 8 lists the simulation results with a 0.55 friction coefficient for the less conservative guard rail installation application.

Tables 9 and 10 list the dynamic curving simulation results on main-line curves with a 0.6 W/R friction coefficient and at speeds of 4.0 and 7.5 in. cant deficiency, respectively.

The following conclusions can be drawn from the flange climb derailment simulations of Type 1 and 2 transit rail cars and light rail vehicles with various flange angle wheels:

- There are many factors leading to flange climb derailment, but three of them have the most critical effects: wheel flange

**Table 7. Flange climb derailment on yard curves with a W/R friction coefficient of 0.6 at 15 mph.**

| Perturbation Level | Transit Rail Car Type 1 | | | Transit Rail Car Type 2 | | | Light Rail VehicleType 1 | | | Light Rail Vehicle Type 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 63 | 70 | 75 | 63 | 70 | 75 | 63 | 70 | 75 | 63 | 70 | 75 |
| 1 | R<=500* | LTN** | LTN | R<=955 | LTN | LTN | R<=500 | R<=320 | LTN | R<=1,145 | LTN | LTN |
| 2 | R<=755 | R<=320 | LTN | R<=2,000 | R<=320 | LTN | R<=1,145 | R<=955 | R<=500 | R<=3,000 | R<=500 | LTN |
| 3 | R<=3,000 | R<=320 | LTN | R<=3,000 | R<=320 | LTN | R<=3,000 | R<=1,145 | R<=755 | R<=3,000 | R<=3,000 | LTN |

Note: *R<=320 indicates that the 3-ft window L/V ratios on curves with radii lower or equal to 320 ft exceeded Nadal values or the vehicle derailed.
**LTN indicates that the L/V ratios of all simulated cases with curve radii from 100 to 3000 ft are less than Nadal values, and derailment is not expected.

**Table 8. Flange climb derailment on yard curves with a W/R friction coefficient if 0.55 at 15 mph.**

| Perturbation Level | Transit Rail Car Type 1 | | | Transit Rail Car Type 2 | | | Light Rail Vehicle Type 1 | | | Light Rail Vehicle Type 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 63 | 70 | 75 | 63 | 70 | 75 | 63 | 70 | 75 | 63 | 70 | 75 |
| 1 | R<=320 | LTN | LTN | R<=500 | LTN | LTN | R<=320 | LTN | LTN | R<=320 | LTN | LTN |
| 2 | R<=500 | LTN | LTN | R<=1,145 | LTN | LTN | R<=955 | R<=500 | LTN | R<=3,000 | LTN | LTN |
| 3 | R<=1,145 | LTN | LTN | R<=1,145 | LTN | LTN | R<=2,000 | R<=755 | LTN | R<=3,000 | LTN | LTN |

**Table 9. Flange climb derailment on main-line curves with a W/R friction coefficient of 0.6 at 4-in. cant deficiency.**

| Perturbation Level | Transit Rail Car Type 1 | | | Transit Rail Car Type 2 | | | Light Rail Vehicle Type 1 | | Light Rail Vehicle Type 2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 63 | 70 | 75 | 63 | 70 | 75 | 70 | 75 | 70 | 75 |
| 1 | R<=500 | LTN | LTN | R<=755 | LTN | LTN | R>=1,145, <=2,000* | LTN | R>=1,145, <=2,000 | LTN |
| 2 | R<=2,000 | R<=320, 3,000 | LTN | R<=3,000 | R<=250 | LTN | R<=3,000 | R<=500 | R<=3,000 | R>=955 |
| 3 | R<=3,000 | R<=3,000 | LTN | R<=3,000 | R<=755, >=2,000 | R>=2,000 | R<=3,000 | R<=3,000 | R<=3,000 | R>=500 |

Note: *R>=1,145,<=2,000 indicates that the 5-ft window L/V ratios on curves with radii greater than or equal to 1145 ft, but less than or equal to 2,000 ft exceeded Nadal values or the vehicle derailed.

**Table 10. Flange climb derailment in main-line curves with a W/R friction coefficient of 0.6 at 7.5-in. cant deficiency.**

| Perturbation Level | Transit Rail Car Type 1 | | | Transit Rail Car Type 2 | | | Light Rail Vehicle Type 1 | | Light Rail Vehicle Type 2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 63 | 70 | 75 | 63 | 70 | 75 | 70 | 75 | 70 | 75 |
| 1 | R<=500 | LTN | LTN | R<=500 | LTN | LTN | R<=320 | LTN | R>=755, <=2,000 | R=2,000 |
| 2 | R<=3,000 | R<=320, >=2,000 | LTN | R<=3,000 | LTN | LTN | R<=755, >=2,000 | R<=500, =3,000 | R<=3,000 | R<=3,000 |
| 3 | R<=3,000 | R<=3,000 | R>=955 | R<=3,000 | R>=755 | R>=1,145 | R<=3,000 | R<=3,000 | R<=3,000 | R<=3,000 |

angle, W/R friction coefficient, and track perturbation amplitude.

- Flange climb derailment risk decreases as the wheel flange angle increases: the larger the wheel flange angle, the smaller the guarded curve radius.
- Flange climb derailment risk decreases as the W/R friction coefficient decreases: the lower the friction coefficient, the smaller the guarded curve radius. No guard rail is needed for all simulated vehicles if the friction coefficient can be controlled under 0.4.
- Flange climb derailment risk increases as track perturbation increases; the smaller the track perturbation amplitude, the smaller the guarded curve radius.
- TTCI recommends to adopt 75° flange angle wheels for both transit rail cars (Type 1 and 2) and light rail vehicles (Type 1 and 2) to prevent flange climb derailment.
- From a safety point of view, the guard rail installation guidelines for the simulated two types of transit rail cars and two types of light rail vehicles (defined in Table 2 in the report) with recommended 75° flange angle wheels are listed below:
  - For yard curves (15 mph speed limit) with the most severe (Level 3, shown in Figure 21 in the report) track perturbations, these are the following guard rail installation guidelines:
    - No guard rails are needed for Type 1 and Type 2 transit rail cars or Type 2 light rail vehicles.
    - Guard rails should be installed on curves with radii less than or equal to 755 ft for the Type 1 light rail vehicle.
  - For main-line curves, these are the following guard rail installation guidelines:
    - No guard rails are needed for Type 1 and 2 transit rail cars running at a 7.5 in. cant deficiency speed with Level 2 (Figure 20) track perturbations.
    - No guard rails are needed for Type 1 light rail vehicles running at a 7.5 in. cant deficiency speed with Level 1 (Figure 19) track perturbations.
    - No guard rails are needed for Type 2 light rail vehicles running at a 4.0 in. cant deficiency speed with Level 1 track perturbations.
    - Guard rails should be installed on curves with radii less than or equal to 500 ft for Type 1 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.
    - Guard rails should be installed on curves with radii greater than or equal to 955 ft for Type 2 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.
- Vehicle curving performance is different from case-to-case due to many factors from vehicle and track aspects. The above guidelines and details in Tables 7 through 10 of the report could be used as a reference and applied by taking into account the specific vehicle/track features and running environment.

CHAPTER 5

# Conclusions

This report compared two guard rail installation philosophies and the effects of vehicle types, wheel flange angle, W/R friction coefficient, curve radius, cant deficiency, and track perturbation on flange climb derailments through NUCARS simulations. As a result, a number of conclusions and recommended guidelines were drawn for guard/restraining rail installation in terms of vehicle type and track geometry, including the following:

- Philosophy I (shared contact between the high-rail flange and the guard rail on the low-rail wheel) leads to better vehicle dynamic performance than Philosophy II (no high-rail flange contact and with the guard rail contact on the low-rail wheel) in terms of lower lateral forces on rails, lower vehicle rolling resistance, and lower leading axle wear.
- Both philosophies lead to higher vehicle rolling resistance and leading axle wheel wear compared with the case with no guard rail.
- The axle steering capability difference between these two philosophies is negligible.
- The Nadal limit and flange climb distance limit are the criteria for flange climb derailment; they are adopted as the guard rail installation criteria in this report.
- There are many factors leading to flange climb derailment. Three factors that have the most critical effects are the wheel flange angle, the W/R friction coefficient, and the track perturbation amplitude.
- Flange climb derailment risk decreases as wheel flange angle increases: the larger the wheel flange angle, the smaller the guarded curve radius.
- The flange climb derailment risk decreases as the W/R friction coefficient decreases; the lower the friction coefficient is, the smaller the guarded curve radius will be. No guard rail is needed for all simulated vehicles if the friction coefficient can be controlled under 0.4.
- Flange climb derailment risk increases as track perturbation increases; the smaller the track perturbation amplitude is, the smaller the guarded curve radius will be.
- TTCI recommends the adoption of 75° flange angle wheels for both transit rail cars (Type 1 and 2) and light rail vehicles (Type 1 and 2) to prevent flange climb derailment.
- From a safety point of view, the guard rail installation guidelines for the simulated Type 1 and Type 2 transit rail cars and the Type 1 and Type 2 light rail vehicles (defined in Table 2 in the report) with recommended 75° flange angle wheels are listed below:
  - For yard curves (15 mph speed limit) with the most severe (Level 3, shown in Figure 21) track perturbations, the following guard rail installation guidelines are recommended:
    - No guard rails are needed for Type 1 and Type 2 transit rail cars or Type 2 light rail vehicles.
    - Guard rails should be installed on curves with radii less than or equal to 755 ft for the Type 1 light rail vehicle.
  - For main-line curves, the following guard rail installation guidelines are recommended:
    - No guard rails are needed for Type 1 and 2 transit rail cars running at a 7.5 in. cant deficiency speed with Level 2 (Figure 20) track perturbations.
    - No guard rails are needed for Type 1 light rail vehicles running at a 7.5 in. cant deficiency speed with Level 1 (Figure 19) track perturbations.
    - No guard rails are needed for Type 2 light rail vehicles running at a 4.0 in. cant deficiency speed with Level 1 track perturbations.
    - Guard rails should be installed on curves with radii less than or equal to 500 ft for Type 1 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.

    - Guard rails should be installed on curves with radii greater than or equal to 955 ft for Type 2 light rail vehicles running at a 4 in. cant deficiency speed with Level 2 track perturbations.
- Vehicle curving performance is different from case-to-case due to many factors from vehicle and track aspects. The above guidelines and details in Tables 7 through 10 of the report could be used as a reference and applied by taking into account the specific vehicle/track features and running environment.
- These guard rail installation guidelines do not apply to special trackwork, such as the guard rail for switches, crossings, and turnouts.

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4. Elkins, J., J. Peters, G. Arnold, and B. Rajkumar. "Steady-state Curving and Wheel/Rail Wear Properties of a Transit Vehicle on the Tight Turn Loop." UMTA-CO-06-0009-83-1, Washington, D.C., Dec. 1982.
5. Shu, X. and J. Tunna. "Investigation into Flange Climbing Derailment and Distance Criterion with Wheel and Worn Rail Profiles." Research Report R-982, Association of American Railroads, Transportation Technology Center, Inc., Feb. 2007.

*Abbreviations and acronyms used without definitions in TRB publications:*

| | |
|---|---|
| AAAE | American Association of Airport Executives |
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACI–NA | Airports Council International–North America |
| 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 | Air Transport Association |
| 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 |
| HMCRP | Hazardous Materials Cooperative Research Program |
| 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 |
| NASAO | National Association of State Aviation Officials |
| NCFRP | National Cooperative Freight Research Program |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| RITA | Research and Innovative Technology Administration |
| 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 |