CONVENTIONAL PASSENGER RAIL VEHICLE SAFETY

Volume I: Summary of Safe Performance Limits

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F. Blader

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Final Report

September 1998

03 - Rail Vehicles &
Components

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1998

3. REPORT TYPE AND DATES COVERED
Final Report, July 1995 - January 1997

4. TITLE AND SUBTITLE
Conventional Passenger Rail Vehicle Safety,
Volume I: Summary of Safe Performance Limits

5. FUNDING NUMBERS

6. AUTHOR(S)
G. Samavedam, J. Gomes, P. Warren and F. Blader**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Foster-Miller, Inc.
350 Second Avenue
Waltham, MA 02451-1196

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation*
Federal Railroad Administration
Office of Research and Development
Washington, DC 20593

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-

11. SUPPLEMENTARY NOTES
*COTR: Dr. Thomas N. Tsai
**Consultant

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE
N/A

13. ABSTRACT *(Maximum 200 words)*

This report presents a methodology based on computer simulation that assesses the safe dynamic performance limits of commuter passenger vehicles. The methodology consists of determining the critical design parameters and characteristic properties of both the vehicle and the track, establishing the failure modes, and then using a computer model to determine under what conditions the failure occurs. The computer tool predicts the dynamics of the vehicles at varying speeds and safety limits and margins are established based on when the predicted behavior approaches a derailment.

This report also presents numerical examples of this methodology that were produced using the software tool OMNISIM to predict the response of single and bi-level vehicles as they negotiate both tangent tracks and tracks with curves up to 20 deg. Imperfections such as cusps, misalignments, and switch points are simulated to determine conditions of unsafe vehicle behavior. Safe performance limits for the cars with assumed parameters are developed and presented in terms of maximum imperfection amplitudes and vehicle speeds.

14. SUBJECT TERMS
Passenger rail vehicles, equalized and non-equalized trucks, OMNISIM, safety limits

15. NUMBER OF PAGES
48

16. PRICE CODE
N/A

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	1.1 yards (yd)
		1 kilometer (k)	0.6 mile (mi)
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1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	1 hectare (he) = 2.5 acres
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[(x-32)(5/9)] °F	= y °C	[(9/5) y + 32] °C	x °F

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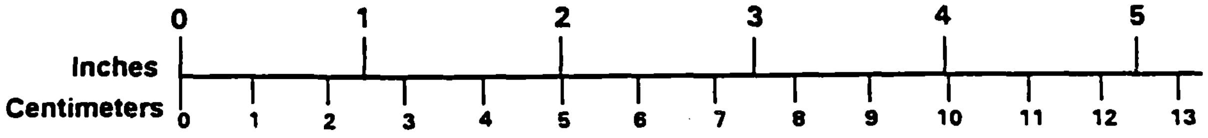
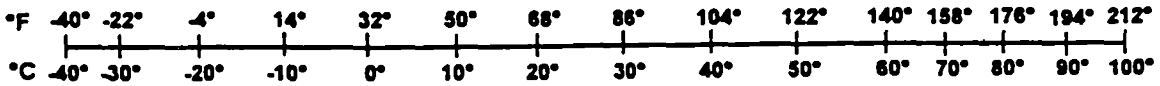


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 1/23/95

PREFACE

This report presents a summary of a research study to assess the safe dynamic performance limits of commuter passenger vehicles with typical truck and body constructions operated on a variety of track configurations. A companion report (Volume II) presents detailed analytic tools and results on dynamic response of the vehicles as they negotiate tracks with varying curvatures and with vertical and lateral misalignments. This work was performed under the contract DTFR-53-95-C-00049 from the Federal Railroad Administration (FRA) to Foster-Miller, Inc.

The authors wish to express their thanks to Dr. Thomas Tsai of FRA, under whose technical supervision this work was performed. Thanks are also due to Mr. David Tyrell and Dr. Herbert Weinstock of the Volpe Center for their inputs and comments during this work. The technical guidance from Dr. David Wormley is also gratefully acknowledged.

CONTENTS

Section **Page**

ILLUSTRATIONS

TABLES

LIST OF SYMBOLS

A	Amplitude of the gage narrowing
B	Length of slope in gage narrowing
G	Initial gage
L/V	Ratio of lateral to vertical forces
λ	Wavelength
δ_V	Vertical cusp amplitude
δ_L	Lateral cusp amplitude

EXECUTIVE SUMMARY

This work has been performed by Foster-Miller in support of the safety standards being developed by the Federal Railroad Administration for conventional commuter and intercity rail passenger vehicles operating at speeds of 110 mph or less with the ultimate objective of developing a methodology for safety assessments of rail vehicles. Research has been conducted to identify and resolve technical issues related to the safety assessment of commuter cars. The research program examines existing car designs, required analysis tasks, required car and track parameters, safety criteria, critical operational scenarios and the development of safe performance limits. The analytical results of the research program which are presented in this report will be validated by future experimental work.

As a starting point for this work, candidate vehicle body and truck constructions are identified including single and bi-level cars with equalized and non-equalized trucks. The dynamic response of these vehicles as they are operated at different speeds on tracks with different curvatures is evaluated through a computer simulation tool known as OMNISIM.

Specific safety related operational scenarios simulated include: high speed truck hunting, steady curving, dynamic curving on tracks with a single cusp, dynamic curving on tracks with multiple "down and out" cusps with imperfections in the vertical and lateral plane, negotiation of gage narrowing lateral imperfections and negotiation of switch points with imperfections in the vertical plane. The track curvature is varied through the range of 2-1/2 to 20 deg in some of the studies.

Using appropriate safety criteria, conditions which result in vehicle derailment due to wheel climb or wheel lift in each of the foregoing operational scenarios are identified for each of the vehicle types: single/bi-level with equalized/non-equalized trucks. These conditions are used with conservative margins to establish safe performance limits.

For truck hunting, the limits are expressed in terms of critical speeds.

For steady curving, lateral to vertical force ratios (L/V) are used as indicators of vehicle safety performance.

Simulations have been conducted which identify limiting performance of cars with both equalized and nonequalized trucks transversing single and

multiple cusps. These simulations determine the effects of truck equalization in accommodating different types and combinations of cusps. For example, a bilevel car with typical equalized trucks operating at balance speed is shown to accommodate a cusp amplitude 1.5 times greater than the typical nonequalized trucks that were modeled.

When gage narrowing occurs on a tangent track, the safe speed is limited by the type of vehicle and truck negotiating the imperfection. For a given truck type, the safe speed is dependent on the rate at which the gage reduces. Safe maximum speeds are expressed as functions of gage reduction ratios for each truck configuration. Safe speeds for example cars with equalized and non-equalized trucks are also determined when the cars negotiate an AREA No. 8 switch.

The report presents conclusions of practical interest and test recommendations for model validations and verification of the safe performance limits generated here. A methodology for rapid assessment of commuter car safety, which requires demonstration and experimental validation, is also presented.

1. INTRODUCTION

The 1994 amendment of the Federal Railroad Safety Authorization Act requires that the Federal Railroad Administration (FRA) establish regulations for minimum safety standards of conventional railroad passenger vehicles including commuter or intercity passenger cars operating at speeds of 110 mph or less.

Passenger rail vehicles have to operate on a variety of track geometries: tangent, curved and spirals connecting tangents to constant radius curves. The maximum levels of vertical and lateral misalignment and the maximum amount of crosslevel variation that can be safely negotiated are both important in safety evaluations. The overall objective of the work reported herein is the development of a comprehensive method for evaluating the safety-related performance of commuter passenger rail vehicles and its application for generating a preliminary set of safe dynamic performance limits in vehicle operations over a variety of track conditions. Derailments occur for a variety of reasons, including track failures, equipment failures, and improper train operation. However, the primary focus of this research is on how different body and truck configurations influence the vehicle dynamic response and may cause derailment through wheel climb or wheel lift. A number of scenarios need to be identified for investigation, including truck hunting, steady-state curving, dynamic curving, and transient response to vertical and lateral perturbations in the track alignment.

An indication of the limiting track conditions and the associated issues for safe vehicle operation can be determined through the detailed simulations and evaluations of the vehicle dynamic response. These evaluations of vehicle dynamic response require mathematical models and computer software. Hence, the development of modeling and computational "tools" for use in the assessment of vehicle and track safety limits is a major program effort undertaken here.

This report presents a summary of the research findings on commuter car safety, detailed analyses of which are presented in a companion volume (1). The report is organized as follows. Section 2 presents the overall safety evaluation methodology developed by this work. Generic single and bi-level passenger cars with equalized and non-equalized trucks are identified as candidates for this study. The body and truck design features are broadly representative of selected commuter passenger rail vehicles currently operating in the United States. Section 2 also presents the analytical tools and the safety criteria used in the study.

Section 3 presents a parametric study and a summary of preliminary safe performance limits for typical examples of single and bi-level cars with equalized and non-equalized trucks. Critical speeds for truck hunting on the tangent track are presented. The vehicle performance limits for dynamic curving on tracks with single cusp and multiple "down and out" cusps with crosslevel variations and misalignments are presented. Safe gage narrowing limits are presented for both equalized and non-equalized trucks. Safe cusp amplitudes at AREA No. 8 switch and safe speeds are also presented.

Section 4 presents a safety assessment methodology for new vehicles using the tools and techniques described in Sections 2 and 3. This methodology would utilize validated computer tools to determine the safe performance limits of new car designs over the track conditions and operational scenarios anticipated in revenue service.

Section 5 presents conclusions of practical interest derived from the study. This section also presents recommendations for additional studies including those for test validations.

2. TECHNICAL APPROACH TO SAFETY ASSESSMENT METHODOLOGY

The overall approach adopted for the evaluation of commuter car safety involves the following tasks, and is schematically shown in Figure 2-1.

1. Identify generic types of commuter cars in revenue service with sufficient variations in their design for use as candidates in the simulation studies and testing.

2. Assemble car and truck parameters which will be used in the analysis. Supplement the experimental parameter characterization with the manufacturer's data.

3. Identify the critical track parameters that significantly affect the performance of the vehicle. The parameters act as the input conditions to the vehicle dynamic system.

4 Measure the values of the critical track parameters that are expected in service and in any acceptance/qualification testing that may take place.

5. Define conditions and criteria for safe operations.

   - High speed operations on tangent track to assure stability against possible truck hunting.
   - Steady-state curve negotiation.
   - Dynamic curving under single cusp crosslevel variations.
   - Dynamic curving under multiple "down and out" cusp crosslevel and misalignment variations.
   - Negotiation of gage narrowing variations.
   - Negotiations through switches.

6. Select investigation tools which are capable of providing the analysis required to determine the car's performance under the conditions and failure modes identified.

7. Using the assembled vehicle and track data, analyze the vehicle's dynamic response under the critical scenarios.

8. Develop performance limits for safe vehicle operations on the basis of analysis and safety criteria in the form of limiting speeds, crosslevels,

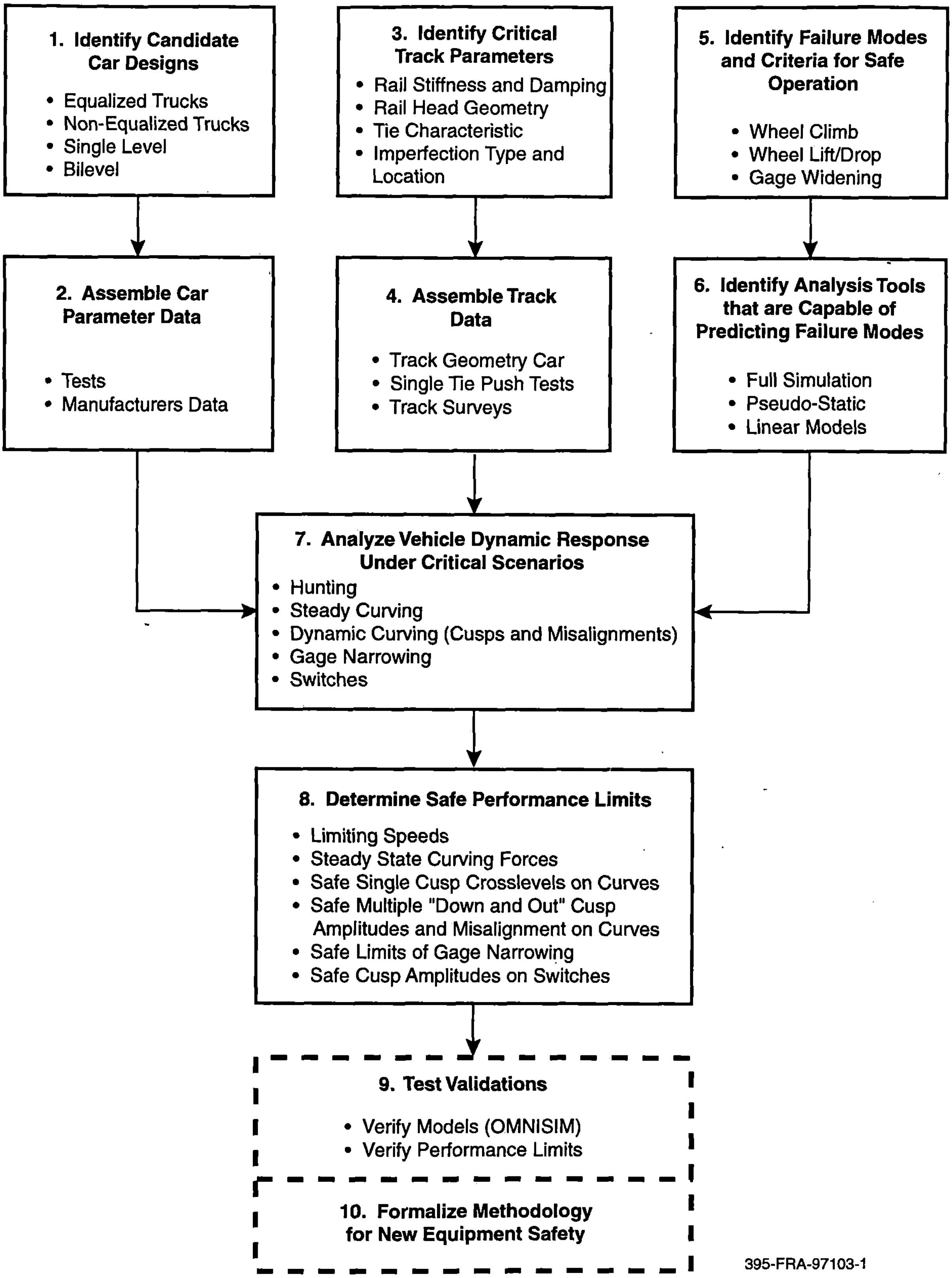


Figure 2-1. Overall methodology

misalignments, and lateral to vertical force ratios generated in the vehicle operations.

9. Perform validation tests.
   - Validate the simulation model by measuring vehicle parameters and dynamic response under the scenarios listed in item 5.
   - Verify safe performance limits generated through selective tests on candidate car designs.
10. On the basis of the foregoing tasks, develop and formalize a practical safety assessment methodology for new car equipment.

This report covers the work performed on task items 1 through 8. Validation tests to show the effectiveness of this methodology are currently being planned. This report presents a preliminary safety assessment methodology for new equipment which requires further development and validation.

2.1 Identify Candidate Commuter Car Equipment

The data required for predicting the safety related dynamic performance of single and bi-level cars in a consist under various loadings has been collected from a review of vehicles in general use (3). Key parameters for the body, trucks, wheels, couplers, and other critical components are obtained as either design, experimental, or estimated values. Measured parameters are sought to the extent that they are readily available. Otherwise, characteristics are estimated or taken from existing knowledge of similar cars and components. Body and suspension features and parameters for transit vehicles are selected to reflect the variety of commuter passenger rail vehicles that are in current U.S. operation. A review of this information led to the following observations:

Single Level Cars

The GSI "General 70," which is an equalized truck design, accounts for 67 percent of all trucks in service; 87 percent of these trucks have been placed into service since 1970.

Bi-Level Cars

The GSI "Traditional," which is also an equalized truck design, represents 46 percent of trucks in service. However, the majority of these were placed into service prior to 1970. For those trucks placed into service after 1970, the 051 "General 70" (equalized) and the Dofasco/Atchison (non-equalized) designs constitute the majority of the population.

Differences in body design are generally found to be of lesser importance within each class of car (that is, single-level and bi-level). Two "generic" cars are selected as basic and variations such as single-level and bi-level vehicle bodies and different loading conditions are considered. This allows key design features and parameter variations to be systematically modeled and studied. The study evaluates both equalized and non-equalized truck designs. The following significant design features are assumed for the truck designs:

- Rigid truck frame.
- With and without equalizer beam primary suspension.
- Axle bearings located outboard of the wheels.
- Yaw pivot located beneath the secondary suspension.

Views of trucks incorporating these design features are presented for the equalized truck in Figure 2-2 and for the non-equalized truck in Figure 2-3.

2.2 Assemble Car Parameter Data

Several car body and truck parameters are required as inputs in the analytic model. Current methods of evaluating these tools are rather elaborate and can be used only at special test sites such as the Transportation Technology Center in Pueblo, CO. Simpler and more rapid methods are

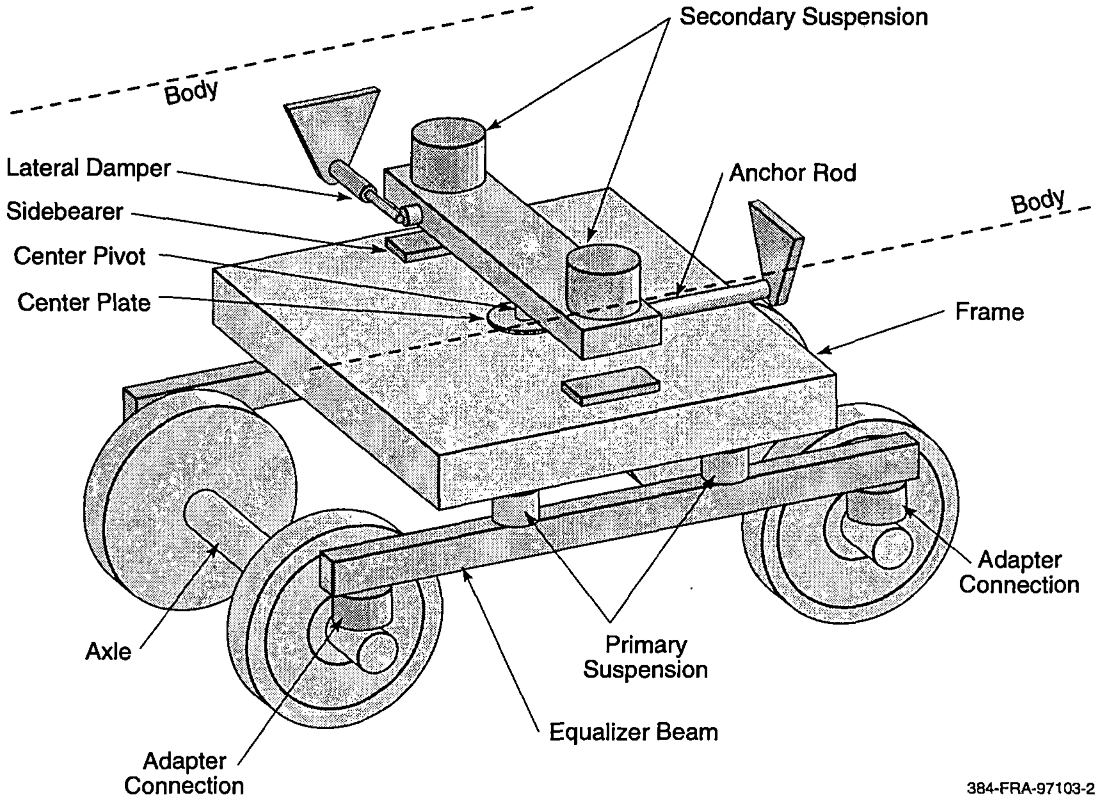


Figure 2-2. View of the equalized truck

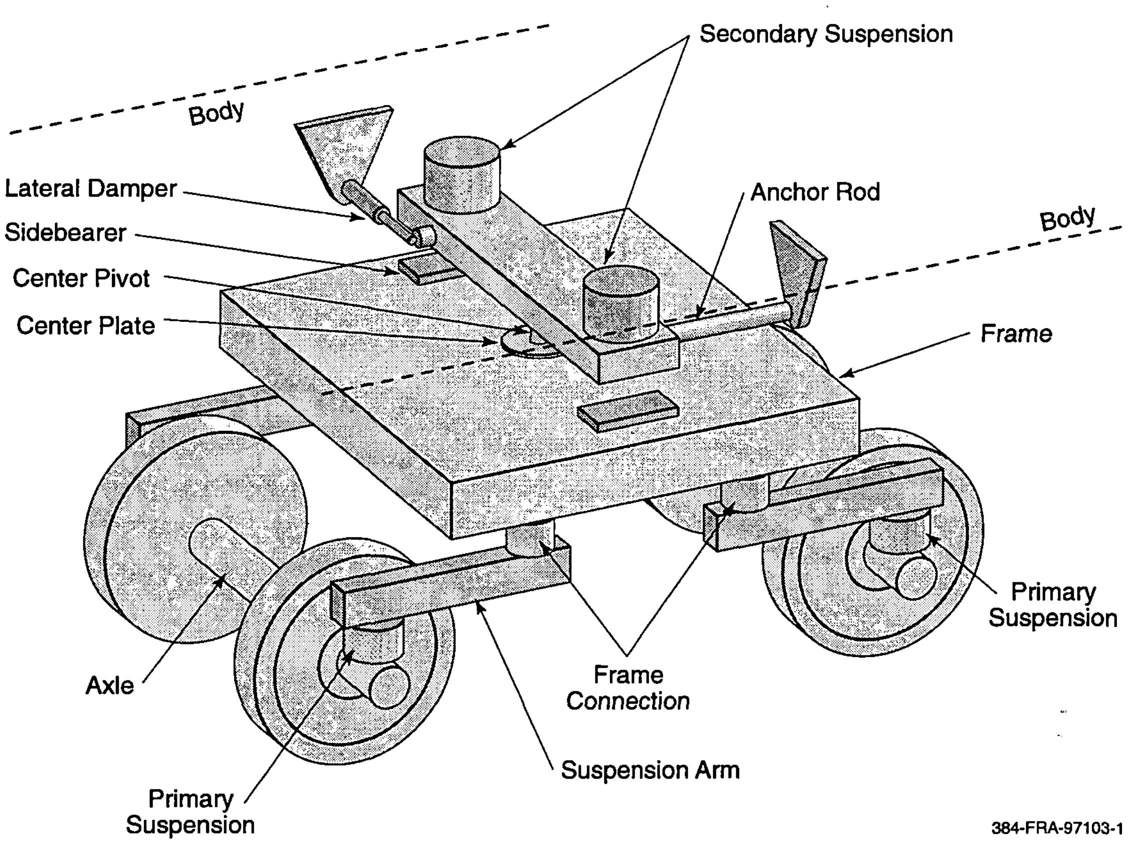


Figure 2-3. View of the non-equalized truck

required for use by commuter car property owners and users at their sites. These are currently being developed for future applications. The parameter data obtained from such tests will be supplemented by manufacturer's data.

For the purpose of the work conducted here, the required parameters for the equalized/non-equalized trucks and single/bi-level car bodies are assumed on the basis of previously published works, including Ref. (3). This data is shown in Table 2-1 so as to provide examples of the input parameters for the computer simulation tools.

Major differences in the equalized and non-equalized trucks are found in the primary stiffness parameters of the longitudinal, lateral, vertical and resulting bending, shear, and equalization properties. The two trucks differ in their dynamic behavior owing to these differences in their stiffnesses. Cars with non-equalized trucks have been described as having some problems in negotiating yard trackage. In some cases, these trucks' primary suspensions have been redesigned to overcome such problems. Testing will be required when the data is not available for a proper assessment of the vehicle parameters for use in the analytic predictions of safe operating limits.

Table 2-1. Example vehicle physical characteristics

	Units	Parameter Description	Bi-Level, Equalized Trucks, Outboard Bearing	Single-Level, Equalized Trucks, Outboard Bearing	Bi-Level, Not Equalized
<u>INERTIAS</u>	lb-sec^2/in	Truck frame mass	14.5	14.5	14.2
	lb-sec^2/in	Car body mass	250	170	250
	lb-sec^2/in	Wheelset mass	8.8	8.8	11
	lb-in-sec^2	Truck frame yaw moment of inertia	10000	10000	19400
	lb-in-sec^2	Car body yaw moment of inertia	2.30E+07	1.50E+07	2.30E+07
	lb-in-sec^2	Wheelset yaw moment of inertia	6060	6060	7200
	lb-in-sec^2	Truck frame roll moment of inertia	7588	7588	14755
	lb-in-sec^2	Car body roll moment of inertia	1.00E+06	6.60E+05	1.00E+06
<u>SPRING RATES</u>	lb/in	Longitudinal primary stiffness (per wheel)	3500	3500	2.25E+05
	lb/in	Lateral primary stiffness (per wheel)	3500	3500	60200
	lb/in	Vertical primary stiffness (per wheel)	6064	6064	12100
	lb/in	Inter-axle yaw stiffness (per truck)	1.56E+08	1.56E+08	0
	lb/in	Lateral secondary stiffness (per truck)	2100	2100	3220
	in-lb/rad	Yaw secondary stiffness (per truck)	0	0	0
	in-lb/rad	Roll secondary stiffness (per truck)	1.57E+07	1.57E+07	1.32E+07
<u>DAMPING</u>	lb-sec/in	Lateral secondary damping (per truck)	560	560	520
	in-lb-sec/in	Yaw secondary damping (per truck)	285	285	260
	in-lb-sec/in	Roll secondary damping (per truck)	1.63E+06	1.63E+06	1.41E+06
<u>DIMENSIONS</u>	in	Half of truck wheelbase	51	51	51
	in	Half lateral distance between primary suspension	39.5	39.5	39.5
	in	Half distance between truck centers	357	357	357
	in	Vertical distance, truck c.g. to secondary suspension	18	18	15.8
	in	Vertical distance, carbody c.g. to secondary suspension	47	28	47

2.3 Identify Critical Track Parameters

In a similar manner to that described for the vehicles in subsection 2.2, the characteristics of the rails, ties and ballast that contribute to the dynamics of the rail vehicle also have to be identified. The parameters identified for the purposes of OMNISIM and the example simulations described in this report include:

- Rail head geometry.
- Degree of curvature.
- Height of superelevation.
- Amplitude and wavelength of cusps (vertical imperfections).
- Amplitude and wavelength of lateral imperfections.
- Location of switches/switch geometry.
- Lateral stiffness and damping in rail fasteners.
- Vertical stiffness and damping in rail fasteners.
- Ballast stiffness and damping.

While this list is derived from the input parameters required by OMNISIM, not all analyses or simulation tools may utilize all of this data.

2.4 Assemble Track Data

To determine the actual values of the track parameters described in the previous section, the track condition must be physically measured. Unlike the vehicle parameters which can sometimes be obtained from manufacturer's specifications, track class and maintenance records provide insufficient detail for the purposes of simulation. To gather this information, therefore, requires specific experimental test equipment (such as the Track Geometry Car or the Single Tie Push Test equipment). For the purposes of the simulations described in this report, example data based on previous tests was used to illustrate the vehicle dynamics.

2.5 Identify Failure Modes and Criteria for Safe Operations

Several potential modes of failure during vehicle operations can arise as the vehicle negotiates track scenarios at prescribed speeds. These and the criteria governing them have been previously identified by Tyrell and co-workers (4) and are reproduced in Table 2-2. These form the basis of analytical investigations as well as the test validations. The safety criteria in Table 2-2 are empirical and simple for routine usage. These criteria have a built-in margin of safety. Using simulation tools such as OMNISIM, the margin of safety for any specific vehicle operating on any range of track conditions could be explicitly calculated and used during the vehicle's operation.

Table 2-2. Failure modes and safety criteria (4)

Parameter	Safety Limit	Filter/Window	Failure Modes
Vertical Wheel Load Ratio	0.1	5 ft window	Wheel lift and potential derailment.
Single Wheel L/V Ratio	$\leq \left(\frac{\tan\delta - 0.5}{1 + 0.5 \tan\delta} \right)$(Nadal's Limit)	5 ft window	Wheel climb derailment.
Net Axle L/V Ratio	0.5	5 ft window	Track shift and potential derailment and ride quality deterioration.
Truck Side L/V Ratio	0.6	5 ft window	Rail rollover/gage widening derailment.
Carbody Lateral	0.5g, peak-to-peak	10 Hz 1 sec window	Falling down of standing passengers, human fatigue.
Carbody Vertical	0.6g, peak-to-peak	10 Hz 1 sec window	Falling down of standing passengers, human fatigue.
Truck Lateral	0.4g, RMS	10 Hz 2 sec window	Truck hunting potential and human fatigue.

In this work, attention is paid to the derailment potential due to wheel climb and wheel lift and drop. When the Nadal limit is reached or exceeded, wheel climb is considered to be incipient. In some of the scenarios considered, wheel climb is directly inferred from the simulation program which can simulate and monitor the physics of the wheel climbing over the rail. Track scenarios such as cusps and misalignments are likewise evaluated in this manner. It is anticipated that such data will be valuable in the validation of the OMNISIM simulation tool as well as the validation of the methodology for determining the safe performance limits.

2.6 Identify Analytical Tools

An advanced simulation model to handle all operational scenarios listed in the previous section and two simpler models for prediction of truck hunting and vehicle behavior on a single cusp have been developed as a part of investigations carried out in this program. The advanced simulation model is a computer program called OMNISIM which models vehicles and the track as a multibody lumped parameter system, maintaining the rolling contact mechanism between the wheels and the rails. It accounts for the nonlinearities in the suspension and other parameters. The simulation tool can rigorously determine the incipience of derailment due to wheel climb and lift. Analytic descriptions of the simulation tool are presented elsewhere (2).

The simpler model for truck hunting is based on a linear theory and is intended for a rapid evaluation of critical speeds at the threshold of hunting. The results from this model as well as comparisons with OMNISIM simulation results are presented in Volume II (1). The linear model results are found to be significantly different from those of OMNISIM. This is attributed to inadequate representation of truck characteristics such as pedestal clearance. The OMNISIM simulation accounts for more realistic nonlinear characteristics without making simplifications typically involved in the linear models. The results presented in this report are based on the OMNISIM program. Another simpler model is based on combined pseudo-static and steady curving theories to evaluate safe cusp amplitudes on curves. Comparisons of the results from this model with those from OMNISIM are presented in Volume II (1). The results from the simpler model do not agree with those from OMNISIM and are considered to be overly conservative.

2.7 Analyze Vehicle Response Under Critical Track Scenarios

Based on the previous studies, the following scenarios and criteria are selected as critical in the safety evaluation of commuter cars.

- Hunting: Truck and car body hunting should not be permitted at operational speeds so as to avoid passenger fatigue and potential damage to vehicle and track structure. The hunting speed for the commuter car operating FRA Class 6 should be well above the 110 mph maximum operating speed.

- Steady Curving: The single wheel L/V ratio should be limited under the Nadal value to prevent potential wheel climb when the vehicle is negotiating high degree curves.

- Dynamic Curving: Wheel climb and wheel lift/drop should not occur when the vehicle is negotiating curves with cusps and misalignments that are permissible under current FRA track standards.

- Gage Narrowing: The vehicle should safely negotiate gage narrowing scenarios permissible under current FRA track standards, without wheel climb or wheel drop.

- Switches: The vehicle should safely negotiate switches with cusp type irregularities allowed by track standards without wheel climb or generating large lateral loads exceeding the Nadal limit.

2.8 Determine Safe Performance Limits

To express safe dynamic performance limits, the following parameters are used: maximum safe speeds for hunting, L/V ratios for steady curving, maximum permissible cusp and misalignment amplitudes for dynamic curving, maximum safe speeds for gage narrowing and safe cusp amplitudes for switch negotiation. The specific operational scenarios, the types of failure modes considered and the parameters used for the safe performance limits are summarized in Table 2-3.

2.9 Test Validations

An important part of the technical approach in the program described in this report is the validation of the simulations and resulting safety margins. The validation is achieved by comparing the analytically derived results with results of experiments that monitor the vehicle dynamic response during the same car and track scenario. Experimental validation is specifically required for:

1. Verification of car and track parameters used as inputs to the simulation tools. In any case where the experimental parameters vary significantly from the estimated parameters, the experimentally derived values will be used in the model and the safety limits reevaluated.

2. Validation of the simulation code through comparisons of the measured and predicted vehicle dynamic response as determined by the accelerations measured and the loads generated.

Table 2-3. Operational scenarios, failure modes and parameters for safety limits

Operational Scenario	Failure Mode	Parameters for Safety Limits
High Speed on Tangent	Truck Hunting	Critical Speeds
Steady-State Curving	Wheel Climb	L/V Ratio
Dynamic Curving on Single Vertical Cusp	Wheel Climb	Cusp Amplitude
Dynamic Curving on "Down and Out Cusps"	Wheel Climb	Cusp Amplitudes and Misalignment
Negotiation of Gage Narrowing	Wheel Climb	Gage Reduction Ratio
Switch Negotiation	Wheel Climb and Large Lateral Forces	L/V Ratio

3. Assessment of the margin of safety derived through the safety criteria that have been established. Since this may require certain intentionally created scenarios that would cause vehicle derailment, it would be desirable to minimize the requirement for this testing.
4. Validation of the commuter car safety assessment methodology under development for use by commuter car owners and users as well as other interested parties.

3. SAFE PERFORMANCE LIMITS OF REPRESENTATIVE CAR DESIGNS ON TYPICAL TRACK SCENARIOS

Safe performance limits are determined by OMNISIM analysis and are presented here for the candidate car designs described in Section 2. Table 2-3 presented the operational scenarios considered, the type of potential failure, and the parameters used to define the safe limits, as described in Section 2.

There are also other operational scenarios, such as negotiation of vertical and lateral misalignments which may pose safety problems but are not included here as they are considered to be well understood in the literature. Some of the operational scenarios, such as single and multiple cusp negotiation, are considered to be more important on the basis of experience with the Chapter 11 (4) safety evaluations for freight cars. The safety limits presented here are preliminary, based on analytical studies, and need test validations prior to their usage in commuter rail operations.

3.1 Critical Speeds on Tangent Track

Vehicle hunting oscillations on tangent track can occur at and above the nominal critical speed, which must be above the maximum operational speed to avoid hunting and potential flange contact in revenue operations. In addition to causing passenger fatigue, hunting can cause track damage by generating large net axle lateral loads. Critical speeds for hunting depend on the wheel profile and other parameters such as vehicle load and suspension characteristics. Three wheel profiles, the new AAR1B standard, the Amtrak AAR1B and the worn AAR1B with tread angles of 1/20, 1/40 and 1/20, respectively, are considered in this study. The worn AAR1B has a concave shape added to the tread region.

Analytical results have been generated using both OMNISIM and a linear model. The linear model significantly underestimates the critical speeds, particularly for the equalized truck, when compared with the OMNISIM predictions. The linear model does not account for nonlinearities such as those due to the pedestal clearances. When such nonlinearities are ignored in OMNISIM, the results agree with the linear model. For the study presented here, the OMNISIM program incorporating all the nonlinearities is used to derive the critical speeds.

Table 3-1 shows the critical truck hunting speeds for the profiles considered when the candidate vehicles are operated on track with 136 lb rail. From this table, it is seen that bi-level equalized trucks have very high critical speeds compared to existing FRA speed limits on Class 6 tracks. The single-level cars have reduced critical speeds due to their smaller weight compared to that of bi-level cars but are well above the permissible limits as per the current FRA standards on Class 6 track. The single level car with non-equalized truck and AAR1B worn wheel has the lowest critical speed of about 160 mph, which is also above the FRA limit of 110 mph for the commuter cars on Class 6. The conclusion is that hunting is not a safety problem for the cars studied here.

Table 3-1. Truck hunting critical speeds for representative car parameters

Body	Truck	Profile	Load	Track*	Truck Hunting Speed (mph)
Bi-level	Equalized	A1B	Empty	Hard	>300
Bi-level	Equalized	A1B	Empty	Soft	>300
Bi-level	Equalized	A1B	Loaded	Hard	>300
Bi-level	Equalized	A1B	Loaded	Soft	>300
Bi-level	Equalized	M1B	Empty	Hard	>300
Bi-level	Equalized	M1B	Empty	Soft	>300
Bi-level	Equalized	W1B	Empty	Hard	260
Bi-level	Equalized	W1B	Empty	Soft	>300
Bi-level	Non-Equalized	A1B	Empty	Hard	190
Bi-level	Non-Equalized	A1B	Empty	Soft	>300
Bi-level	Non-Equalized	A1B	Loaded	Hard	215
Bi-level	Non-Equalized	A1B	Loaded	Soft	270
Bi-level	Non-Equalized	W1B	Empty	Hard	185
Bi-level	Non-Equalized	W1B	Empty	Soft	260
Single-level	Equalized	A1B	Empty	Hard	260
Single-level	Equalized	W1B	Empty	Hard	235
Single-level	Non-Equalized	A1B	Empty	Hard	165
Single-level	Non-Equalized	W1B	Empty	Hard	160

A1B - New AAR 1B Std (1/20) on new 136 lb/yd rail
M1B - Amtrak AAR 1B (1/40) on new 136 lb/yd rail
W1B - Worn Tread on AAR 1B on new 136 lb/yd rail

*The soft and hard tracks differ in the assumed stiffnesses at rail fasteners, which are given in Ref. (1).

3.2 Steady Curving

The objective of this task is to determine the wheel/rail forces generated by the generic commuter passenger rail vehicles during steady curving. Steady curving, as investigated, neglects the transient dynamic response which occurs when a rail vehicle traverses the entrance and exit spirals found in all real-world curved track geometry. However, the assumption of steady curving is a useful tool for engineering studies and design tradeoffs.

Steady curving solutions at balance speed conditions are evaluated. Curves of 2.5, 5, and 7.5 deg are traversed at 35 mph. Curves of 10, 15, and 20 deg are traversed at 20 mph. Both empty and loaded single-level and bi-level vehicles are considered. Each vehicle type is evaluated with equalized and non-equalized trucks.

For each combination of vehicle and track configuration/parameters, the lead-outer wheel L/V ratios are plotted as functions of track curvature. Figure 3-1 presents these results for single-level cars. The Nadal Value of 1.34 for a wheel/rail coefficient of friction of 0.4 is also indicated for reference. Figure 3-2 presents similar results for bi-level cars.

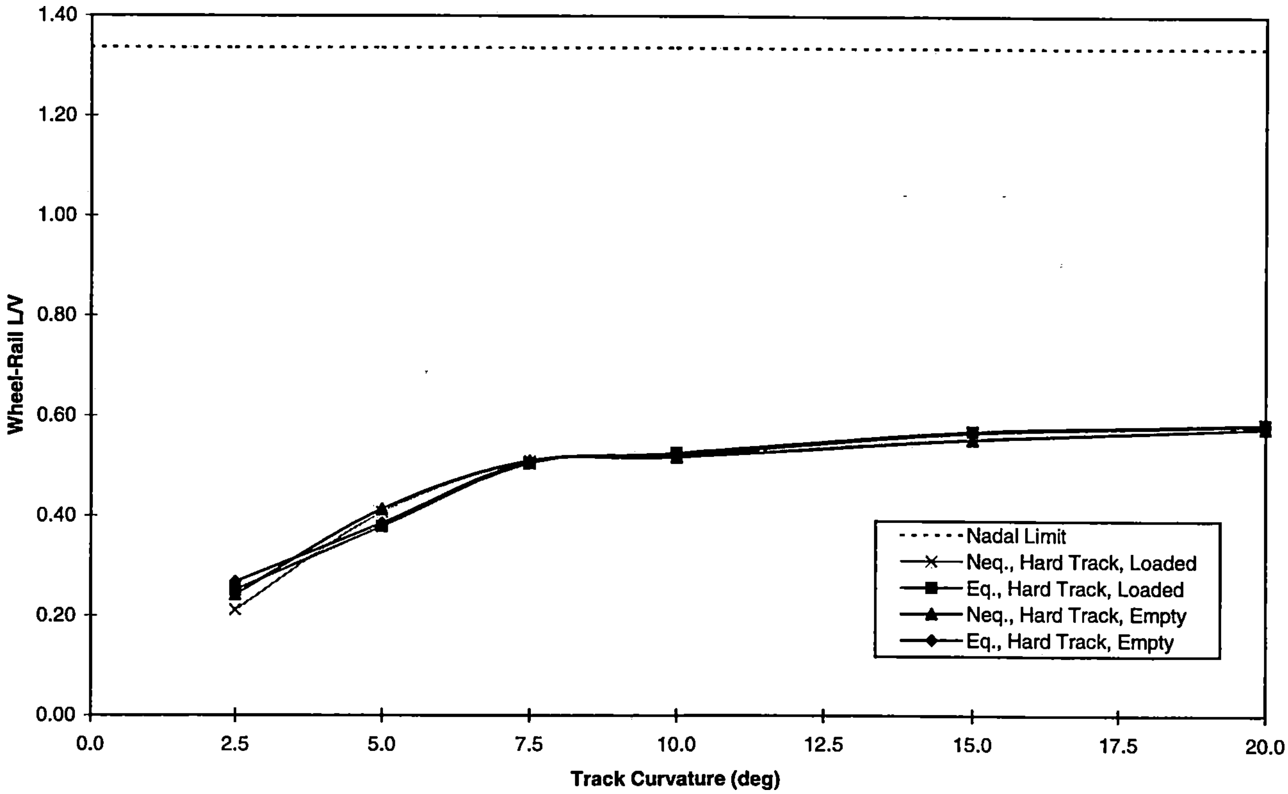


Figure 3-1. Lead outer wheel L/V versus track curvature (representative single-level car, steady curving)

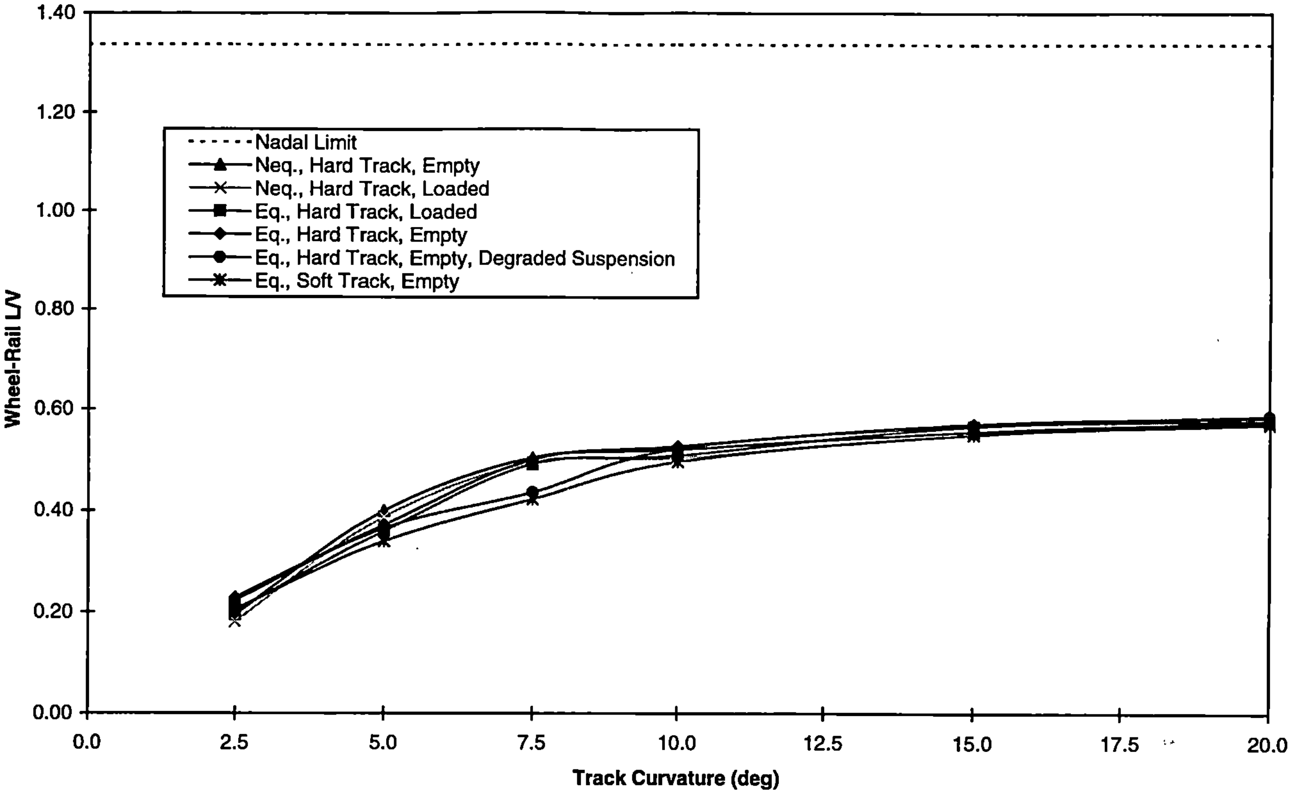


Figure 3-2. ***Lead outer wheel L/V versus track curvature (representative bi-level car, steady curving)***

In all of the cases that are investigated, no wheel climb derailment occurs under steady-state curving. It is anticipated that the vehicle behavior even at 3 in. cant deficiency will be safe under steady curving.

Figures 3-1 and 3-2 indicate that the influence of track stiffness and load are not significant on the steady curving behavior. Even for degraded suspension (by about 10 percent), the results are not greatly different from those with normal suspension values.

3.3 Safe Single Cusp Crosslevels

A single cusp perturbation in the outer rail of curved tracks can pose a safety problem for the commuter cars to negotiate. The cusp is defined in Figure 3-3 by its amplitude, δ_V, and wavelength, λ. The cusp causes crosslevel variations which can be measured by a track-geometry car or other means. Since the wavelength of the cusp is also an important parameter, it is included here in the form of simple sinusoidal wavelengths: one a short wavelength of 10 ft and another a longer wavelength of 39 ft. The objective here is to determine the safe maximum amplitudes of the cusp for these wavelengths, at and below which no wheel climb or lift is predicted by the OMNISIM simulation code. For this purpose the cusp amplitude is varied over the range 1, 1.5, 2, 3 and 4 in. in the simulation program with vehicle speed at balance for curvatures in the range of 2.5 to 20 deg.

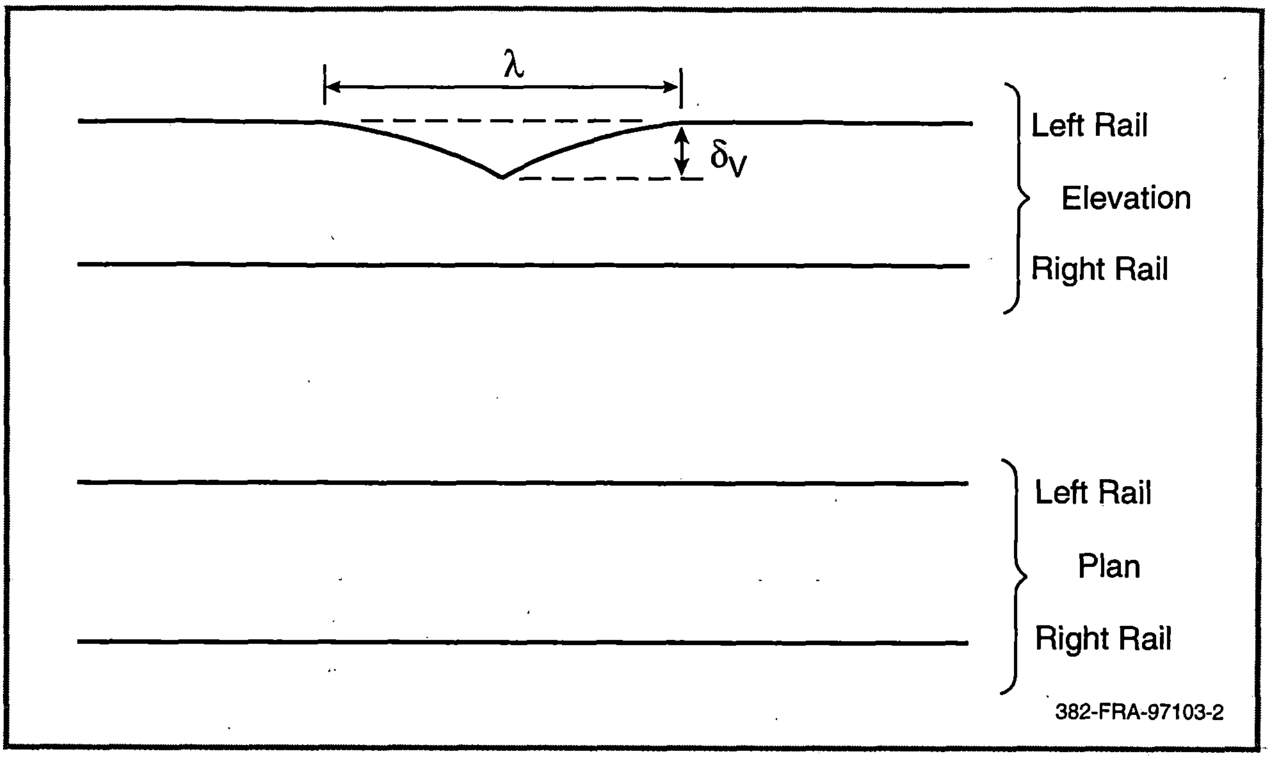


Figure 3-3. Single cusp geometry

For the purposes of this demonstration of the safety analysis, the cars were assumed to be running at balance speed. For a thorough safety analysis of a car design, the complete range of possible speed cases would have to be analyzed as it has been shown that on some types of cusps unsafe conditions can occur well below balance speed.

A simple pseudo-static method has also been used to generate initial data for safe cusp amplitudes. It does not account for the shear stiffness of the truck in wheel unloading. The results of this method are found to be nonconservative when compared to OMNISIM results. OMNISIM is considered to be more accurate and reliable for this class of problems. Two modes of unsafe behavior have been identified from the OMNISIM results. The first is the classical pseudo-static wheel unloading due to the severity of the crosslevel gradient. The second results from the bounce of the wheel on the rail at a point just beyond the cusp apex. The vertical stiffness of the track is also found to be an important parameter in this work.

3.3.1 Results for Short Wavelength Cusps

Figure 3-4 presents the safe limits based on the criteria of wheel lift for the range of curvatures and amplitudes considered. The safe and unsafe values are identified, respectively, by the blank and shaded spaces. From this figure, it is seen that a single level car with both types of trucks can safely negotiate 1 in.

Single-Level Car with Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1	SAFE				
1.5	UNSAFE				
2					
3					
4					

Single-Level Car with Non-Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1	SAFE				
1.5	UNSAFE				
2					
3					
4					

Bi-Level Car with Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1	SAFE				
1.5					
2	UNSAFE				
3					
4					

Bi-Level Car with Non-Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1	SAFE				
1.5	UNSAFE				
2					
3					
4					

Blank: Safe—No Wheel Lift

Hatched: Unsafe—Wheel Lift

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Figure 3-4. Example limits for safe/unsafe operation through single cusp (short wavelength) of example car designs (balance speed)

cusp amplitude, but not 1.5 in. or higher. The precise value at the transition between safe and unsafe regimes is not determined. It is also seen from the figure that bi-level cars with equalized trucks fare better than single level cars in negotiating the cusp. The unsafe behavior in this track regime arises from vertical bounce of the wheel on contact of the rail immediately following cusp negotiation.

Table 3-2 shows the specific wheel experiencing wheel lift when the perturbation exceeds the safe limits. Wheel 1 refers to the outer wheel on the first axle of the leading truck. The odd numbers are successive outer wheels. Likewise, the even numbers represent successive inner wheels. It is noted that in the majority of cases of unsafe behavior, involve the first outer wheel lift; outer wheels of second and third axles can also experience wheel lift in some cases.

3.3.2 Results for Long Wavelength Cusps

The results for the longer wavelength of 39 ft are shown in Figure 3-5. The figure illustrates that the bi-level cars with equalized trucks can safely negotiate a 3 in. amplitude cusp up to a maximum of about 10 deg curvature. The non-equalized truck cars can only accommodate lower amplitudes of disturbances than the cars with equalized trucks for both single and bi-level constructions. This result is consistent with the field experience with the non-equalized truck car. Table 3-3 identifies the specific wheels involved in the predicted wheel lift, which shows that the majority of these cases experience

Table 3-2. Wheel lift at balance speed in the single cusp (short wavelength) of typical car designs

		Equalized Trucks		Non-Equalized Trucks	
Curve (deg)	Cusp (in.)	Bi-Level	Single-Level	Bi-Level	Single-Level
2.5	1.0	None	None	None	None
5	1.0	None	None	None	None
10	1.0	None	None	None	None
15	1.0	None	None	None	None
20	1.0	None	None	None	None
2.5	1.5	None	wheel 1	wheel 1	wheel 1
5	1.5	None	wheel 1	wheel 1	wheel 1
10	1.5	None	wheel 1	wheel 1	wheel 1
15	1.5	None	wheel 4	wheel 5	wheel 1
20	1.5	None	wheel 6	wheel 1	wheel 1
2.5	2.0	wheel 1	wheel 1	wheel 1	wheel 1
5	2.0	wheel 1	wheel 1	wheel 1	wheel 1
10	2.0	wheel 1	wheel 1	wheel 1	wheel 1
15	2.0	wheel 3	wheel 1	wheel 1	wheel 1
20	2.0	wheel 1	wheel 1	wheel 1	wheel 1

Single-Level Car with Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1					
1.5			SAFE		
2					
3	▨	▨	▨ UNSAFE	▨	▨
4	▨	▨	▨	▨	▨

Single-Level Car with Non-Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1					
1.5		SAFE	▨	▨	▨
2	▨	▨	▨	▨	▨
3	▨	▨	▨ UNSAFE	▨	▨
4	▨	▨	▨	▨	▨

Bi-Level Car with Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1					
1.5			SAFE		
2					
3				▨	▨ UNSAFE
4	▨	▨	▨	▨	▨

Bi-Level Car with Non-Equalized Trucks

Cusp (in.)	Curve (°)				
	2.5	5	10	15	20
1			SAFE		
1.5					▨
2			▨	▨	▨
3	▨	▨	▨ UNSAFE	▨	▨
4	▨	▨	▨	▨	▨

Blank: Safe—No Wheel Lift or Wheel Climb

Hatched: Unsafe—Wheel Lift or Wheel Climb

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Figure 3-5. Example limits for safe/unsafe operation through single cusp (long wavelength) derived from simulation (balance speed)

Table 3-3. ***Wheel climb or lift at balance speed in the single cusp (long wavelength) of typical car designs***

		Equalized Trucks		Non-Equalized Trucks	
Curve (deg)	Cusp (in.)	Bi-Level	Single-Level	Bi-Level	Single-Level
2.5	1.0	None	None	None	None
5	1.0	None	None	None	None
10	1.0	None	None	None	None
15	1.0	None	None	None	None
20	1.0	None	None	None	None
2.5	1.5	None	None	None	None
5	1.5	None	None	None	None
10	1.5	None	None	None	*wheel 5
15	1.5	None	None	None	*wheel 1
20	1.5	None	None	•wheel 5	*wheel 1
2.5	2.0	None	None	None	•wheel 1
5	2.0	None	None	None	•wheel 1
10	2.0	None	None	•wheel 5	•wheel 1
15	2.0	None	None	•wheel 1	*wheel 1
20	2.0	None	None	•wheel 1	*wheel 1
2.5	3.0	None	•wheel 1	•wheel 1	•wheel 1
5	3.0	None	•wheel 1	•wheel 1	•wheel 1
10	3.0	None	•wheel 1	•wheel 1	•wheel 1
15	3.0	*wheel 1	*wheel 1	*wheel 1	*wheel 1
20	3.0	*wheel 1	*wheel 1	*wheel 1	*wheel 1
2.5	4.0	•wheel 1	•wheel 1	•wheel 1	•wheel 1
5	4.0	•wheel 1	•wheel 1	•wheel 1	•wheel 1
10	4.0	•wheel 1	•wheel 1	•wheel 1	•wheel 1

*Wheel climb
•Wheel lift

wheel lift of the outer wheel of the lead axle. Unsafe behavior in this track regime arise from both dynamic and pseudo-static causes. In general, the equalized truck experiences wheel bounce only.

3.4 Safe Down and Out Cusp Amplitudes and Misalignments

Cusps with outward lateral misalignments on curves can pose potential safety problems for commuter cars. Multiple cusps with lateral misalignments over wavelengths of 39 ft for each cusp, as shown in Figure 3-6, are considered in this study. Commuter car response to five sequential "down and out" cusps are simulated using OMNISIM; however, it is found that wheel response is the same at each cusp. The vertical amplitude of each cusp is taken as one half of its lateral amplitude. The lateral amplitude is varied over the range 0.8, 1.0,

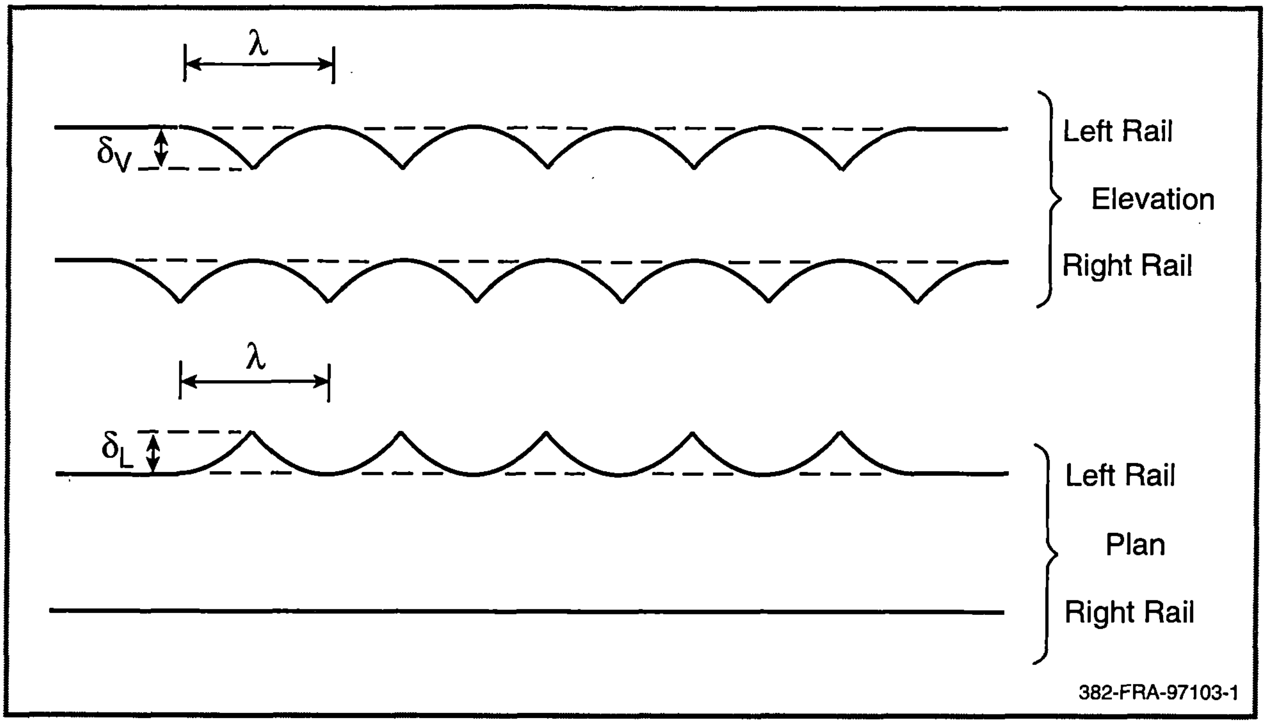

Figure 3-6. Down and out cusp geometry

1.2, 1.4, and 1.6 in. with the corresponding vertical amplitudes of 0.4, 0.5, 0.6, 0.7, and 0.8 in. The track curvature is varied in the range 2.5, 5, 10, 15, and 20 deg.

As in the single cusp simulations, all runs were computed with the vehicle speed equal to the balance speed. Again, a thorough safety analysis of any vehicle would have to examine the full range of speeds over any given track condition to uncover any unsafe behavior.

Figure 3-7 shows the results for single and bi-level cars with both types of trucks. For the range of cusp lateral and vertical amplitudes, the cars traverse the 2.5 deg curve without any wheel climb. The bi-level car with equalized trucks can accommodate the entire range of curves with cusps studied here. The non-equalized truck cannot accommodate the same level of perturbation as the equalized trucks. The single level car can traverse slightly lower amplitude deviations than the bi-level car for the same type of truck. Table 3-4 shows the specific wheel that experiences wheel climb. As in the previous investigation, the outer wheel of the first axle generally is the candidate for the wheel climb when the safe perturbation limit is exceeded. However, there are a few exceptions when the outer and inner wheel of the third axle can also experience wheel climb, as noted from Table 3-4.

3.5 Safe Gage Narrowing Limits

Gage variation may occur in revenue service, and must be negotiated safely by the passenger vehicles. Figure 3-8 shows the basic track shape for the gage

Single-Level Car with Equalized Trucks

Cusp (in.)		Curve (°)				
Lateral	Vertical	2.5	5	10	15	20
0.8	0.4					
1.0	0.5		SAFE			
1.2	0.6					
1.4	0.7					
1.6	0.8		▨	▨	▨	▨ UNSAFE

Single-Level Car with Non-Equalized Trucks

Cusp (in.)		Curve (°)				
Lateral	Vertical	2.5	5	10	15	20
0.8	0.4					
1.0	0.5		SAFE			
1.2	0.6			▨	▨	▨
1.4	0.7		▨	▨	▨ UNSAFE	▨
1.6	0.8		▨	▨	▨	▨

Bi-Level Car with Equalized Trucks

Cusp (in.)		Curve (°)				
Lateral	Vertical	2.5	5	10	15	20
0.8	0.4					
1.0	0.5					
1.2	0.6		SAFE			
1.4	0.7					
1.6	0.8					

Bi-Level Car with Non-Equalized Trucks

Cusp (in.)		Curve (°)				
Lateral	Vertical	2.5	5	10	15	20
0.8	0.4					
1.0	0.5		SAFE			
1.2	0.6					
1.4	0.7					
1.6	0.8		▨	▨	▨	▨ UNSAFE

Blank: Safe—No Wheel Climb

Hatched: Unsafe—Wheel Climb

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Figure 3-7. Example limits for safe/unsafe operation through down and out cusps derived from simulations (balance speed)

Table 3-4. Wheel climb in the down and out cusps for representative car parameters

	Cusp (in.)		Equalized Trucks		Non-Equalized Trucks	
Curve (deg)	Lateral	Vertical	Bi-Level	Single-Level	Bi-Level	Single-Level
2.5	0.8	0.4	None	None	None	None
5	0.8	0.4	None	None	None	None
10	0.8	0.4	None	None	None	None
15	0.8	0.4	None	None	None	None
20	0.8	0.4	None	None	None	None
2.5	1.0	0.5	None	None	None	None
5	1.0	0.5	None	None	None	None
10	1.0	0.5	None	None	None	None
15	1.0	0.5	None	None	None	None
20	1.0	0.5	None	None	None	None
2.5	1.2	0.6	None	None	None	None
5	1.2	0.6	None	None	None	None
10	1.2	0.6	None	None	None	wheel 1
15	1.2	0.6	None	None	None	wheel 1
20	1.2	0.6	None	None	None	wheel 1
2.5	1.4	0.7	None	None	None	None
5	1.4	0.7	None	None	None	wheel 1
10	1.4	0.7	None	None	None	wheel 1
15	1.4	0.7	None	None	None	wheel 1
20	1.4	0.7	None	None	None	wheel 1
2.5	1.6	0.8	None	None	None	None
5	1.6	0.8	None	wheel 1	wheel 5	wheel 1
10	1.6	0.8	None	wheel 1	wheel 1	wheel 1
15	1.6	0.8	None	wheel 1	wheel 1	wheel 1
20	1.6	0.8	None	wheel 5	wheel 1	wheel 1

narrowing investigated. One of the rails is considered as a reference rail from which the effective gage can be determined based on the relative position of the other rail. This is regarded as providing the worst case in that it produces the largest slope of gage reduction. From Figure 3-8, it is seen that the slope of the gage narrowing is constant along the distance. The speed at which incipient wheel climb occurs has been established here through OMNISIM simulations for vehicle and truck types considered in this work. The truck types have a significant influence on the vehicle behavior in the gage narrowing scenario. In numerical work presented here, the inverse of the slope is used as a

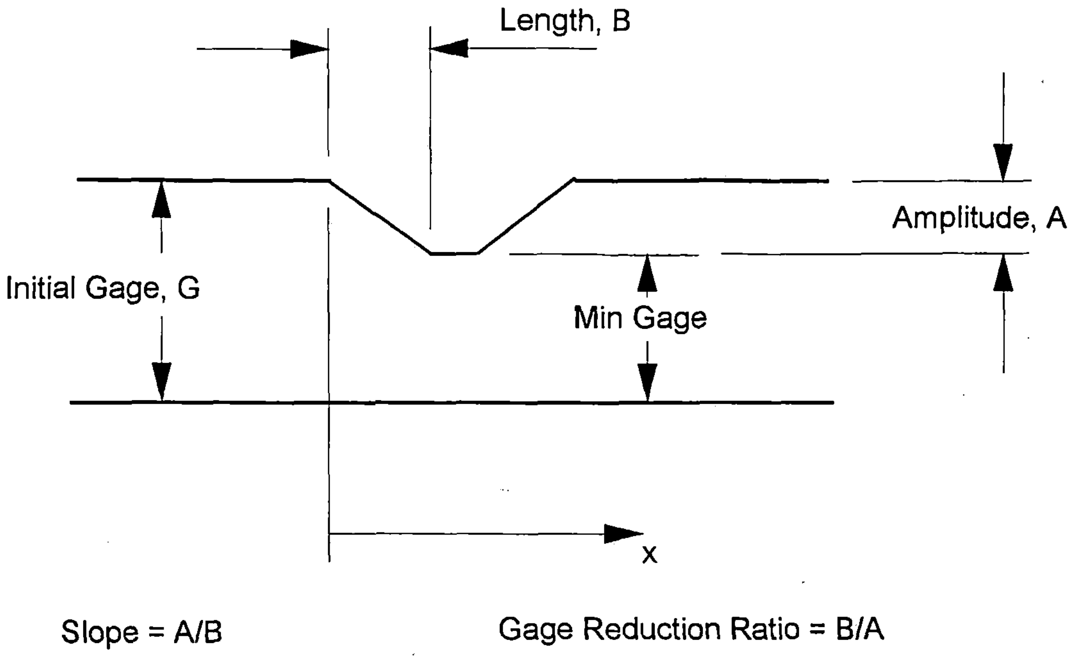

Figure 3-8. Constant gage narrowing scenario

characteristic parameter in terms of which safe operational speeds can be expressed. This parameter is defined as the Gage Reduction Ratio (GRR). In addition to GRR, the track gage (G) is also important in the determination of wheel climb threshold speeds.

An alternative sinusoidal shape has been used in the past to examine the likelihood of wheel climb in gage narrowed track. This is shown in Figure 3-9. In this shape, the necessary parameters in gage narrowing are the initial gage (G), the amplitude (A), and the wavelength (λ). Since the slope of gage narrowing on the sinusoid at the point of flange contact varies with the axle initial, lateral, and yaw positions, the potential for derailment will similarly vary with these positions. The safety limits can be more conveniently expressed for the constant gage narrowing scenario rather than the sinusoidal scenario.

Using knowledge of track geometry, measured or simulated, it is possible to isolate the worst case of gage narrowing misalignment. This may be absolute or may be related to particular sinusoidal wavelengths in the track gage as measured. In either case the inverse of the largest slope, or smallest GRR, can be determined and plotted for the car investigated and a maximum safe speed established.

Current FRA standards permit a maximum limit of 1/2 in. for the amplitude in gage narrowing for all classes of track. If this occurs sinusoidally over a wavelength of 6 ft, the largest GRR is about 46; for a wavelength of 12 ft, it is 92. For these GRRs, the maximum permissible speeds for the passenger

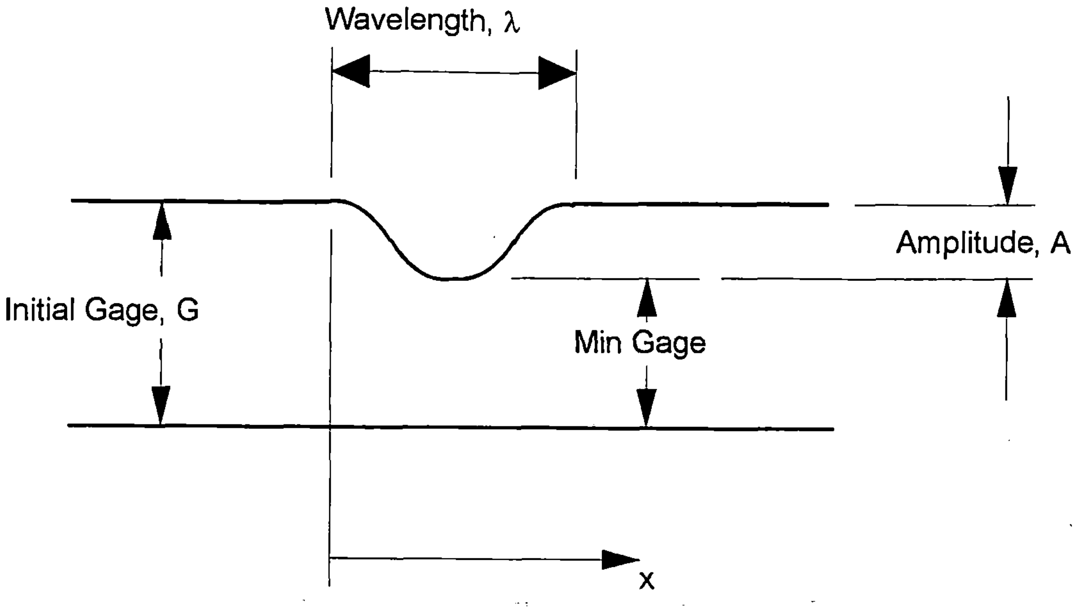

Figure 3-9. Sinusoidal gage narrowing scenario

vehicle with equalized trucks on track with a nominal gage of 56.5 in. are shown to be 40 mph and over 120 mph respectively. The safety criterion implied here is that wheel climb derailment will occur if the vehicles operate at higher speeds than the safe speeds identified.

3.5.1 Safe Speeds for Equalized Trucks

The maximum safe speeds without wheel climb derailment are determined for vehicles with the nominal equalized truck and are summarized in Figure 3-10. These results are applicable for both single and bi-level cars. The results are given for the nominal (initial) gage of 56.5 in. and up to 59 in. As the GRR decreases, the allowable speed becomes considerably smaller. It may also be noted that an initially wider gage allows a higher speed for the same GRR.

Specific data for two sinusoidal gage narrowings are included. These are for a sinusoidal amplitude of 2.5 in. with a wavelength of 20 ft and for an amplitude of 3 in. with a wavelength of 40 ft. Each result is interpreted as a point on the plot of critical speed against gage reduction ratio and shown in Figure 3-10 for the initial gage of 59 in. The results are seen to be conservative and are due to the fact that the axle moves off the track centerline used in the calculation of GRR prior to flange contact. The true value of GRR is therefore slightly larger than that used in the figure.

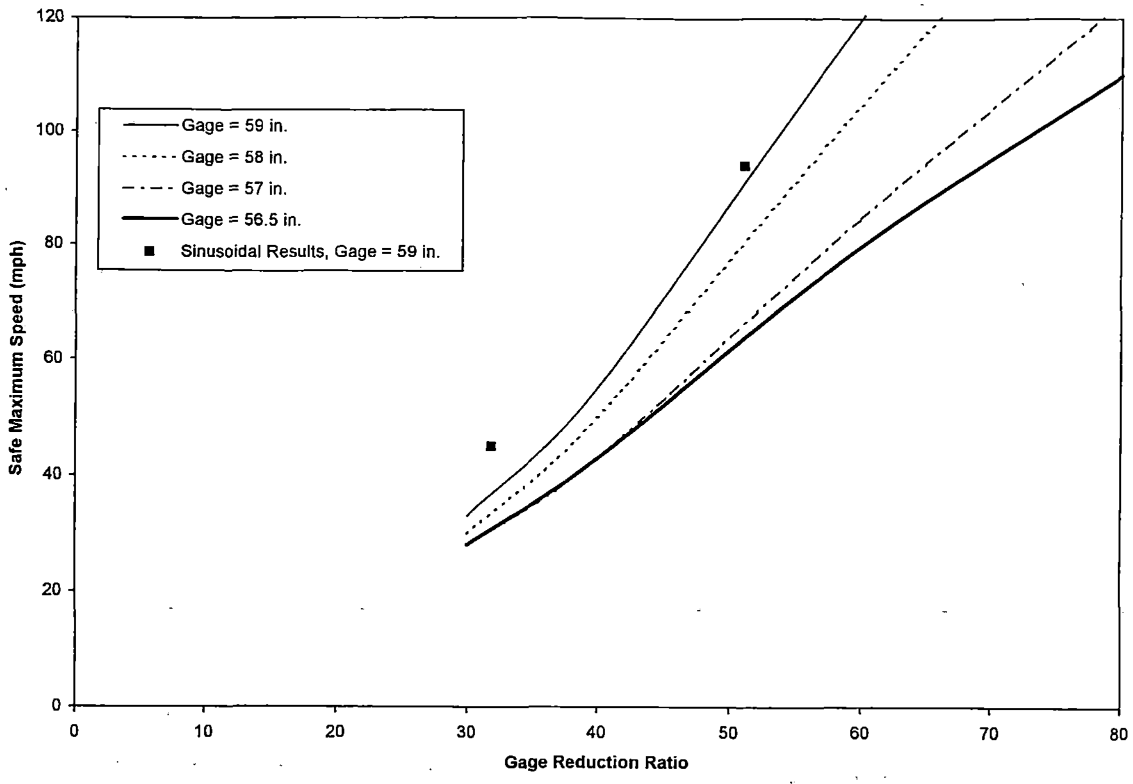

Figure 3-10. Maximum safe speed for a car with typical equalized trucks

3.5.2 Safe Speeds for Non-Equalized Trucks

The maximum safe speeds for the nominal non-equalized truck are shown in Figure 3-11, and are applicable for both single and bi-level cars. The same points for a sinusoidal gage reduction are also included. Comparing these results with those presented in Figure 3-10 for equalized trucks, the safe speeds are again lower with decreasing GRR. However, the results suggest that the safe speeds at incipient wheel climb for the equalized truck are higher than those for the non-equalized truck. As with the equalized trucks, an initial wider flangeway clearance allows higher speed for the same GRR without wheel climb.

3.6 Safety in Switches

Large motions of the body and lateral wheel-rail forces can occur at sudden changes in the direction of the guiding rails at switches. OMNISIM was used to simulate vehicle behavior passing through an AREA No. 8 crossover at speeds from 5 to 25 mph. In the simulation program, wheel climb potential is examined for movement of the wheel up and onto the rail head using the value of L/V. The lateral shift of the rails is also studied for increase in gage beyond safe limits.

The AREA No. 8 switch and crossover is modeled to show a sudden change in yaw angle at the switch entry followed by a straight switching rail and a

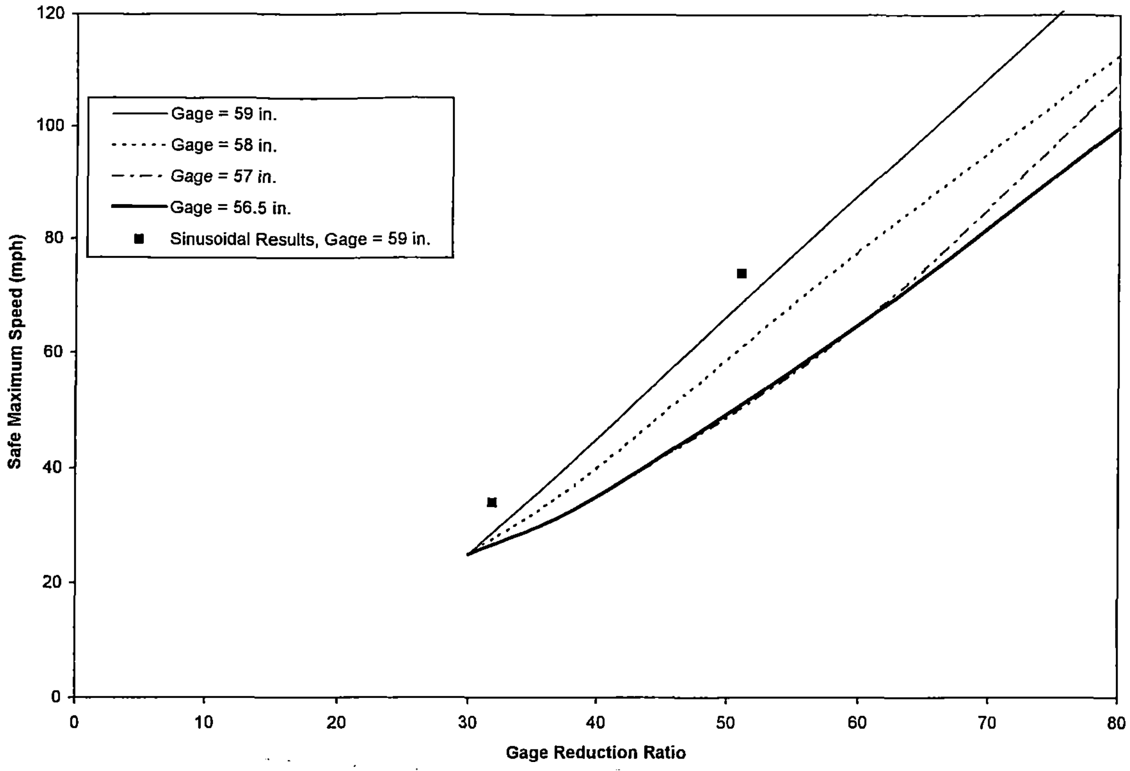

Figure 3-11. Maximum safe speed for a car with typical non-equalized trucks

curved rail with curvature equivalent to just over 11 deg up to the entry to the frog, which is straight. The gage is slightly tight at the switch entry. The second part of the crossover is a reverse mirror image of the first. In other runs, downward cusps are also added at the entrance to the frog.

Without downward cusps, the results for both vehicles (single and bi-level) with equalized and non-equalized trucks are similar. Neither the speed nor the differences in truck design influences the L/V values significantly over the unsuperelevated crossover. L/V values close to 0.6, well below the Nadal value for the profiles and friction, occur at initial flange contact and through the curved sections as shown in Figures 3-12 and 3-13 for the equalized and non-equalized trucks respectively. The non-equalized truck has marginally better steering in the switch curves.

3.6.1 The Effect of a 39 ft Wavelength Downward Cusp

Figures 3-12 and 3-13 also show the effect of a downward cusp at the end of the first curved rail in the crossover ahead of the frog. In these, the car with equalized trucks has an increase in the peak L/V ratio of the lead axle in the trailing truck to a maximum of 1.52 in the 3 in. cusp. Although this is greater than the Nadal value shown, no derailment is seen as the effective angle of attack is small (<7 mrads). At the lower cusp amplitude of 1.5 in., the increase of the L/V with speed is much less for this car and shows no likelihood of

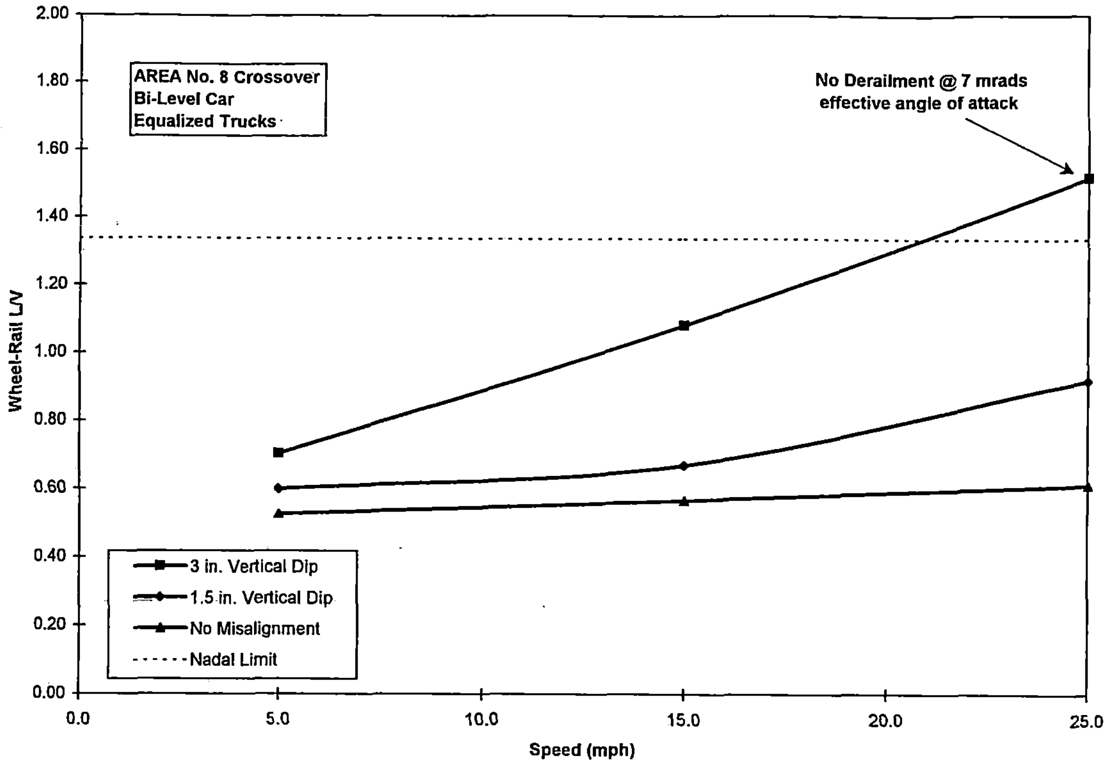

Figure 3-12. Wheel L/V versus speed for an example car with typical equalized trucks

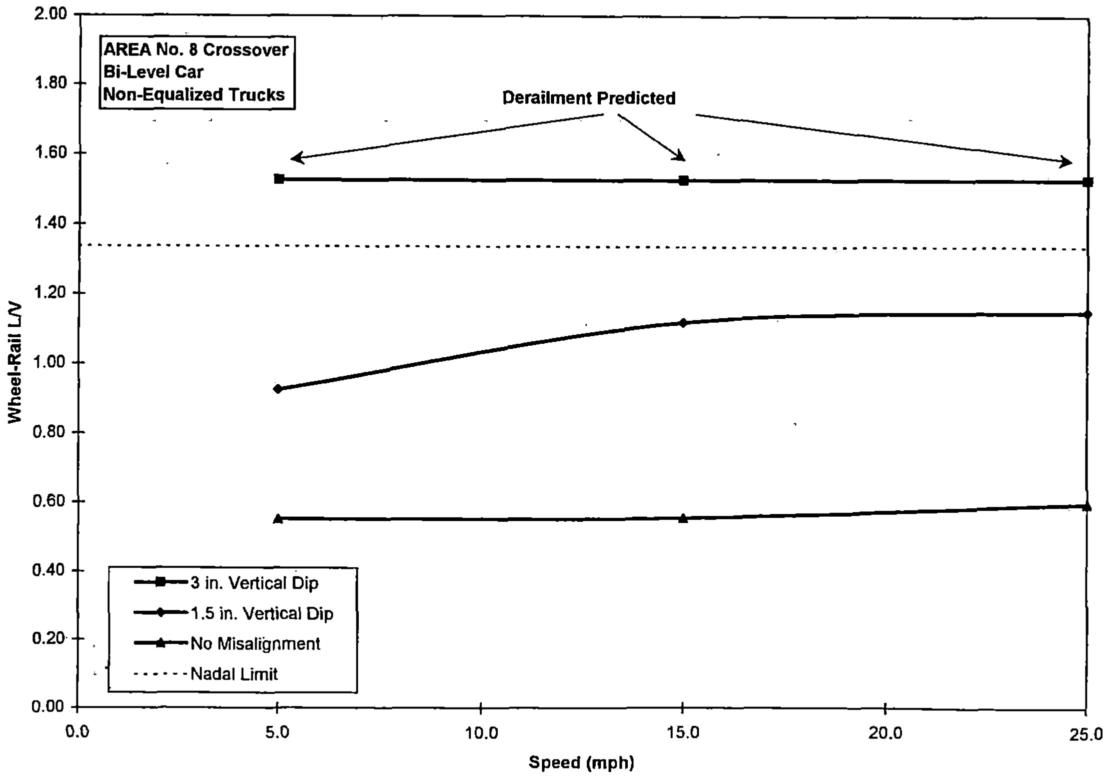

Figure 3-13. Wheel L/V versus speed for an example car with typical non-equalized trucks

derailment. Figure 3-14 shows the variation with cusp amplitude for both truck leading wheels at 25 mph, indicating that the trailing truck has the largest L/V ratio. It should be noted that the curvature of the rail ahead of the cusp is 11.77 deg and the results reflect those shown in Figure 3-5.

The car with non-equalized trucks is predicted to derail at all speeds in the crossover with the 3 in. cusp amplitude. The L/V at the climb is about 1.5, greater than the Nadal value of 1.34 for the maximum profile angle of 75 deg and the coefficient of friction of 0.4 used throughout the simulations. However, the effective angle of attack is greater than 11 mrads in each case. Figure 3-15 again shows the lead axle in the trailing truck to have a greater potential for derailment. No derailments occur in the 1.5 in. cusp amplitude, which has an L/V of 1.15 at 25 mph. The derailments predicted are again consistent with those investigated and reported for the single downward cusp in Figure 3-5.

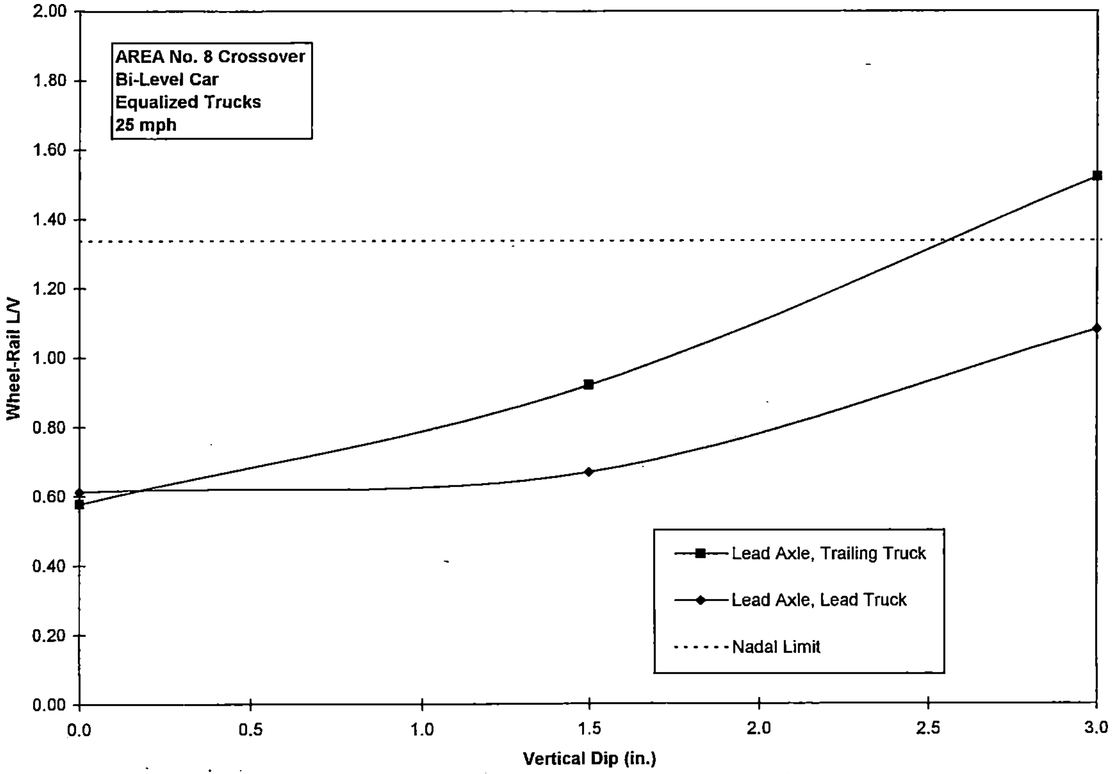

Figure 3-14. Wheel L/V versus cusp amplitude for an example car with typical equalized trucks

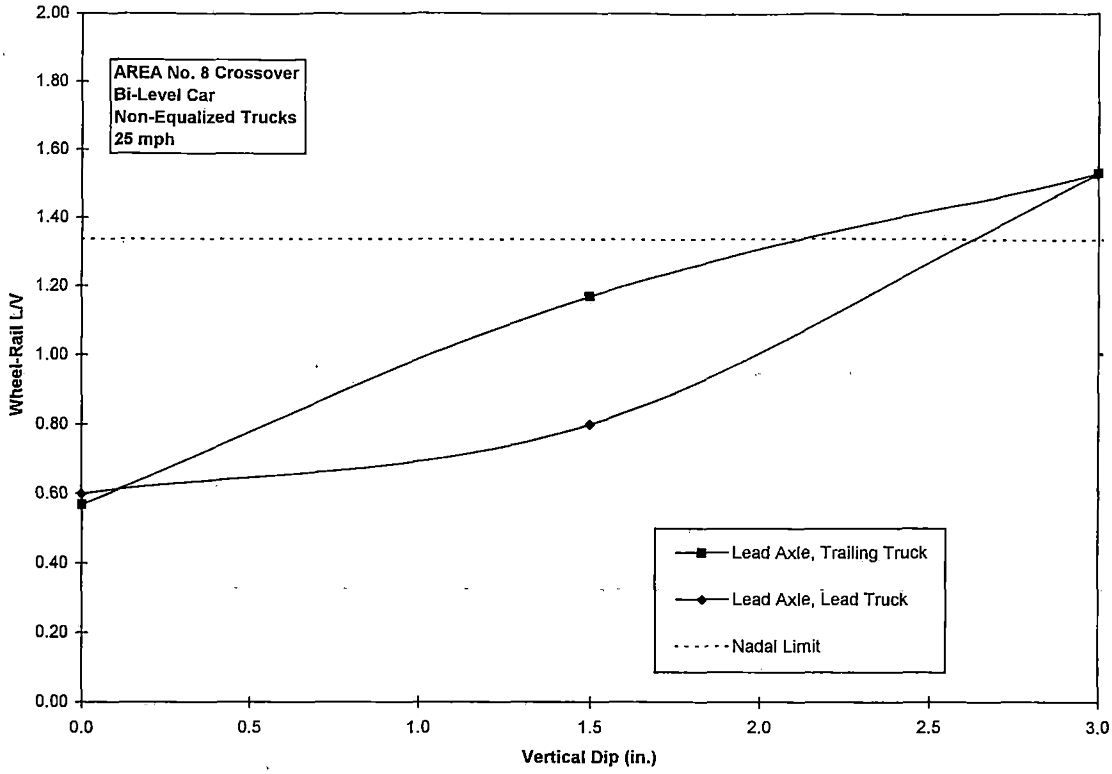

Figure 3-15. Wheel L/V versus cusp amplitude for an example car with typical non-equalized trucks

4. SAFETY ASSESSMENT METHODOLOGY FOR NEW EQUIPMENT

In the previous sections, an overall research approach has been developed for an assessment of commuter rail vehicle safety. This research approach was shown in Section 3 to determine dynamic performance limits for cars with an assumed set of generic parameters. When the safety of new equipment is to be evaluated, the performance limits of the new car design must be evaluated. This can be a laborious process, involving many hundreds of man-hours dedicated to physically testing the car's performance over a wide range of possible operational scenarios. However, this process can be simplified using the methodology described in this report, providing that the steps required to validate the modeling technique have been performed.

The proposed methodology would be applied with the following steps:

1. *Develop Simple Test Procedures and Tools for Determining the Car Parameters*

- Car body and truck masses and moments of inertia.
- Primary suspension and damping characteristics.
- Secondary suspension and damping characteristics.
- Wheel profile.

Even if the manufacturer provides technical data on these parameters, tests will still be required to verify the data to account for any in-process changes, or post-manufacturing faults. These tests could include, but are not limited to:

- Wheel unloading.
- Rigid body modal excitation.
- Truck interaxle shear.
- Truck interaxle bending.
- Damper characterization.

Currently, these parameter characterization tests are performed with complex machinery, requiring a dedicated test facility, such as at the Transportation Technology Center in Pueblo, CO. Simpler and more rapid methods of performing these tests on stationary cars on a siding or in a yard using portable and simple instrumentation are required for the rapid and low cost assessment of car parameters.

2. Analyze Car Dynamic Behavior Under Selected Track Scenarios

Using the measured input parameters, the dynamic behavior of the equipment should be simulated and quantified for selected track scenarios. The simulation program or other analytic tools used for this analysis would have been previously validated. A list of candidate scenarios has been described in subsection 2.7. The OMNISIM code used to demonstrate the methodology in this report is capable of addressing all of the scenarios but is still in the process of being validated.

3. Define Safe Performance Limits

Using the simulation code, the safe performance limits can be expressed in terms of speeds and maximum permissible track perturbations. If these limits are not adequate for the planned use of the vehicle, it may have to be redesigned and modified to enlarge the safe performance envelope. It is also beneficial for all the parties involved if the track scenarios are an integral part of the performance specifications to be followed by the manufacturer at the design stage of any new car equipment.

4. Design and Perform Specific Dynamics Experiments

If any specific safety issues arise from the analyses described in items 1 through 3 which need experimental resolution, appropriate dynamic tests would have to be designed and executed to validate the safety concern. If no safety concern arises from the simulation analyses of vehicle operations on all track scenarios, a minimal set of standard vehicle acceptance tests may be adequate for an assurance of vehicle safety in revenue service.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. A safety assessment methodology for conventional passenger vehicles has been presented. The approach identifies required vehicle parameters, critical vehicle operational scenarios and required analysis tools for quantification of vehicle dynamic response and potential for vehicle derailment.

    - The vehicle parameters can be conveniently grouped as those of single/ bi-level car bodies and equalized/non-equalized truck types, which are representative of the variations in the current vehicle dynamic behavior, and their safety performance.

    - The vehicle operational scenarios studied include 1) truck hunting on tangent track, 2) steady curving, 3) dynamic curving on tracks with single cusp imperfections, 4) dynamic curving on tracks with multiple "down and out" cusp imperfections, and 5) negotiation of switches with imperfections.

    - An advanced simulation tool such as OMNISIM is essential for a proper assessment of vehicle dynamics under the various operational scenarios. The tool can evaluate the derailment potential with reasonable accuracy.

    - The safe performance limits for the operational scenarios can be expressed in terms of appropriate parameters such as critical speeds for hunting, safe cusp amplitudes for dynamic curving, safe speeds at gage narrowing, safe maximum vertical irregularities at switches, and also in terms of safe maximum wheel L/V ratios. Preliminary data on these are presented for the vehicle types considered here.

2. For the assumed vehicle, OMNISIM simulation results show that truck hunting is not likely to occur for the vehicles considered here within their normal operational ranges. The lowest speed at which cyclic full-flange contact can occur is about 160 mph for the single car with non-equalized trucks on worn wheels and "hard" (stiff) track conditions.

3. For the assumed vehicle, the simulation results do not show any specific derailment potential for the vehicles under steady curving on tracks up to

20 deg curvatures at balance speeds. No problems are anticipated on cant deficient curves, permissible according to the existing FRA specifications (3 in. cant deficiency) for vehicles with similar parameters to those considered.

4. In the negotiation of a single cusp over a long wavelength, the example vehicle with non-equalized trucks did not perform as well as one with equalized trucks. The single level car with an equalized truck can negotiate a 2 in. cusp over a 39 ft wavelength on tracks up to 15 deg curvature, whereas with non-equalized trucks, it can negotiate no more than 1.5 in. cusp amplitudes on tracks with up to 5 deg curvature. The example bi-level car with a non-equalized truck can negotiate safely up to 2 in. cusp amplitudes (over a 39 ft wavelength). An example of the same car with an equalized truck has a safety margin up to 3 in. amplitude on tracks with a 10 deg curvature limit. These performance comparisons are made for the sake of developing an "engineering feeling" for the behavior of the different types of cars and are not intended as recommendations for their usage in revenue service.

5. The conclusion on safe performance comparisons of vehicles on "down and out" cusps is qualitatively similar to the foregoing conclusion for the single cusp. As an example, the single level car with an equalized truck can negotiate "down and out" cusps with 1.4 in. vertical and 0.7 in. lateral amplitudes safely on tracks with up to 10 deg curvatures, whereas the same car with non-equalized trucks is restricted to curvatures under 5 deg for safe negotiation of similar cusps. The sample bi-level cars can accommodate higher amplitude cusps than the single level cars in these scenarios.

6. A valuable key parameter is the "Gage Reduction Ratio" for the assessment of safety on gage narrowing scenarios. A scenario simpler than the traditional sinusoidal gage narrowing is identified and simulated, which is represented by a straight rail angled to represent a constant rate of gage reduction. The Gage Reduction Ratio is defined as the inverse of this constant. The maximum safe vehicle speed can be expressed as a function of the Gage Reduction ratio parameter (in field conditions, this is the equivalent of the maximum rate of gage variations, which can be easily measured). Typical safe maximum speeds are presented for the assumed vehicle parameters. The vehicle with equalized trucks has a higher safe speed than the one with non-equalized trucks for the same level of gage narrowing condition.

7. Negotiation of the AREA No. 8 crossover has been simulated in this study. An added cusp at the entrance to the frog causes a response similar to that investigated for the single cusp in a curve and shows the importance of retaining vertical wheel load during curving. Only the sample non-equalized trucks derailed and then only at the 3 in. amplitude cusp.

5.2 Recommendations

1. The safety assessment methodology presented here should be considered as preliminary and must be validated through testing. Testing should include both single and bi-level car bodies with equalized and non-equalized trucks. Testing should have the following objectives:

    - Car parameter characterization: The assumed parameters in this report need to be checked against experimental data.

    - Validation of OMNISIM: The vehicle-dynamic response under the various scenarios must be experimentally quantified using L/V ratios, truck and car body accelerations, and other test outputs, and compared with OMNISIM predictions.

    - Verification of Safe Performance Limits: The derived safe performance limits should be verified by tests specially designed for this purpose, including a few specific tests with predicted conditions for wheel climb derailment (slow speeds on high curvature tracks with cusp type imperfections).

    - Verification of simple test tools (under development) for characterizing car body and truck parameters.

2. Other potential safety critical scenarios (e.g., irregularities on both rails) should also be examined. Parametric studies using OMNISIM for such scenarios, as well as to extend the range of variables for scenarios considered in this report, should be conducted.

3. The OMNISIM program should be extended for use in the Windows environment for ease of its application in the vehicle dynamic simulation. This should be a single software package evaluating car safety under all the critical scenarios and giving safe dynamic performance limits for the scenarios.

6. REFERENCES

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