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Federal Railroad Administration

Validating a 70-ton Higher Speed Freight Truck Design: Phase II

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Washington, DC 20590

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13. ABSTRACT (Maximum 200 words)

Previously, Phase I of this project demonstrated viable market potential and operating economics for high speed freight service, and established that the higher speed truck (HST) prototype design is capable of meeting the dynamic and structural requirements expected in higher speed freight operations.

In Phase II, the design was evaluated through full-scale track testing per the track-worthiness requirements defined in the Association of American Railroads' (AAR) Manual of Standards and Recommended Practices (MSRP), Section D, Specification M-976 and those proposed in the Federal Railroad Administration's (FRA) Technical Report published August 2015, "Validation of A 70-Ton Higher Speed Freight Truck Design for Operations of up to 125 Mph—Higher Speed Freight Truck Vehicle Dynamics Analysis." The results confirm that the design successfully meets all dynamic performance criteria specified including high speed stability (hunting) up to 106.5 mph, which was the maximum achievable speed with the available locomotive.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lbs)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lbs)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lbs)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

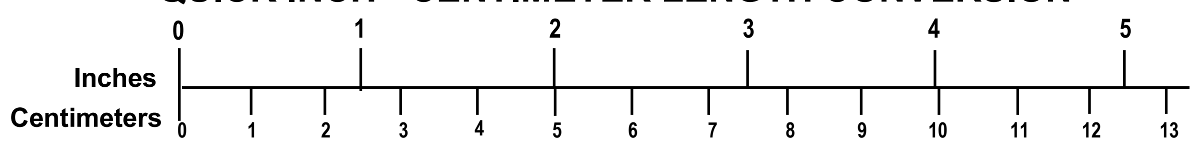
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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

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Executive Summary

From February 11, 2013, to October 10, 2014, the Federal Railroad Administration (FRA) contracted Sharma & Associates, Inc. (SA), and Transportation Technology Center, Inc. (TTCI), in the testing of SA's higher speed freight truck (HST) designed for 150 mph, 70-ton service, per the Association of American Railroads' Specification M-976, Truck Performance for Rail Cars, track-worthiness requirements. This testing demonstrated that the HST design is robust, track worthy, and successfully met all applicable M-976 safety performance criteria.

The high-speed stability testing above the M-976 limiting speed of 70 mph was carried out per specifications proposed in FRA's Technical Report published in 2013, "Higher Speed Freight Truck Vehicle Dynamics Analysis" [1] (referred to in this report as Proposed Rules). The empty and loaded car performance testing clearly demonstrated the inherent stability of the truck up to the maximum achieved speed of 106.5 mph (limited by the available locomotive). FRA plans to supply a locomotive with a maximum operating speed of 130 mph for further high-speed lateral stability testing of the 70-ton HST. Additionally, regarding to the 70-ton design, SA recommends the designing, building and testing of a braking system for speeds above 110 mph, to demonstrate safe braking performance up to 125 mph.

Moving forward, SA recommends the design of a HST for 286,000 lbf (286 kip) gross rail load (GRL) service. This is because new uses of 286 kip railcars are increasing and fit into previous and current market analyses that point to the need for higher speed freight movement in those heavier services. In fact, the industry's 10-year trend shows refrigerated car orders exclusively for 286-kip service.

The purpose of testing at the Transportation Technology Center (TTC) was to validate the HST design's functionality and track worthiness under industry standard acceptance requirements, and to gain confidence in the simulation model's capabilities to predict the HST vehicle's behavior at higher speeds.

In summary, the successful testing of the HST at the TTC included the following activities:

- Fitment of two HSTs under a box car modified to represent a refrigerated car
- Carbody and suspension characterization to acquire data on the vehicle's weight, center of gravity, roll, pitch and yaw inertias, and rigid body resonant modes for use in the vehicle dynamics simulation model
- Static lean testing of the vehicle to assess the vehicle's stability against rollover on a highly super-elevated track
- Wheel load equalization testing to determine the vehicle's ability to negotiate extremely poor-quality track such as that seen in yards
- Steady state curving, dynamic curving and spiral negotiation to determine the vehicle's ability to safely negotiate curved track geometry
- Twist & roll, pitch & bounce, and yaw & sway rigid body resonant mode on-track testing to determine the vehicle's ability to negotiate and respond to track geometry vertical and lateral deviations

- High speed lateral stability (hunting) testing to assess the ability of the HST for stable operation at speeds up to 125 mph

The results of this testing demonstrated that the 70-ton HST design met the acceptance criteria required for higher speed freight service in North America up to the maximum possible testing speed of 106.5 mph.

1. Introduction

Under the 2010 Broad Agency Announcement program, the Federal Railroad Administration's (FRA) Office of Research, Development and Technology funded research for the possible implementation of higher speed freight trucks (HST) for use in higher speed freight operations of up to 125 mph. This research is an important part of the agency's goal to promote higher speed rail service.

1.1 Background

FRA, through the Small Business Innovative Research (SBIR) program, previously funded a project at Sharma & Associates, Inc. (SA) to develop a freight truck for higher speed operations. Under this project, SA developed an HST design concept for speeds up to 150 mph, completed the detailed design, fabricated two prototypes, and successfully ran low speed tests in high degree curves.

Additionally, SA conducted a market analysis for higher speed freight needs and developed dynamic performance requirements for higher speed freight equipment for FRA to propose for future use [1]. SA also carried out dynamic performance simulations per the performance requirements developed, and conducted structural analysis of its HST design.

The market analysis showed that higher speed freight operations have the potential to meet current market needs and will most likely create new freight service opportunities. The market analysis revealed additional unforeseen revenue potential in the form of dedicated train sets like refrigerator car trains and long-distance shipments of short shelf life perishable produce as well as overnight city pairs (e.g., Chicago, IL, to St. Louis, MO) among other channels of higher speed opportunities.

The dynamic simulations and analyses were carried out to assess the performance of the HST against proposed dynamic performance requirements. Dynamic performance requirements were derived from state-of-the-art principles and methodologies for evaluating higher speed performance, including those called out in FRA's Technical Report published in 2015 [2]. The vehicle dynamics simulations were conducted for speeds from 95 mph to 130 mph in 5 mph increments on Class 7 track, in addition to simulations over Class 6 track at up to 115 mph. These simulations predicted that the HST will meet all dynamic performance test criteria.

Detailed structural evaluations of the HST frame and components also indicated that the HST design meets the structural strength criteria, suitable for high speed operations.

In summary, the previous effort demonstrated good market potential and operating economics for higher speed freight service, and established that the HST prototype could meet the dynamic and structural requirements expected in higher speed freight operations.

The purpose of this Phase II effort was to evaluate and confirm the dynamic performance of the prototype HSTs through field testing including the higher speed stability regime.

The following sections describe the test methodology, performance criteria and on-track test regimes and discuss the test results.

1.2 Organization of the Report

This report introduces the basis for the research and testing in Section 1, while Section 2 provides the objectives and methodology for the testing. Section 3 describes the test setup that includes the vehicle and instrumentation information, while Section 4 gives an in-depth review of the model simulation. Section 5 provides the testing results, while Section 6 offers concluded information and recommendations. Following the report, Appendix A gives a more detailed discussion of each simulated regime, associated results, and acceptance criteria.

2. Test Objective

The objective of this Phase II effort was to test, evaluate and confirm the dynamic performance of the prototype HSTs using the railroad vehicle testing facilities at the TTC located in Pueblo, CO.

2.1 Test Methodology, Regimes and Performance Criteria

As shown in Table 1, testing followed the performance requirements of the Association of American Railroads' (AAR) Specification M-976, Truck Performance for Rail Cars from AAR's Manual of Standards and Recommended Practices (MSRP) [3]. Instead of using a standard cover hopper or a long-covered hopper, the test vehicle was chosen based on selection criteria outlined in Section 3.1.1.

Table 1 – AAR MSRP M-976 Specification

Regime		Car	Section	Criteria	Limiting Value
Hunting	Empty	SC	4.1.2.4	Maximum lateral acceleration (G)	1.5[a/]
				Standard deviation	0.13
Steady State Curving	Empty and Loaded	SC	4.1.2.1	95th percentile maximum wheel lateral over vertical (L/V)	0.8
				95th percentile maximum axle sum L/V	1.5
Curve Resistance	Loaded	SC	4.1.2.2	Average resistance (lb/ton/deg) (1.5, 4.0, 7.5, 10.0 degree curves)	0.4
Spiral	Empty and Loaded	SC	4.1.2.3	Minimum vertical load (%)	10[b/]
		LC		Maximum wheel L/V	1.0[c/]
				Maximum axle sum L/V	1.5[c/]
Twist, Roll	Empty and Loaded	SC	4.1.2.5	Maximum axle sum L/V	1.5[c/]
				Minimum vertical load (%)	10[b/]
				Dynamic load augment (G)	1.0
	Loaded			Spring capacity maximum (%)	95
Pitch, Bounce	Empty and Loaded	SC	4.1.2.5	Minimum vertical load (%)	10[b/]
				Dynamic load augment (G)	1.0
	Loaded			Spring capacity maximum (%)	95
Yaw, Sway	Loaded	SC		Maximum L/V truck side	0.7[d/]
				Maximum axle sum L/V	1.5[c/]
Dynamic Curving	Loaded	SC	4.1.2.5	Maximum wheel L/V	1.0[c/]
				Maximum axle sum L/V	1.5[c/]
				Minimum vertical load (%)	10[b/]

* Key: SC: Standard Covered Hopper—LC: Long Covered Hopper

a) Peak to peak

b) Not to fall below indicated value for a period greater than 50 milliseconds a distance greater than 3 ft. per instance

c) Not to exceed indicated value for a period greater than 50 milliseconds a distance greater than 3 ft. per instance

d) Not to exceed 0.6 for a duration equivalent for 6 feet of track

The M-976 requirements specify the test regimes, and associated criteria, to assess the vehicle's steady state, resonance and transient dynamic behavior.

M-976 test regimes limit the testing speeds to 70 mph. The performance criteria provided in the Proposed Rules was used for the high-speed stability tests above 70 mph [1].

To ensure safety during testing, SA and the Transportation Technology Center, Inc. (TTCI) developed a protocol for each test regime to analyze results and determine follow up steps during the testing process. Each test regime was stepped through in speed increments with the measured results compared to simulation results. These comparisons were made between each speed change to assess whether or not it was safe to proceed to the next speed.

A representative vehicle, discussed in the following section, was procured and two HSTs were installed under it for testing.

3. Test Setup

3.1 Test Vehicle

3.1.1 Requirements – Car Selection

The carbody used for this HST testing was chosen based on the following criteria:

- Must be a refrigerator car or a box car that is a close representation of a refrigerator car

  This requirement was put forth based on the market analysis that indicated that one of the most viable uses of higher speed freight equipment would be in the shipments of short shelf life produce from the west coast to the east coast.

- Must have 45-feet or greater truck center spacing
- Must be able to accept the HSTs with minimal modifications

These criteria led to the selection of a 100-ton box car, shown below in Figure 1, equipped with its original trucks.

Figure 1 – Carbody used for testing HSTs

3.1.2 Carbody Modifications

For the HSTs to fit under the box car, some minor modifications to the under-frame structure were needed. The following lists the general modifications that were made to the carbody:

- Locked-out the sliding sill
- Moved the lateral channels outboard under the carbody frame, in the truck area
- Moved the longitudinal channels outboard under the carbody frame, in the truck area
- Moved the in-board flanges outwards on the center-plate weldment
- Applied shims to the carbody bolster for proper constant contact side bearing setup

3.2 Instrumentation

3.2.1 Instrumented HST

It is crucial to monitor vertical and lateral wheel loads during track worthiness testing of any new railcar or truck design. These measurements allow for the assessment of safe operations as the test speeds are increased. Due to the prototype HST design having a damper bracket in line with the axle center line and the currently available Instrumented Wheel Sets (IWS) having an electrical connector coming out the end of each end of the axle, the HSTs could not be outfitted with such IWSs. In lieu of the IWS, SA, and TTCI agreed to instrument the H-frame of one of the HST assemblies to obtain vertical and lateral wheel loads.

Using finite element analyses of the truck frame, strain gauges and physical loading of the frame, the HST frame was calibrated to gain a high level of confidence in the wheel loads estimates.

A finite element analysis method was used to determine strain gauge locations for measuring vertical and lateral loads. Figure 2 shows strain gauge locations on the bottom plates of the sideframes and the bolster. Figure 3 shows the strain gauge locations on the side plates of the sideframes.

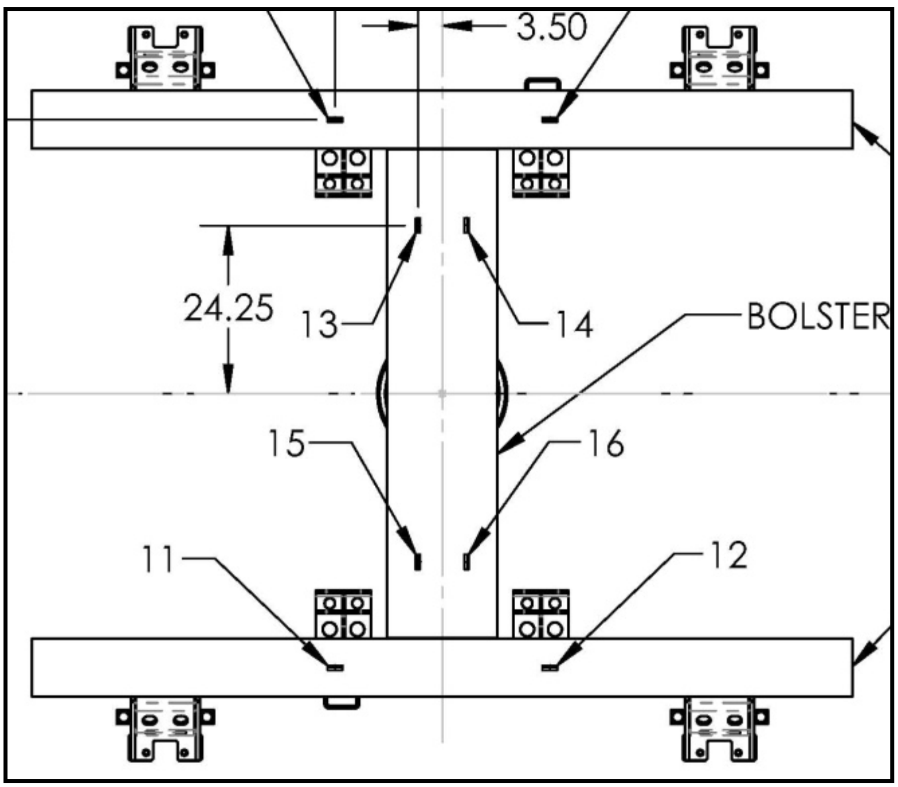

Figure 2 – Bottom plate strain gauge locations

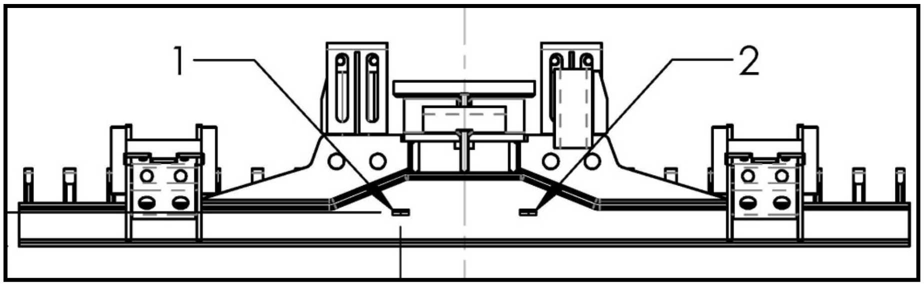

Figure 3 – Side plate strain gauge locations

3.2.2 Other Instrumentation

Additional transducers were used for measuring the parameters needed to calculate values for assessment against the AAR M-976 and Proposed Rules performance criteria. The following transducers were applied and the corresponding parameters were measured and collected during testing:

- Linear Variable Differential Transformers - Primary vertical and lateral suspension displacements, truck rotation
- Accelerometers - Truck lateral acceleration, carbody vertical and lateral accelerations
- Gyros - Carbody roll

3.2.3 Data Acquisition System (DAS)

TTCI supplied the data acquisition system (DAS) and collected the data. Details of the DAS are in TTCI's HST test report [1].

3.2.4 Test Configuration

The HST test consist configuration included a locomotive, the instrumentation car, the HST equipped test car, and a trailing buffer car. The locomotive was rated for a maximum speed of 105 mph. Figure 4 shows the test consist without the locomotive.

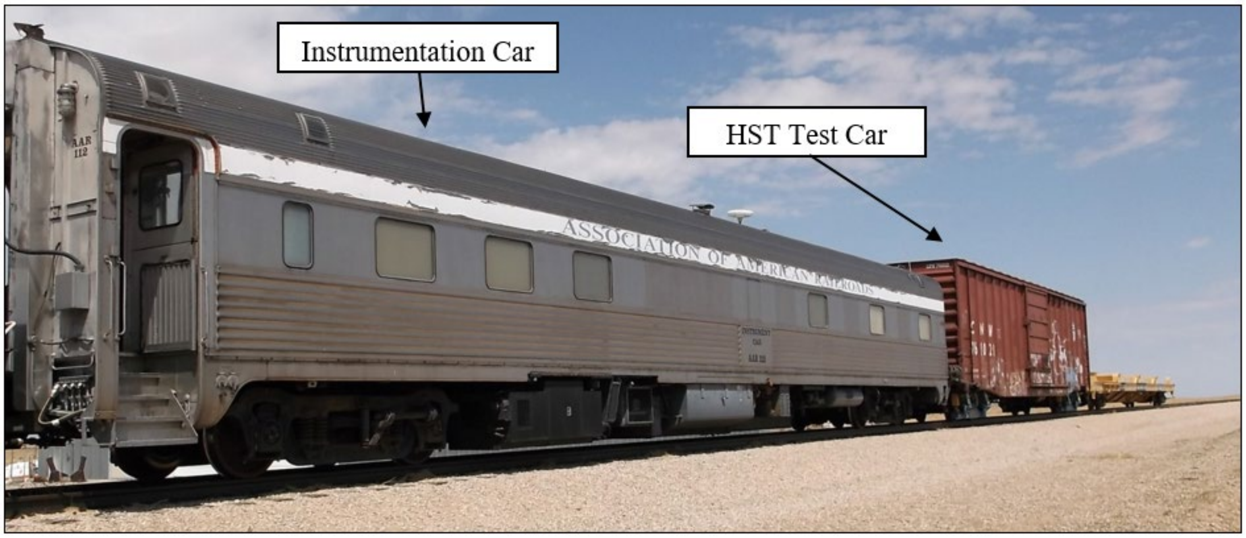

Figure 4 – HST test configuration (locomotive not shown)

3.3 Test Bed and Regimes

The track worthiness testing was conducted at the TTC over the test regimes as required by M-976. A brief overview of the regimes and speeds is provided below:

- Precision Test Track (PTT)
  - Twist & Roll – 10 to 70 mph
  - Pitch & Bounce – 30 to 70 mph
  - Yaw & Sway (Y&S) – 30 to 70 mph
- Wheel Rail Mechanisms Loop (WRM)
  - Constant Curving – Unbalance speeds of -3, 0 and 3 inches, clockwise (CW) and counterclockwise (CCW)
  - Dynamic Curving – 10 to 32 mph in 2 mph increments, CW and CCW
- Railroad Test Track (RTT)
  - Lateral Stability – 50 to 105 mph, CW and CCW

Figure 5 shows the TTC track layout and locations of the various test regimes.

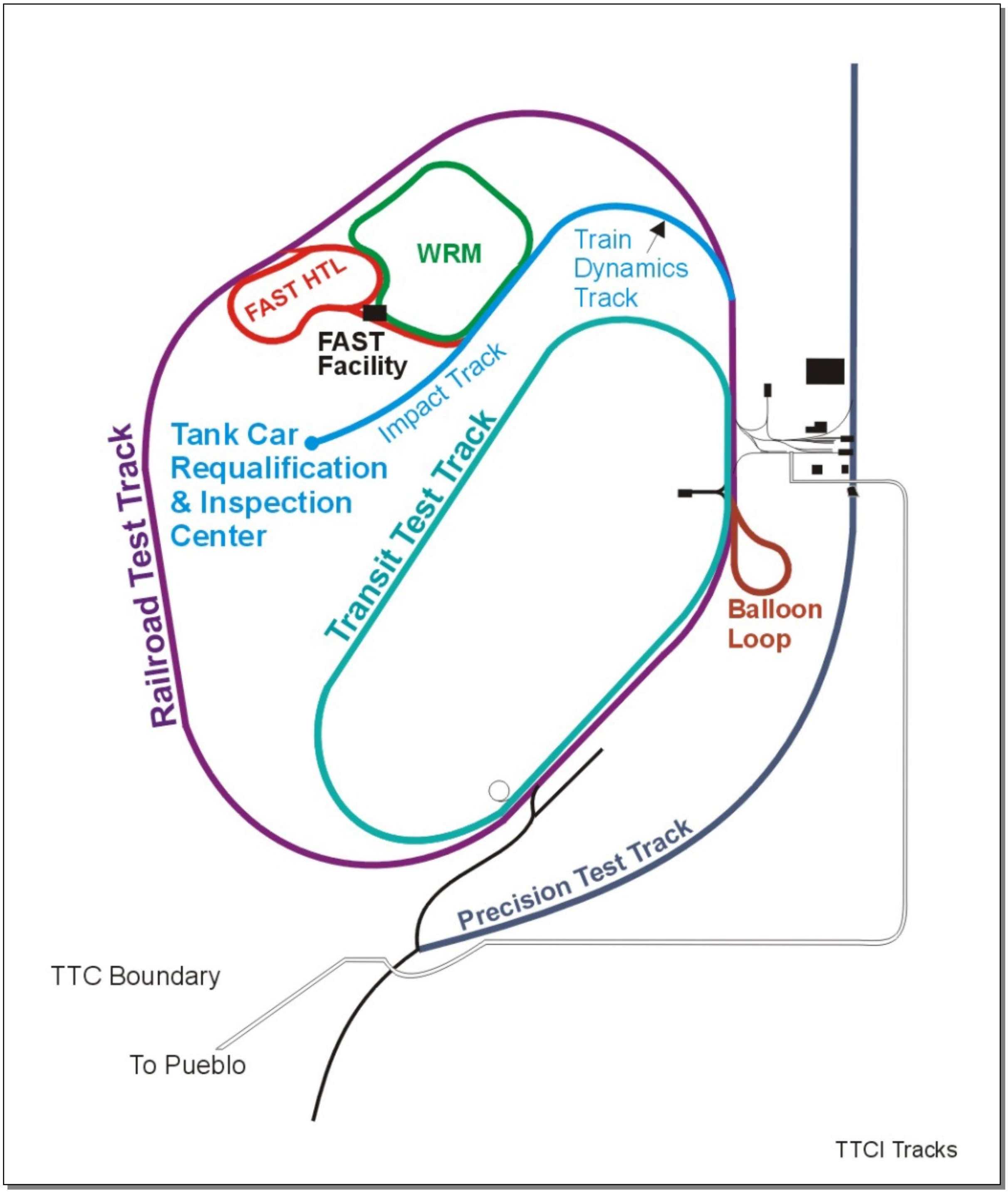

Figure 5 – TTC test track layout

4. Dynamic Model Simulations and Analysis

Prior to testing, SA developed a vehicle dynamics model of the test car equipped with the HSTs in Vampire® to simulate the on-track behavior over the test regimes that were to be used at the TTC. This analysis was crucial to ensuring confidence in the design and to help in monitoring performance trends for safe operations during testing. Table 2 shows a summary of these simulations with Pass/Fail results for the simulated regimes. This summary is followed by the numerical results for all regimes inclusive of the limiting criterion value and the closest value of the parameters from the modeling results. Appendix A gives a more detailed discussion of each regime, associated results, and acceptance criteria.

Table 2 – Pre-test vehicle dynamics simulation results

Regime	Limiting Value	Empty Car	Loaded Car
Steady-state Curving		**Passed**	**Passed**
Max. wheel L/V	0.8	0.52	0.54
Max. axle-sum L/V	1.5	1.0	1.0
Limiting Spiral		**Passed**	**Passed**
Max. wheel L/V	1	0.78	0.64
Max. axle-sum L/V	1.5	1.28	1.15
Min. vertical wheel load	10%	47.7%	58.2%
Dynamic Curving		**Passed**	**Passed**
Max. peak-to-peak roll (degrees)	6.0	4.8	4.8
Min. vertical wheel load	10%	0.1%*	26%
Max. wheel L/V	1.0	0.8	0.8
Max. axle-sum L/V	1.5	1.3	1.3
Yaw & Sway (Y&S)		**Passed**	**Passed**
Max. truck-side L/V	0.7	0.12	0.45
Max. axle-sum L/V	1.5	0.42	1.19
Twist & Roll (T&R)		**Passed**	**Passed**
Max. peak-to-peak roll (degrees)	6.0	1.3	0.7
Min. vertical wheel load	10%	1.8%*	40.3%
Max. axle-sum L/V	1.5	0.8	0.9
Dynamic Augment Acceleration (g)	1.0	0.21	0.11
Max. spring capacity	95%	Not Required	89.7
Pitch and Bounce (P&B)		**Passed**	**Passed**
Min. vertical wheel load	10%	62.8%	72.7%
Dynamic augment acceleration (g)	1.0	0.5	0.3
Max. spring capacity	95%	Not Required	87.7%
Lateral Stability		**Passed**	**Passed**
Max. peak-to-peak lateral acceleration	1.5 g	0.07 g	0.4 g
Lateral acceleration standard deviation	0.13 g	< 0.01g	< 0.01 g

* 50 millisecond duration and 3 ft. distance criteria not exceeded

5. Testing and Results

5.1 Characterization Tests

Car characterization (rigid body resonance) tests were carried out on the test car using TTCI's characterization trucks to determine roll, pitch, and yaw moments of inertia and carbody center of gravity location. These data were used to update the vehicle dynamics model for validation purposes prior to the on-track testing.

5.2 Static Lean

Static lean tests were performed on the test vehicle equipped with HSTs in empty and loaded conditions, per Title 49 Code of Federal Regulations (CFR) Section 213.329 [4], to determine wheel unloading for specified cant deficiencies.

Table 3 lists the criteria for lean angle and the minimum vertical wheel load, along with corresponding values obtained from the tests. The HST vehicle passed the performance criteria for both the empty and loaded car conditions.

Table 3 – Static lean test results

Test Parameter	Limiting value	Empty Car	Loaded Car
Maximum super-elevation	7 inches	7 inches	7 inches
Minimum wheel load (any wheel), as a percentage of static wheel load	>60%	73%	70%
Maximum roll angle between vehicle floor and horizontal (degrees)	<8.6	7.5	8.2

5.3 Wheel Load Equalization

Wheel load equalization tests were carried out to determine vertical wheel unloading per American Public Transportation Association (APTA) specification SS-M-014-06 [3]. This test regime is used for evaluating a vehicle's ability to negotiate twisted track without any wheel lift.

The HSTs are considered APTA Class R equipment and are expected to comply with Class R acceptance criteria. Table 4 shows the results from the load equalization tests. It is clear that the HST did not pass the minimum vertical wheel load criteria in 3 of the 32 test conditions. Due to small exceedances, TTCI discussed with SA whether to continue testing or not, and deemed it safe to continue with the remaining stationary and track testing.

Table 4 – Wheel load equalization results

Car Condition	Wheel (Lifted/Dropped)	Maximum Wheel Unloading Results (Location)			
		2-inch Lift	2-inch Drop	2.5-inch Lift	2.5-inch Drop
Empty	Axle 1 Left (L1)	50% (R1)	72% (L1)	63% (R1)	89% (L1)
	Axle 2 Left (L2)	54% (R2)	64% (L2)	67% (R2)	75% (L2)
	Axle 1 Right (R1)	56% (L1)	67% (R1)	70% (L1)	82% (R1)
	Axle 2 Right (R2)	48% (R1)	73% (R2)	59% (R1)	90% (R2)
Loaded	Axle 1 Left (L1)	30% (L2)	44% (L1)	38% (L2)	54% (L1)
	Axle 2 Left (L2)	33% (L1)	42% (L2)	40% (L1)	52% (L2)
	Axle 1 Right (R1)	30% (R2)	42% (R1)	38% (R2)	53% (R1)
	Axle 2 Right (R2)	29% (R1)	44% (R2)	37% (R1)	53% (R2)
* **Note**: Max. Allowable wheel unloading: 2-inch lift or drop: 65%; 2.5-inch lift or drop: 100%					

5.4 Curve Negotiation

Curve negotiation tests were conducted on the Wheel Rail Mechanisms loop as shown in Figure 6. The steady state curving tests were conducted over the 4, 7.5, 10, and 12-degree curvature segments at speeds of 12 mph, 24 mph, and 32 mph in clockwise as well as counter-clockwise directions. The dynamic curving tests were conducted over the 10-degree bypass segment at speeds from 10 to 32 mph in 2 mph increments in clockwise and counter-clockwise directions.

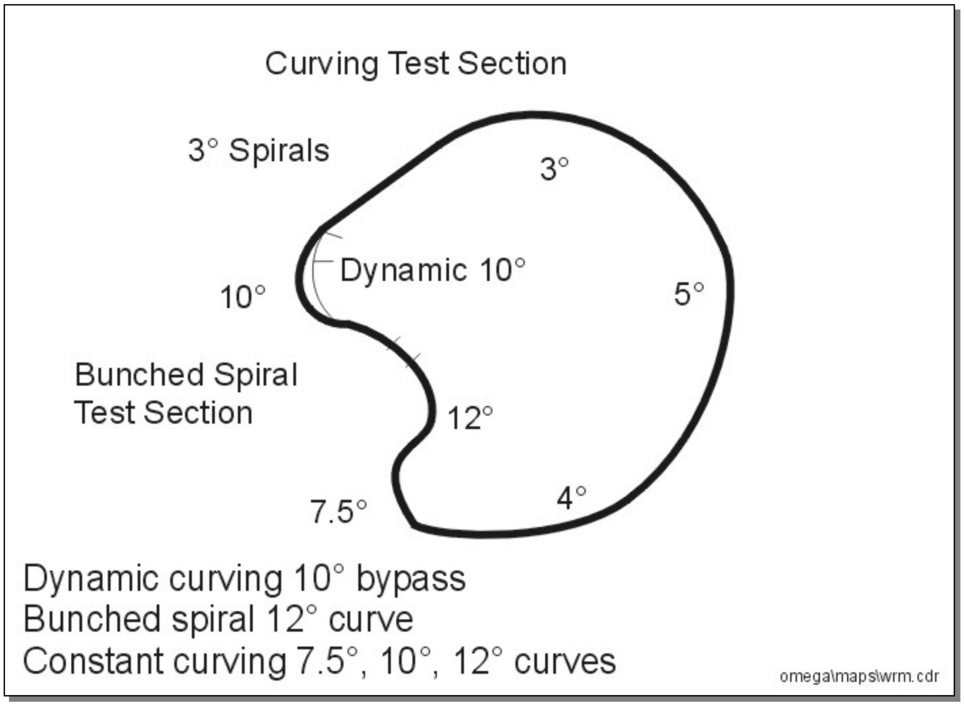

Figure 6 – TTC's wheel and rail mechanism loop

Table 5 and Table 6 show the results of steady-state and dynamic curve testing results. The HST successfully met the criteria of wheel L/V, carbody roll angle and minimum wheel loads under both empty and loaded car conditions with a significant margin. It should be noted that freights trucks designed for higher speed operations generally have poor curving abilities. The HSTs have demonstrated excellent curving abilities in combination with excellent high-speed stability as will be shown in Section 5.8.

Table 5 – Steady-state curving results

Steady-state Curving Criterion	Limiting Value	Empty Car Results		Loaded Car Results	
		Clockwise	Counter-clockwise	Clockwise	Counter-clockwise
Maximum wheel L/V	0.8	0.26	0.43	0.27	0.26

Table 6 – Dynamic curving results

Dynamic Curving Criteria	Limiting Value	Empty Car Results		Loaded Car Results	
		Clockwise	Counter-clockwise	Clockwise	Counter-clockwise
Maximum Peak-to-Peak Roll (degrees)	6	1.5	1.6	1.7	1.4
Minimum Vertical Load	10%	53%	57%	68%	65%

5.5 Yaw & Sway

Y&S tests were conducted on the Y&S test section of the PTT to excite the Y&S modes of the test vehicle. This section consists of five sinusoidal-shaped alignment perturbations of wavelength of 39 feet and 1 inch amplitude. The entire section has a track gage that is 1 inch wider than the standard gage of 56 ½ inches.

Tests were conducted at speeds from 30 to 70 mph in 5 mph increments using the loaded car configuration. Table 7 shows the HST vehicle performed extremely well within the performance criteria.

Table 7 – Yaw & sway test results

Criteria	Limiting Values	Loaded Car Results
Maximum Truck Side L/V	0.6	0.1
Maximum Axle Sum L/V	1.5	<0.1

5.6 Twist & Roll

Tests were conducted on the T&R test section of the PTT to excite the T&R modes of the test vehicle. This section consists of 10 staggered cusp-shaped perturbations having wavelength of 39 feet and 3/4-inch amplitude. The tests were carried out at speeds from 10 to 30 mph in 2 mph increments and from 30 to 70 mph in 5 mph increments, for both empty and loaded conditions.

Table 8 shows the T&R test results where. The HST vehicle met all four requirements: maximum roll angle, minimum vertical load, as well as dynamic augment for carbody vertical acceleration and loaded spring capacity.

Table 8 – Twist & roll test results

Criteria	Limiting Values	Empty Car Results	Loaded Car Results
Maximum Roll (degrees)	6	2.8	2.4
Minimum Vertical Load	10%	42%	58%
Dynamic Augment Acceleration (g)	1.0	0.6	0.6
Loaded Spring Capacity Maximum	95%	Not Required	92%

5.7 Pitch & Bounce

Tests were conducted on the P&B test section of the PTT to excite the P&B modes of the test vehicle. The P&B section consists of 10 parallel cusp-shaped perturbations having a wavelength of 39 feet and 3/4-inch amplitude. The tests were conducted at speeds from 30 to 70 mph in 5 mph increments for both empty and loaded conditions.

Table 9 lists the results from the P&B testing. Although the spring deflection capacity maximum was exceeded by 4 percent, the other two measurement criteria were well below their respective limiting values. The diminished spring capacity beyond the criteria limit might be addressed through minor modifications to the suspension system stiffness and damping.

Table 9 – Pitch & bounce test results

Criteria	Limiting Values	Empty Car Results	Loaded Car Results
Minimum Vertical Load	10%	58%	48%
Dynamic Augment Acceleration (g)	1.0		0.70
Loaded Spring Capacity Maximum	95%	Not Required	99%

5.8 Lateral Stability (hunting)

Lateral stability (hunting) tests were conducted on the RTT. The RTT is a 13.5-mile loop consisting of four 0.86 degree curves, one 1.25-degree curve and tangent sections. Tests were conducted at speeds from 50 mph to the maximum achievable in 5 mph increments, in clockwise and counter-clockwise directions, for both empty and loaded conditions.

Since the maximum test speed for M-976 is 70 mph, the higher speed tests were carried out per the criteria specified in the Proposed Rules. The maximum speed achieved was 106.5 mph, limited by the operating speed of the locomotive available for testing.

Table 10 below shows the HSTs' successful results from the higher-speed hunting tests. The acceleration values are far lower than the limiting performance criteria, which demonstrates that the truck is highly stable.

Table 10 – Lateral stability (hunting) test results

Criterion	Limiting Value	Empty Car Results	Loaded Car Results
Max. Lateral Acceleration, Peak-to-Peak (M-976)	1.5 g	0.3 g	0.2 g
Max. Standard Deviation of Lateral Acceleration (M-976)	0.13 g	0.04 g	0.05 g
Max. Carbody Lateral Sustained Acceleration, rms (Proposed Rules)	0.12 g	0.03 g	0.03 g
Max. Carbody Vertical Acceleration, Loaded Car Only (Proposed Rules)	≤1 g dynamic augment	N/A	0.4 g

6. Conclusion

SA's higher speed freight truck design for 70-ton service was tested for track worthiness per currently accepted industry standards included in AAR's MSRP specification M-976. Since M-976 test regimes limit test speeds to 70 mph, high speed stability testing above 70 mph was conducted per specifications outlined in FRA's Technical Report published in 2013 [1].

Vehicle characterization tests were carried out to confirm the car weight, inertia, and truck suspension parameters.

To prepare for on-track testing, vehicle dynamics simulations were conducted using parameters obtained from vehicle characterization results. These simulation results provided the necessary data to evaluate and ensure safe operations during high speed testing.

The vehicle dynamic tests for resonance in T&R, P&B, and Y&S were conducted up to the maximum speed of 70 mph per M-976 requirements.

Curving tests were carried out for steady-state curve negotiation, spiral entry and exit, and dynamic curving under lateral and vertical geometry defects in curves.

In all the test regimes, the HST successfully met the performance criteria, except for a minor exceedance of spring capacity in the loaded car P&B regime, and wheel unloading for the empty car wheel load equalization with 2.5-inch wheel drop.

High speed stability tests were conducted up to a maximum speed of 106.5 mph. The locomotive used in the test could not go faster. The HST truck was very stable up to the highest test speed achieved, and met the performance criteria specified in M-976 as well as those proposed in FRA's Technical Report published in 2013 [1].

Overall, test performance of the HSTs shows that a freight truck can be capable of higher speed service.

6.1 Recommendations

Overall, the HST design has successfully met the performance criteria generally accepted in the industry. To further advance the cause of higher speed freight service capabilities in the rail industry, SA recommends the following efforts:

1. Support design, prototyping and testing of a braking system for the 70-ton HST trucks for safe braking performance up to 125 mph.
2. Support design, prototyping and testing of an HST for 286,000 lbf (286 kip) gross rail load (GRL) service. This is worthy in view of the increasing use of 286 kip railcars in transporting refrigerated goods, identified in the previous market analysis of higher speed freight service. In fact, the industry's 10-year car purchase trend shows refrigerated car orders exclusively for 286,000 lbf GRL (286 kip GRL) service.

7. References

[1] Federal Railroad Administration, "Higher Speed Freight Truck Market Analysis," Technical Report No. DOT/FRA/ORD-13/32, U.S. Department of Transportation, Washington, DC, July 2013.

[2] Federal Railroad Administration, "Validation of A 70-Ton Higher Speed Freight Truck Design for Operations of up to 125 Mph—Higher Speed Freight Truck Vehicle Dynamics Analysis," Technical Report No. DOT/FRA/ORD-15/27, U.S. Department of Transportation, Washington, DC, 2015.

[3] Association of American Railroads, "Truck and Truck Details - Truck Performance for Rail Cars," AAR.

[4] Federal Register, "Vehicle/Track Interaction Safety Standards; High-Speed and High Cant Deficiency Operations: Final Rule," *Federal Register,* vol. 78, no. 49, 13 March 2013.

[5] American Public Transportation Association Standards, "Standard for Wheel Load Equalization of Passenger Railroad Rolling Stock," APTA, 2014.

Appendix A.
Dynamic Model Simulations and Analysis

Static Lean

The goal of the static lean test is to ensure that a railcar parked on a curve having the maximum super-elevation allowed under FRA regulations is not in danger of rolling over. The criteria for evaluating safety against the propensity to roll over are as follows:

- Maximum carbody roll angle ≤8.6 degrees
- Minimum wheel load ≥60% of the nominal static wheel load.

Vampire® simulations of both the empty and loaded railcar equipped with HSTs were conducted at 4 and 6 inches of super-elevation. Figure A1 shows the carbody roll angles are. The maximum lean was 6.5 degrees, with the loaded car on 6 inches of super-elevation, which is well below the limit of 8.6 degrees.

The minimum vertical wheel loads for these four cases were determined by evaluating the wheel load on each of the eight wheels and are shown in Figure A2. The minimum wheel load was 69.4 percent, again with the loaded car on 6 inches of super-elevation. This is well above the minimum limit of 60 percent and therefore the truck passed the static lean test.

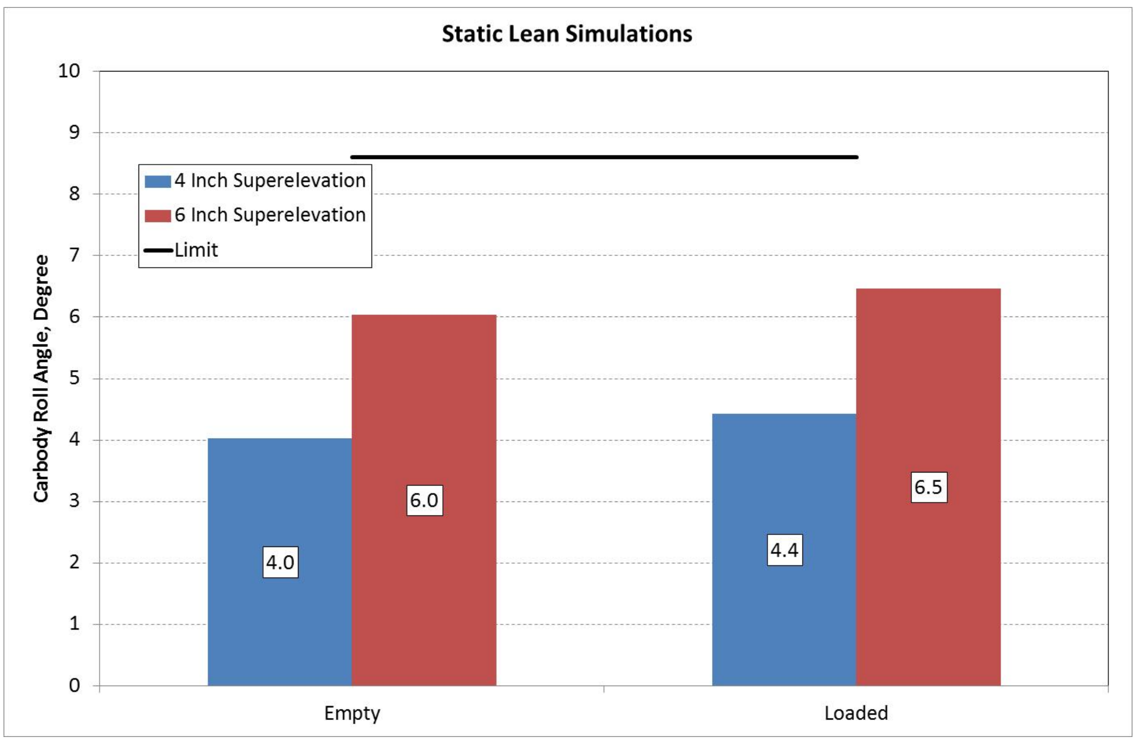

Figure A1 – Static lean carbody roll angle

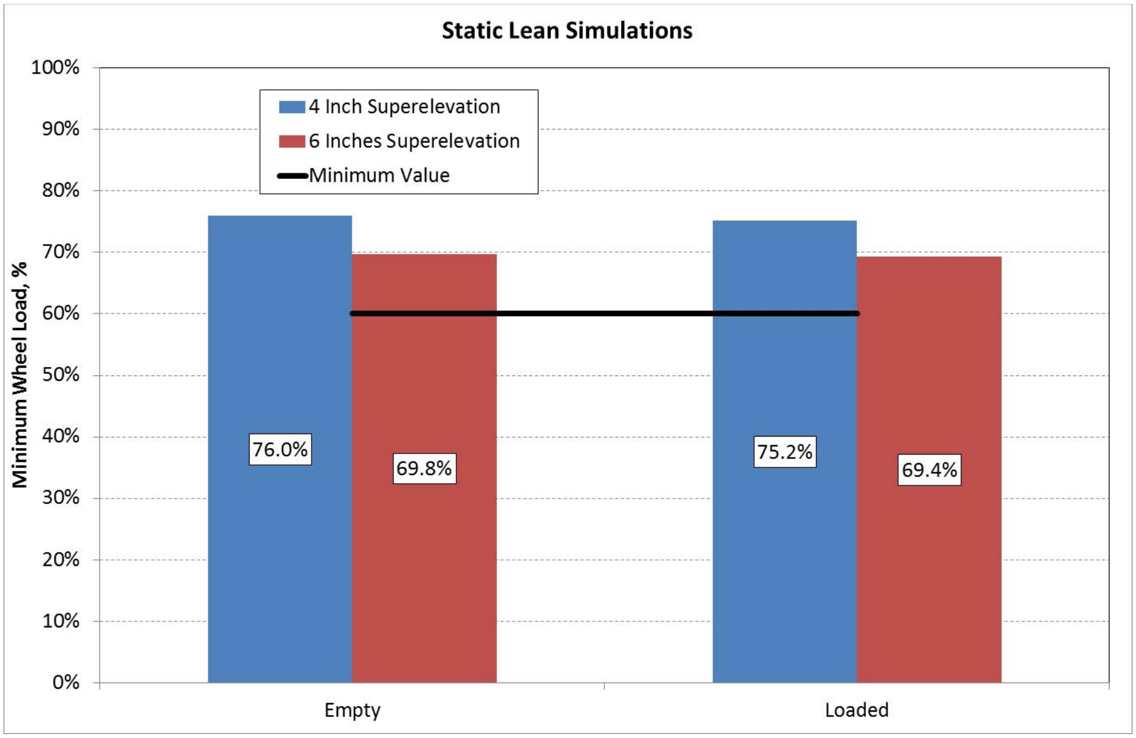

Figure A2 – Static lean minumum vertical wheel load percentage

Wheel Load Equalization

Wheel load equalization testing measures the ability of the truck to remain on the track while negotiating severely warped track at low speeds, such as in yards. The wheel load equalization test includes lifting a single wheel of the truck to a maximum of 3 inches, and also dropping the wheel down to a maximum of 3 inches. This is conducted on all four wheels of one truck, one wheel at a time.

The American Public Transportation Association (APTA) Class R criterion to evaluate this requirement is that the minimum wheel load seen by the truck must not fall below 67 percent when any wheel is either lifted or dropped by 2 inches, and all wheels must remain on the track with 2.5 inches of either lift or drop at any one wheel.

The results of the Vampire® simulations of wheel lift and drop are shown in Figures A3 and A4, respectively. As expected, the car unloads more in the empty condition than in the loaded condition. However, the APTA criterion is satisfied in both empty and loaded conditions.

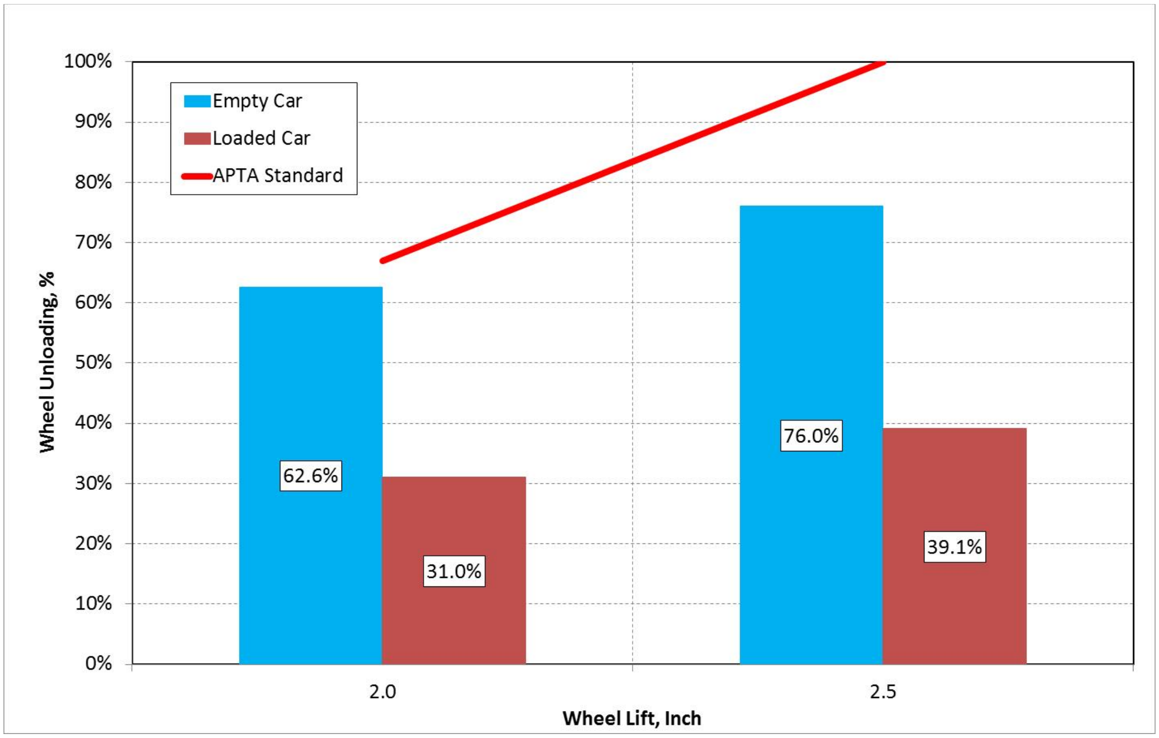

Figure A3 – Wheel lift test; wheel unloading

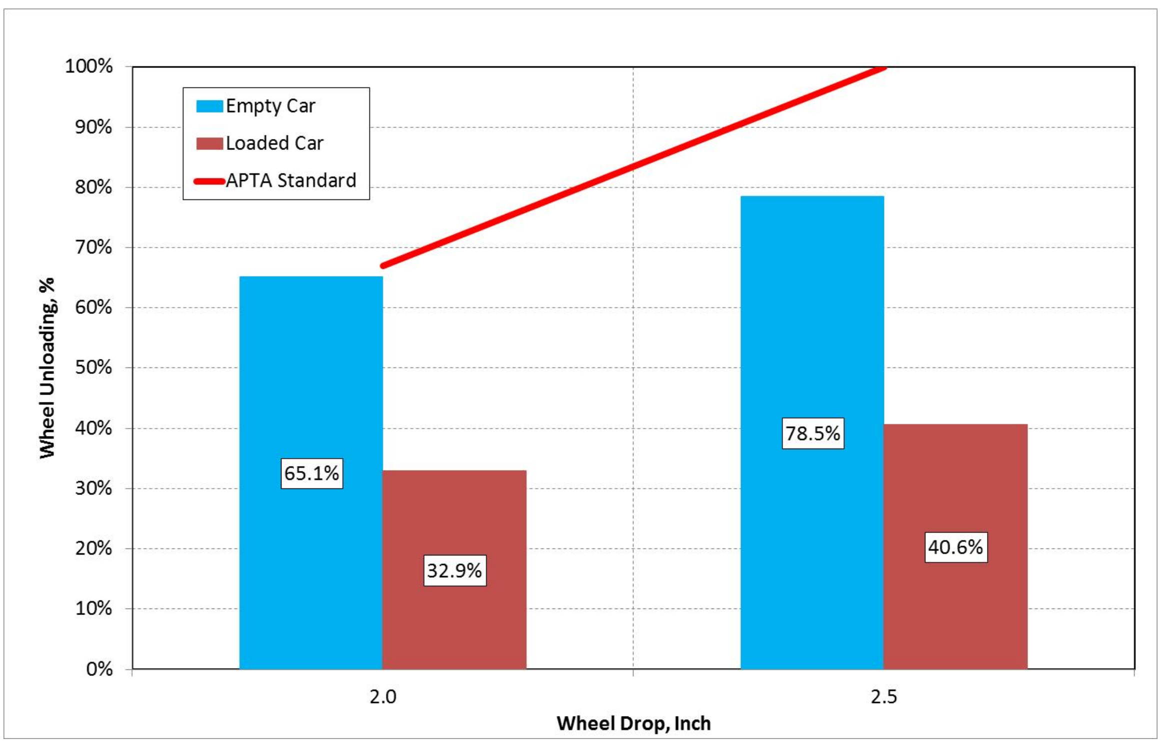

Figure A4 – Wheel drop test; wheel unloading

Steady-State Curving

The steady-state curving regime evaluates the performance of the truck against wheel climb in a long, constant radius curve. The criteria a truck must satisfy are that the maximum wheel L/V ratio cannot be greater than 0.8, and the maximum axle-sum L/V cannot be greater than 1.5.

The truck was evaluated in 6, 8, 10, and 12 degree curves at speeds equivalent to 3 inches of cant excess (under balance speed), balance speed, and 3 inches of cant deficiency (over balance speed). Table A1 shows the steady-state curving regime simulation matrix.

Table A1 – Steady-state simulation matrix

Curvature, degree	Super-elevation, inch	Speed (mph)		
		3 inches under balance	Balance speed	3 inches over balance
6	5.15	22.6	35.0	44.1
8	5.04	19.1	30.0	37.9
10	4.38	14.0	25.0	32.5
12	5.25	16.4	25.0	31.3

The results of the Vampire® simulations for of the steady-state curving test regime are shown in Figure A5 and Figure A6 for the empty car, and Figures A7 and A8, for the loaded car. In each figure, the values plotted represent the maximum L/V in the truck for the indicated condition. Both the empty and loaded car configurations passed all criteria.

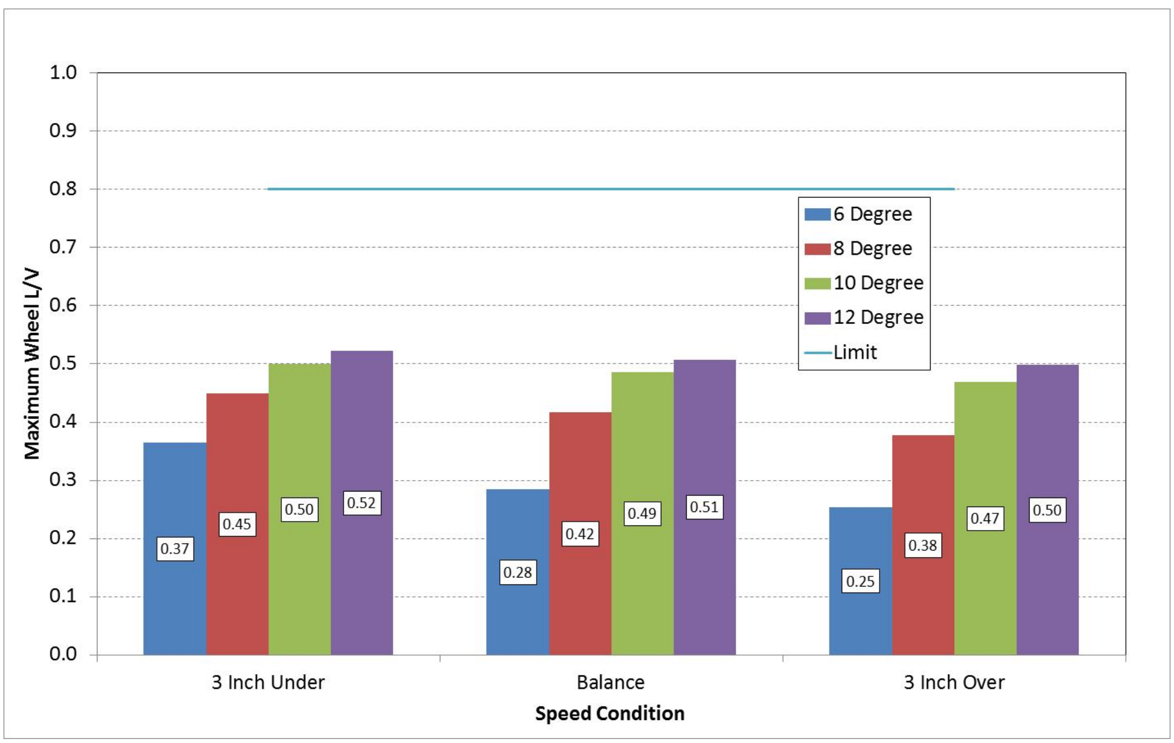

Figure A5 – Steady-state curving empty car wheel L/V ratios

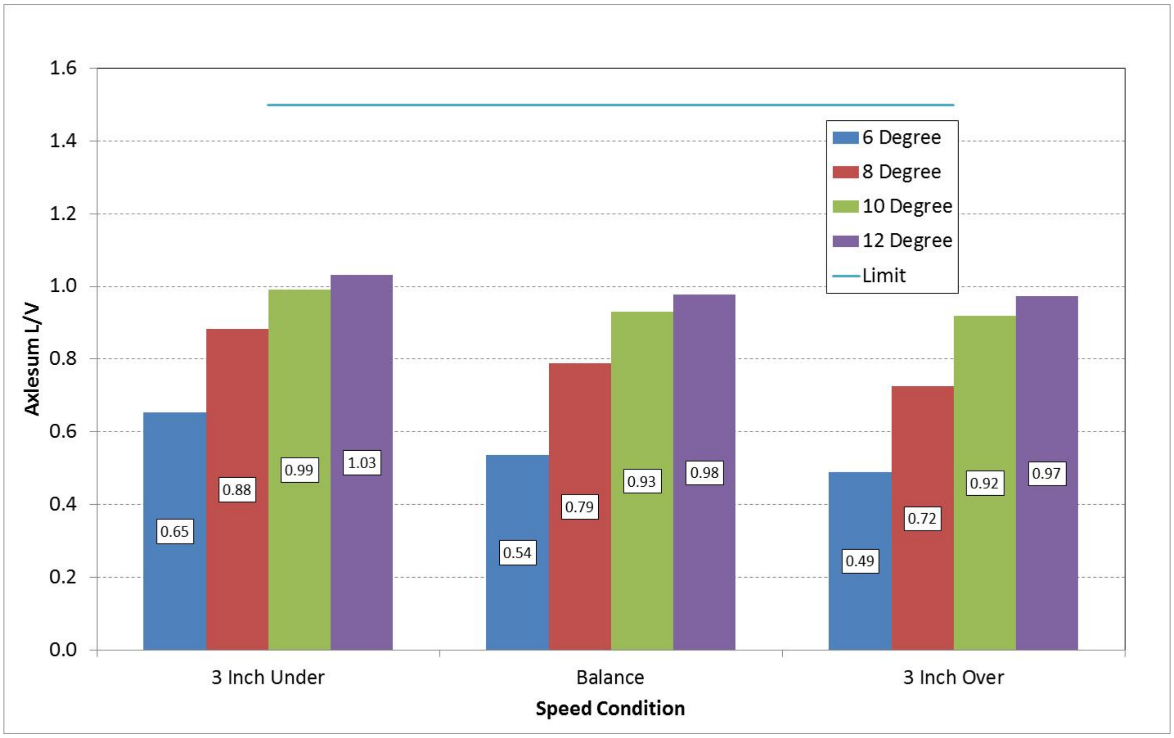

Figure A6 – Steady-state curving empty car axle-sum L/V ratios

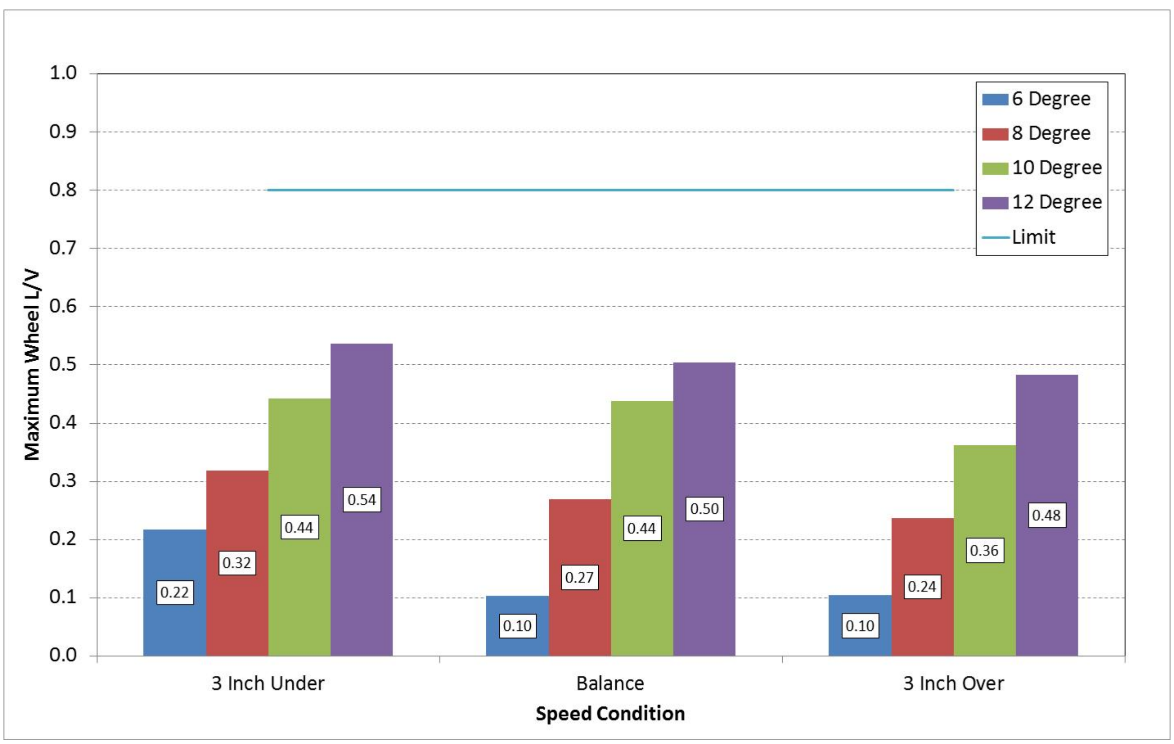

Figure A7 – Steady-state curving loaded car wheel L/V ratios

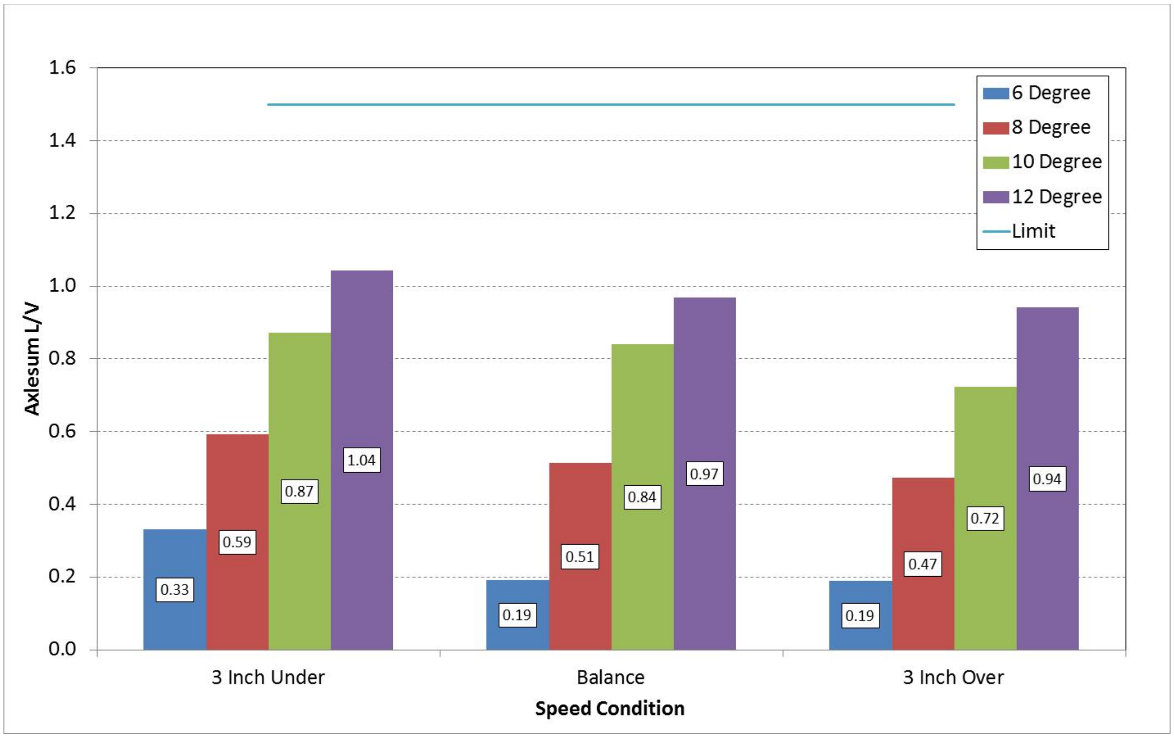

Figure A8 – Steady-state curving loaded car axle-sum L/V ratios

Limiting Spiral

The limiting spiral regime evaluates the performance of the truck while negotiating tight spirals (curve entry and exit), which create conditions for a carbody to experience twist. The criteria that must be satisfied in this regime include wheel L/V ratio limit of 1.0, axle sum L/V ratio limit of 1.5, and a minimum wheel load limit of 10 percent. The speed and curvature simulation matrix is shown in Table A2.

Table A2 – Limiting spiral simulation matrix

Curvature, degree	Super-elevation, inch	Speed (mph)		
		3 inches under balance	Balance speed	3 inches over balance
6	5.15	22.6	35.0	44.1
8	5.04	19.1	30.0	37.9
10	4.38	14.0	25.0	32.5
12	5.25	16.4	25.0	31.3

The results of the Vampire® simulations for the limiting spiral regime are shown in Figure A9, Figure A10 and Figure A11, for the empty car, and Figures A12, A13 and A14, for the loaded car. The truck satisfies all the criteria in the limiting spiral regime.

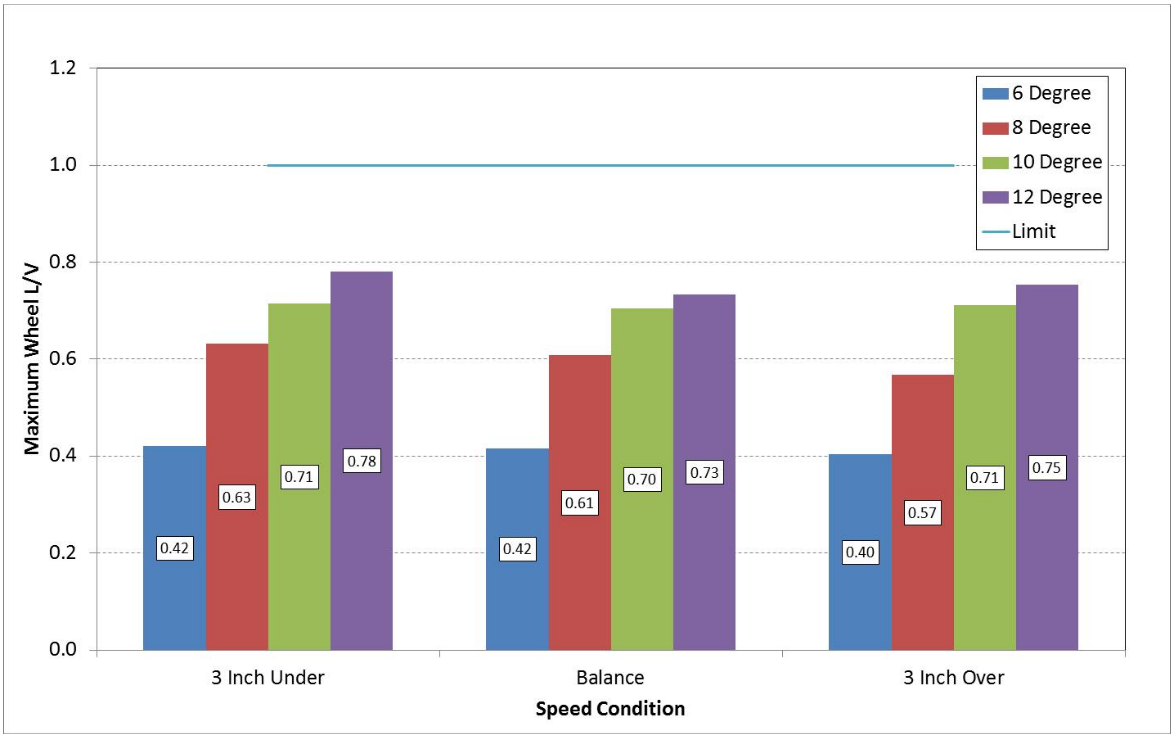

Figure A9 – Limiting spiral empty car wheel L/V ratios

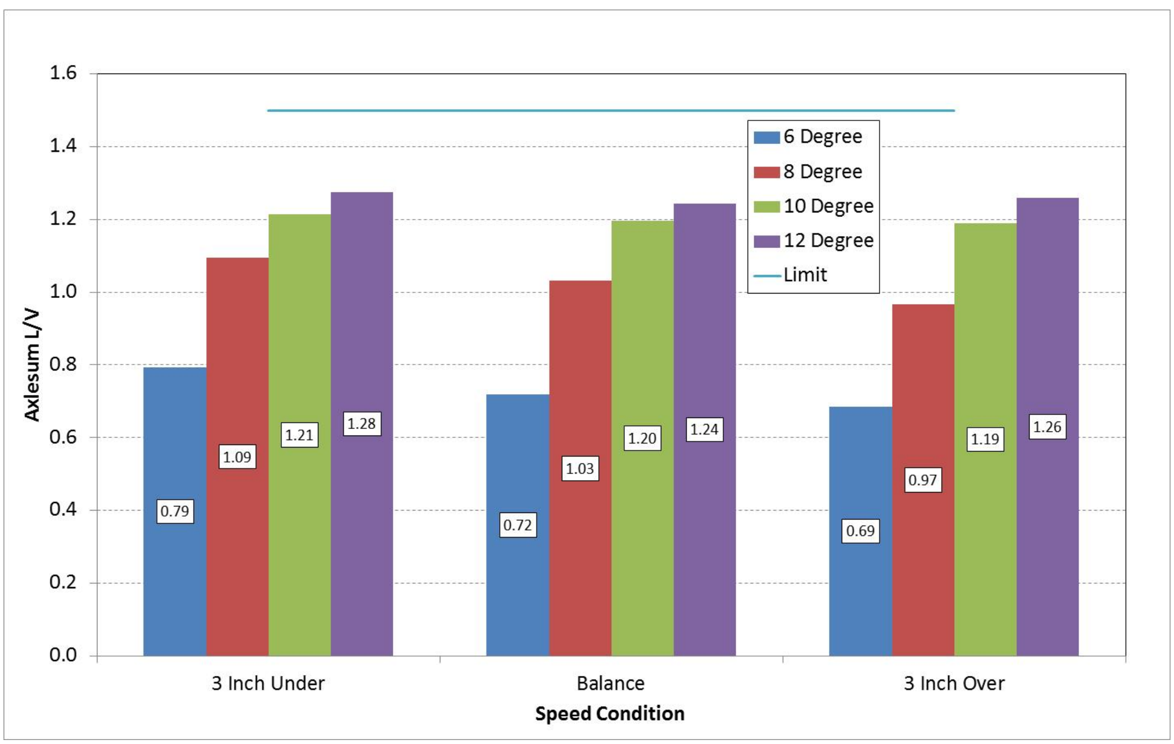

Figure A10 – Limiting spiral empty car axle-sum L/V ratios

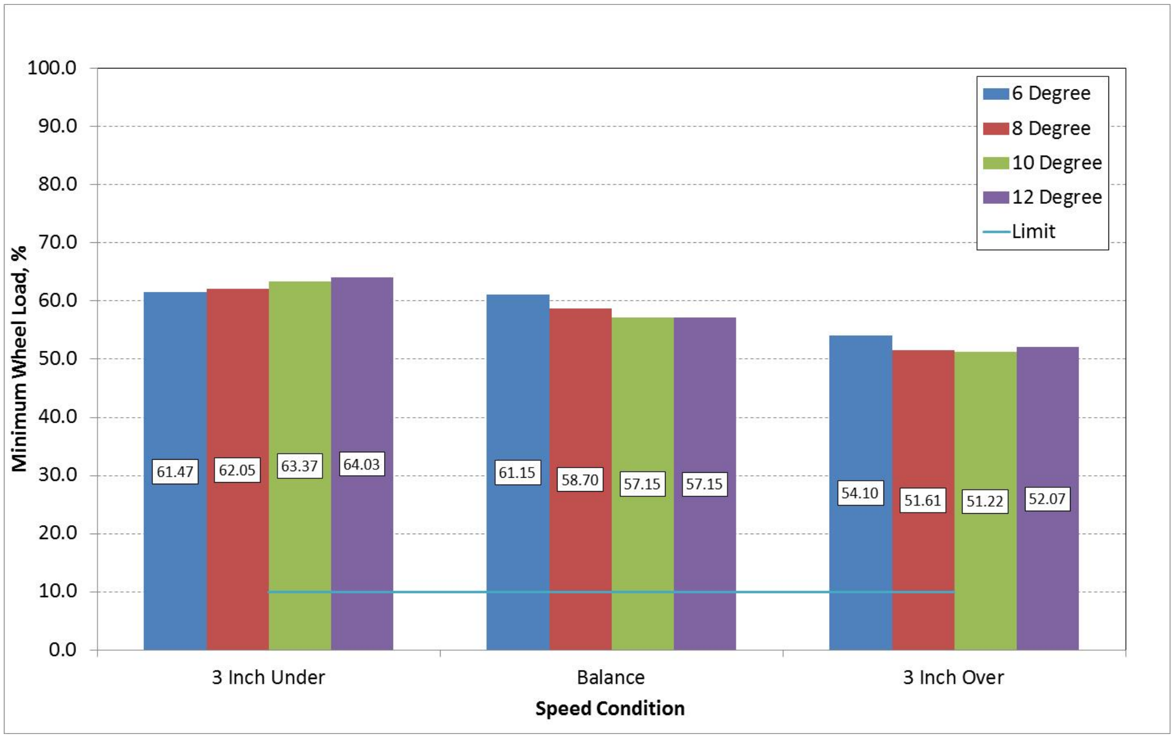

Figure A11– Limiting spiral empty car vertical wheel load percentage

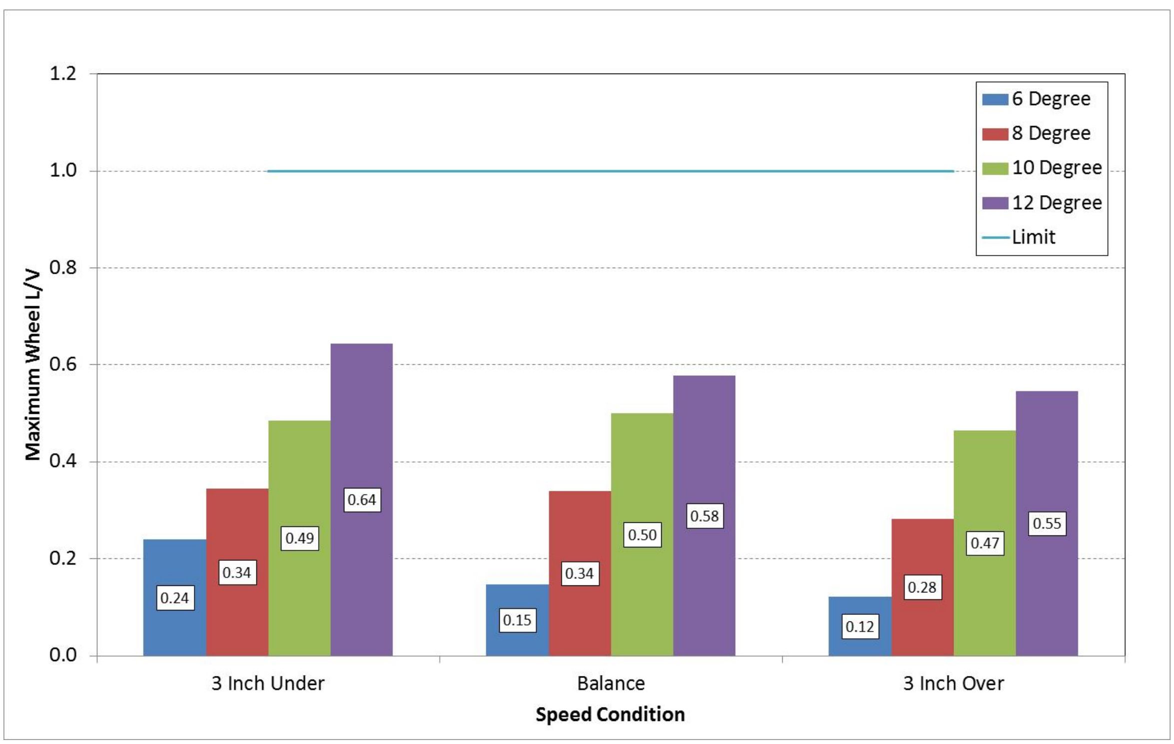

Figure A12 – Limiting spiral loaded car wheel L/V ratios

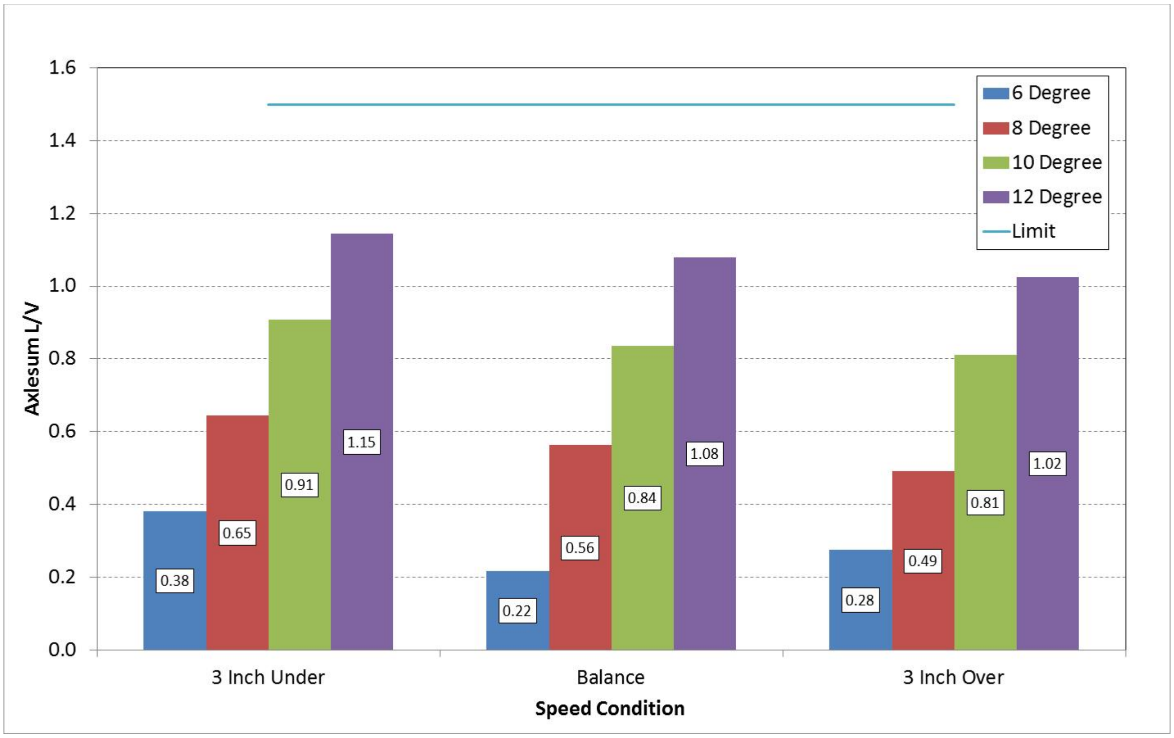

Figure A13 – Limiting spiral loaded car axle-sum L/V ratios

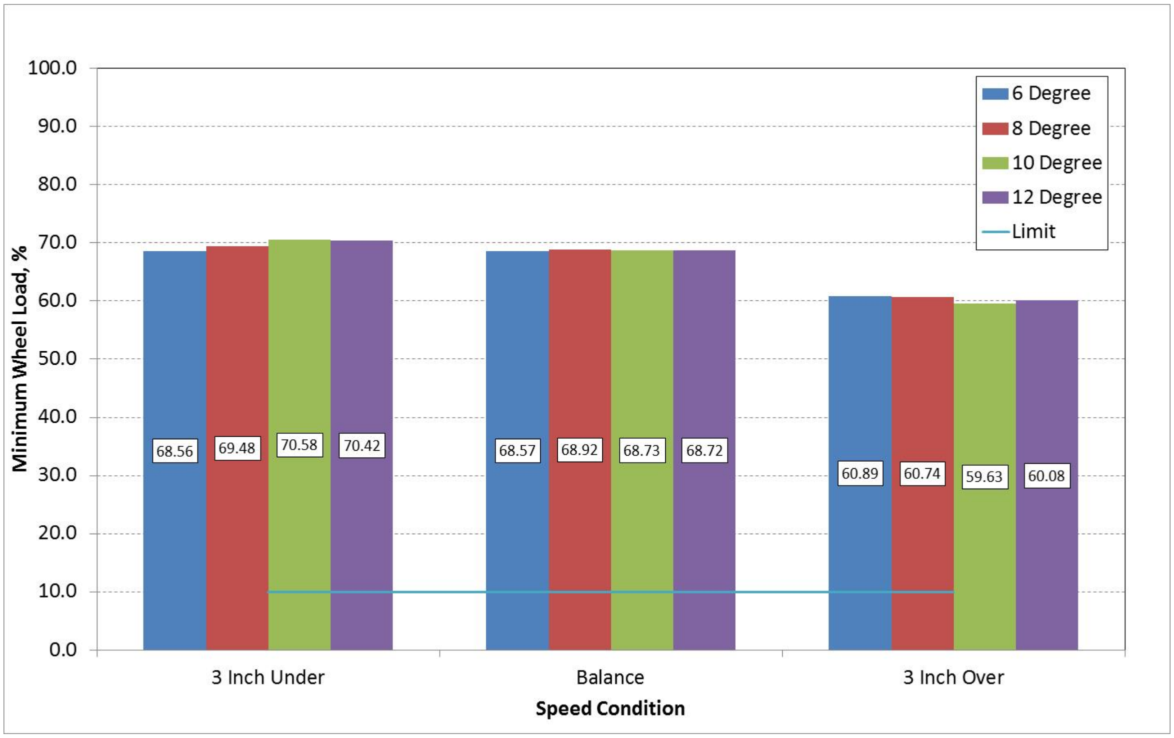

Figure A14 – Limiting spiral loaded car minimum vertical wheel load

Dynamic Curving

The dynamic curving test regime evaluates a vehicle's performance in negotiating a curve with cross level and gage deviations occurring simultaneously throughout a curve. The criteria that must be satisfied in this regime are shown in Table A3. The speeds simulated included 12, 14, 16, 18, 20, 22, 23.9, 26, 28, 30 and 31.6 mph.

Table A3 – Dynamic curving test criteria

Criterion	Limiting value
Maximum wheel L/V ratio	1.0
Maximum axle-sum L/V ratio	1.5
Maximum roll angle, degree	6
Minimum vertical wheel load, %	10

The exceedance of the minimum vertical wheel load limiting value cannot be longer than a distance along the track of 3 feet and no more than 50 milliseconds (0.05 seconds) in duration.

The results of the Vampire® simulations of the dynamic curving regime for the empty car are shown in Figures A15, A16, A17, A18, and A19. No minimum vertical wheel load fell below the 10 percent lower limit for any of the simulated speeds from 12 mph to 28 mph; hence, they are not shown. Of the two highest speed cases (30 and 31.6 mph), the maximum time and distance durations that a minimum wheel load fell below the 10 percent limit are shown in Figures A18 and A19, respectively.

The results for the loaded car are shown in Figures A20, A21 A22 and A23.

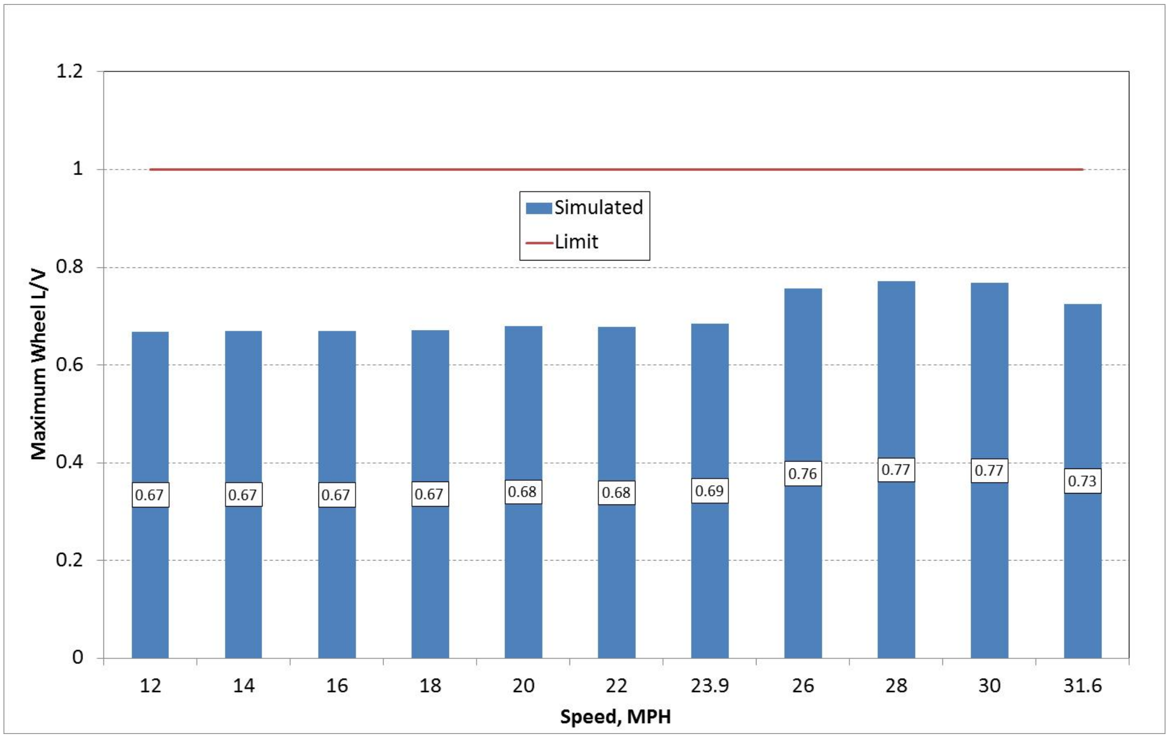

Figure A15 – Dynamic curving empty car wheel L/V ratios

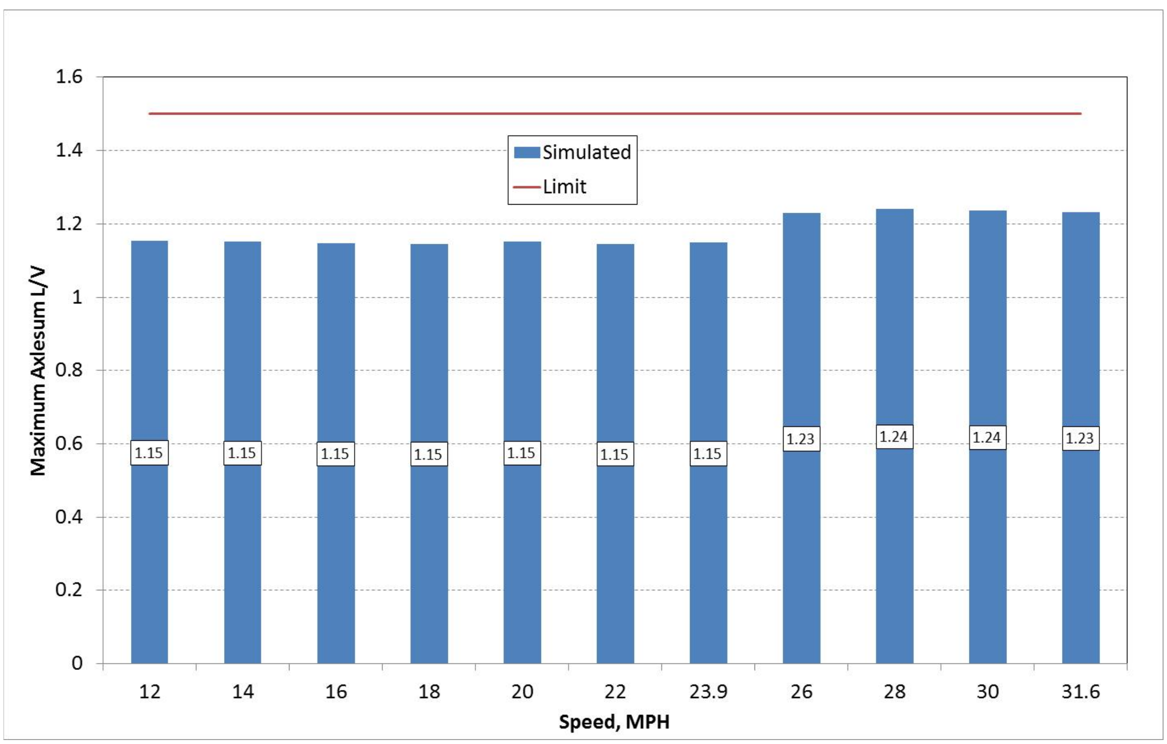

Figure A16 – Dynamic curving empty car axle-sum L/V ratios

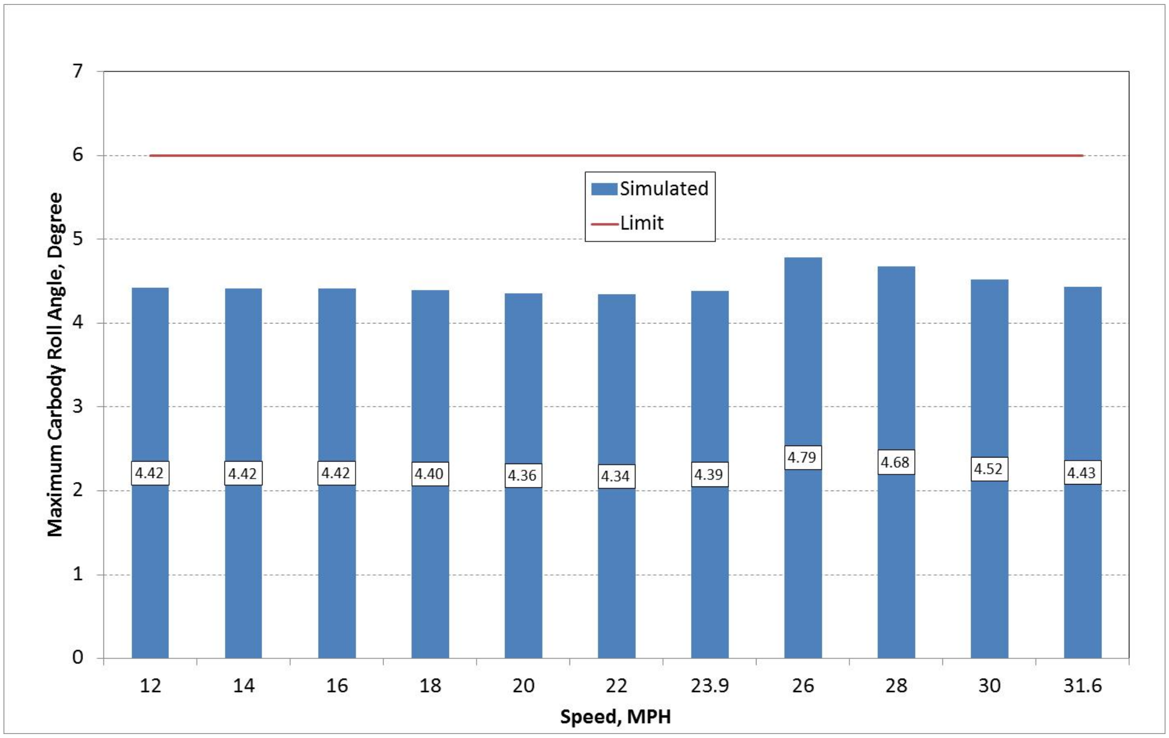

Figure A17 – Dynamic curving empty car carbody roll angles

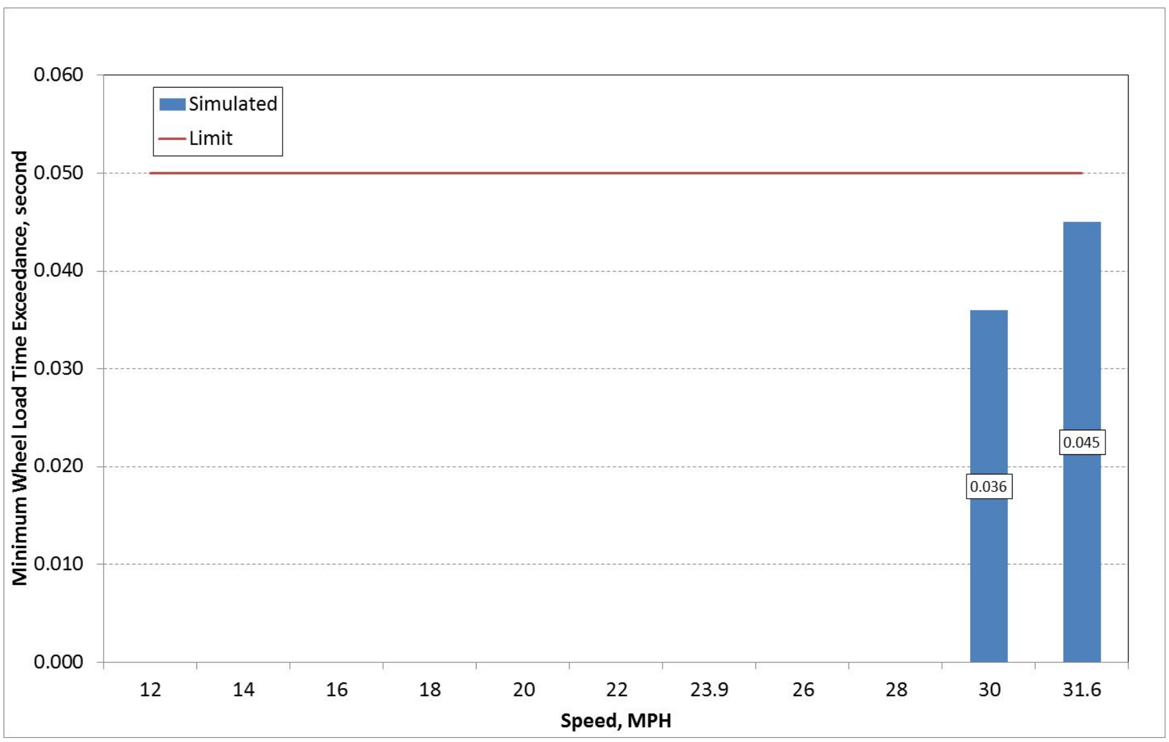

Figure A18 – Dynamic curving empty car minimum vertical wheel load exeedance duration

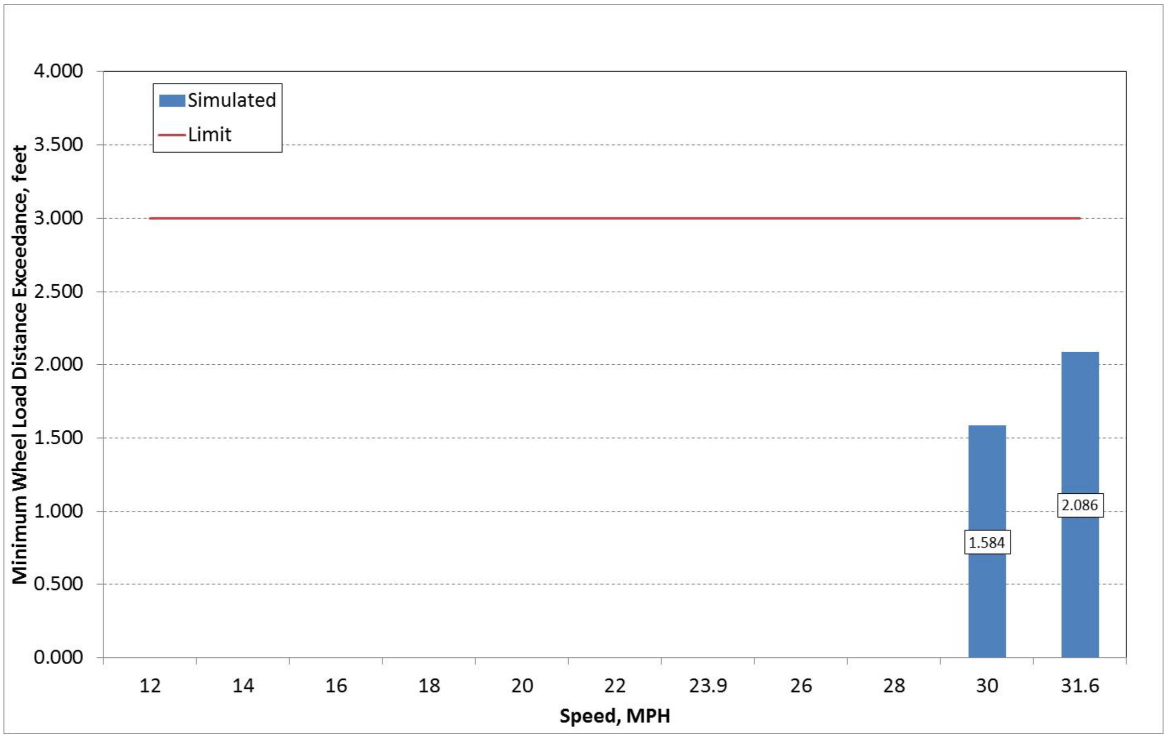

Figure A19 – Dynamic curving empty car minimum vertical wheel load exeedance distance

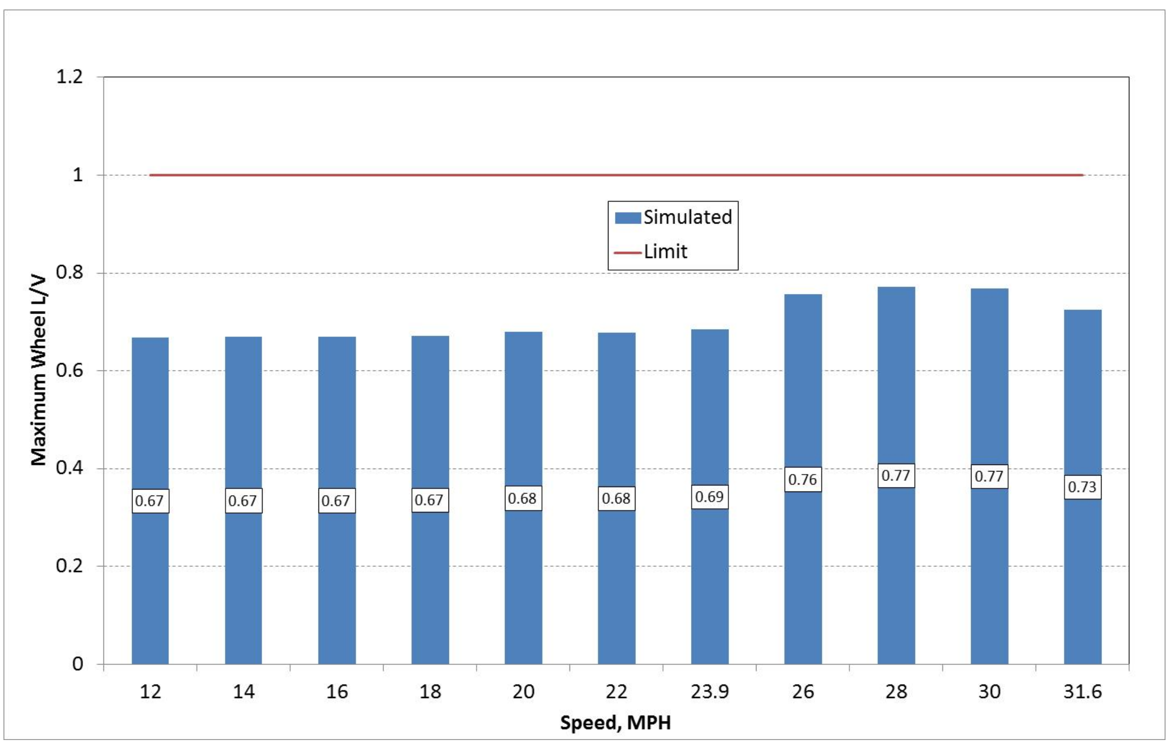

Figure A20 – Dynamic curving loaded car wheel L/V ratios

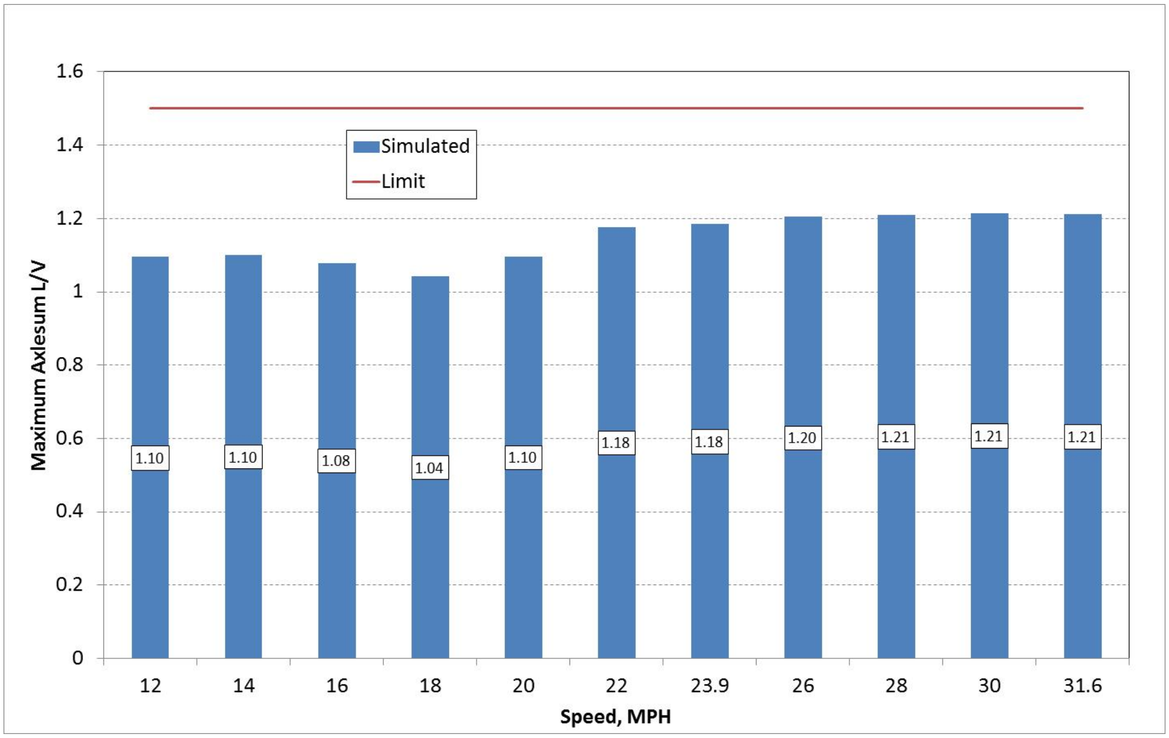

Figure A21 – Dynamic curving loaded car axle-sum L/V ratios

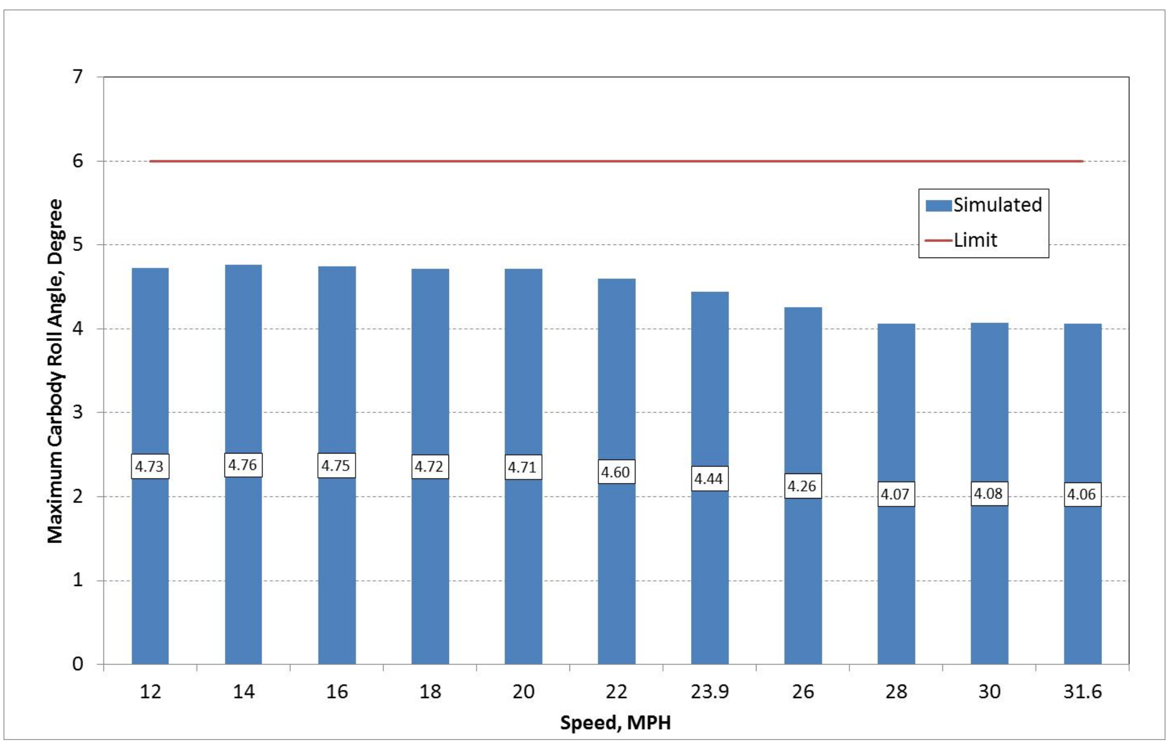

Figure A22 – Dynamic curving loaded car carbody roll angles

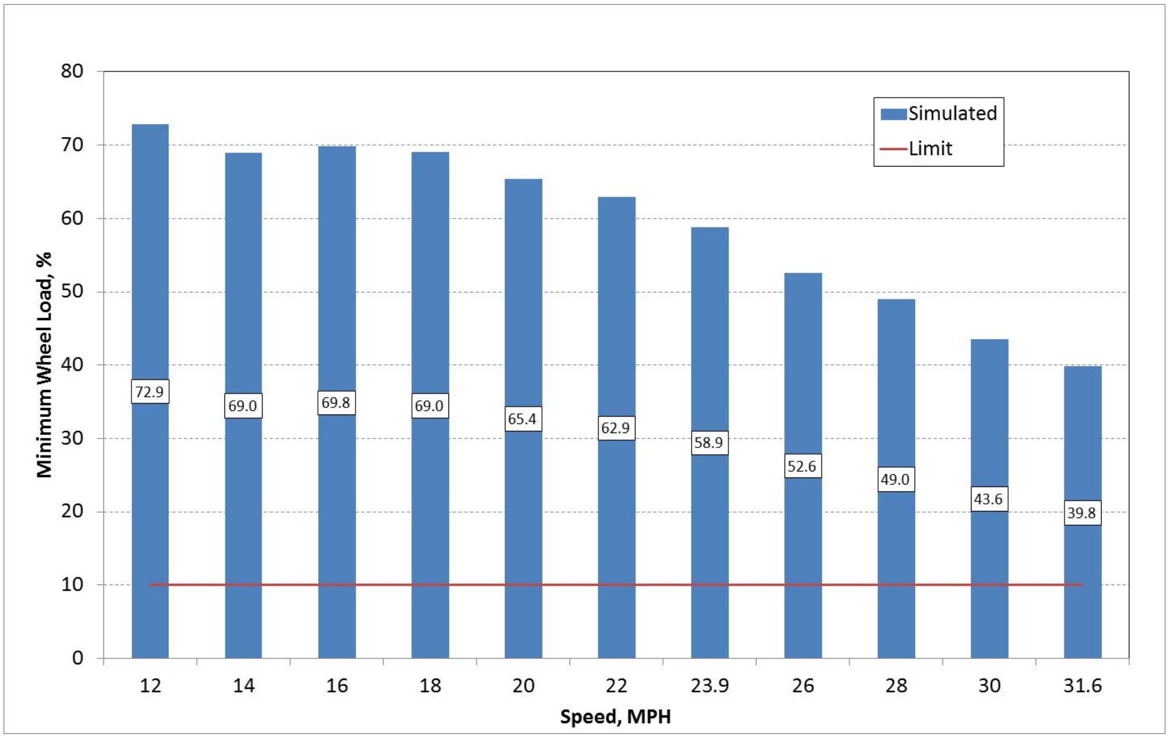

Figure A23 – Dynamic curving loaded car minimum vertical wheel load

Yaw & Sway

The yaw and sway (Y&S) regime evaluates the truck performance on track designed to induce yawing motion. The criteria that must be satisfied in this regime include a limit of 0.7 on the truck-side L/V ratio to minimize the potential for panel shift, and a limit of 1.5 on the axle-sum L/V ratio to minimize the potential for wheel climb.

The results of the Vampire® simulations of the Y&S regime are shown in Figures A24 and A25, for the empty car, and Figures A26 and A27, for the loaded car. The HST satisfies all criteria tested to in this regime.

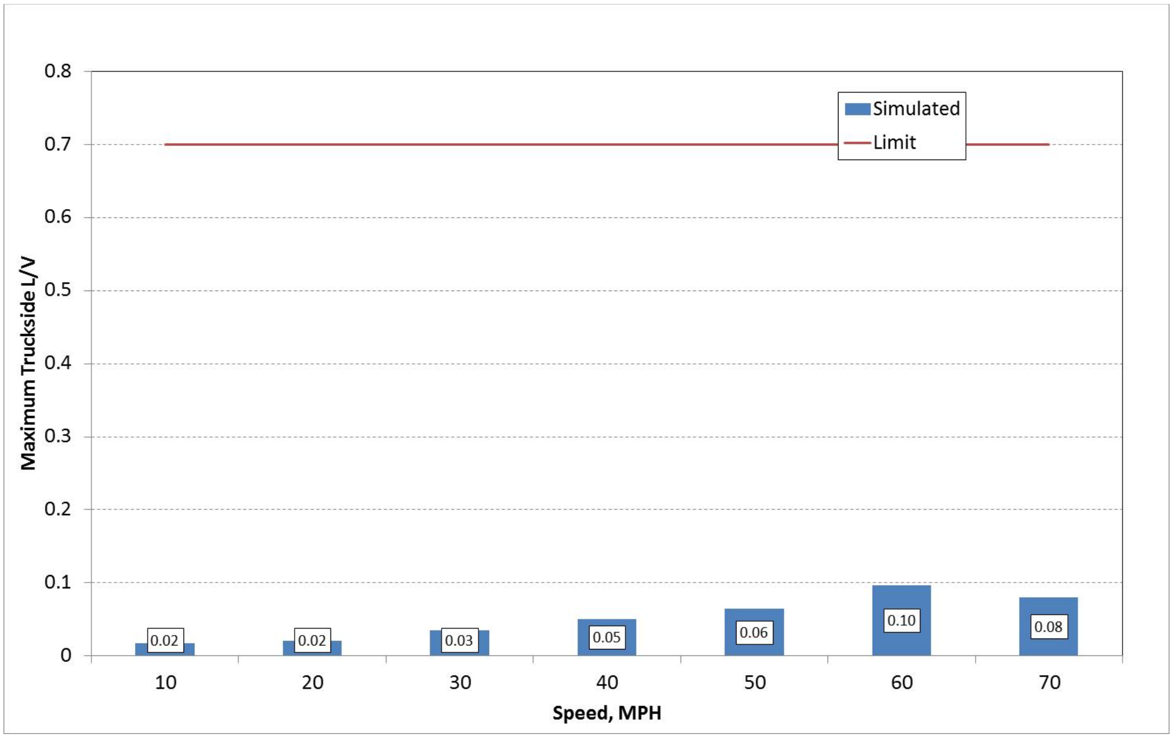

Figure A24 – Yaw & sway empty car truck-side L/V ratios

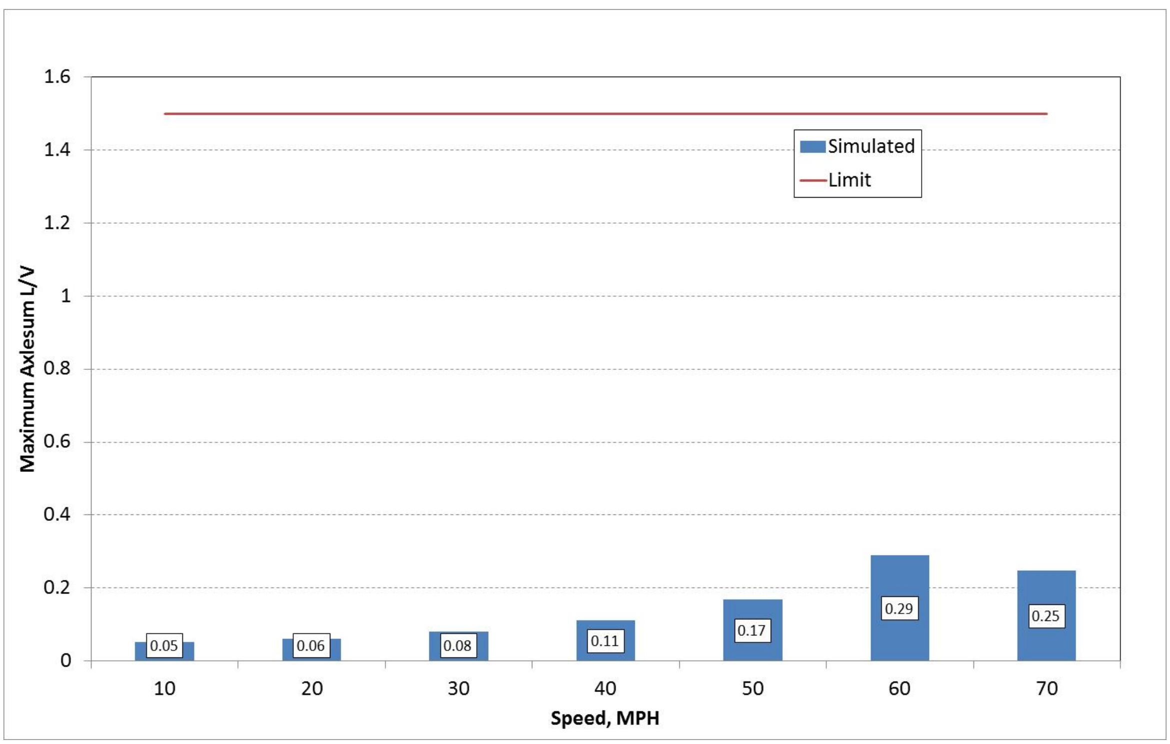

Figure A25– Yaw & sway empty car axle-sum L/V ratios

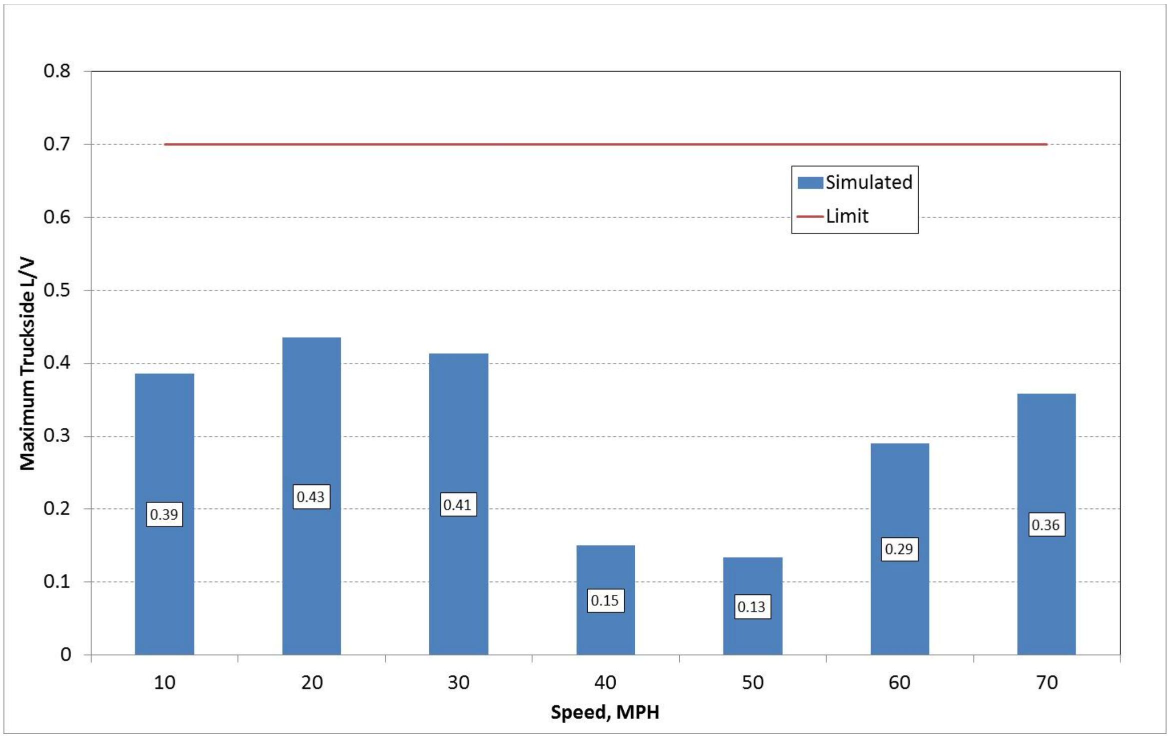

Figure A26 – Yaw & sway loaded car truck-side L/V ratios

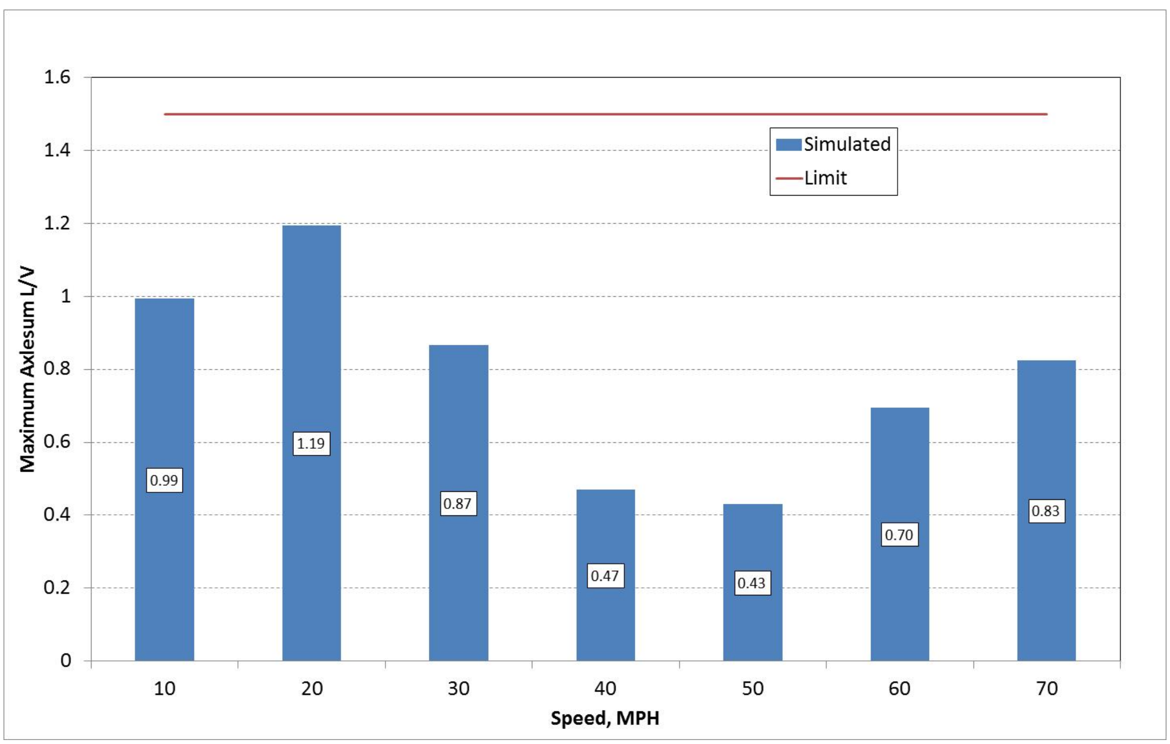

Figure A27 – Yaw & sway loaded car axle-sum L/V ratios

Twist & Roll

The twist and roll (T&R) regime includes cross-level deviations which induce rigid body roll, and flexible body twist modes. The qualifying criteria in this regime include axle-sum L/V limit of 1.5, minimum vertical load limit of 10 percent, and a maximum dynamic augment carbody vertical acceleration limit of 1 g.

The results of the Vampire® simulations of the T&R regime are shown in Figures A28 through A31, for the empty car, and Figures A32, A33, and A34 for the loaded car. The truck passes all test criteria for this regime. The minimum vertical wheel load limit was exceeded by the empty car for the maximum speed; however, the duration and distance over which it occurred was within the limits allowed by the specification. Therefore, the truck satisfies the criteria for the T&R regime.

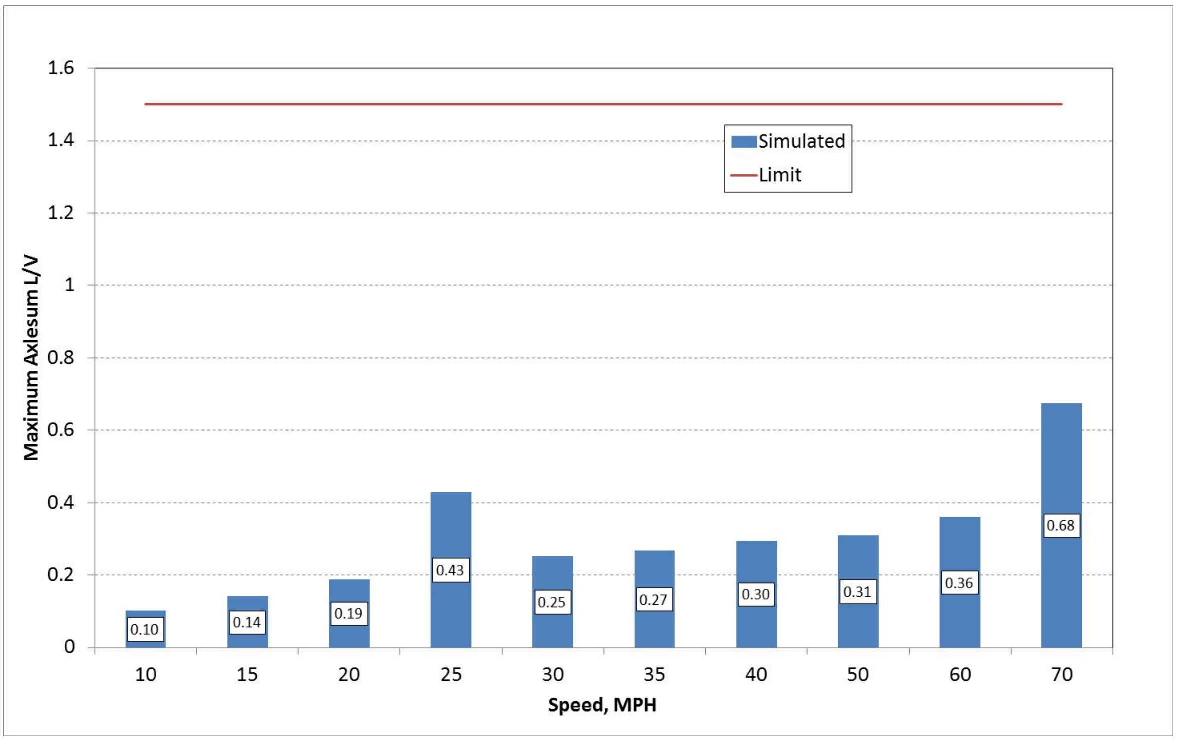

Figure A28 – Twist & roll empty car axle-sum L/V ratios

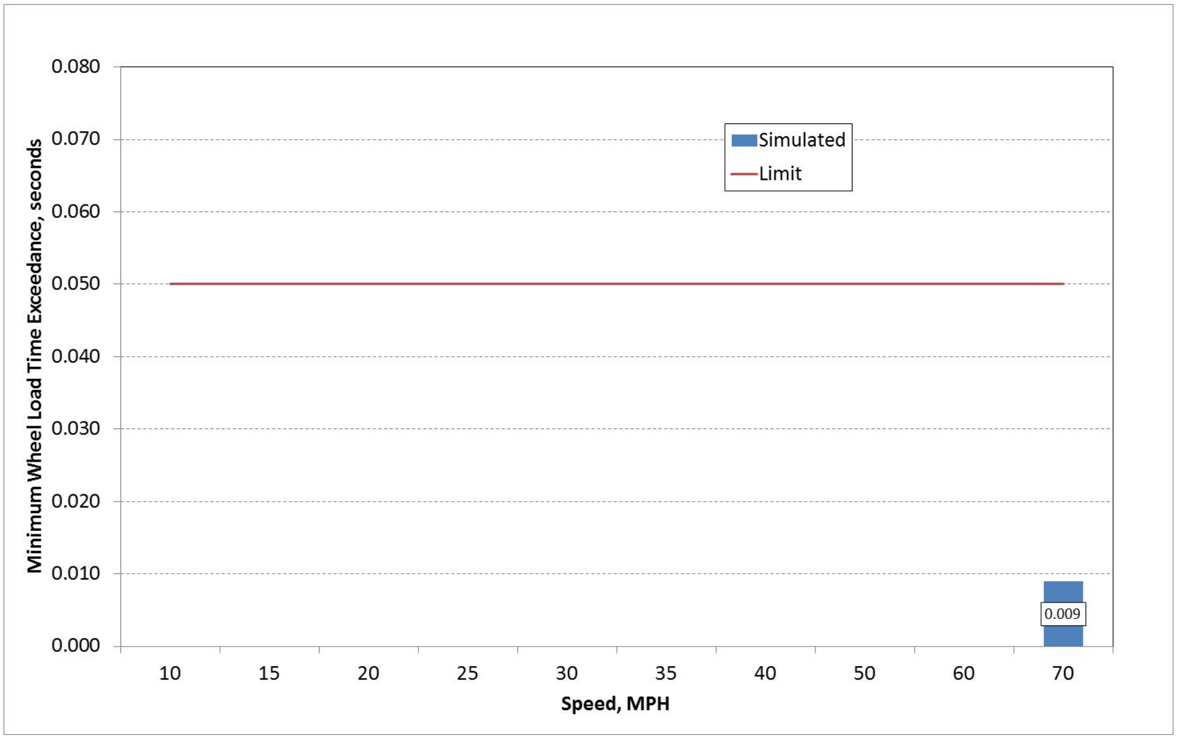

Figure A29 – Twist & roll empty car minimum vertical wheel load exceedance duration

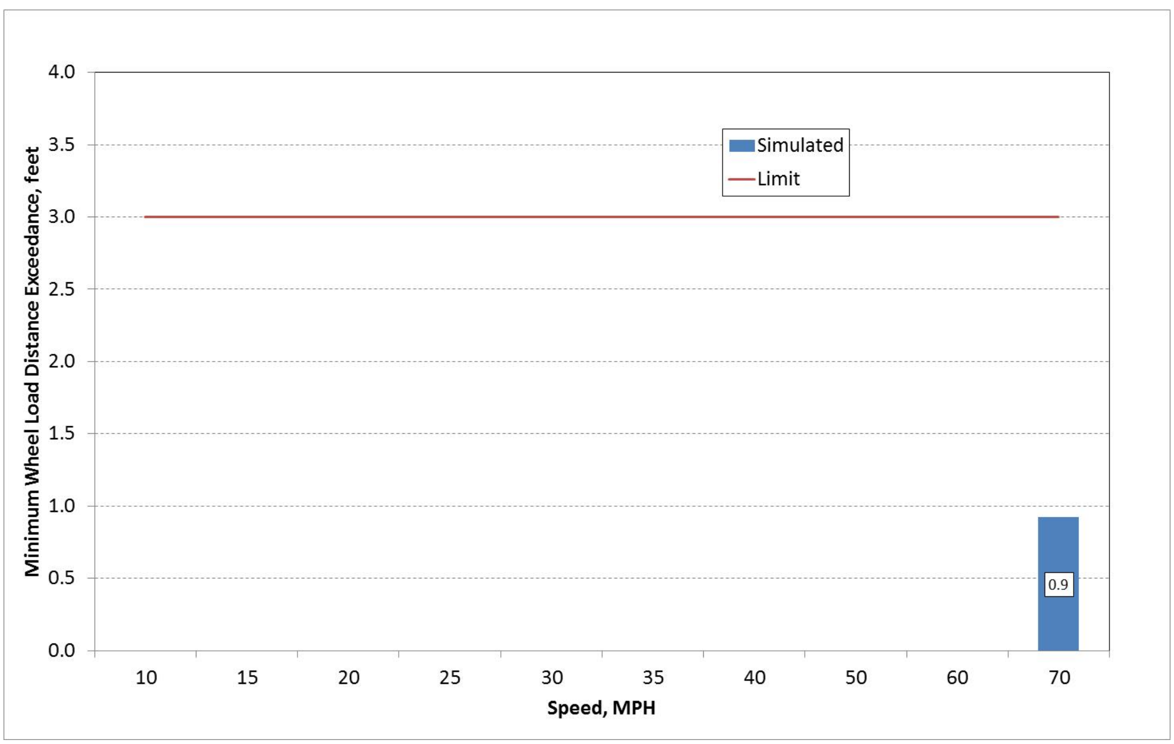

Figure A30 – Twist & roll empty car minimum vertical wheel load exceedance distance

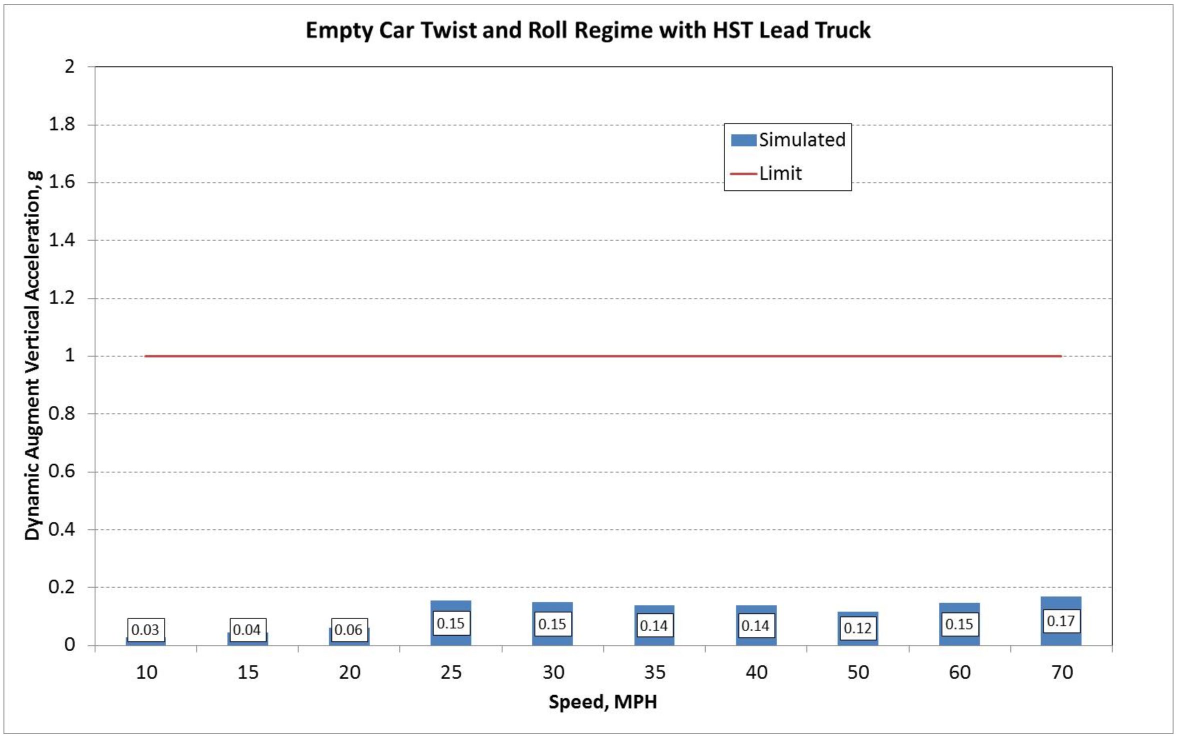

Figure A31 – Twist & roll empty car vertical acceleration dynamic augment

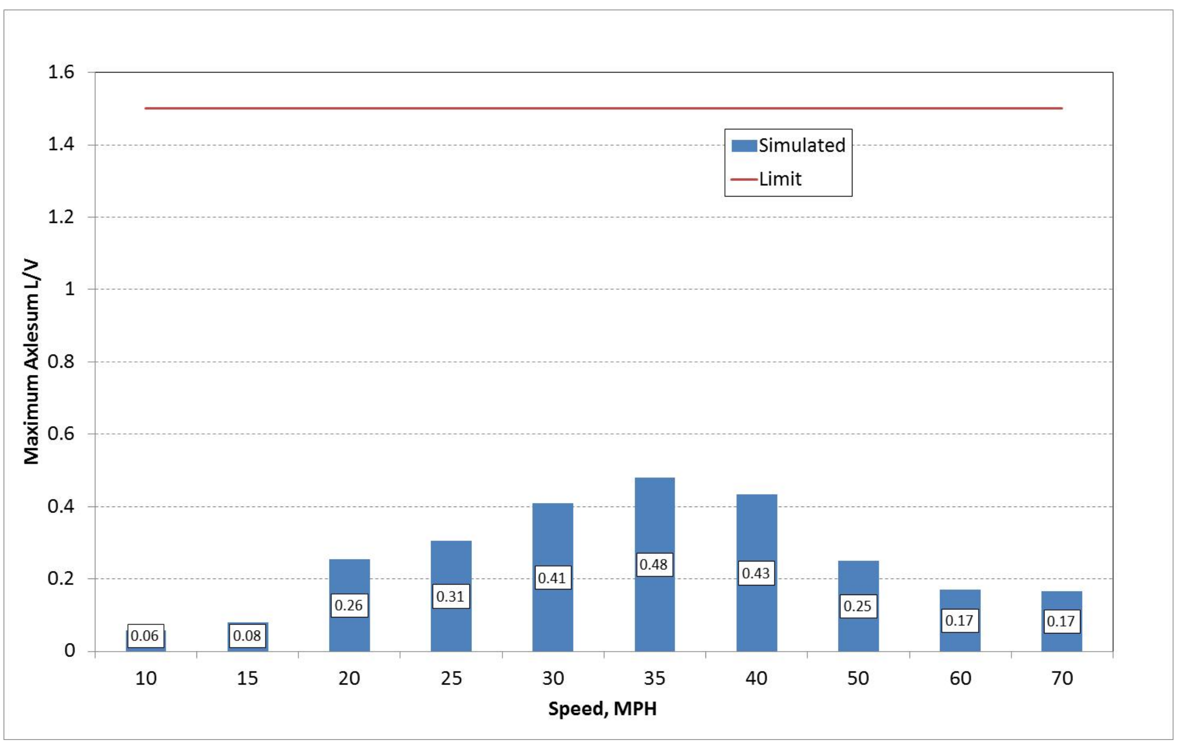

Figure A32 – Twist & roll loaded car axle-sum L/V ratios

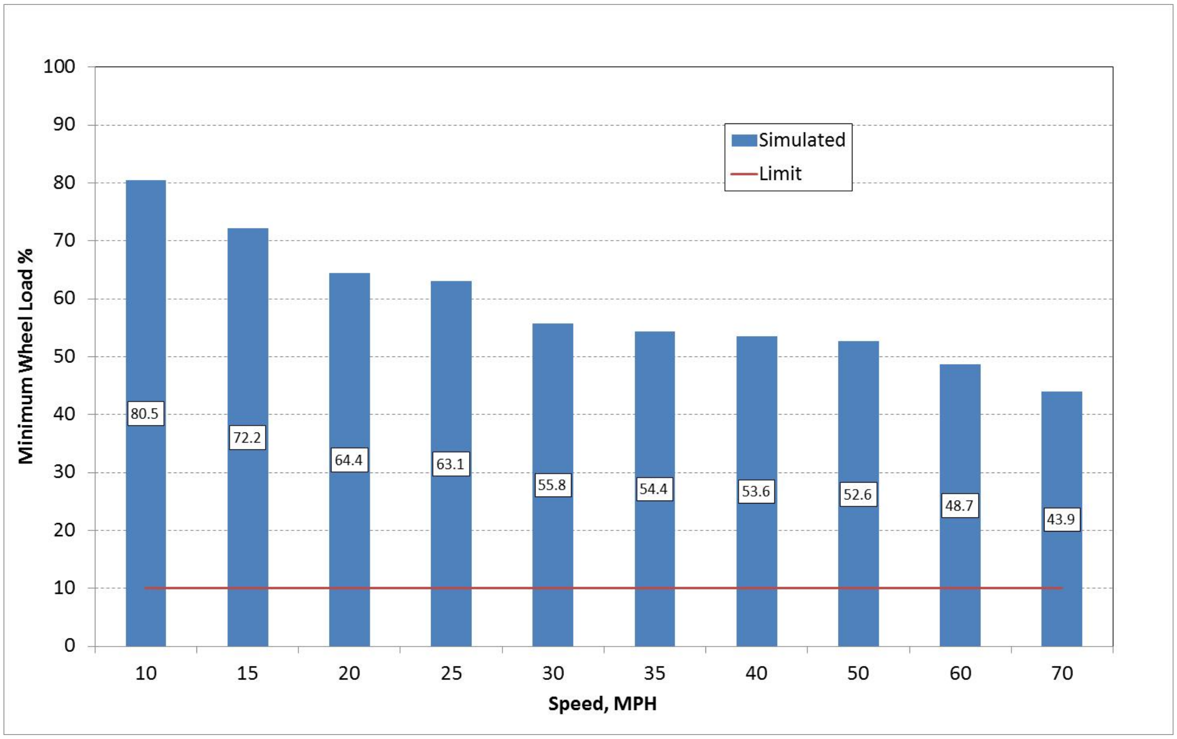

Figure A33 – Twist & roll loaded car minimum vertical wheel load

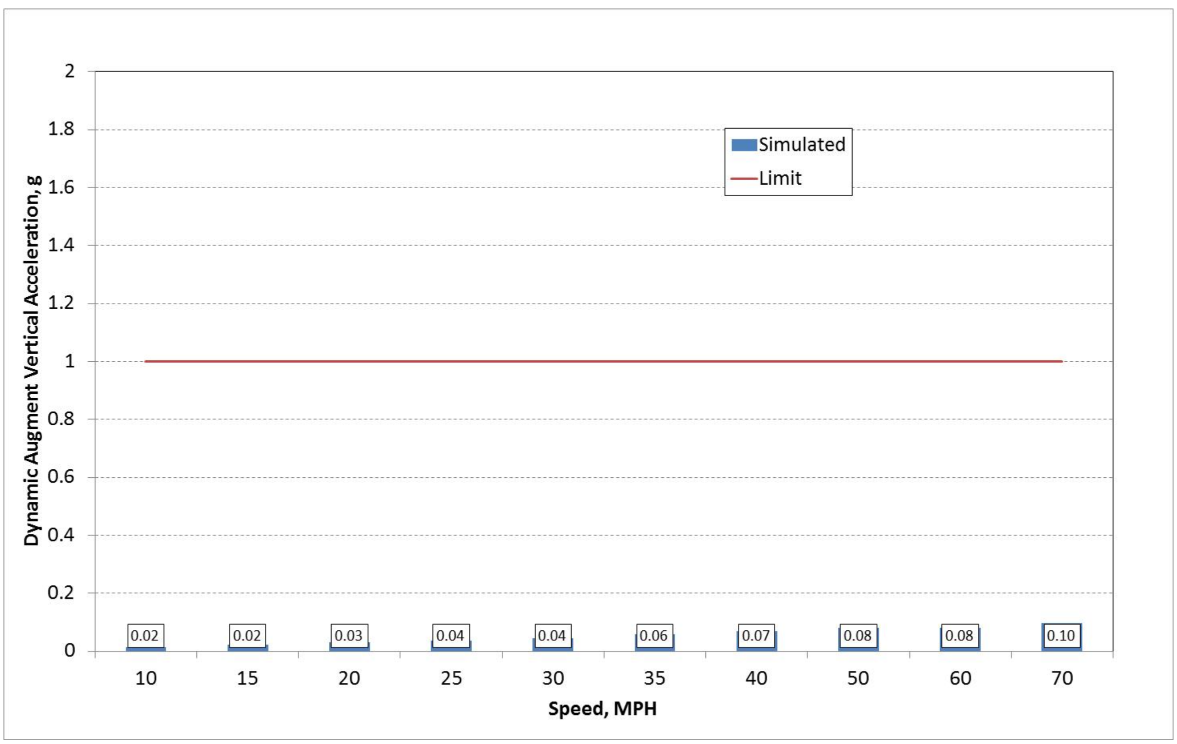

Figure A34 – Twist & roll loaded car vertical acceleration dynamic augment

Pitch & Bounce

The pitch and bounce (P&B) regime is used to evaluate the vertical stability of the vehicle over track designed to induce vertical motion, both asynchronous (pitch) and synchronous (bounce) between the two ends of the car. The criteria that must be satisfied in this regime include a 1 g limit on the dynamic augment vertical acceleration and a minimum vertical wheel load of 10 percent.

The results of the Vampire® simulations of the P&B regime is shown in Figures A35 and A36, for the empty car, and Figures A37 and A38, for the loaded car. The truck satisfies all the criteria in the P&B regime.

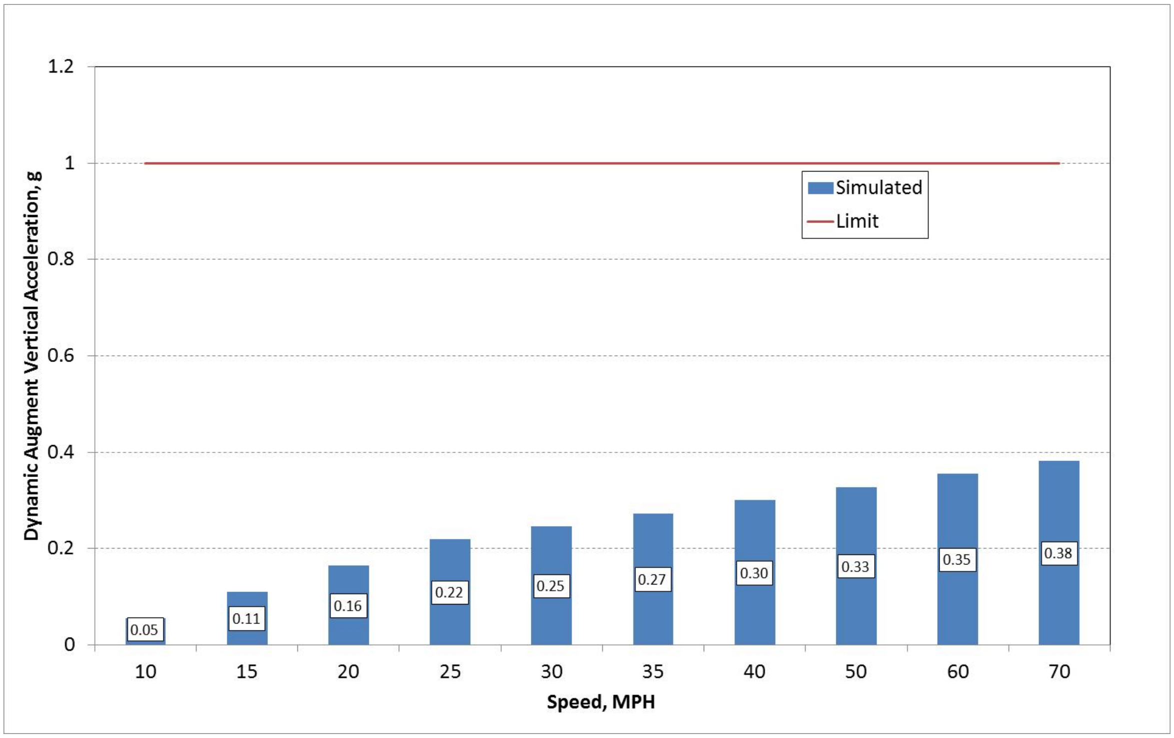

Figure A35 – Pitch & bounce empty car vertical acceleration dynamic augment

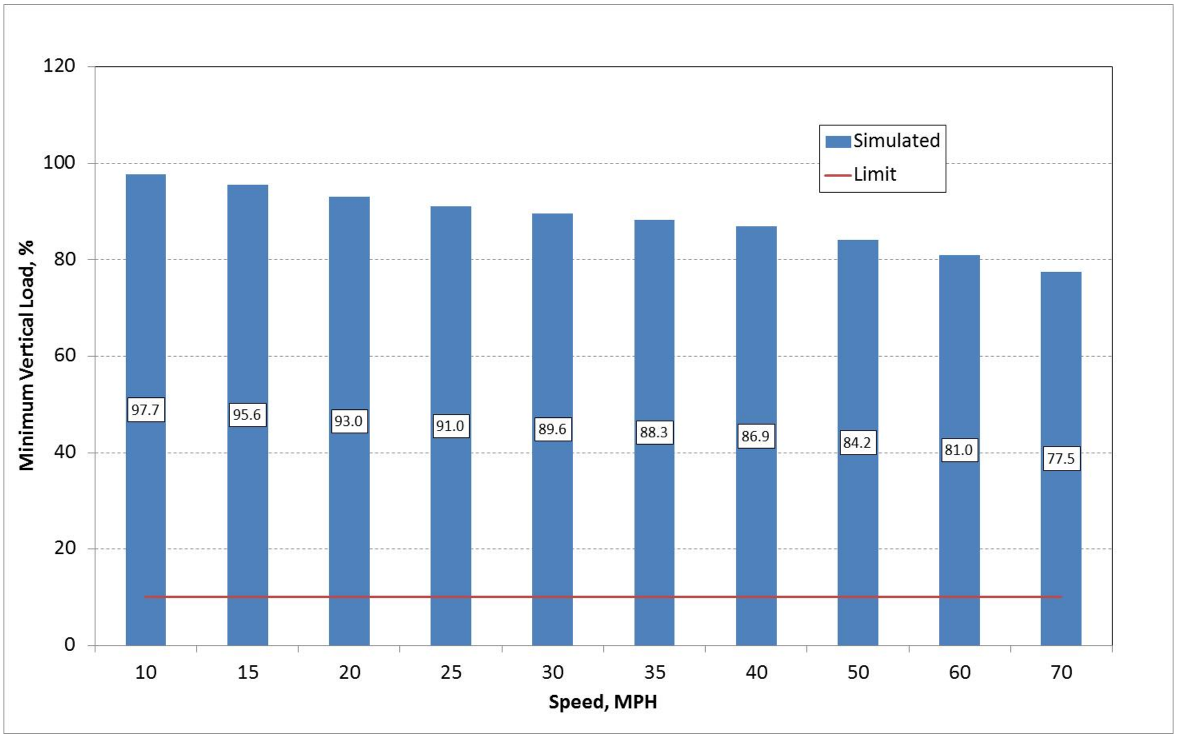

Figure A36 – Pitch & bounce empty car minimum vertical wheel load

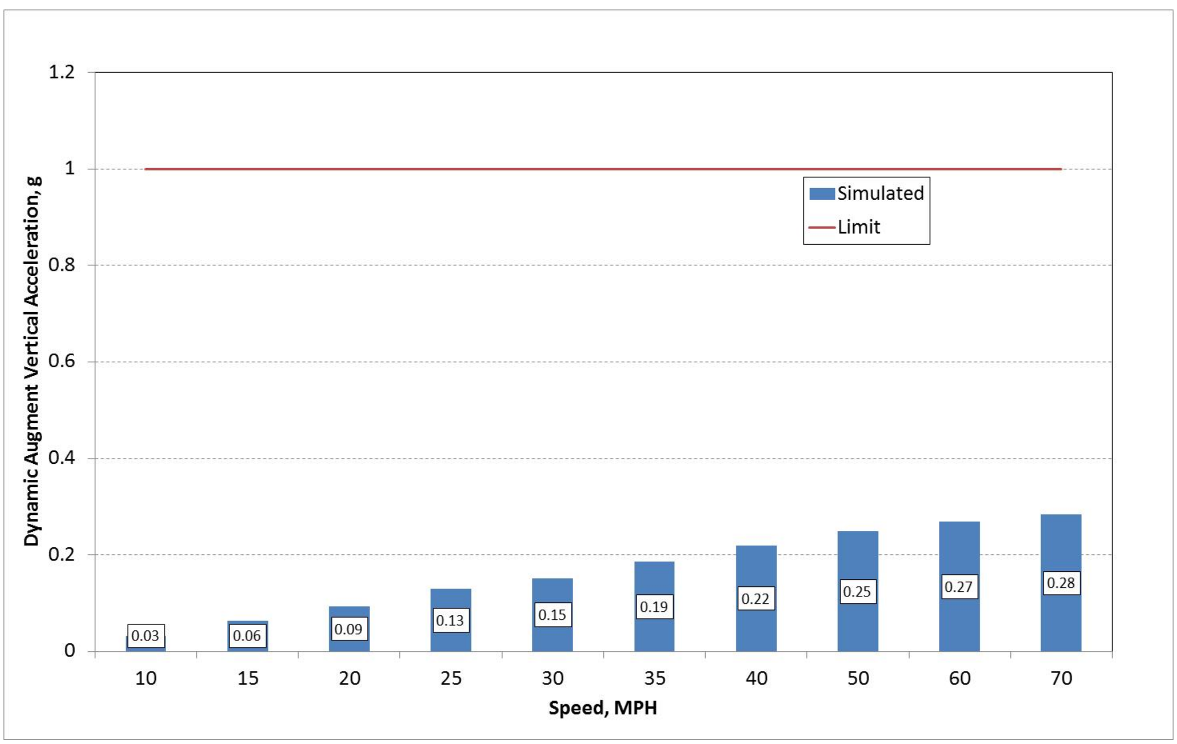

Figure A37 – Pitch & bounce loaded car vertical acceleration dynamic augment

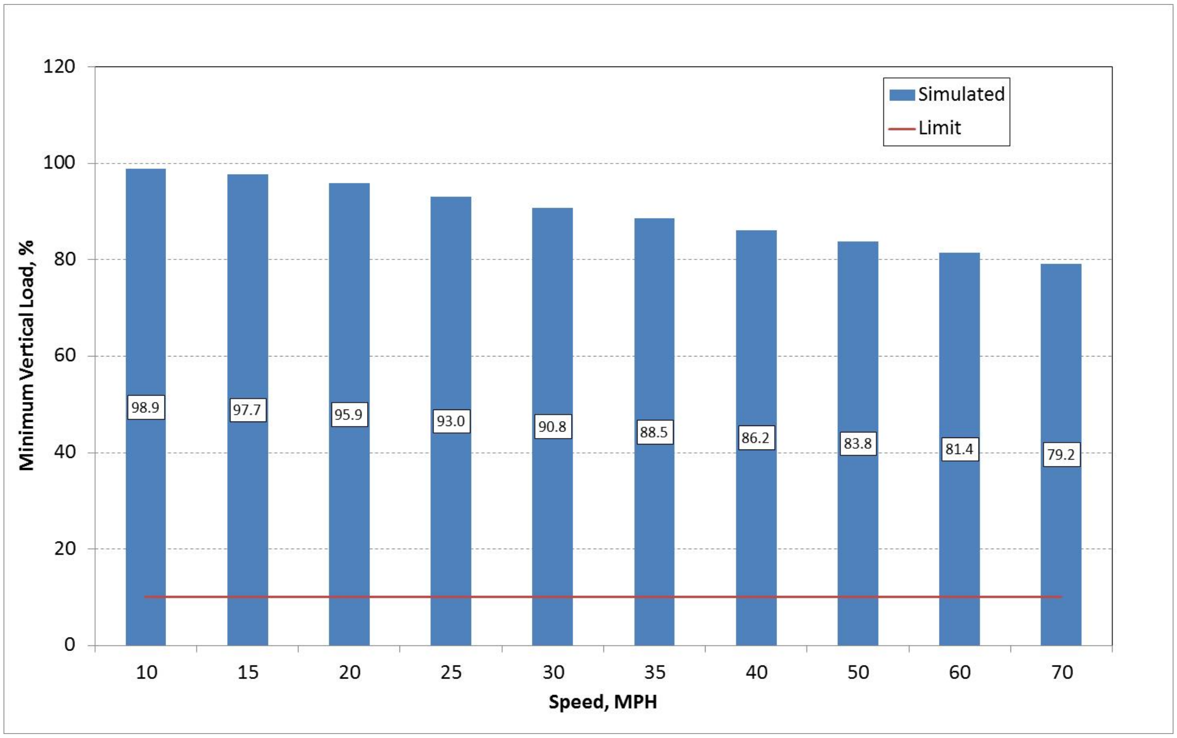

Figure A38 – Pitch & bounce loaded car minimum vertical wheel load

Lateral Stability (hunting)

Truck hunting is a phenomenon in which a vehicle exhibits a cyclical yawing or swaying motion as the trucks tend to "hunt" for center along the track. It is not a resonant phenomenon, but a dynamic event, that begins at a certain vehicle speed and increases in severity as the speed is increased. Truck hunting onset speed is lower for empty cars than for loaded cars. The hunting motion can damage both the track and the car from the violent activity. More importantly, hunting can cause a car's wheel to climb a rail and cause a derailment. The only solution is to stay under the speed at which hunting begins.

The criteria used to evaluate the onset and continuation of hunting is the carbody peak-to-peak lateral acceleration limit of 1.5 g and the carbody lateral acceleration standard deviation limit of 0.13 g. These accelerations are measured at a point close to the center of the truck, but located on the floor of the carbody near the center plate.

The simulation matrix for hunting included speeds of 40, 50, 60, 70, 80, 90, 100 and 110 mph. The results of the Vampire® simulations of the empty car hunting regime are shown in Figures A39 and A40.

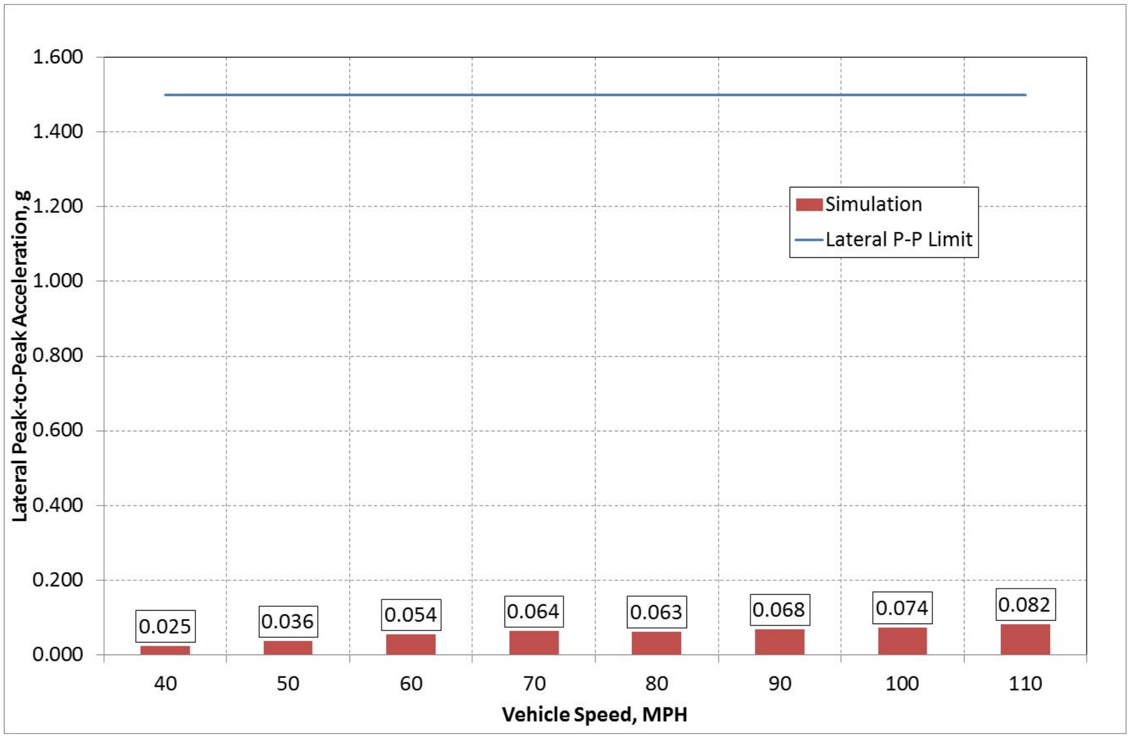

Figure A39 – Hunting empty car lateral accelerations peak-to-peak

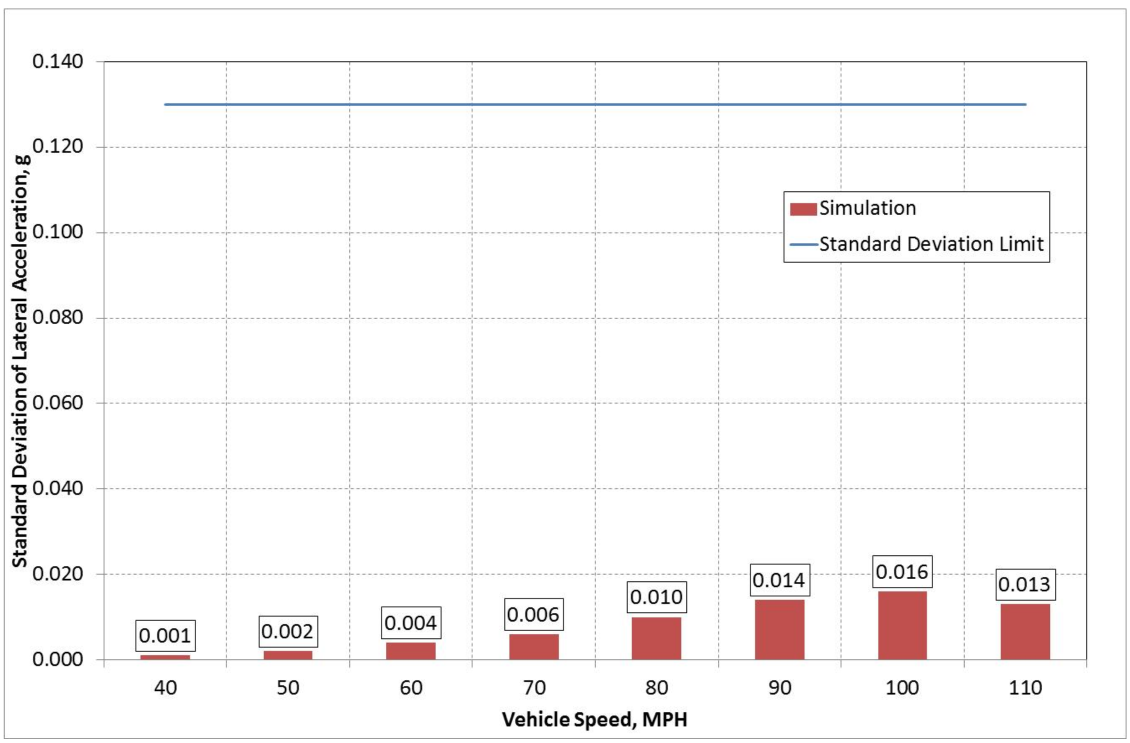

Figure A40 – Hunting empty car lateral accelerations standard deviation

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
APTA	American Public Transportation Association
AAR	Association of American Railroads
CW	Clockwise
CFR	Code of Federal Regulations
CCW	Counterclockwise
DAS	Data Acquisition System
FRA	Federal Railroad Administration
g	Gravitational Force
GRL	Gross Rail Load
HST	Higher Speed Truck
IWS	Instrumented Wheel Sets
L/V	Lateral Over Vertical
MSRP	Manual of Standards and Recommended Practices
PTT	Precision Test Track
RTT	Railroad Test Track
SA	Sharma & Associates, Inc.
SBIR	Small Business Innovative Research
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
WRM	Wheel Rail Mechanisms
Y&S	Yaw & Sway