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FRA DOTX-216 Passenger Vehicle Characterization and Modeling



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Executive Summary

Between 2013 and 2015 Transportation Technology Center, Inc. (TTCI), now MxV Rail, performed work funded by the Federal Railroad Administration (FRA) to characterize and model a high-speed passenger vehicle. The tests were performed at FRA's Transportation Technology Center (TTC) in Pueblo, Co., and provided recommendations on modeling, model validation, and testing to qualify high-speed vehicles under operating speed. FRA tasked TTCI with developing a dynamic model of FRA's DOTX-216 car and providing guidance in the modeling and model validation.

The team was tasked to develop a list of parameters necessary to complete a dynamic model of the passenger vehicle, perform tests to measure the parameters, develop a mathematical model using the measured parameters, and perform on-track tests to validate the model. This report details the performance of the tasks listed above and provides guidance to perform these tasks.

Researchers identified specific parameters that must be determined to develop a dynamic vehicle model. It recommended specific characterization tests to determine these parameter values. The team then performed all characterization tests from the outlined testing regimen to determine various mass, stiffness, and damping characteristics of the DOTX-216 car.

Team members used the measured parameter values to create a mathematical model of the vehicle, tuning the initial model parameters using comparisons of quasi-static and dynamic characterization tests performed on the DOTX-216 car. The tuned model and test data comparisons showed reasonable agreement for these stationary tests.

Researchers performed a series of on-track validation tests using the DOTX-216 car to facilitate model validation efforts, using a model of the DOTX-216 car to simulate this same test regime. The team compared results from the simulations and test data to assess the validity of the DOTX-216 model. Model validation was first evaluated using only displacement and acceleration measurements; direct comparisons and the Sprague and Geers method were used for this purpose. The model of the DOTX-216 car demonstrated good agreement with measured test data for suspension displacement, carbody accelerations, and truck accelerations. Researchers further proved model validation by evaluating wheel-rail force data from simulation and measured instrumented wheelset (IWS) data; direct comparisons and the Polach method were used for this purpose. The model of the DOTX-216 car again demonstrated good agreement with measured test data.

The model DOTX-216 car proved valid for on-track modeling. The procedures, results, and analyses in this report provide guidance and suggestions for future projects that may need to model and qualify rail vehicles.

1. Introduction

Between 2013 and 2015 Transportation Technology Center, Inc. (TTCI), now MxV Rail, performed work funded by the Federal Railroad Administration (FRA) to characterize and model a high-speed passenger vehicle. The tests were performed at FRA's Transportation Technology Center (TTC) in Pueblo, Co., and provided recommendations on modeling, model validation, and testing to qualify high-speed vehicles under operating speed. FRA tasked TTCI with developing a dynamic model of FRA's DOTX-216 car (shown in [Figure 1](#)) and providing guidance in the modeling and model validation.



Figure 1. DOTX-216 Car

1.1 Background

FRA established safety performance standards for high-speed trains in 49 Code of Federal Regulations (CFR) Track Safety Standards Part 213 Subpart G Class of Track 6 and Higher, which defines track requirements for Class 6 and higher track. It also defines vehicle test requirements and safety performance criteria for trains that are to operate at speeds above 90 mph [1].

FRA amended 49 CFR Part 213 to promote the safe interaction of rail vehicles with the track over which they operate. As part of vehicle qualification, the final rule requires demonstration of safe dynamic response to allowable track geometry variations using simulation with a validated computer model.

1.2 Objectives

The objectives of this project were:

- To develop parameters necessary to complete a dynamic model of the passenger vehicle
- To derive parameter values using a defined testing methodology
- To develop a validated model using the developed parameters
- To perform on-track tests to validate the model

1.3 Overall Approach

Project efforts involved a combination of testing and mathematical simulations to develop a validated dynamic model of a DOTX-216 car. The process began with planning vehicle characterization tests, including the identification of parameters and the recommendation of appropriate tests. The team then focused on developing a NUCARS® model of the DOTX-216 car using the identified parameters, with preliminary validation achieved through comparisons with these tests. This task also included pre-test simulations for final validation tests. The team then conducted on-track tests at TTC to gather vehicle-track interaction data for the final validation of the developed model, culminating in a final validation report.

1.4 Scope

This report presents the findings of the project to develop a validated dynamic model of the DOTX-216 passenger car. The project involved developing the parameters necessary for constructing a passenger vehicle dynamic model, deriving these parameter values through defined testing techniques, developing a validated model using these parameters, and performing on-track tests to validate the model.

1.5 Organization of the Report

This report has 8 sections. [Section 2](#) identifies the necessary parameters for the dynamic model, categorized into masses, geometry, and stiffness and damping. [Section 3](#) describes the various characterization tests performed to measure these parameters and presents the corresponding results. [Section 4](#) details the development and tuning of the mathematical model. [Section 5](#) covers the on-track Validation Tests. [Section 6](#) presents the results of the Initial Model Validation using displacement and acceleration measurements, and [Section 7](#) covers further validation using instrumented wheelset data. In [Section 8](#), the report concludes with a summary of findings, recommendations for future work, and supporting references and appendices.

2. Parameters Required to Model the DOTX-216

This section contains a list of parameters necessary to construct a dynamic model of the DOTX-216 car. Mass properties, geometry (i.e., location of connections), and stiffness and damping parameters are discussed in subsections. Model parameters are listed in tables, showing the parameter, units of measure, and the source. Where appropriate, the source refers to the section of this test plan that describes the test used to measure or calculate the parameter value.

2.1 Masses

Mass parameters include the center of gravity (CG) location of the body and its mass and rotational inertias. The model allows movement of each body in all six degrees of freedom. The equalizer beams included an additional degree of freedom that allows body flex in twist which was required to match truck load equalization tests. [Table 1](#) shows the carbody parameters.

Table 1. Carbody Parameters

Parameter	Units	Source
Longitudinal CG offset from center + for cab leading	inches	Calculated from scale weights (Section 3.1)
Lateral CG offset + for cab leading	inches	Calculated from scale weights (Section 3.1)
Vertical CG	inches	Calculated from rigid body modal test (Section 3.2)
Mass	pounds	Calculated from scale weights and truck weights (Section 3.1)
Ixx	lb-in-sec ²	Calculated from rigid body modal test (Section 3.2)
Iyy	lb-in-sec ²	Calculated from rigid body modal test (Section 3.2)
Izz	lb-in-sec ²	Calculated from rigid body modal test (Section 3.2)

[Figure 2](#) is a photograph of the vestibule end truck of the DOTX-216 car.

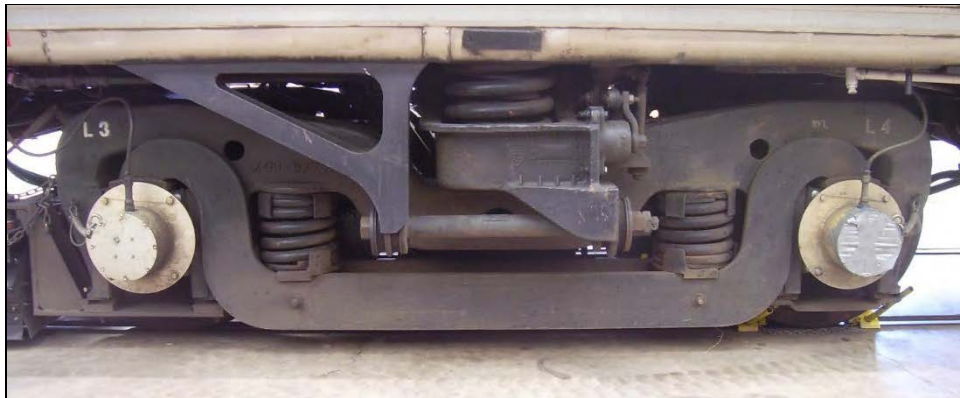


Figure 2. Vestibule End Truck of the DOTX-216 Car

The car has a coil spring secondary suspension between the carbody and truck bolster. The secondary suspension uses rotary dampers oriented vertically and laterally at each corner. The truck bolster is fixed to the carbody longitudinally with bolster anchor rods. The bolster is connected to the truck frame through a center plate. Simple gap-type side bearings limit the roll motion between the bolster and the truck frame. The truck frame is supported on coil primary

springs that rest on equalizer beams. The equalizer beams rest on the bearing boxes. The longitudinal and lateral motion of the primary suspension is limited by the clearance between the bearing box and the truck frame pedestals.

The bodies to be modeled in each truck are the truck bolster, the truck frame, two equalizer beams, and two axles. If the friction behavior of the bearing box to truck frame connection is more complicated than expected, it also may be necessary to model the axle boxes as separate bodies.

Table 2 through Table 5 show the body properties for the truck bolster, equalizer beams, and axles. In each case, the bodies were weighed to determine the mass. The team attempted to calculate the truck frame rotational inertias from the bogie modal test, but all the other body properties were estimated.

Table 2. Truck Bolster Body Properties

Parameter	Units	Source
Longitudinal CG offset from truck center to outside	inches	Assumed to be 0
Lateral CG offset + for cab leading	inches	Assumed to be 0
Vertical CG	inches	Estimated
Mass	pounds	Measured (Section 3.1)
Ixx	lb-in-sec ²	Estimated (6.53E3)
Iyy	lb-in-sec ²	Estimated (2.68E2)
Izz	lb-in-sec ²	Estimated (6.61E3)

Table 3. Truck Frame Body Properties

Parameter	Units	Source
Longitudinal CG offset from center + for cab leading	inches	Assumed to be 0
Lateral CG offset + for cab leading	inches	Assumed to be 0
Vertical CG	inches	Assumed to be equal to nominal wheel radius
Mass	pounds	Measured (Section 3.1)
Ixx	lb-in-sec ²	Estimated (1.73E4); attempted to calc. from truck modal test (Section 3.4)
Iyy	lb-in-sec ²	Estimated (3.40E4); attempted to calc. from truck modal test (Section 3.4)
Izz	lb-in-sec ²	Estimated (3.40E4); attempted to calc. from truck modal test (Section 3.4)

Table 4. Equalizer Beam Body Properties

Parameter	Units	Source
Longitudinal CG offset from truck center to outside	inches	Assumed to be 0
Lateral CG offset + for cab leading	inches	Measured (Section 3.1)
Vertical CG	inches	Estimated
Mass	pounds	Measured (Section 3.1)
Ixx	lb-in-sec ²	Estimated (5.70E1)
Iyy	lb-in-sec ²	Estimated (2.67E3)
Izz	lb-in-sec ²	Estimated (2.63E3)
GJ (shear modulus x shear moment of inertia about x)	lb-in ²	Estimated by matching truck load equalization test (Section 3.8)
Modal damping ratio	N/A	Estimated (0.2)

Table 5. Axle Body Properties

Parameter	Units	Source
Longitudinal CG offset from truck center to outside	inches	Assumed to be 0
Lateral CG offset + for cab leading	inches	Assumed to be 0
Vertical CG	inches	Assumed to be equal to nominal wheel radius
Mass	pounds	Measured (Section 3.1)
Ixx	lb-in-sec ²	Estimated (7.98E3)
Iyy	lb-in-sec ²	Estimated (2.50E3)
Izz	lb-in-sec ²	Estimated (7.98E3)

2.2 Geometry

The parameters listed in this section determine the location of bodies and connections in the model.

Table 6 lists some basic measurements which roughly locate the major bodies. Table 7 includes geometric parameters that are specific to the suspension configuration of the DOTX-216 car. Normally most of these parameters would be available from drawings of the vehicle, but for this project all dimensions were measured.

Table 6. Car Geometric Properties

Parameter	Units	Source
Length over pulling faces	inches	Measured (Section 3.1)
Truck center spacing	inches	
Axle spacing	inches	
Rail center spacing	inches	
Nominal wheel radius at tapeline	inches	
Lateral spacing of journals	inches	
Coupler height	inches	

Table 7. Location of Car Connections

Parameter	Units	Source
Primary springs longitudinal offset from truck center	inches	Measured (Section 3.1)
Primary springs vertical position	inches	
Equalizer beam to axle box vertical position	inches	
Secondary coil springs longitudinal offset from truck center	inches	
Secondary coil springs lateral position	inches	
Secondary coil springs vertical position	inches	
Lateral damper longitudinal offset from truck center	inches	
Lateral damper lateral position	inches	
Lateral damper vertical position	inches	
Vertical damper longitudinal offset from truck center	inches	
Vertical damper lateral position	inches	
Vertical damper vertical position	inches	
Traction rod longitudinal offset from truck center	inches	
Traction rod lateral position	inches	
Traction rod vertical position	inches	
Lateral bump stop longitudinal offset from truck center	inches	
Lateral bump stop lateral position	inches	
Lateral bump stop vertical position	inches	

Parameter	Units	Source
Center plate longitudinal offset from truck center	inches	
Center plate lateral position	inches	
Center plate vertical position	inches	
Center plate center plate diameter	inches	
Center plate centerplate rim height	inches	
Side bearing longitudinal offset from truck center	inches	
Side bearing lateral position	inches	
Side bearing vertical position	inches	
Axle box length	inches	
Axle box width	inches	
Axle box height	inches	

2.3 Stiffness and Damping

This section lists parameters related to the stiffness and damping of the connections in the DOTX-216 car, as well as suspension clearances. [Table 8](#) lists the primary suspension parameters and [Table 9](#) lists the secondary suspension parameters.

Table 8. Primary Suspension and Rail Stiffness Parameters

Parameter	Units	Source
Primary Spring Longitudinal Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Primary Spring Longitudinal Damping	lb/(in/s)	Estimated (from 0 to 1% critical)
Primary Spring Lateral Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Primary Spring Lateral Damping	lb/(in/s)	Estimated (from 0 to 1% critical)
Primary Spring Vertical Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Primary Spring Vertical Damping	lb/(in/s)	Estimated (from 0 to 1% critical)
Equalizer Beam to Axle Box Vertical Stiffness	lb/in	Estimated (steel on steel 1E6)
Equalizer Beam to Axle Box Vertical Damping	lb/(in/s)	Estimated (from 0 to 1% critical)
Axle Box Longitudinal/Stop Stiffness	lb/in	Estimated (steel on steel 0.5E6)
Axle Box Longitudinal Clearance	inches	Measured (Section 3.1)
Axle Box Friction – Longitudinal Stop	None	Estimated (steel on steel 0.3)
Axle Box Lateral/Stop Stiffness	lb/in	Estimated (steel on steel 1E6)
Axle Box Lateral Clearance	inches	Measured (Section 3.1)
Axle Box Friction – Lateral Stop	None	Estimated (steel on steel 0.3)
Rail Lateral Stiffness	lb/in	Estimated (Typically 100,000)
Rail Lateral Damping	lb/(in/s)	Estimated (Typically 100)
Rail Vertical Stiffness	lb/in	Estimated (Typically 250,000)
Rail Vertical Damping	lb/(in/s)	Estimated (Typically 250)

Table 9. Secondary Suspension and Coupler Stiffness Parameters

Parameter	Units	Source
Coupler Stiffness, provided only to restrain the longitudinal degree of freedom	lb/in	Estimated (typically 10,000)
Coupler Damping	lb/(in/s)	Estimated (typically 5% critical)
Center Pin Translational Stiffness	lb/in	Estimated (steel on steel 1E6)
Center Pin Translational Damping	lb/(in/s)	Estimated (steel on steel 1E3)
Centerplate Friction	None	Truck Rotation Test (Section 3.4)
Centerplate Vertical Stiffness	lb/in	Estimated (steel on steel 1E6)
Centerplate Vertical Damping	lb/(in/s)	Estimated (steel on steel 1E3)
Secondary Spring Longitudinal Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Secondary Spring Longitudinal Damping	lb/(in/s)	Estimated (1% of critical)
Secondary Spring Lateral Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)

Parameter	Units	Source
Secondary Spring Lateral Damping	lb/(in/s)	Estimated (1% of critical)
Secondary Spring Vertical Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Secondary Spring Vertical Damping	lb/(in/s)	Estimated (1% of critical)
Lateral Damper Characteristic (Nonlinear)	lb/(in/s)	Damper Test (Section 3.6)
Vertical Damper Characteristic (Nonlinear)	lb/(in/s)	Damper Test (Section 3.6)
Traction Rod Longitudinal Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Traction Rod Longitudinal Damping	lb/(in/s)	Estimated (5% of critical)
Traction Rod Lateral Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Traction Rod Lateral Damping	lb/(in/s)	Estimated (5% of critical)
Traction Rod Vertical Stiffness	lb/in	Suspension Stiffness Test (Section 3.3.2)
Traction Rod Vertical Damping	lb/(in/s)	Estimated (5% of critical)
Lateral Bump Stop Clearance	inches	Measured (Section 3.1)
Lateral Bump Stop Stiffness	lb/in	Estimated (Approx. 50,000)
Vertical Bump Stop Clearance	inches	Measured (Section 3.1)
Vertical Bump Stop Stiffness	lb/in	Estimated (Approx. 50,000)
Side Bearing Friction	None	Estimated (steel on steel 0.3)
Side Bearing Clearance	inches	Measured (Section 3.1)
Side Bearing Vertical Stiffness	lb/in	Estimated (steel on steel 1E6)
Side Bearing Vertical Damping	lb/in	Estimated (steel on steel 1E3)

3. Characterization Tests and Results

This section describes the equipment and methods used to measure the required vehicle parameters listed in [Section 2](#) and presents the results of the various characterization tests. Example plots and tabulated results are included for each subsection. [Appendix A](#) contains additional results from the characterization tests. The general methods used in this report were described in a previous report [2].

To facilitate model-to-test comparisons, the team made measurements of the body motion, secondary suspension displacement, and primary suspension displacement simultaneously. Some tests required specialized measurements, and those measurements are described in the specific subsection for those tests. [Table 10](#) shows the measurements taken for most of the characterization tests.

Table 10. Measurement List

Channel Name	Description	Range
AZCBF1	Cab End Vertical Accelerometer	2 g
AYCBF1	Cab End Lateral Floor Accelerometer	2 g
AYCBR1	Cab End Lateral Roof Accelerometer	2 g
AZCBF2	Non-Cab End Vertical Accelerometer	2 g
AYCBF2	Non-Cab End Lateral Floor Accelerometer	2 g
AYCBR2	Non-Cab End Lateral Roof Accelerometer	2 g
DZSSL1	Cab End Left Side Secondary Suspension Vertical Displacement	10 inches
DZSSR1	Cab End Right Side Secondary Suspension Vertical Displacement	10 inches
DZSSL2	Non-Cab End Left Side Secondary Suspension Vertical Displacement	10 inches
DZSSR2	Non-Cab End Right Side Secondary Suspension Vertical Displacement	10 inches
DYSS1	Cab End Secondary Suspension Lateral Displacement	5 inches
DYSS2	Non-Cab End Secondary Suspension Lateral Displacement	5 inches
DXSS1	Cab End Secondary Suspension Longitudinal Displacement (Truck Rotation)	10 inches
DXSS2	Non-Cab End Secondary Suspension Longitudinal Displacement (Truck Rotation)	10 inches
DZPSL1	Vertical Primary Suspension Displacement Left Side Axle 1	3 inches
DZPSR1	Vertical Primary Suspension Displacement Right Side Axle 1	3 inches
DZPSL2	Vertical Primary Suspension Displacement Left Side Axle 2	3 inches
DZPSR2	Vertical Primary Suspension Displacement Right Side Axle 2	3 inches
DYPS1	Lateral Primary Suspension Displacement Axle 1	1 inch
DYPS2	Lateral Primary Suspension Displacement Axle 2	1 inch
DXPSL1	Longitudinal Primary Susp. Displacement Left Side Axle 1	0.2 inch
DXPSR1	Longitudinal Primary Susp. Displacement Right Side Axle 1	0.2 inch
DXPSL2	Longitudinal Primary Susp. Displacement Left Side Axle 2	0.2 inch
DXPSR2	Longitudinal Primary Susp. Displacement Right Side Axle 2	0.2 inch
FInput1	Force Input 1	25 kips
FInput2	Force Input 1	25 kips

[Figure 3](#) demonstrates a string potentiometer measuring vertical displacement across the secondary suspension. [Figure 4](#) shows a string potentiometer measuring vertical displacement across the primary suspension.



Figure 3. Secondary Suspension String Potentiometer – Vertical Displacement Measurement



Figure 4. Primary Suspension String Potentiometer – Vertical Displacement Measurement

3.1 Basic Measurements

3.1.1 Basic Measurement Procedures

Many of the parameters listed in [Section 2](#) were measured with basic tools such as tape measures, feeler gages, or calipers. These parameters included the positions of bodies, the positions of suspension components, and suspension clearances.

The weight of the car was measured using the TTC track scale with four load cells located under the scale platform. The platform is large enough to accommodate one truck of a railcar. Two load cells were centered laterally under each rail, close to each end of the platform. The output of each individual load cell used in the scale was recorded while weighing the car. The longitudinal CG of the car was then calculated from the difference in weight between the vestibule end truck and the observation end truck. The lateral CG of the car was calculated from the difference in weight between the left and right side of the car.

During the characterization tests, one truck was removed from the car and disassembled. A load cell was used together with the shop crane to measure the weight of the following components:

- Truck bolster
- Truck frame
- Equalizer beam
- Axle box
- Axle

Wheel profiles and wheel back-to-back measurements were also measured for each wheelset.

3.1.2 Basic Measurement Results

Car and Component Weights

Table 11 shows the measured weights of the DOTX-216 car, including weight per truck, weight per side, and total vehicle weight. The car was weighed using the TTC track scale. Car weight was also measured using load bars during the lean test (Section 3.9). Both measurement methods gave results within 1 percent of each other. Depending on the available equipment, either method could be used to determine the weight of a vehicle.

Table 11. Measured Car Weights

Measurement Description	Weight from Track Scale (lbf)	Weight from Load Bars (lbf)
F Truck	64,700	64,400
R Truck	68,800	69,400
Total Left Side	68,600	69,100
Total Right Side	64,900	64,700
Total Car Weight	133,500	133,800

Researchers removed the F truck from the DOTX-216 car and disassembled it. The team weighed each component in the truck by suspending it, in series with a load cell, from an overhead crane. Table 12 shows the measured component weights.

Table 12. Component Weights

Component	Weight (lbf)
Truck Bolster (without springs)	2,130
Truck Frame (without springs)	6,240
Equalizer Beam	875
Axle with Axle Boxes	4,045
Axle Box	170
Primary Springs (1 outer, 1 inner from one corner of truck)	130
Secondary Springs (1 outer, 1 inner, 1 inner-inner from one side of truck bolster)	350

The weight of the carbody was determined by subtracting the component weights in Table 12 from the total car weight in Table 11. The carbody weighed approximately 95,900 pounds.

Geometry

Table 13 shows the list of basic geometry measurements made on the DOTX-216 car to document the major carbody parameters.

Table 13. Basic Geometry of the Car Used for Simulation

Parameter	Measurement (inches)
Length over pulling faces	1,020.00
Truck center spacing	720.00
Axle spacing	102.00
Rail center spacing	59.50
Nominal wheel radius at tapeline	18.00
Lateral spacing of journals	79.00
Coupler height	33.81

Several characterization tests were performed using the jacking pads of the car. The locations of the jacking were measured and recorded so that these tests could be simulated using a vehicle model and compared. Table 14 shows the measured locations of the jacking pads.

Table 14. Details and Geometry of Jacking Pads

Parameter	Measurement (inches)
Jacking pad longitudinal offset from truck center	57.00
Jacking pad lateral position	54.00
Jacking pad vertical position	42.00
Width between jacking pads	108.00
Height of jacking pads	42.00
Longitudinal offset of lateral pull	13.00
Height of lateral pull	34.00

The team measured the connection and interface locations between various components of the vehicle, as shown in Table 15.

Table 15. Connection Measurements

Parameter	Measurement (inches)
Primary Springs Longitudinal offset from truck center	29.00
Primary Springs Vertical Position	39.00
Equalizer Beam to Axle Box Vertical Position	25.00
Secondary Coil Springs Longitudinal offset from truck center	0
Secondary Coil Springs Lateral Position	53.25
Secondary Coil Springs Vertical Position	39.00
Lateral Damper Longitudinal offset from truck center	15.00
Lateral Damper Lateral Position	50.75
Lateral Damper Vertical Position	37.50
Vertical Damper Longitudinal offset from truck center	19.50
Vertical Damper Lateral Position	49.63
Vertical Damper Vertical Position	35.00
Traction Rod Longitudinal offset from truck center	0
Traction Rod Lateral Position	53.50
Traction Rod Vertical Position	20.75

Parameter	Measurement (inches)
Lateral Bump Stop Longitudinal offset from truck center	9.25
Lateral Bump Stop Lateral Position	26.00
Lateral Bump Stop Vertical Position	42.00
Center Plate Vertical Position	18.00
Center Plate Diameter	24.00
Center Plate Rim Height	1.00
Side Bearing Longitudinal offset from truck center	0
Side Bearing Lateral Position	40.44
Side Bearing Vertical Position	25.50
Axle Box Length	12.25
Axle Box Width	6.75
Axle Box Height	18.00

Suspension Clearance

Table 16 through Table 19 list the measured clearances for various suspension elements. Such measurements are important for building an accurate model because they may influence the dynamic behavior of the vehicle.

Table 16. Side Bearing Clearance

Location	Clearance (inch)
F-End Left	0.25
F-End Right	0.19
B-End Left	0.06
B-End Right	0.13

Table 17. Secondary Vertical Stop Clearance

Location	Inside (inches)	Outside (inches)
F-End Left	2.06	2.00
F-End Right	2.56	2.56
B-End Left	2.75	2.38
B-End Right	3.06	2.94

The secondary lateral stop clearance was very difficult to measure when the truck was installed under the car, so researchers measured the clearance on the F-end while the truck was removed. The width between the stops on the truck bolster was 55 inches. The width between the outside edges of the bumpers on the carbody was 52 inches. This indicates an average lateral bump stop clearance of 1.5 inches on each side.

Table 18. Primary Suspension Longitudinal Clearance

Clearance (inch)						
Location	Left			Right		
	Front	Back	Average	Front	Back	Average
Axle 1	0.08	0	0.04	0.08	0.03	0.06
Axle 2	0	0.08	0.04	0.09	0.03	0.06
Axle 3	0.08	0.03	0.06	0.13	0	0.07
Axle 4	0.08	0.01	0.05	0.05	0.04	0.05

Table 19. Primary Suspension Lateral Clearance

Clearance (inch)					
	Left		Right		
Location	Front	Back	Front	Back	Average
Axle 1	0	0.06	0.25	0.25	0.14
Axle 2	0.25	0.25	0.19	0.19	0.22
Axle 3	0.25	*	0	*	0.13
Axle 4	0.25	0.19	0.13	0	0.14
* Could not reach this location for measurement. Track geometry measurement beam restricted access.					

3.2 Carbody Resonance Test

3.2.1 Resonance Test Procedure

Carbody resonance tests were used to determine suspension stiffness, as well as roll, pitch, and yaw moments of inertia, and carbody CG height for input into the vehicle model.

For the carbody resonance tests, the carbody modes of vibration were excited by hand and by mechanical means. Vehicle responses were measured using accelerometers and string potentiometers, and the data was processed to determine modal responses. [Figure 5](#) shows the five rigid body modes that may be excited during a carbody resonance test. The resonance tests were performed in coordination with suspension stiffness tests to reduce the total number of experiments conducted.

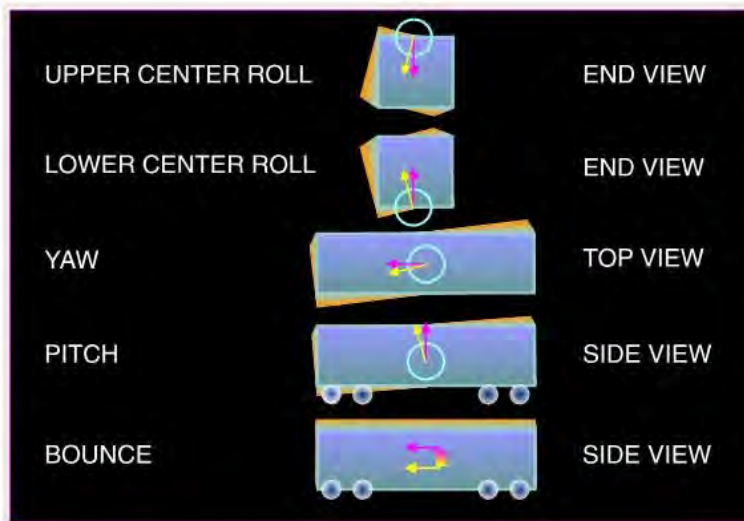


Figure 5. Carbody Rigid Body Modes That May Be Excited During the Test

To mechanically excite the carbody modes, two hydraulic cylinders were connected to load cells and were used to offset the vehicle suspension slightly. The valves on the cylinders were then opened quickly to allow the body to drop and vibrate on the suspension. The hydraulic cylinders were moved to different locations on the vehicle to excite different modes of vibration. These types of tests are commonly referred to as “jack and drop” tests. Tests in which the carbody modes are excited by hand are often referred to as “shake and bake” tests.

The following procedure was used in both types of carbody resonance tests:

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and separated from the rest of the train. The wheels of one axle were chocked, and the brakes were released.
2. Secondary vertical dampers and lateral dampers were disconnected.
3. Accelerometers and displacement transducers were installed to measure carbody motions and were wired to the data acquisition system. See [Table 10](#) for specific instrumentation details.
4. The bounce mode of the DOTX-216 car was excited.
5. The pitch mode of the DOTX-216 car was excited.
6. The yaw mode of the DOTX-216 car was excited.
7. The lower center roll mode of the DOTX-216 car was excited.
8. The upper center roll mode of the DOTX-216 car was excited.
9. The traction rods were then removed, and the entire sequence was repeated with the rods disconnected.

Synthetic channels were created using the accelerometers placed on the car. They used accelerometer channels to calculate the desired rigid body mode outputs. [Figure 6](#) describes accelerometer setup and lists the equations used to calculate the synthetic rigid body mode outputs.

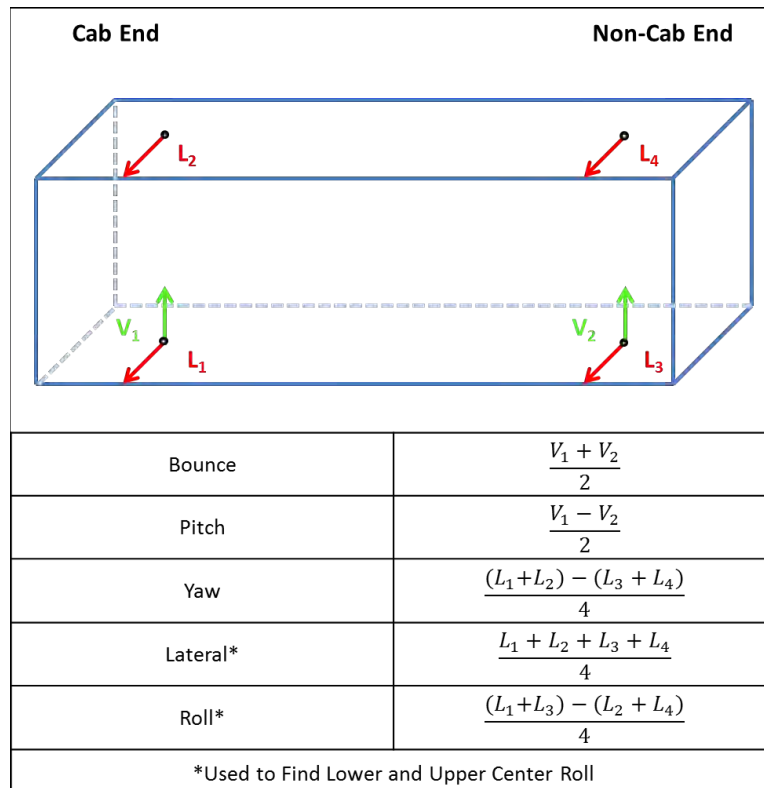


Figure 6. Accelerometer Placement and Formulas for Synthetic Channel Calculation

Lateral and roll synthetic channels were used in combination to find the lower center roll and upper center roll resonant frequencies. When the lateral and roll synthetic channels were in phase, the accelerometer data indicated excitation of the upper center roll mode. When they were out of phase, the data indicated excitation of the lower center roll mode. For the DOTX-216 car, the lateral synthetic channel gave the best indication of lower center roll excitation, and the roll synthetic channel gave the best indication of upper center roll excitation.

Synthetic channels were used only to identify the modal frequencies of the carbody. Rotational synthetic channels (i.e., pitch, yaw, and roll) do not reflect true rotational accelerations because they do not consider the changing angle of the carbody. Synthetic channels could be corrected to reflect roll accelerations by multiplying the measured acceleration by the distance from the carbody CG to the accelerometer.

3.2.2 Resonance Test Results

Table 20 shows the measured resonant frequencies for pitch, bounce, yaw, lower center roll, and upper center roll with and without traction rods. Modal responses were obtained using hand excitation (i.e., shake and bake) and mechanical excitation (i.e., jack and drop) test results.

Table 20. Rigid Carbody Resonant Frequencies – Average Values

Mode	With Traction Rods (Hz)	Without Traction Rods (Hz)
Pitch	1.16	1.11
Bounce	1.04	0.98
Yaw	1.08	0.90
Lower center roll	0.51	0.48
Upper center roll	1.38	1.20

Shake and Bake Test

Figure 7 shows example accelerometer data from a shake and bake (i.e., resonance) test in which the bounce mode of the carbody was excited. Modal frequencies were determined using a combination of cycle counting and power spectral density (PSD) analysis. Figure 8 shows a PSD plot of the carbody bounce mode.

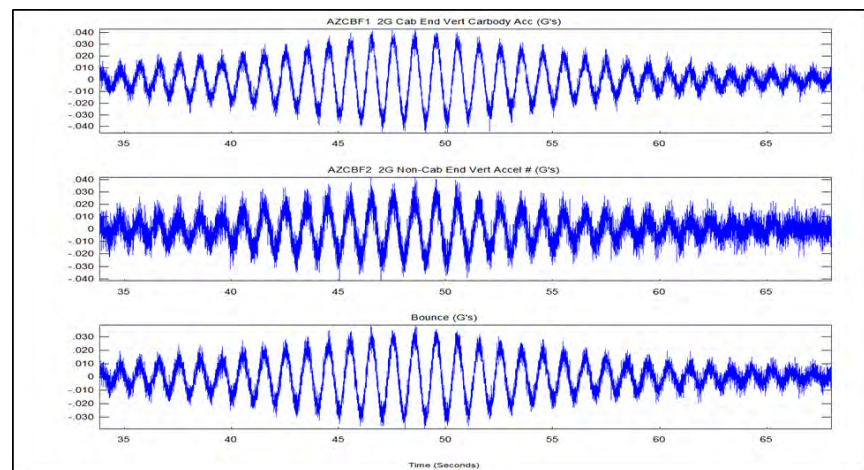


Figure 7. Bounce Mode Excitation – with Traction Rods

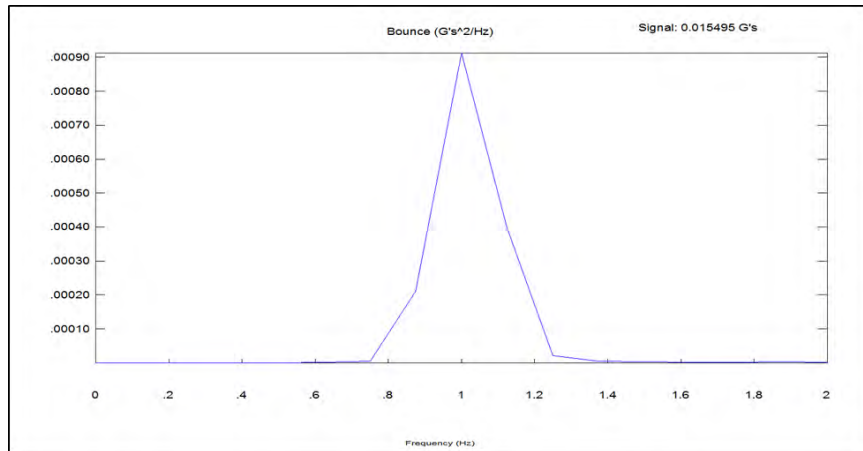


Figure 8. PSD of Bounce Mode – with Traction Rods

Log decrements were calculated from the decay of each modal vibration envelope to determine the effective system damping. These results were used in the development of the DOTX-216 vehicle model.

Jack and Drop Tests

Jack and drop tests are a cost-effective option that allow many vehicle properties to be determined, including dynamic suspension characteristics, using a relatively simple test setup. Vertical and lateral “jacking” tests were performed for several loading configurations on the car. [Appendix A](#) contains additional results from the jack and drop tests.

[Figure 9](#) through [Figure 11](#) show example accelerometer data from a vertical jack and drop test. Vertical loads were applied to the carbody at both jacking pads on the cab end of the vehicle using hydraulic cylinders. After applying the load, the cylinder valves were opened suddenly, allowing the carbody to drop and vibrate. [Figure 9](#) shows test data from the vertical accelerometer channels. [Figure 10](#) shows the processed pitch and bounce synthetic channels (see [Figure 6](#) for synthetic channel formulas.). [Figure 11](#) shows PSD plots for the carbody pitch and bounce modes.

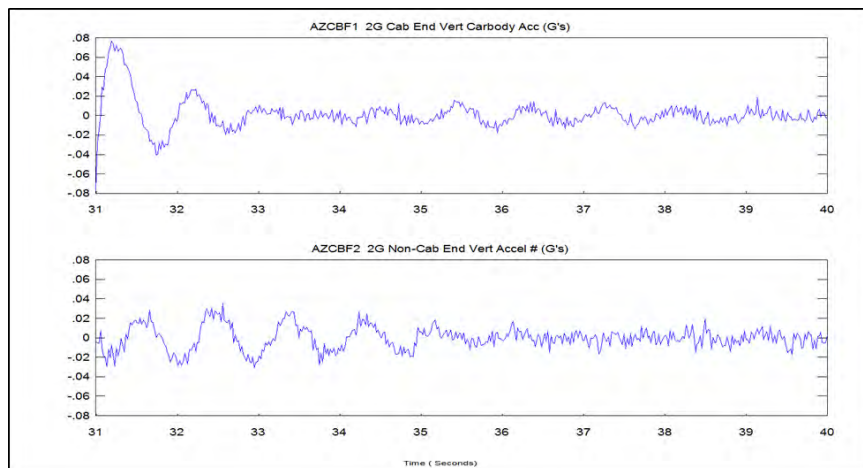


Figure 9. Vertical Accelerometer Data from Jack and Drop Test

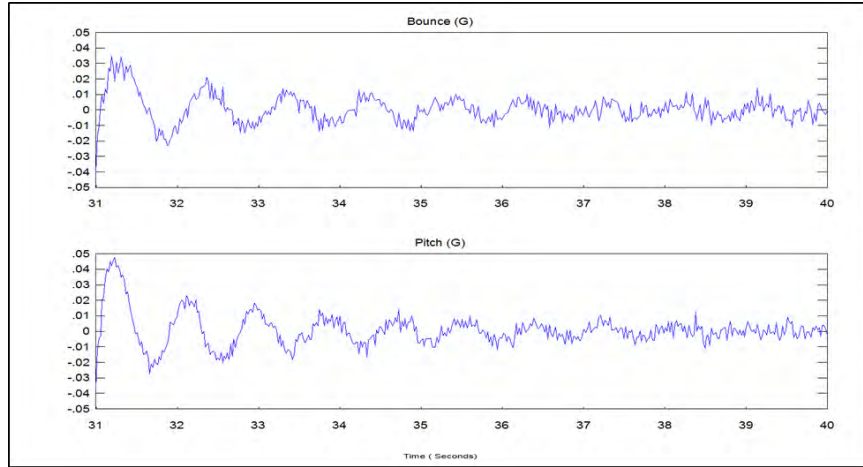


Figure 10. Synthetic Channel Accelerometer Data from Jack and Drop Test

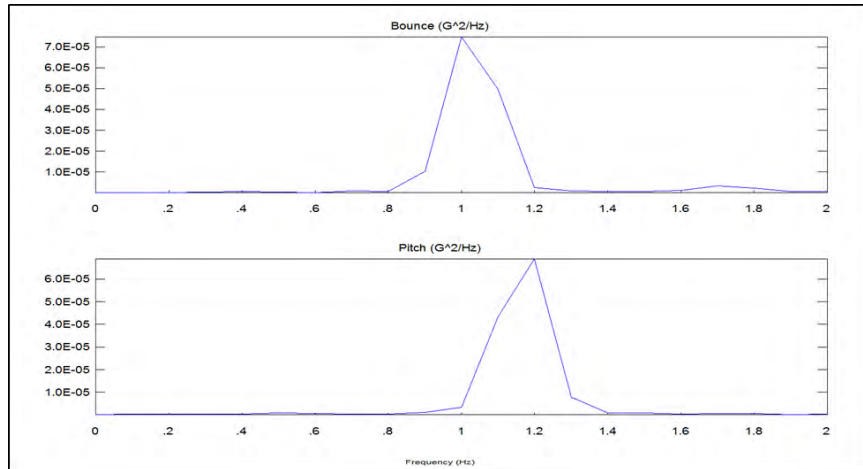


Figure 11. PSDs of Pitch and Bounce Modes from Jack and Drop Test

3.2.3 Carbody Dynamic Properties

In the early 1980s, TTC staff developed a method to estimate carbody rotational inertias, CG height, and suspension stiffness values [4,5]. For this project, measured resonant frequencies were used to solve the equations of motion for a simplified carbody model vibrating on its suspension. Other parameters required for the analysis include the carbody mass (248.4 lb-sec²/in) and the truck semi-spacing (360 inches).

Table 21 lists the calculated rotational inertias and other parameters.

Table 21. Carbody Dynamic Parameters

Mode	Calculated Value
Carbody Pitch Inertia	25 million lb-in-sec ²
Carbody Yaw Inertia	25 million lb-in-sec ²
Carbody Roll Inertia	1 million lb-in-sec ²
Vertical Stiffness (per Truck)	4,700 lb/in
Lateral Stiffness (per Truck)	3,000 lb/in
CG Height Above Roll Center	54 inches

Estimates are not exact values for the parameters of interest; instead, they provide a good starting point for dynamic model development and validation. The values in [Table 21](#) were fine-tuned as a dynamic vehicle model of the DOTX-216 car was developed and compared against test data (see [Section 4](#)).

3.3 Suspension Stiffness Test Results

3.3.1 Suspension Stiffness Test Procedure

Suspension stiffness tests were performed to measure the longitudinal, lateral, and vertical stiffnesses of the primary and secondary suspensions. As a force was applied across the suspension in the measurement direction, displacements were measured. Force and displacement graphs were generated to calculate the suspension stiffness per truck. The average slopes of the force and displacement plots represent the average suspension stiffness of a truck across either the primary or secondary suspension. Force across the suspension was measured with a load cell, and displacements were measured with the displacement transducers listed in [Table 10](#).

The following sections describe the procedures used for the suspension stiffness tests. The DOTX-216 car has an H-frame truck with very tight longitudinal pedestal clearances. Researchers expected it to have very high longitudinal stiffness.

Longitudinal Stiffness

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and separated from the rest of the train. The wheels of Axle 1 (the axle to be measured) were chocked, and the brakes were released.
2. Secondary vertical dampers and lateral dampers were disconnected.
3. A large steel weight (approximately 20,000 lb) was placed in line with T-16 car to provide a reaction point.
4. A hydraulic cylinder was connected between the reaction load and the carbody of T-16.
5. Displacement transducers were installed to measure longitudinal displacements between the axle and the truck frame on each side of axle one (primary suspension measurement). Refer to [Table 10](#).
6. Displacement transducers were installed to measure the longitudinal displacement between the lead truck frame and the carbody (secondary suspension measurement). Refer to [Table 10](#).
7. Longitudinal loads were applied, and the displacements were recorded. The applied load was measured using load cell transducers in series with the hydraulic cylinder. Forces and displacements were recorded from zero to full load and back to zero to measure the complete force displacement characteristic.
8. After completing the sequence, the chocks were removed from Axle 1, and the test was repeated with Axle 2 chocked.

Lateral Stiffness

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and separated from the rest of the train. The wheels of one axle were chocked, and the brakes were released.
2. Secondary vertical dampers and lateral dampers were disconnected.
3. A hydraulic cylinder, in series with a load cell, was connected between the carbody above the lead truck and a large steel reaction weight (approximately 20,000 lb).
4. Displacement transducers were installed on the lead truck frame and placed so that they measured the lateral displacement between the truck frame and the carbody (secondary suspension). Refer to [Table 10](#).
5. Displacement transducers were installed on Axle 1 and Axle 2 to measure the lateral displacement between the axles and the truck frame (primary suspension measurement). Refer to [Table 10](#).
6. Lateral loads were applied, and the displacements were recorded. Forces and displacements were recorded from zero to full load to measure the complete force displacement characteristic.
7. For certain test trials, the load was released suddenly, which produced data to calculate damping in the system.
8. The traction rods were then removed, and the entire sequence was repeated with the rods disconnected.

Vertical Stiffness

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and separated from the rest of the train. The wheels of one axle were chocked, and the brakes were released.
2. Secondary vertical dampers and lateral dampers were disconnected.
3. Displacement transducers were installed to measure the displacement between the axles and the truck frame (primary suspension system). Refer to [Table 10](#).
4. Displacement transducers were installed to measure the vertical displacement between the carbody and truck frame (secondary suspension system). Refer to [Table 10](#).
5. Vertical loads were applied, and the displacements were recorded. Forces and displacements were recorded from zero to full load to measure the complete force displacement characteristic.
6. For certain test trials, the load was released suddenly, which produced data for calculation of damping in the system.
7. The traction rods were then removed, and the entire sequence was repeated with the rods disconnected.

3.3.2 Suspension Stiffness Test Results

Table 22 shows the average stiffness results of the primary and secondary suspensions with and without traction rods in vertical, lateral, and longitudinal directions. Stiffness measurements shown in Table 22 represent average values of all trials in a particular test. However, the measured stiffness characteristics were nonlinear for some suspension elements. These nonlinear characteristics will be accounted for in the DOTX-216 vehicle model.

The following sections show example force displacement plots of the primary and secondary suspension stiffness.

Table 22. Suspension Stiffness Test Results Summary

Direction	Secondary with Traction Rods	Secondary without Traction Rods	Primary Suspension
	kips/inch per Corner	kips/inch per Corner	kips/inch per Axle Box
Longitudinal	24.0	N/A	17.1*
Lateral	1.97	1.53	8.35
Vertical	3.19	2.89	3.75

*Primary longitudinal stiffness measurement affected by equalizer beams

Traction rod stiffness in the vertical and lateral directions was found to be approximately 300 kips/inch. The stiffness was calculated using the difference in secondary suspension stiffness with and without traction rods connected.

Longitudinal Stiffness

Figure 12 shows an example force displacement graph of the secondary suspension longitudinal stiffness at the cab end truck with Axle 2 chocked.

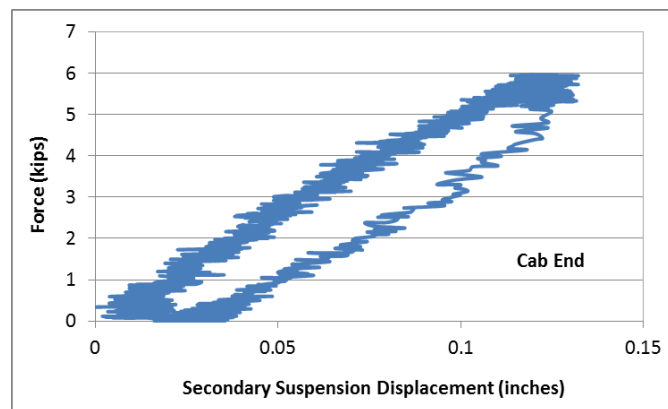


Figure 12. Secondary Suspension Longitudinal Stiffness – Cab End, Axle 2 Chocked

Figure 13 and Figure 14 show example force displacement graphs of the primary suspension longitudinal stiffness at the cab end truck with Axle 2 chocked.

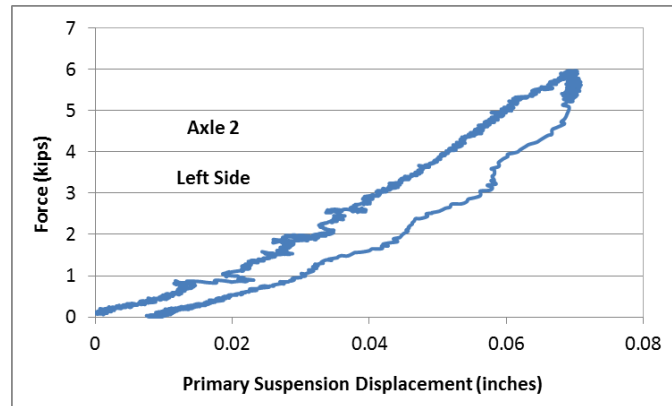


Figure 13. Primary Suspension Longitudinal Stiffness – Chocked Axle 2, Left Side

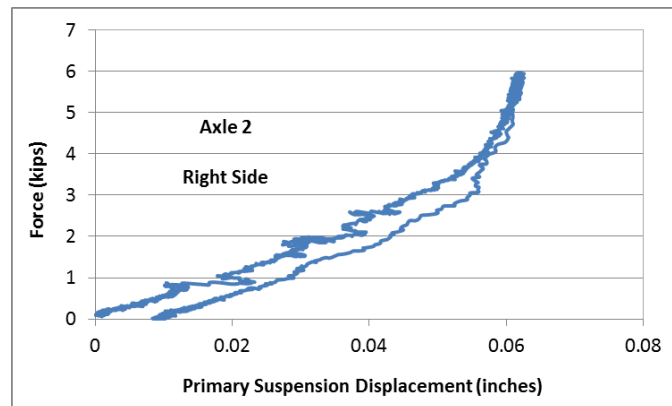


Figure 14. Primary Suspension Longitudinal Stiffness – Chocked Axle 2, Right Side

Lateral Stiffness

Figure 15 shows an example force displacement graph of the secondary suspension lateral stiffness at the cab end truck without traction rods.

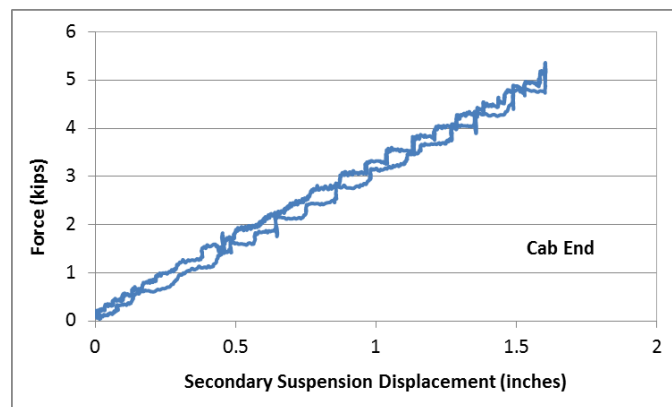


Figure 15. Secondary Suspension Lateral Stiffness without Traction Rods – Cab End

Figure 16 and Figure 17 show example force displacement plots of the primary suspension lateral stiffness at the cab end truck without traction rods.

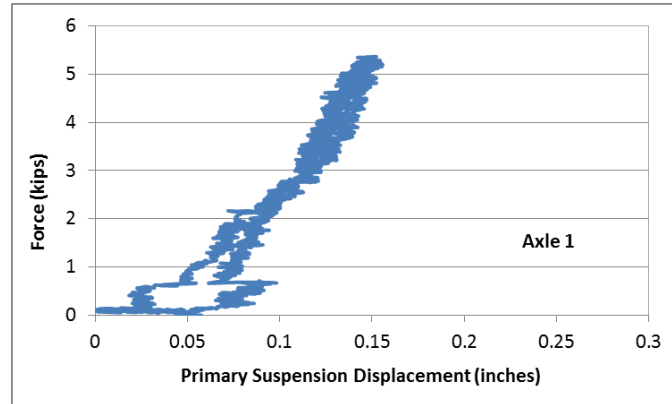


Figure 16. Primary Suspension Lateral Stiffness without Traction Rods – Axle 1

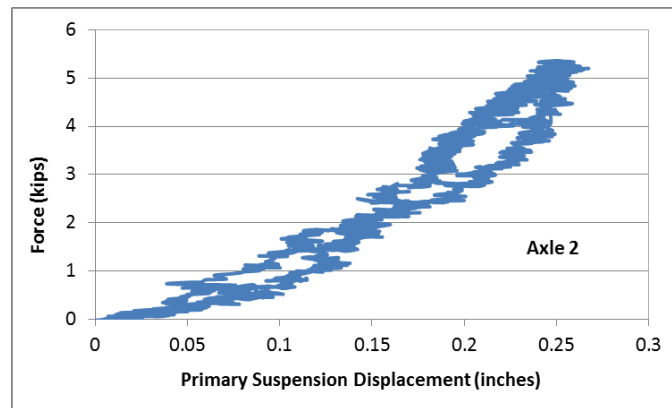


Figure 17. Primary Suspension Lateral Stiffness without Traction Rods – Axle 2

Vertical Stiffness

Figure 18 and Figure 19 show example force displacement plots of the secondary suspension vertical stiffness at the cab end truck with traction rods connected.

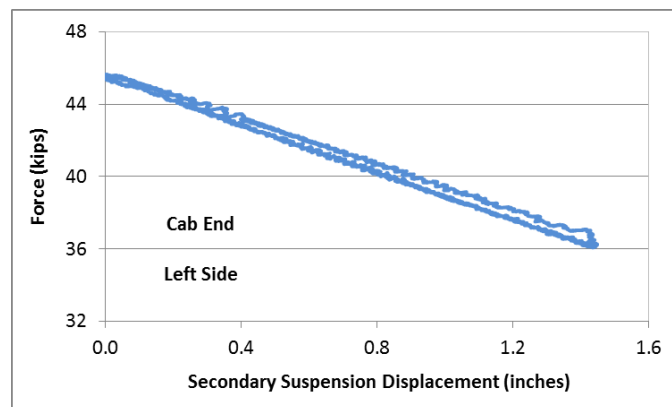


Figure 18. Secondary Suspension Vertical Stiffness with Traction Rods – Cab End Left

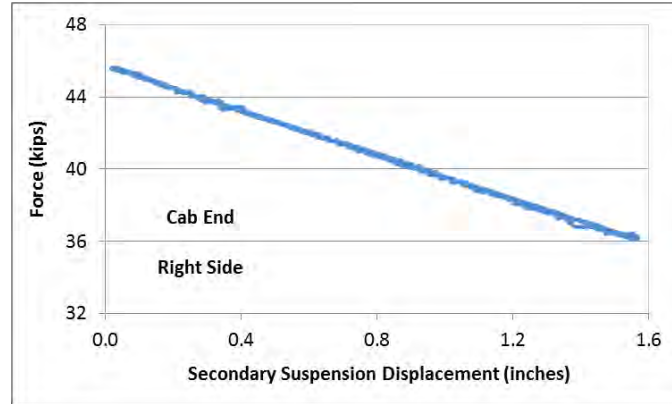


Figure 19. Secondary Suspension Vertical Stiffness with Traction Rods – Cab End Right

Figure 20 and Figure 21 show example force displacement plots of the vertical primary suspension stiffness at the left and right sides of Axle 1.

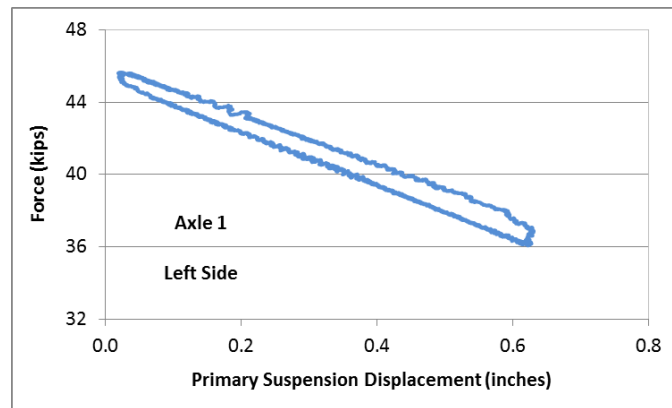


Figure 20. Primary Suspension Vertical Stiffness with Traction Rods – Axle 1 Left

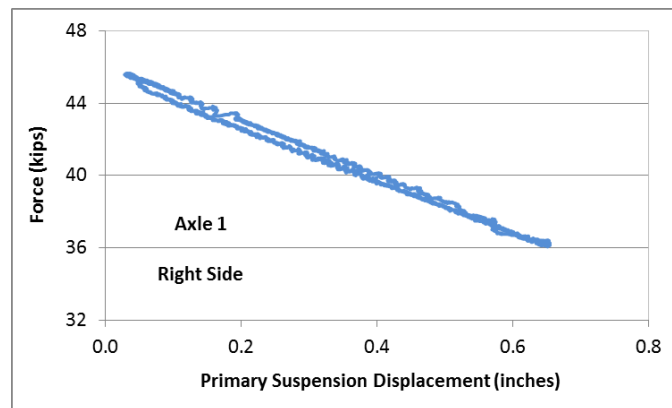


Figure 21. Primary Suspension Vertical Stiffness with Traction Rods – Axle 1 Right

3.4 Spring Stiffness Measurements

3.4.1 Spring Stiffness Measurement Procedure

Individual primary and secondary springs were tested in a load frame machine to determine the vertical stiffness contribution of each component. Deflections were measured across each spring

as the vertical load was applied and measured. Each secondary suspension consisted of three nested coil springs: an outer spring, an inner spring, and an inner/inner spring. Each primary suspension consisted of two nested coil springs: an outer spring and an inner spring. Each suspension spring set was disassembled and tested spring by spring to determine the stiffness contribution of each component.

The following procedure was used to characterize each spring:

1. Each suspension spring set was disassembled into individual component springs.
2. Each spring was installed vertically in the load frame.
3. Deflection and force measurements were made internally by the load frame machine as load was applied.
4. Each spring was compressed approximately 6 inches at a loading rate of 0.1 in/s.
5. The process was repeated for each component.

Average stiffness values were computed for each component using the measured force displacement characteristics. Individual spring stiffness values were added together to determine the overall stiffness of the primary and secondary coils.

Lateral and longitudinal stiffness values were not measured using this method. Force displacements characteristics in these directions must account for complex interactions between multiple components. In general, suspension stiffness can be more accurately measured using tests like those outlined in [Section 3.3](#), because the methodology accounts for interactions between different elements in the system.

[Figure 22](#) shows a picture of the load frame used to measure individual spring stiffness.



Figure 22. Suspension Spring in Load Frame

3.4.2 Spring Stiffness Results

[Table 23](#) and [Table 24](#) show the average stiffness values measured for the primary and secondary coil components. The tables also describe how the average stiffness was calculated for the primary and secondary suspensions at each spring location and each truck. Vertical suspension

stiffness results calculated from the individual spring tests were lower than measured results in [Section 3.2.3](#). The results differ slightly because interactions between components were not accounted for in the individual spring component tests.

Table 23. Primary Spring Stiffness Measurements

Component	Average Stiffness (kips/inch)
Primary Outer	2.51
Primary Inner	1.10
Primary per Spring Location (Outer + Inner)	3.61
Primary per Truck (Primary per Spring Location x 4)	14.44

Table 24. Secondary Spring Stiffness Measurements

Component	Average Stiffness (kips/inch)
Secondary Outer	1.56
Secondary Inner	0.81
Secondary Inner-Inner	0.43
Secondary per Spring Location (Outer + Inner + Inner/Inner)	2.80
Secondary per Truck (Secondary per Spring Location x 2)	5.60

[Figure 23](#) shows the force displacement characteristics of the outer and inner primary springs at the left side of Axle 1. [Figure 24](#) shows force displacement characteristics of the outer, inner, and inner/inner secondary springs at the cab end left side.

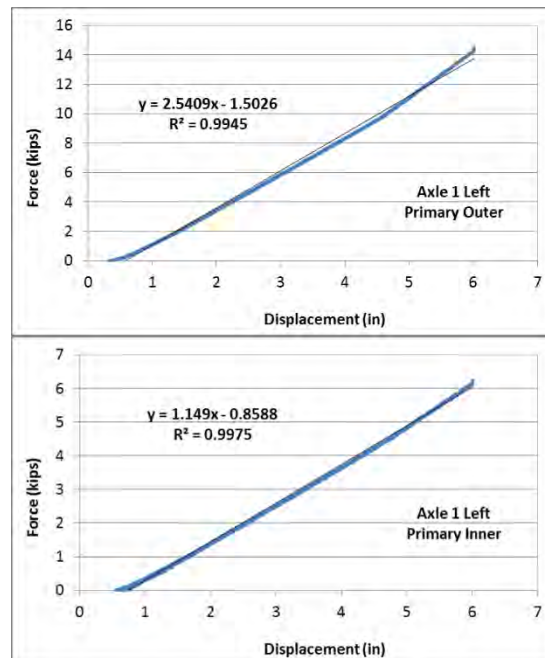


Figure 23. Primary Spring Stiffness Measurements – Axle 1 Left

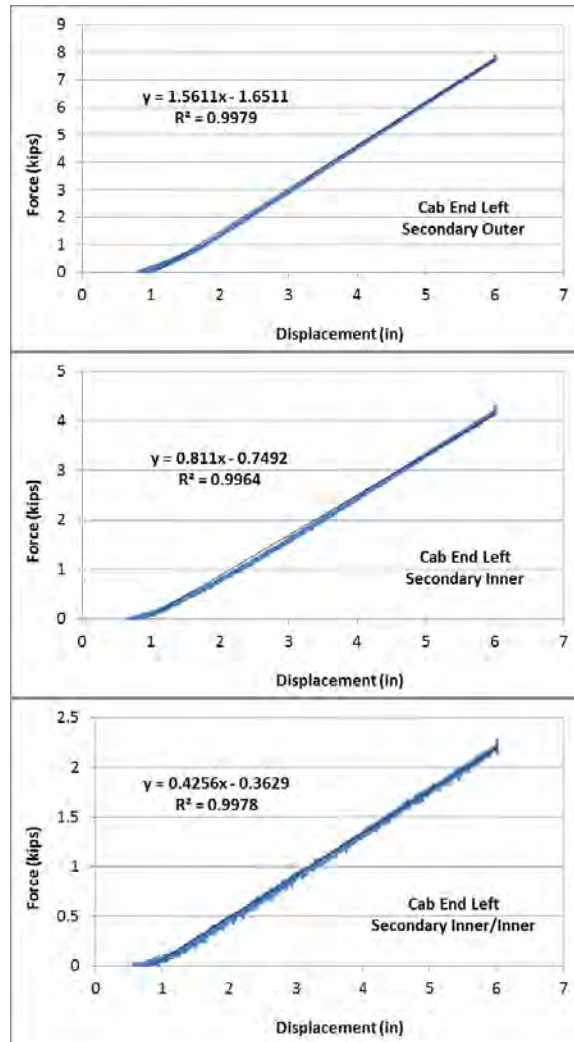


Figure 24. Secondary Spring Stiffness Measurements – Cab End Left

Table 25 shows the suspension stiffness values calculated using the suspension stiffness tests (Section 3.3) and the individual spring stiffness tests (Section 3.4). Results from the two testing methodologies are similar, but the suspension stiffness test results (Section 3.3) give a better description of the suspension system.

Table 25. Vertical Suspension Stiffness Results

Test Method	Primary Spring Stiffness (kips/inch)	Secondary Spring Stiffness (kips/inch)
Suspension Stiffness Test (Section 3.3)	3.75	2.89
Spring Stiffness Measurement (Section 3.4)	3.61	2.80
Percent Difference	3.73%	3.11%

3.5 Truck Resonance Test

3.5.1 Truck Resonance Test Procedure

Truck modes of vibration were excited using an instrumented hammer impact. The truck frame modal test used a different set of instrumentation than that described in Section 3. Responses of

the truck were measured using four 10-g accelerometers and were processed to determine the resonant frequencies. Accelerometers were placed at each corner of the measured truck and were oriented to measure accelerations in the desired directions. Pitch, bounce, and roll responses were determined using vertical accelerometers. Lateral and yaw responses were determined using lateral accelerometers.

Table 26 lists the instrumentation to be used for the test. Accelerometers with a frequency response of 200 Hz or greater were used.

Table 26. Instrumentation for Truck Modal Test

Channel Name	Description	Range
HMMR	Instrumented Hammer	5,000 lb
Acc1	Accelerometer 1	10 g
Acc2	Accelerometer 2	10 g
Acc3	Accelerometer 3	10 g
Acc4	Accelerometer 4	10 g

The following procedure was used for the truck resonance test:

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track over a pit and was separated from the rest of the train. The wheels of one axle (not on the instrumented truck) were chocked, and the brakes were released.
2. Secondary vertical dampers and lateral dampers were disconnected.
3. Accelerometers were placed at each corner on the truck frame and were oriented in the direction of interest.
4. The accelerometers and instrumented hammer were wired to a data acquisition system near the car.
5. The truck frame was tapped laterally above the lead axle to excite the yaw mode, and accelerations were recorded.
6. The truck frame was tapped laterally in the center to excite the lateral mode, and accelerations were recorded.
7. The truck frame was tapped vertically above the lead axle to excite the pitch mode, and accelerations were recorded.
8. The truck frame was tapped vertically in the center of one edge to excite the roll mode, and accelerations were recorded.
9. The truck frame was tapped vertically in the center (from underneath) to excite the bounce mode, and accelerations were recorded.

3.5.2 Truck Resonance Test Results

Pitch, bounce, and roll responses were determined using processed data from vertical accelerometers. Lateral and yaw responses were determined using processed data from lateral accelerometers. Table 27 shows the measured resonant frequencies for pitch, bounce, yaw, lateral, and roll modes.

Table 27. Truck Modal Frequencies

Mode	Frequency (Hz)
Pitch	22.0
Bounce	8.0
Yaw	11.5
Lateral	5.0
Roll	10.5

Transfer functions were generated between the input hammer force and output accelerations to determine the modal responses of the truck. Figure 25 and Figure 26 show an example of the lateral response of the cab end truck to a lateral hammer impact at the left side of the truck frame. The impact location was slightly offset in the longitudinal direction from the truck center. Consequently, both the lateral (5.0 Hz) and yaw (11.5 Hz) truck modes were excited.

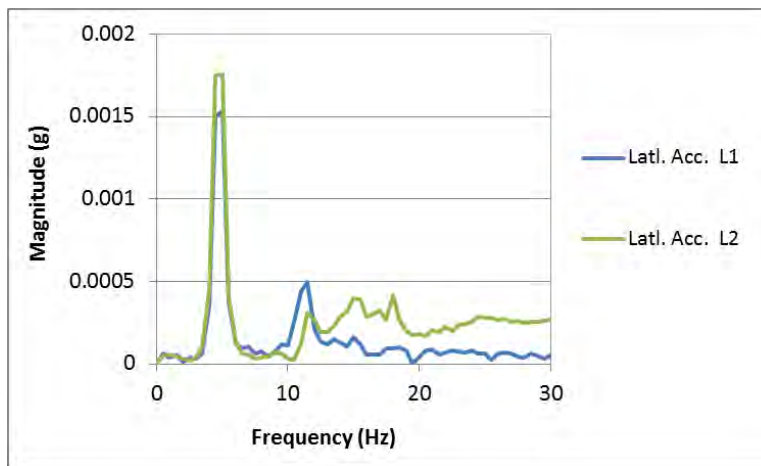


Figure 25. Truck Response to Lateral Hammer Impact (Magnitude)

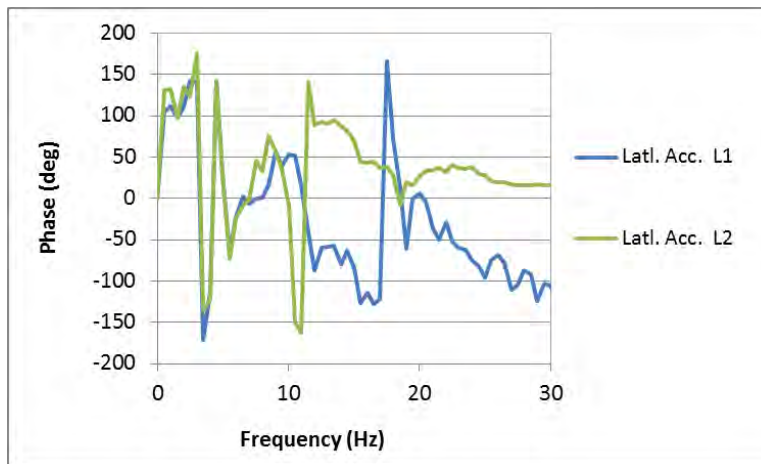


Figure 26. Truck Response to Lateral Hammer Impact (Phase Angle)

At a frequency of 5 Hz, the transfer functions of the lead and trail accelerometers had similar relative maximum magnitudes, and the signals were in phase. This indicates excitation of the lateral mode. At 11.5 Hz, the transfer functions of the lead and trail accelerometers also had similar relative maximum magnitudes, but the signals were 180 degrees out of phase. This indicates excitation of the yaw mode.

Mass moments of inertia were difficult to calculate from the test data because some resonant frequencies could not be reliably identified. Additionally, high frequency responses from the track structure (greater than 100 Hz) dominated the frequency response data [6]. This may have resulted from improper isolation of the truck from the rails at the test location. For these reasons, truck frame rotational inertias were not calculated using the measured data. Instead, the rotational inertias were estimated using the component's geometry and tuned when developing the dynamic vehicle model.

3.6 Damper Characterization Test

3.6.1 Damper Characterization Procedure

All the dampers were tested in a load frame to determine the force-velocity relationship and the end bushing stiffness. Transducers were installed to measure the deflections and velocities across the bushings and across the entire damper.

The following procedure was used to characterize each damper:

1. The damper was manually compressed to find the minimum length and manually extended to find the maximum length.
2. The damper was installed in the load frame. Vertical dampers were characterized in vertical orientation, and lateral dampers were characterized at an angle consistent with their installation on the vehicle.
3. Transducers were installed to measure the deflection and velocity across the bushing and the entire damper.
4. The damper was cycled about the nominal length at about one third to one half of the available stroke.
5. Desired stroke velocities (1 in/s, 2 in/s, 5 in/s, 10 in/s, and 15 in/s) were tested to determine the shape of the damper characteristic.
6. Damper force was plotted against velocity to build the damper characteristic.

Figure 27 shows an example of the test setup for a vertical rotary damper.



Figure 27. Damper Characterization Test

Figure 28 shows the vertical and lateral rotary dampers used on the T-16 car. Special fixtures were built to install the dampers in the load frame.



Figure 28. Vertical and Lateral Secondary Suspension Dampers on T-16 Car

3.6.2 Damper Characterization Results

Table 28 lists the average damper characteristics measured for the vertical and lateral damper tested. At velocities near zero, the dampers provided almost no damping force. A “dead band” can be seen in each force/velocity plot at very low velocities (Figure 29 through Figure 32). The “dead band” feature of these damper characteristics was accounted for in the vehicle model of the DOTX-216 car.

Table 28. Average Damper Characteristics

Damper Type	Damping (lb-s/in) at Velocities from -20 in/s to -5 in/s	Damping (lb-s/in) at Velocities from -5 in/s to 5 in/s	Damping (lb-s/in) at Velocities from 5 in/s to 20 in/s
Lateral	30	280*	30
Vertical	30	190*	30

*At near zero velocity, the dampers provide very little or no damping force.

Table 29 lists the measured stiffness of the vertical damper bushings. A range of stiffness values was measured. The stiffness variability may be due to the age of the bushing, the bushing preload, or the manufacturing of each component.

Table 29. Average Vertical Damper Bushing Stiffness

Damper Type	Average Stiffness (kips/inch)
Cab End Left Side	27.2
Cab End Right Side	51.2
Non-Cab End Left Side	17.8
Non-Cab End Right Side	34.1

Figure 29 and Figure 30 show the force and velocity relationship of the lateral dampers at the cab end left and right sides of the DOTX-216 car, respectively. The damper force and velocity plots displayed a distinctly nonlinear shape.

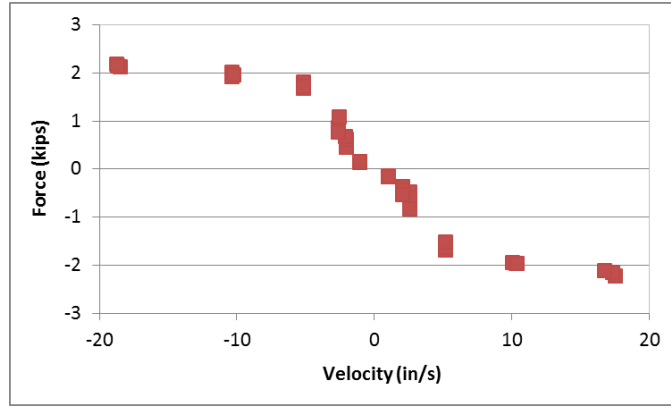


Figure 29. Lateral Damper – Cab End Left

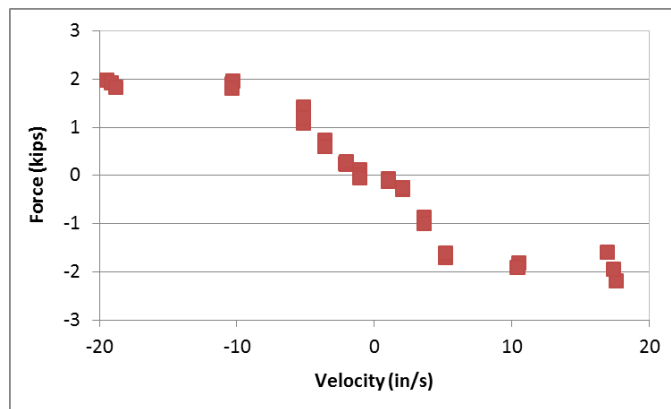


Figure 30. Lateral Damper – Cab End Right

Figure 31 and Figure 32 show the force and velocity relationship of the vertical dampers at the cab end left and right side of the DOTX-216 car, respectively. Data from the damper characterization tests was used to model the nonlinear damping characteristics of the components. Appendix A contains force displacement plots showing the vertical bushing stiffness at each damper.

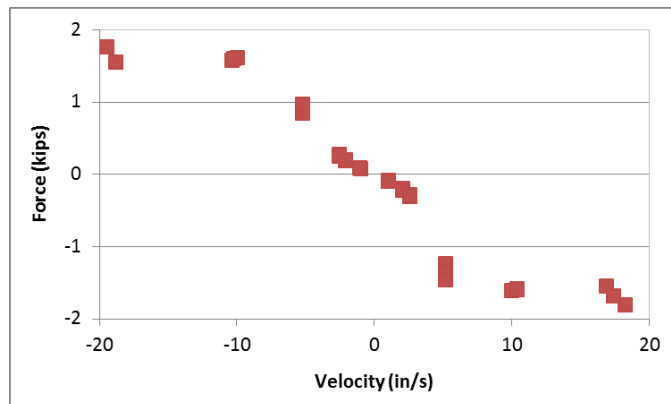


Figure 31. Vertical Damper – Cab End Left

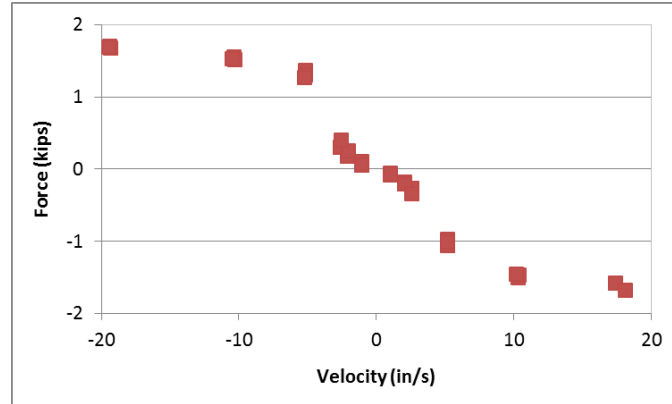


Figure 32. Vertical Damper – Cab End Right

3.7 Truck Resistive Torque Test

3.7.1 Truck Resistive Torque Test Procedure

A truck resistive torque test was performed using an air table. The air table was used in the test to reduce the friction between the truck and the floor. Both trucks were rotated relative to the carbody while floating on the air table. Displacement and force data were measured and used to calculate the degree of truck rotation and the applied truck turning torque. Truck swivel indices (TSIs) were then calculated for the truck. TSIs may be calculated from the following formula:

$$TSI = \frac{T}{2Qd} \quad (1)$$

Where

T = Truck turning torque (breakaway moment)

Q = Wheel load

d = Truck wheel base

The following procedure was used for the truck resistive torque test:

1. Hydraulic actuators with load-measuring transducers were placed at opposite corners of the air table to provide the force necessary to rotate the truck. [Figure 33](#) shows the actuators perpendicular to the table. The test setup described is accurate only for very small displacements, but it was deemed acceptable because only the breakaway torque was needed.
2. Hydraulic actuators were connected to the air table and adjacent concrete reaction points.
3. Displacement transducers were placed between the carbody and truck to measure truck rotation. Refer to [Table 10](#). [Figure 34](#) shows a photograph of the setup.
4. The truck to be tested was centered on the air table and was held in place using wheel chocks. The non-test end of the car was restrained from moving longitudinally.
5. Rotations of the truck were performed in alternating clockwise (CW) and counterclockwise (CCW) directions.
6. Force data and displacement data were collected during repeated rotations.

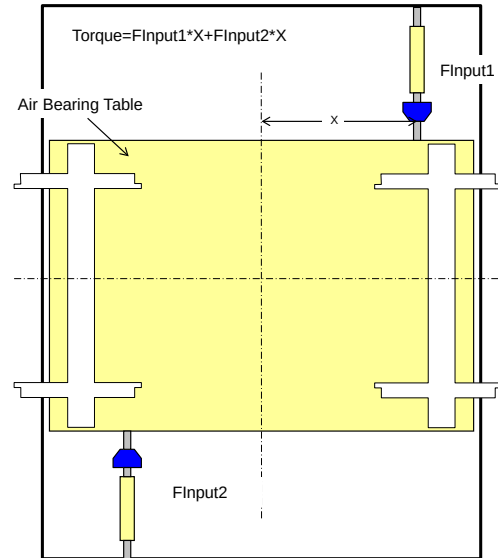


Figure 33. Air Bearing Table for Truck Rotation Test



Figure 34. Photo of Truck Resistive Torque Test Setup

3.7.2 Truck Resistive Torque Test Results

Using the force and displacement data recorded during the test, average TSIs were calculated for each truck. [Table 30](#) shows the average TSI calculated for trucks at the cab and non-cab ends.

Table 30. Average Truck Swivel Index

Truck	Truck Swivel Index
Cab End Truck	0.04
Non-Cab End Truck	0.06

[Figure 35](#) shows the truck rotation (radians) versus the applied torque (inch-kips) at the cab end. [Figure 36](#) shows the truck rotation as torque was applied at the non-cab end.

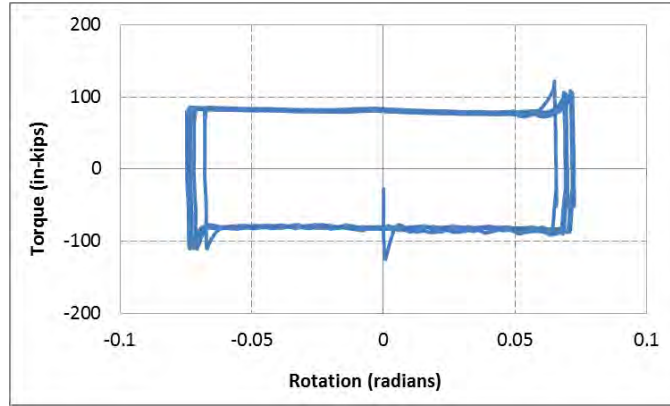


Figure 35. Cab End Truck Rotation

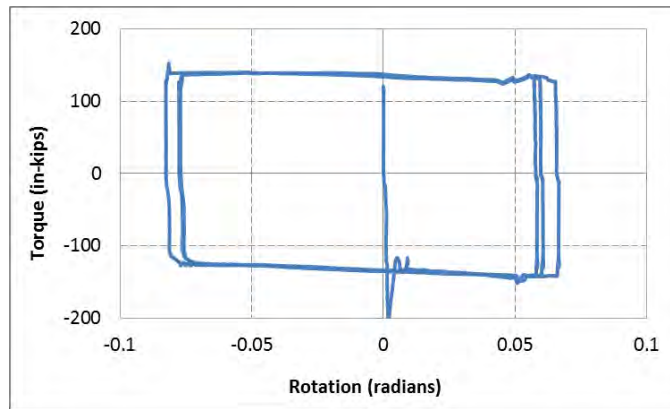


Figure 36. Non-Cab End Truck Rotation

The effective centerplate friction coefficients were estimated for each truck by dividing the breakout moments by the normal load at each truck and by the distance from the rotational center of the truck. The moment arm for the centerplate edge friction calculation was assumed to be the radius of the centerplate (12 inches). The moment arm for the centerplate horizontal surface calculation was assumed to be half of the centerplate radius (6 inches). The results are shown in [Table 31](#).

Table 31. Effective Centerplate Friction Coefficients

Truck	Centerplate Surface	Centerplate Edges
Cab End Truck	0.3	0.2
Non-Cab End Truck	0.4	0.2

3.8 Wheel Load Equalization Test Results

3.8.1 Wheel Load Equalization Test Procedure

A wheel load equalization test was performed to ensure compliance with the American Public Transportation Association (APTA) specification SS-M-014-06 “Standard for Wheel Load Equalization of Passenger Railroad Rolling Stock” [7]. Data collected during the wheel load equalization test was compared to computer simulation results to show that the computer dynamic model correctly calculates static wheel loads for variations in track twist ([Section 4.2.1](#)). The data was also used to determine the flexibility of the equalizer beams.

The test was performed by placing each wheel of one truck on load cells and leveling the car. After static wheel loads were measured, shims were incrementally inserted under one wheel of the test truck (usually to a maximum 3 inches) to measure the load equalization of each wheel. The load equalization test setup is illustrated in [Figure 37](#).



Figure 37. Wheel Load Equalization Test Setup

This test required additional measurements beyond those listed in [Table 10](#). [Table 32](#) shows the additional channels. The accelerometers listed in [Table 10](#) were not used in the test and could have been removed to make room for the additional eight wheel force measurements.

Table 32. Additional Instrumentation for Wheel Load Equalization Test

Channel Name	Description	Range (lbs)
LB1L	Load Bar - Wheel Force Axle 1 Left	50,000
LB1R	Load Bar - Wheel Force Axle 1 Right	50,000
LB2L	Load Bar - Wheel Force Axle 2 Left	50,000
LB2R	Load Bar - Wheel Force Axle 2 Right	50,000
LB3L	Load Bar - Wheel Force Axle 3 Left	50,000
LB3R	Load Bar - Wheel Force Axle 3 Right	50,000
LB4L	Load Bar - Wheel Force Axle 4 Left	50,000
LB4R	Load Bar - Wheel Force Axle 4 Right	50,000

The test was conducted to directly measure vertical wheel unloading, based on the wheel load equalization tests recommended by APTA specification SS-M-014-06 [7]. The test was conducted with the following guidelines:

- Wheel Load Measurement: All loads must be applied and measured at the wheel-rail interface.
- Wheel Lift: Wheel load shall be measured on the wheel opposite the wheel lifted and on the wheel on the same side of the truck as the wheel lifted as shown by arrows in [Figure 38](#).

- Wheel Drop: Wheel load shall be measured on the wheel dropped and the wheel diagonally opposite the wheel dropped. That means when wheel L1 is dropped, wheel loads on L1 and R2 are measured.

Figure 38 shows a depiction of the test methodology.

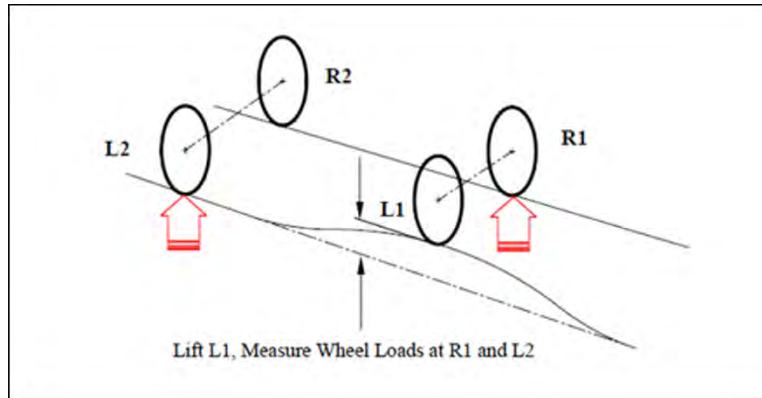


Figure 38. Measurement of Wheel Loads – Wheel Lifted

Table 33 explains which wheel loads were measured while different wheels were lifted and dropped.

Table 33. Wheel Lift and Drop Different Conditions

Wheel	Measure Wheel Loads on	
	Lifting	Dropping
L1	R1 and L2	L1 and R2
L2	R2 and L1	L2 and R1
R1	L1 and R2	R1 and L2
R2	L2 and R1	R2 and L1

The following procedure was used for the wheel load equalization tests:

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and was separated from the other units in the train. Wheels were chocked and the brakes were set on the non-test end truck.
2. The cross level was measured adjacent to each axle of the vehicle to ensure all wheels were within 1/16 inch of a “virtual” level rail established by all wheels on the car.
3. The car was lifted slightly to place load cells under all wheels.
4. Static vertical wheel loads were measured.
5. One wheel was raised sufficiently to insert the first shims under the wheel load bar.
6. The wheel was placed back onto the load bar, and the vertical wheel load was measured.
7. Steps 4 and 5 were repeated, adding shims until the wheel was raised 3 inches or until wheel lift, whichever occurred first. The shim heights were 0, 1, 2, 2½, and 3 inches.
8. Steps 4 and 5 were repeated, except shims were removed until the wheel was back at zero displacement. The shim heights were 3, 2½, 2, 1, and 0 inches.

9. Steps 4-8 were repeated twice per wheel.
10. Steps 4-9 were repeated for the other wheels in the truck.
11. Steps 4-10 were repeated starting with all wheels shimmed 3 inches, and the wheel was dropped rather than raising it. The shim heights were 3, 2½, 2, 1, and 0 inches.

3.8.2 Data Reduction Technique

Figure 39 depicts the method applied for recording measured wheel loads and the calculation of wheel unloading. This method considers the hysteresis effect that could be present in the suspension arrangements. The process is illustrated for one wheel, but the approach was applied for all wheels tested.

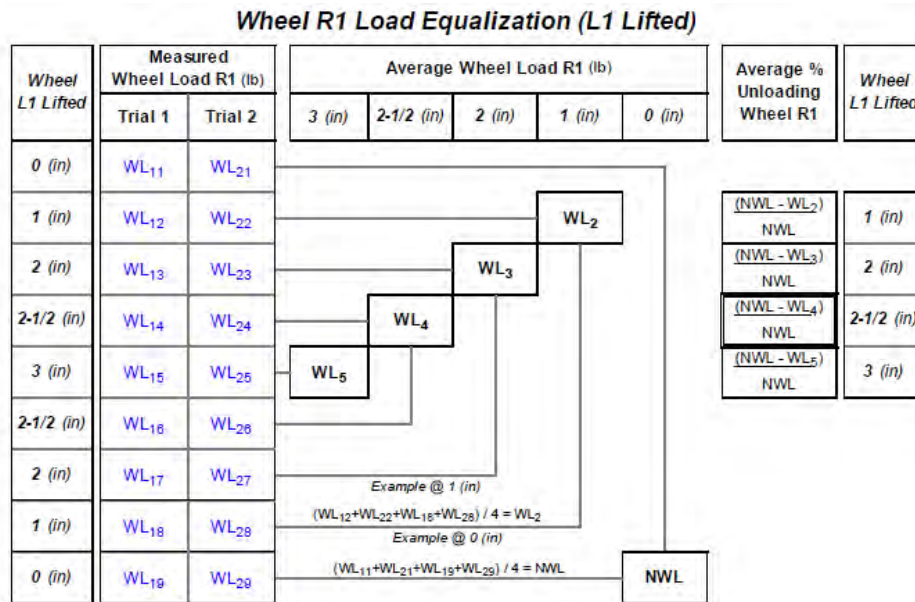


Figure 39. Wheel Unloading Calculation Form – Wheel L1 Lifted

Wheel unloading was calculated according to the requirements of APTA Class G for equipment operating on track with a maximum allowable difference in cross level of 3 inches in 62 feet. At 2.5 inches of wheel lift, wheel unloading per truck corner, based on the lifting or dropping of that corner's wheel, was computed by measuring the unloading of the remaining wheels, averaging the unloading per each wheel for two consecutive trials, and retaining the highest average. This unloading per truck corner must not exceed 67 percent for the test. The average of all four corner wheel unloading must not exceed 65 percent for the test. At 3.0 inches of lift or drop all wheels must remain in contact with the rails [7].

3.8.3 Wheel Load Equalization Results

Table 34 shows an example of the test data while wheel L1 was lifted and dropped. When this was done, the average percent wheel unloading met APTA specifications of unloading per truck corner (i.e., not exceeding 67 percent). Figure 40 shows a plot of the average wheel unloading results for each wheel at the cab end truck. Appendix A contains additional results from lifting and dropping other wheels. Results from these tests were used to determine the flexibility of the equalizer beams using NUCARS simulations.

Table 34. Wheel L1 Lift and Drop

Wheel Vertical Displacement	Class G limit (percent)	R1 (percent)	L2 (percent)	L1 (percent)	R2 (percent)
0	0	0.0	0.0	0.0	0.0
1	27	8.2	5.9	6.1	5.0
2	54	14.7	11.1	13.9	11.6
2.5	67	16.9	12.9	18.4	15.4
3	100	20.7	15.2	24.3	20.0

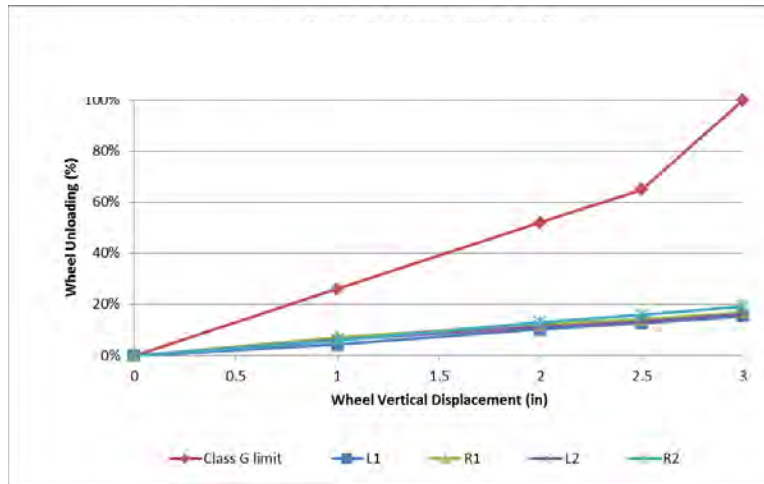


Figure 40. Average Wheel Unloading for Each Wheel at the Cab End Truck

3.9 Lean Test

3.9.1 Lean Test Procedure

The static lean test was performed per Track Safety Standards 49 CFR 213.57, which states:

“When positioned on track with a uniform 4-inch superelevation, roll angle between floor of equipment and horizontal does not exceed 5.7 degrees and on 6-inch superelevation, roll angle between floor of equipment and horizontal does not exceed 8.6 degrees and no wheel of equipment unloads to a value of 60 percent of its static value on perfectly level track.” [1]

Data collected during the lean test was compared to computer simulation results to show that the computer dynamic model correctly calculates static wheel loads for variations in superelevation (Section 4.2.2). The lean test results will also help to determine the carbody CG height used in the dynamic model. Figure 41 shows the lean test setup.

This test required additional measurements beyond those listed in Table 10. Table 32 shows the additional channels. Like the wheel load equalization test, the accelerometers listed in Table 10 could have been removed to make room for the additional eight wheel force measurements.

1. Before starting any work, the track was flagged and locked out per shop procedure. The DOTX-216 car was placed on a tangent shop track (embedded in concrete) and separated from the other units in the train. Wheels were chocked and the brakes were set on the non-test end truck.

2. The cross level was measured adjacent to each axle of the vehicle to ensure all wheels were within 1/16 inch of a “virtual” level rail established by all wheels on the car.
3. The car was lifted slightly to place load cells under all wheels.
4. Static vertical wheel loads were measured.
5. The wheels on one side of the vehicle were lifted just high enough to insert first shims under the wheel load bars.
6. The wheels were placed back onto the load bar, and the vertical wheel load was measured.
7. Steps 5 and 6 were repeated, adding shims until the wheels on one side of the vehicle were raised to 7 inches or until wheel loads dropped below 60 percent of static, whichever occurred first. Shim heights were increased in 1-inch increments.
8. The team repeated steps 5 and 6 removing shims until the wheel was back at zero displacement. Shim heights were decreased in 1-inch increments.
9. Steps 4-9 were repeated leaning the car to the left and to the right.



Figure 41. Lean Test Setup

3.9.2 Lean Test Results

Results from the lean test were used to determine the correct CG height by simulating the test using NUCARS ([Section 4.2.2](#)). [Table 35](#) shows the wheel load results as a percent of the static wheel load for the lean test. [Figure 42](#) shows a plot of the wheel load percentages for the left lean test.

Table 35. Lean Left Showing Wheel Loads

Wheel Height (inches)	Lean Left Wheel Loads (Percent)							
	1L	1R	2L	2R	3L	3R	4L	4R
0	98.1	102.5	95.1	102.1	97.0	103.2	97.3	103.5
1	101.6	97.7	101.6	97.3	102.0	96.7	103.7	96.0
2	106.4	93.1	106.6	93.7	107.2	91.8	108.1	90.9
3	111.3	87.8	111.3	89.8	111.0	88.1	112.1	86.3
4	115.7	84.0	116.0	85.1	114.9	84.8	116.5	81.5
5	119.8	79.4	121.3	80.0	119.2	79.9	120.3	77.5
6	124.0	74.7	126.2	75.7	123.2	75.6	124.4	72.9
7	128.3	70.2	129.7	71.8	127.8	70.6	128.1	68.3
6	126.5	71.9	127.7	75.4	124.9	74.0	124.7	72.6
5	123.2	75.5	124.5	79.7	122.4	77.0	121.7	75.6
4	120.6	78.8	119.9	84.0	118.2	81.2	118.7	79.5
3	116.5	83.8	115.9	88.3	114.5	85.2	115.9	82.8
2	112.1	89.4	112.9	92.2	111.1	88.6	112.4	86.7
1	107.3	93.9	108.7	96.6	107.6	92.4	107.1	92.1
0	101.9	97.5	104.9	97.9	103.0	96.8	102.7	96.5

Figure 42 shows that no wheel of the equipment unloaded to a value of 60 percent of its static value on perfectly level track, and it met 49 CFR 213.57 specifications.

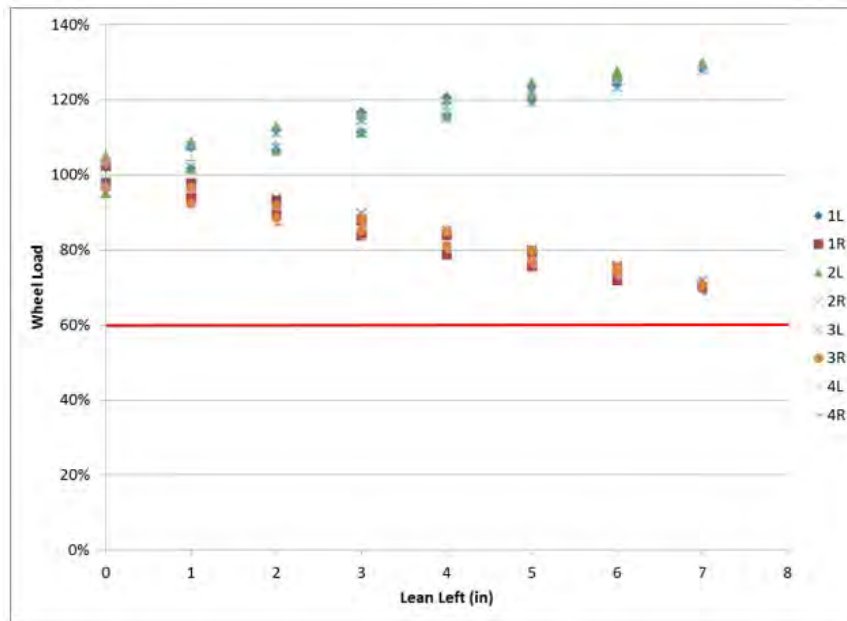


Figure 42. Lean Left Wheel Unloading

Figure 43 shows, when positioned on track with a uniform 4 inches of superelevation, the roll angle between the floor of the equipment and horizontal was 5.11 degrees (not exceeding 5.7 degrees, as per 49 CFR 213.57). The plot also shows, when positioned on track with 6 inches of superelevation, the roll angle between the floor of the equipment and horizontal was 7.6 degrees (not exceeding 8.6 degrees), meeting the requirements of 49 CFR 213.57.

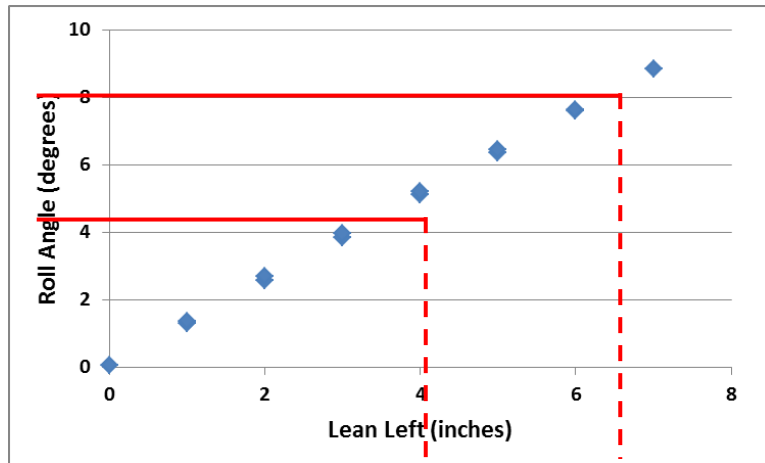


Figure 43. Lean Left Roll Angle

4. Modeling

4.1 Model Description

The research team developed a dynamic vehicle model of the DOTX-216 car using NUCARS software. The parameters used in the model were determined using measurements from the vehicle characterization tests ([Section 3](#)). The model of the DOTX-216 car consists of 13 masses: the carbody, two truck bolsters, two truck frames, four equalizer beams, and four axles. Most of the masses in the car are modeled as rigid bodies. The equalizer beams are modeled as flexible components with a torsional degree of freedom to better replicate the load distribution within each truck. The masses in the model are joined to each other and the track using 120 connections. The characteristics of these connections, including the stiffness, damping, and friction features, define the interactions between the different bodies in the model and between the axles and the track. A list of the baseline model mass properties is shown in [Table 36](#).

Table 36. Baseline Model Mass Properties

Body	Mass	Roll Inertia	Pitch Inertia	Yaw Inertia
	lb-s ² /in	lb-in-s ²	lb-in-s ²	lb-in-s ²
Carbody	246.95	1.00E+06	2.50E+07	2.50E+07
Truck bolster	6.42	6.53E+03	2.68E+02	6.61E+03
Truck frame	16.84	1.73E+04	3.40E+04	3.40E+04
Equalizer beam	2.60	5.70E+01	2.67E+03	2.63E+03
Axle with axle boxes	10.48	7.98E+03	2.50E+03	7.98E+03

The vehicle is modeled with 720-inch truck spacing. The carbody is connected to each truck, specifically each truck bolster, using two parallel secondary suspension springs. The carbody is also connected to each truck bolster using two traction rods. Each secondary suspension coil is modeled in NUCARS using a parallel spring and damper element. Each spring and damper connection has characteristics defined in the longitudinal, lateral, and vertical directions. The longitudinal and lateral stiffness of each connection represent the shearing action of the vertical coil springs. Traction rods are also modeled using parallel spring and damper connections in the vertical, lateral, and longitudinal directions. Vertical and lateral stop connections are included in the model for the bump stop displacement limitations between the carbody and truck bolster.

Vertical and lateral rotary dampers also connect the carbody to the truck bolsters. Lateral dampers are modeled using simple damper connections acting only in the lateral direction. Vertical dampers are modeled using series spring damper connections to account for the effects of rotary damper and connecting bushings in the vertical direction.

The truck bolster and truck frame use simple gap-type side bearings. These are modeled in NUCARS with surface friction connections. The friction level at the side bearings is assumed to be 0.3.

Truck bolsters are connected to the truck frames below using centerplates. Each centerplate connection is represented in NUCARS using four line friction elements and a surface friction connection. Line friction elements are used to represent the friction and normal loads reacted at the centerplate rim. Line friction connections are located at the front, back, left, and right sides of

the centerplate rim. Surface friction elements are used to model the friction and normal load interactions between the centerplate and center bowl horizontal surfaces.

The vehicle's trucks are modeled with 102-inch axle spacing. Each truck frame is supported by four primary suspension coils (two per side) resting on two equalizer beams (one per side). Each equalizer beam connects to the tops of both axle boxes on one side of a truck. The equalizer beams help distribute vertical load among the wheels of a truck, which requires the equalizer beams to be torsionally flexible. Like the secondary springs, the primary suspension coils are modeled as parallel spring and damper elements with longitudinal, lateral, and vertical degrees of freedom. The longitudinal and lateral components of the connection are due to the shear of the vertical coil springs.

In the physical system the axle boxes can slide up and down vertically and have small clearances laterally and longitudinally in the truck pedestal jaws. These clearances can close as the axles move during operation. Longitudinal and lateral stops between the truck frame and axle boxes are therefore modeled with surface friction connections to account for any friction effects between the axle boxes and the truck frame.

Track connections are modeled with the standard NUCARS wheel-rail element, which includes rail vertical and lateral stiffness and damping. Measured wheel and rail profiles were used for the on-track simulations. The wheel profiles were measured on all four axles, and the rail profiles were measured at all the necessary test track locations. Track geometry data was measured on all the test tracks. The geometry data was processed and converted to the NUCARS coordinate system for use in the simulations.

The model of car is represented using a NUCARS system file. Separate system files were constructed to model the car in the observation end leading and vestibule end leading orientations. [Appendix B](#) contains copies of the system files. [Figure 44](#) shows a wireframe depiction of the DOTX-216 NUCARS model.

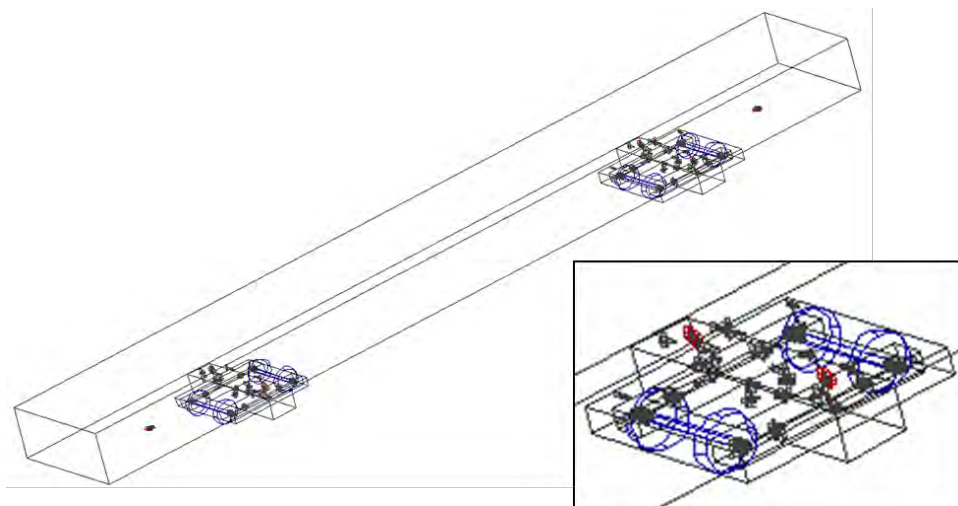


Figure 44. Wireframe Depiction of the DOTX-216 Car NUCARS Model

4.2 Model Tuning

The baseline model of the DOTX-216 car was constructed using parameter values obtained from the vehicle characterization tests ([Section 3](#)) and estimates. In many cases, models built using

initial parameter values like these require tuning and/or major model modifications to match the measured vehicle responses to different input loads. The model of the DOTX-216 car was subjected to several quasi-static and dynamic tests, including wheel load equalization, static lean, and dynamic jack and drop tests. Data from these simulations was compared to the measured responses of the DOTX-216 car, and the appropriate model parameters were adjusted to obtain a better model fit. The following sections show some of these test comparisons and describe the parameter adjustments made to the model.

4.2.1 Wheel Load Equalization Test Comparison

Wheel load equalization tests were simulated and compared to test data to ensure that the model distributed vertical load within a truck similarly to the physical system. Initial simulation results showed a poor match between the test and model wheel load data. The flexibility of the equalizer beams was adjusted to obtain a better model fit. Torsional flexibility of components in NUCARS is defined by the term GJ, where G is the shear modulus of the component and J is the shear moment of inertia about the torsional axis. The original GJ estimated at approximately $1\text{E}8 \text{ lb-in}^2$. The tuned model GJ was decreased 40 percent to $6\text{E}7 \text{ lb-in}^2$. Figure 45 shows a comparison of the tuned model data and the test data. The model and test show reasonable agreement. Appendix C contains additional comparison plots for the wheel load equalization tests.

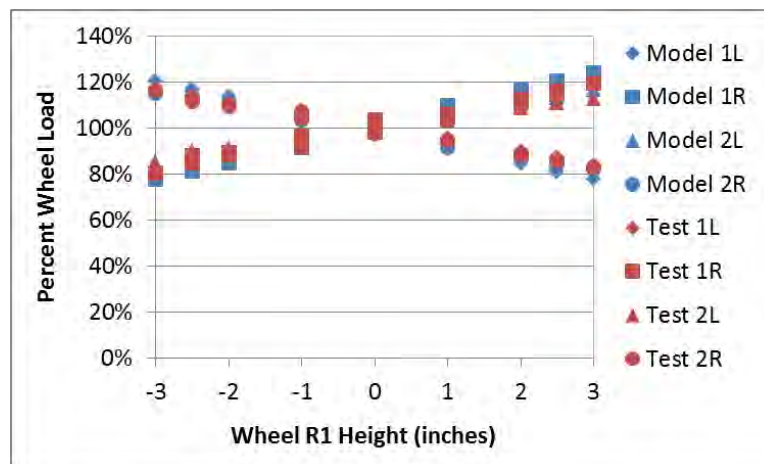


Figure 45. Wheel Load Equalization Comparison – Wheel R1 Lift and Drop

4.2.2 Lean Test Comparison

Static lean tests were simulated and compared to test data to ensure that the DOTX-216 model distributed vertical loads between the left and right sides of the car appropriately when the car was leaned to one side. Lean test comparisons can be particularly helpful when determining the proper CG height of the carbody. Initial simulation results showed considerable agreement between the model and test wheel load data as the car was leaned to the right and left. The model CG height above the rails (73 inches) was determined to be correct. Figure 46 shows a comparison of the tuned model data and the test data. Appendix C contains additional comparison plots for the static lean tests.

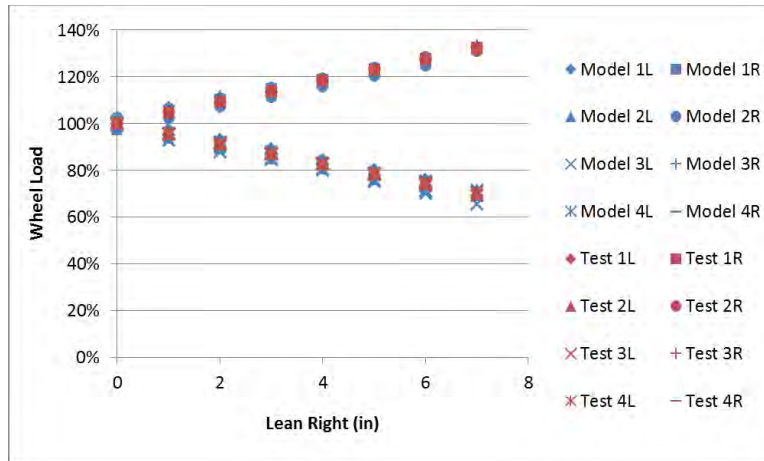


Figure 46. Lean Test Comparison – Lean Right

4.2.3 Resonance Test Comparison

Dynamic jack and drop tests were simulated and compared to test data to examine the measured responses of the vehicle. Specified loads were applied to the model at different locations and were released suddenly. Data was recorded as the vehicle vibrated on its suspension and came to rest. Initial simulation results showed poor comparisons between the test and model modal responses. To achieve the desired vehicle response, the model's suspension characteristics and rotational inertias were tuned using resonance test data. The following process was used to tune these characteristics:

1. The bounce modal frequency was tuned by increasing the vertical suspension stiffness, since the carbody mass is constant. Test data indicated that the vestibule end secondary coils were stiffer than those at the observation end. The stiffness of these coils was increased accordingly.
2. The pitch mode of the model was tuned by decreasing the carbody's pitch inertia.
3. Yaw inertia was initially set equal to the pitch inertia, because these parameter values tend to be similar (within 10-15 percent) for long, slender carbodies. The yaw inertia was then decreased to match the measured yaw modal frequency.
4. Upper and lower center roll modal frequencies were tuned by decreasing the carbody's roll inertia. Generally, the roll modes are tuned by varying both the roll inertia and the carbody CG height, but the CG height did not need to be modified in this case.

Table 37 lists the measured resonant frequencies of the DOTX-216 car and the model with traction rods connected and rotary dampers disconnected. Tuned modal frequencies were all within about 5 percent of the measured test values.

Table 37. Comparison of Model and Test Car Rigid Body Resonant Frequencies

Mode	Test Modal Frequency (Hz)	Model Modal Frequency (Hz)
Pitch	1.16	1.12
Bounce	1.04	1.00
Yaw	1.08	1.06
Lower center roll	0.51	0.48
Upper center roll	1.38	1.31

Figure 47 shows the responses of the model and test vehicle during a vertical jack and drop test at the vestibule end of the vehicle. Figure 48 shows the responses of the model and test vehicle during a lateral jacking test at the observation end of the vehicle. These figures demonstrate the dynamic similarity of the DOTX-216 car and the NUCARS model. Appendix C contains additional comparison plots for the resonance tests.

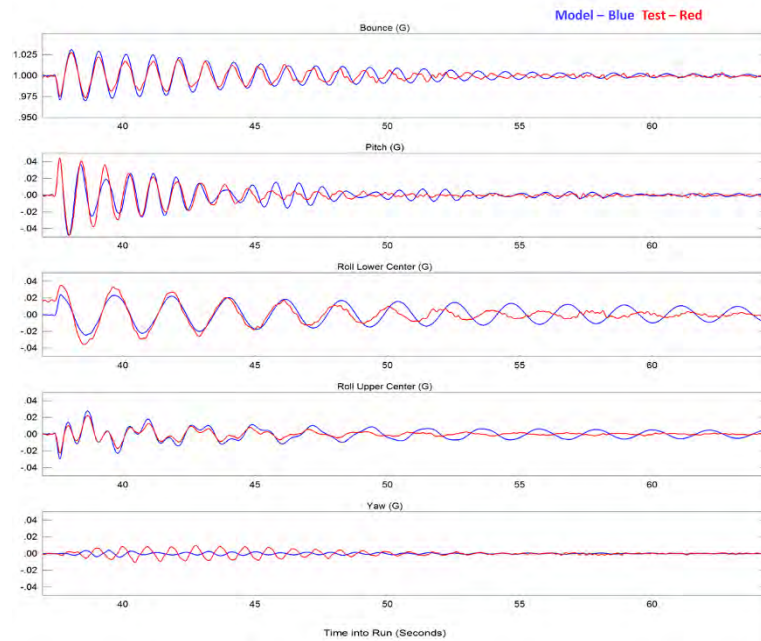


Figure 47. Comparison – Vertical Jack and Drop at Non-Cab End on Left Side

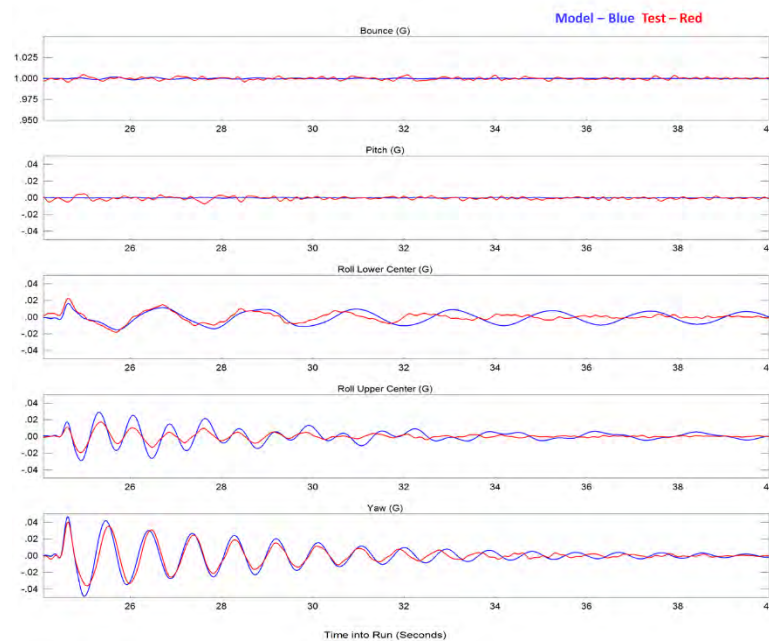


Figure 48. Comparison – Lateral Jacking at Cab End on Right Side

Table 38 lists the model connection parameters that were examined during the tuning process. The table also lists the initial parameter value, the value after tuning, and the percent change in parameter value.

Table 38. Tuned Model Suspension Parameters

Connection	Direction	Initial Value	Tuned Value	Percent Change
Observation end secondary spring stiffness	Longitudinal	1,530 lb/in	1,600 lb/in	+4.6
	Lateral	1,530 lb/in	1,600 lb/in	+4.6
	Vertical	2,890 lb/in	2,900 lb/in	+0.4
Vestibule end secondary spring stiffness	Longitudinal	1,530 lb/in	1,600 lb/in	+4.6
	Lateral	1,530 lb/in	1,600 lb/in	+4.6
	Vertical	2,890 lb/in	3,200 lb/in	+10.7
Traction rods stiffness	Longitudinal	24,000 lb/in	24,000 lb/in	0.0
	Lateral	440 lb/in	500 lb/in	+13.6
	Vertical	300 lb/in	350 lb/in	+16.7
Primary suspension spring stiffness	Longitudinal	8,350 lb/in	8,500 lb/in	+1.8
	Lateral	8,350 lb/in	8,500 lb/in	+1.8
	Vertical	3,750 lb/in	4,000 lb/in	+16.7
Equalizer beam flexibility	Torsional	1E8 lb-in ²	6E7 lb-in ²	-40.0
Car CG height	Vertical	73 inches	73 inches	0.0

During the characterization tests, lateral jacking and stiffness measurements were taken only on the observation end to prevent damage to equipment and instrumentation located on the vestibule end truck. Due to this limitation, the research model of the DOTX-216 car assumes that the vestibule end lateral suspension was like the observation end lateral suspension. This assumption may affect the model's ability to accurately represent the physical system.

5. Validation Tests

Researchers performed a series of on-track validation tests to facilitate model-to-test comparisons. The team performed the validation tests on regular tracks, including the Railroad Test Track (RTT) and the Transit Test Track (TTT), and on perturbed tracks, such as the Precision Test Track (PTT). Team members also performed tests to measure the performance of the DOTX-216 car over a severe track geometry deviation in a sharp curve. The complete validation test regime is discussed in more detail in [Section 5.1](#).

FRA requested that the team demonstrate model validation with the simplest approach. The validation process presented in this report contains two steps. The first step demonstrates model validation using only acceleration and displacement data. The second step demonstrates model validation by incorporating measured wheel-rail force data from IWS installed in the DOTX-216 car. Measured wheel-rail forces from the second step will help to confirm the effectiveness of the validation methodology of the first step.

5.1 Validation Test Regimes

[Figure 49](#) shows various test tracks at TTC. Test runs were performed on the following tracks:

- Precision Test Track (PTT)
 - Twist and Roll – 10 mph to 70 mph
 - Pitch and Bounce – 25 mph to 70 mph
 - Yaw and Sway – 25 mph to 70 mph
- Wheel Rail Mechanisms (WRM) Loop
 - Constant Curving – 12 mph, 24 mph, and 32 mph, CW and CCW
 - Dynamic Curving – 10 mph to 32 mph, CW and CCW
- Urban Rail Building (URB) North Wye with Twist Perturbation
 - Includes diverging route on turnout as well as curve with twist perturbation – 5 mph to 15 mph
- Transit Test Track (TTT)
 - 70 mph and 80 mph, CW and CCW
- Railroad Test Track (RTT)
 - 80 mph, 90 mph, 100 mph, and 105 mph, CW and CCW

Test zones and speeds are described in more detail in [Section 5.5](#) through [Section 5.9](#). All tests and speeds were run with the observation end leading. Runs on the RTT were repeated with the vestibule end leading.

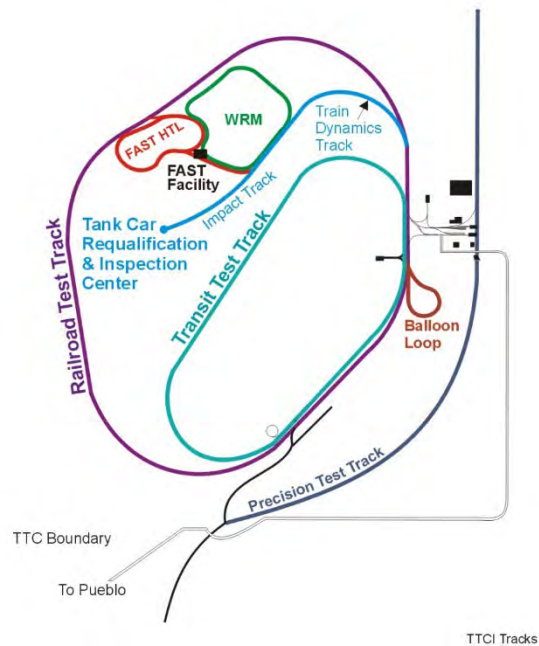


Figure 49. TTC Tracks

5.2 Test Train

The test train consisted of a single locomotive and the DOTX-216 car. The locomotive was coupled to the DOTX-216 car in the pulling position for all test runs in the regimes. Figure 50 shows the test train with the DOTX-216 car in both the observation end and vestibule end leading positions. All tests were performed with the observation end leading. Test runs on the RTT were repeated with the vestibule end leading.

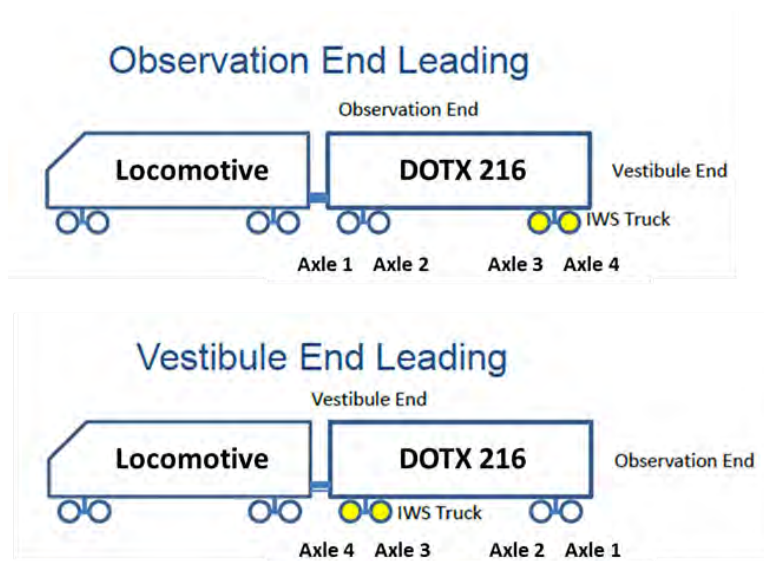


Figure 50. Test Train Depiction

5.3 Measurements

Table 39 shows the measurements recorded during the validation tests. Data was sampled at a minimum of 300 Hz and was processed in accordance with 49 CFR 213 requirements. During on-track tests, ENSCO recorded wheel-rail forces for both axles in the vestibule end truck (Axles 3 and 4).

Table 39. Measurement List

No.	Channel Name	Description	Range
1	Speed	T-16 Speed	110 mph
2	ALD	Automatic Location Device	0-5V
NA	GPS	Global Positioning Data including Latitude, Longitude and Speed	
3	AZCBF1	Observation End Vertical Accelerometer	2 g
4	AYCBF1	Observation End Lateral Floor Accelerometer	2 g
5	AYCBR1	Observation End Lateral Roof Accelerometer	2 g
6	AZCBF2	Vestibule End Vertical Accelerometer	2 g
7	AYCBF2	Vestibule End Lateral Floor Accelerometer	2 g
8	AYCBR2	Vestibule End Lateral Roof Accelerometer	2 g
9	AYTRA1	Truck Accelerometer Near Axle 1	10 g
10	AYTRA2	Truck Accelerometer Near Axle 2	10 g
11	AYTRA3	Truck Accelerometer Near Axle 3	10 g
12	AYTRA4	Truck Accelerometer Near Axle 4	10 g
13	DZSSL1	Observation End Left Side Secondary Suspension Vertical Displacement	10 inches
14	DZSSR1	Observation End Right Side Secondary Suspension Vertical Displacement	10 inches
15	DZSSL2	Vestibule End Left Side Secondary Suspension Vertical Displacement	10 inches
16	DZSSR2	Vestibule End Right Side Secondary Suspension Vertical Displacement	10 inches
17	DYSS1	Observation End Secondary Suspension Lateral Displacement	5 inches
18	DYSS2	Vestibule End Secondary Suspension Lateral Displacement	5 inches
19	DXSS1	Observation End Secondary Suspension Long. Displacement (Truck Rotation)	10 inches
20	DXSS2	Vestibule End Secondary Suspension Long. Displacement (Truck Rotation)	10 inches
21	DZPSL1	Vertical Primary Suspension Displacement Left Side Axle 1	3 inches
22	DZPSR1	Vertical Primary Suspension Displacement Right Side Axle 1	3 inches
23	DZPSL2	Vertical Primary Suspension Displacement Left Side Axle 2	3 inches
24	DZPSR2	Vertical Primary Suspension Displacement Right Side Axle 2	3 inches
25	DYPS1	Lateral Primary Suspension Displacement Axle 1	1 inch
26	DYPS2	Lateral Primary Suspension Displacement Axle 2	1 inch
27	DXPSL1	Longitudinal Primary Suspension Displacement Left Side Axle 1	0.2 inch
28	DXPSR1	Longitudinal Primary Suspension Displacement Right Side Axle 1	0.2 inch
29	DXPSL2	Longitudinal Primary Suspension Displacement Left Side Axle 2	0.2 inch
30	DXPSR2	Longitudinal Primary Suspension Displacement Right Side Axle 2	0.2 inch

5.4 Safety Limits

Table 40 shows the FRA vehicle track interaction (VTI) safety limits from 49 CFR 213.333. The DOTX-216 car had already been qualified for 125 mph service, but regardless of this, measurements were compared to VTI safety limits following each test run. The team measured and monitored vehicle acceleration measurements during the test and monitored wheel forces, comparing them to the 49 CFR 213 safety limits.

Table 40. FRA Vehicle Track Interaction Safety Limits [1]

Wheel-Rail Forces ¹			
Parameter	Safety Limit	Filter/Window	Requirements
Single Wheel Vertical Load Ratio	≥ 0.15	5 ft	No wheel of the vehicle shall be permitted to unload to less than 15% of the static vertical wheel load for 5 or more continuous feet. The static vertical wheel load is defined as the load that the wheel would carry when stationary on level track.
Single Wheel L/V Ratio	$\leq \frac{\tan(\delta) - 0.5}{1 + 0.5\tan(\delta)}$	5 ft	The ratio of the lateral force that any wheel exerts on an individual rail to the vertical force exerted by the same wheel on the rail shall not be greater than the safe limit calculated for the wheel flange angle (δ) for 5 or more continuous feet.
Net Axle Lateral L/V Ratio	$\leq 0.4 + \frac{5.0}{V_a}$	5 ft	Net axle lateral force, in kips, exerted by any axle on the track, shall not exceed a total of 5 kips plus 40% of the static vertical load that the axle exerts on the track for 5 or more continuous feet.
Truck Side L/V Ratio	≤ 0.6	5 ft	The ratio of the lateral forces that the wheels on one side of any truck exert on an individual rail to the vertical forces exerted by the same wheels on that rail shall not be greater than 0.6 for 5 or more continuous feet.
Carbody Accelerations ²			
Parameter	Passenger Cars	Other Vehicles	Requirements
Carbody Lateral (Transient)	$\leq 0.65g$ peak-to-peak 1 sec window ³ excludes peaks < 50 msec	$\leq 0.75g$ peak-to-peak 1 sec window ³ excludes peaks < 50 msec	Peak-to-peak accelerations, measured as the algebraic difference between the two extreme values of measured acceleration in any 1-second time period, excluding any peak lasting less than 50 milliseconds, shall not exceed 0.65g and 0.75g for passenger cars and other vehicles respectively.
Carbody Lateral (Sustained Oscillatory)	$\leq 0.10g$ RMS _t ⁴ 4 sec window ³ 4 sec sustained	$\leq 0.12g$ RMS _t ⁴ 4 sec window ³ 4 sec sustained	Sustained oscillatory lateral acceleration for the carbody shall not exceed the prescribed (root mean squared) safety limits of 0.10g and 0.12g for passenger cars and other vehicles, respectively. Root mean squared values are to be determined over a sliding 4-second window with linear trend removed and shall be sustained for more than 4 seconds.
Carbody Vertical (Transient)	$\leq 1.0g$ peak-to-peak 1 sec window ³ excludes peaks < 50 msec	$\leq 1.25g$ peak-to-peak 1 sec window ³ excludes peaks < 50 msec	Peak-to-peak accelerations, measured as the algebraic difference between the two extreme values of measured acceleration in any 1-second time period, excluding any peak lasting less than 50 milliseconds, shall not exceed 1.0g and 1.25g for passenger cars and other vehicles respectively.
Carbody Vertical (Sustained Oscillatory)	$\leq 0.25g$ RMS _t ⁴ 4 sec window ³ 4 sec sustained	$\leq 0.25g$ RMS _t ⁴ 4 sec window ³ 4 sec sustained	Sustained oscillatory vertical acceleration for the carbody shall not exceed the prescribed (root mean squared) safety limits of 0.25g. Root mean squared values are to be determined over a sliding 4-second window with linear trend removed and shall be sustained for more than 4 seconds.
Truck Lateral Acceleration ⁵			
Parameter	Safety Limit	Filter/Window	Requirements
Truck Lateral Acceleration	$\leq 0.30g$ RMS _t ⁴	2 sec window ³ 2 sec sustained	Truck hunting shall not develop below the maximum authorized speed. Truck hunting is defined as a sustained cyclic oscillation of the truck evidenced by lateral accelerations exceeding 0.3g root mean squared for more than 2 seconds. Root mean squared values are to be determined over a sliding 2-second window with linear trend removed.

¹Lateral and vertical wheel forces shall be measured and processed through a low pass filter (LPF) with a minimum cut-off frequency of 25 Hz. The sample rate for wheel force data shall be at least 250 samples per second.

²Carbody accelerations in the vertical and lateral directions shall be measured by accelerometers oriented and located in accordance with § 213.333(k).

³Acceleration measurements shall be processed through an LPF with a minimum cut-off frequency of 10 Hz. The sample rate for acceleration data shall be at least 100 samples per second.

⁴RMS_t = RMS with linear trend removed.

⁵Truck lateral acceleration shall be measured on the truck frame by accelerometers oriented and located in accordance with § 213.333(k).

5.5 PTT Tests

The DOTX-216 car was tested on the PTT, which contains three test zones designed to excite specific modes of vibration of the vehicle. The following sections describe the zones and the test speeds for each zone.

5.5.1 Twist and Roll

The twist and roll test section contains 10 staggered cusp-shaped perturbations with 39-foot wavelength and 0.75-inch amplitude. The perturbations on the left and right rails are offset 19.5 feet (out of phase) to excite the twist and roll motions of the vehicle. The undamped natural frequency of the lower center roll mode of the DOTX-216 car is 0.51 Hz, which corresponds to a speed of 15 mph. The undamped natural frequency of the upper center roll mode of the DOTX-216 car is 1.38 Hz, which corresponds to a speed of 37 mph. The truck center spacing of the car is 60 feet. This is approximately 1.5 times the wavelength of the inputs, so the staggered perturbations tended to twist the car more than roll it. Test speeds started at 10 mph and increased in 1 mph increments until the lower center roll resonance was passed (up to 17 mph). Speeds were then increased in 5 mph increments, starting from 20 mph until the critical speed for upper center roll was reached (up to 55 mph). Once the upper center mode was passed, speeds were increased in 10 mph increments to a maximum of 70 mph.

5.5.2 Pitch and Bounce

The pitch and bounce test section contains 10 parallel (in phase) cusp-shaped perturbations with 39-foot wavelength and 0.75-inch amplitude. The perturbations on the left and right rails are designed to excite the pitch and bounce modes of the vehicle. The undamped natural frequency of the bounce mode of the DOTX-216 car is 1.04 Hz, which corresponds to a speed of 27 mph. The undamped natural frequency of the pitch mode of the DOTX-216 car is 1.16 Hz, which corresponds to a speed of 32 mph. The perturbations tended to excite the pitch mode more than the bounce mode, because of the 60-foot truck center spacing of the vehicle. Test speeds started at 25 mph and increased in 2 mph increments until the critical speed for both the bounce and pitch modes was reached (up to 32 mph). Once the pitch mode was passed, speeds were increased in 10 mph increments to 70 mph.

5.5.3 Yaw and Sway

The yaw and sway test section contains five sine-shaped alignment perturbations with 39-foot wavelength and 1-inch amplitude on a section with 1-inch wide gage. The zone excites the yaw and upper center roll motions of the vehicle. The undamped natural frequency of the yaw mode is 1.08 Hz, which corresponds to a speed of approximately 29 mph. The undamped natural frequency of the upper center roll mode is 1.38 Hz, which corresponds to a speed of 37 mph. The perturbations tended to excite the yaw mode of the vehicle because of the 60-foot truck center spacing of the vehicle. Test speeds started at 25 mph and were increased in 5 mph increments up to 70 mph.

5.6 WRM Loop

Figure 51 shows the WRM loop, used for vehicle curving tests, containing 3-, 4-, 5-, 7.5-, 10-, and 12-degree curves. The 10-degree curve of the WRM loop has a bypass track. One end of the bypass track has an 88-foot spiral, used for Association of American Railroads (AAR) certification tests. The dynamic curve test section is in the body of the curve of the bypass track. The dynamic curve contains five cusp-shaped profile deviations with 39-foot wavelength and 0.5-inch amplitude. The outside rail contains five alignment deviations with 39-foot wavelength and 1.0-inch amplitude. The alignment deviations are positioned so that the location of wide gage corresponds to the location of the dip in the outside rail.

The mainline track of the WRM loop was run at 12, 24, and 32 mph. The bypass track on the 10-degree curve was run at speeds from 10 to 16 mph in 2-mph increments and 20 to 32 mph in 4-mph increments. Runs were performed in CW and CCW directions for both the constant curving and dynamic curving test sections.

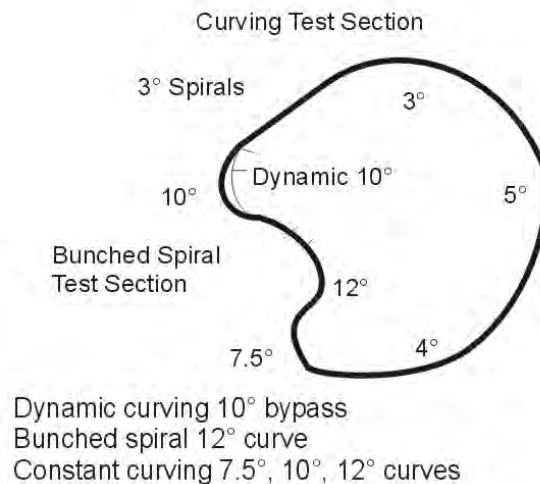


Figure 51. WRM Loop

5.7 Turnout and Special Perturbation Section

The DOTX-216 car was operated over a test section containing a No. 8 turnout and a 12-degree curve to evaluate low speed derailment potential. The team used a rail bent as part of a special test zone required in Paragraph 5.5.15 of AAR S-2043, “Performance Specification for Trains Used to Carry High-Level Radioactive Material” [8]. Researchers installed this rail in the URB North Wye track. Test runs were performed from the TTT across the No. 8 turnout through this zone, which has a 2-inch flat bottom dip in the outside rail. Figure 52 shows a depiction of the special test zone and the perturbation. The test was run at speeds from 5 to 15 mph in 2-mph increments in the facing point direction of the turnout. The observation end of the car was leading for all test runs in this scenario.

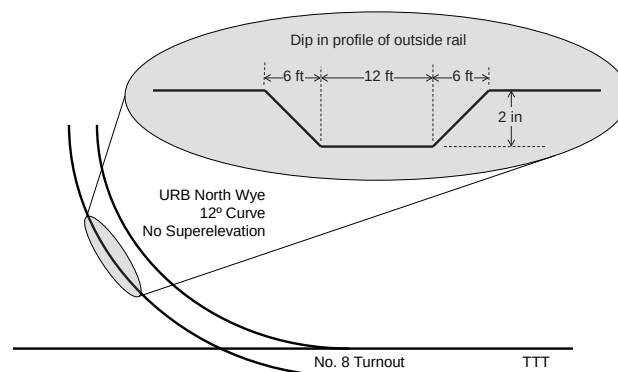


Figure 52. Turnout and Special Perturbation Section

5.8 TTT Tests

Figure 53 shows the TTT, which is a 9.1-mile loop consisting of two 1.5-degree curves, one 0.86-degree curve, and a tangent track. The speed limit on the TTT in test mode is 80 mph. The TTT tests included runs at 70 and 80 mph in both CW and CCW directions. The TTT was included for these moderate speed runs (rather than doing these runs on the RTT) because its track geometry is more representative of typical U.S. track than the RTT.

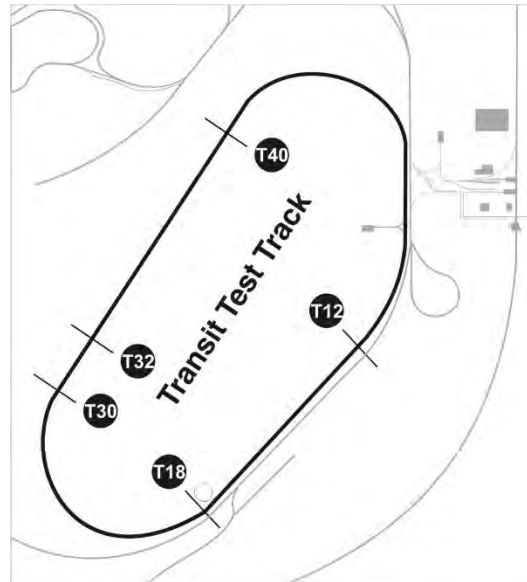


Figure 53. Transit Test Track

5.9 RTT Tests

Figure 54 shows the RTT, a 13.5-mile loop consisting of four 0.86-degree curves, one 1.25-degree reverse curve, and tangent sections.

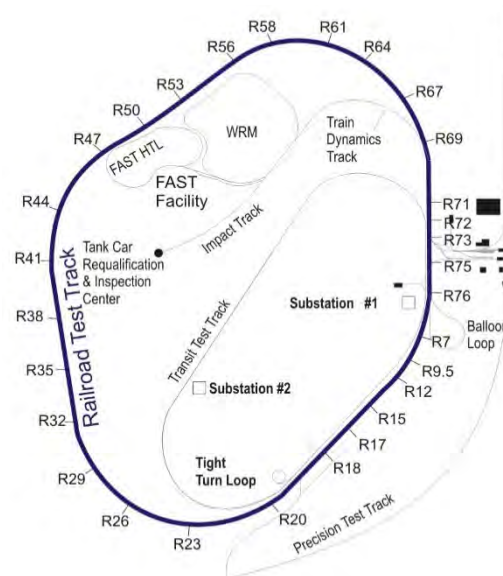


Figure 54. Railroad Test Track

The speed limit on the RTT in test mode is 103 mph in the reverse curve and 165 mph on other sections. Although the DOTX-216 car has been qualified to 125 mph, the locomotive used during the test was only capable of 105 mph. Test speeds on the RTT included 80, 90, 100, and 105 mph (reverse curve limited to 103 mph). Runs were performed in CW and CCW directions with both the observation end leading and with the vestibule end leading.

6. Initial Model Validation

6.1 Model Validation Strategy

The model of the DOTX-216 car was first partially validated by comparing only displacement and acceleration measurements to the corresponding simulation outputs. Researchers used traditional direct comparisons in combination with the Sprague and Geers method [9,10] to assess the goodness of fit between the model and test data channels. Per FRA request, no attempts were made to adjust the model to improve the correlation to the on-track test data during this effort. Normally, a complete validation effort would include adjustments to the model to improve the correlations.

Direct comparisons of model and test data are usually performed by comparing plots of measured and simulated data side-by-side or by comparing the summary statistics for two data channels, including maximum and minimum values. Maximum displacement and acceleration values were computed and compared to FRA VTI safety limits where applicable. The following maximum displacement and acceleration values were calculated and compared for each model and test case:

- Maximum 2-second peak-to-peak vertical suspension displacements
- Maximum 2-second peak-to-peak lateral suspension displacements
- Maximum vertical transient and sustained oscillatory carbody accelerations
- Maximum lateral transient and sustained oscillatory carbody accelerations
- Maximum lateral sustained oscillatory truck accelerations
- Maximum 2-second peak-to-peak lateral carbody accelerations at floor and roof level

Direct comparisons were made for the model and test data using carbody and truck accelerations calculated in accordance with 49 CFR 213.333 (see [Table 40](#)). Qualitative comparisons like these are subjective in nature and depend heavily on the experience and judgment of the analyst. Measured and simulated results never agree perfectly, and the judgment of an analyst can vary from one comparison to the next. Some qualitative judgments in the model validation process can be replaced with validation metrics to make the analysis more quantitative and less subjective [3].

The team used the Sprague and Geers validation method to assess the fit between the DOTX-216 model and test data. The Sprague and Geers metric uses magnitude, phase, and comprehensive error measures to determine a model's validity. These computed metrics provide a direct quantitative comparison measure for data in the time domain.

The Sprague and Geers method can be used to compare two vectors, given that the vectors are aligned in the time domain, have the same length, and are sampled at the same rate [3]. The two vectors should include a measured (i.e., test) data channel and a corresponding calculated (i.e., simulated) data channel.

The error measures are defined as follows:

$$M = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1 \quad (2)$$

$$P = \frac{1}{\pi} \cos^{-1} \left(\frac{\sum c_i m_i}{\sqrt{\sum c_i^2 \sum m_i^2}} \right) \quad (3)$$

$$C = \sqrt{M^2 + P^2} \quad (4)$$

where M , P , and C are the magnitude, phase, and comprehensive error measures, and c_i and m_i are the i^{th} elements of the computed and measured data vectors.

The first term of the M equation, equation (2), equals the ratio of root mean square (rms) values of the computed data to the measured data. The magnitude measure M ranges from -1 to ∞ . $M = 0$ corresponds to the case in which the c and m vectors have identical magnitudes. $M = -1$ corresponds to the case in which all elements of the computed data vector are zero. The upper limit (M approaches ∞) corresponds to the case in which all elements of the measurement vector are zero. Values larger than 1 occur when the computed data vector is two times as large as the measured data vector or greater. The phase error measure shown in equation (3) ranges from 0 to 1. $P = 0$ corresponds to no phase error. $P = 1$ corresponds to the out of phase case. The comprehensive error measure calculated from equation (4) combines the magnitude and phase measures into a single value that describes both subcomponents.

In a previous report, researchers recommended the quality scale for the comprehensive error metric shown in Figure 55 [3]. The scale is based on experience modeling rail vehicles. The scale shows general levels of quality that help describe a model's goodness of fit. Models are not necessarily disqualified even if the error metrics fall in the unacceptable range. Sprague and Geers metrics provide guidelines that indicate what a model does and does not do well. Even when quantitative validation metrics are used in the model validation process, sound engineering judgments must be used to determine if a model is suitable for a particular use.

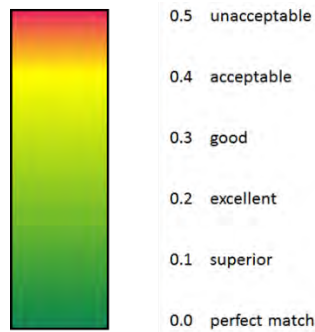


Figure 55. Sprague and Geers Comprehensive Quality Levels for Model Validation

The team documented several limitations of the Sprague and Geers method related to rail vehicle model validation [3]. The primary limitations outlined in this work include:

- Mean value offsets can cause overly optimistic comparisons and require adjustment.
- Different quality of fit results can be observed between two ends of the same vehicle.
- Agreement between model and test results can be inconsistent.
- Weighting of the phase component in the comprehensive metric may be too high.

The following sections give direct comparisons of the model and tests results and comparisons using the Sprague and Geers metrics. Direct comparisons are made for primary and secondary suspension displacements and for carbody and truck accelerations. Suspension displacements were compared using 2-second peak-to-peak values. Carbody and truck accelerations were processed in accordance with 49 CFR 213.333 (see [Table 40](#)) and compared using the maximum values. Sprague and Geers metrics were calculated and compared for the most important data channels in each run. Tables are provided for each test regime with color-coded Sprague and Geers metrics that correspond to the scale in [Figure 55](#). The validity of the DOTX-216 model is assessed using both methods in combination.

6.2 Twist and Roll

Results from the twist and roll test section indicated a good match between the model and test data. [Figure 56](#) shows maximum 2-second peak-to-peak suspension displacements for the model and test runs. Maximum vertical suspension displacements were similar in magnitude for most of the test and simulation runs. Lateral primary suspension displacements were also similar for the model and test data at the lower speeds, but maximum peak-to-peak displacements in the model tended to be lower on Axle 2 than the test data at higher speeds. Lateral primary suspension displacements at Axles 1 and 2 were measured approximately 14 inches above the actual primary spring locations. The primary suspension displacements in [Figure 56](#) appear to exceed the stop clearances in the model, which is probably due in part to the location of the transducers allowing vertical motions between the truck frame and axle box to amplify the apparent lateral motion. Lateral secondary suspension displacements were similar for the model and test data at the lead (i.e., observation) end of the vehicle, but model and test peak-to-peak maximums differed significantly at the trail (i.e., vestibule) end of the vehicle, especially at speeds greater than 20 mph.

The discrepancy between model and test lateral displacements may be a result of the modeling assumption that the observation end and vestibule end lateral suspensions were equivalent. Results from the track test indicated that stiffness and damping characteristics at the vestibule end truck may be significantly different than those at the observation end truck.

The discrepancy between model and test results may also be due to differences in the way the model and test vehicle were laterally restrained by the coupler connection to the pulling locomotive. A locomotive was coupled directly to the DOTX-216 car at the observation end during the tests. The lateral effects of the coupler connection may not have been accurately represented in the model, which could cause the displacement differences seen between the two trucks of the DOTX-216 car.

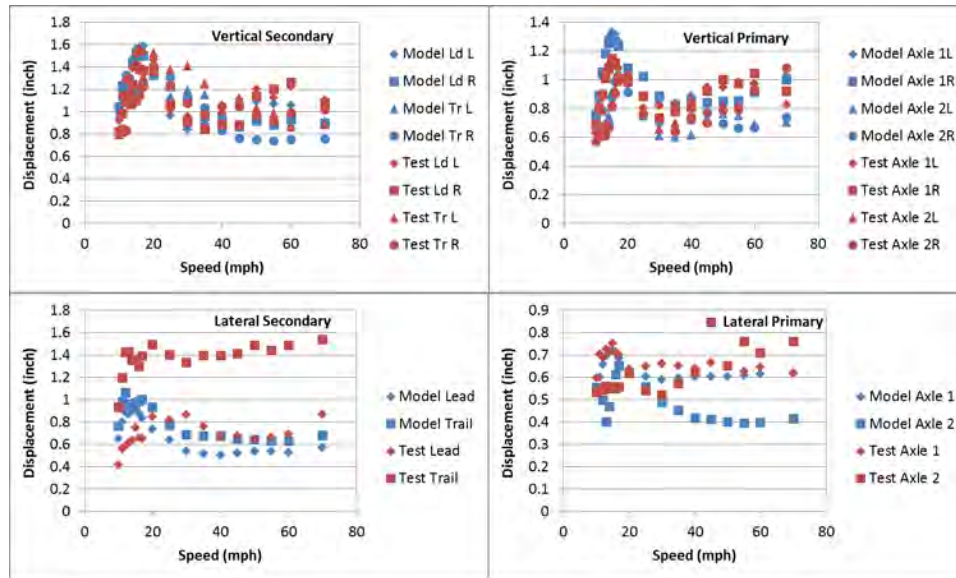


Figure 56. Maximum Peak-to-Peak Suspension Displacements – Twist and Roll

Figure 57 shows the maximum lateral carbody accelerations. Simulated transient and sustained oscillatory lateral accelerations were slightly lower than the measured values; however, both the model and test values were well below FRA limits. The bottom plot in Figure 57 shows the lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody. Like the secondary suspension lateral displacement results, the test results for peak-to-peak lateral accelerations at the trail end tended to be larger than at the lead end, whereas the model showed similar amplitudes at both ends. Model accelerations at floor level matched the test data more closely than the accelerations at roof level, suggesting that during the test the DOTX-216 car experienced greater roll motions than the model showed.

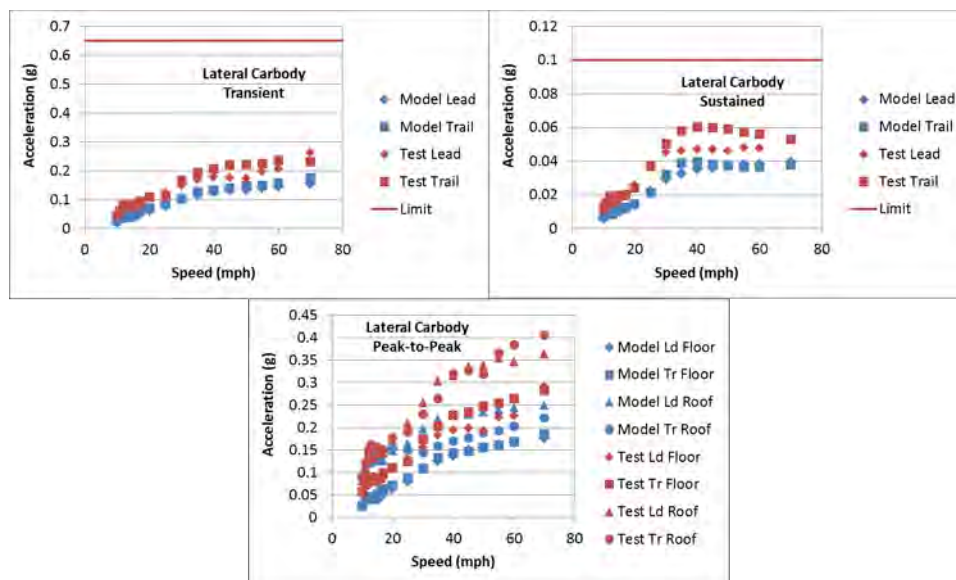


Figure 57. Maximum Peak-to-Peak Carbody Accelerations – Twist and Roll

Figure 58 through Figure 60 show time histories of the critical roll speed (16 mph) running through the twist and roll test section. For each comparison plot, Sprague and Geers metrics, including the magnitude, phase, and comprehensive error measures, were calculated and displayed at the bottom of each graph. Table 41 and Table 42 list the Sprague and Geers comprehensive error measures for the most important data channels.

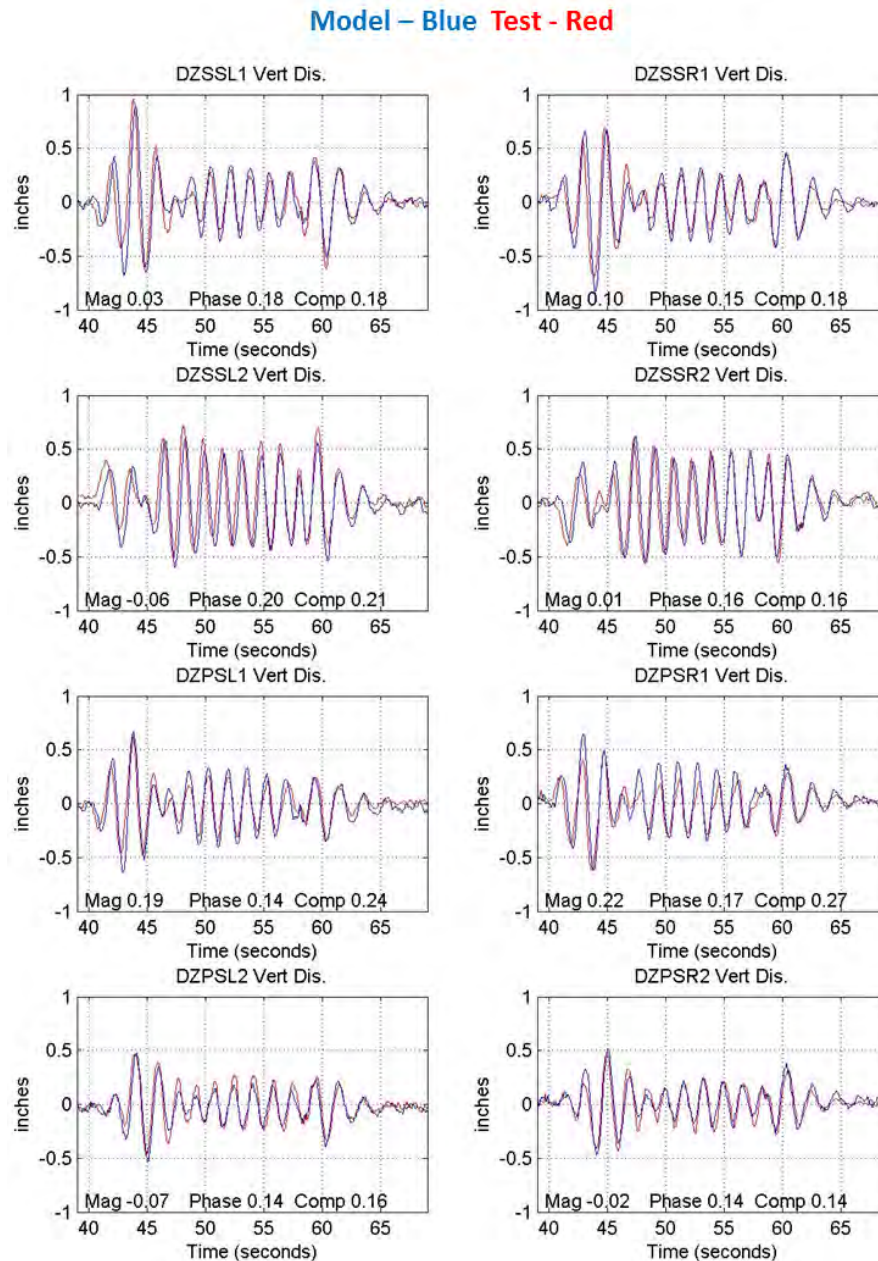


Figure 58. Vertical Primary and Secondary Suspension Displacements – Twist and Roll 16 mph

Vertical displacement plots in Figure 58 show close agreement between the measured and calculated data channels. The magnitude and phase of the model and test data matched quite closely. The average comprehensive error measures of the vertical displacement channels ranged

from 0.22 to 0.25, as shown in Table 41. According to the recommended scale in Figure 55, these comprehensive metrics indicate an excellent model fit for the vertical displacement measurements.

Lateral displacement plots in Figure 59 show generally good model-to-test data agreement, though the channels did not match nearly as closely as the vertical displacement plots.

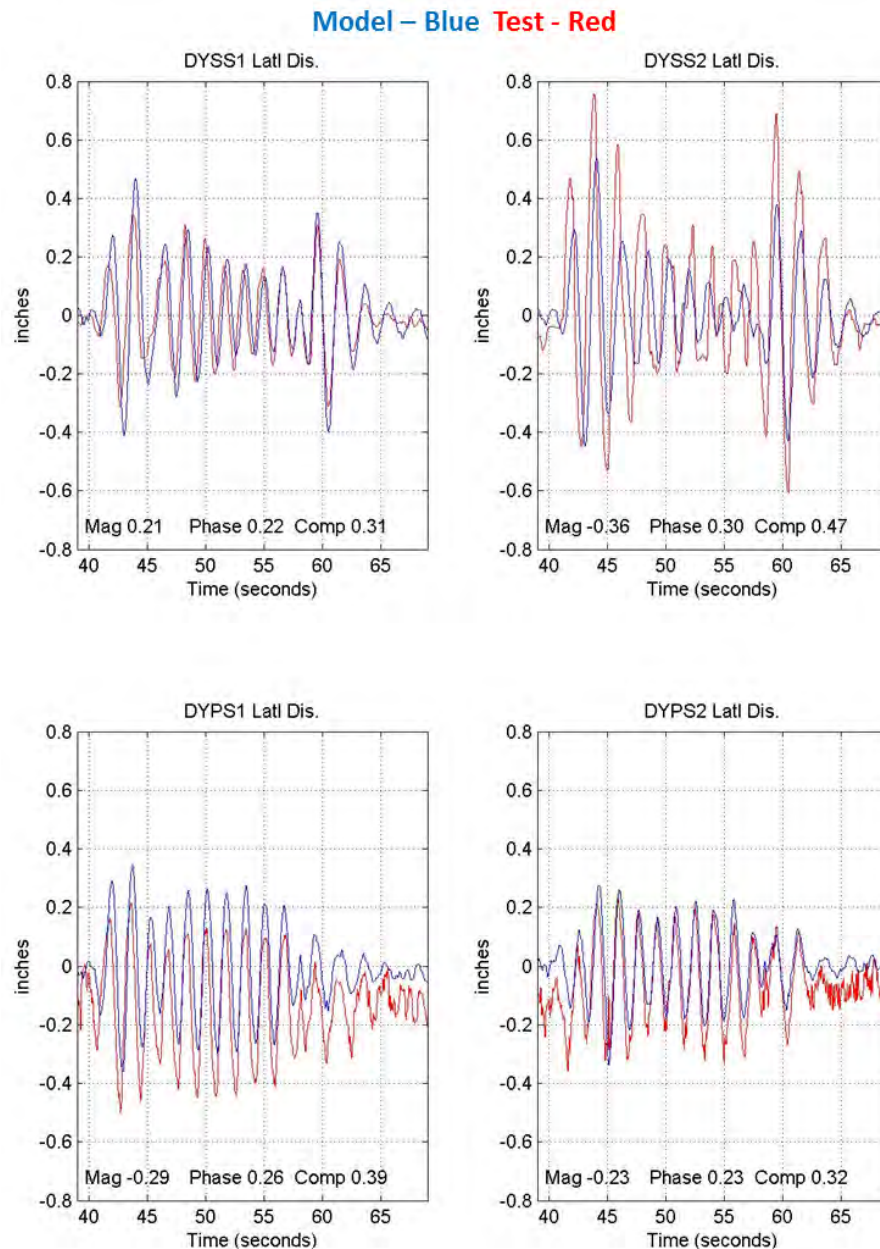


Figure 59. Lateral Primary and Secondary Suspension Displacements – Twist and Roll 16 mph

The magnitudes of the model and test secondary displacement at the observation end (DYSS1) matched more closely than the same measurements at the vestibule end (DYSS2). The measured primary suspension displacements had a slight offset when compared to the calculated data

channels. This offset, though small, increases the value of the comprehensive metrics for these channels. Average comprehensive error measures ranged from 0.33 to 0.53, which indicates a good to marginally acceptable model fit, according to the scale in [Figure 55](#).

Lateral carbody acceleration plots in [Figure 60](#) also demonstrate generally good agreement between the measured and calculated data channels. Overall carbody accelerations were similar, but the model tended to underpredict the maximum acceleration values, particularly at the floor level. Average comprehensive error measures ranged from 0.28 to 0.46, which fall in the acceptable to marginally acceptable range of the scale in [Figure 55](#). Refer to [Table 39](#) for the detailed channel naming convention.

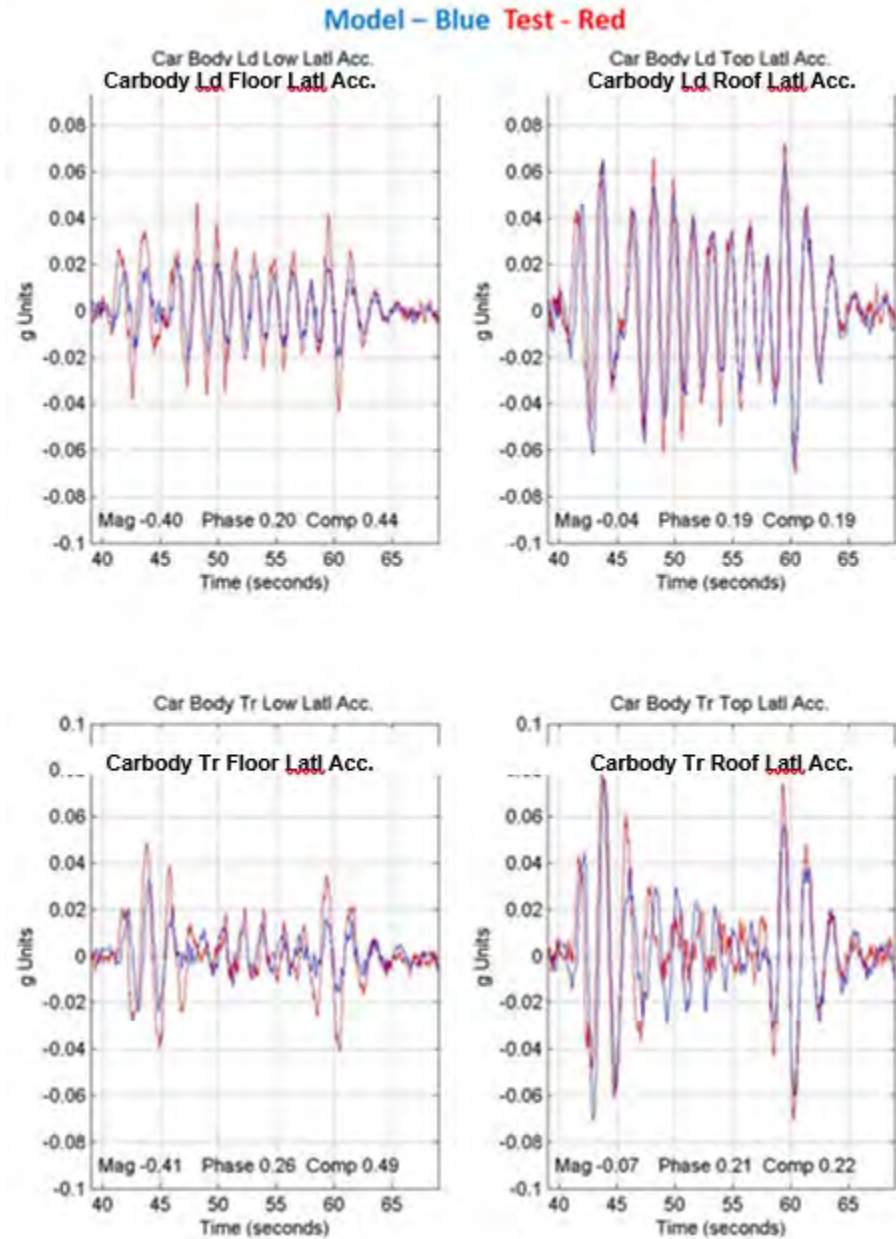


Figure 60. Lateral Carbody Accelerations – Twist and Roll 16 mph

Table 41. Comprehensive Error Measures for Twist and Roll Suspension Displacements

Test Run	DZSSL1	DZSSR1	DZSSL2	DZSSR2	DZPSL1	DZPSR1	DZPSL2	DZPSR2	DYSS1	DYSS2	DYPS1	DYPS2
TR-10MPH	0.16	0.14	0.18	0.23	0.14	0.20	0.18	0.17	0.86	0.40	0.52	0.18
TR-11MPH	0.16	0.15	0.31	0.35	0.19	0.19	0.12	0.19	0.79	0.34	0.49	0.17
TR-12MPH	0.27	0.26	0.44	0.47	0.28	0.25	0.23	0.20	0.89	0.35	0.46	0.27
TR-13MPH	0.23	0.22	0.23	0.24	0.35	0.31	0.34	0.30	0.54	0.44	0.29	0.34
TR-14MPH	0.19	0.20	0.16	0.17	0.36	0.35	0.33	0.29	0.40	0.48	0.41	0.32
TR-15MPH	0.23	0.23	0.22	0.20	0.29	0.30	0.27	0.25	0.31	0.50	0.28	0.30
TR-16MPH	0.18	0.18	0.21	0.16	0.24	0.27	0.16	0.14	0.31	0.47	0.39	0.32
TR-17MPH	0.26	0.26	0.24	0.25	0.30	0.32	0.30	0.29	0.31	0.52	0.34	0.40
TR-20MPH	0.22	0.15	0.23	0.11	0.17	0.20	0.24	0.21	0.25	0.57	0.35	0.27
TR-25MPH	0.14	0.18	0.25	0.10	0.15	0.22	0.14	0.16	0.31	0.62	0.24	0.41
TR-30MPH	0.20	0.38	0.18	0.17	0.19	0.20	0.25	0.20	0.36	0.62	0.30	0.46
TR-35MPH	0.19	0.27	0.19	0.16	0.25	0.15	0.25	0.20	0.30	0.59	0.26	0.50
TR-40MPH	0.19	0.17	0.20	0.20	0.23	0.18	0.23	0.18	0.29	0.56	0.25	0.55
TR-45MPH	0.26	0.20	0.18	0.31	0.22	0.22	0.26	0.25	0.35	0.59	0.27	-
TR-50MPH	0.25	0.24	0.21	0.30	0.26	0.25	0.28	0.28	0.28	0.63	0.24	-
TR-55MPH	0.24	0.26	0.21	0.32	0.24	0.22	0.28	0.28	0.33	0.62	0.25	-
TR-60MPH	0.24	0.32	0.24	0.26	0.22	0.28	0.35	0.33	0.24	0.65	0.23	-
TR-70MPH	0.27	0.33	0.24	0.39	0.20	0.20	0.27	0.28	0.39	0.65	0.41	-
Average	0.22	0.23	0.23	0.24	0.24	0.24	0.25	0.23	0.42	0.53	0.33	0.35

Table 42. Comprehensive Error Measures for Twist and Roll Carbody Accelerations

Test Run	AYCBR1	AYCBF1	AYCBR2	AYCBF2
TR-10MPH	0.37	0.34	0.48	0.23
TR-11MPH	0.32	0.35	0.49	0.21
TR-12MPH	0.27	0.48	0.56	0.28
TR-13MPH	0.34	0.24	0.57	0.23
TR-14MPH	0.40	0.19	0.55	0.24
TR-15MPH	0.47	0.24	0.54	0.29
TR-16MPH	0.44	0.19	0.49	0.22
TR-17MPH	0.47	0.26	0.52	0.30
TR-20MPH	0.46	0.24	0.48	0.31
TR-25MPH	0.43	0.26	0.46	0.47
TR-30MPH	0.41	0.27	0.41	0.53
TR-35MPH	0.34	0.23	0.35	0.49
TR-40MPH	0.36	0.27	0.37	0.49
TR-45MPH	0.36	0.30	0.41	0.50
TR-50MPH	0.32	0.32	0.43	0.48
TR-55MPH	0.30	0.30	0.41	0.46
TR-60MPH	0.34	0.34	0.43	0.49
TR-70MPH	0.33	0.27	0.35	0.46
Average	0.37	0.28	0.46	0.37

6.3 Pitch and Bounce

Results from the pitch and bounce test section indicated an excellent match between the model and test data. Figure 61 shows maximum 2-second peak-to-peak suspension displacements for the model and test runs. Maximum vertical suspension displacements were similar (within 10 percent) for most of the test and simulation runs. At speeds greater than 60 mph, the maximum model displacements tended to be about 25 percent lower than the measured values.

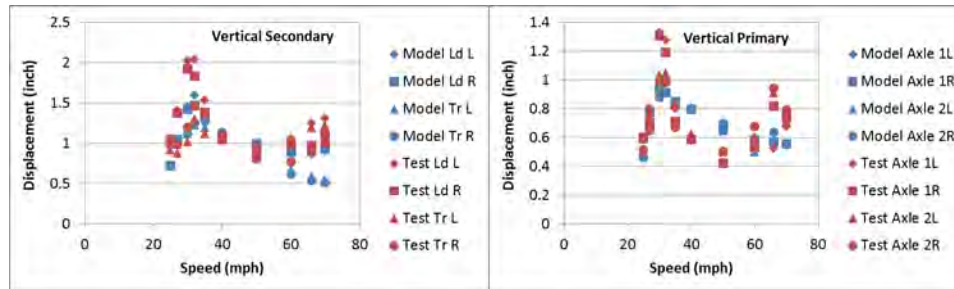


Figure 61. Maximum Peak-to-Peak Suspension Displacements – Pitch and Bounce

Figure 62 shows the maximum vertical carbody accelerations. Transient and sustained oscillatory accelerations were similar for most of the simulated and measured values. Measured vertical accelerations were approximately 25 percent higher than the simulated values near 30 mph; however, both the model and test values were still well below FRA limits.

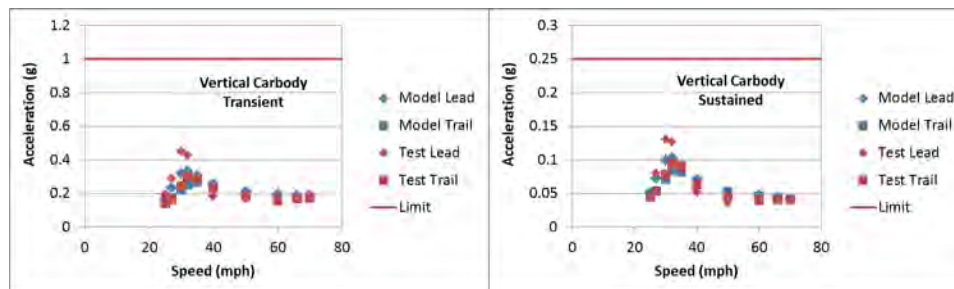


Figure 62. Maximum Peak-to-Peak Carbody Accelerations – Pitch and Bounce

Figure 63 and Figure 64 show time histories of the critical bounce speed (27 mph) run through the pitch and bounce test section. Sprague and Geers metrics were calculated and displayed at the bottom of each graph. Table 43 and Table 44 list the Sprague and Geers comprehensive error measures for the vertical displacement and acceleration channels.

Vertical displacement plots in Figure 63 show close agreement between the measured and calculated data channels. The magnitude and phase of the model and test data match closely for the primary and secondary suspension displacements. The model tended to underpredict the secondary suspension displacements, and it tended to overpredict the primary suspension displacements. Average comprehensive error measures of the vertical displacement channels ranged from 0.17 to 0.40, as shown in Table 43, all of which fall within the acceptable range of scale in Figure 55.

Vertical carbody acceleration plots in Figure 64 also demonstrate good agreement between the measured and calculated data channels. Measured and simulated vertical carbody accelerations matched closely, both in magnitude and phase, at both ends of the vehicle. Average

comprehensive error measures were 0.26 at the observation end and 0.16 at the vestibule end of the car, indicating an excellent model fit, according to Figure 55. Refer to Table 39 for the detailed channel naming convention.

Model – Blue Test - Red

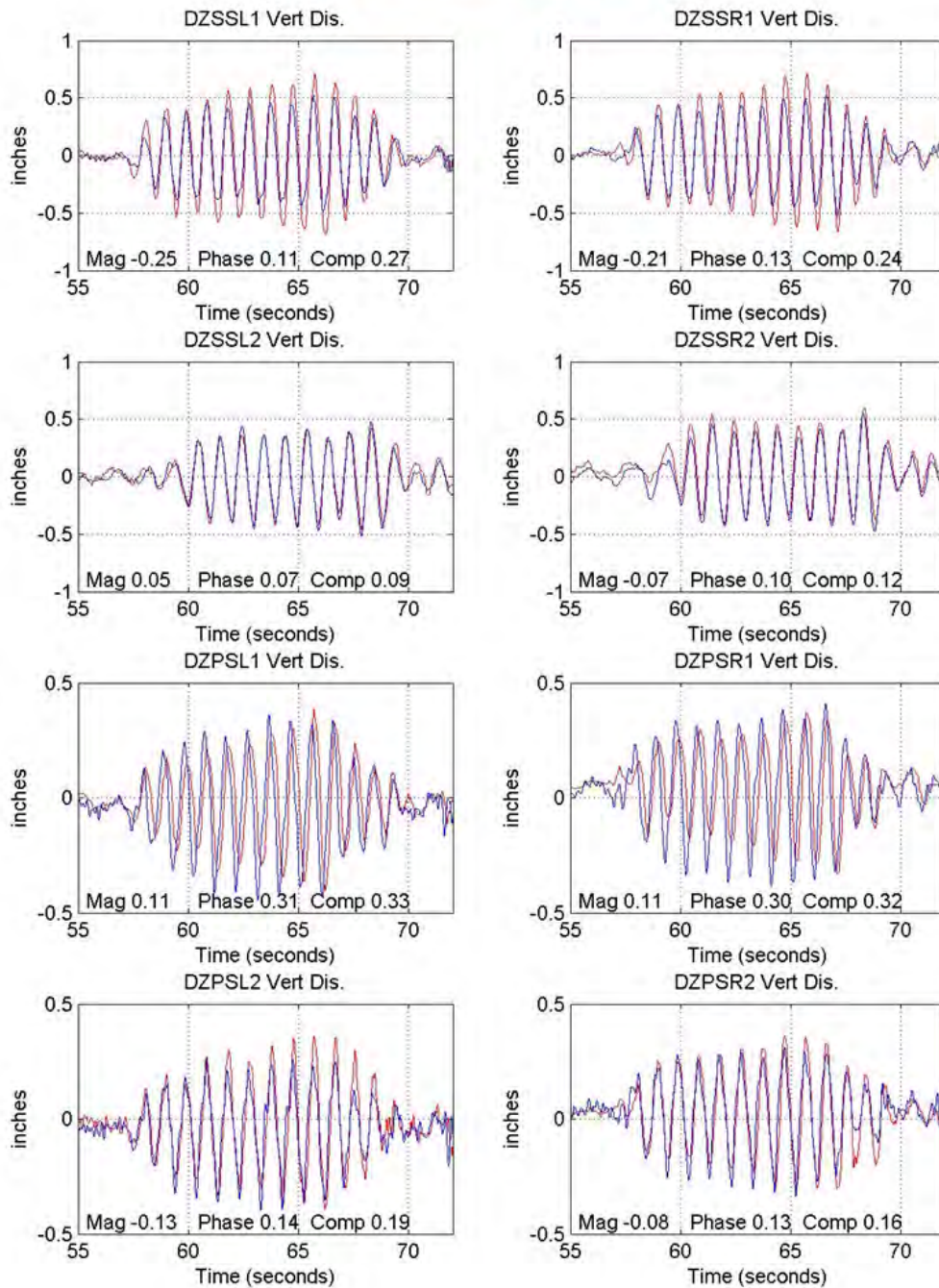


**Figure 63. Vertical Primary and Secondary Suspension Displacements – Pitch and Bounce
27 mph**

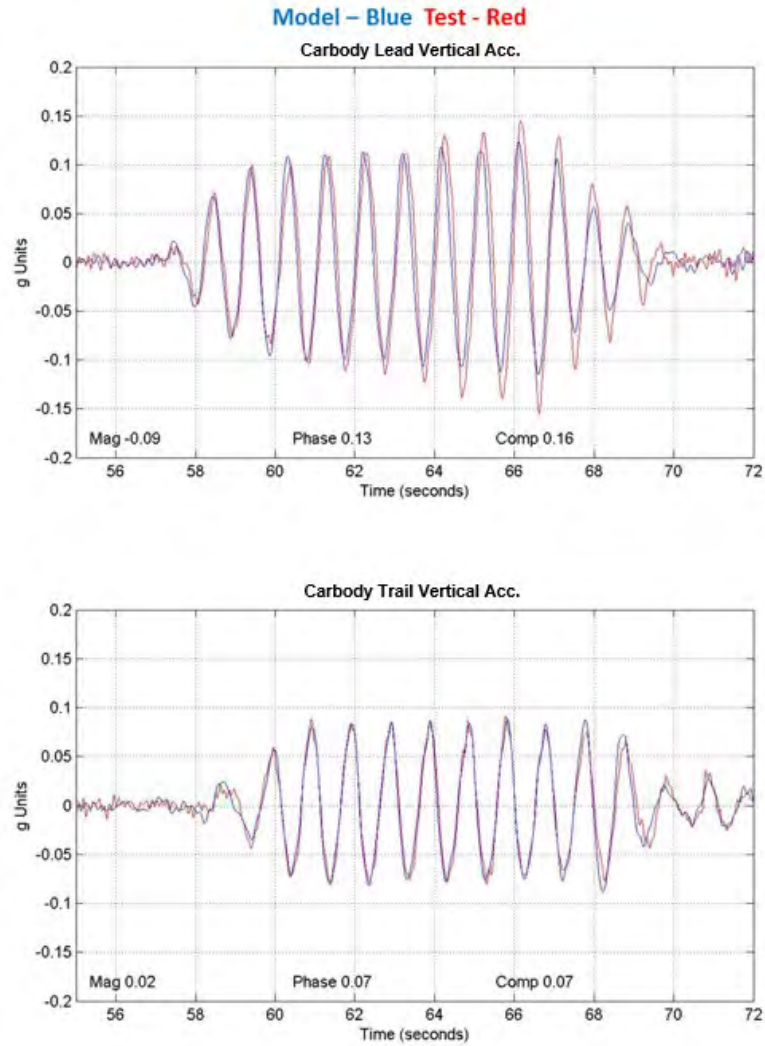


Figure 64. Vertical Carbody Accelerations – Pitch and Bounce 27 mph

Table 43. Comprehensive Error Measures for Pitch and Bounce Suspension Displacements

Test Run	DZSSL1	DZSSR1	DZSSL2	DZSSR2	DZPSL1	DZPSR1	DZPSL2	DZPSR2
PB-25MPH	0.32	0.30	0.18	0.15	0.34	0.30	0.27	0.23
PB-27MPH	0.27	0.24	0.09	0.12	0.33	0.32	0.19	0.16
PB-30MPH	0.35	0.30	0.13	0.17	0.31	0.31	0.26	0.25
PB-32MPH	0.31	0.23	0.14	0.24	0.30	0.28	0.24	0.20
PB-35MPH	0.18	0.14	0.10	0.22	0.34	0.36	0.17	0.16
PB-40MPH	0.20	0.22	0.22	0.21	0.45	0.41	0.41	0.44
PB-50MPH	0.28	0.20	0.15	0.22	0.43	0.41	0.34	0.33
PB-60MPH	0.22	0.23	0.20	0.24	0.43	0.43	0.42	0.41
PB-66MPH	0.18	0.19	0.23	0.26	0.57	0.45	0.36	0.34
PB-70MPH	0.20	0.19	0.28	0.43	0.45	0.32	0.36	0.31
Average	0.25	0.22	0.17	0.23	0.40	0.36	0.30	0.28

Table 44. Comprehensive Error Measures for Pitch and Bounce Carbody Accelerations

Test Run	AZCBF1	AZCBF2
PB-25MPH	0.20	0.18
PB-27MPH	0.16	0.07
PB-30MPH	0.26	0.11
PB-32MPH	0.22	0.26
PB-35MPH	0.16	0.12
PB-40MPH	0.36	0.18
PB-50MPH	0.46	0.20
PB-60MPH	0.26	0.19
PB-66MPH	0.26	0.14
PB-70MPH	0.23	0.14
Average	0.26	0.16

6.4 Yaw and Sway

Results from the yaw and sway test section showed a reasonable match between the model and test data. [Figure 65](#) shows maximum 2-second peak-to-peak suspension displacements for the model and test runs. Maximum lateral suspension displacements differed slightly between the test and simulation runs. Both the model and test data showed that the secondary suspension displaced more laterally at the trail (i.e., vestibule) end of the DOTX-216 car than at the lead (i.e., observation) end, but the difference in displacement was much greater in the measured data than the simulation data. Simulated lateral primary suspension displacements tended to be much smaller than the measured values, and do not show the sharp increase in amplitude with speed that can be seen in the test data. As discussed in [Section 6.2](#), the discrepancy between model and test lateral displacements may be due to modeling assumptions.

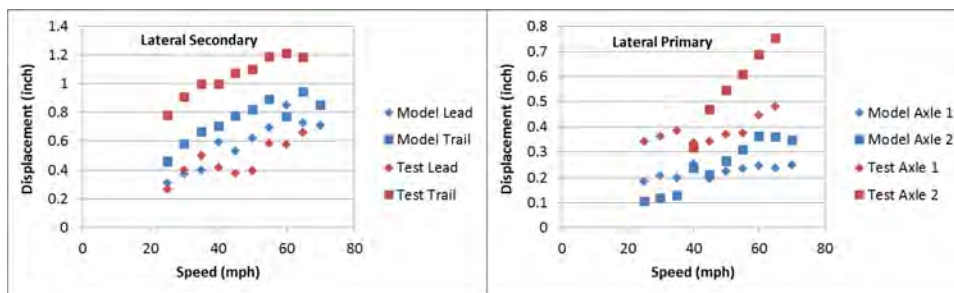


Figure 65. Maximum Peak-to-Peak Lateral Suspension Displacements – Yaw and Sway

[Figure 66](#) shows the maximum lateral carbody accelerations. The transient and sustained oscillatory accelerations were close for the model and test runs at all speeds. Simulated lateral accelerations tended to be somewhat higher than the simulated values, likely due to the model generating small impacts when the wheel flange moves toward contact with the rail gage faces. Maximum values of both model and test data were still lower than FRA limits.

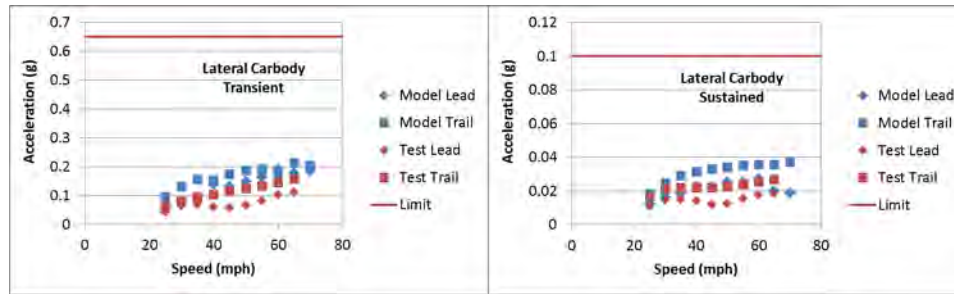


Figure 66. Maximum Carbody Lateral Accelerations – Yaw and Sway

Figure 67 and Figure 68 show time histories of the 35 mph run through the yaw and sway test section. Sprague and Geers metrics were calculated and displayed at the bottom of each graph. Table 45 and Table 46 list the Sprague and Geers comprehensive error measures for the lateral displacement and acceleration channels.

Lateral displacement plots in Figure 67 show reasonable agreement between the measured and calculated data channels. The magnitude and phase of the model and test data match relatively well, but the match is not as close as similar measurements in the twist and roll and pitch and bounce test sections. The model tended to underpredict the primary and secondary suspension lateral displacements. Model secondary suspension displacements matched test data more closely at the observation end than at the vestibule end of the car. The average comprehensive error measures for the lateral secondary displacement channels were 0.40 at the observation end and 0.48 at the vestibule end, both of which fall in the acceptable range in Figure 55. The average comprehensive error measures for the lateral primary displacement channels were 0.53 and 0.64, which fall in the unacceptable range of Figure 55. Data was not collected for the primary suspension displacement channel DYPS2 during several test runs because of a data acquisition error.

Lateral carbody acceleration plots in Figure 68 demonstrate good agreement between the model and test data channels. Simulated and measured vertical carbody accelerations matched closely at both ends of the vehicle, especially at speeds below 45 mph. The average comprehensive error measures ranged from 0.35 to 0.49, indicating an acceptable to marginally acceptable model fit.

Comprehensive error measures greater than 0.50 do not necessarily disqualify a model, nor does it make a model invalid for a particular use. Lateral primary suspension error measures were outside of the acceptable range, and the secondary suspension and carbody acceleration error measures were within the acceptable range. The model did not perform as well in the yaw and sway regime as it did in the twist and roll or pitch and bounce regimes, but it did agree with the general trends and values of the test data. Refer to Table 39 for the detailed channel naming convention.

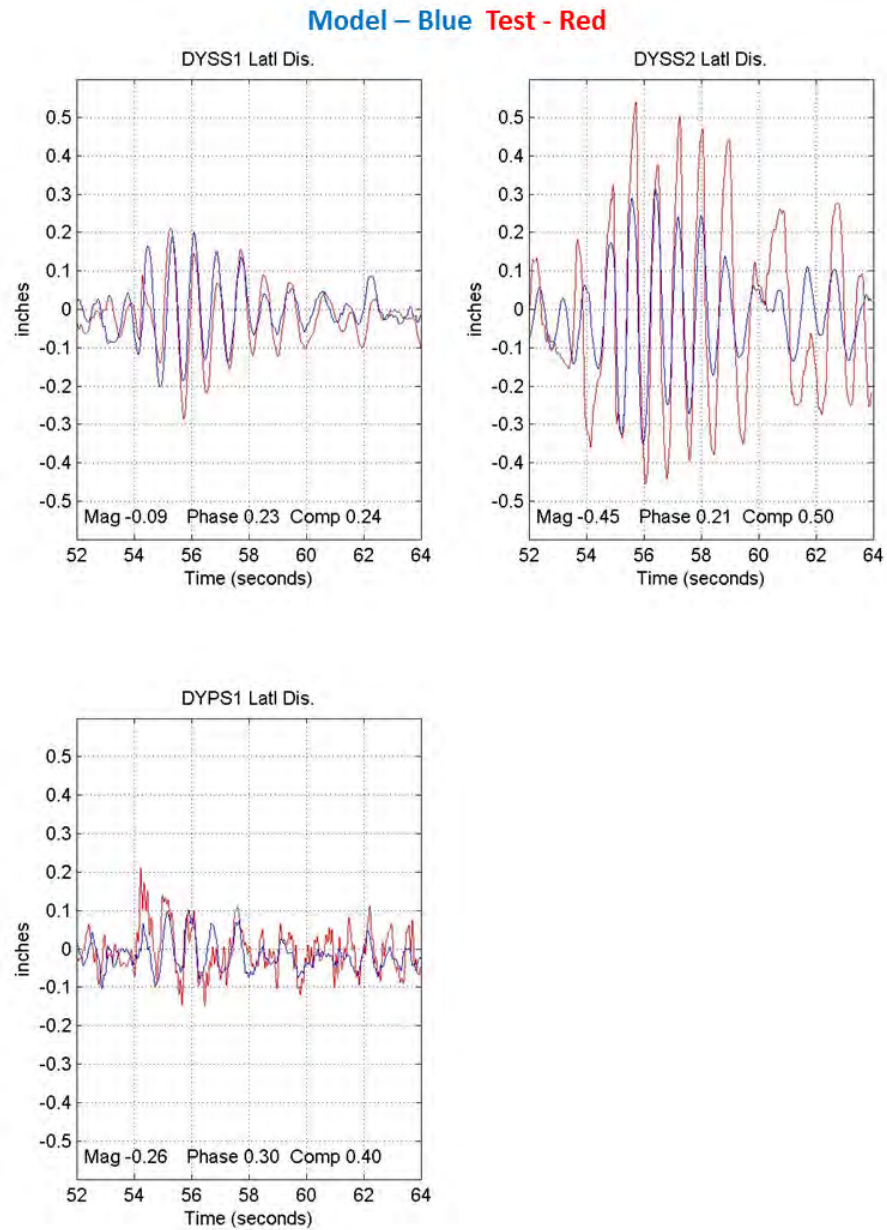


Figure 67. Lateral Primary and Secondary Suspension Displacements – Yaw and Sway 35 mph

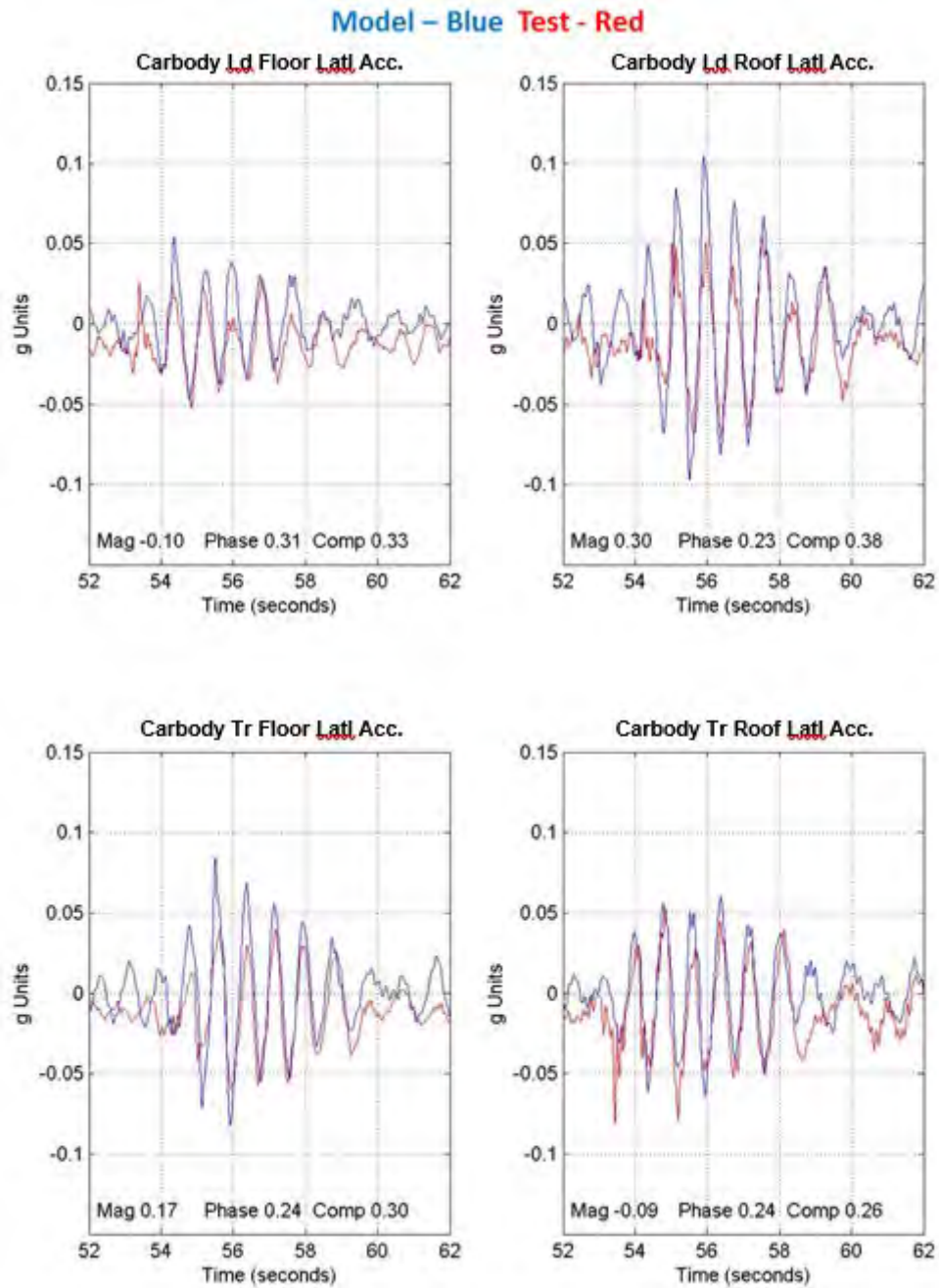


Figure 68. Lateral Carbody Accelerations – Yaw and Sway 35 mph

Table 45. Comprehensive Error Measures for Yaw and Sway Suspension Displacements

Test Run	DYSS1	DYSS2	DYPS1	DYPS2
YS-25MPH	0.27	0.63	0.53	-
YS-30MPH	0.24	0.56	0.43	-
YS-35MPH	0.24	0.50	0.40	-
YS-40MPH	0.47	0.47	0.60	0.48
YS-45MPH	0.54	0.44	0.62	0.69
YS-50MPH	0.52	0.41	0.60	0.69
YS-55MPH	0.46	0.37	0.50	0.66
YS-60MPH	0.45	0.48	0.57	0.67
YS-65MPH	0.43	0.42	0.51	0.67
Average	0.40	0.48	0.53	0.64

Table 46. Comprehensive Error Measures for Yaw and Sway Carbody Accelerations

Test Run	AYCBR1	AYCBF1	AYCBR2	AYCBF2
YS-25MPH	0.48	0.28	0.34	0.42
YS-30MPH	0.36	0.28	0.25	0.32
YS-35MPH	0.33	0.38	0.30	0.26
YS-40MPH	0.37	0.45	0.34	0.31
YS-45MPH	0.46	0.60	0.41	0.42
YS-50MPH	0.55	0.65	0.38	0.46
YS-55MPH	0.65	0.63	0.40	0.46
YS-60MPH	0.70	0.63	0.33	0.49
YS-65MPH	0.55	0.55	0.39	0.38
Average	0.49	0.49	0.35	0.39

6.5 WRM – Dynamic Curve

Results from the dynamic curving test section indicated a good match between the model and test data for both the CW and CCW directions. Results from the test runs are presented separately for each direction in the following sections.

6.5.1 CW

Figure 69 shows maximum 2-second peak-to-peak suspension displacements for the dynamic curving model and test runs in the CW direction. Maximum vertical suspension displacements were similar in magnitude for most of the test and simulation runs, particularly at speeds of 20 mph and below. As with the twist and roll tests, lateral suspension displacements were also similar at both ends for the model over most of the speed range, whereas the test data showed the leading end secondary suspension matched the test results relatively well, but the trailing end secondary suspension had much larger amplitudes. Test data for the lateral primary suspension displacement at axle 2 (DYPS2) tended to be much higher than the corresponding model value, and it tended to be higher than the similar measured value at axle 1 (DYPS1). Lateral secondary

suspension displacements for the model and test data tended to match more closely at speeds less than 20 mph.

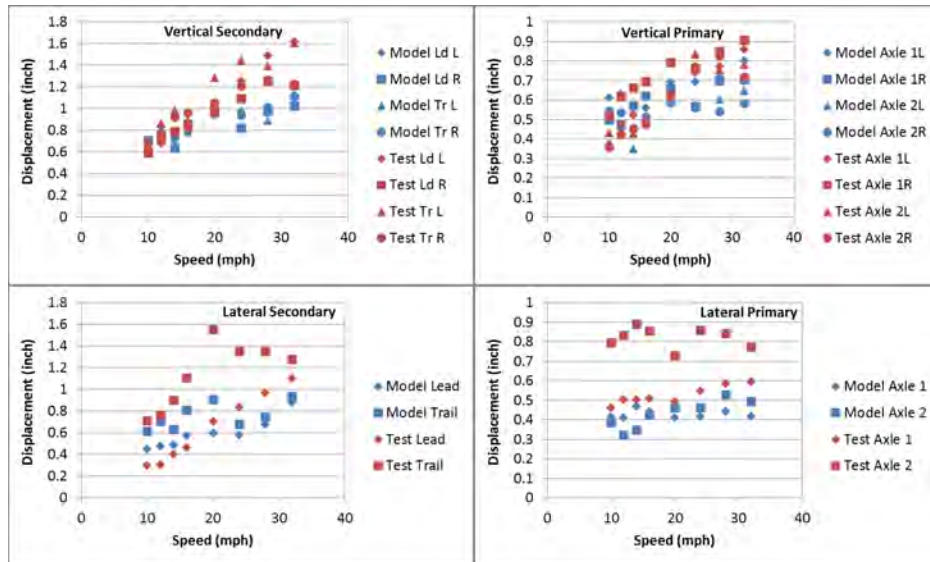


Figure 69. Maximum Peak-to-Peak Suspension Displacements – Dynamic Curving in CW Direction

Figure 70 shows the maximum lateral carbody and truck accelerations in the model and test cases. Simulated transient and sustained oscillatory lateral accelerations were like the measured values for all of the speeds tested, though the values were below FRA limits. The bottom right plot in Figure 70 shows the lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody. Model accelerations at both the floor and roof levels agreed with the trends of the test data reasonably well, although the model amplitudes tended to be lower than the test at higher speeds.

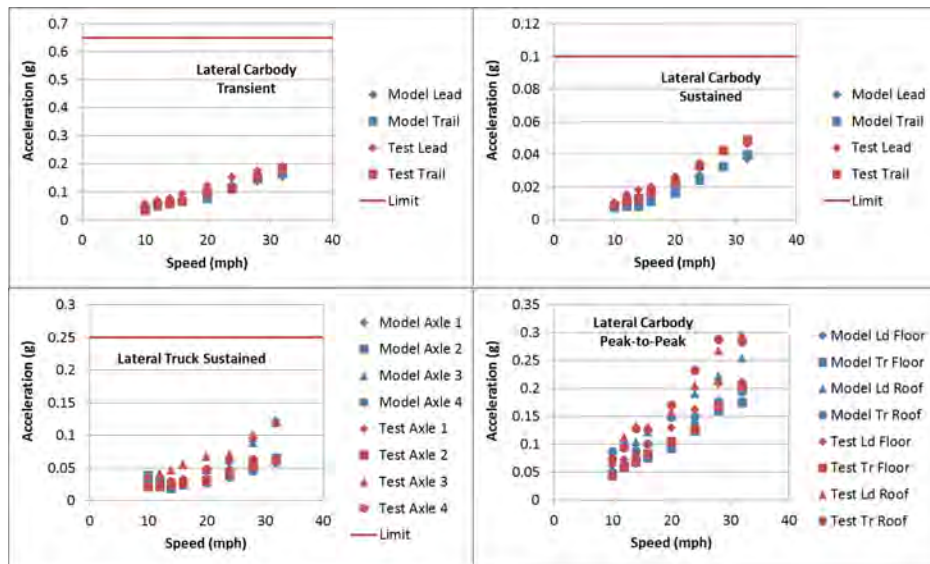


Figure 70. Maximum Peak-to-Peak Carbody Accelerations – Dynamic Curving in CW Direction

Figure 71 through Figure 74 show time histories of the 32 mph test run through the dynamic curving test section in the CW direction. For each comparison plot, Sprague and Geers metrics, including the magnitude, phase, and comprehensive error measures, were calculated and displayed at the bottom of each graph. Table 47 through Table 49 list the Sprague and Geers comprehensive error measures for the most important data channels.

Vertical displacement plots in Figure 71 show close agreement between the measured and calculated data. The magnitude and phase of the model and test data match closely through the curve. The average comprehensive error measures of the vertical displacement channels ranged from 0.15 to 0.24, which indicates an excellent model fit according to Figure 55.

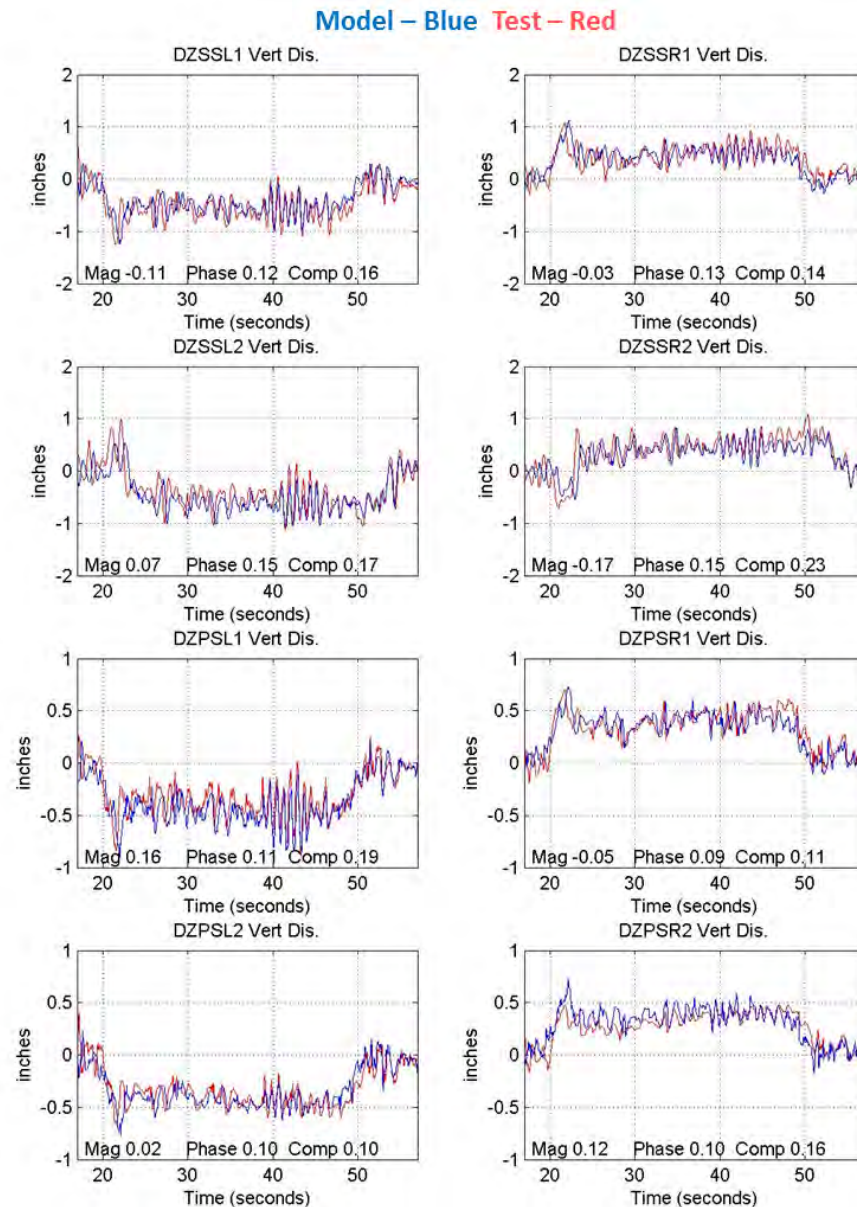


Figure 71. Vertical Primary and Secondary Suspension Displacements – Dynamic Curving 32 mph in CW Direction

Lateral displacement plots in Figure 72 show generally good model-to-test data agreement. The mean values of the simulated suspension displacements in the body of the curve tended to differ slightly from the measured values. Regardless, model and test data still followed the same general trends. The average comprehensive error measures ranged from 0.26 to 0.32, all of which fall into the good range of the scale in Figure 55.

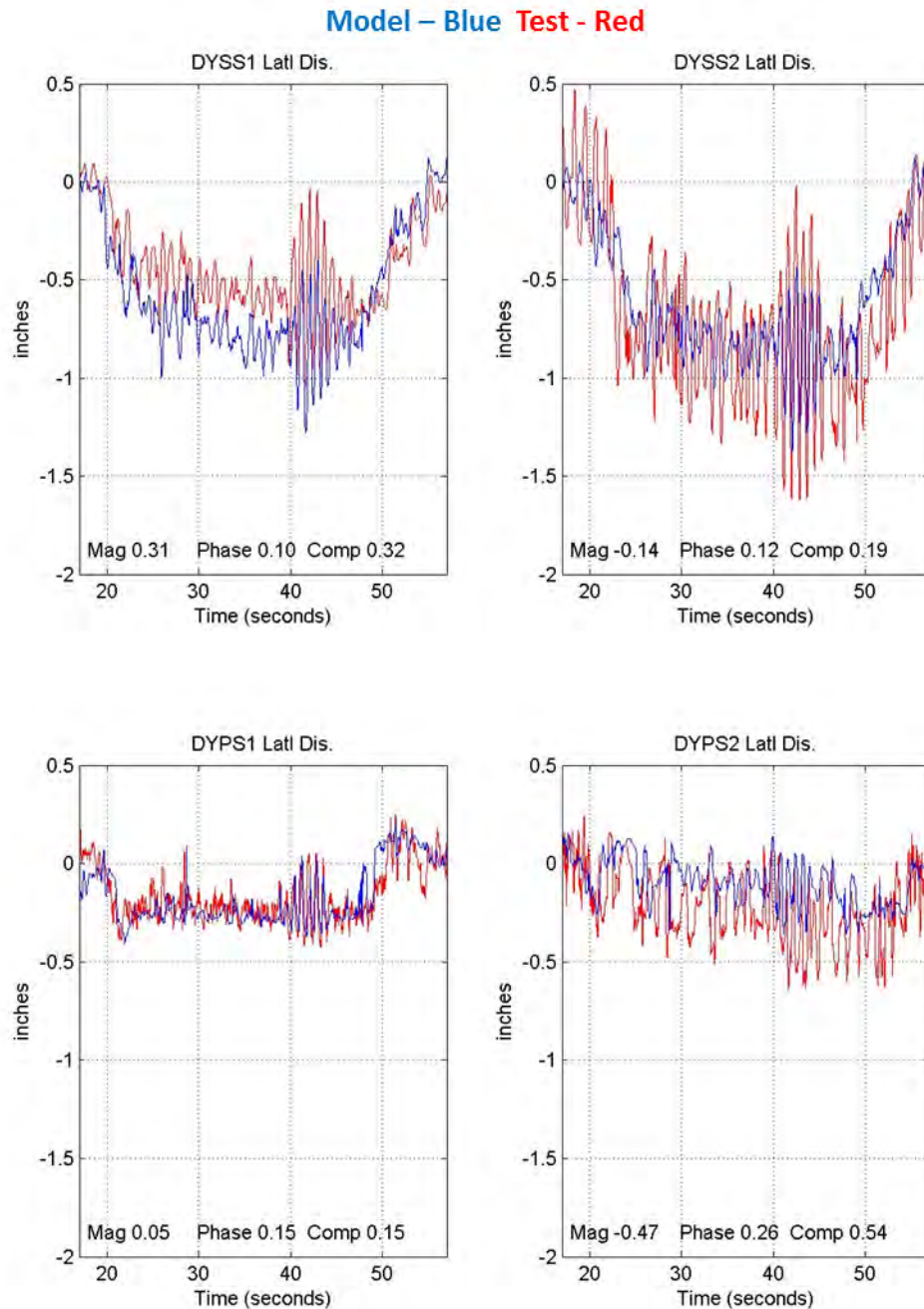


Figure 72. Lateral Primary and Secondary Suspension Displacements – Dynamic Curving 32 mph in CW Direction

Lateral carbody acceleration plots in [Figure 73](#) also show good model-to-test data agreement. Overall carbody accelerations and trends were similar for all speeds tested, but the model tended to underpredict the maximum acceleration values. The average comprehensive error measures ranged from 0.32 to 0.34, indicating good model-to-test agreement.

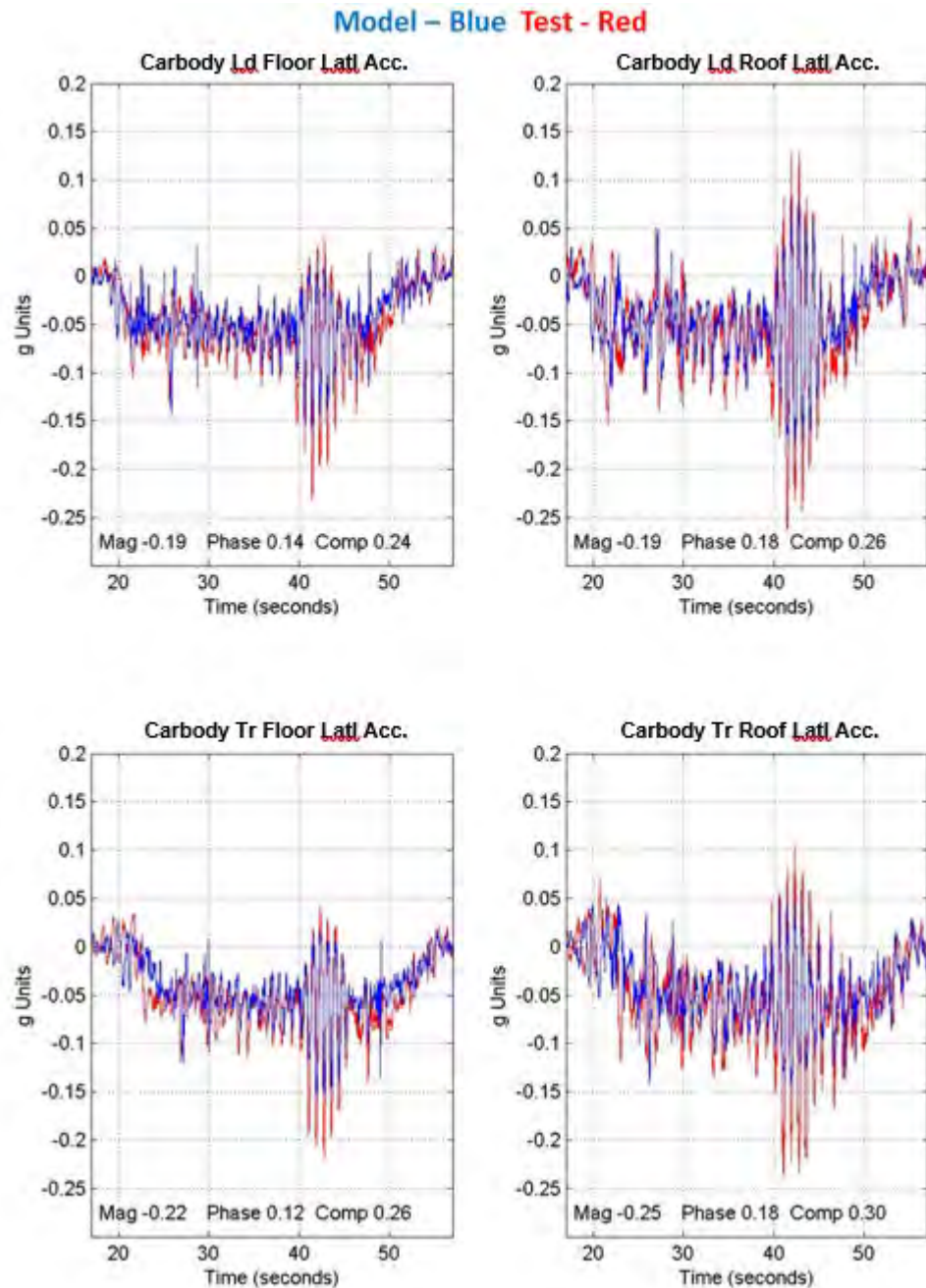


Figure 73. Lateral Carbody Accelerations – Dynamic Curving 32 mph in CW Direction

Lateral truck acceleration plots in [Figure 74](#) show reasonable model-to-test agreement. The model predicted carbody and truck accelerations reasonably well for the observed cases. Refer to [Table 39](#) for the detailed channel naming convention.

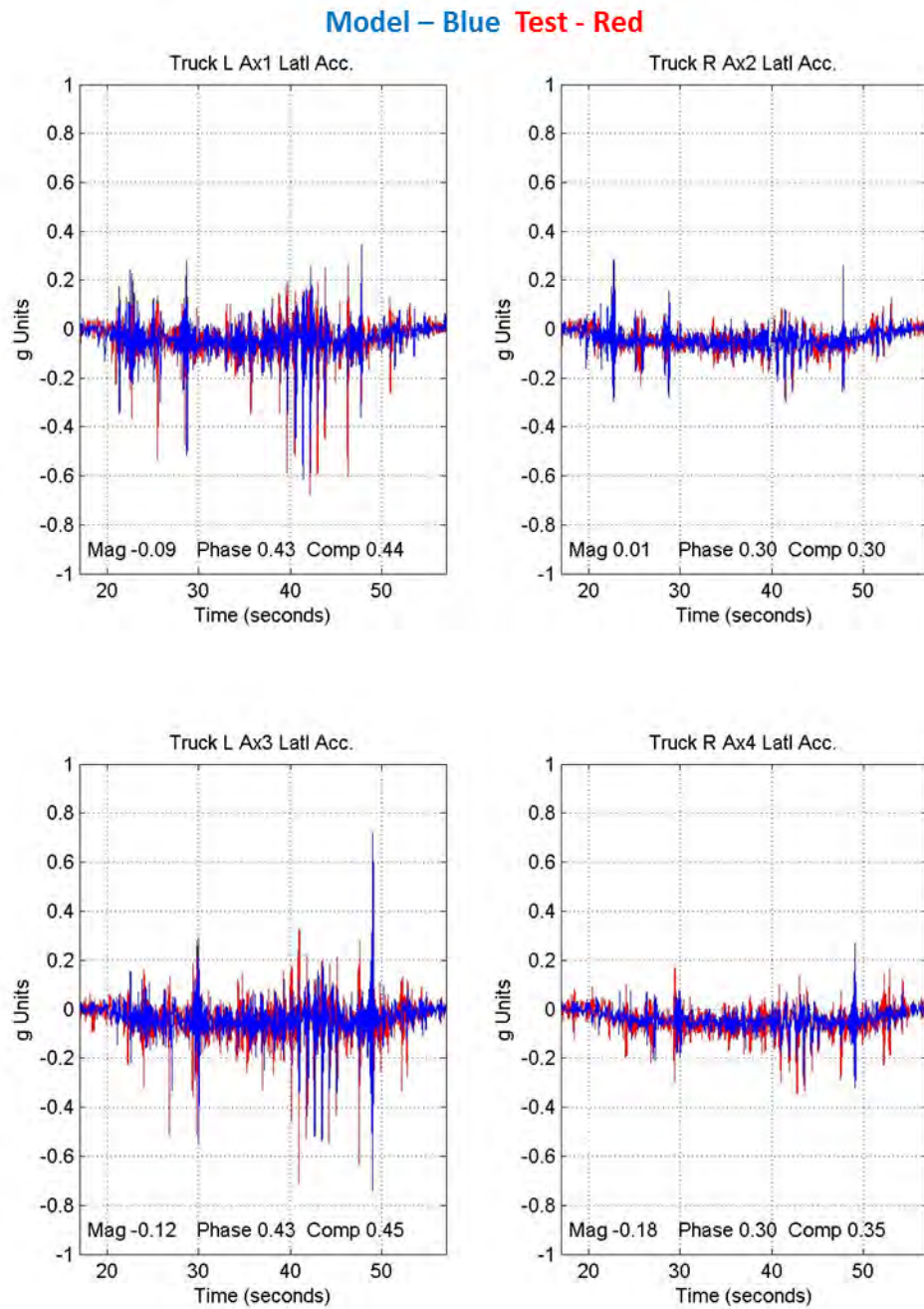


Figure 74. Lateral Truck Accelerations – Dynamic Curving 32 mph in CW Direction

Table 47. Comprehensive Error Measures for Dynamic Curving Suspension Displacements in CW Direction

Test Run	DZSSL1	DZSSR1	DZSSL2	DZSSR2	DZPSL1	DZPSR1	DZPSL2	DZPSR2	DYSS1	DYSS2	DYPS1	DYPS2
DC_CW-10MPH	0.25	0.06	0.19	0.06	0.10	0.20	0.19	0.06	0.16	0.17	0.39	0.13
DC_CW-12MPH	0.32	0.09	0.19	0.07	0.24	0.30	0.29	0.10	0.17	0.24	0.58	0.21
DC_CW-14MPH	0.28	0.10	0.19	0.10	0.21	0.27	0.26	0.09	0.17	0.19	0.31	0.27
DC_CW-16MPH	0.21	0.11	0.25	0.09	0.17	0.12	0.15	0.09	0.13	0.16	0.29	0.26
DC_CW-20MPH	0.24	0.19	0.27	0.15	0.28	0.20	0.23	0.17	0.21	0.32	0.27	0.27
DC_CW-24MPH	0.23	0.22	0.27	0.22	0.30	0.23	0.28	0.40	0.38	0.64	0.28	0.31
DC_CW-28MPH	0.21	0.25	0.20	0.28	0.30	0.16	0.21	0.30	0.52	0.31	0.28	0.41
DC_CW-32MPH	0.16	0.14	0.17	0.23	0.19	0.11	0.10	0.16	0.32	0.19	0.15	0.54
Average	0.24	0.15	0.22	0.15	0.22	0.20	0.21	0.17	0.26	0.28	0.32	0.30

Table 48. Comprehensive Error Measures for Dynamic Curving Carbody Accelerations in CW Direction

Test Run	AYCBR1	AYCBF1	AYCBR2	AYCBF2
DC_CW-10MPH	0.32	0.32	0.32	0.32
DC_CW-12MPH	0.38	0.38	0.35	0.35
DC_CW-14MPH	0.35	0.33	0.36	0.35
DC_CW-16MPH	0.33	0.33	0.32	0.35
DC_CW-20MPH	0.40	0.36	0.38	0.38
DC_CW-24MPH	0.32	0.28	0.36	0.37
DC_CW-28MPH	0.26	0.27	0.23	0.31
DC_CW-32MPH	0.24	0.26	0.26	0.30
Average	0.33	0.32	0.32	0.34

Table 49. Comprehensive Error Measures for Dynamic Curving Truck Accelerations in CW Direction

Test Run	AYTRA1	AYTRA2	AYTRA3	AYTRA4
DC_CW-10MPH	0.24	0.24	0.32	0.23
DC_CW-12MPH	0.29	0.28	0.28	0.25
DC_CW-14MPH	0.28	0.28	0.35	0.29
DC_CW-16MPH	0.31	0.29	0.36	0.30
DC_CW-20MPH	0.45	0.39	0.48	0.40
DC_CW-24MPH	0.45	0.46	0.52	0.51
DC_CW-28MPH	0.48	0.42	0.48	0.43
DC_CW-32MPH	0.44	0.30	0.45	0.35
Average	0.37	0.33	0.41	0.35

6.5.2 CCW

Results for the dynamic curving test runs in the CCW direction were like those in the CW direction. Maximum vertical suspension displacements were similar in magnitude for most of the test and simulation runs, especially at the lower speeds. As with twist and roll tests and the CW dynamic curving tests, lateral suspension displacements were also similar at both ends for the model over most of the speed range, whereas the test data showed the leading end secondary suspension matched the test results relatively well, but the trailing end secondary suspension had much larger amplitudes. Test data for the lateral primary suspension displacements at Axle 2 (DYPS2) again tended to be much higher than the corresponding model value and the measurement at Axle 1 (DYPS1). Figure 75 shows maximum 2-second peak-to-peak suspension displacements for the dynamic curving model and test runs in the CCW direction.

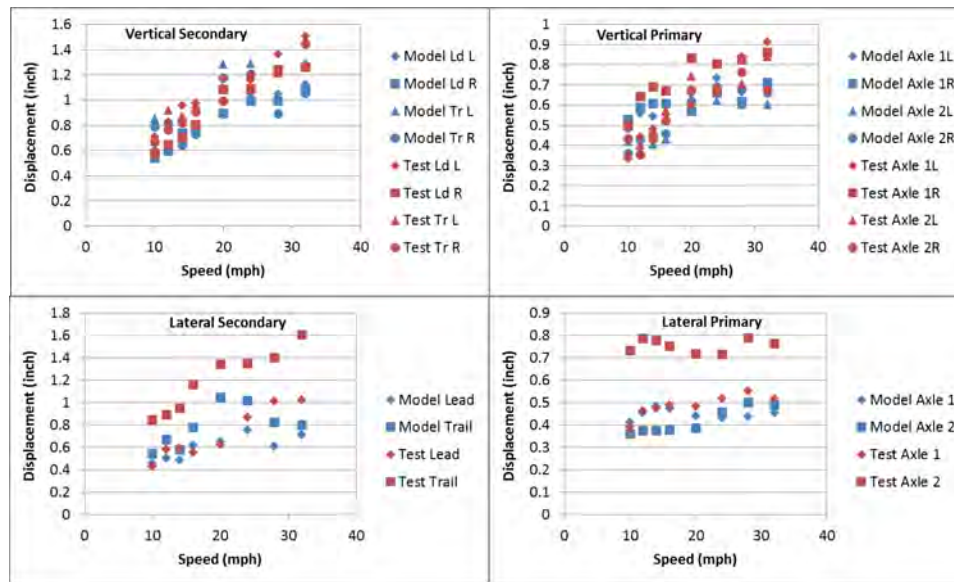


Figure 75. Maximum Peak-to-Peak Suspension Displacements – Dynamic Curving in CCW Direction

Similarly, simulated transient and sustained oscillatory lateral accelerations matched measured values closely, and the maximum values were still below FRA limits. Figure 76 shows the maximum lateral carbody and truck accelerations in the model and test cases. The bottom right plot of the figure shows lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody, which again match well for the model and test cases.

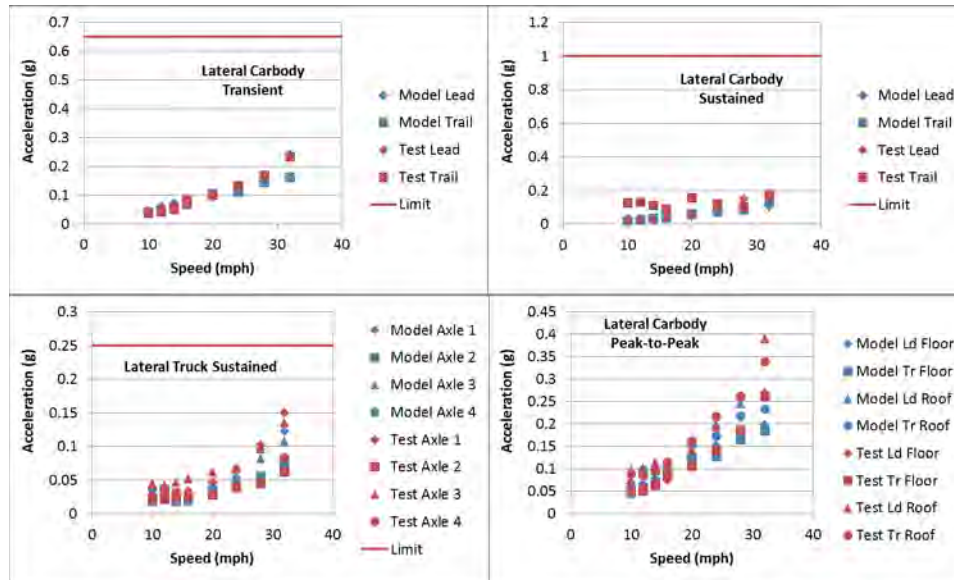


Figure 76. Maximum Peak-to-Peak Carbody Accelerations – Dynamic Curving in CCW Direction

Suspension displacement plots in [Figure 77](#) and [Figure 78](#) show generally good agreement between the measured and calculated data, although secondary lateral displacements measured on the trail truck were considerably larger than the lead truck and the corresponding simulation results. The average comprehensive error measures of the vertical displacement channels ranged from 0.13 to 0.24, indicating an excellent model fit. The average comprehensive error measures of the lateral displacement channels ranged from 0.05 to 0.44, indicating good model-to-test data agreement.

Lateral carbody acceleration plots in [Figure 79](#) also show good agreement between simulated and measured values. The average comprehensive error measures ranged from 0.26 to 0.29, indicating a good model fit. Lateral truck acceleration plots in [Figure 80](#) also show reasonable model-to-test agreement. Like the CW test runs, the model predicted carbody and truck accelerations reasonably well for the CCW cases. [Table 50](#) through [Table 52](#) list the Sprague and Geers comprehensive error measures for the suspension displacement and acceleration channels. Refer to [Table 39](#) for the detailed channel naming convention.

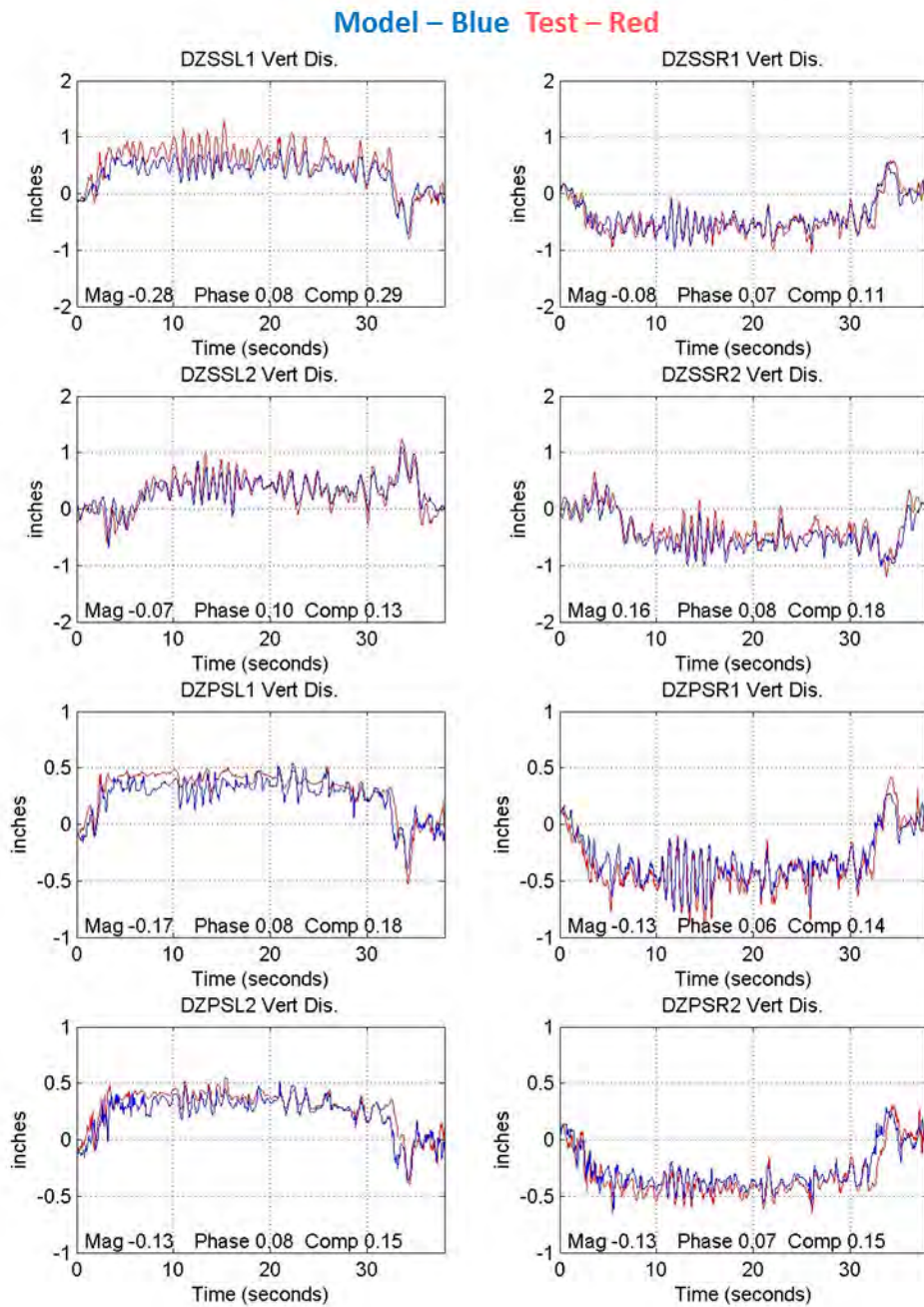


**Figure 77. Vertical Primary and Secondary Suspension Displacements – Dynamic Curving
32 mph in CCW Direction**

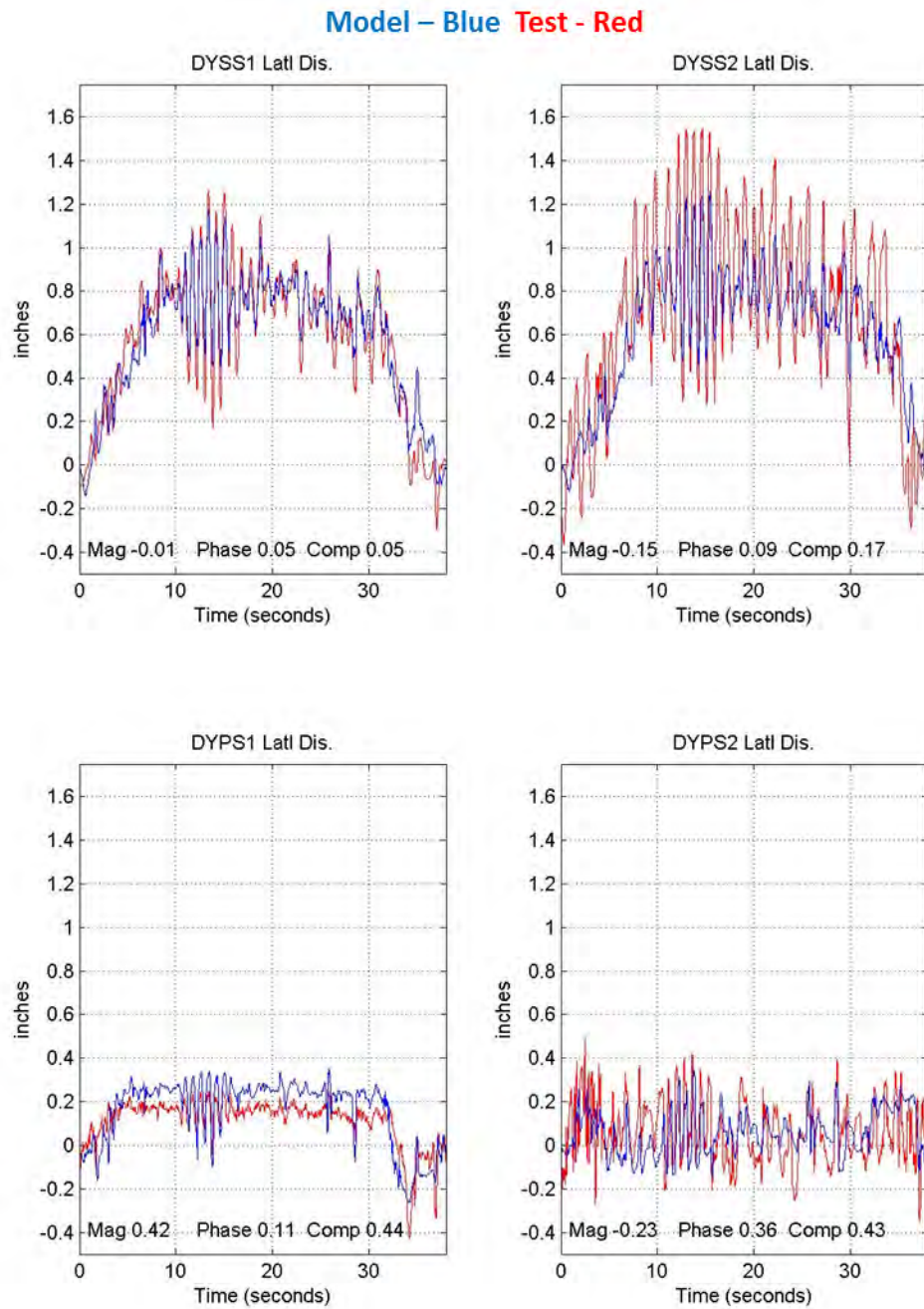


**Figure 78. Lateral Primary and Secondary Suspension Displacements – Dynamic Curving
32 mph in CCW Direction**

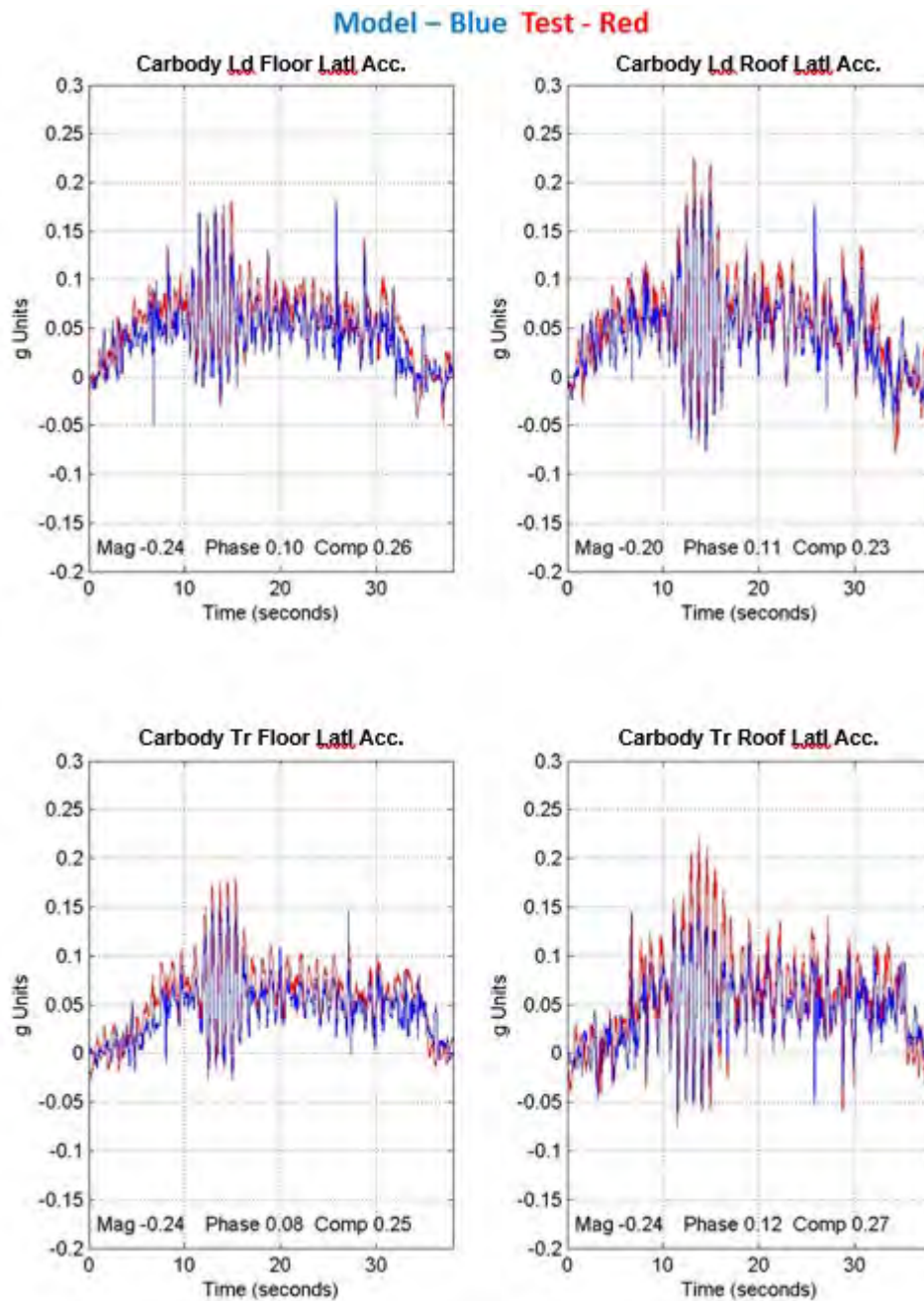


Figure 79. Lateral Carbody Accelerations – Dynamic Curving 32 mph in CCW Direction

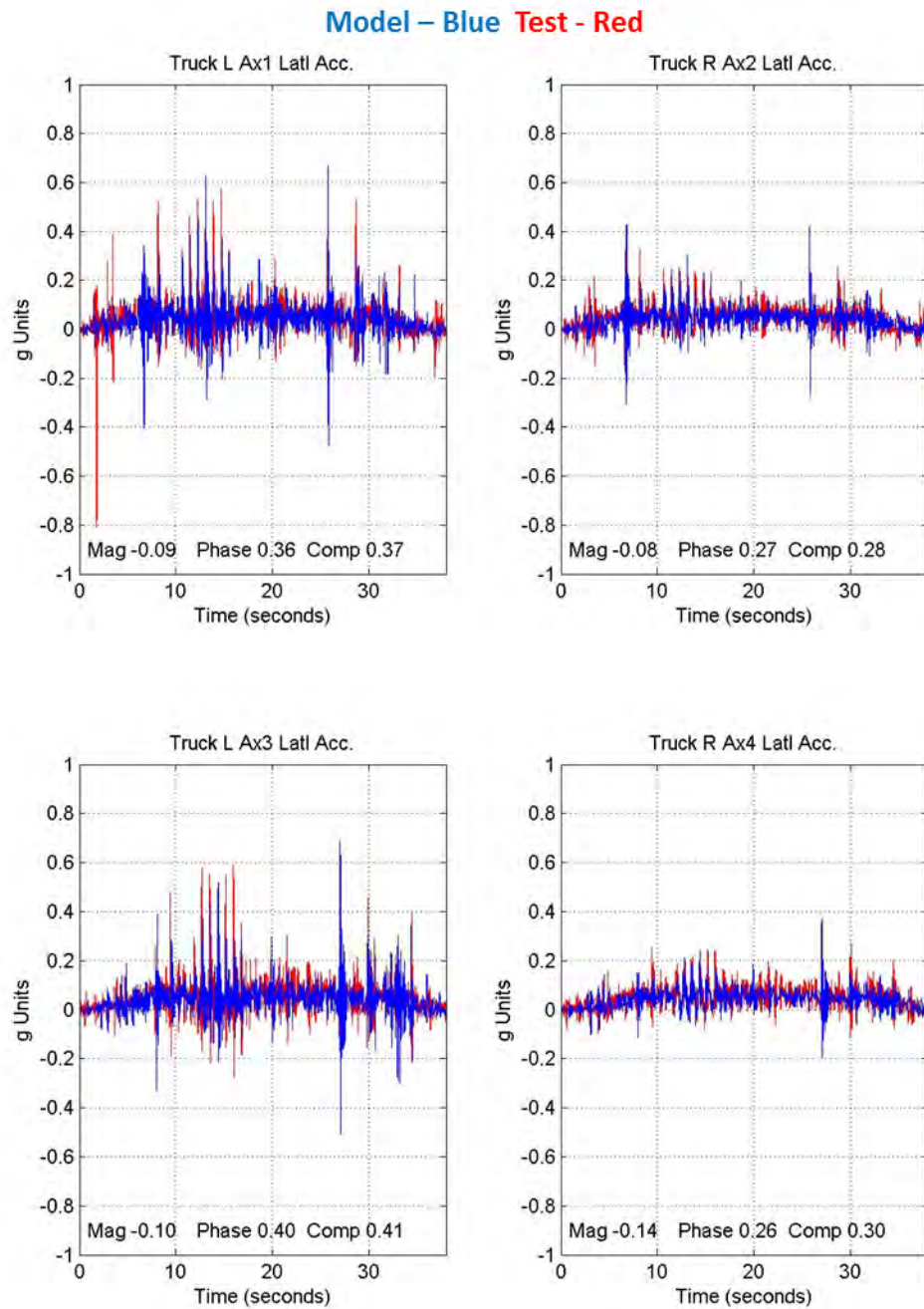


Figure 80. Lateral Truck Accelerations – Dynamic Curving 32 mph in CCW Direction

Table 50. Comprehensive Error Measures for Dynamic Curving Suspension Displacements in CCW Direction

Test Run	DZSSL 1	DZSSR 1	DZSSL 2	DZSSR 2	DZPSL 1	DZPSR 1	DZPSL 2	DZPSR 2	DYSS 1	DYSS 2	DYPS 1	DYPS 2
DC_CCW-10MPH	0.23	0.22	0.40	0.10	0.11	0.20	0.08	0.13	0.23	0.08	0.40	0.37
DC_CCW-12MPH	0.11	0.10	0.06	0.23	0.18	0.13	0.28	0.05	0.28	0.07	0.25	0.33
DC_CCW-14MPH	0.11	0.09	0.07	0.25	0.06	0.09	0.22	0.06	0.13	0.16	0.21	0.32
DC_CCW-16MPH	0.11	0.10	0.10	0.27	0.16	0.10	0.32	0.07	0.16	0.23	0.25	0.35
DC_CCW-20MPH	0.15	0.17	0.17	0.26	0.17	0.18	0.36	0.17	0.12	0.25	0.24	0.34
DC_CCW-24MPH	0.23	0.24	0.26	0.24	0.22	0.29	0.22	0.19	0.35	0.60	0.34	0.33
DC_CCW-28MPH	0.23	0.16	0.16	0.11	0.26	0.22	0.27	0.18	0.45	0.25	0.71	0.62
DC_CCW-32MPH	0.29	0.11	0.13	0.18	0.18	0.14	0.15	0.15	0.05	0.17	0.44	0.43
Average	0.18	0.15	0.17	0.21	0.17	0.17	0.24	0.13	0.22	0.23	0.36	0.39

Table 51. Comprehensive Error Measures for Dynamic Curving Carbody Accelerations in CCW Direction

Test Run	AYCBR1	AYCBF1	AYCBR2	AYCBF2
DC_CCW-10MPH	0.33	0.31	0.30	0.30
DC_CCW-12MPH	0.26	0.24	0.26	0.26
DC_CCW-14MPH	0.33	0.31	0.32	0.32
DC_CCW-16MPH	0.31	0.29	0.30	0.31
DC_CCW-20MPH	0.29	0.25	0.27	0.25
DC_CCW-24MPH	0.34	0.27	0.34	0.33
DC_CCW-28MPH	0.20	0.19	0.19	0.25
DC_CCW-32MPH	0.26	0.23	0.25	0.27
Average	0.29	0.26	0.28	0.29

Table 52. Comprehensive Error Measures for Dynamic Curving Truck Accelerations in CCW Direction

Test Run	AYTRA1	AYTRA2	AYTRA3	AYTRA4
DC_CCW-10MPH	0.22	0.20	0.24	0.21
DC_CCW-12MPH	0.21	0.18	0.23	0.19
DC_CCW-14MPH	0.27	0.25	0.30	0.25
DC_CCW-16MPH	0.29	0.26	0.34	0.27
DC_CCW-20MPH	0.41	0.37	0.51	0.47
DC_CCW-24MPH	0.52	0.51	0.56	0.60
DC_CCW-28MPH	0.43	0.39	0.47	0.48
DC_CCW-32MPH	0.37	0.28	0.41	0.30
Average	0.34	0.31	0.38	0.35

6.6 WRM – Constant Curving

Results from the constant curving test section show good agreement between model and test data for both CW and CCW directions. Results from the test runs are presented separately for each direction in the following sections. Results from this test section are divided and examined by curve section to look more closely at data trends and values.

6.6.1 CW

Figure 81 shows maximum 2-second peak-to-peak suspension displacements for the constant curving model and test runs in the CW direction. Maximum vertical suspension displacements were similar in magnitude for the test and simulation runs. Lateral secondary suspension displacements were similar for the model and test data at the lead end of the vehicle, but model and test maximums differed significantly at the trail end of the vehicle. Lateral primary suspension displacement at Axle 2 tended to be higher than the corresponding model values and the measurements taken at Axle 1. As discussed in Section 6.2, the discrepancy between model and test lateral displacements may be due to modeling assumptions.

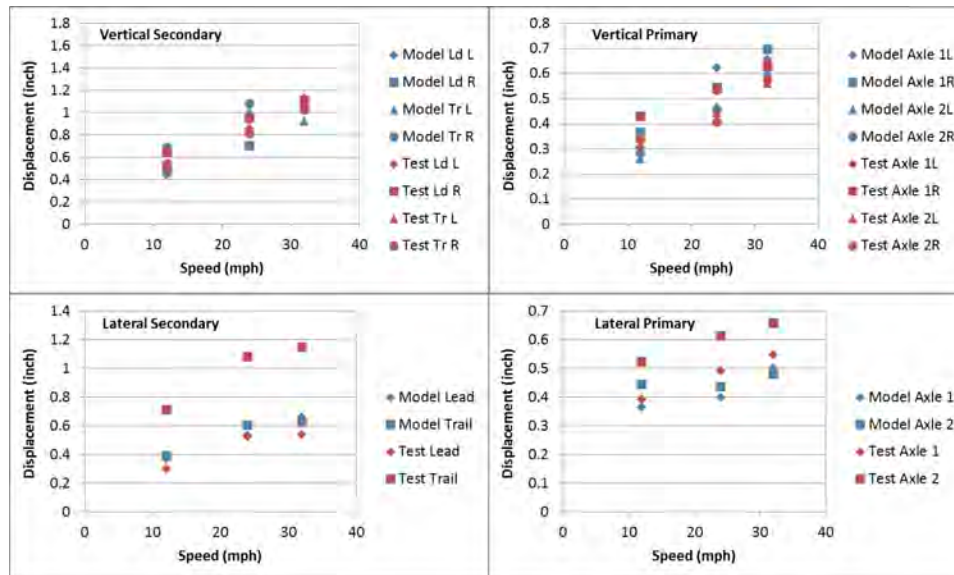


Figure 81. Maximum Peak-to-Peak Suspension Displacements – Constant Curving in CW Direction

Figure 82 shows the maximum lateral carbody accelerations in the model and test cases. Simulated transient and sustained oscillatory lateral accelerations were like the measured values for the three test speeds. All measured and calculated values were below FRA limits. The bottom plot in Figure 70 shows the lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody. Model accelerations at the floor and roof levels demonstrated considerable agreement with the test data.

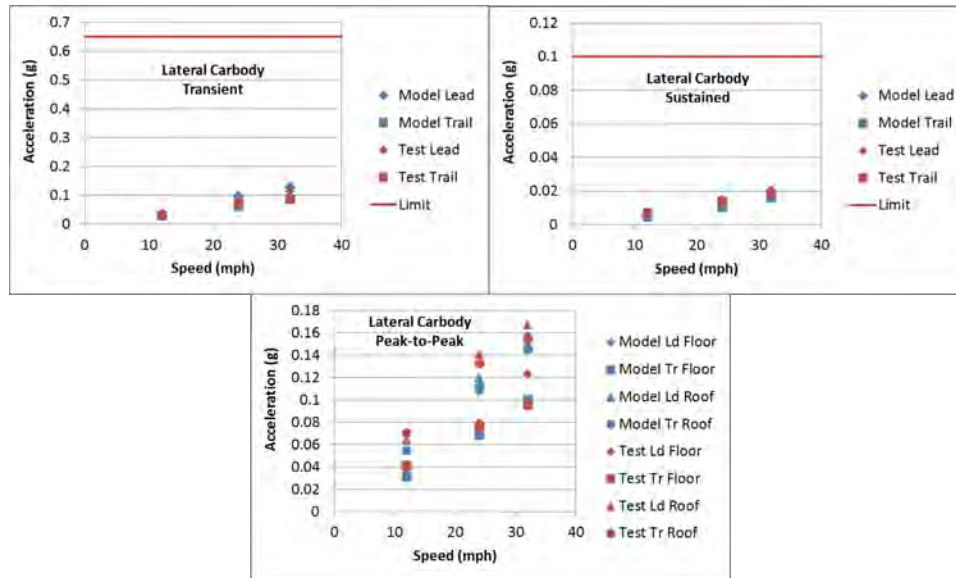


Figure 82. Maximum Peak-to-Peak Carbody Accelerations – Constant Curving in CW Direction

Figure 83 through Figure 86 show time histories of the 32 mph test run through the 12-degree curve of the constant curving test section in the CW direction. Sprague and Geers metrics were calculated and displayed at the bottom of each graph. Table 53 and Table 54 list the Sprague and Geers comprehensive error measures for the most important data channels.

Vertical displacement plots in Figure 83 show good agreement between the measured and calculated data, both at the primary and secondary suspension levels. The magnitude and phase of the model and test data match closely throughout the curve. The average comprehensive error measures of the vertical displacement channels ranged from 0.17 to 0.33, which indicates a good model fit according to Figure 55.

Lateral displacement plots in Figure 84 show generally reasonable model-to-test data agreement. Measured data for channels DYSS2 and DYPS2 show significant variability through the 12-degree curve, variability that was not matched by the other data channels or the simulation data. Regardless, model and test data still followed the same general trends. The average comprehensive error measures ranged from 0.28 to 0.44, which falls into the acceptable range of Figure 55.

Figure 85 shows comparison plots of the longitudinal suspension displacement time histories. In general, the model echoed the same trends that were seen in the test data, though the magnitudes of maximum displacement values were not matched exactly. The model demonstrated the same type of curving and truck rotation behavior that was seen in the tests.

Lateral carbody acceleration plots in Figure 86 also show good agreement between model and test data. Overall carbody accelerations and trends were similar for all speeds tested. The average comprehensive error measures ranged from 0.29 to 0.33, indicating good model-to-test agreement. Refer to Table 39 for the detailed channel naming convention.

Model – Blue Test - Red

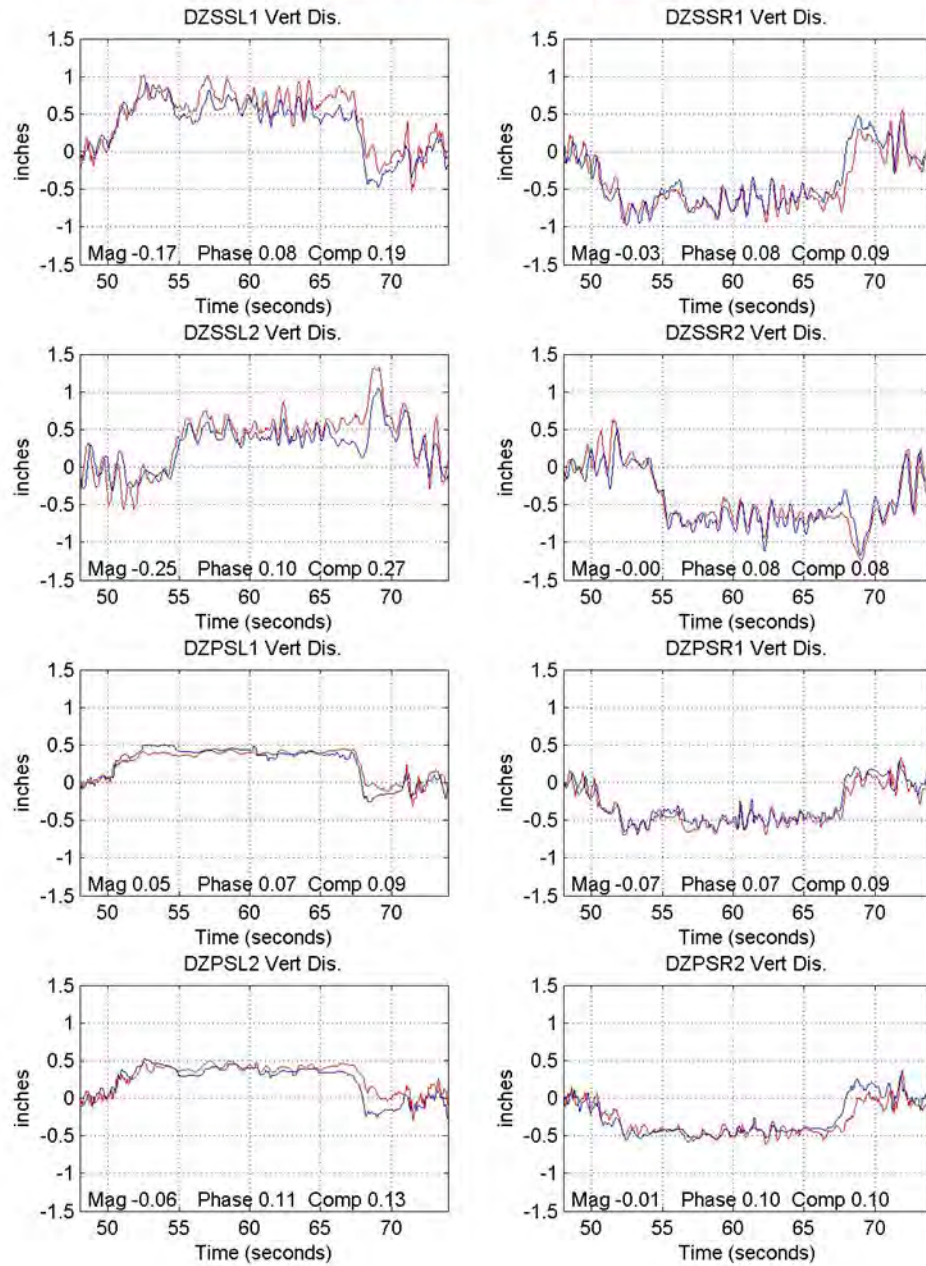


Figure 83. Vertical Primary and Secondary Suspension Displacements – Constant Curving 32 mph in CW Direction on 12-Degree Curve

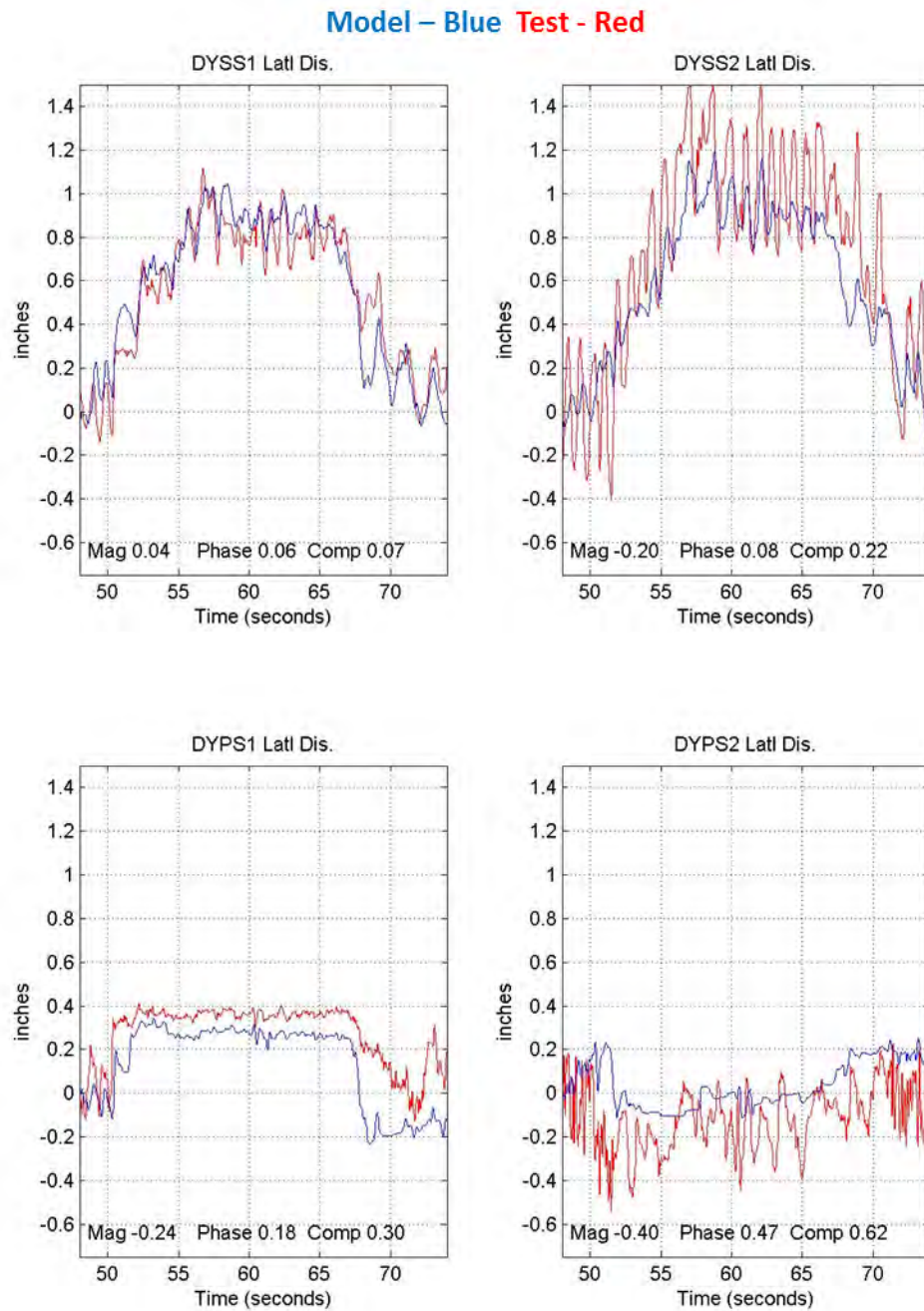


**Figure 84. Lateral Primary and Secondary Suspension Displacements – Constant Curving
32 mph in CW Direction on 12-Degree Curve**

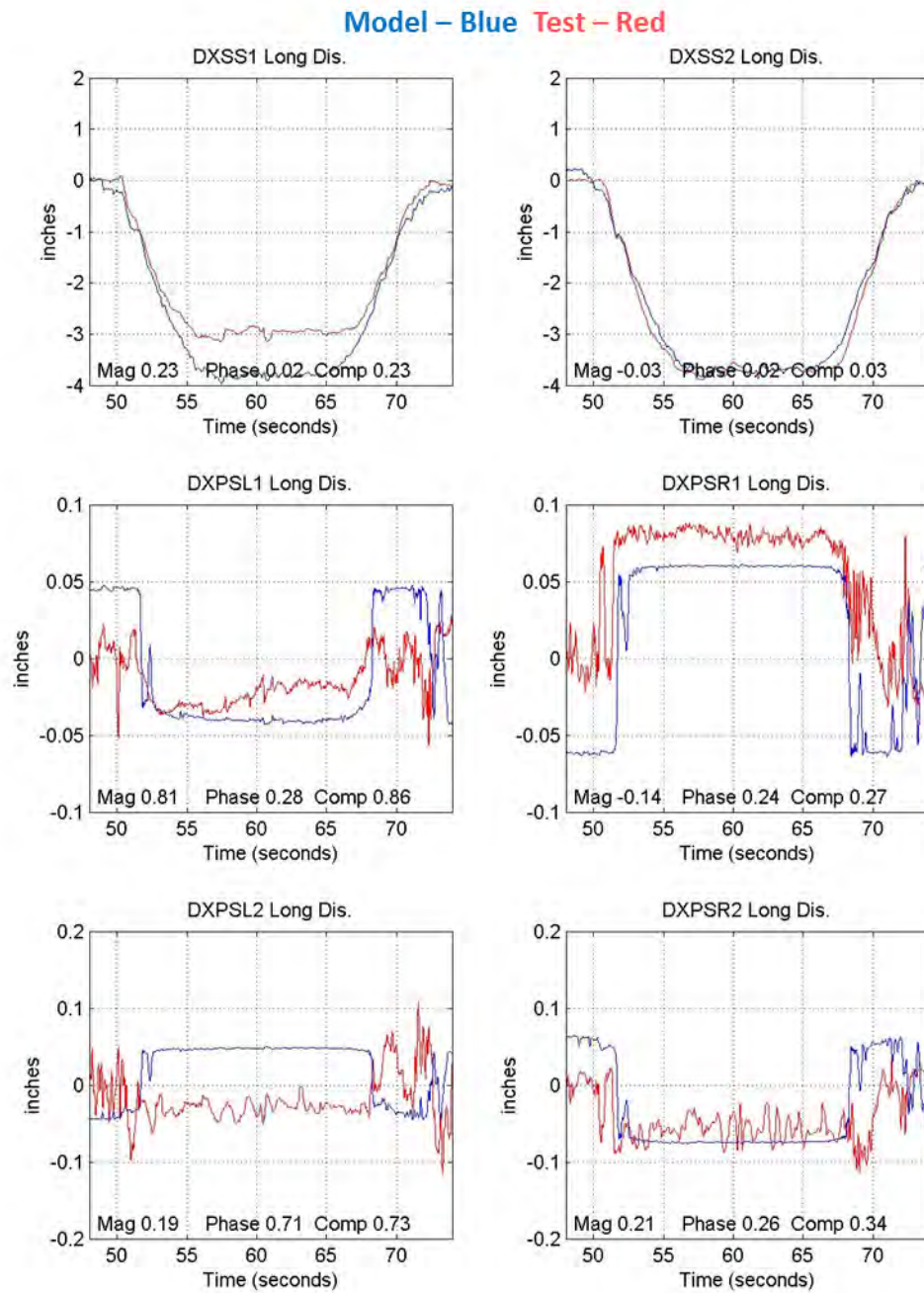


Figure 85. Longitudinal Primary and Secondary Suspension Displacements – Constant Curving 32 mph in CW Direction on 12-Degree Curve

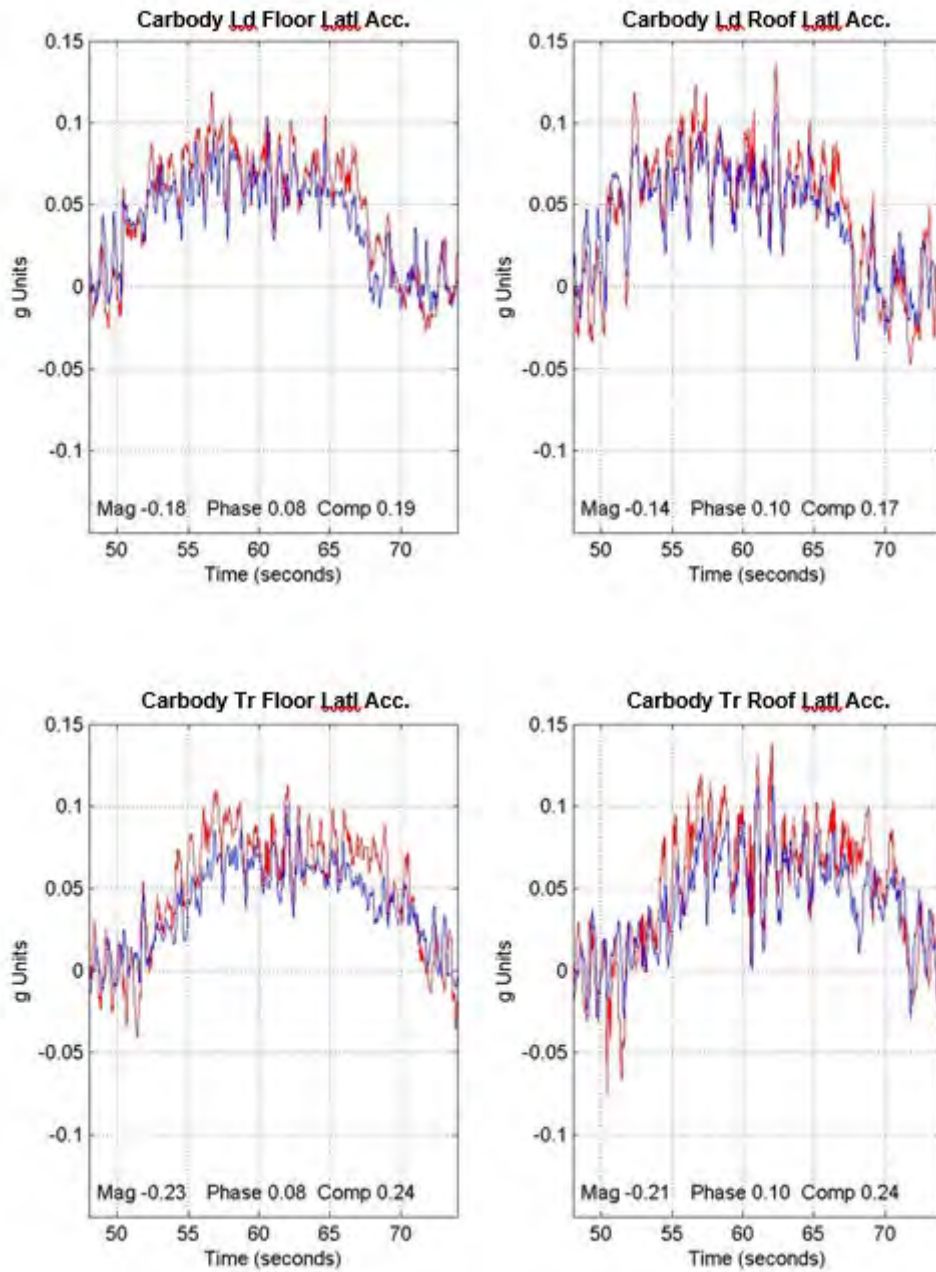


Figure 86. Lateral Carbody Accelerations – Constant Curving 32 mph in CW Direction on 12-Degree Curve

Table 53. Comprehensive Error Measures for Constant Curving Suspension Displacements in CW Direction

Test Run		DZSSL 1	DZSSR 1	DZSSL 2	DZSSR 2	DZPSL 1	DZPSR 1	DZPSL 2	DZPSR 2	DYSS 1	DYSS 2	DYPS 1	DYPS 2
10° Curve	CC_CW-12MPH	0.33	0.15	0.16	0.11	0.27	0.32	0.30	0.15	0.22	0.26	0.68	0.45
	CC_CW - 24MPH	0.28	0.35	0.24	0.30	0.71	0.44	0.71	0.69	0.64	0.59	0.46	0.27
	CC_CW-32MPH	0.09	0.12	0.09	0.30	0.17	0.09	0.08	0.12	0.20	0.16	0.23	0.70
12° Curve	CC_CW-12MPH	0.05	0.05	0.18	0.17	0.06	0.05	0.25	0.16	0.15	0.15	0.27	0.50
	CC_CW-24MPH	0.13	0.19	0.17	0.15	0.13	0.14	0.64	0.38	0.28	0.53	0.22	0.41
	CC_CW-32MPH	0.19	0.09	0.27	0.08	0.09	0.09	0.13	0.10	0.07	0.22	0.30	0.62
7.5° Curve	CC_CW-12MPH	0.38	0.28	0.09	0.16	0.33	0.40	0.31	0.21	0.21	0.18	0.55	0.18
	CC_CW-24MPH	0.16	0.24	0.21	0.13	0.39	0.28	0.36	0.51	0.48	0.66	0.24	0.36
	CC_CW-32MPH	0.11	0.16	0.13	0.24	0.21	0.11	0.15	0.16	0.25	0.23	0.18	0.51
Average		0.19	0.18	0.17	0.18	0.26	0.21	0.33	0.28	0.28	0.33	0.35	0.44

Table 54. Comprehensive Error Measures for Constant Curving Carbody Accelerations in CW Direction

Test Run		AYCBR1	AYCBF1	AYCBR2	AYCBF2
10° Curve	CC_CW-12MPH	0.41	0.40	0.41	0.41
	CC_CW-24MPH	0.54	0.49	0.44	0.43
	CC_CW-32MPH	0.19	0.22	0.17	0.21
12° Curve	CC_CW-12MPH	0.33	0.32	0.32	0.33
	CC_CW-24MPH	0.28	0.24	0.42	0.30
	CC_CW-32MPH	0.19	0.17	0.24	0.24
7.5° Curve	CC_CW-12MPH	0.36	0.36	0.36	0.37
	CC_CW-24MPH	0.31	0.22	0.31	0.27
	CC_CW-32MPH	0.23	0.23	0.24	0.26
Average		0.32	0.29	0.32	0.31

6.6.2 CCW

Results for the constant curving test runs in the CCW direction were like those seen in the CW direction. Maximum vertical suspension displacements were similar in magnitude for the test and simulation runs. Lateral secondary suspension displacements matched more closely at the lead end of the vehicle than at the trail end, and the lateral primary suspension displacements at Axle 2 were higher than the corresponding model values and the measurements taken at Axle 1. As discussed in [Section 6.2](#), the discrepancy between model and test lateral displacements may be due to modeling assumptions. [Figure 87](#) shows maximum 2-second peak-to-peak suspension displacements for the constant curving model and test runs in the CCW direction.

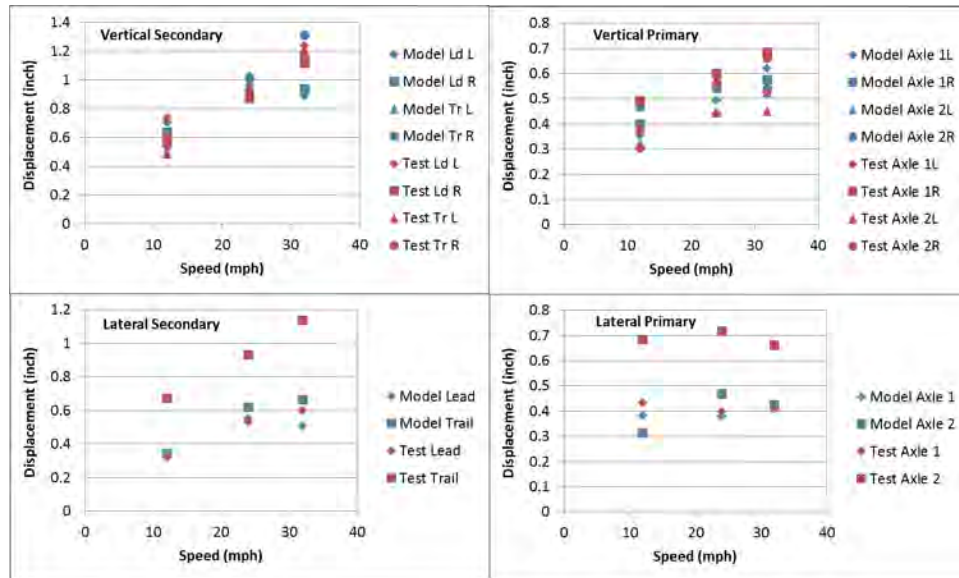


Figure 87. Maximum Peak-to-Peak Suspension Displacements – Constant Curving in CCW Direction

Like test runs in the CW direction, simulated transient and sustained oscillatory lateral accelerations in the CCW direction matched measured values reasonably well, and the maximum values were still below FRA limits. Figure 88 shows the maximum lateral carbody accelerations in the model and test cases. The bottom plot of the figure shows lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody, which again match well for the model and test cases.

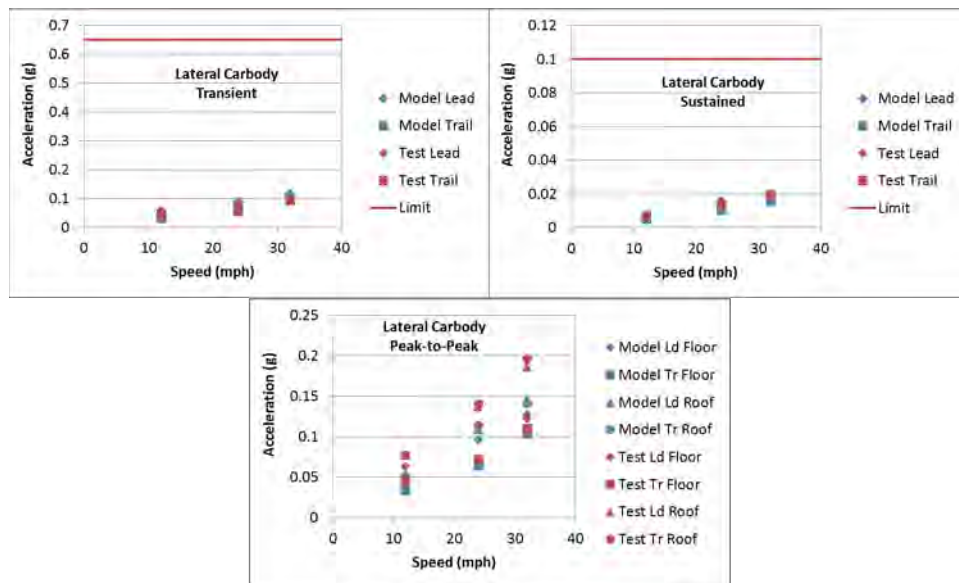


Figure 88. Maximum Peak-to-Peak Carbody Accelerations – Constant Curving in CCW Direction

The suspension displacement plots in Figure 89 and Figure 90 show generally good agreement between the measured and calculated data; however, the vertical displacement channels in the model tended to match the test data better than the lateral displacement channels. Average

comprehensive error measures of the vertical displacement channels ranged from 0.13 to 0.20, indicating an excellent model fit. Average comprehensive error measures of the lateral displacement channels ranged from 0.21 to 0.47, indicating acceptable agreement between model and test data. Like the CW constant curving test cases, the longitudinal displacement plots in [Figure 91](#) show generally good agreement between model and test curving and truck rotation behavior.

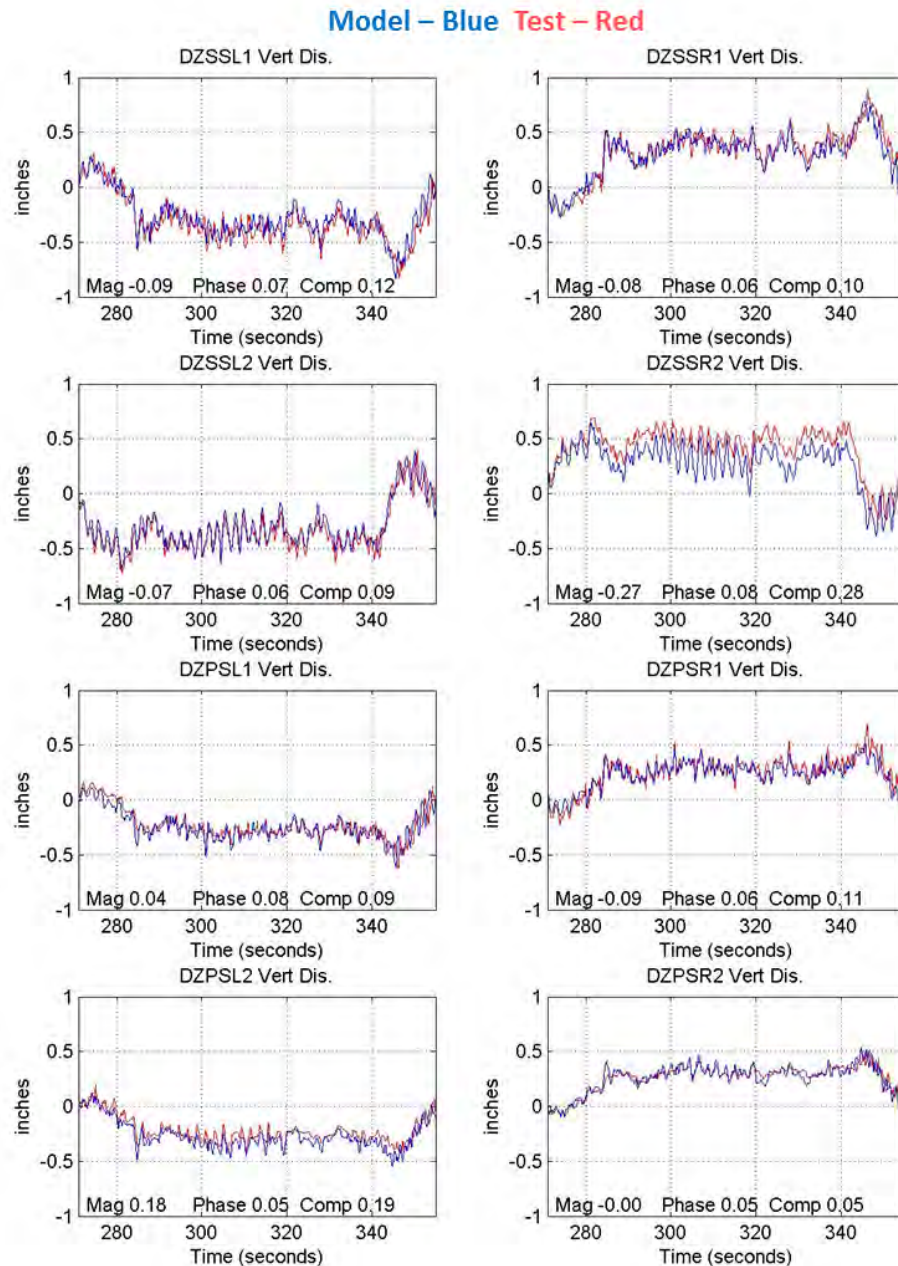


Figure 89. Vertical Primary and Secondary Suspension Displacements – Constant Curving 12 mph in CCW Direction on 7.5-Degree Curve

Model – Blue Test - Red

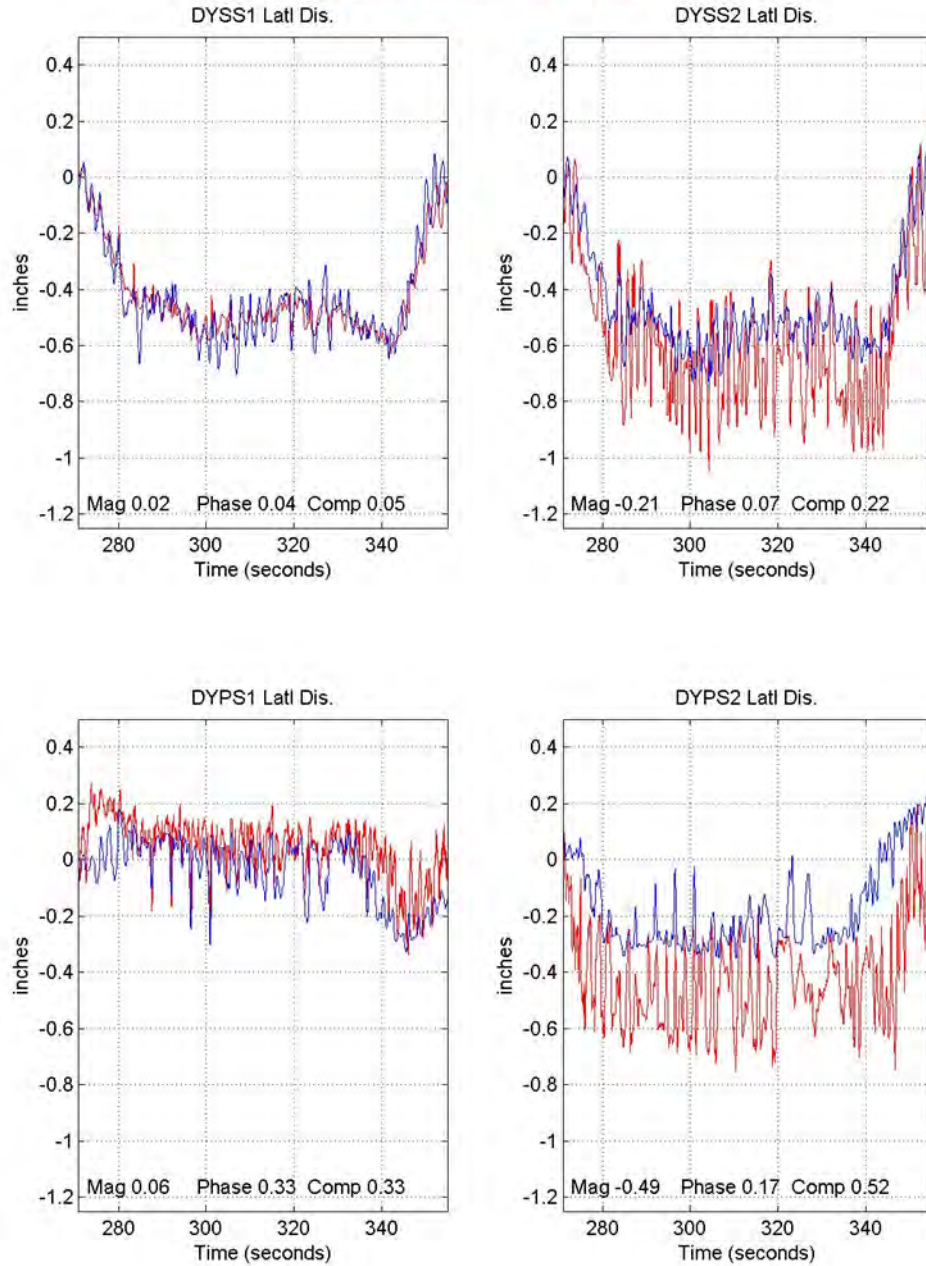


Figure 90. Lateral Primary and Secondary Suspension Displacements – Constant Curving 12 mph in CCW Direction on 7.5-Degree Curve

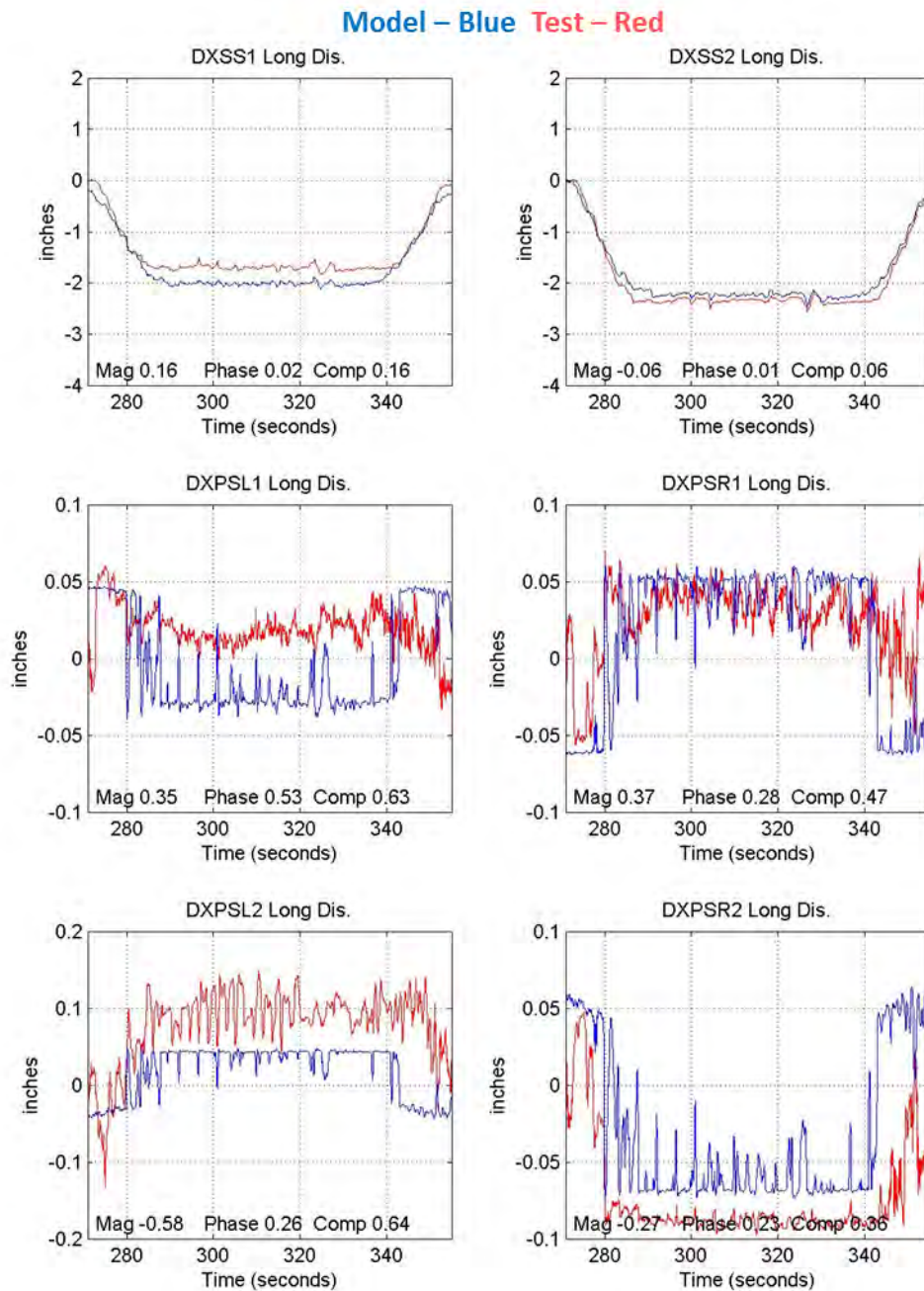


Figure 91. Longitudinal Primary and Secondary Suspension Displacements – Constant Curving 12 mph in CCW Direction on 7.5-Degree Curve

Lateral carbody acceleration plots in [Figure 92](#) also show good agreement between simulated and measured values. Average comprehensive error measures ranged from 0.28 to 0.31, indicating good agreement between model and test data. [Table 55](#) and [Table 56](#) list the Sprague and Geers comprehensive error measures for the most important data channels of this test section. Refer to [Table 39](#) for the detailed channel naming convention.

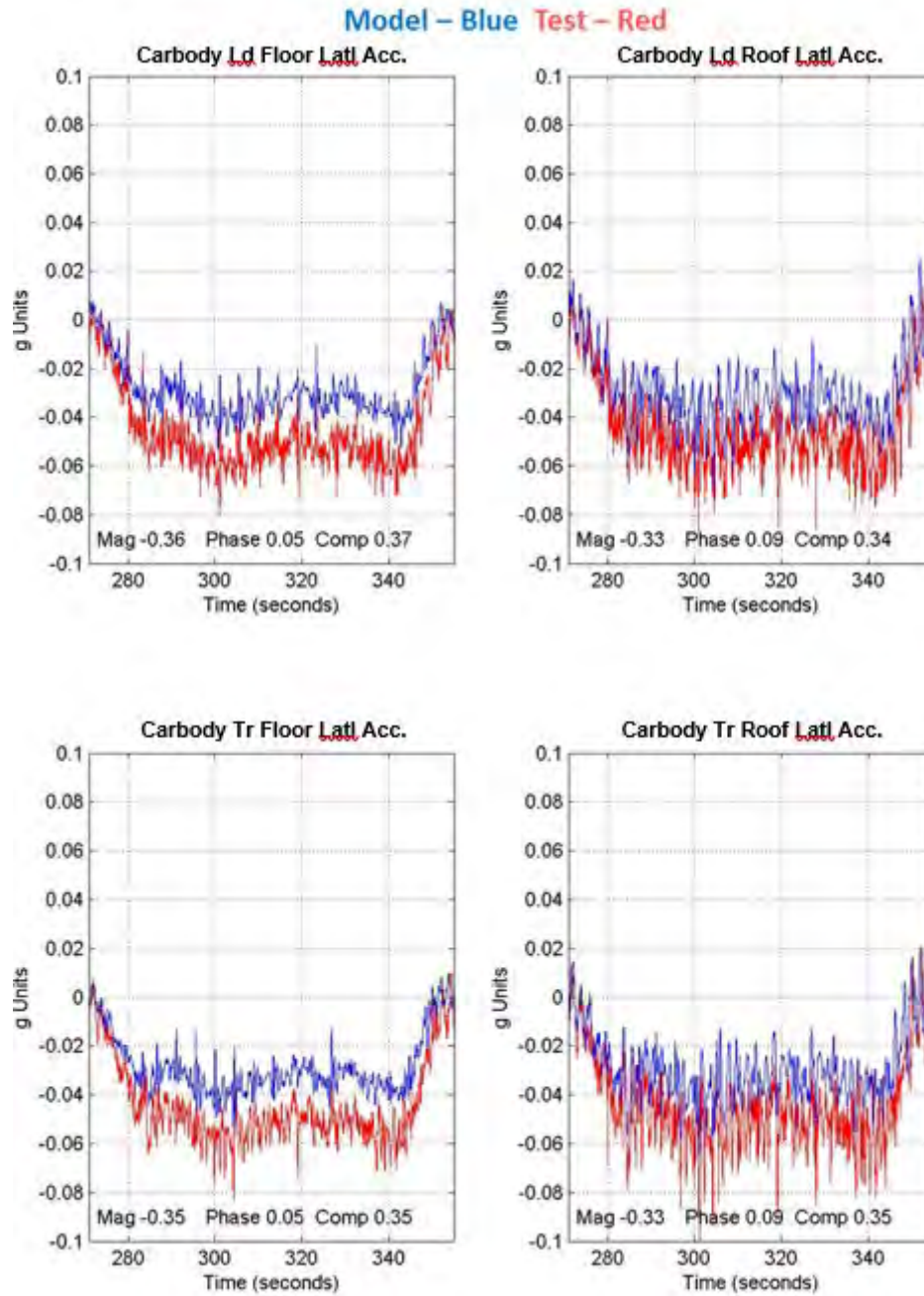


Figure 92. Lateral Carbody Accelerations – Constant Curving 12 mph in CW Direction on 7.5-Degree Curve

Table 55. Comprehensive Error Measures for Constant Curving Suspension Displacements in CCW Direction

Test Run		DZSSL 1	DZSSR 1	DZSSL 2	DZSSR 2	DZPSL 1	DZPSR 1	DZPSL 2	DZPSR 2	DYSS 1	DYSS 2	DYPS 1	DYPS 2
10° Curve	CC_CCW-12MPH	0.20	0.23	0.14	0.15	0.07	0.18	0.11	0.12	0.15	0.14	0.46	0.47
	CC_CCW-24MPH	0.22	0.20	0.17	0.22	0.24	0.25	0.32	0.25	0.43	0.54	0.33	0.47
	CC_CCW-32MPH	0.14	0.11	0.13	0.16	0.11	0.08	0.11	0.09	0.06	0.09	0.30	0.62
12° Curve	CC_CCW-12MPH	0.20	0.05	0.24	0.04	0.11	0.20	0.26	0.07	0.08	0.02	0.48	0.18
	CC_CCW-24MPH	0.12	0.20	0.11	0.11	0.20	0.27	0.22	0.40	0.27	0.51	0.16	0.27
	CC_CCW-32MPH	0.07	0.09	0.28	0.08	0.26	0.08	0.15	0.18	0.45	0.11	0.12	0.48
7.5° Curve	CC_CCW-12MPH	0.12	0.10	0.09	0.28	0.09	0.11	0.19	0.05	0.05	0.22	0.33	0.52
	CC_CCW-24MPH	0.15	0.16	0.16	0.23	0.20	0.23	0.32	0.17	0.32	0.59	0.25	0.67
	CC_CCW-32MPH	0.17	0.07	0.07	0.21	0.14	0.10	0.08	0.13	0.07	0.12	0.17	0.58
Average		0.15	0.13	0.15	0.16	0.16	0.17	0.20	0.16	0.21	0.26	0.29	0.47

Table 56. Comprehensive Error Measures for Constant Curving Carbody Accelerations in CCW Direction

Test Run		AYCBR1	AYCBF1	AYCBR2	AYCBF2
10° Curve	CC_CCW-12MPH	0.35	0.33	0.34	0.33
	CC_CCW-24MPH	0.34	0.30	0.31	0.30
	CC_CCW-32MPH	0.22	0.22	0.20	0.21
12° Curve	CC_CCW-12MPH	0.30	0.30	0.30	0.31
	CC_CCW-24MPH	0.38	0.31	0.29	0.26
	CC_CCW-32MPH	0.23	0.22	0.22	0.22
7.5° Curve	CC_CCW-12MPH	0.37	0.34	0.35	0.35
	CC_CCW-24MPH	0.35	0.28	0.34	0.29
	CC_CCW-32MPH	0.19	0.19	0.20	0.22
Average		0.30	0.28	0.28	0.28

6.7 URB North Wye

The DOTX-216 model was simulated over a test section containing a No. 8 turnout on a 12-degree curve with a 2-inch flat bottom dip in the outside rail. Results from the simulations were compared to data measured over a similar test section. The simulation environments built for this test section, unlike the other test section discussed in this report, did not make full use of track geometry measurements, which is a vital component of VTI. Track geometry data was measured for this test section, but data was only recorded for curvature, gage, and superelevation. Alignment and surface channels were not measured. As a result of this issue, NUCARS simulation data for this test section was affected by the lack of adequate track geometry data.

Despite this limitation, results from the special perturbation test section on the URB North Wye track indicated a relatively good match between the model and test data. [Figure 93](#) shows maximum 2-second peak-to-peak suspension displacements for the model and test runs. Maximum vertical and lateral suspension displacements showed similar trends for most of the test and simulation runs, but vertical displacement data from the model tended to match the test data amplitude better than the lateral displacement data matched (see [Section 6.2](#)). As with other test regimes, the test data shows much larger secondary displacements on the trail end than the lead end, whereas the model showed the two ends with similar displacements. The primary lateral suspension measurements were generally larger than the model predicted.

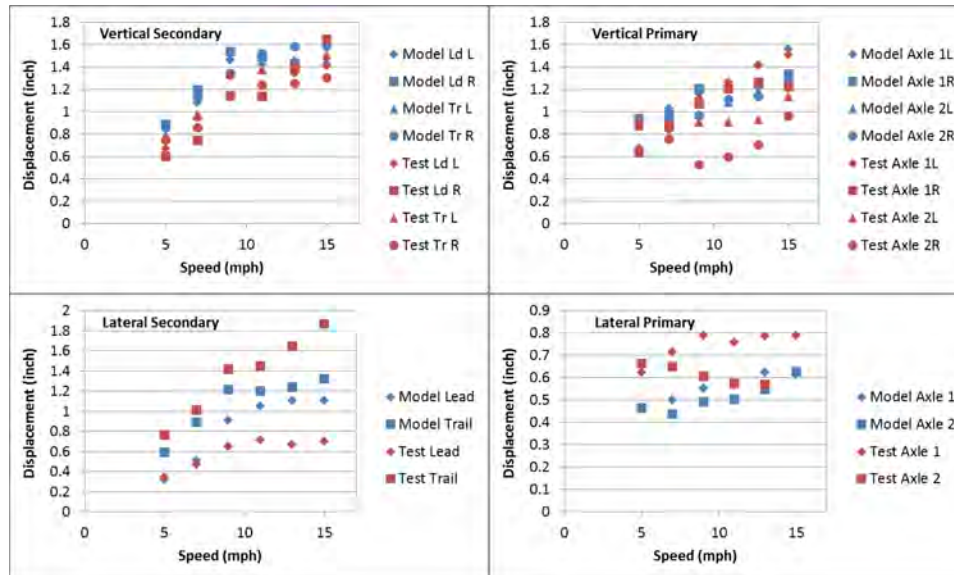


Figure 93. Maximum Peak-to-Peak Suspension Displacements – URB North Wye

[Figure 94](#) shows the maximum lateral carbody accelerations for the model and test cases.

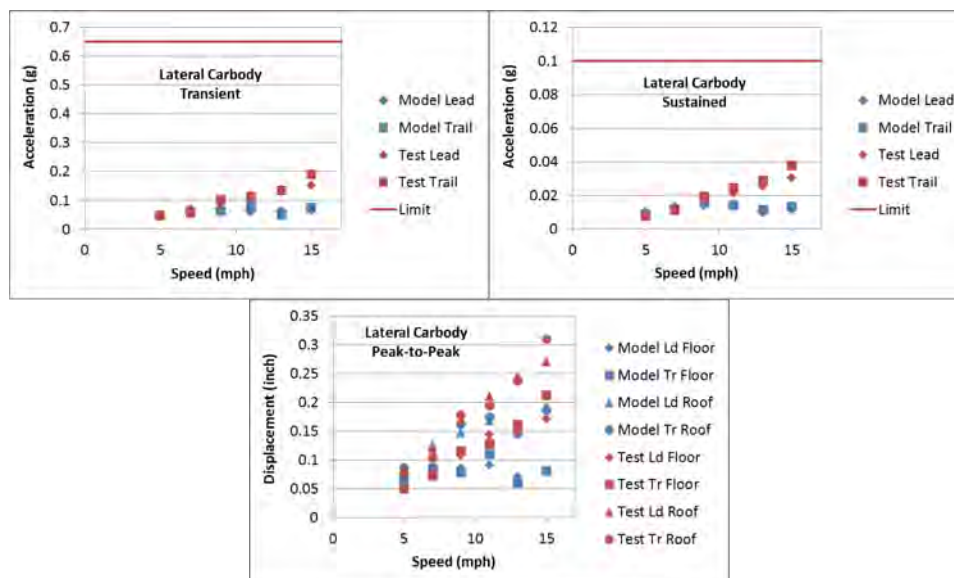


Figure 94. Maximum Peak-to-Peak Carbody Accelerations – URB North Wye

The simulated transient and sustained oscillatory lateral accelerations did not show a significant increasing trend with speed and were slightly lower than the measured values; however, both the model and test values were well below FRA limits. The bottom plot in Figure 57 shows the lateral 2-second peak-to-peak accelerations at the roof and floor of the carbody. The model accelerations matched the measured data more closely at speeds less than 11 mph.

Figure 95 through Figure 97 show time histories of the 7 mph run through the twist and roll test section. For each comparison plot, Sprague and Geers metrics were calculated and displayed at the bottom of each graph. Table 57 and Table 58 list the Sprague and Geers comprehensive error measures for the most important data channels.

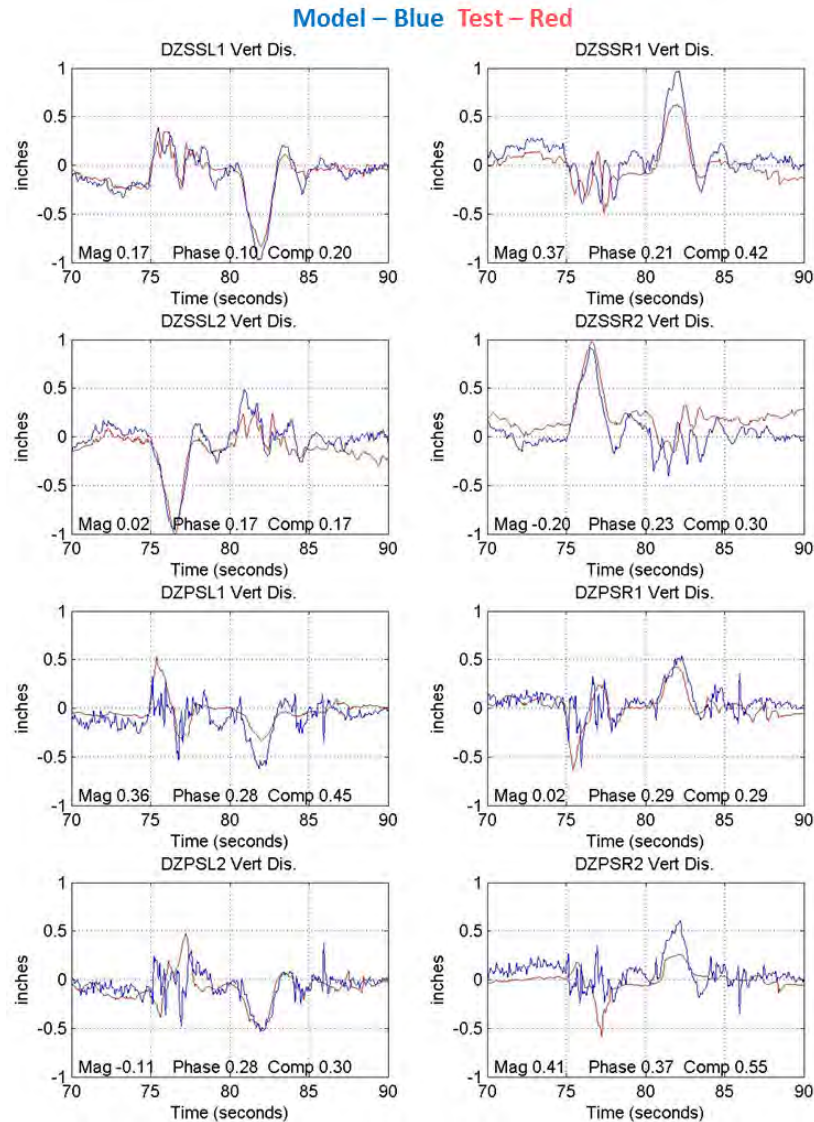


Figure 95. Vertical Primary and Secondary Suspension Displacements – URB North Wye at 7 mph

Vertical displacement plots in Figure 95 show relatively close agreement between the measured and calculated data channels. The magnitude and phase of the model and test data appear to match well, even though the track geometry data lacked important information. Average

comprehensive error measures of the vertical displacement channels ranged from 0.15 to 0.37, as shown in Table 57. According to the recommended scale in Figure 55, these comprehensive metrics indicate a good model fit for the vertical displacement measurements.

Lateral displacement plots in Figure 96 show reasonable model-to-test data agreement, though the channels did not match as closely as the vertical displacement plots. The magnitudes of the model and test are similar, but not identical. Average comprehensive error measures ranged from 0.28 to 0.39, which indicates a good model fit according to Figure 55.

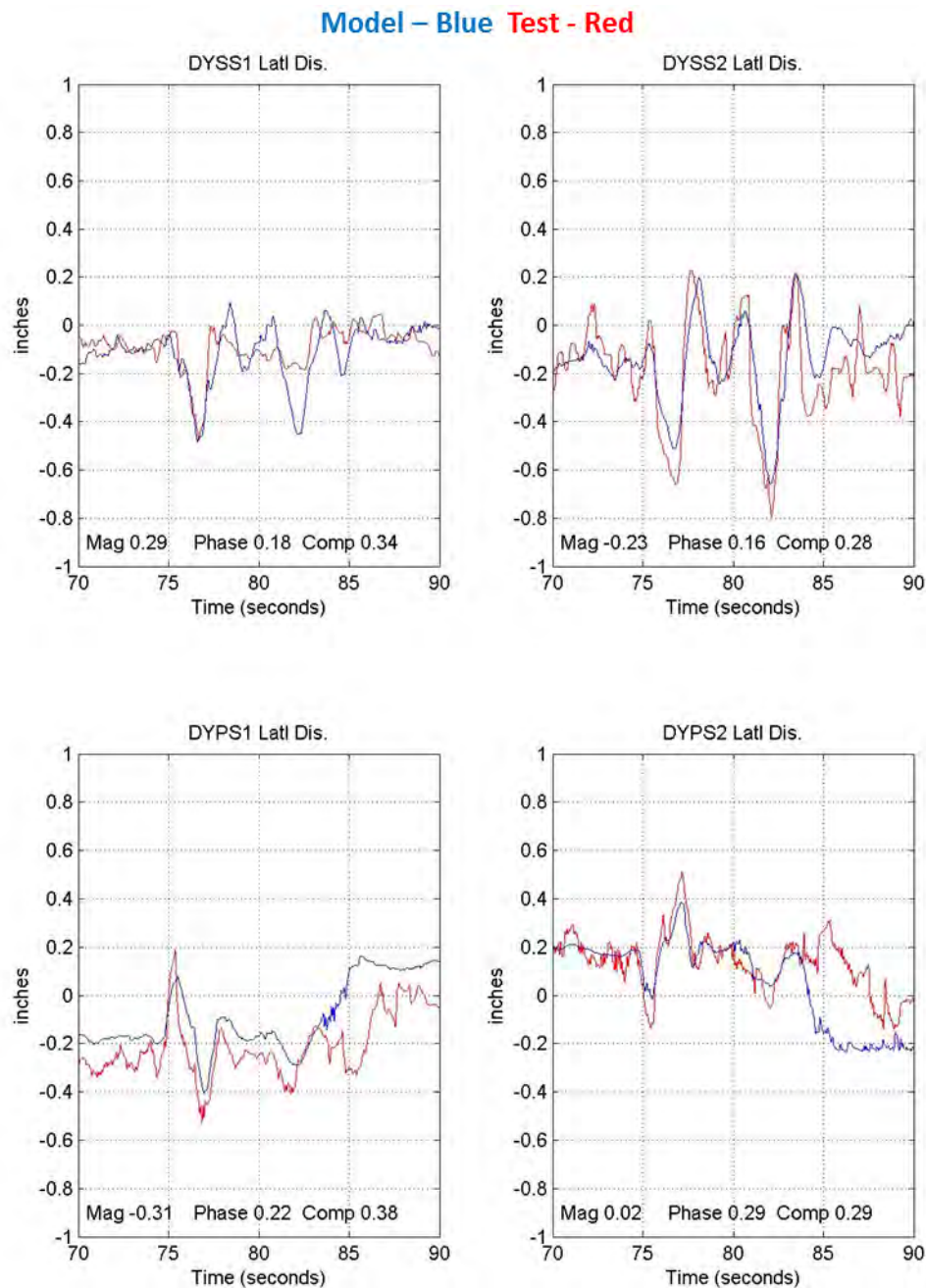


Figure 96. Lateral Primary and Secondary Suspension Displacements – URB North Wye at 7 mph

Lateral carbody acceleration plots in [Figure 97](#) also demonstrated generally good agreement between the measured and calculated data channels, but the magnitudes of the accelerations did not match well. Average comprehensive error measures ranged from 0.32 to 0.44, which fall in an acceptable to marginally acceptable range of the scale in [Figure 55](#). Refer to [Table 39](#) for the detailed channel naming convention.

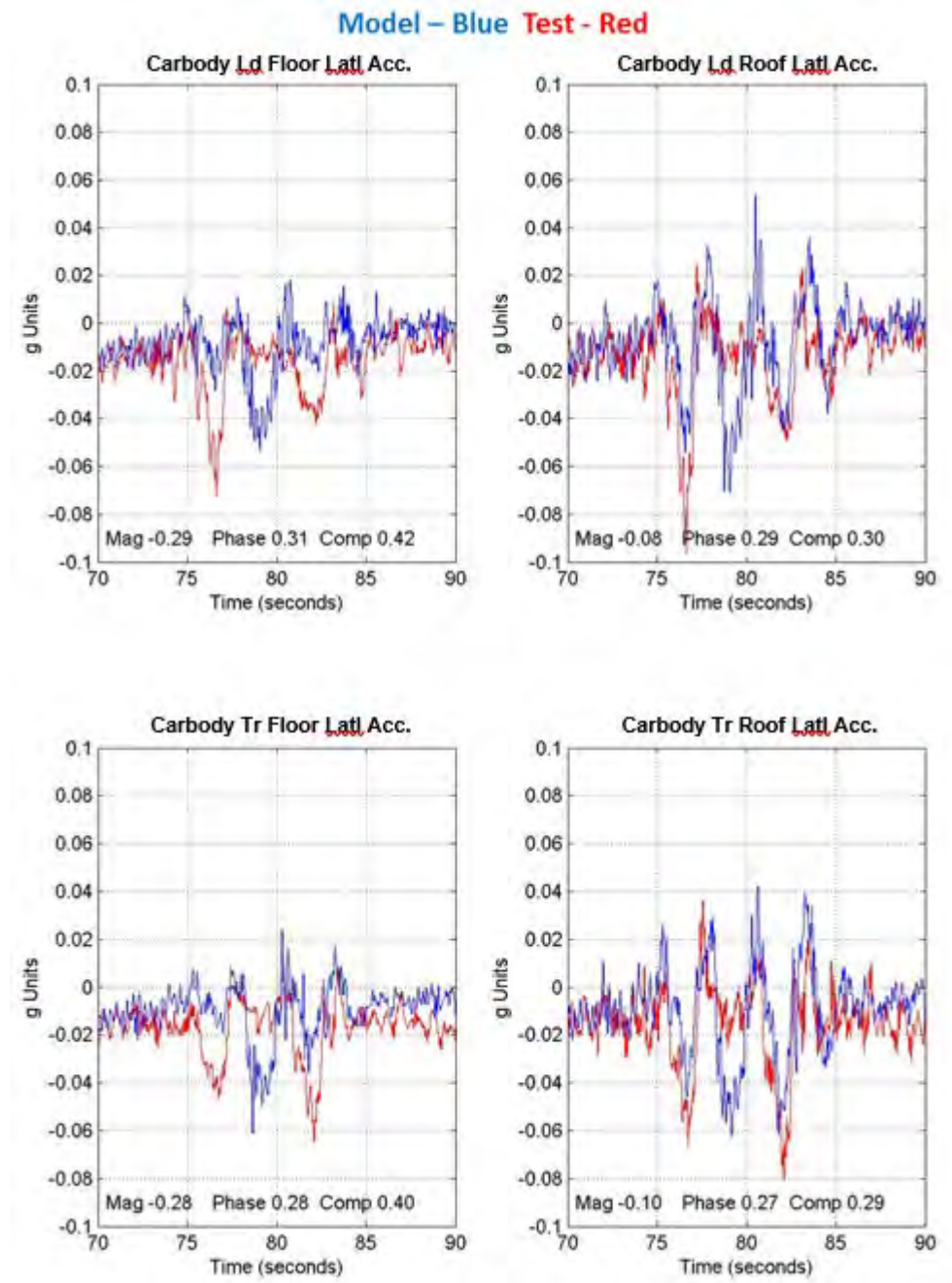


Figure 97. Lateral Carbody Accelerations – URB North Wye at 7 mph

**Table 57. Comprehensive Error Measures for
URB North Wye Suspension Displacements**

Test Run	DZSSL1	DZSSR1	DZSSL2	DZSSR2	DZPSL1	DZPSR1	DZPSL2	DZPSR2	DYSS1	DYSS2	DYPS1	DYPS2
URB-5MPH	0.18	0.24	0.19	0.18	0.31	0.35	0.43	0.38	0.31	0.44	0.50	0.46
URB-7MPH	0.20	0.42	0.17	0.30	0.45	0.29	0.30	0.55	0.34	0.28	0.38	0.29
URB-9MPH	0.14	0.19	0.30	0.19	0.29	0.27	0.25	0.51	0.31	0.23	0.45	0.56
URB-11MPH	0.13	0.16	0.21	0.20	0.28	0.22	0.22	0.39	0.30	0.24	0.26	0.35
URB-13MPH	0.12	0.17	0.18	0.22	0.19	0.24	0.23	0.20	0.22	0.25	0.30	0.34
URB-15MPH	0.13	0.19	0.20	0.22	0.15	0.27	0.21	0.18	0.31	0.21	0.42	0.35
Average	0.15	0.23	0.21	0.22	0.28	0.27	0.27	0.37	0.30	0.28	0.39	0.39

**Table 58. Comprehensive Error Measures for
URB North Wye Carbody Accelerations**

Test Run	AYCBR1	AYCBF1	AYCBR2	AYCBF2
URB-5MPH	0.44	0.39	0.46	0.40
URB-7MPH	0.42	0.30	0.40	0.29
URB-9MPH	0.41	0.25	0.40	0.23
URB-11MPH	0.45	0.26	0.44	0.29
URB-13MPH	0.46	0.35	0.45	0.39
URB-15MPH	0.46	0.35	0.46	0.30
Average	0.44	0.32	0.44	0.32

6.8 Transit Test Track

Results from the TTT test track indicated a good match between the model and test data for both the CW and CCW directions. Results from the test runs are presented separately for each direction.

6.8.1 CW

Figure 98 shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire TTT in the CW direction. Figure 99 shows the maximum carbody and truck accelerations for the model and test cases compared to limiting FRA values. Aside from a few discrepancies in maximum values, model and test data maximums showed similar magnitudes. Because the TTT is 9.1 miles long, plots like this give indications of a vehicle's worst-case performance during a particular test run, but they do not give any indication of where the event occurred. The plots show that the model demonstrated the same trends in data with increases in speed and that vehicle acceleration values were within FRA limits.

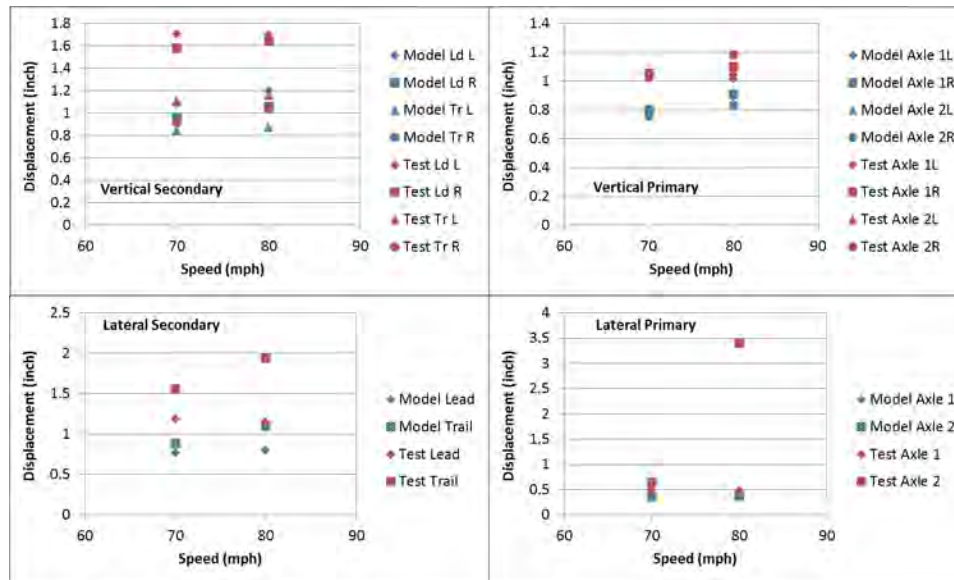


Figure 98. Maximum Peak-to-Peak Suspension Displacements – TTT in CW Direction

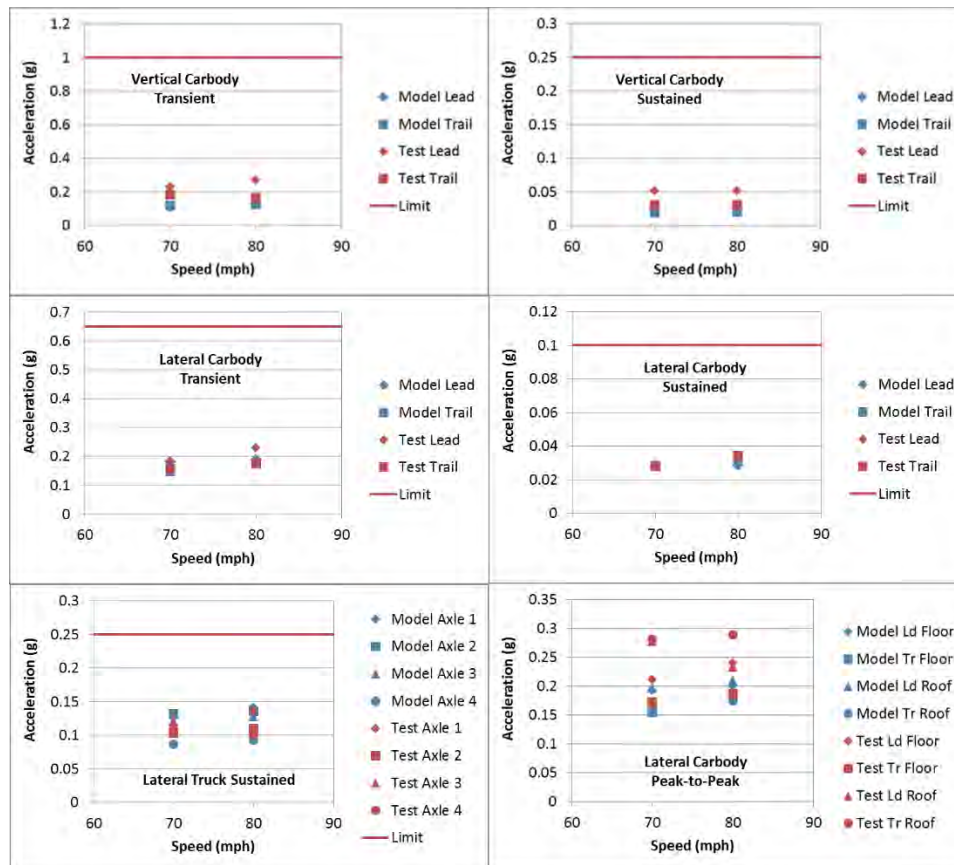


Figure 99. Maximum Peak-to-Peak Accelerations – TTT in CW Direction

To get a better understanding of the measured and simulated vehicle performance, comparisons were also made over a smaller portion of track where the vehicle exhibited less than ideal dynamic behavior. [Figure 100](#) and [Figure 101](#) are time history comparisons of the vertical

suspension displacements and carbody accelerations. This location is a section of tangent track containing a 0.5-inch dip in profile on both the left and right rails. This dip in profile excited the vertical modes of the car, resulting in elevated but relatively low vehicle response measurements. When vehicle response measurements of a car are small, Sprague and Geers error measures tend to be overly high and misleading, because the maximum response measurements do not differ enough from the average performance values. In a scenario like this, sound engineering judgment is crucial to the fair assessment of a model. For the TTT test runs, the model matches the frequency response and general trends, but underestimates the peak-to-peak and maximum values of suspension displacement and carbody acceleration. These results imply that the model is likely to underestimate the maximum and minimum vertical wheel-rail forces at this location. These results also suggest that the model may have too much vertical damping. [Table 59](#) and [Table 60](#) list Sprague and Geers comprehensive error measures for the vertical displacement and acceleration channels, calculated only for the section containing the perturbation on the TTT. Refer to [Table 39](#) for the detailed channel naming convention.

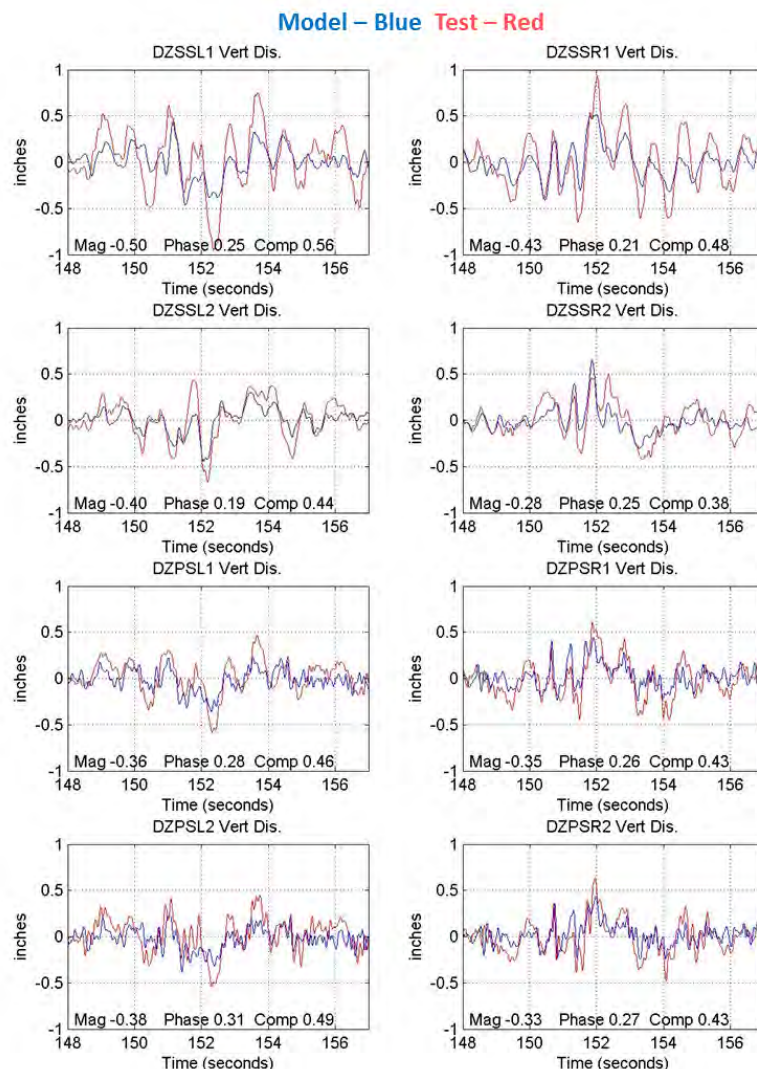


Figure 100. Vertical Primary and Secondary Suspension Displacements – TTT 70 mph in CW Direction

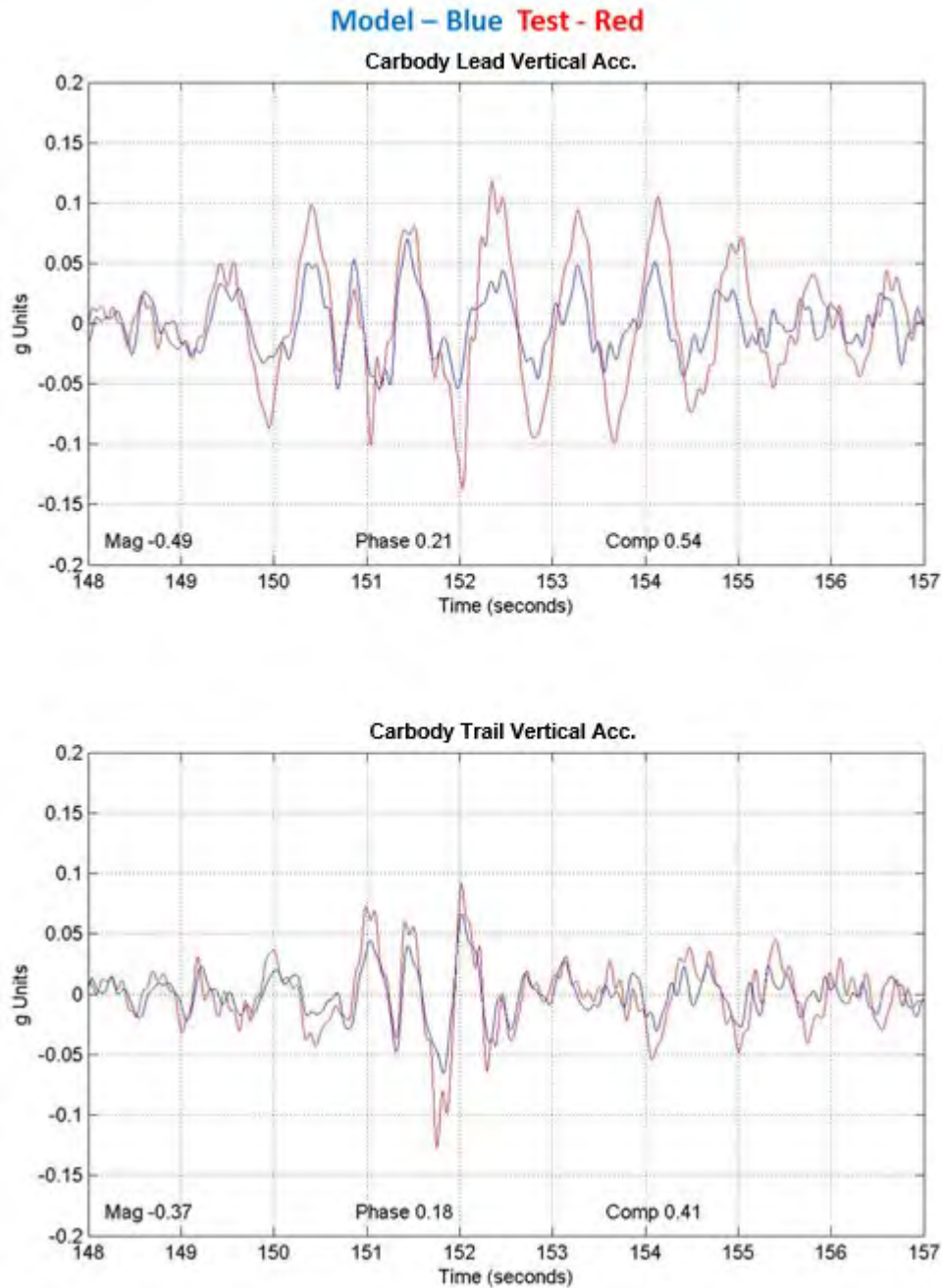


Figure 101. Vertical Carbody Accelerations – TTT 70 mph in CW Direction

During the on track tests performed on the TTT and RTT, the lateral truck accelerations measured at Axle 1 were inconsistent. The data exhibited frequent dropouts and offsets throughout the test runs that were not seen with the other wheelsets. These results indicated that a problem existed with the accelerometer or instrumentation cabling at Axle 1. The acceleration measurements at Axle 1 were excluded from the remaining analysis for this reason. [Figure 102](#) shows the questionable data of Axle1 compared to the data of the other three axles.

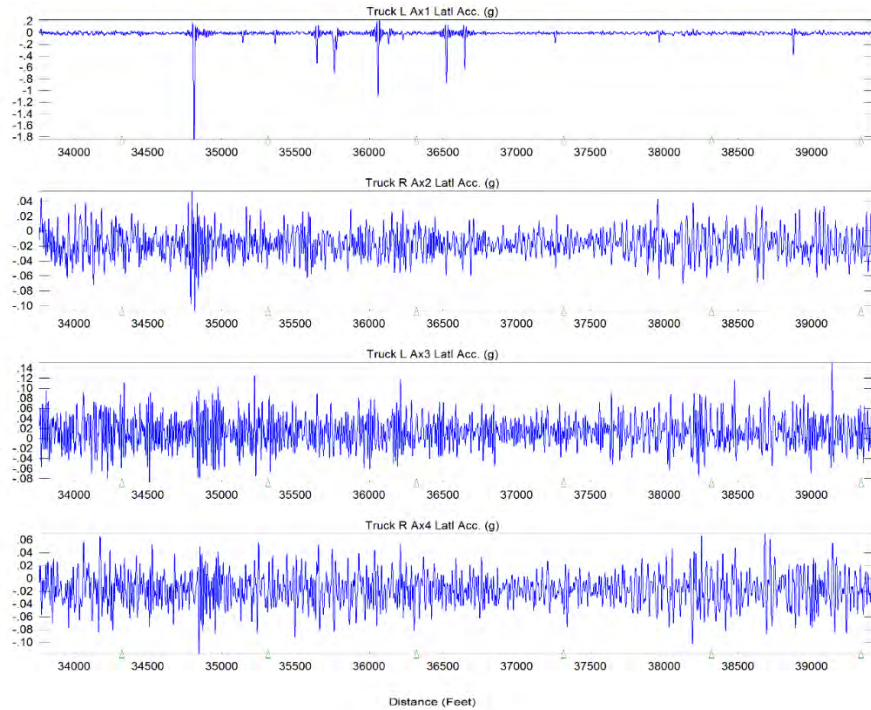


Figure 102. Issues with Axle 1 Lateral Accelerations

6.8.2 CCW

Figure 103 shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire TTT in the CCW direction. Figure 104 shows maximum carbody and truck accelerations for the model and test cases compared to limiting FRA values. Model and test data demonstrated the same trends with increases in speed and had similar maximum values. All model and test vehicle acceleration values were within FRA limits. Refer to Table 39 for the detailed channel naming convention.

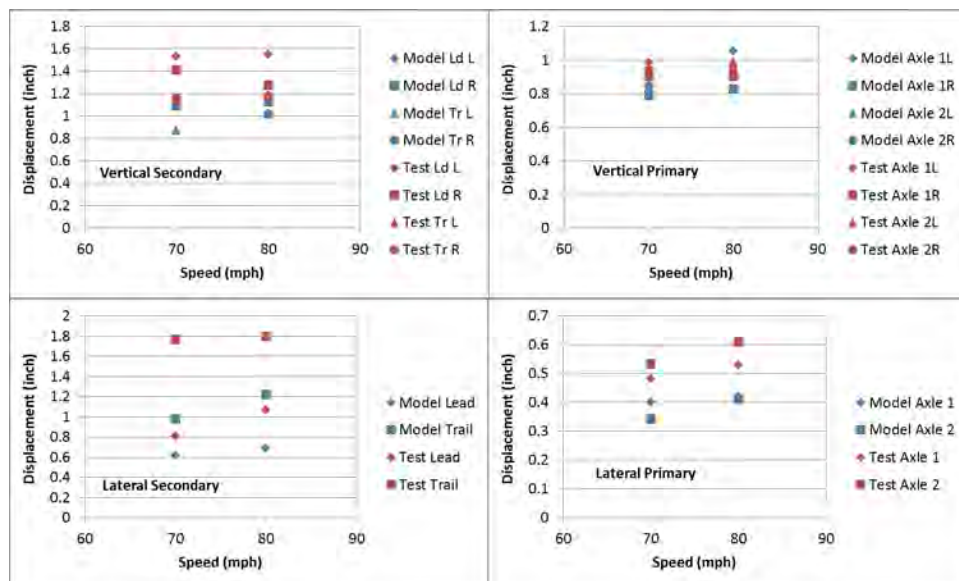


Figure 103. Maximum Peak-to-Peak Suspension Displacements – TTT in CCW Direction

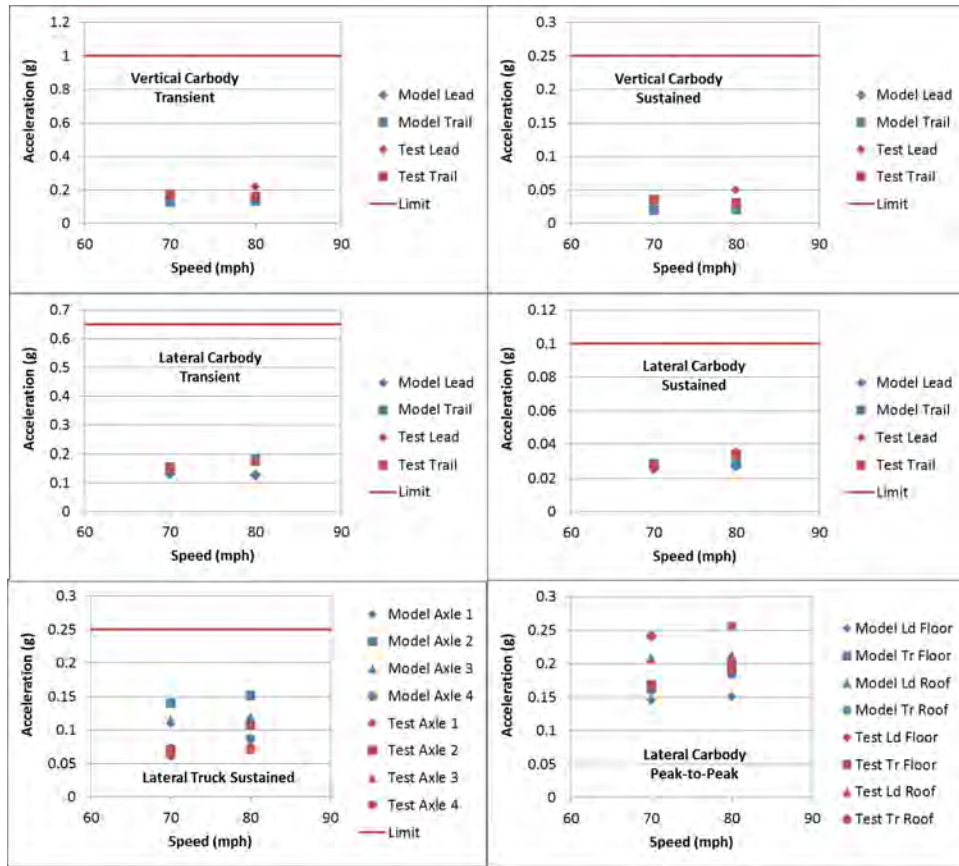


Figure 104. Maximum Peak-to-Peak Accelerations – TTT in CCW Direction

Figure 105 and Figure 106 are time history comparisons of the vertical suspension displacements and carbody accelerations, respectively. Suspension displacement channels matched reasonably well in both CW and CCW directions. Average comprehensive error measures for the displacement channels ranged from 0.37 to 0.49, which fall in the acceptable to marginally acceptable range. Carbody accelerations show about the same level of agreement in both CW and CCW directions. Average comprehensive error measures for the carbody acceleration channels ranged from 0.39 to 0.49, which indicates acceptable to marginally acceptable model performance. Table 59 and Table 60 list Sprague and Geers comprehensive error measures for the vertical displacement and acceleration channels, calculated only for the section containing the perturbation on the TTT. Refer to Table 39 for the detailed channel naming convention.

Model – Blue Test - Red

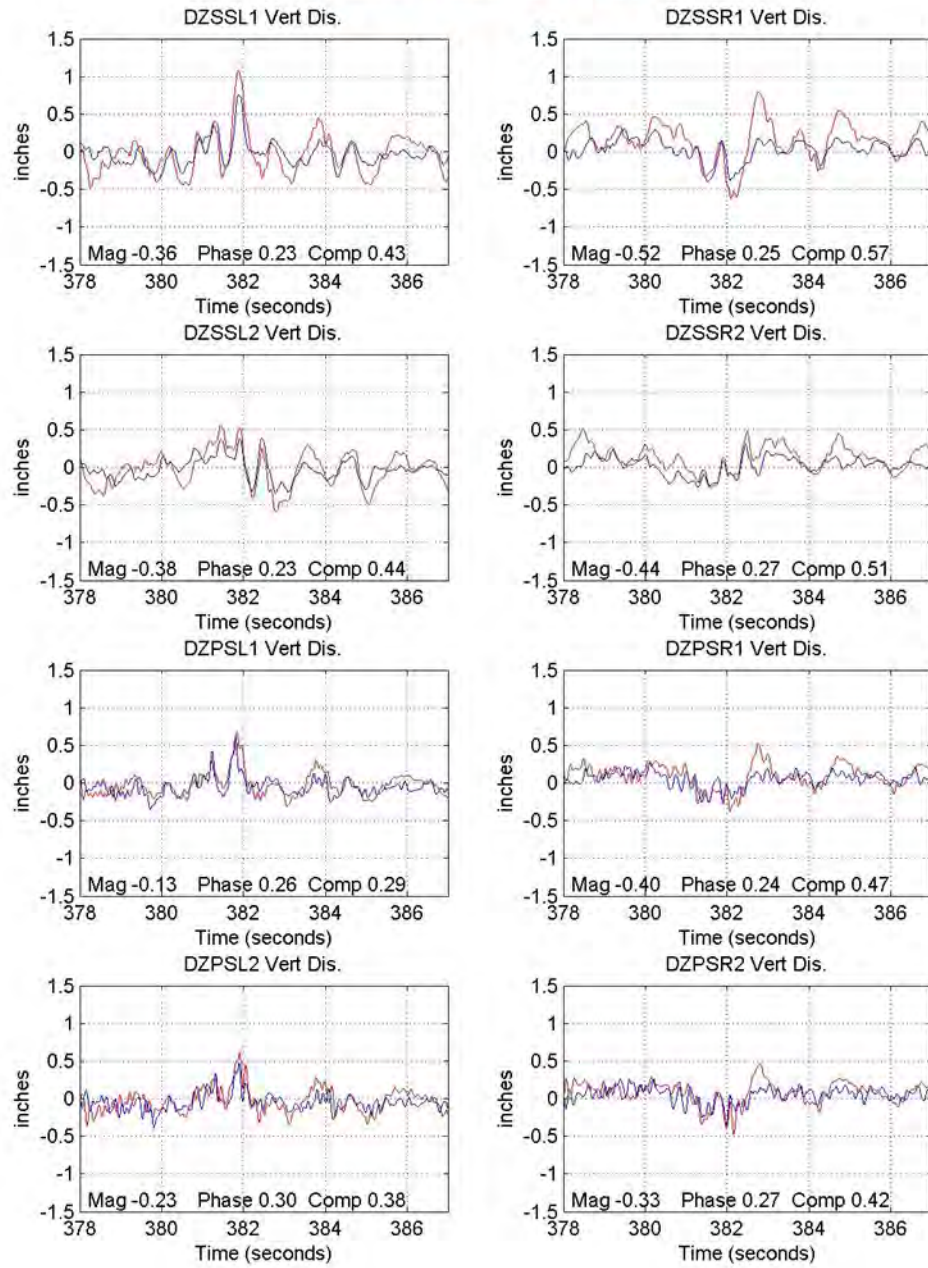


Figure 105. Vertical Primary and Secondary Suspension Displacements – TTT 70 mph in CCW Direction

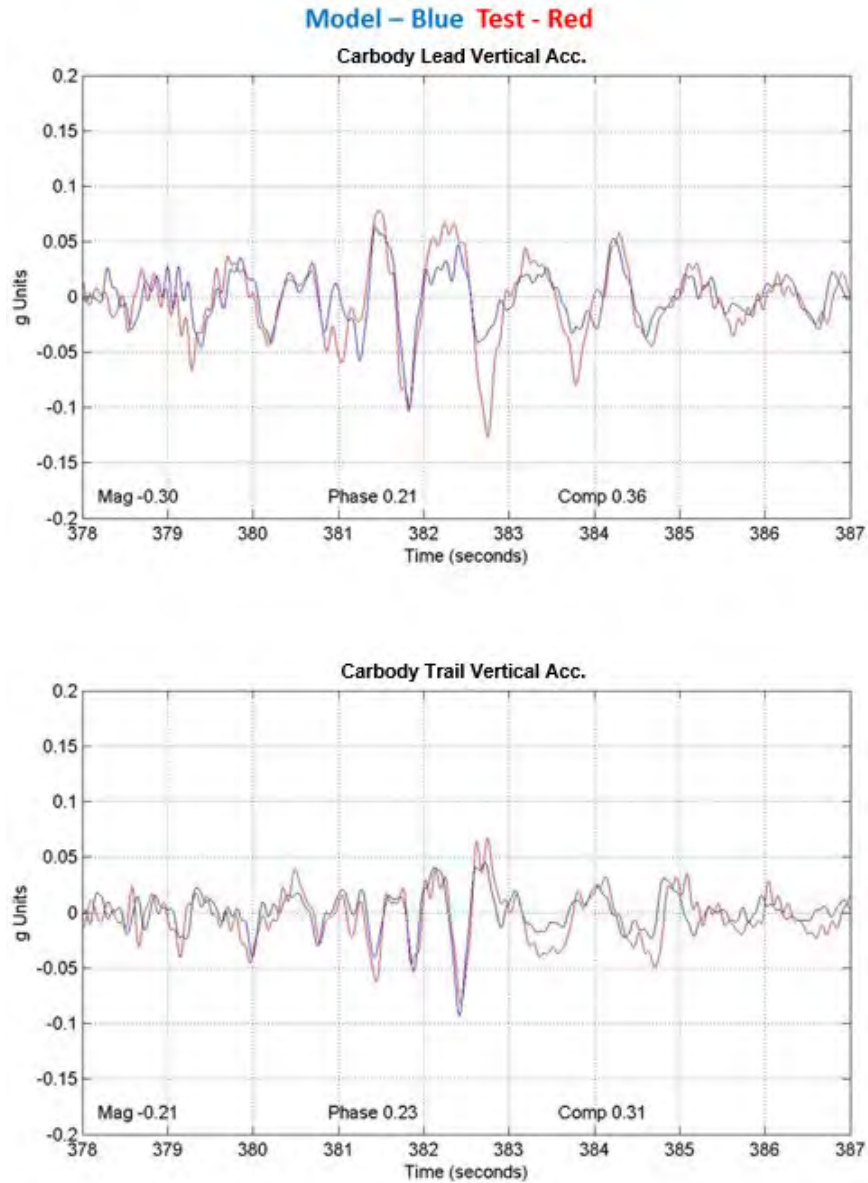


Figure 106. Vertical Carbody Accelerations – TTT 70 mph in CCW Direction

Table 59. Comprehensive Error Measures for TTT Suspension Displacements

Test Run	DZSSL1	DZSSR1	DZSSL2	DZSSR2	DZPSL1	DZPSR1	DZPSL2	DZPSR2
TTT_CW-70MPH	0.56	0.48	0.44	0.38	0.46	0.43	0.49	0.43
TTT_CW-80MPH	0.53	0.44	0.48	0.42	0.42	0.38	0.47	0.39
TTT_CCW-70MPH	0.43	0.57	0.44	0.51	0.29	0.47	0.38	0.42
TTT_CCW-80MPH	0.45	0.48	0.36	0.39	0.29	0.36	0.35	0.37
Average	0.49	0.49	0.43	0.43	0.37	0.41	0.42	0.40

Table 60. Comprehensive Error Measures for TTT Carbody Accelerations

Test Run	AZCBF1	AZCBF2
TTT_CW-70MPH	0.54	0.41
TTT_CW-80MPH	0.55	0.42
TTT_CCW-70MPH	0.36	0.31
TTT_CCW-80MPH	0.52	0.40
Average	0.49	0.39

6.9 Railroad Test Track

Results from the RTT test track showed good agreement between the model and test results in both the CW and CCW directions and with both ends of the vehicle in the leading position. In the following sections, results from the test run comparisons are presented separately for each direction and leading end of the vehicle.

6.9.1 CW

Observation End Leading

Figure 107 shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire RTT in the CW direction with the observation end of the car leading. Figure 108 shows the maximum carbody and truck accelerations for the model and test cases compared to limiting FRA values. Like the TTT test comparisons, the plots below show the worst-case maximum values observed during the test on the 13-mile RTT track. They do not give details regarding specific vehicle performance issues. Instead, they help demonstrate general trends in the data and worst-case performance of the vehicle.

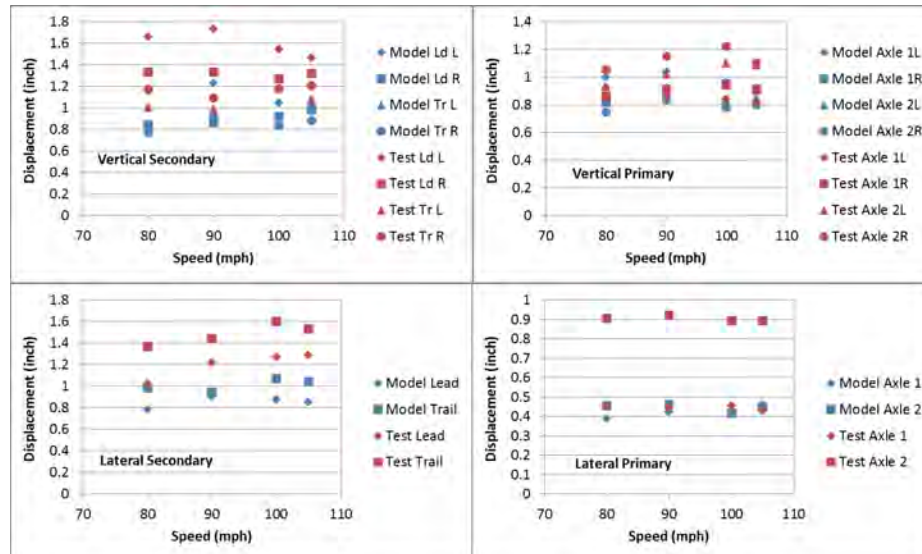


Figure 107. Maximum Peak-to-Peak Suspension Displacements – RTT in CW Direction with Observation End Leading

Model and test suspension displacements in Figure 107 exhibited the same general trends as speed was increased; however, the maximum model displacements tended to be less than the

measured values, and as with other test regimes, the trailing truck measured lateral displacements were larger than the leading truck.

Model and test carbody accelerations in Figure 108 also display similar data trends and maximum values in both the lateral and vertical directions. Lateral sustained truck accelerations were similar for all test runs in the simulated and measured data. No data is provided for the accelerometer near Axle 1, because the transducer and/or cabling proved to be faulty during all RTT runs.

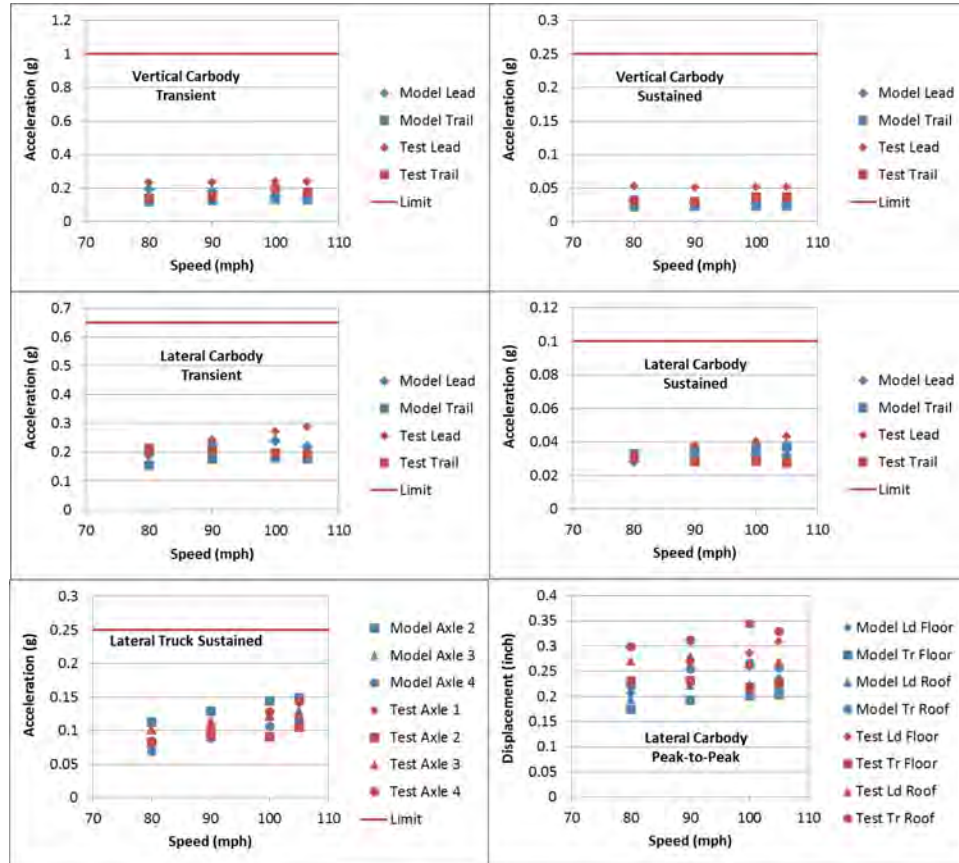


Figure 108. Maximum Peak-to-Peak Accelerations – RTT in CW Direction with Observation End Leading

For tests on the RTT, performance was also compared over a short section of track on one of the 0.86-degree curves. This track section contained a 0.5-inch alignment deviation toward the outside of the curve on both rails and a 0.5-inch dip in profile on the high rail. The geometry deviation helped excite lateral and roll responses in the car. Figure 109 through Figure 111 contain time history comparisons of the suspension displacement and carbody acceleration responses due to this geometry deviation. Table 61 and Table 62 list Sprague and Geers comprehensive error measures for suspension displacement and carbody acceleration responses. Model and test data exhibit a similar response when subjected to input from the geometry deviation, although the lateral displacements of the lead truck secondary suspension and primary suspension on Axle 2 show a noticeable oscillatory response that is not seen in the model, and that had occurred previous to the track perturbation. This oscillatory response is also visible in

the left and right sides of Axle 2 primary vertical suspension. Refer to [Table 39](#) for the detailed channel naming convention.

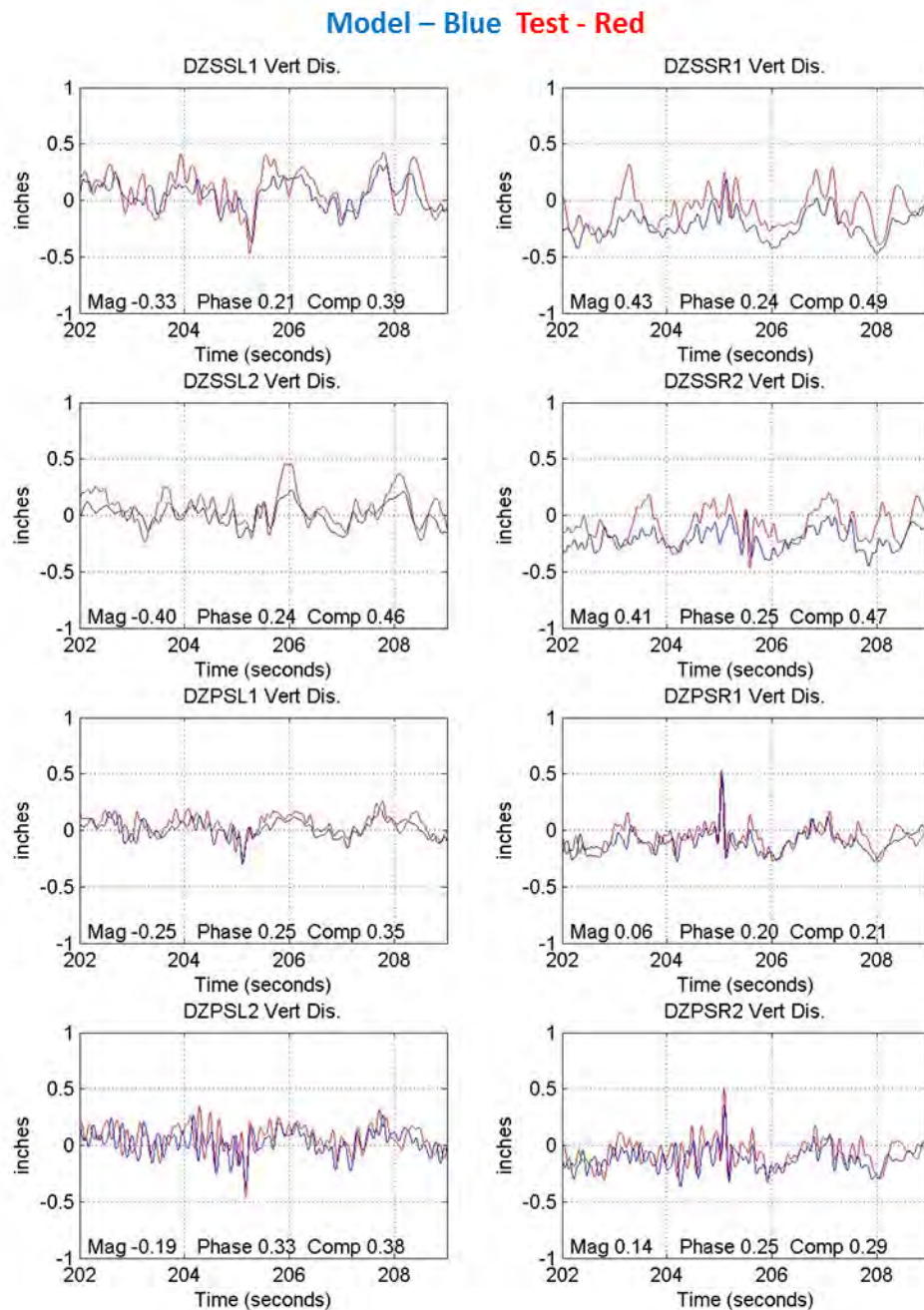


Figure 109. Vertical Primary and Secondary Suspension Displacements – RTT 105 mph in CW Direction with Observation End Leading

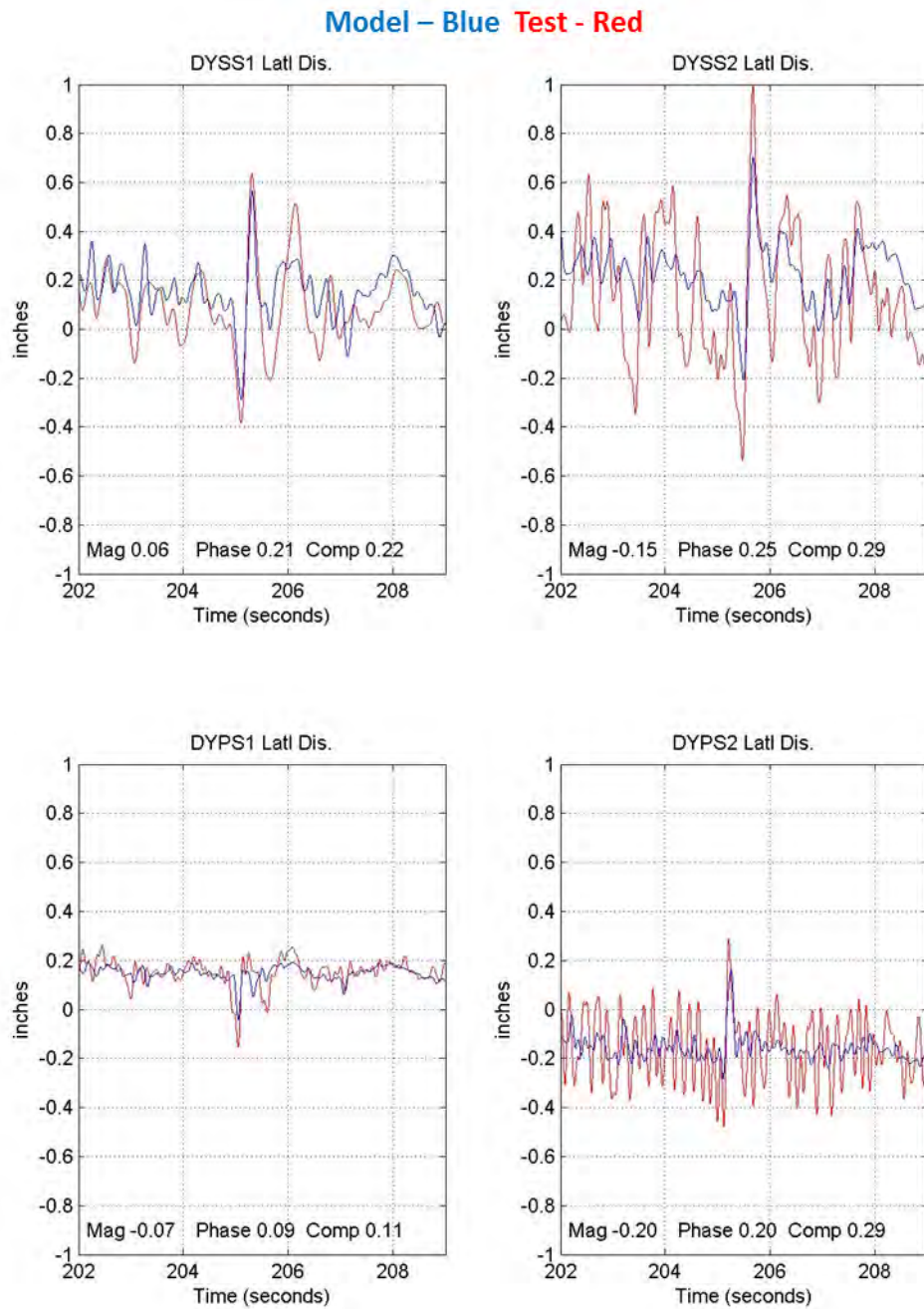


Figure 110. Lateral Primary and Secondary Suspension Displacements – RTT 105 mph in CW Direction with Observation End Leading

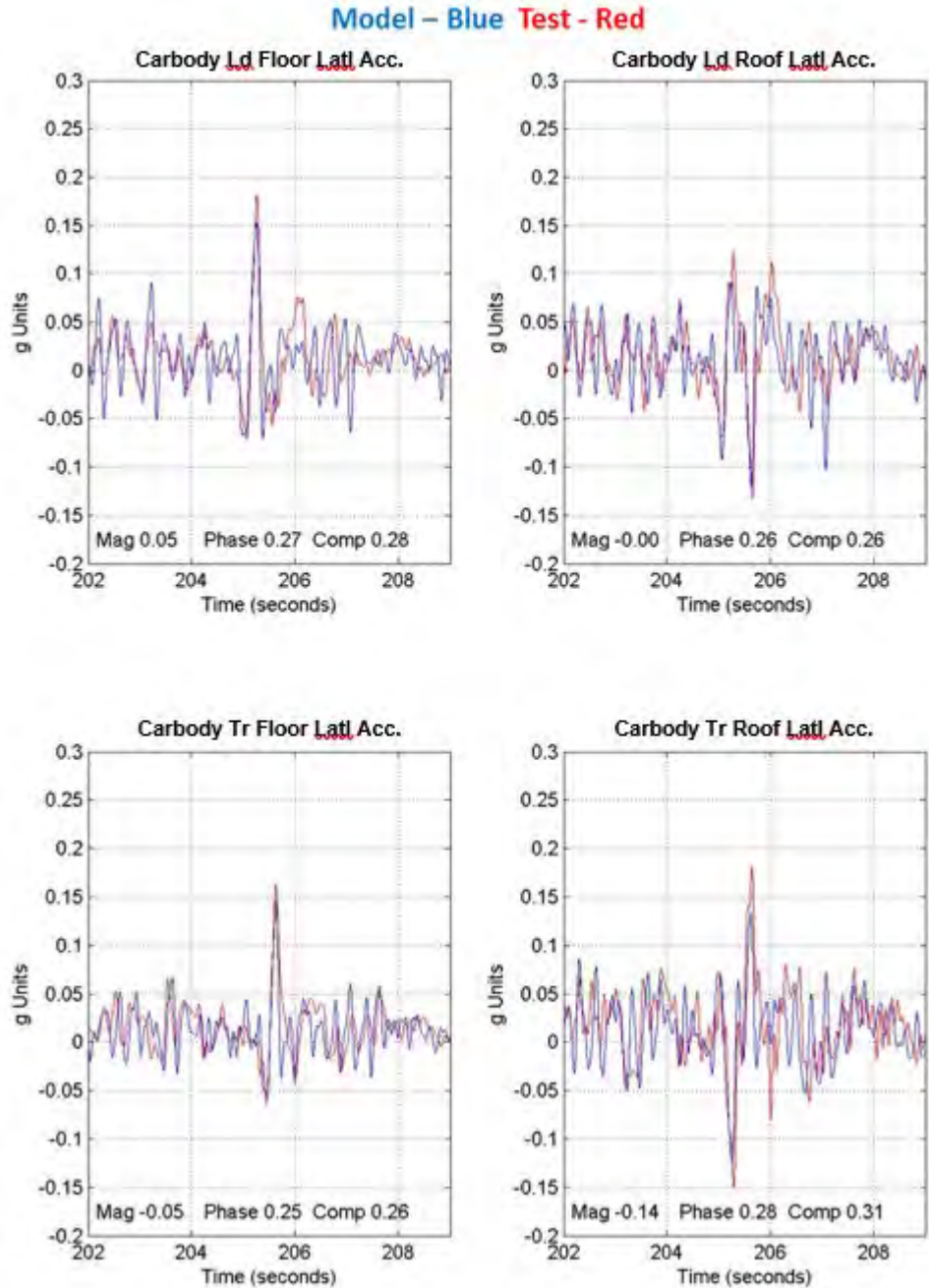


Figure 111. Vertical Carbody Accelerations – RTT 105 mph in CW Direction with Observation End Leading

Vestibule End Leading

With the orientation of the car reversed (i.e., vestibule end leading), the model and test data still showed good agreement for the various measurements during test runs in the CW direction. [Figure 112](#) shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire RTT in the CW direction with the vestibule end of the car leading. [Figure 113](#) describes the maximum carbody and truck accelerations for the model and test cases compared to limiting FRA values. Model and test suspension displacements exhibited the same

general trends as speed was increased and similar displacement magnitudes. However, in this case, the vestibule end was in the leading position, and as with other test regimes, it showed secondary suspension lateral displacements that are larger than the observation end truck. This result implies that the differences between model and test are due to different suspension characteristics at the two ends of the car.

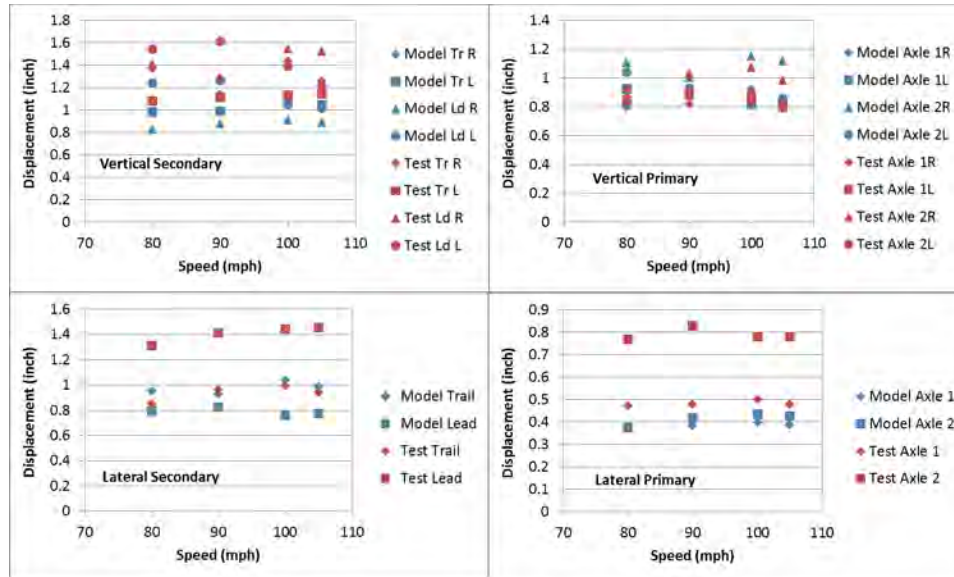


Figure 112. Maximum Peak-to-Peak Suspension Displacements – RTT in CW Direction with Vestibule End Leading

Figure 113 shows that simulated and measured carbody and truck accelerations had similar maximum values and displayed similar trends as speed increases. These values were also within FRA specifications. No data is provided for the accelerometer near Axle 1, because the transducer and/or cabling proved to be faulty during all RTT runs.

Figure 114 through Figure 116 illustrate time history comparisons of the suspension displacement and carbody acceleration responses due to the previously mentioned track geometry perturbation. Table 61 and Table 62 list the Sprague and Geers comprehensive error measures for the suspension displacement and carbody acceleration responses. Again, the model and test data exhibit a similar response when subjected to input from the geometry deviation. The average comprehensive error measures for the vertical displacement channels ranged from 0.24 to 0.42, which indicates acceptable model-to-test agreement. Average comprehensive error measures for the lateral displacement channels ranged from 0.22 to 0.56, which borders on the edge of unacceptable performance. Average comprehensive error measures for the carbody acceleration channels ranged from 0.21 to 0.25, which indicates excellent model performance according to Figure 55, although the lateral displacements of the lead truck secondary suspension and primary suspension on Axle 2 show a noticeable oscillatory response that is not seen in the model, and that was occurring before the track perturbation. This oscillatory response is also slightly noticeable in the corresponding primary vertical suspension. Refer to Table 39 for the detailed channel naming convention.

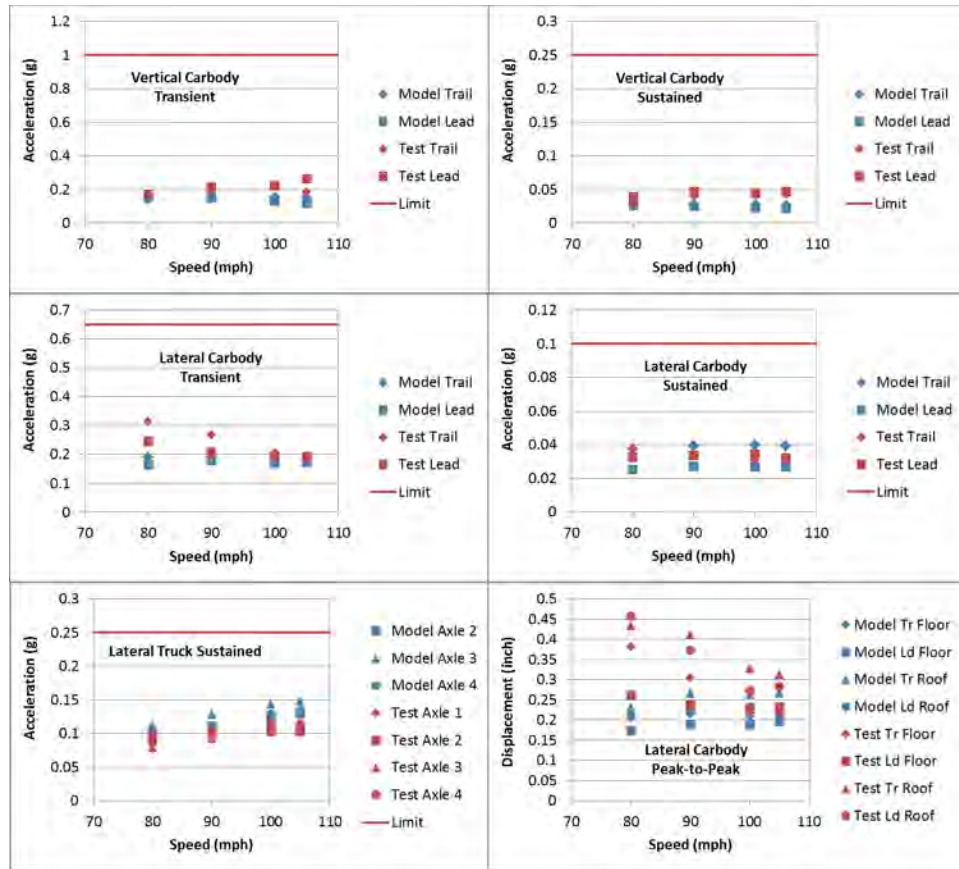


Figure 113. Maximum Peak-to-Peak Accelerations – RTT in CW Direction with Vestibule End Leading

Model – Blue Test - Red

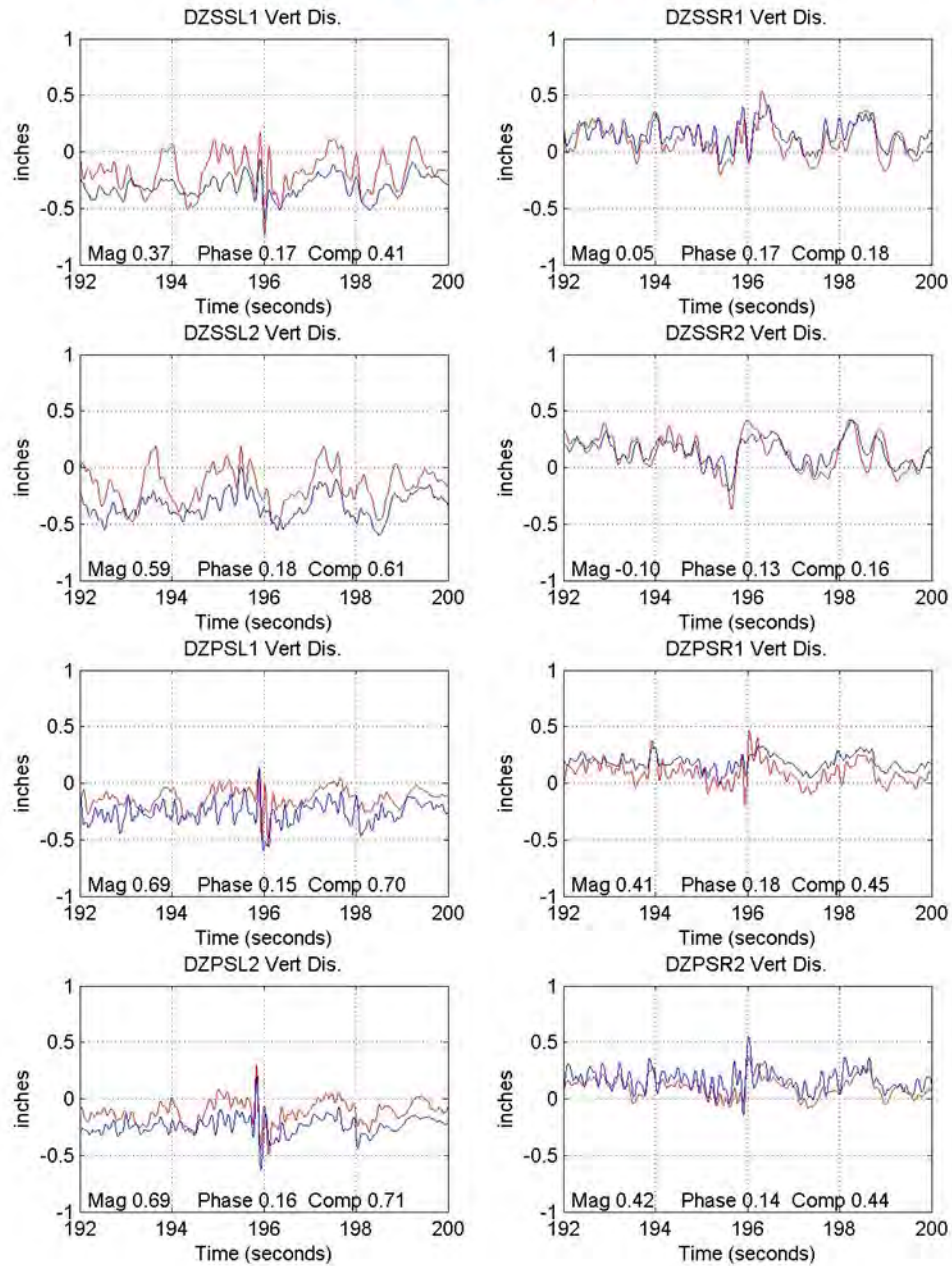


Figure 114. Vertical Primary and Secondary Suspension Displacements – RTT 100 mph in CW Direction with Vestibule End Leading

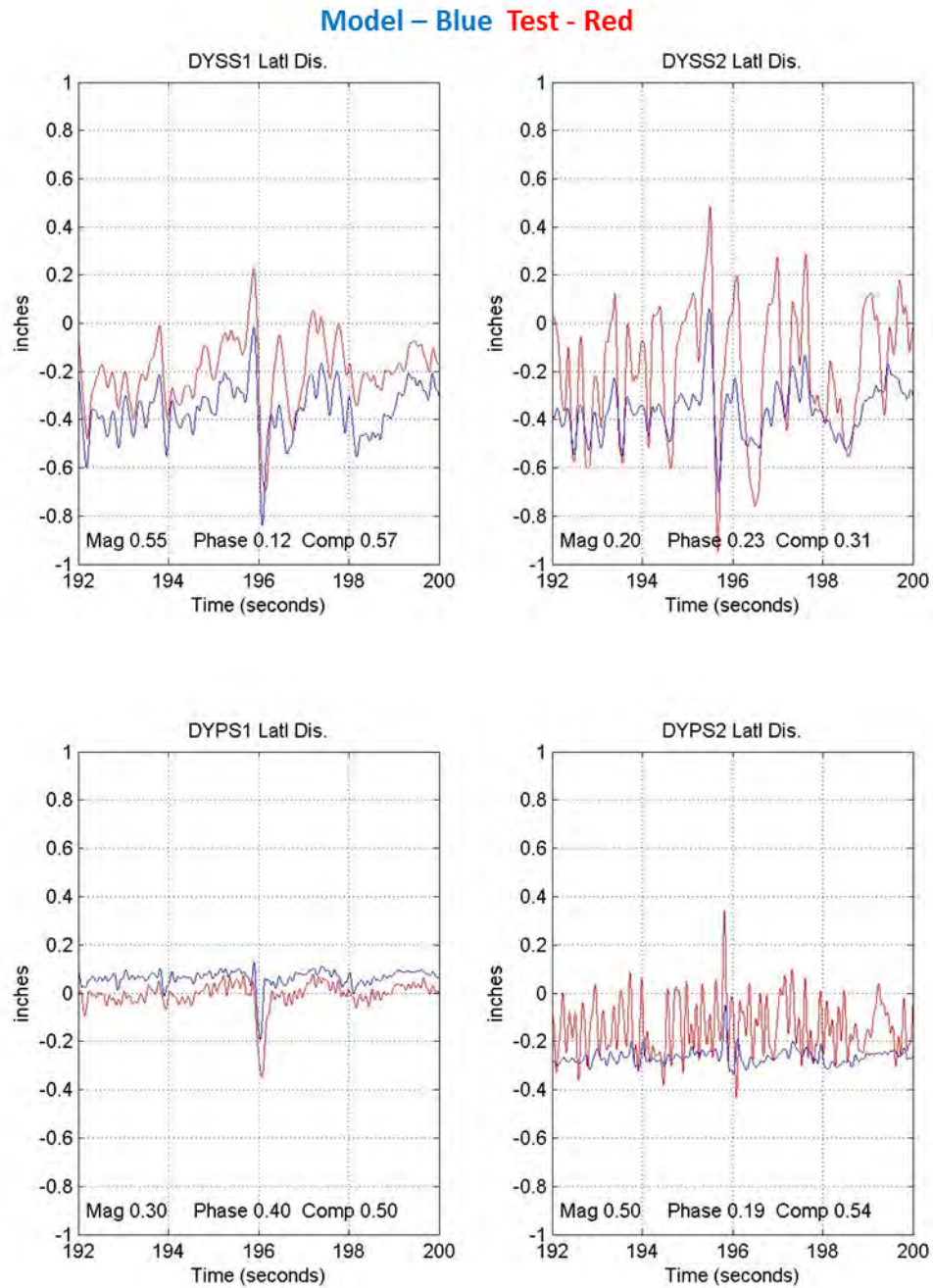


Figure 115. Lateral Primary and Secondary Suspension Displacements – RTT 100 mph in CW Direction with Vestibule End Leading

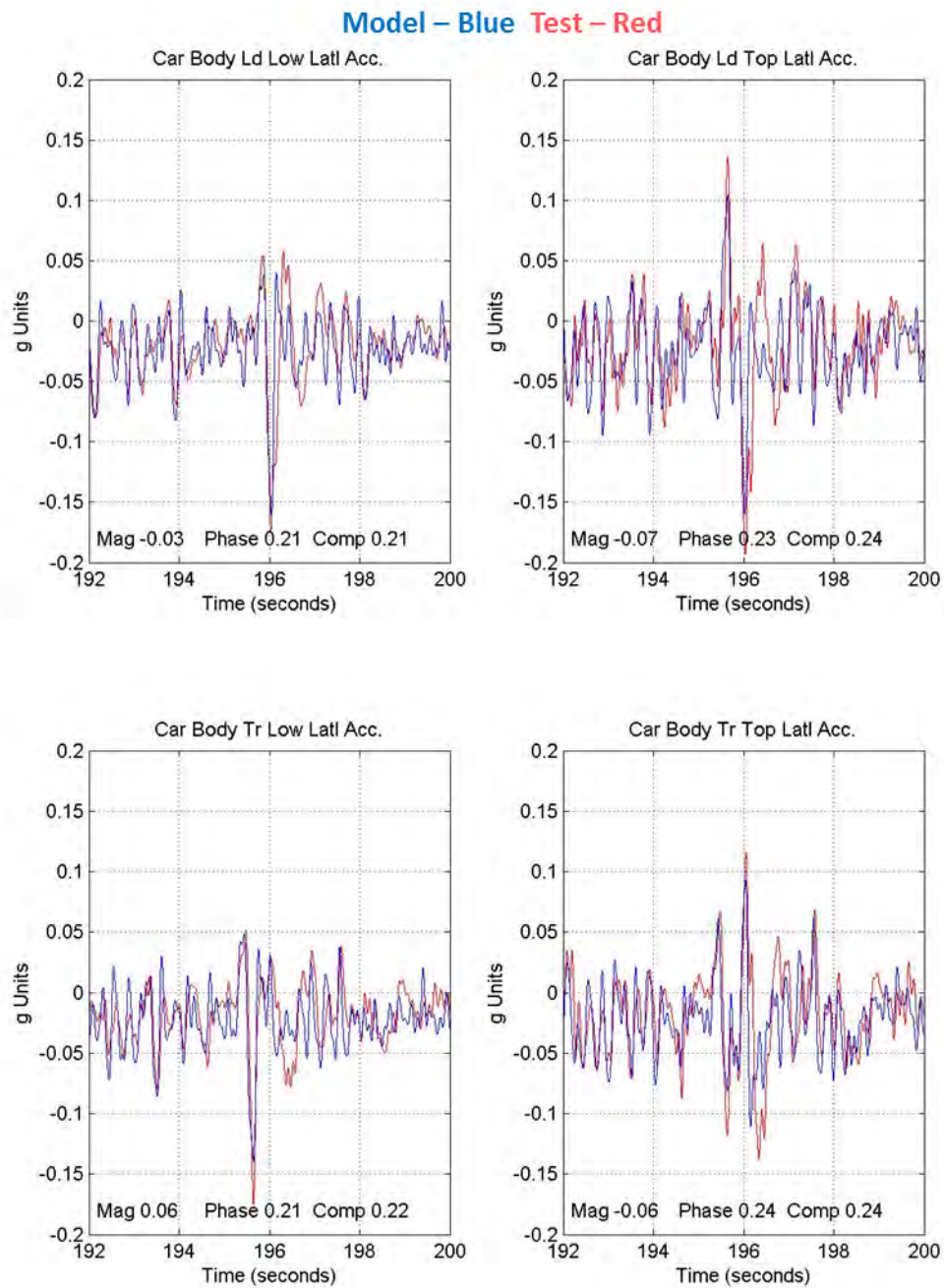


Figure 116. Lateral Carbody Accelerations – RTT 100 mph in CW Direction with Vestibule End Leading

Table 61. Comprehensive Error Measures for RTT Suspension Displacements in CW Direction

Test Run		DZSSL 1	DZSSR 1	DZSSL 2	DZSSR 2	DZPSL 1	DZPSR 1	DZPSL 2	DZPSR 2	DYSS 1	DYSS 2	DYPS 1	DYPS 2
Observation End Leading	RTT_C W-80MPH	0.23	0.40	0.18	0.27	0.05	0.12	0.07	0.20	0.12	0.09	0.47	0.70
	RTT_C W-90MPH	0.28	0.45	0.21	0.40	0.14	0.15	0.17	0.23	0.16	0.10	0.36	0.69
	RTT_C W-100MPH	0.19	0.32	0.26	0.84	0.16	0.14	0.22	0.22	0.32	0.26	0.20	0.38
	RTT_C W-105MPH	0.39	0.49	0.46	0.47	0.35	0.21	0.38	0.29	0.22	0.29	0.11	0.29
Vestibule End Leading	RTT_C W-80MPH	0.27	0.08	0.57	0.10	0.33	0.14	0.28	0.13	0.57	0.07	0.65	0.70
	RTT_C W-90MPH	0.47	0.80	0.48	0.20	0.64	0.26	0.58	0.25	0.57	0.18	0.64	0.73
	RTT_C W-100MPH	0.41	0.18	0.61	0.16	0.70	0.45	0.71	0.44	0.57	0.31	0.50	0.54
	RTT_C W-105MPH	0.55	0.30	0.47	0.40	0.70	0.41	0.92	0.56	0.61	0.44	0.22	0.41
Average		0.35	0.38	0.41	0.36	0.38	0.24	0.42	0.29	0.39	0.22	0.39	0.56

Table 62. Comprehensive Error Measures for RTT Carbody Accelerations in CW Direction

Test Run		AYCBR1	AYCBF1	AYCBR2	AYCBF2
Observation End Leading	RTT_CW-80MPH	0.18	0.19	0.18	0.18
	RTT_CW-90MPH	0.18	0.19	0.19	0.21
	RTT_CW-100MPH	0.25	0.24	0.19	0.25
	RTT_CW-105MPH	0.28	0.26	0.26	0.31
Vestibule End Leading	RTT_CW-80MPH	0.23	0.23	0.19	0.24
	RTT_CW-90MPH	0.23	0.25	0.20	0.25
	RTT_CW-100MPH	0.21	0.24	0.22	0.24
	RTT_CW-105MPH	0.27	0.30	0.24	0.28
Average		0.23	0.24	0.21	0.25

6.9.2 CCW

Observation End Leading

Figure 117 shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire RTT in the CCW direction with the observation end of the car leading. Figure 118 shows maximum carbody and truck accelerations for the model and test cases compared to limiting FRA values. Like test cases in the CW direction, model and test suspension displacements displayed the similar maximum values and general trends with increasing speeds. The plots also show that the model and tests displacement magnitudes are similar, though the model maximum values are slightly lower. As discussed in Section 6.2, the discrepancy between model and test lateral displacements may be due to modeling assumptions.

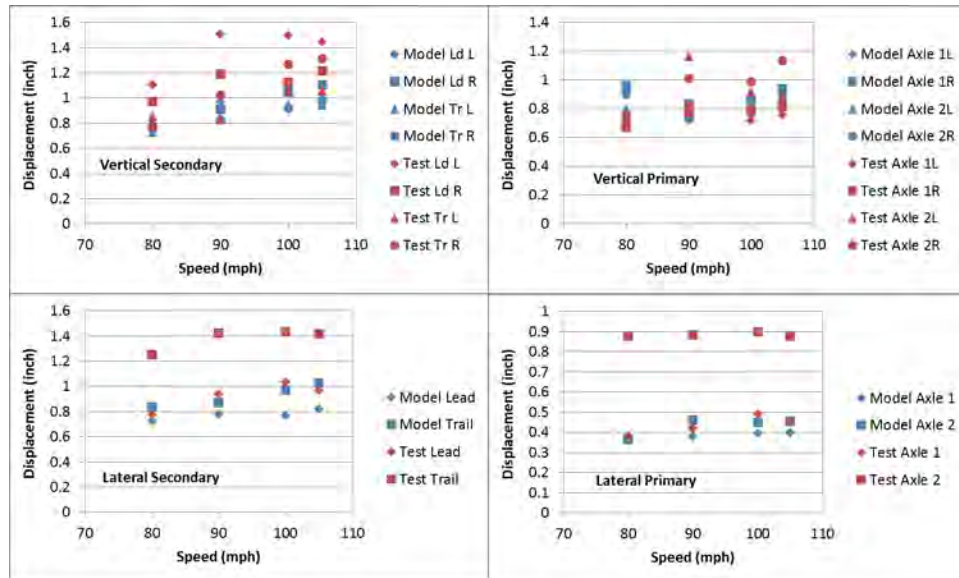


Figure 117. Maximum Peak-to-Peak Suspension Displacements – RTT in CCW Direction with Observation End Leading

Simulated and measured carbody and truck accelerations also had similar maximum values, except for truck accelerations at Axle 1. Acceleration measurements displayed similar trends with increases in speed, and the values were well within FRA specifications.

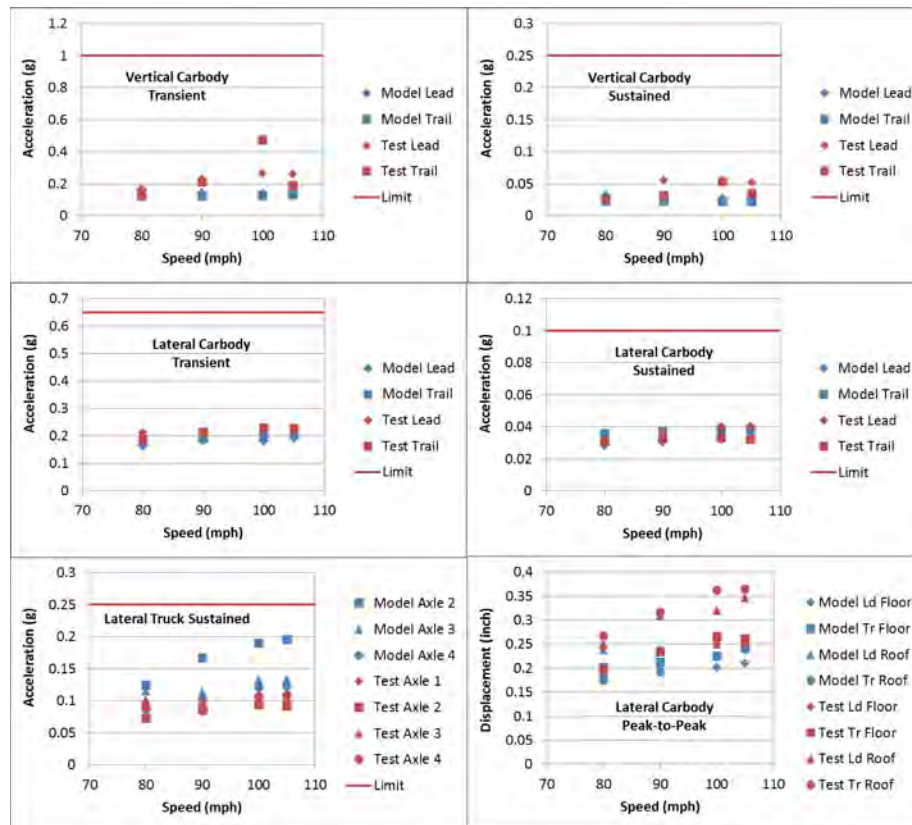


Figure 118. Maximum Peak-to-Peak Accelerations – RTT in CCW Direction with Observation End Leading

Figure 119 through Figure 121 show time history comparisons of the suspension displacement and carbody acceleration responses due to the 0.5-inch alignment and 0.5-inch profile geometry deviation. Table 63 and Table 64 list Sprague and Geers comprehensive error measures for suspension displacement and carbody acceleration responses. Model and test vehicles responded similarly, in phase and magnitude, to input from the geometry deviation. Refer to Table 39 for the detailed channel naming convention.

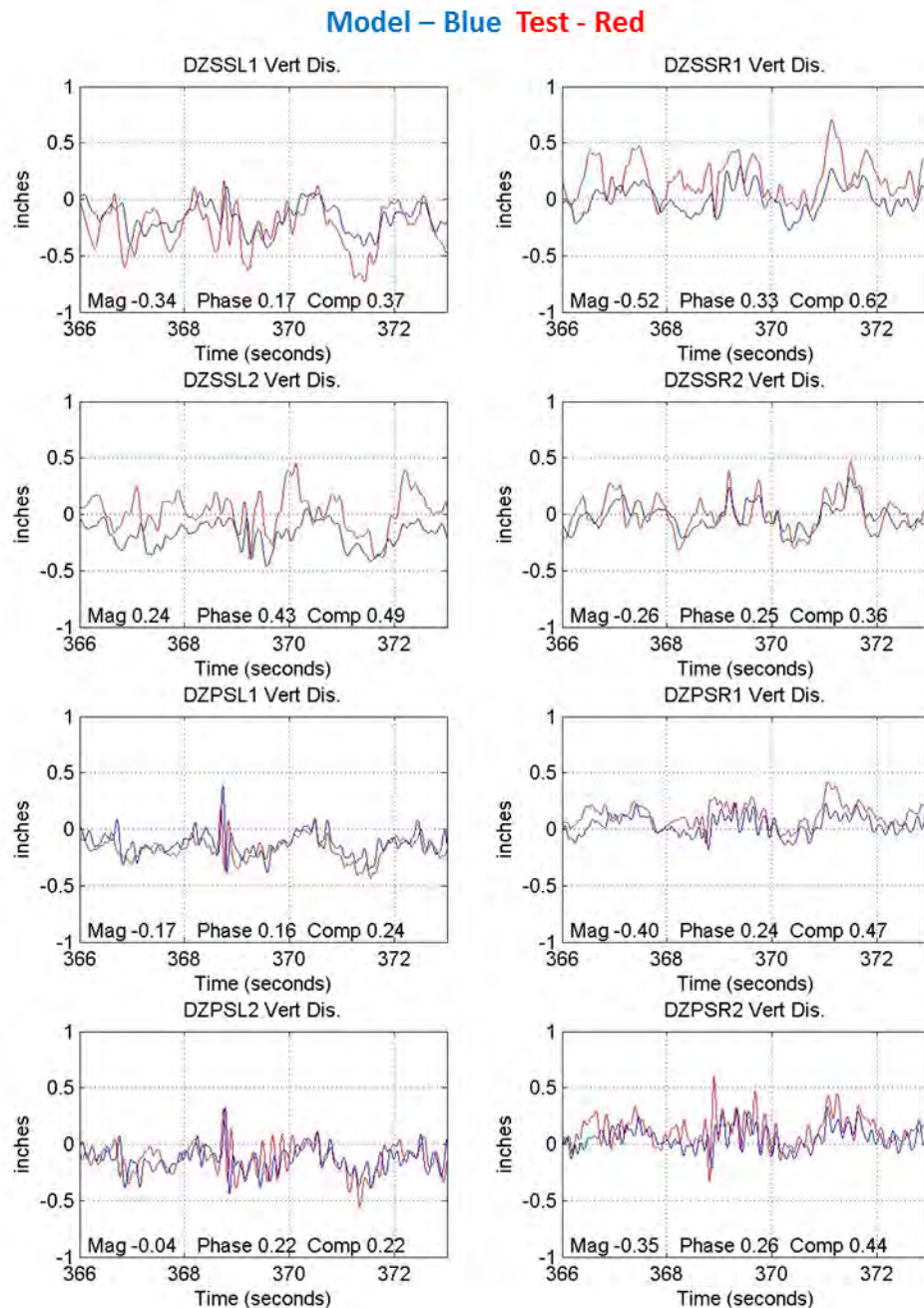


Figure 119. Vertical Primary and Secondary Suspension Displacements – RTT 105 mph in CCW Direction with Observation End Leading

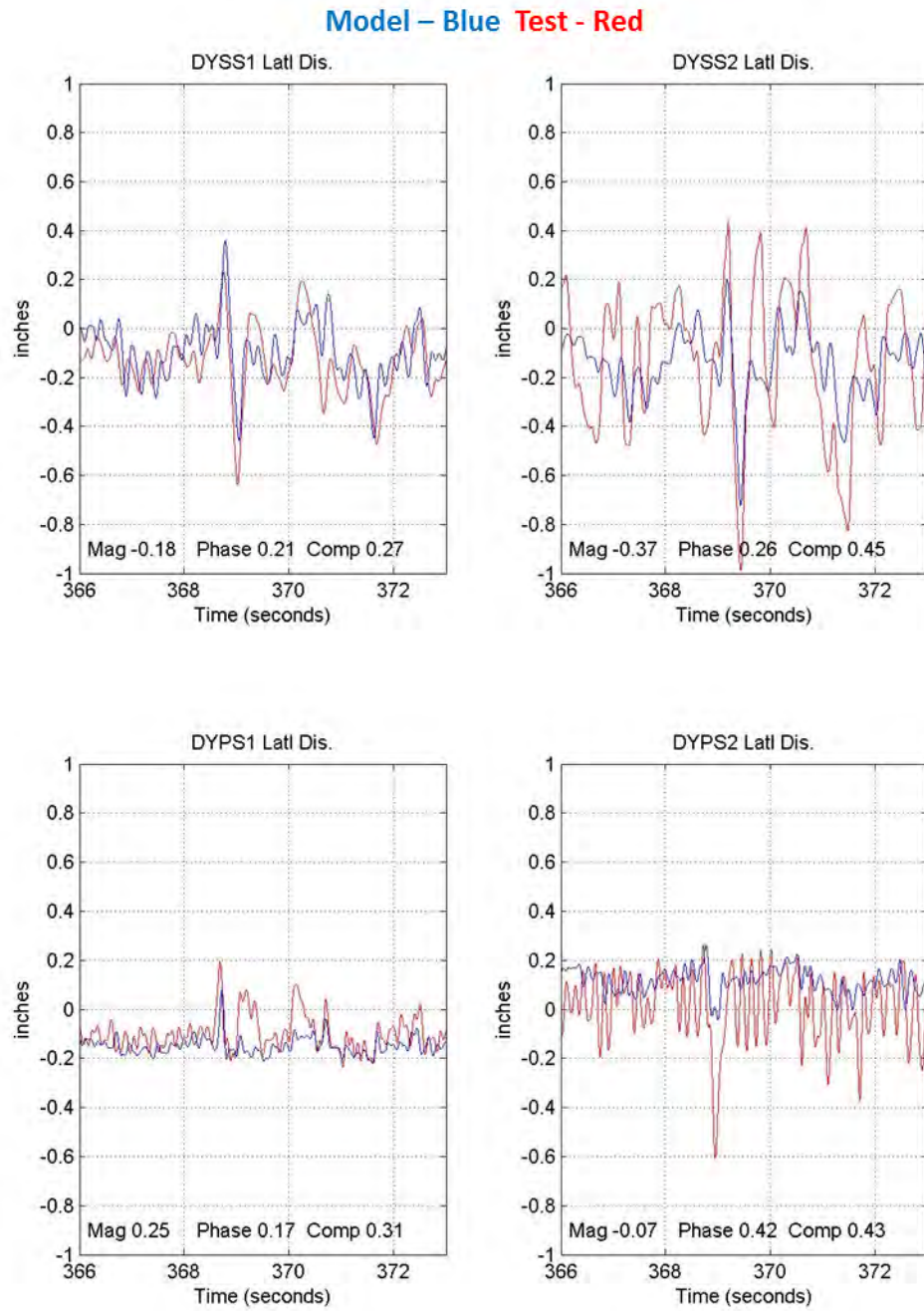


Figure 120. Lateral Primary and Secondary Suspension Displacements – RTT 105 mph in CCW Direction with Observation End Leading

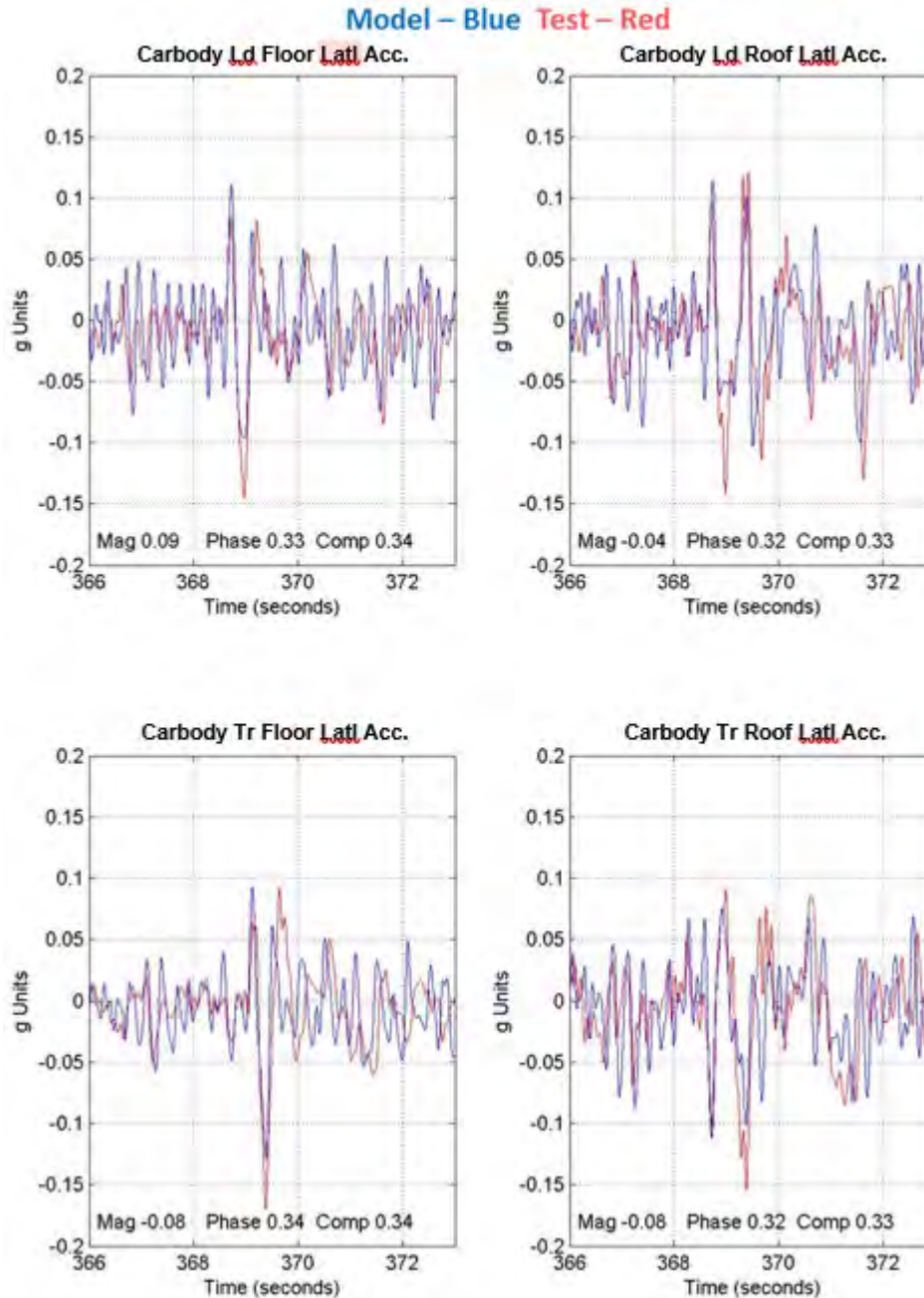


Figure 121. Vertical Carbody Accelerations – RTT 105 mph in CCW Direction with Observation End Leading

Vestibule End Leading

With the vestibule end of the car leading, model and test data still showed generally good agreement for the various measurements taken during CCW test runs. [Figure 122](#) shows maximum 2-second peak-to-peak suspension displacements for model and test runs around the entire RTT in the CCW direction with the observation end of the car leading. [Figure 123](#) shows maximum carbody and truck accelerations for model and test cases compared to limiting FRA values. Model-to-test data comparisons were similar in nature to CCW runs around the RTT with

the observation end leading. Model and test suspension displacements displayed trends as speed was increased, and similar maximum displacement magnitudes were observed.

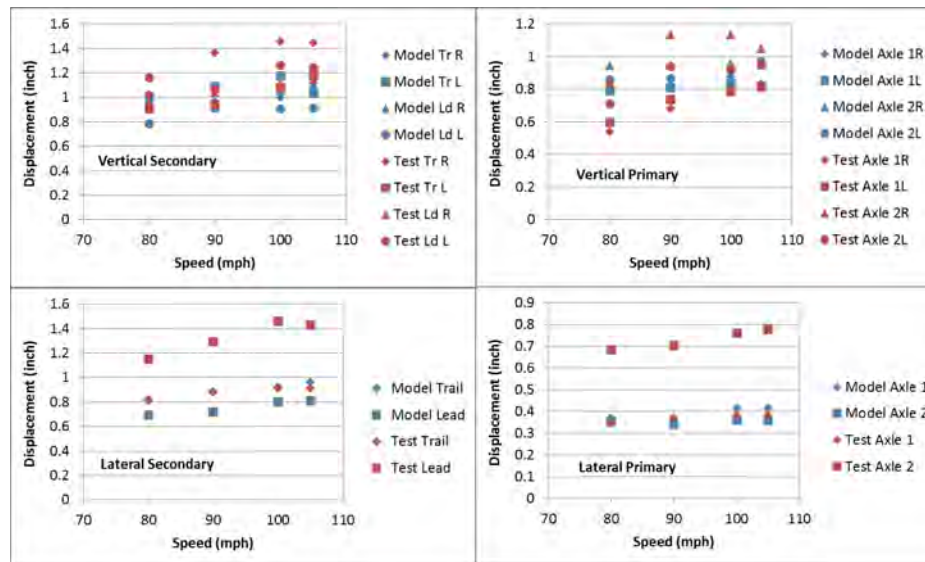


Figure 122. Maximum Peak-to-Peak Suspension Displacements – RTT in CCW Direction with Vestibule End Leading

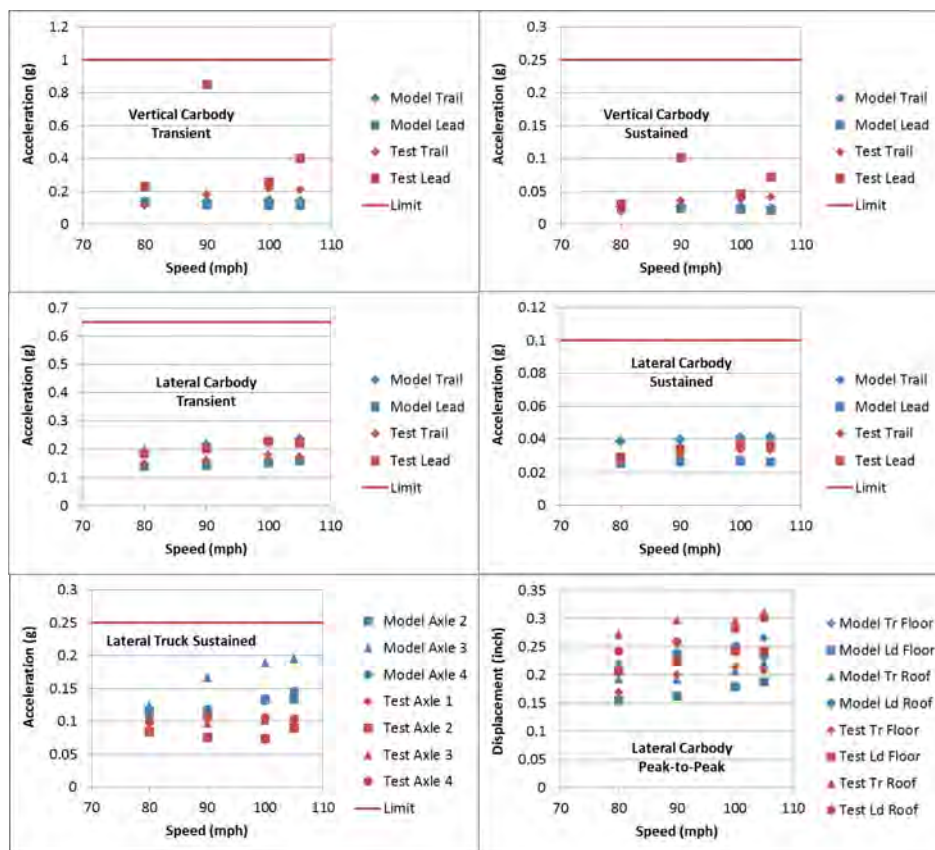


Figure 123. Maximum Peak-to-Peak Accelerations – RTT in CCW Direction with Vestibule End Leading

Aside from a few outlying values, simulated and measured carbody and truck accelerations had similar maximum values, except for truck lateral acceleration at Axle 1. Model and test data displayed similar trends with increases in speed, and the maximum values were within FRA limits. As discussed in [Section 6.2](#), the discrepancy between model and test lateral displacements may be due to modeling assumptions.

[Figure 124](#) through [Figure 126](#) are time history comparisons of the suspension displacement and carbody acceleration responses due to the track geometry deviation on the RTT. [Table 63](#) and [Table 64](#) list Sprague and Geers comprehensive error measures for the suspension displacement and carbody acceleration responses. Model and test data exhibit a similar response to the RTT geometry deviation both vertically and laterally. Average comprehensive error measures for vertical displacement channels ranged from 0.25 to 0.41, which indicates acceptable model-to-test agreement. Average comprehensive error measures for lateral displacement channels ranged from 0.20 to 0.62, which borders on the edge of unacceptable performance. Average comprehensive error measures for carbody acceleration channels ranged from 0.30 to 0.33, which indicates good model performance according to [Figure 55](#). Refer to [Table 39](#) for the detailed channel naming convention.

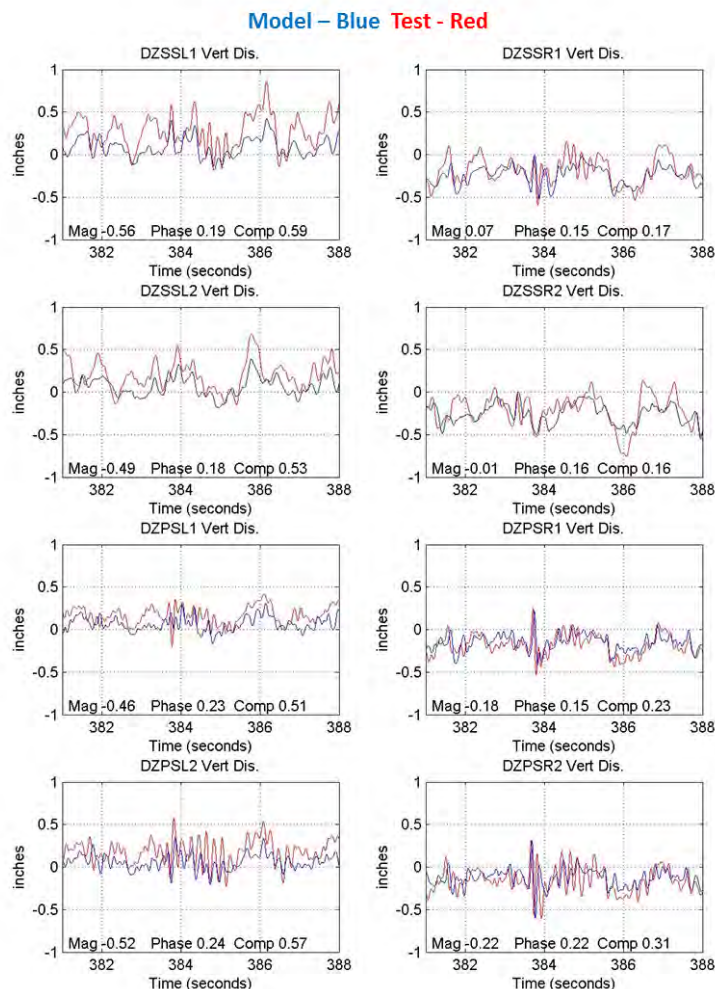


Figure 124. Vertical Primary and Secondary Suspension Displacements – RTT at 100 mph in CCW Direction with Vestibule End Leading

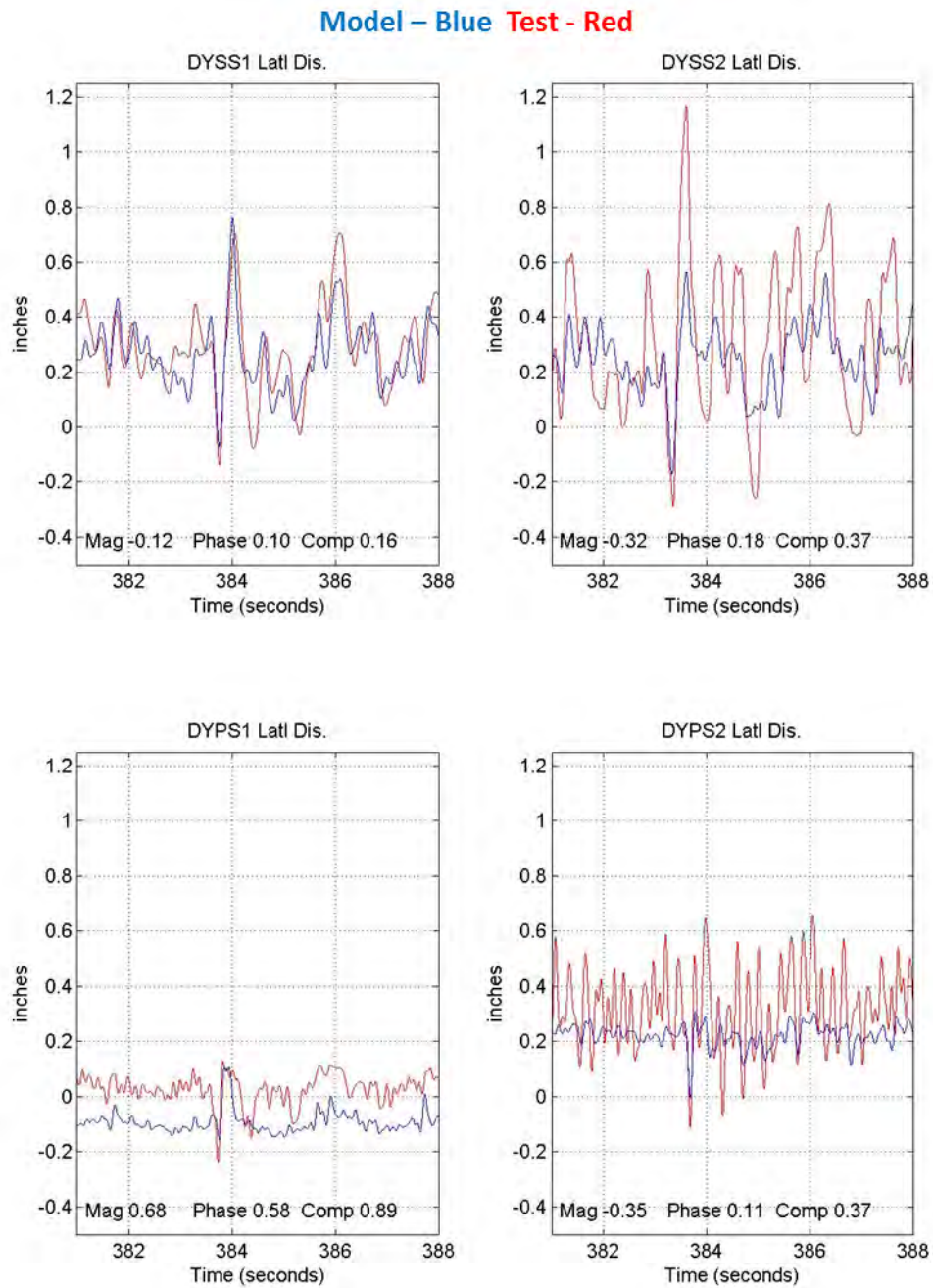


Figure 125. Lateral Primary and Secondary Suspension Displacements – RTT at 100 mph in CCW Direction with Vestibule End Leading

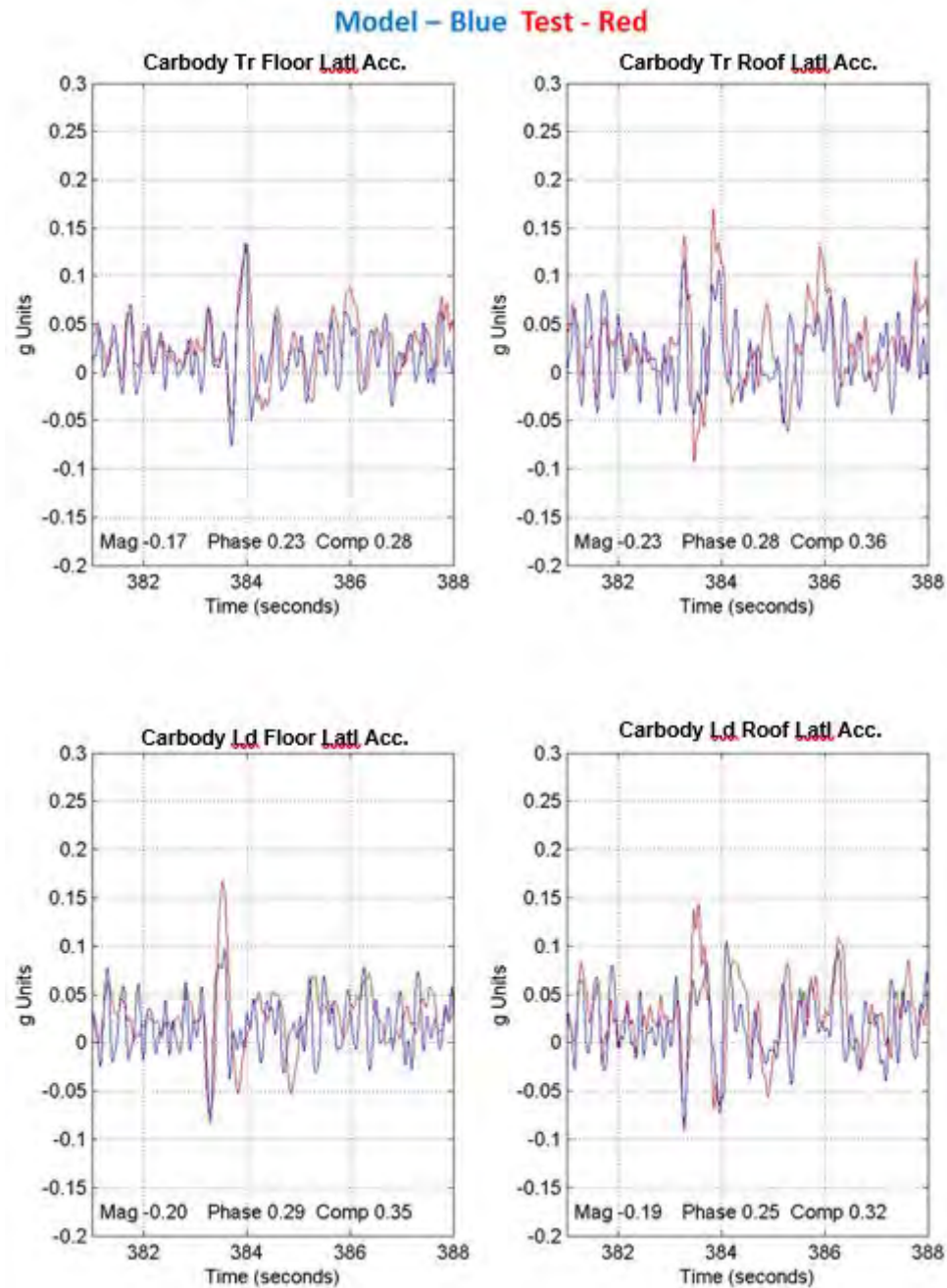


Figure 126. Lateral Carbody Accelerations – RTT at 100 mph in CCW Direction with Vestibule End Leading

Table 63. Comprehensive Error Measures for RTT Suspension Displacements in CCW Direction

Test Run		DZSSL 1	DZSSR 1	DZSSL 2	DZSSR 2	DZPSL 1	DZPSR 1	DZPSL 2	DZPSR 2	DYSS 1	DYSS 2	DYPS 1	DYPS 2
Observation End Leading	RTT_CC W-80MPH	0.34	0.19	0.48	0.18	0.28	0.07	0.35	0.08	0.33	0.08	0.17	0.74
	RTT_CC W-90MPH	0.24	0.48	0.21	0.40	0.17	0.35	0.25	0.32	0.12	0.22	0.10	0.96
	RTT_CC W-100MPH	0.21	0.31	0.25	0.35	0.25	0.18	0.27	0.26	0.13	0.31	0.67	0.72
	RTT_CC W-105MPH	0.37	0.62	0.49	0.36	0.24	0.47	0.22	0.44	0.27	0.45	0.31	0.43
Vestibule End Leading	RTT_CC W-80MPH	0.37	0.18	0.27	0.18	0.17	0.08	0.21	0.09	0.05	0.13	0.71	0.38
	RTT_CC W-90MPH	0.45	0.23	0.39	0.33	0.29	0.10	0.35	0.13	0.07	0.21	0.75	0.34
	RTT_CC W-100MPH	0.59	0.17	0.53	0.16	0.51	0.23	0.57	0.31	0.16	0.37	0.89	0.37
	RTT_CC W-105MPH	0.66	0.38	0.63	0.36	0.64	0.50	0.67	0.55	0.47	0.72	1.33	0.42
Average		0.40	0.32	0.41	0.29	0.32	0.25	0.36	0.27	0.20	0.31	0.62	0.55

Table 64. Comprehensive Error Measures for RTT Carbody Accelerations in CCW Direction

Test Run		AYCBR1	AYCBF1	AYCBR2	AYCBF2
Observation End Leading	RTT_CCW-80MPH	0.27	0.27	0.29	0.28
	RTT_CCW-90MPH	0.37	0.38	0.34	0.34
	RTT_CCW-100MPH	0.25	0.26	0.33	0.31
	RTT_CCW-105MPH	0.34	0.33	0.34	0.33
Vestibule End Leading	RTT_CCW-80MPH	0.27	0.27	0.27	0.28
	RTT_CCW-90MPH	0.25	0.27	0.30	0.29
	RTT_CCW-100MPH	0.28	0.36	0.35	0.32
	RTT_CCW-105MPH	0.40	0.43	0.45	0.44
Average		0.30	0.31	0.33	0.32

6.10 Initial Model Validation Conclusions

The NUCARS DOTX-216 car agreed well with measured on-track test data for most measured parameters, although some important parameters did not match well. Comparisons of the model and test data over both perturbed tracks, such as the PTT, and regular track, such as the TTT and RTT, showed the model does a reasonable job of modeling the general response of the physical DOTX-216 system to various track inputs. The model tended to match vertical responses of the vehicle best, and it tended to match roll responses better than lateral responses.

Vertical displacement channels matched well for most model-to-test comparisons at both the primary and secondary suspension levels. Model and test vertical carbody accelerations were also similar for most of the test cases evaluated.

Lateral displacement data varied more than vertical data between the model and test runs. The discrepancies in lateral displacement data may have resulted from model assumptions. Characterization tests were not performed directly on the vestibule end truck to protect the equipment and instrumentation at that location. Because of this limitation, the research model of the DOTX-216 car assumed that the vestibule end primary and secondary lateral suspensions were like the observation end lateral suspension, which may not be completely accurate. This assumption probably led to incorrect properties being used in the model, including stiffness and damping characteristics at the vestibule end truck and the yaw inertia of the carbody. Overall model accuracy probably could have been improved if the vestibule end truck was instrumented and tested like the observation end truck during both characterization and on-track testing.

During the on-track tests, primary suspension displacements and accelerations at Axle 2 indicated that the axle was oscillating at 6 Hz. This oscillation was present in that data at almost every test run. The model did not predict this oscillation, but the results indicated that the behavior may have had a considerable effect on the performance of the observation end truck. [Figure 127](#) shows the time histories of the displacements and accelerations at Axle 2 during the 70 mph test run around the TTT in the CW direction. This discrepancy is one significant area where the model could be improved to match the test.

For the observation end truck, the discrepancies between the model and test lateral displacements are probably large enough to significantly affect the accuracy of the lateral force calculation at the wheel-rail interface. These discrepancies could affect the ability of the model to accurately predict and evaluate safety performance measures criteria such as L/V ratios at the observation end truck. IWS measurements were only taken at the vestibule end truck during the tests.

The NUCARS model also did not consider the effect of the coupler connection to the pulling locomotive. The lateral restraint provided by the coupler connection in the physical system was not represented in the model, which may have adversely affected the results.

The lateral carbody and truck accelerations matched well between the model and test data for most of the test runs examined, except for Axle 2 lateral accelerations as noted above, even though the lateral displacement data differed significantly on the vestibule end in many cases.

The Sprague and Geers methodology did a reasonable job at highlighting those data channels that matched well and those that did not. However, it remained necessary to use expert judgement to determine whether the areas where there was not a good match are critical to achieving a validated model.

The lateral displacements and carbody lateral accelerations at the vestibule end tended to be larger than at the observation end. This effect was less pronounced in the simulation results, indicating that the model could use some improvement. Unfortunately, no primary lateral displacement measurements were available at the vestibule end to further investigate this discrepancy.

Overall, the model of the DOTX-216 car predicts similar trends in suspension displacements and carbody and truck accelerations that can be used for dynamic comparisons with FRA requirements. However, the discrepancies between model and test data discussed in the previous sections show that the model tends to underpredict the actual dynamic response.

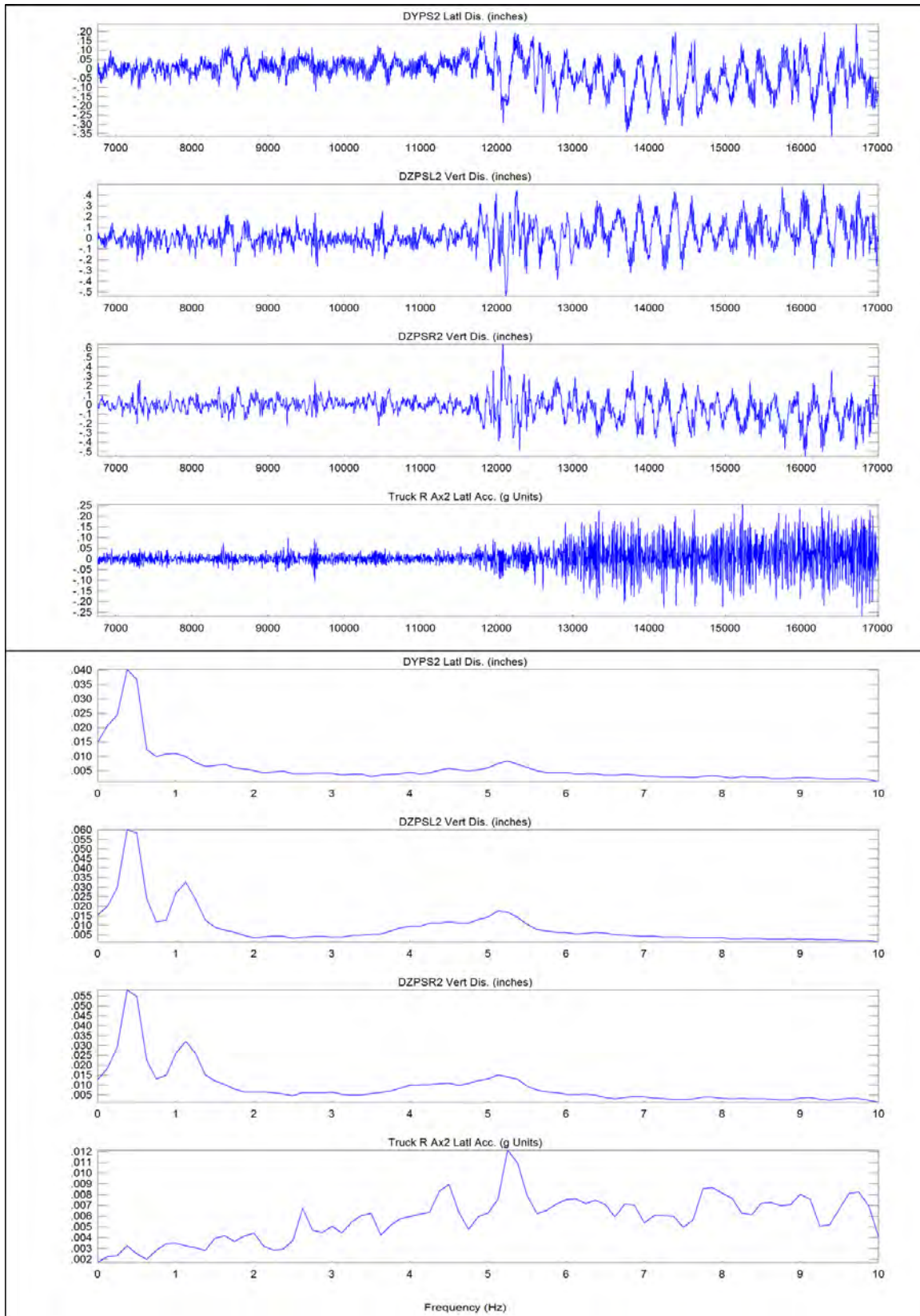


Figure 127. Time History and FFT Showing 5-6 Hz Oscillations of Axle 2

From the perspective of using models for the purpose of vehicle qualification, it is usually preferred to have the model err on the conservative side and overpredict the response. Therefore, the DOTX-216 car should be considered only partially validated for this purpose. A particular concern is that the oscillations of Axle 2 are not predicted at all.

Under normal circumstances for a test without IWS, this stage of the model validation process would see more effort to further understand the discrepancies noted above and revise the model to reduce the discrepancies. In this second validation stage, attention would be focused on:

- Oscillations of Axle 2
- Differences in lateral displacement and acceleration between the two ends of the car
- Effects of the differences in lateral displacement and acceleration on roll and yaw response

However, in accordance with the project plan, no adjustments were made to the model to improve the validation. In the following section, wheel-rail forces measured using IWS will be used to further investigate the effectiveness of this validation methodology.

7. Model Validation with IWS

7.1 Model Validation Strategy Using IWS

After the initial attempt at validating the model DOTX-216 car using only displacement and acceleration data (see [Section 6](#)), the team employed wheel-rail force data measured using IWS to evaluate the effectiveness of the methodology and to further validate the model. Per FRA request, the same model and simulations were used as in the initial validation effort, and no model adjustments were made to improve the correlation to the test data. Normally, a complete validation effort would include adjustments to the model to improve the correlations.

Researchers intended to use traditional direct comparisons in combination with the Sprague and Geers method to assess the goodness of fit between the model and test wheel-rail force channels; however, data from the IWS proved to be unsatisfactory. The team supplemented direct comparisons with a model validation analysis using a method outlined by Polach [11].

7.2 Issues with IWS Data

Data from IWS had several problems that precluded using the Sprague and Geers method analysis. The vertical force channels contained initial offsets that did not match the wheel loads measured using the track scale ([Section 3.1.2](#)). The initial IWS vertical loads differed by over 10 percent on the right wheel of Axle 3 and on the left wheel of Axle 4. The discrepancy can be seen in [Figure 128](#). Measured data from the IWS should not differ from the known static wheel loads by an amount of this magnitude and brings into question the accuracy of the rest of the measured force data.

Also, the IWS data contained excessive noise that resulted from the rotational frequency of the wheelset, which interfered with the measurement. To meet the requirements of 49 CFR 213.333, the IWS data must first be processed by a low-pass filtering of the data at a filter frequency no greater than 25 Hz. The IWS data recorded in this test was processed in this manner, but excessive noise was still contained in the data. [Figure 128](#) shows comparison plots of the vertical force measurements for model and test data during a 27 mph test run through the pitch and bounce test section. Both model and test data in the figure were low-pass filtered at 25 Hz. The rotational frequency of a 36-inch diameter wheelset rolling at this speed (assuming no slip) is calculated in the following equation:

$$f_r = \frac{v}{2\pi R} = \frac{27\text{mph}\left(5280\frac{\text{ft}}{\text{mile}}\right)\left(\frac{1\text{hr}}{3600\text{sec}}\right)}{2\pi(18\text{inch})\left(\frac{1\text{ft}}{12\text{inch}}\right)} = 4.2\text{ Hz} \quad (5)$$

The wheelset in this test run rotates at approximately 4.2 Hz. The second and third harmonics of this frequency are 8.4 Hz and 12.6 Hz. All three frequencies appear prominently in Fast Fourier Transform (FFT) comparison plots shown in [Figure 129](#). Without filtering the data using multiple band-stop frequency filters or developing complicating harmonic frequency filters, the IWS data cannot be used in point-for-point comparison techniques, including calculating Sprague and Geers error measures.

The Sprague and Geers method of model validation is also limited for this type of application because offsets in the data, including expected static offsets in wheel-rail force data, need to be removed from the data to give a fair comparison of the data vectors. This is not always desirable or practical for an analysis.

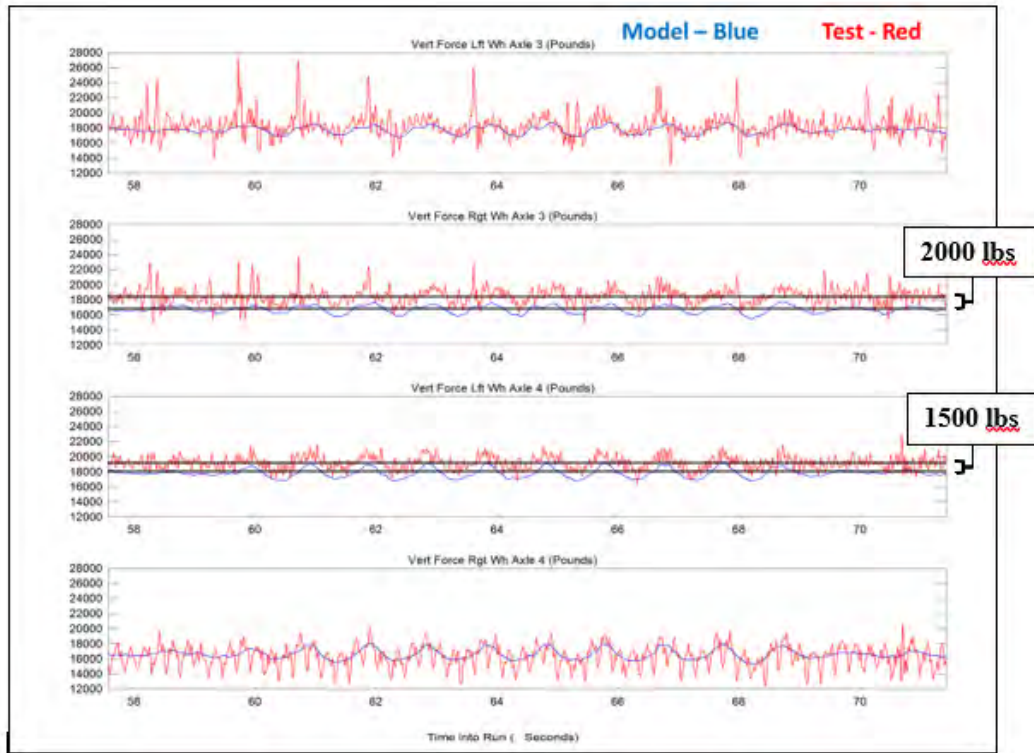


Figure 128. Vertical Forces from Pitch and Bounce 27 mph Run

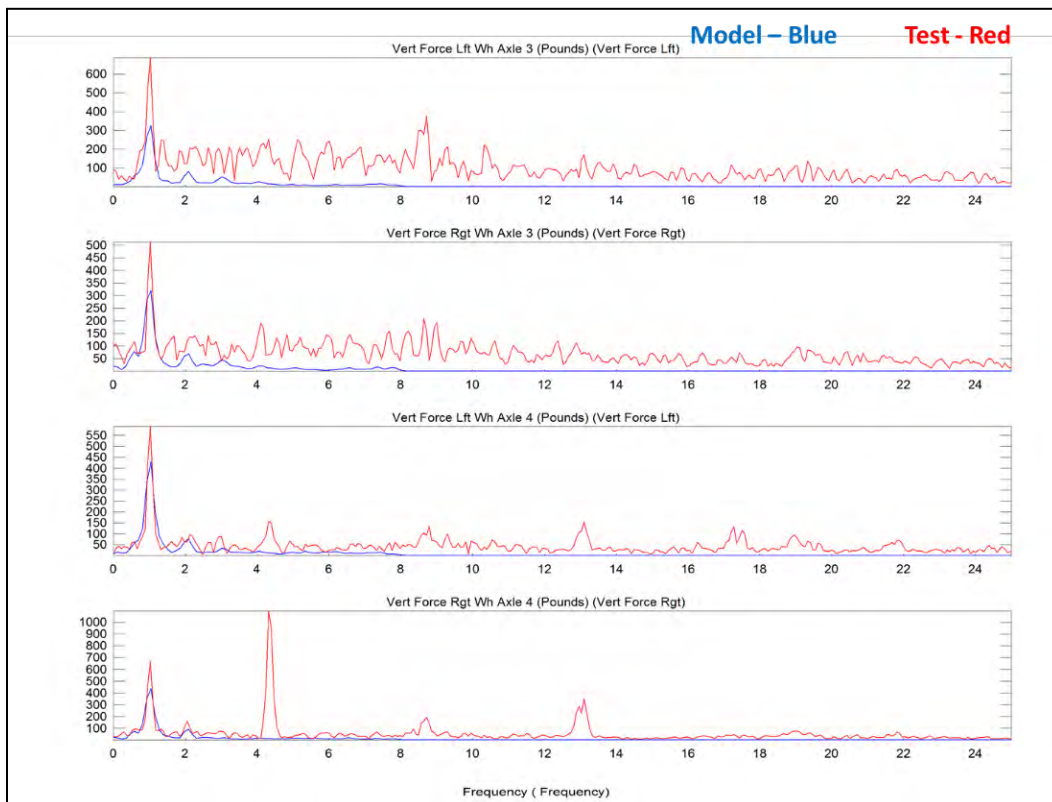


Figure 129. FFT Comparison of Vertical Forces from Pitch and Bounce 27 mph Run

The following sections give direct comparisons of the model and tests results using FRA VTI safety criteria. Direct comparisons are made for wheel-rail force statistics calculated in accordance with 49 CFR 213.333 (see [Table 40](#)). The following VTI safety criteria were calculated using the measured wheel-rail force data:

- Minimum vertical load ratio (limit: 15%)
- Maximum single wheel L/V ratio (limit: 1.0)
- Maximum axle sum L/V ratio (limit: 0.55)
- Maximum truck side L/V ratio (limit: 0.6)

Maximum wheel-rail force values were evaluated for the model and test cases. These values were also compared to the limiting VTI safety criteria. Data from this exercise will help evaluate the effectiveness of the previous validation methodology, and it will be used to further validate the DOTX-216 model.

7.3 Twist and Roll

Maximum model and test wheel-rail force values matched well through the twist and roll test section. The minimum vertical load ratios calculated were very similar for all test speeds, ranging from 90 percent to 75 percent, which is significantly higher than the 15 percent FRA safety limit. The DOTX-216 model slightly underpredicted the maximum L/V ratio values, though the measured values were always much lower than the FRA safety limits. [Figure 130](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

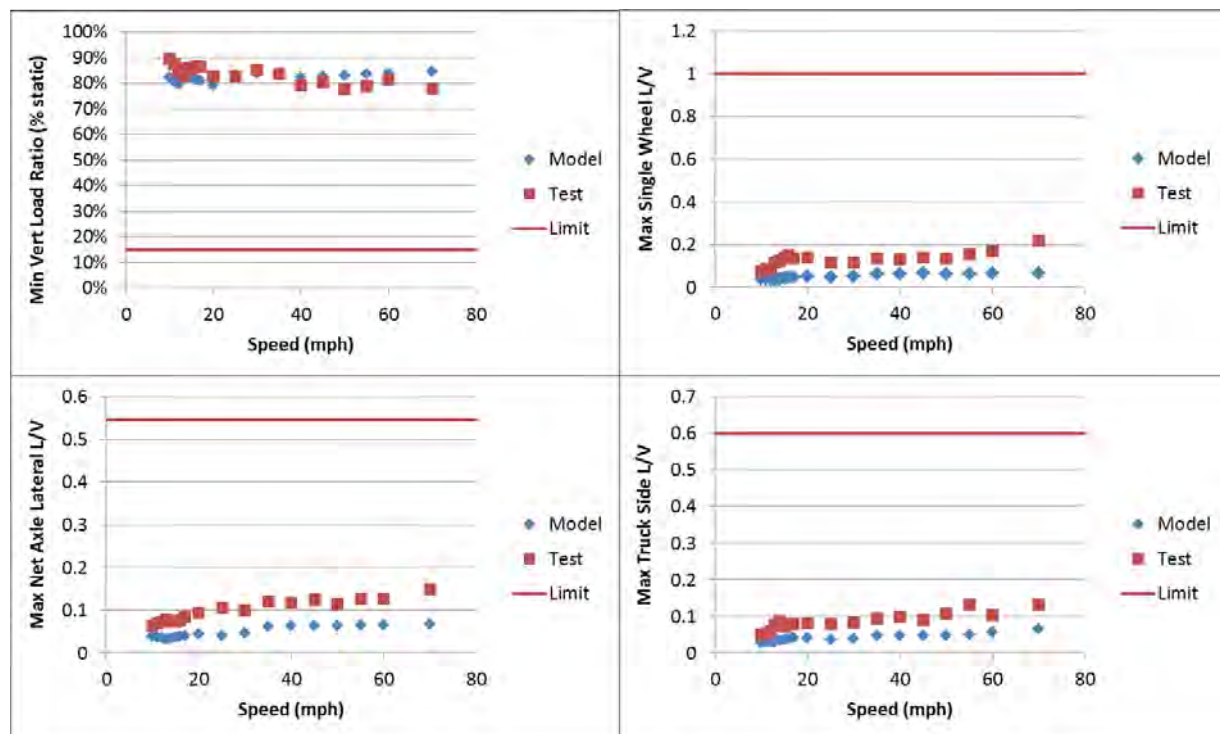


Figure 130. Maximum Wheel-Rail Force Measures – Twist and Roll

7.4 Pitch and Bounce

Maximum model wheel-rail force values matched the measured test data reasonably well through the pitch and bounce test section. Like the data from the twist zone, minimum vertical load ratios were similar for all test speeds through the pitch and bounce zone, but the model tended to overpredict the maximum vertical wheel unloading, which indicates somewhat conservative model performance. The model also underpredicted the maximum L/V ratio values observed through the test zone. The measured and simulated values were always within corresponding FRA safety limits. Figure 131 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

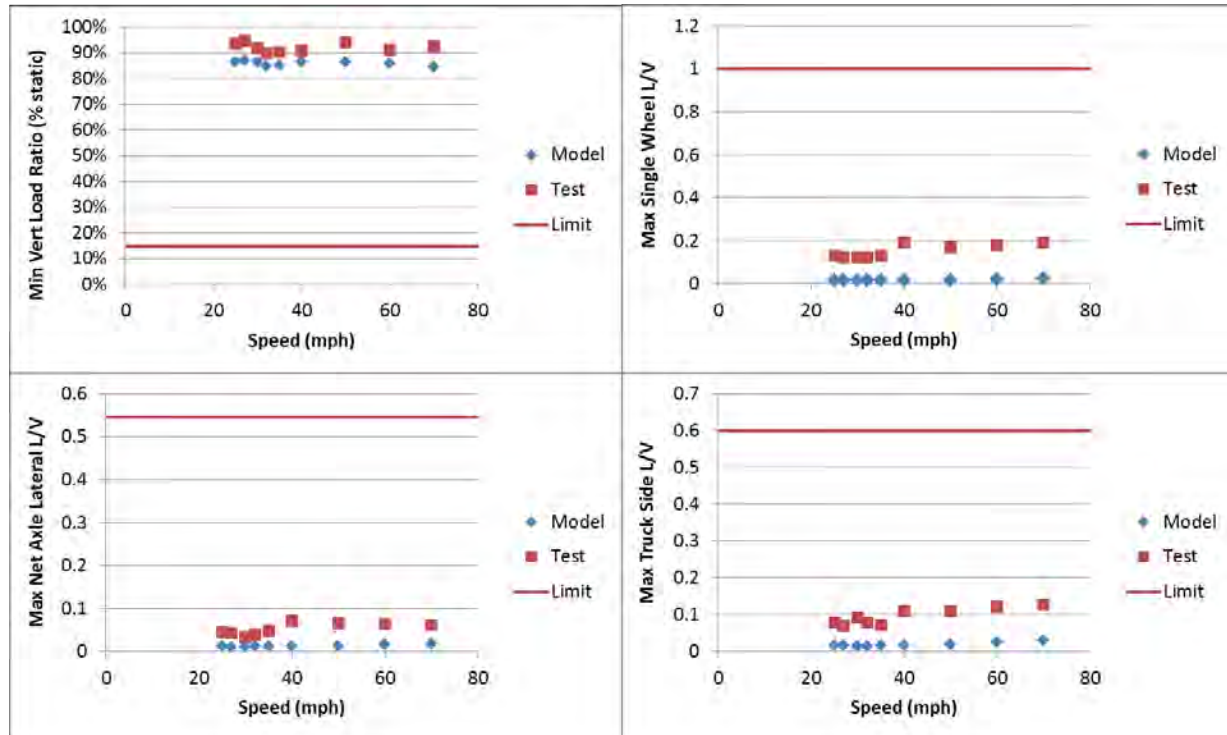


Figure 131. Maximum Wheel-Rail Force Measures – Pitch and Bounce

7.5 Yaw and Sway

Maximum model and test wheel-rail force values matched reasonably well through the yaw and sway test section, though the model-to-test agreement was not as close as previous test sections. This discrepancy is partially because lateral responses are more difficult to model than either vertical or roll responses [3]. The minimum vertical load ratios calculated were close for the speeds tested. Model and test results also showed good agreement for the single wheel L/V measurements. Model predictions were less accurate for the maximum net axle truck side L/V ratios, but the model did correctly capture the overall data trend. Regardless, the measured and simulated values were always within the FRA safety specifications. Figure 132 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

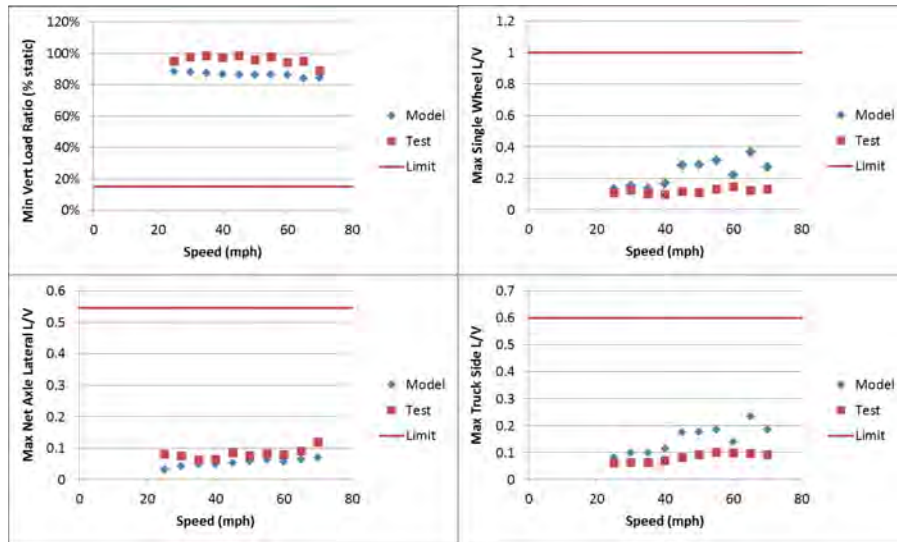


Figure 132. Maximum Wheel-Rail Force Measures – Yaw and Sway

7.6 Dynamic Curving – WRM Loop

Model and test results from the dynamic curving test section showed good model-to-test agreement in both the CW and CCW directions. Results from the test runs are presented separately for each direction.

7.6.1 CW

The model tended to overpredict the maximum vertical wheel unloading measured through the constant curving section in the CW direction. The model also overpredicted the L/V ratio values for most speeds in the test section. These discrepancies, though small, demonstrated conservative model performance on this specific track. Measured and simulated values were still well within FRA safety specifications. [Figure 133](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

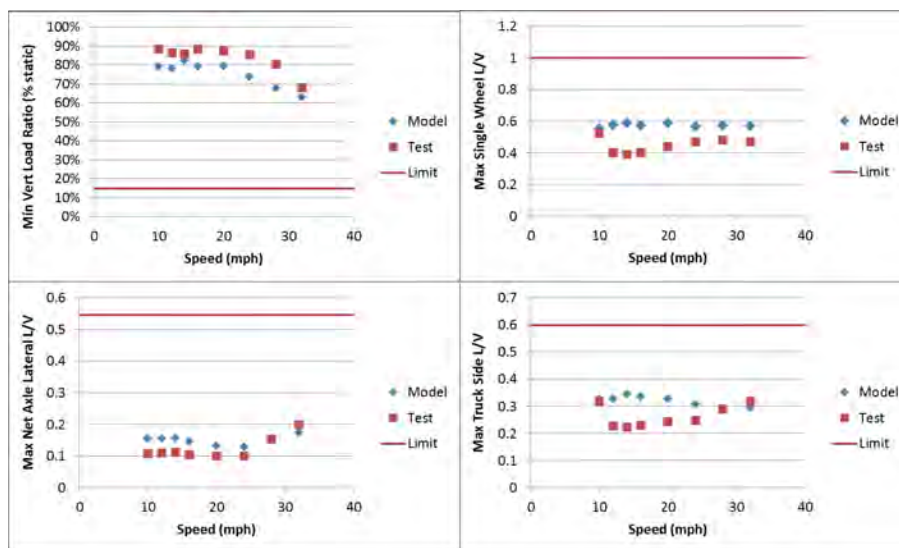


Figure 133. Maximum Wheel-Rail Force Measures – Dynamic Curving in CW Direction

7.6.2 CCW

Results from dynamic curving test runs in the CCW direction demonstrated roughly the same level of agreement between the model and test results that was observed in the CW cases. The model predicted minimum vertical load and L/V ratios that were similar in magnitude to the test value and the values calculated in the CW direction. Figure 134 shows comparison plots of the maximum wheel-rail force values and the FRA safety limits for each case.

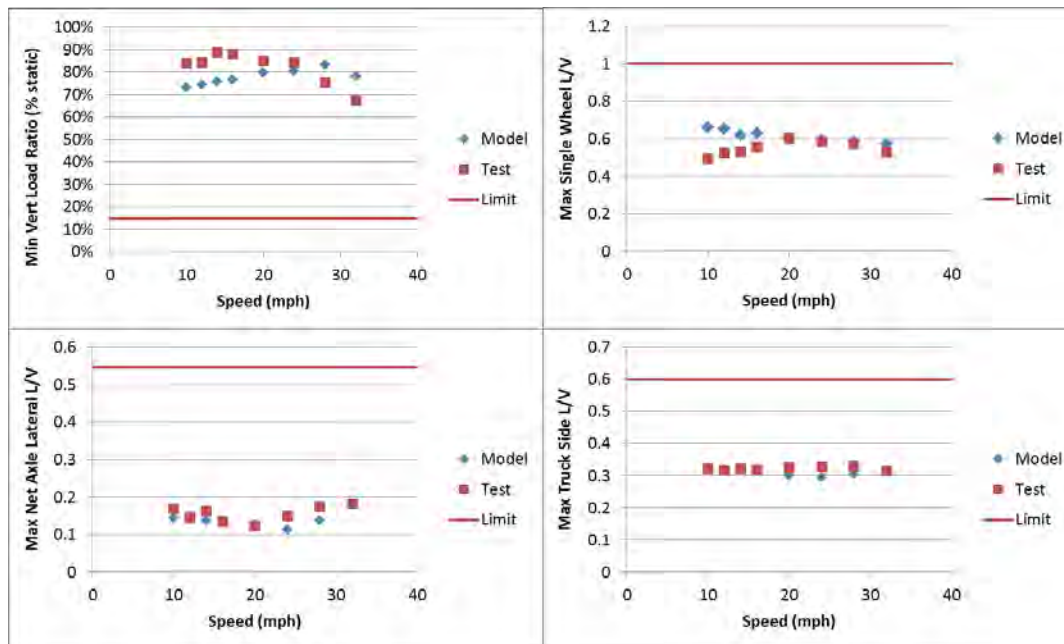


Figure 134. Maximum Wheel-Rail Force Measures – Dynamic Curving in CCW Direction

7.7 Constant Curving – WRM Loop

Model and test results from the constant curving test section showed very good model-to-test agreement in both the CW and CCW directions. Model and test results had similar magnitudes for each test speed in the range. Results from the test runs are presented separately for each direction.

7.7.1 CW

Results from the tests in the CW direction showed that the model tended to slightly overpredict the maximum vertical wheel unloading measured through the test section in the CCW direction. The overpredicted values show generally conservative model behavior in this aspect. Model predictions of L/V ratio values, including single wheel, axle sum, and truck side L/V ratios, were very similar to the measured values in the test section. Figure 135 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

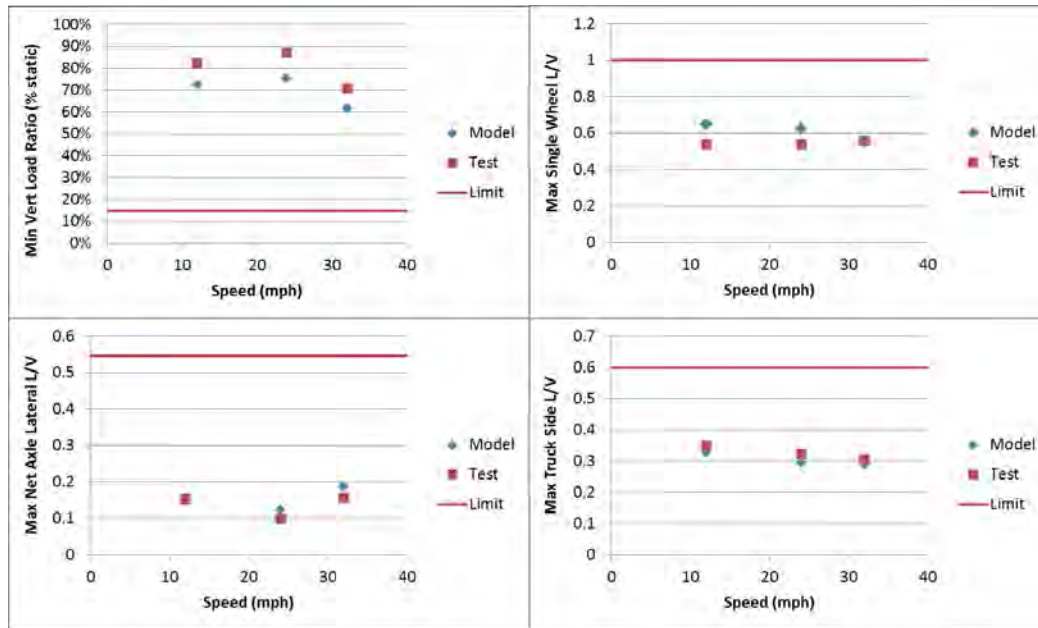


Figure 135. Maximum Wheel-Rail Force Measures – Constant Curving in CW Direction

7.7.2 CCW

Model data from the constant curving test runs in the CCW direction were again like the CCW direction simulations. Results from the simulations showed considerable agreement between the model and test data. Model predictions of L/V ratio values were very similar to the measured values in the test section. The model slightly overpredicted the minimum vertical load ratios measured through the test section, but the overpredictions demonstrate generally conservative model behavior. Figure 136 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

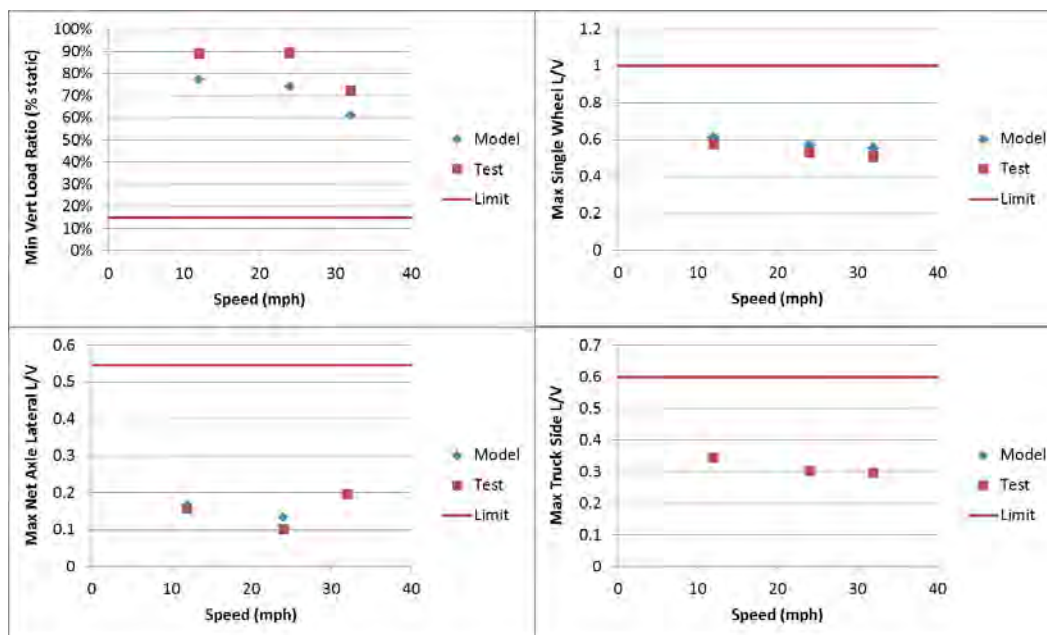


Figure 136. Maximum Wheel-Rail Force Measures – Constant Curving in CCW Direction

7.8 URB North Wye

As discussed in [Section 6.7](#), simulations of the special perturbation on the URB North Wye track lacked adequate track geometry input. For this reason, the simulated wheel-rail forces may not be as accurate as simulations of previous test sections.

Even without ideal track geometry data, maximum model wheel-rail force values matched the measured test data relatively well through the No. 8 turnout and 12-degree curve test section. VTI safety values were similar for all speeds through the test section. The model generally overpredicted the maximum vertical wheel unloading and L/V values, but the difference between model and test values was usually 10 percent or less. [Figure 137](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

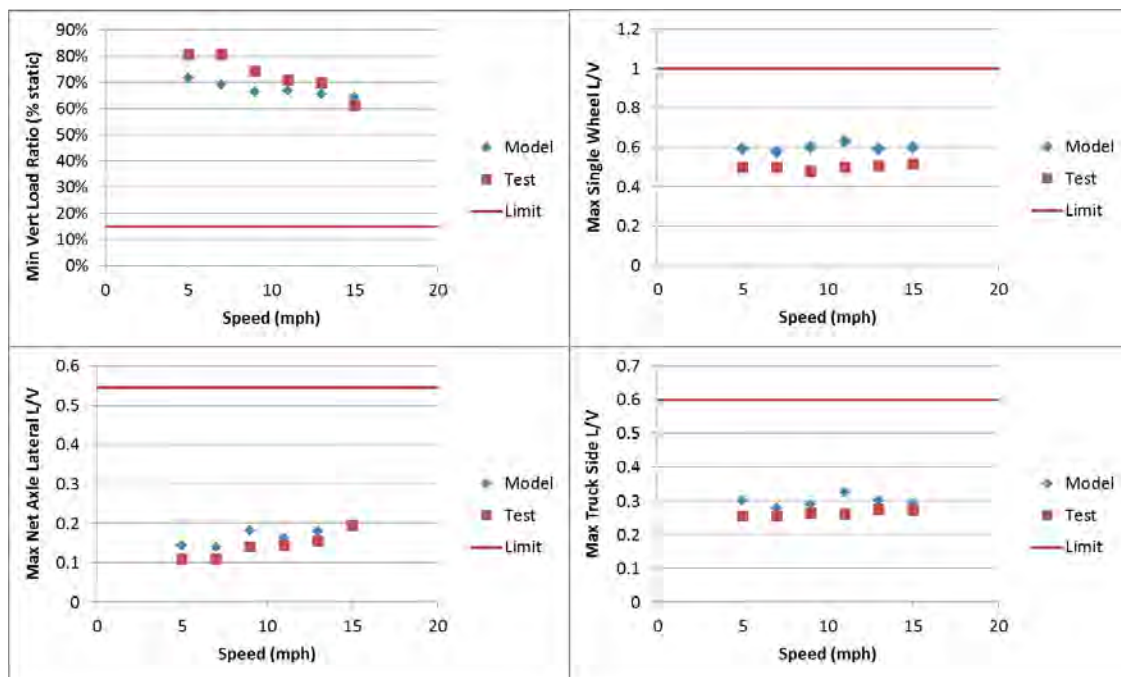


Figure 137. Maximum Wheel-Rail Force Measures – URB North Wye

7.9 Transit Test Track

Model and test results from the TTT test track agreed closely in both the CW and CCW directions. Only two speeds (70 and 80 mph) were tested on the track, but model and test results did have similar magnitudes for both test speeds and both directions. Results from the test runs are shown separately for each direction.

7.9.1 CW

Results from wheel-rail force measurements in the CW direction showed good model-to-test agreement for both test speeds. VTI safety values were similar for 70 and 80 mph test speeds. Model predictions of minimum vertical load ratios and L/V ratio values, including single wheel, axle sum, and truck side L/V ratios, were like the measured values and were well within the FRA limiting values. [Figure 138](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

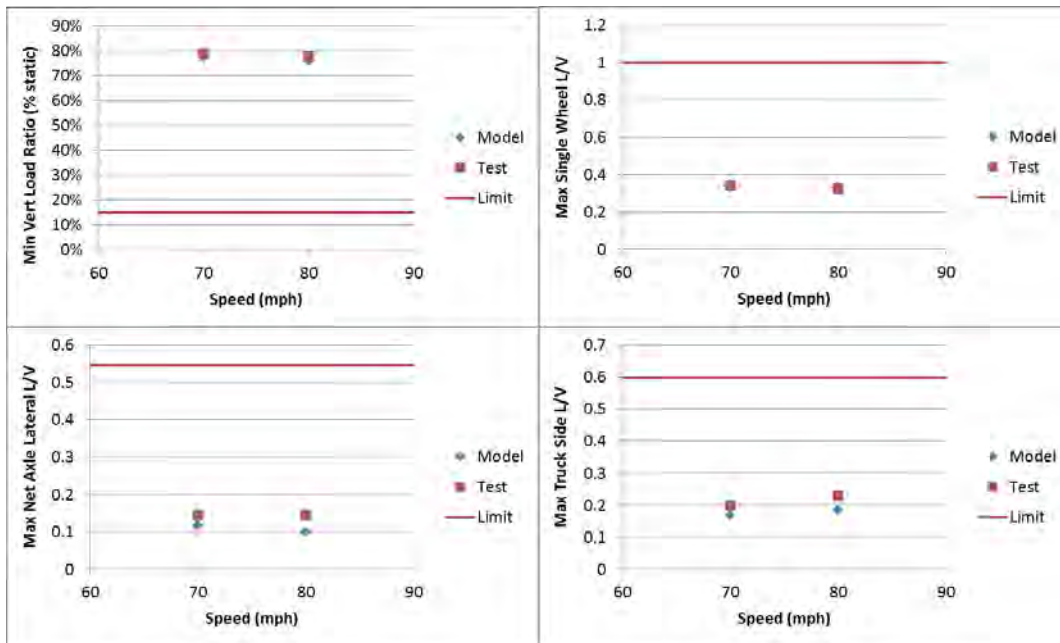


Figure 138. Maximum Wheel-Rail Force Measures – TTT in CW Direction

7.9.2 CCW

Model and test wheel-rail force measurement agreed closely in the CCW direction, but the results differed more than those in the CW direction. VTI safety values were similar for 70 and 80 mph test speeds, differing by about 10 percent or less. [Figure 139](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

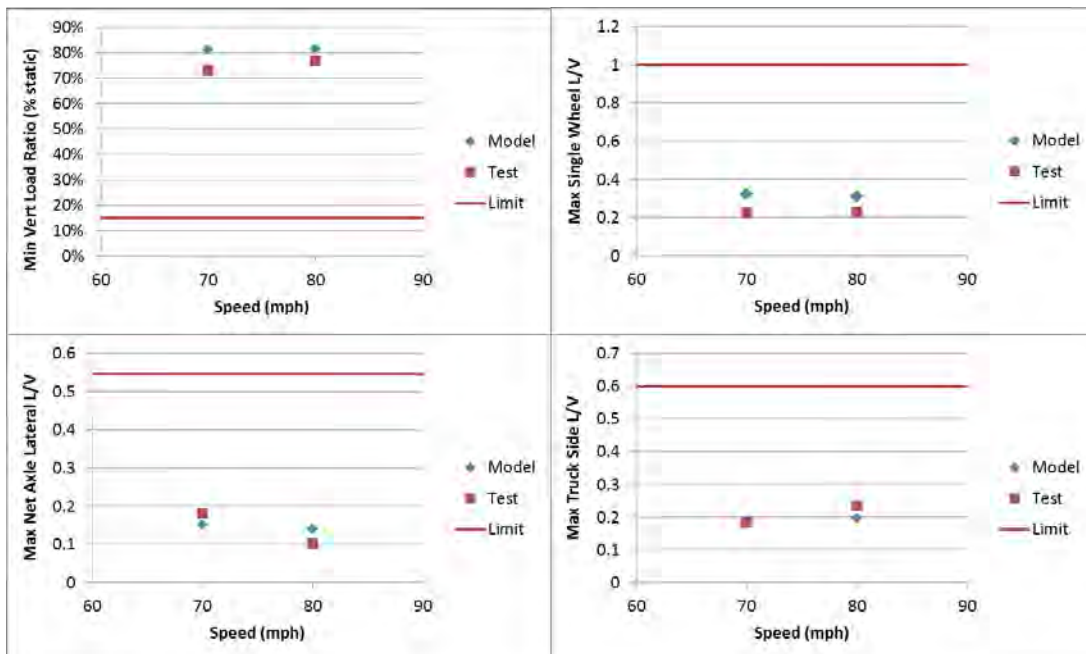


Figure 139. Maximum Wheel-Rail Force Measures – TTT in CCW Direction

7.10 Railroad Test Track

Model and test results from the RTT test track generally agreed for test runs in both the CW and CCW directions and with both ends of the vehicle in the leading position. Model and test results had similar magnitudes for each of these cases and experienced the same general trends in the data with increases in speed. Results from the test runs are shown separately for each direction and each end of the vehicle leading in the following sections.

7.10.1 CW

Observation End Leading

Model and test wheel-rail forces in the CW direction with the observation end leading showed good model-to-test agreement. Model prediction L/V values agreed with measured data more closely than minimum vertical load ratio data. Still, all model and test VTI safety values were well within FRA limits. [Figure 140](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

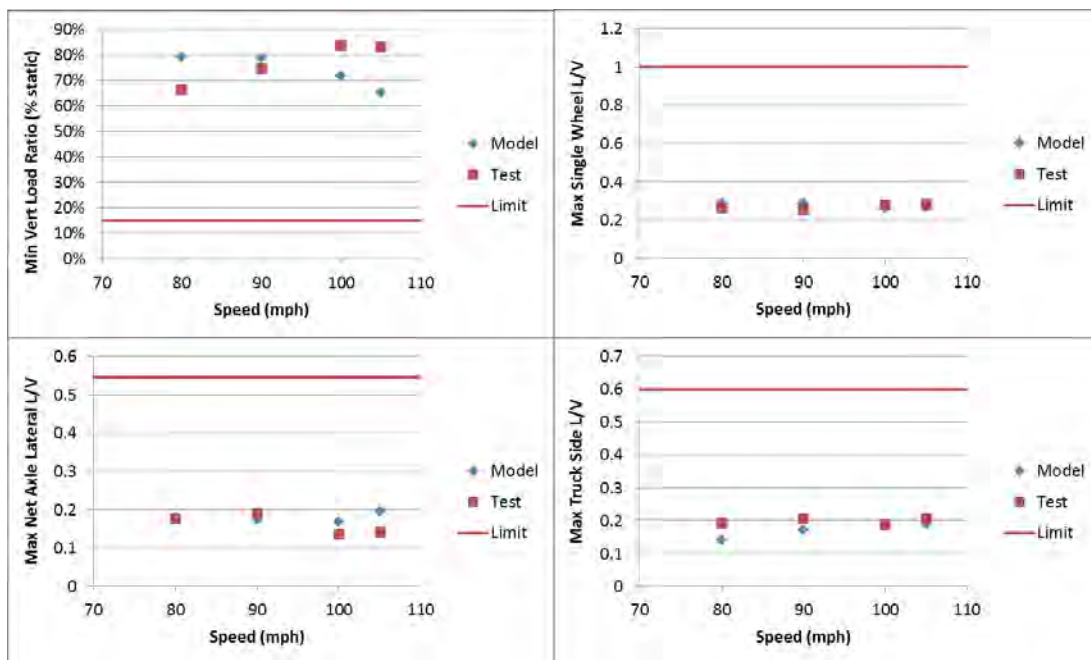


Figure 140. Maximum Wheel-Rail Force Measures – RTT in CW Direction with Observation End Leading

Vestibule End Leading

Like the observation end leading runs, model and test forces in the CW direction with the vestibule end leading agreed reasonably well. Model predictions of L/V values were closer to the measured values than minimum vertical load ratio data. All model and test VTI safety values were still well within the FRA limits. [Figure 141](#) shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

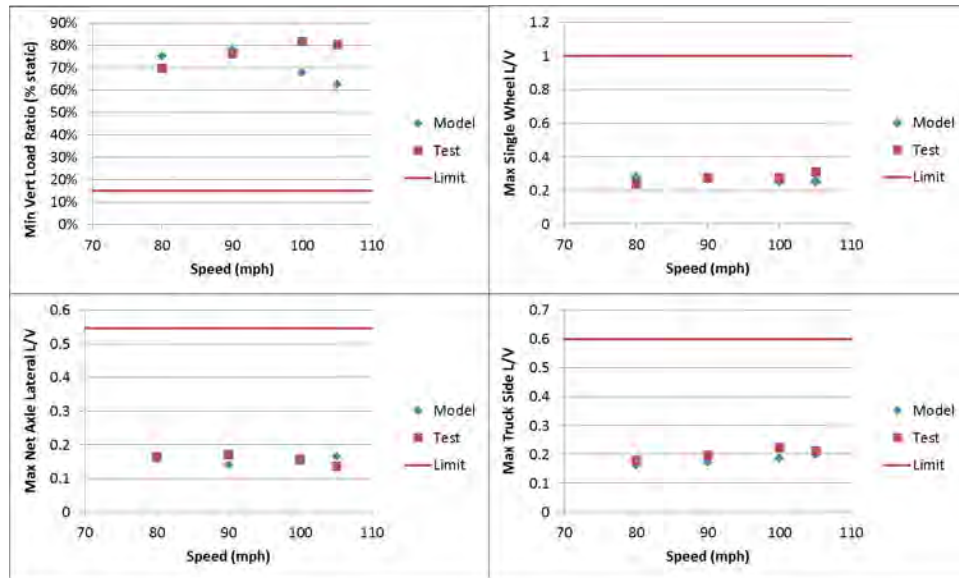


Figure 141. Maximum Wheel-Rail Force Measures – RTT in CW Direction with Vestibule End Leading

7.10.2 CCW

Observation End Leading

Wheel-rail force results in the CCW direction with the observation end leading matched closely between the model and test data. Like the test cases in the CW direction, model predictions of L/V values tended to agree more closely with measured data than minimum vertical load ratio data. All model and test VTI safety values were still well within the FRA specified criteria.

Figure 142 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

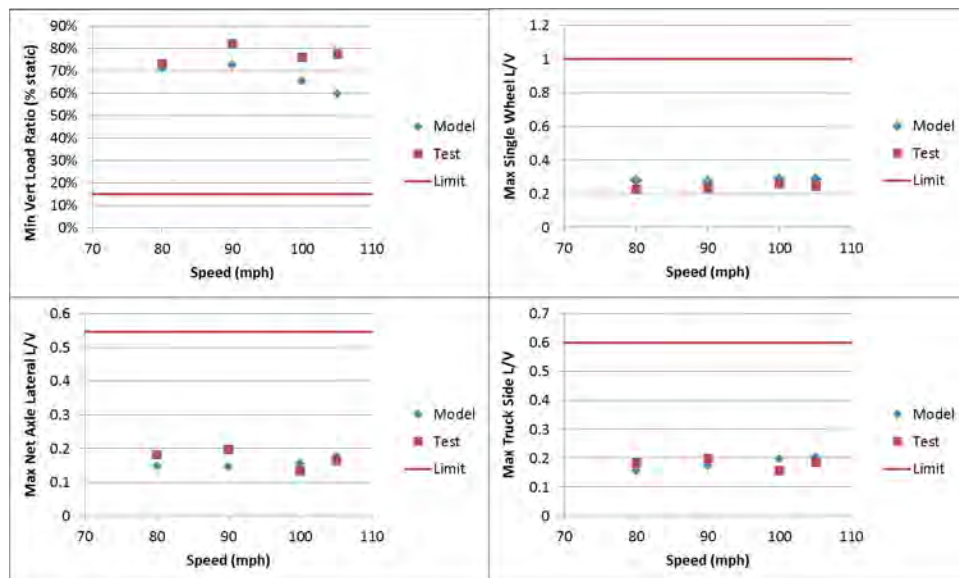


Figure 142. Maximum Wheel-Rail Force Measures – RTT in CCW Direction with Observation End Leading

Vestibule End Leading

Wheel-rail force results in the CCW direction with the vestibule end leading also matched closely between the model and test data. Like the other test runs on the RTT, model predictions of L/V values tended to agree more closely with measured data than minimum vertical load ratios. Figure 143 shows comparison plots of the maximum wheel-rail force values and the limiting FRA safety criteria for each case.

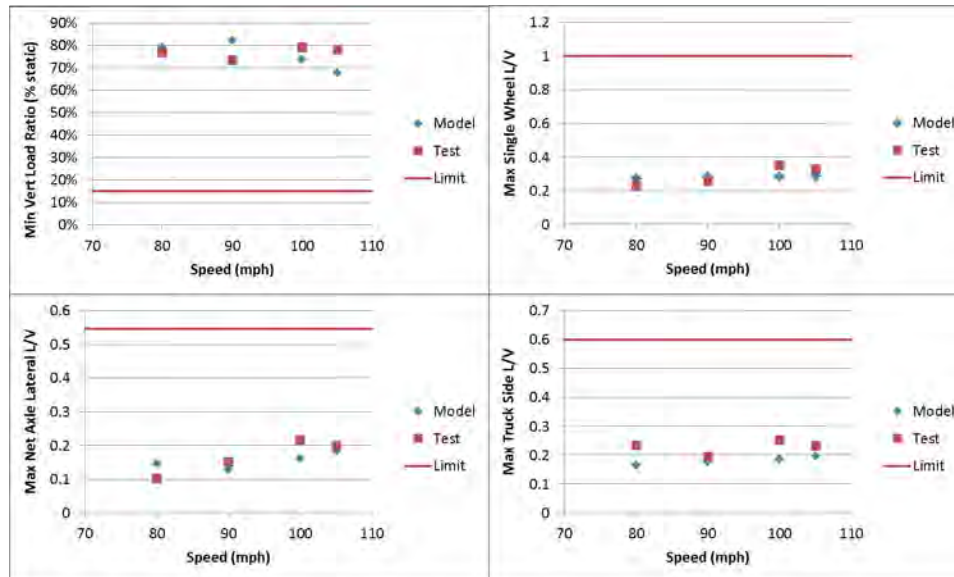


Figure 143. Maximum Wheel-Rail Force Measures – RTT in CCW Direction with Vestibule End Leading

7.11 Polach Method

7.11.1 Method Description

Polach proposed a model validation method that evaluates vehicle models by examining the differences between simulated and measured data channels [11]. The method involves analyzing 12 important measurements for both simulation and test data, filtering the data, and processing the channel statistics according to the requirements in Table 65 [11]. The measurements listed in Table 65 are measured for both model and test data on 12 EN14363 type test sections and processed like EN14363 standards [11,12]. After filtering and processing the data, the differences between corresponding simulation and measurement statistics are calculated. Differences between the model and test statistics are evaluated by determining the mean and standard deviations of the required statistics. The mean and standard deviation of differences between the model and test data are computed using the statistics from all simulation and test regimes in the analysis. Model validation is then determined by comparing the means and standard deviations of the differences to the validation limits listed in Table 65 [11].

The validation limits proposed by Polach in Table 65 were determined based on comparisons of model and test data for an entire set of test runs. Results from the entire set of the DOTX-216 car tests and simulations were compared against the proposed validation limits in Table 65.

Table 65. Validation Limits for Differences between Simulated and Measured Data

Quantity	Notation	Filtering	Processing	Validation Limit: Standard Deviation of Differences Simulation- Measurement	Validation Limit: Mean of Differences Simulation- Measurement
Quasi-Static Guiding (Lateral) Force	Y_{qst}	20Hz Low-Pass Filter	50%-Value (Median)	5 kN [1.12 kips]	3.33 kN [0.75 kips]
Quasi-Static Vertical Wheel Load	Q_{qst}	20Hz Low-Pass Filter	50%-Value (Median)	$4(1+0.01Q_0) =$ 7.06 kN [1.59 kips]	4.71 kN [1.06 kips]
Quasi-Static Ratio Y/Q	$(Y/Q)_{qst}$	20Hz Low-Pass Filter	50%-Value (Median)	0.07	0.05
Sum of Quasi-Static Guiding Forces per Axle	ΣY_{qst}	20Hz Low-Pass Filter	50%-Value (Median)	6 kN [1.35 kips]	4 kN [0.90]
Maximum Quasi-Static Guiding Force	Y_{qst}	20Hz Low-Pass Filter	0.15/99.85%-Value (Maximum)	9 kN [2.02 kips]	6 kN [1.35 kips]
Maximum Quasi-Static Vertical Wheel Load	Q_{qst}	20Hz Low-Pass Filter	0.15/99.85%-Value (Maximum)	$4(1+0.01Q_0) =$ 10.59 kN [2.38 kips]	7.06 kN [1.59 kips]
Maximum Quasi-Static Ratio Y/Q	$(Y/Q)_{qst}$	Sliding mean (2m window, step 0.5m)	00.15/99.85%-Value (Maximum)	0.10	0.07
Maximum Sum of Quasi-Static Guiding Forces per Axle	ΣY_{qst}	Sliding mean (2m window, step 0.5m)	0.15/99.85%-Value (Maximum)	9 kN [2.02 kips]	6 kN [1.35 kips]
RMS Carbody Vertical Acceleration	z''_{rms}	0.4–10 Hz Band-Pass Filter	RMS-Value	0.15	0.10
Maximum Carbody Vertical Acceleration	z''_{max}	0.4–10 Hz Band-Pass Filter	RMS-Value	0.15	0.10
RMS Carbody Lateral Acceleration	y''_{rms}	0.4–10 Hz Band-Pass Filter	0.15/99.85%-Value (Maximum)	0.40	0.27
Maximum Carbody Lateral Acceleration	y''_{max}	0.4–10 Hz Band-Pass Filter	0.15/99.85%-Value (Maximum)	0.40	0.27

7.11.2 Results

Results from the Polach method analysis gave similar results to the other validation efforts. Data from the simulation and test results was filtered and processed according to the requirements in in [Table 65](#). Data from the entire test regime (96 in total test runs) was used to compute the

necessary statistics, which include measurements from a range of track curvatures, regular track test runs, and perturbed track tested runs. Vertical load offsets were removed from measured data at the right wheel of Axle 3 and the left wheel of Axle 4 (Figure 128) to allow a fair comparison to be made between the model and test data channels. The known offsets in the IWS measured vertical load channels were approximately two times higher than the validation limit for quasi-static wheel load value (1.06 kips). Figure 128 in Section 7.1 illustrates the issue.

Figure 144 is a plot of the mean of differences between the model and test statistics for the test regime. The vertical axis of the plot is normalized according to the validation limits in Table 65. The normalized display helps to visualize the shortcomings of the model. Positive differences indicate areas where the model overpredicts the particular response, and negative values indicate underprediction. All mean difference values were within the validation limits.



Figure 144. Normalized Mean of Differences between Simulated and Measured Values

Figure 145 is a plot of the standard deviation of differences between the model and test statistics for the test regime. The vertical axis of the plot is normalized according to the validation limits in Table 65. All the standard deviations of the difference values were lower than the corresponding validation limits, although some of the values did approach the validation limits.



Figure 145. Normalized Standard Deviation of Differences between Simulated and Measured Values

Comparisons of the model and test wheel-rail forces further demonstrate the general goodness of fit of the model. The general good agreement between test and model also underscores the effectiveness of the model validation approach that used only displacement and acceleration data. This exercise showed that IWS data may not necessarily be needed to prove model validation; however, wheel-rail force data can be used as an effective tool in the model validation process.

The IWS data measured in this project was not of the best quality, due partially to the reasons discussed in [Section 7.2](#). The processing of this data was very time intensive, and it showed that for Axles 3 and 4 the model did a good job of predicting the wheel-rail forces. The IWS data was used as supplementary evidence to enhance the effectiveness of the model validation methodology by showing that the model could provide a good prediction of maximum wheel-rail forces and L/V ratios despite concerns raised in [Section 6.10](#) about the model underpredicting the vehicle responses. However, because the IWS were placed in Axles 3 and 4, the wheel-rail force data could not address questions raised about the lateral accelerations on Axle 2 and their effects on wheel-rail forces. IWS data therefore can be useful in evaluating a model's accuracy, but cannot alone determine the accuracy of a vehicle model.

Acceleration and displacement data alone can provide the carbody and component motion information necessary to fairly assess a model. If a suitable number of acceleration and displacement measurements are made for the system, direct wheel-rail forces may not be required. They can be inferred using calculations from an appropriate vehicle dynamics software tool, such as NUCARS. However, if IWS were not available, extra efforts would be required to address the discrepancies identified in [Section 6.10](#) and resolve any concerns about the model underpredicting the dynamic response.

Under normal circumstances for a test with both IWS and displacement and acceleration measurements, at this stage of the model validation process, additional effort would be made to further understand the discrepancies noted in [Section 6.10](#) above and revise the model to reduce the discrepancies. A more detailed analysis of the IWS data including comparison of time histories of wheel-rail forces would assist in understanding the following:

- Differences in lateral displacement and acceleration between the two ends of the car
- Effects of the differences in lateral displacement and acceleration on roll and yaw response
- Resolving concerns about underprediction of dynamic response

The IWS data would be unlikely to resolve concerns about the Axle 2 oscillations.

8. Conclusion

The research team performed work funded by FRA to characterize, model, and validate the model of a high-speed passenger vehicle. The objectives were to develop a list of parameters necessary to complete a dynamic model of the passenger vehicle, perform tests to measure the parameters, develop a mathematical model of the vehicle using the measured parameters, and perform on-track tests to validate the model. This report details the performance of each task and discusses different methods that can be used to perform each task where appropriate.

The team identified specific parameters that need to be determined to develop a dynamic vehicle model. Researchers also recommended specific characterization tests that can be used to determine each of the parameter values. The team used this characterization test regimen to determine the different mass, stiffness, and damping characteristics needed to develop a model of the DOTX-216 car. When a parameter value could not be accurately determined, the characteristics were estimated.

Researchers used the determined parameter values to develop a mathematical model of the vehicle using NUCARS software. For certain parameters, the measured value had to be tuned to help the model achieve the desired vehicle response. The model was then used to simulate a series of on-track tests at TTC over a combination of regular and perturbed test tracks.

The DOTX-216 car was tested over tracks at TTC using the same on-track test regime. Results from the tests were used to evaluate the performance of the NUCARS model of the DOTX-216 car and assess its validity. Model validation was first evaluated using only displacement and acceleration measurements using direct comparisons and the Sprague and Geers method. The model of the DOTX-216 car demonstrated good agreement with most of the measured test data for suspension displacement, carbody accelerations, and truck accelerations; however, the vestibule end lateral truck displacements were consistently higher in the measured data than the simulation data. This difference was possibly due to modeling assumptions resulting from characterization test limitations at the vestibule end truck and modeling simplifications at the coupler connection.

The Sprague and Geers methodology did a reasonable job at highlighting the data channels that matched well and those that did not. However, it remained necessary to use expert judgement to determine whether the areas where there was not a good match were critical to achieving a validated model.

Overall, the model of the DOTX-216 car predicted similar trends in suspension displacements and carbody and truck accelerations that can be used for dynamic comparisons with FRA requirements. However, the discrepancies between model and test data showed that the model tends to underpredict the actual dynamic response.

From the perspective of using models for the purpose of vehicle qualification, it is usually preferred to have the model err on the conservative side and overpredict the response. Therefore, the model DOTX-216 car should be considered only partially validated for this purpose. A particular concern is that the oscillations of Axle 2 are not predicted at all.

Model validation was further evaluated using wheel-rail force data from simulation and measured IWS data using direct comparisons and the Polach method. The model of the DOTX-216 car again demonstrated generally good agreement with measured test data. The modeling

exercise performed for this project demonstrated the usefulness and accuracy of the team's characterization and modeling approach.

The IWS data was used as supplementary evidence to enhance the effectiveness of the model validation methodology by showing that the model was capable of providing a good prediction of minimum and maximum wheel-rail forces and L/V ratios, despite concerns raised in [Section 6.10](#) about the model underpredicting the vehicle dynamic response. However, because the IWS were placed in Axles 3 and 4, the wheel-rail force data could not address questions raised about the lateral accelerations on Axle 2 and their effects on wheel-rail forces. IWS data can be useful in evaluating a model's accuracy, but cannot alone be used to determine the accuracy of a vehicle model.

Test results showed that acceleration and displacement data alone can provide the carbody and component motion information necessary to fairly assess a model. If a suitable number of acceleration and displacement measurements are made for the system, direct wheel-rail forces may not be required. They can be inferred using calculations from an appropriate vehicle dynamics software tool, such as NUCARS. However, if wheel-rail force data from IWS is not available, extra effort would be required to address the discrepancies identified in [Section 6.10](#) and resolve any concerns about the model underpredicting the dynamic response.

At this stage, the model has shown good preliminary validation. No attempts were made to improve the model and address any discrepancies between the test and model results. The next step in the validation process would normally be to perform more detailed analyses to further understand the discrepancies noted in [Section 6.10](#) and revise the model to reduce the discrepancies. A more detailed analysis of the displacement, acceleration, and IWS data – including a comparison of time histories of wheel-rail forces – is needed to understand:

- Differences in lateral displacement and acceleration between the two ends of the car
- Effects of the differences in lateral displacement and acceleration on roll and yaw response
- Concerns about underprediction of dynamic response
- Concerns about the axle 2 oscillations

9. Recommendations

Building upon the research in this report, the team recommends further work be performed to evaluate the effects that changes in certain parameters can have on model performance and validation. The additional analysis would help improve the validity of the model and determine the sensitivity of the model to different parameter variations. It would also help to identify specific parameters that must be measured with a high level of accuracy.

To improve model validity, a more detailed analysis of the displacement, acceleration, and IWS data should be performed, and the model should be updated to address the following discrepancies:

- Differences in lateral displacement and acceleration between the two ends of the car
- Concerns about underprediction of dynamic response
- Concerns about the Axle 2 oscillations

The validated model of the DOTX-216 car could be used as a test subject to vary and examine different parameters and their effects on model performance. The parameter variations could include, but should not be limited to, the following carbody and truck component masses:

- Carbody CG location
 - Longitudinal, lateral, and vertical
- Carbody and truck component moments of inertia
 - Roll, pitch, and yaw
- Primary suspension characteristics
 - Lateral, longitudinal, and vertical stiffness and damping
- Secondary suspension characteristics
 - Lateral, longitudinal, and vertical stiffness and damping
- Vertical and lateral dampers
- Center plate friction
- Axle box friction
- Truck and axle misalignments

Data from the simulations could then be compared to the measured data from the on-track tests in this project.

10. References

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Appendix A. Additional Characterization Test Results

Carbody Resonance Test – Shake and Bake with Traction Rods

Refer to [Figure 6](#) in the body of the report for synthetic channel calculations.

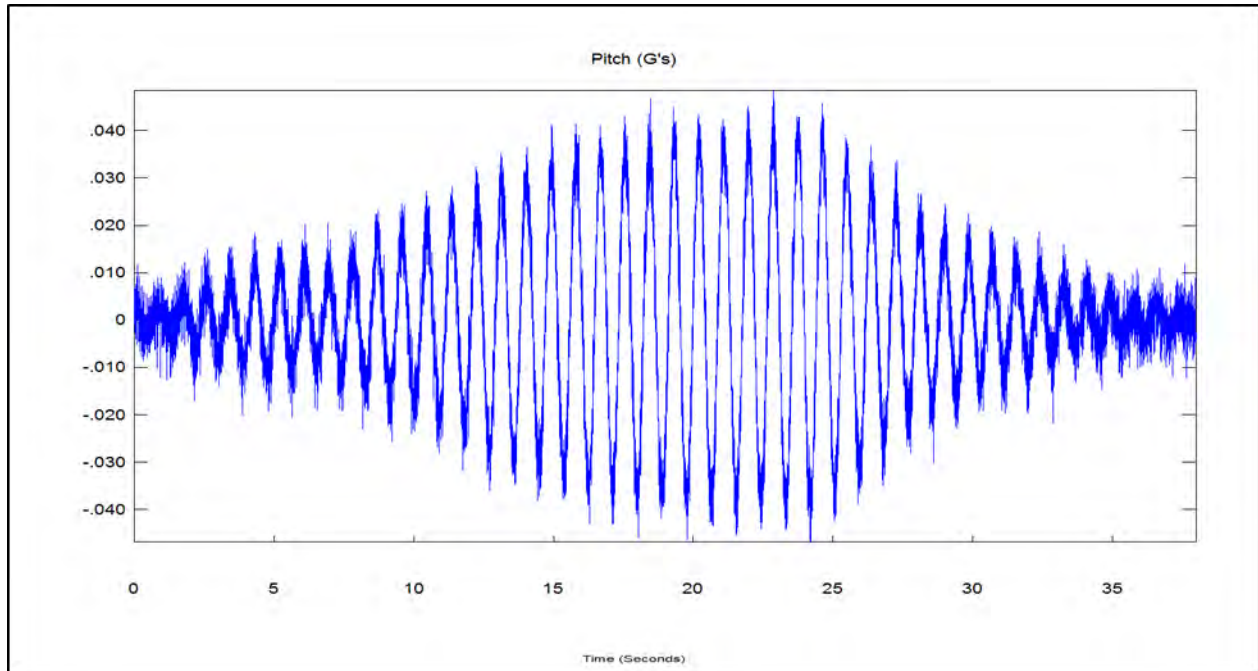


Figure A1. Pitch Mode Excitation – with Traction Rods

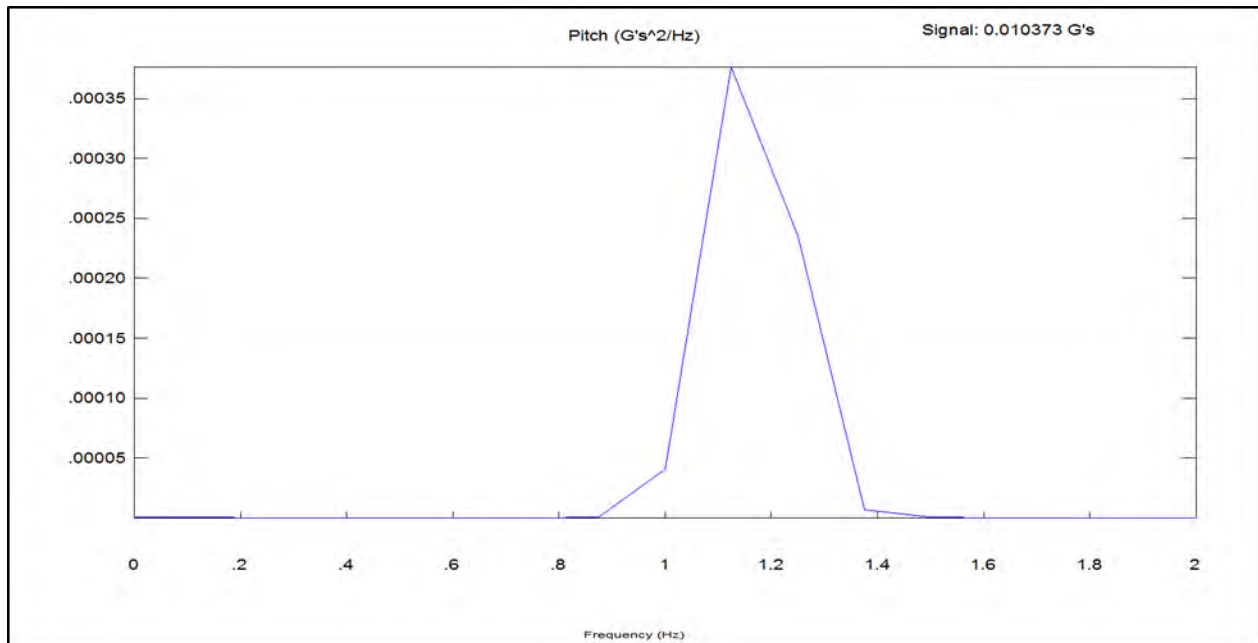


Figure A2. PSD of Pitch Mode – with Traction Rods

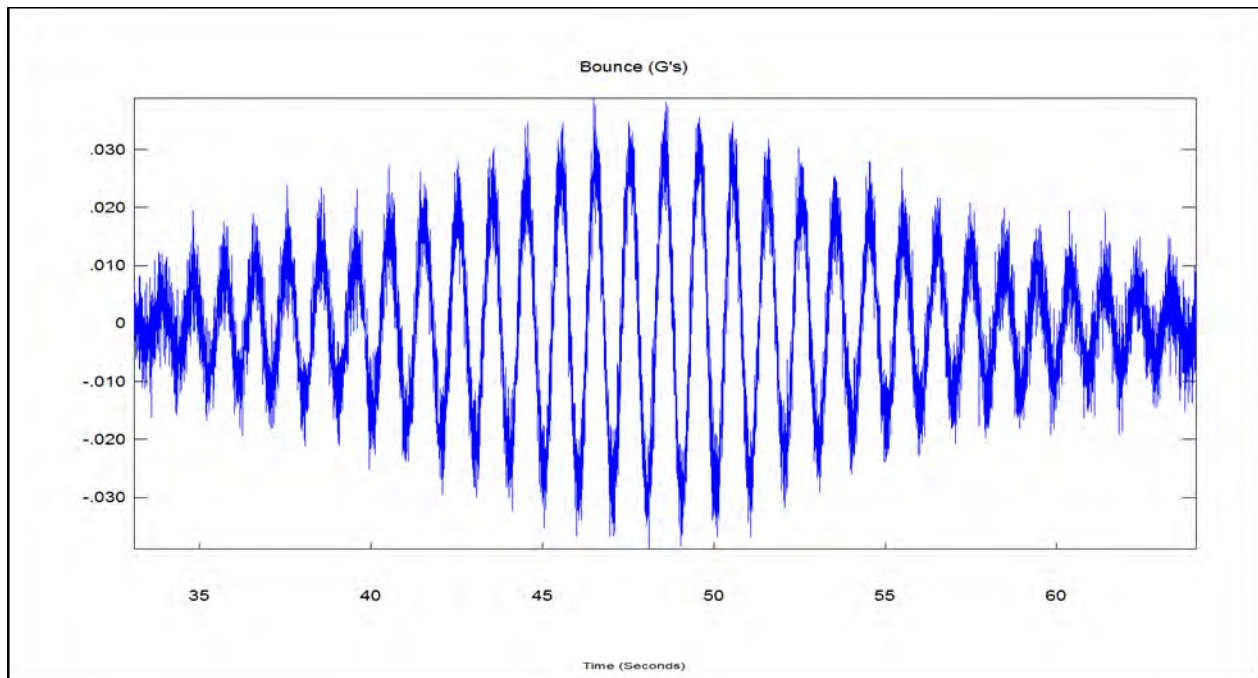


Figure A3. Bounce Mode Excitation – with Traction Rods

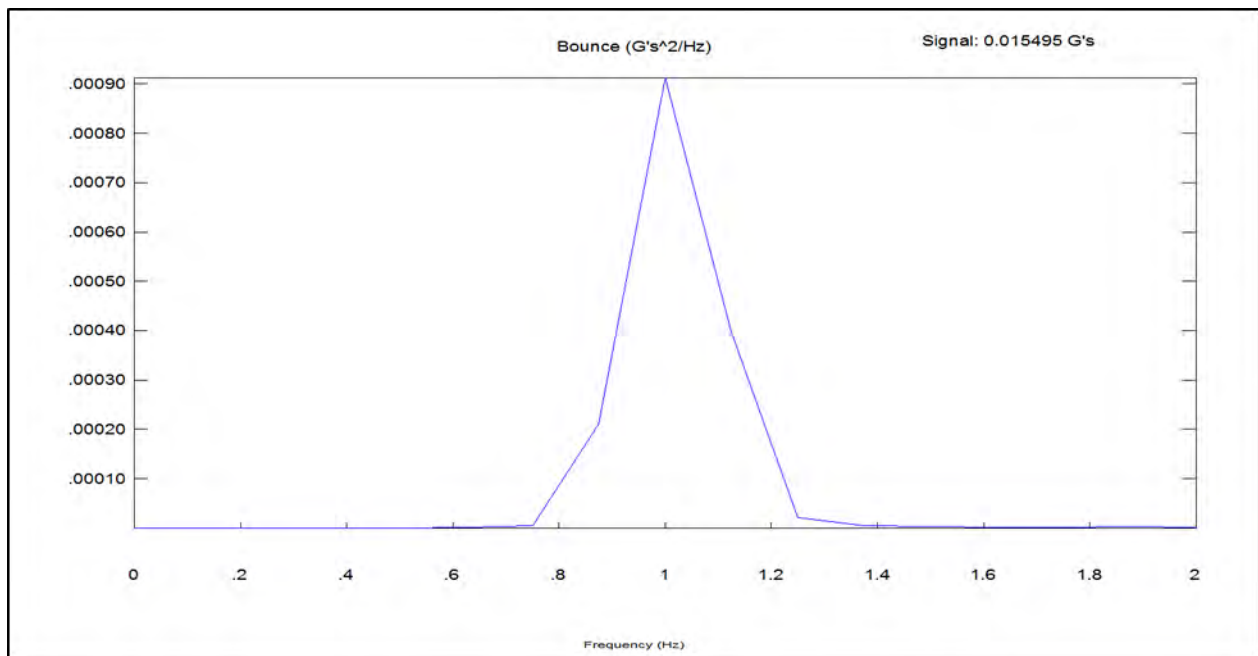


Figure A4. PSD of Bounce Mode – with Traction Rods

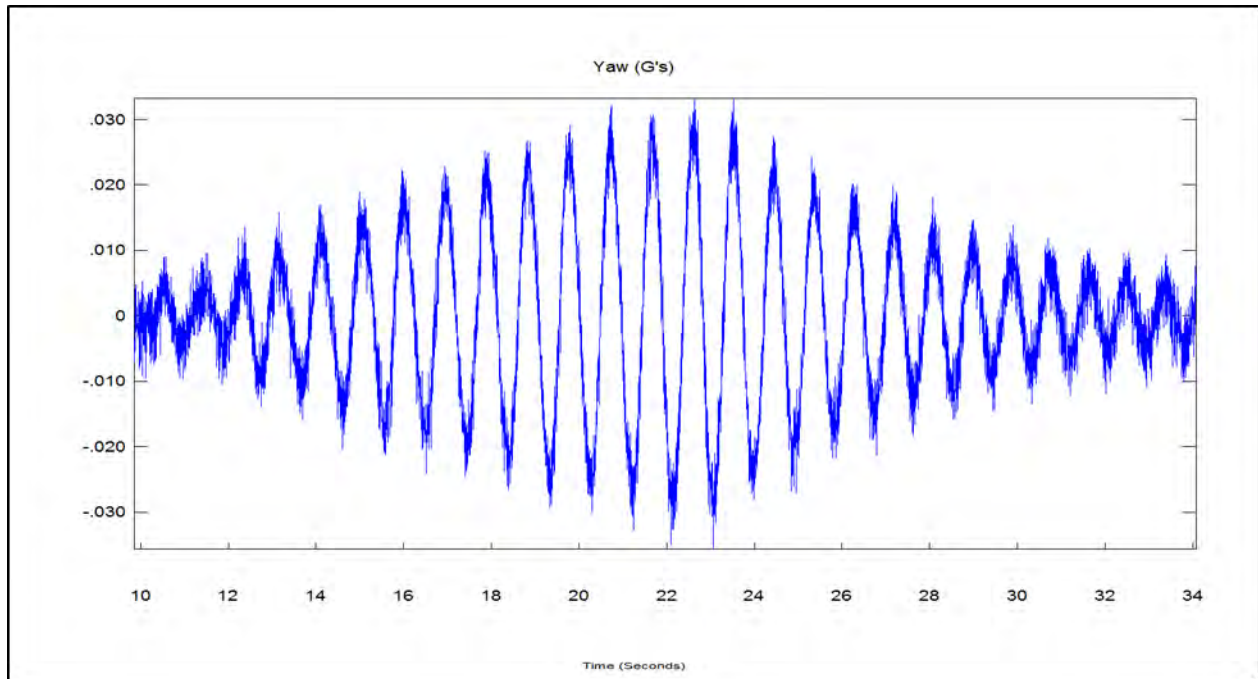


Figure A5. Yaw Mode Excitation – with Traction Rods

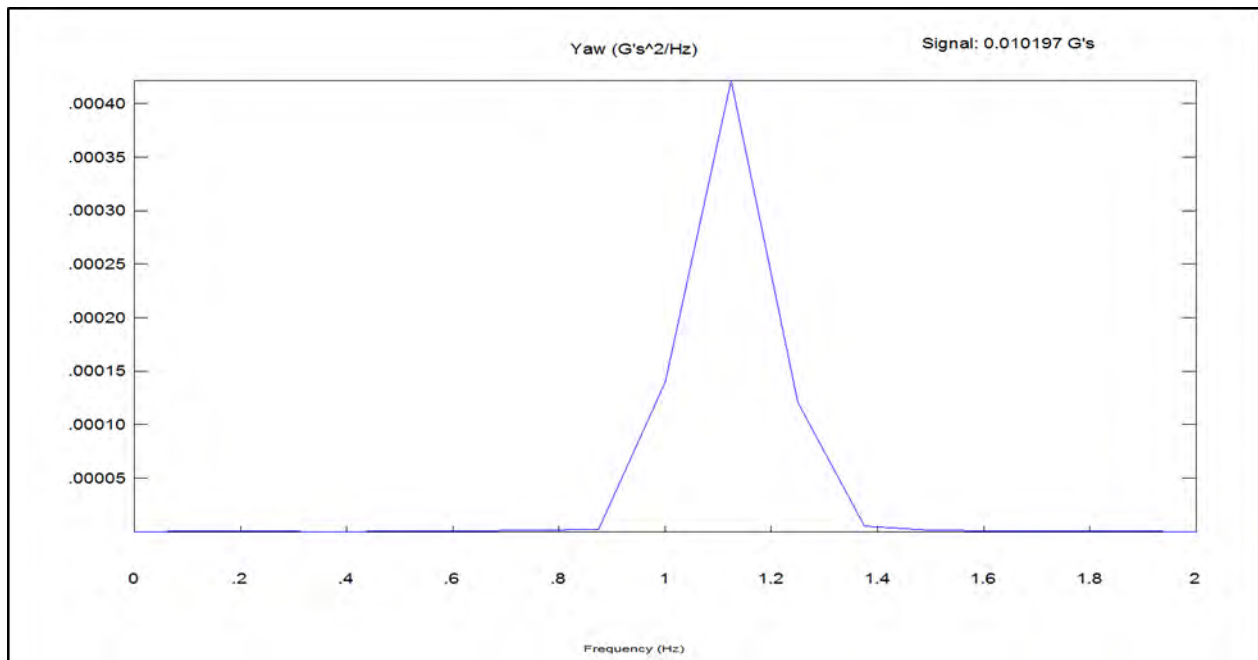


Figure A6. PSD of Yaw Mode – with Traction Rods

Lateral channel labeled **Lower Center Roll**.

Roll channel labeled **Upper Center Roll** .

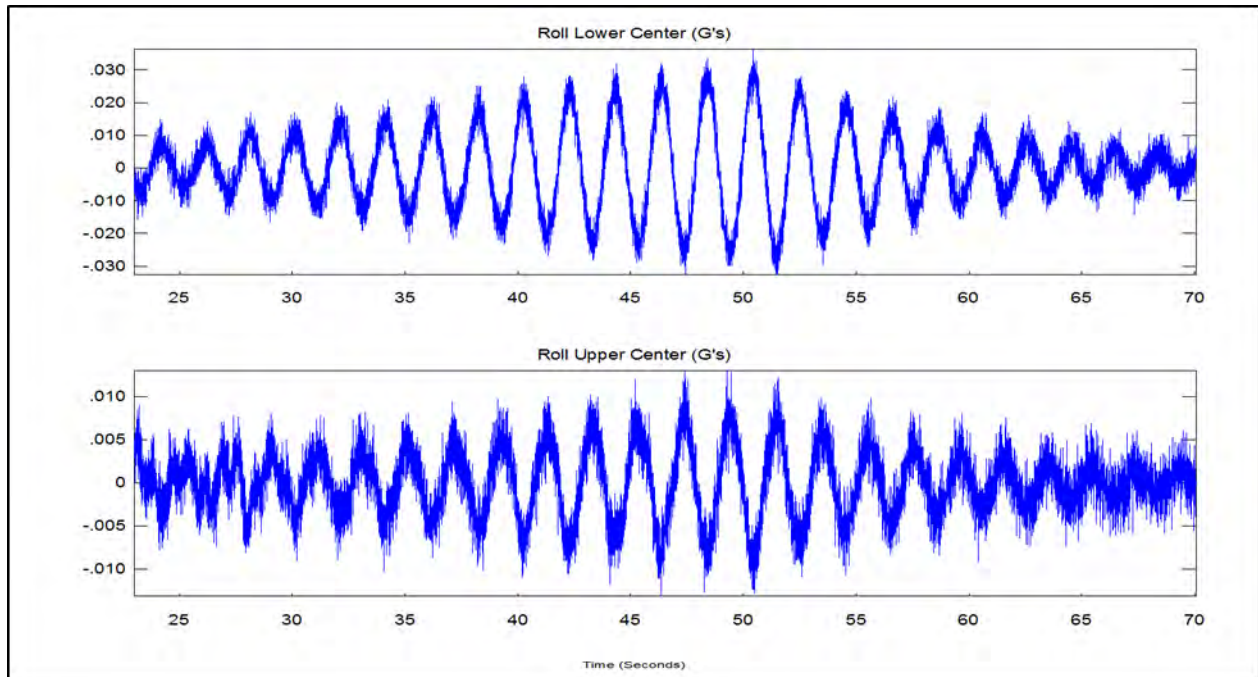


Figure A7. Lower Center Roll Mode Excitation – with Traction Rods

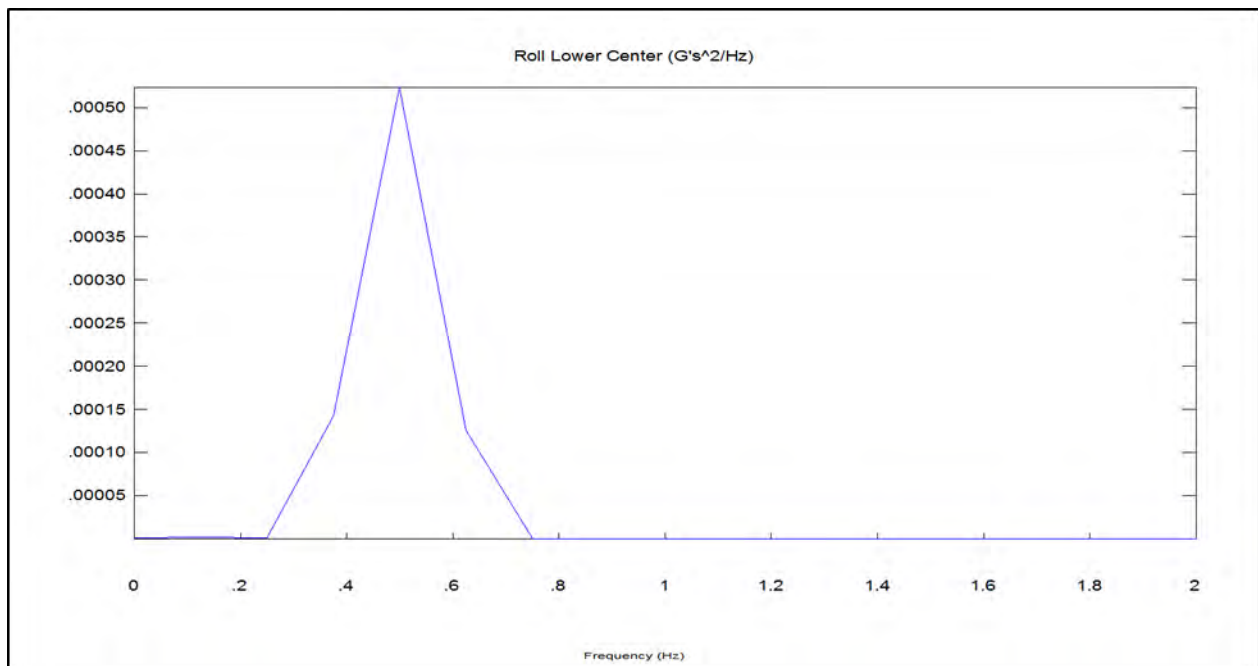


Figure A8. PSD of Lower Center Roll Mode – with Traction Rods

Lateral channel labeled **Lower Center Roll**.

Roll channel labeled **Upper Center Roll**.

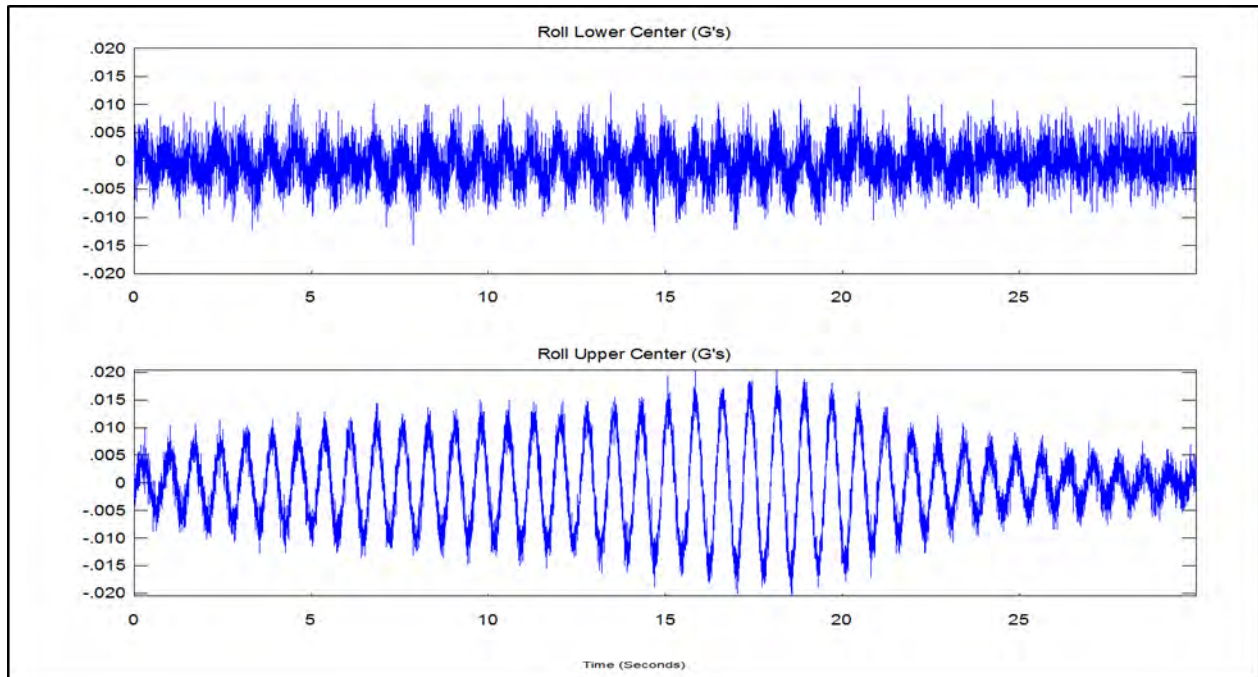


Figure A9. Upper Center Roll Mode Excitation – with Traction Rods

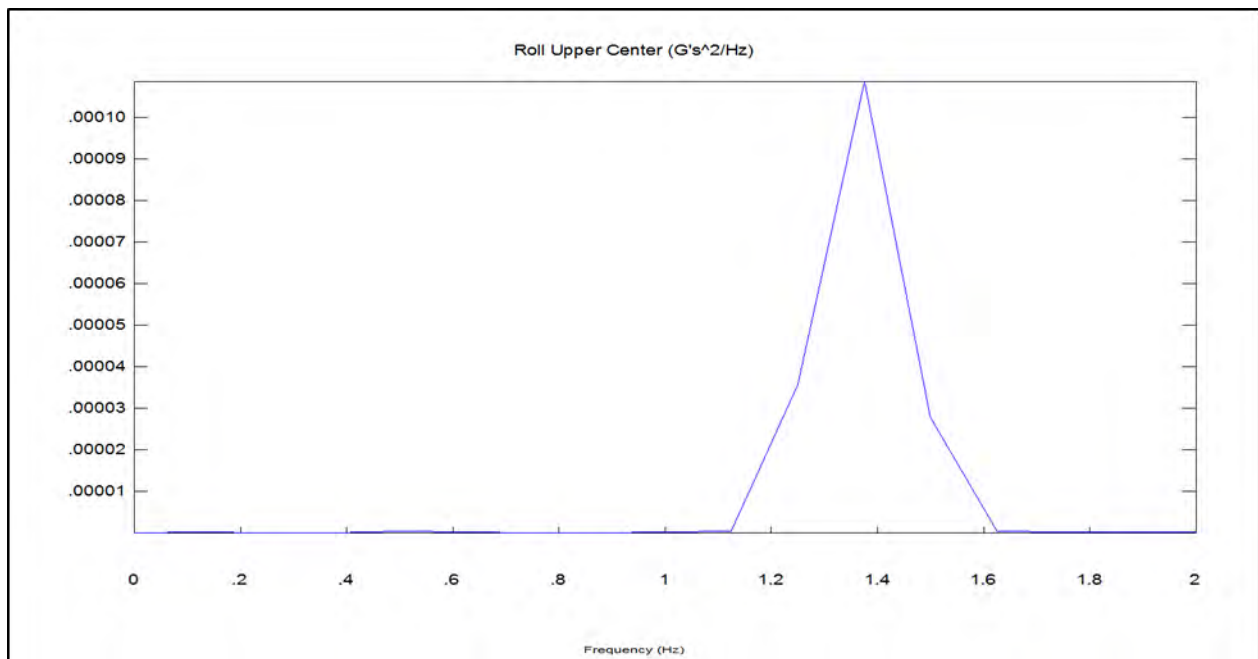


Figure A10. PSD of Upper Center Roll Mode – with Traction Rods

Carbody Resonance Test – Shake and Bake without Traction Rods

Refer to Figure 6 for synthetic channel calculations.

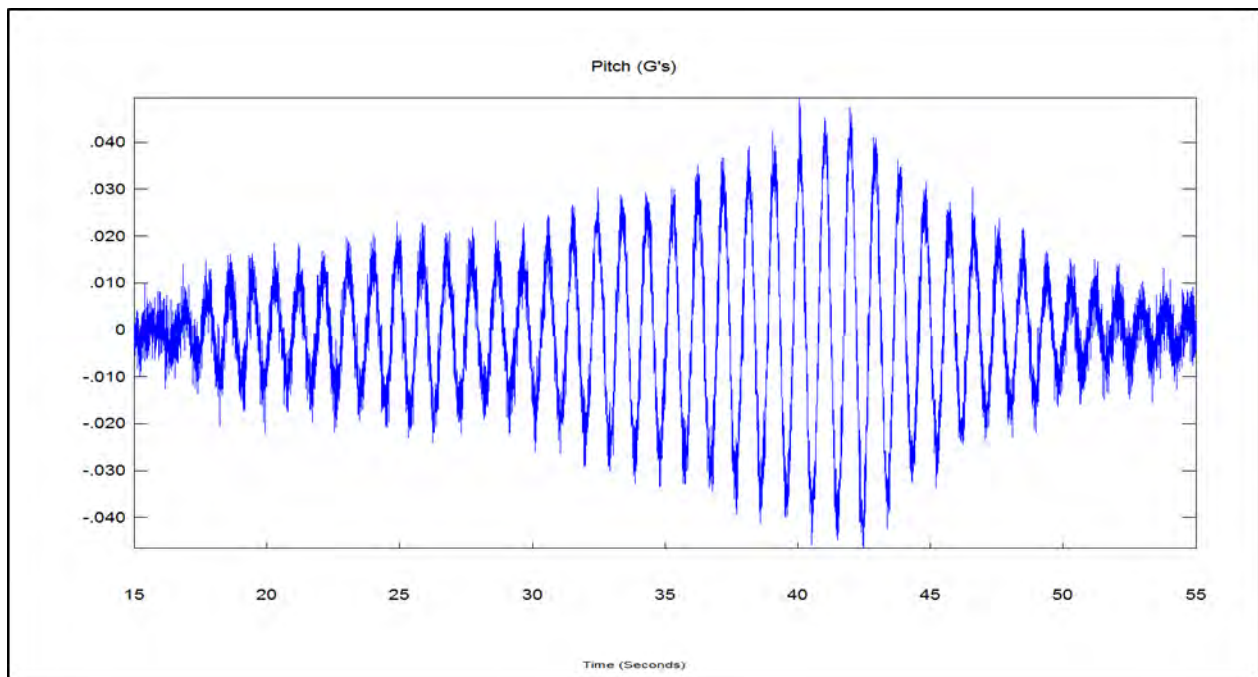


Figure A11. Pitch Mode Excitation – without Traction Rods

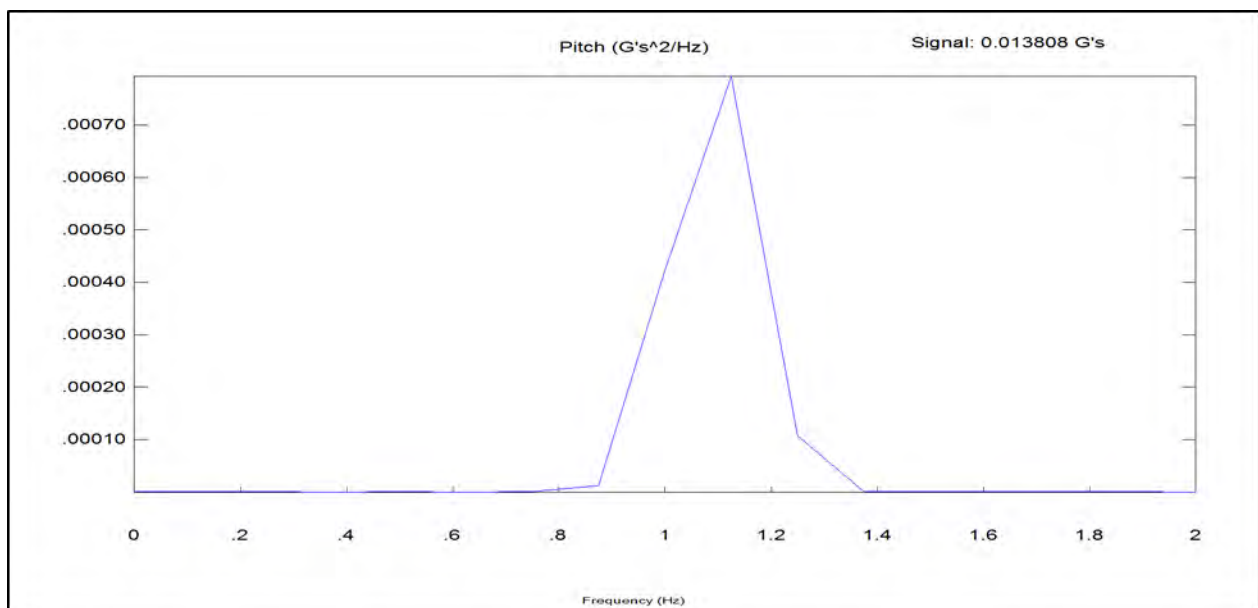


Figure A12. PSD of Pitch Mode – without Traction Rods

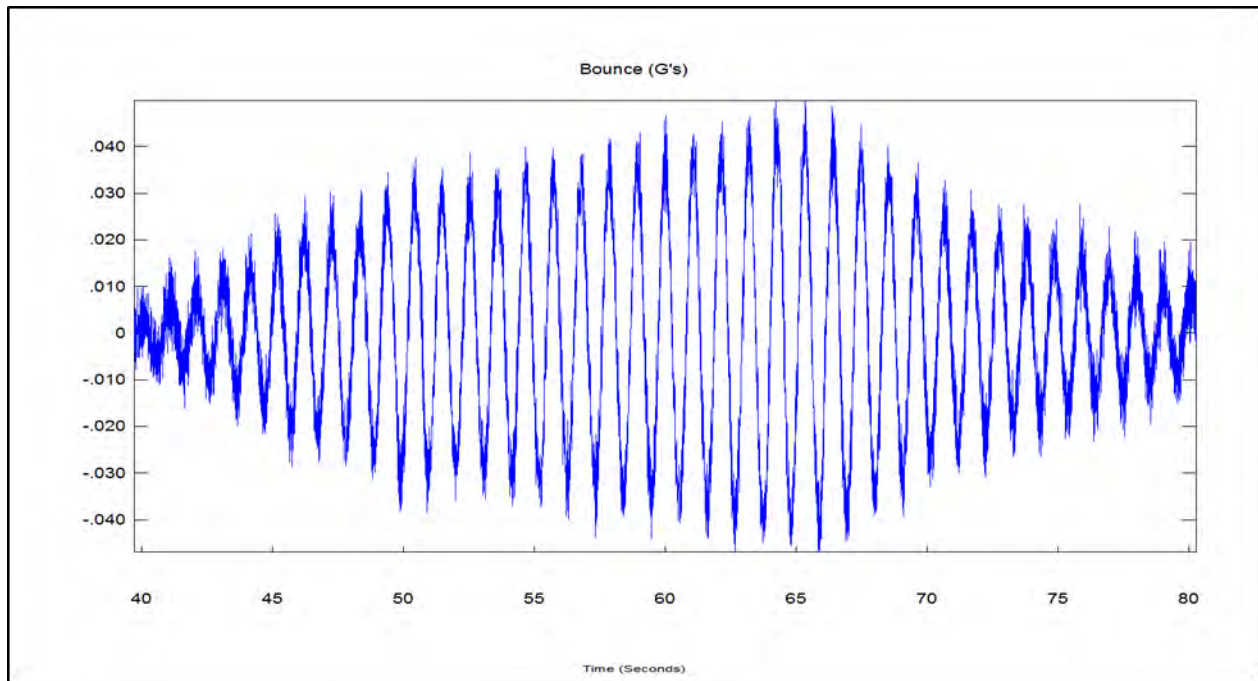


Figure A13. Bounce Mode Excitation – without Traction Rods

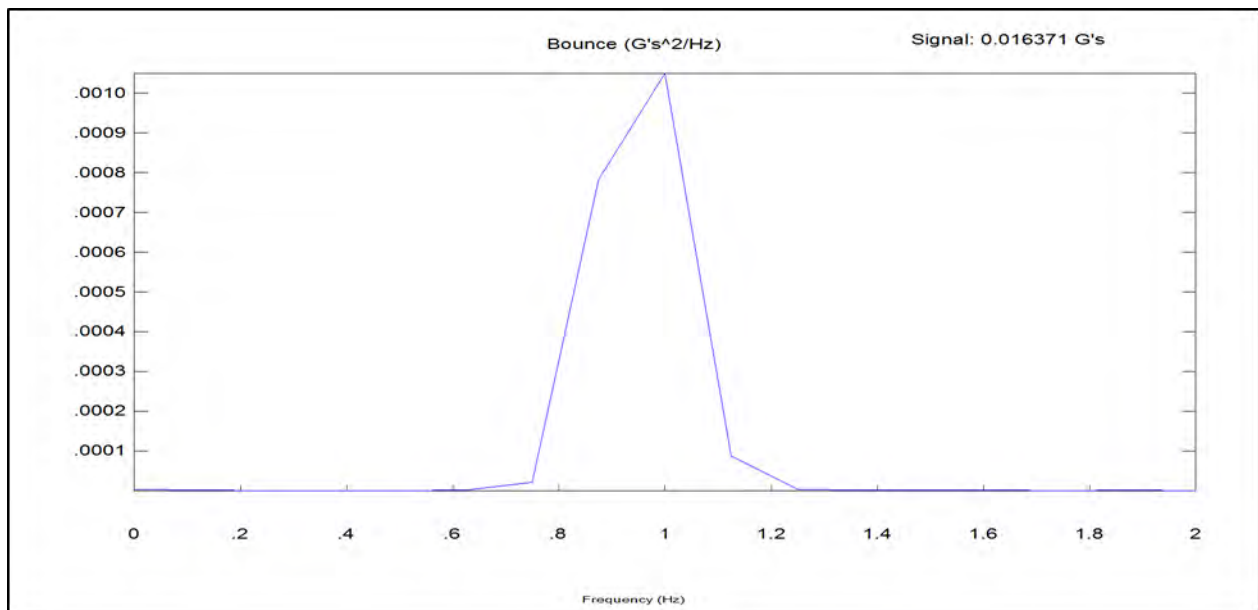


Figure A14. PSD of Bounce Mode – without Traction Rods

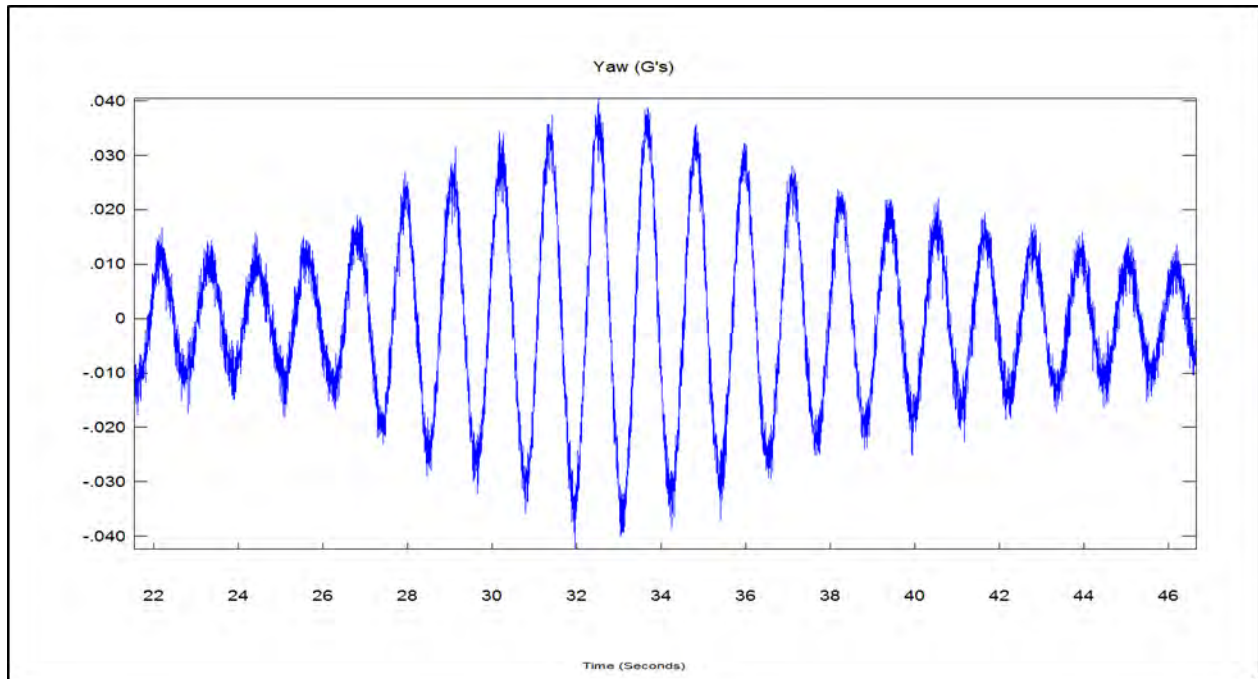


Figure A15. Yaw Mode Excitation – without Traction Rods

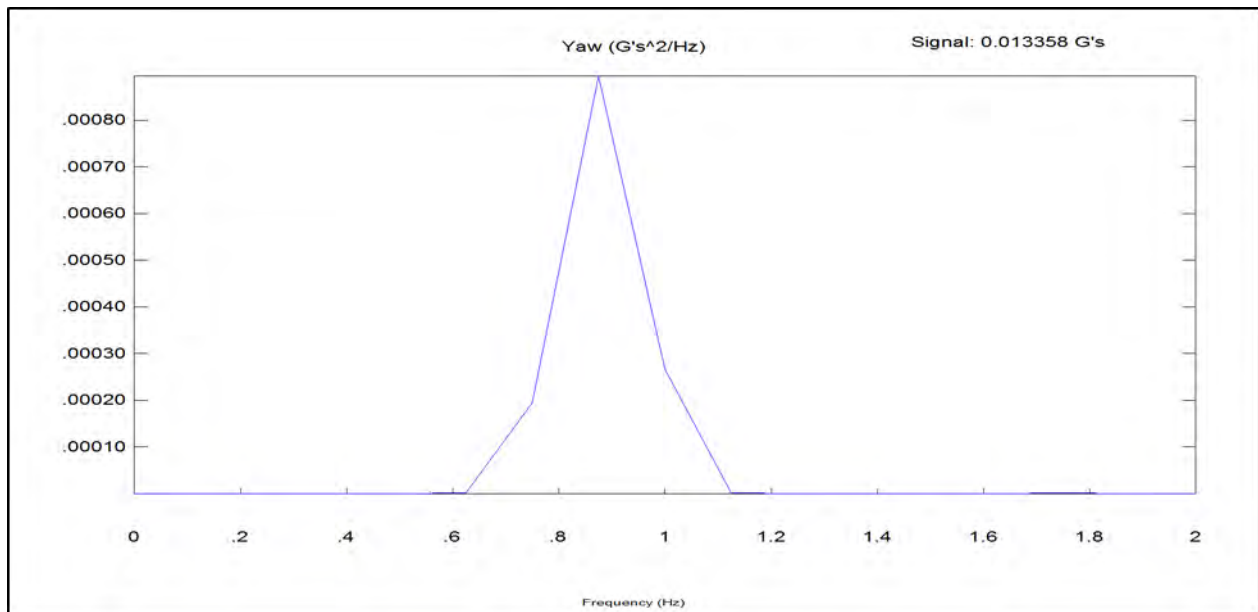


Figure A16. PSD of Yaw Mode – without Traction Rods

Lateral channel labeled **Lower Center Roll**.

Roll channel labeled **Upper Center Roll**.

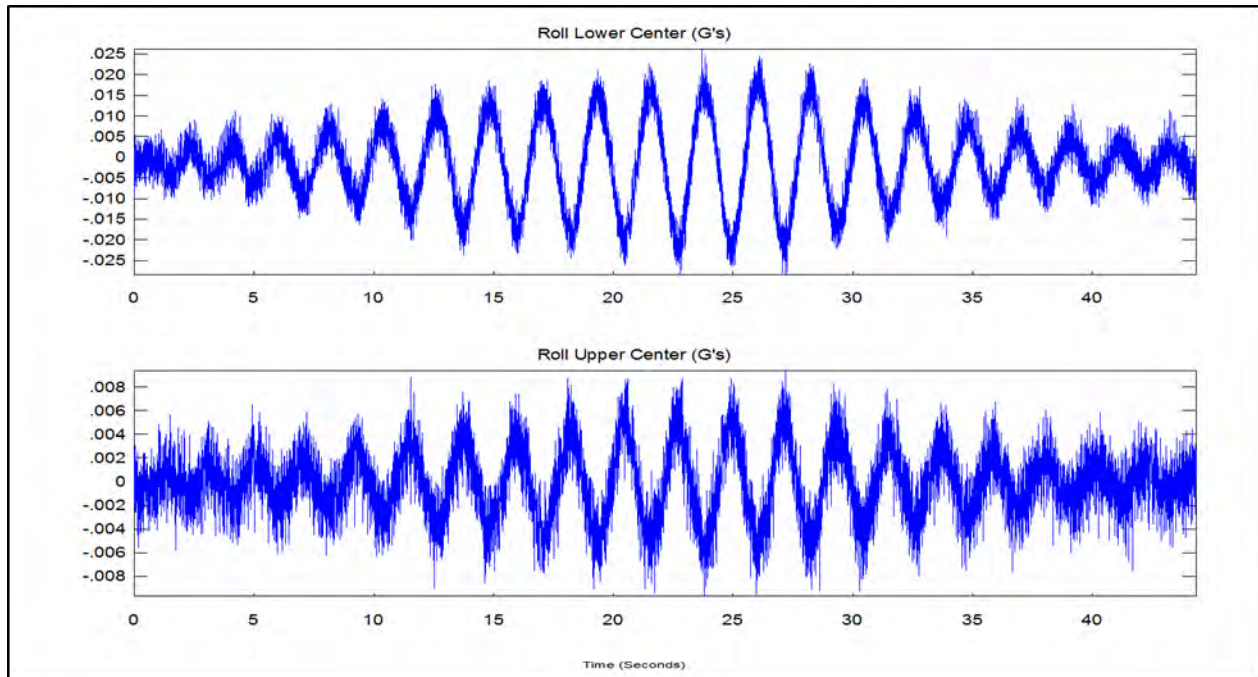


Figure A17. Lower Center Roll Mode Excitation – without Traction Rods

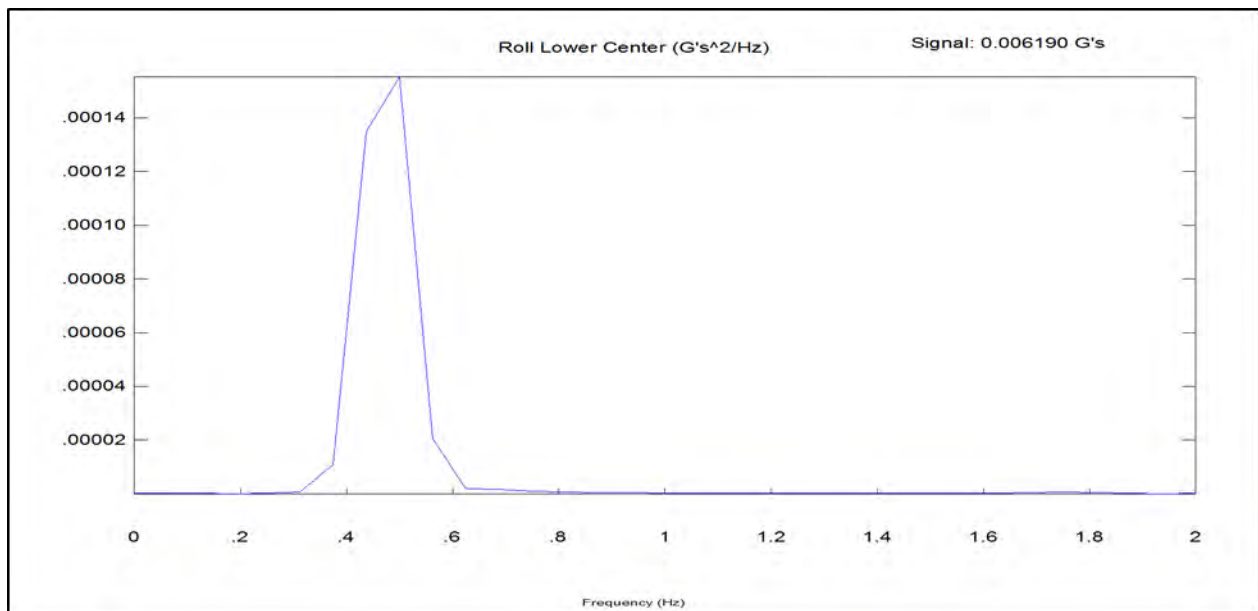


Figure A18. PSD of Lower Center Roll Mode – without Traction Rods

Lateral channel labeled **Lower Center Roll**.

Roll channel labeled **Upper Center Roll**.

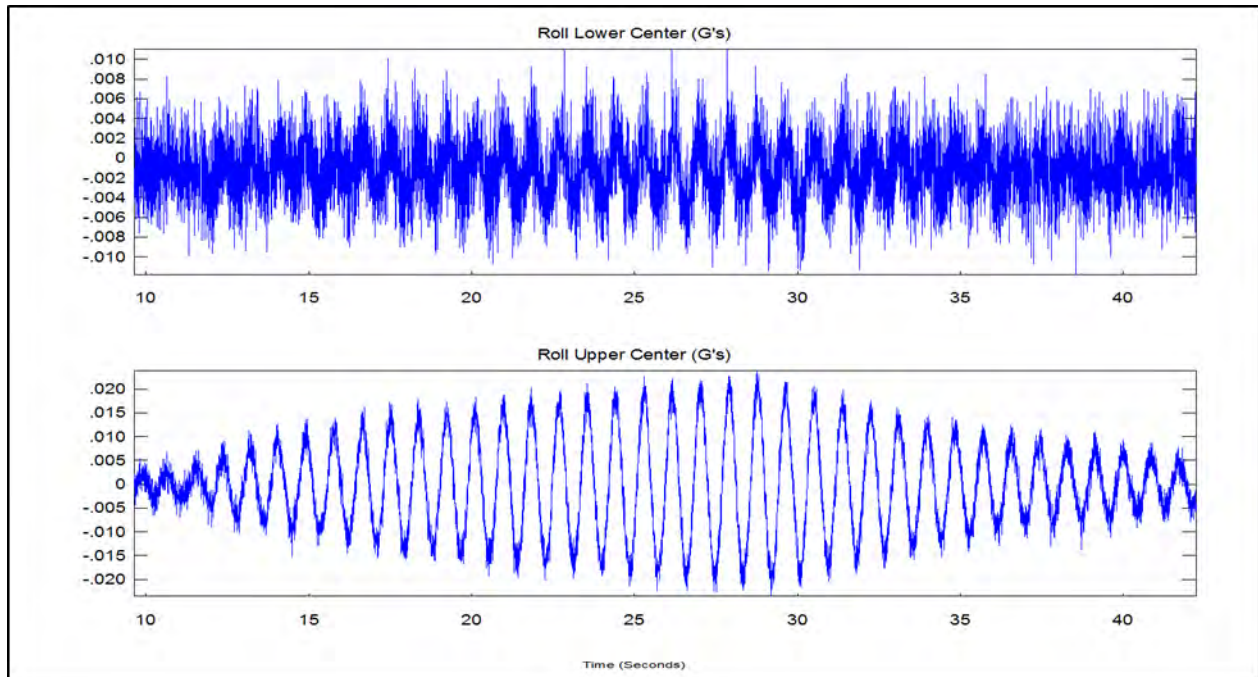


Figure A19. Upper Center Roll Mode Excitation – without Traction Rods

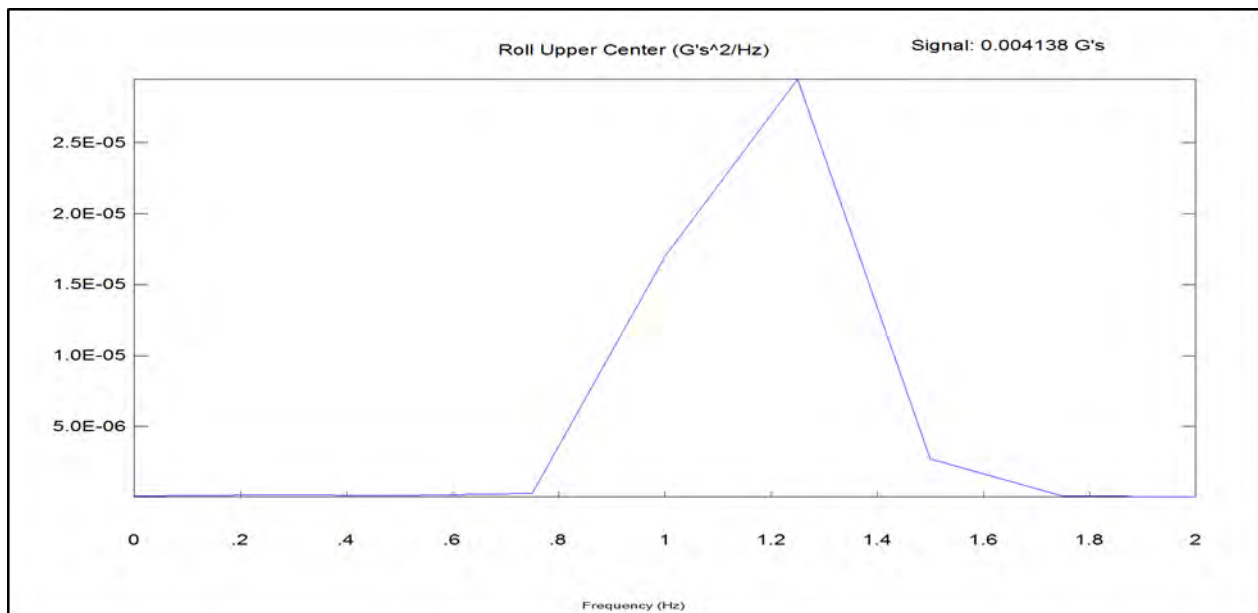


Figure A20. PSD of Upper Center Roll Mode – without Traction Rods

Jacking Tests

With Traction Rods Connected

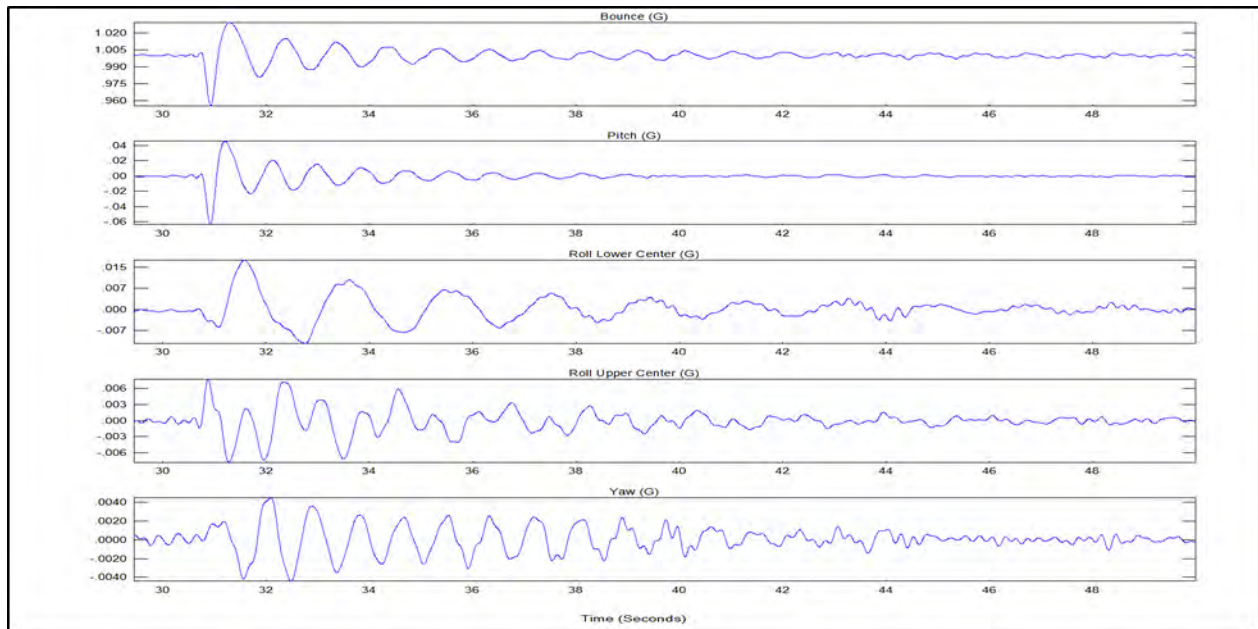


Figure A21. Vertical Jack and Drop at Cab End on Left and Right Sides

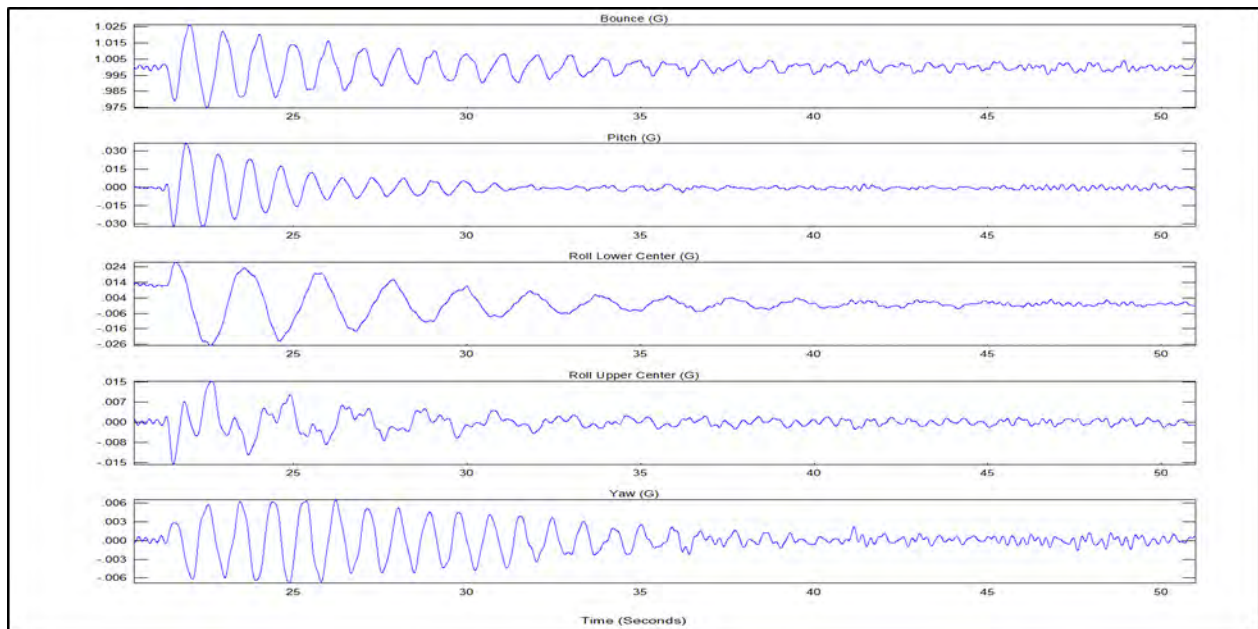


Figure A22. Vertical Jack and Drop at Cab End on Left Side

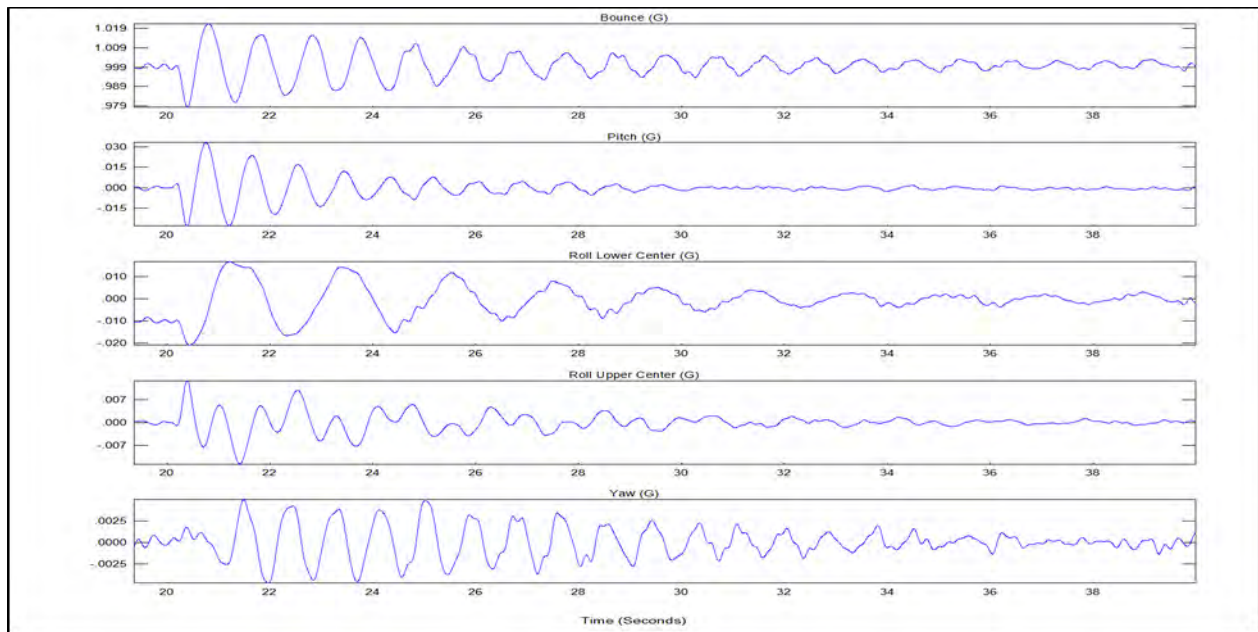


Figure A23. Vertical Jack and Drop at Cab End on Right Side

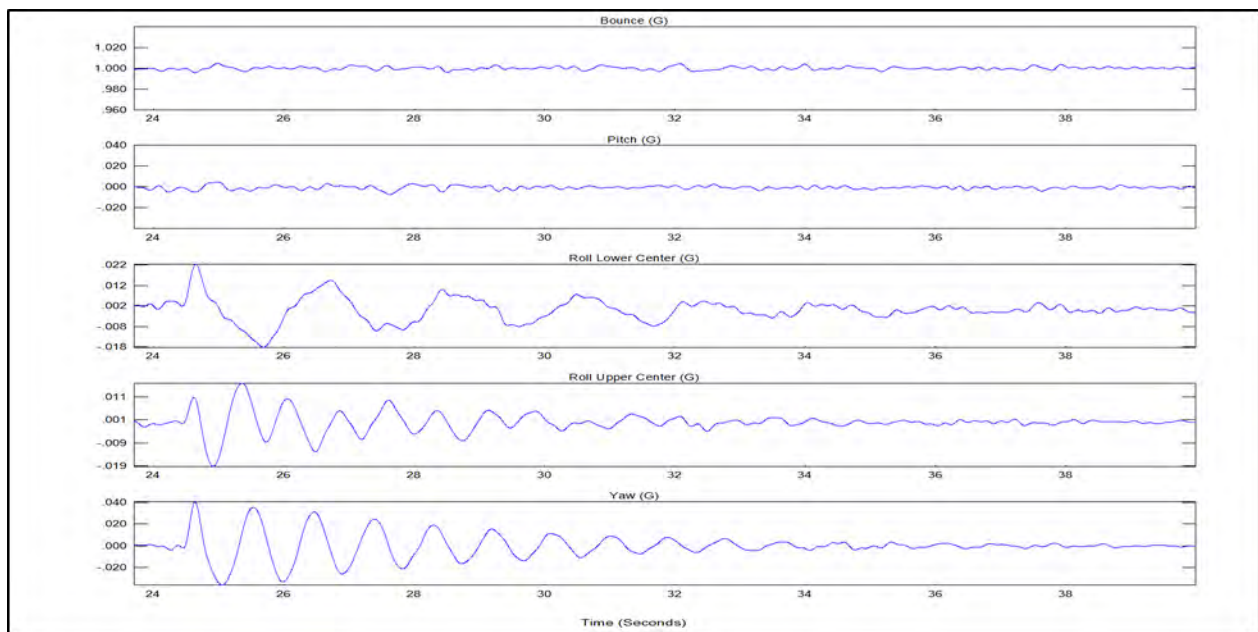


Figure A24. Lateral Jacking at Cab End on Right Side

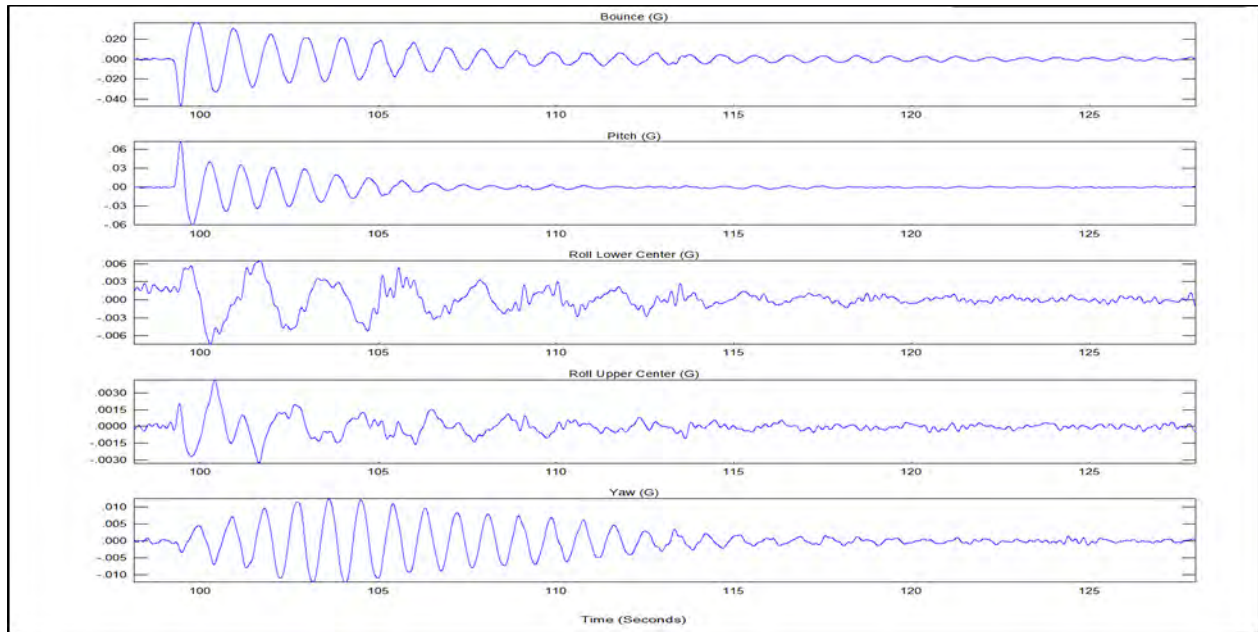


Figure A25. Vertical Jack and Drop at Non-Cab End on Left and Right Sides

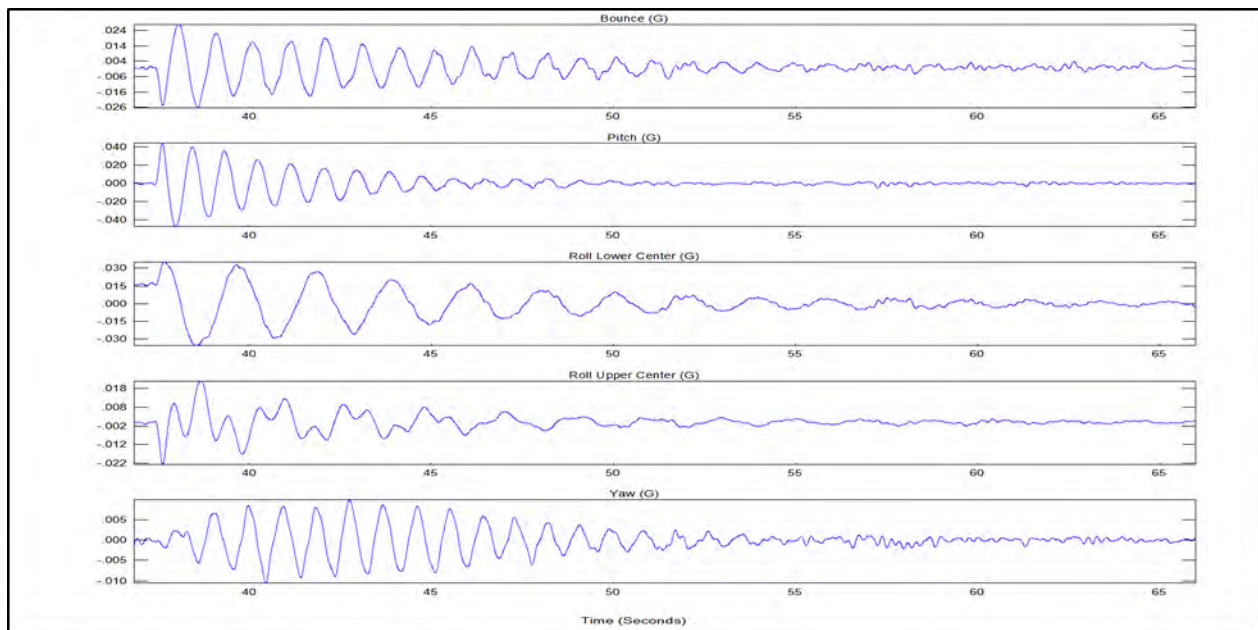


Figure A26. Vertical Jack and Drop at Non-Cab End on Left Side

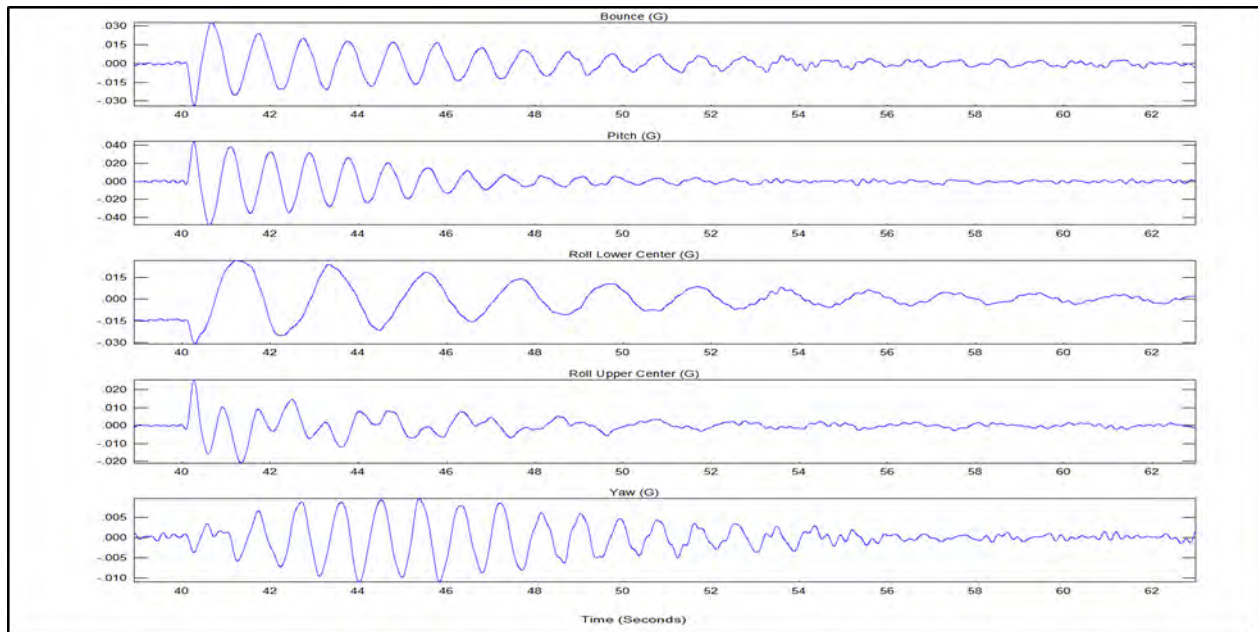


Figure A27. Vertical Jack and Drop at Non-Cab End on Right Side

Without Traction Rods Connected

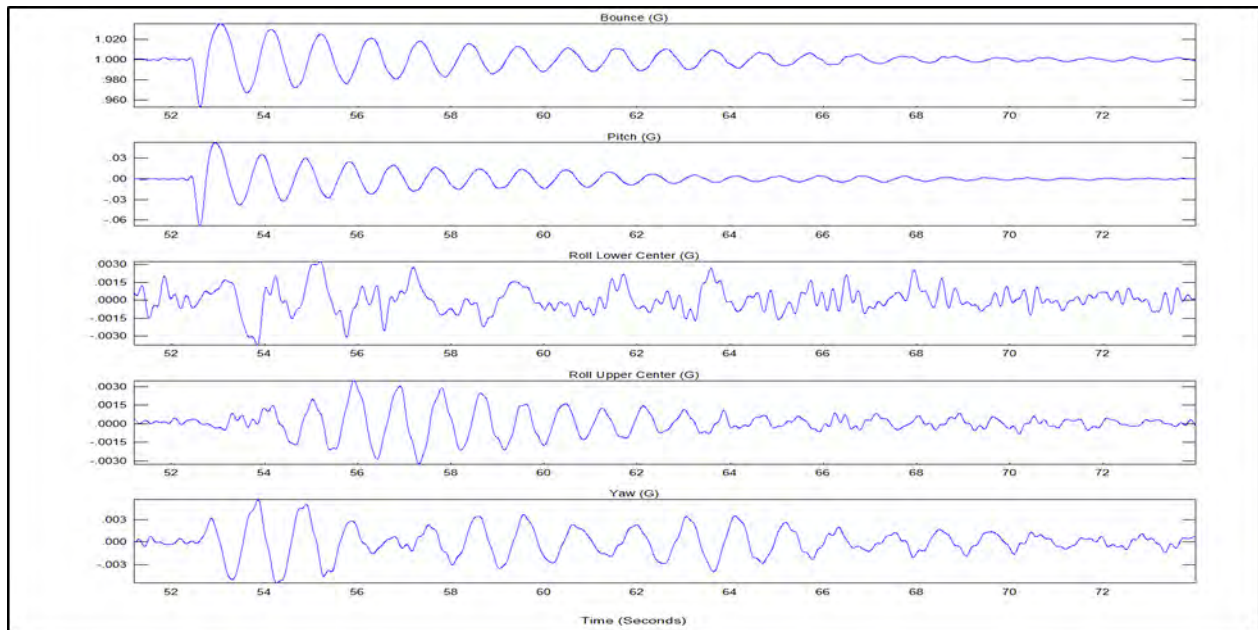


Figure A28. Vertical Jack and Drop at Cab End on Left and Right Sides – No Traction Rods

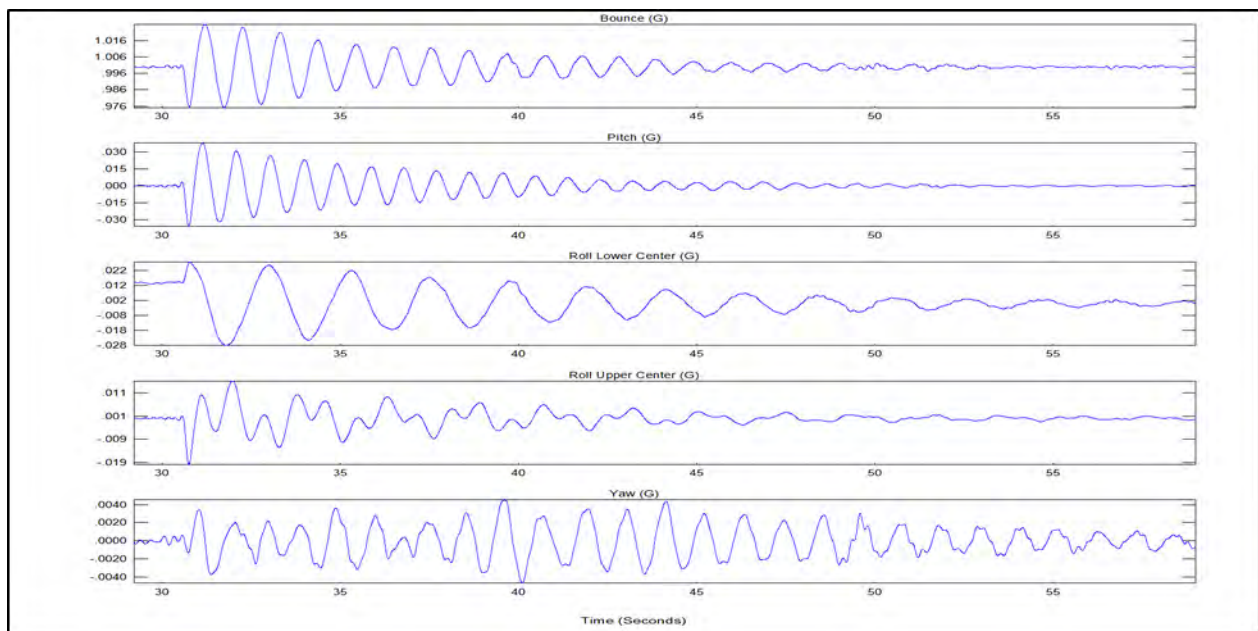


Figure A29. Vertical Jack and Drop at Cab End on Left Side – No Traction Rods

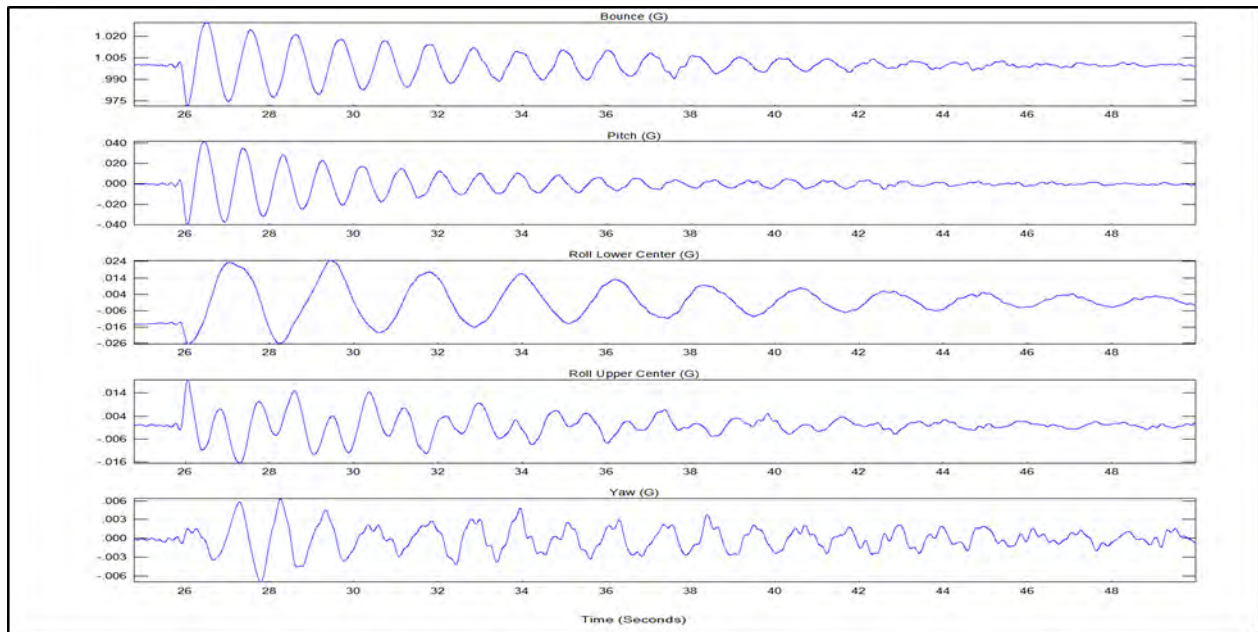


Figure A30. Vertical Jack and Drop at Cab End on Right Side – No Traction Rods

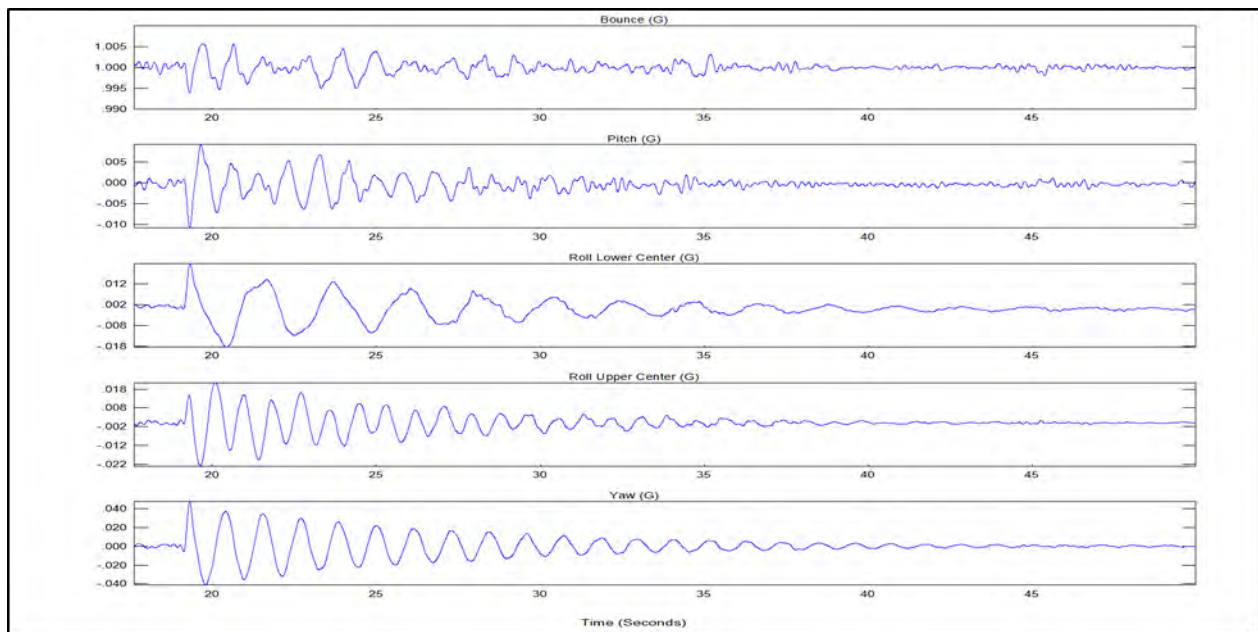


Figure A31. Lateral Jacking at Cab End on Right Side – No Traction Rods

Longitudinal Suspension Stiffness Test – Chocked Axle 1

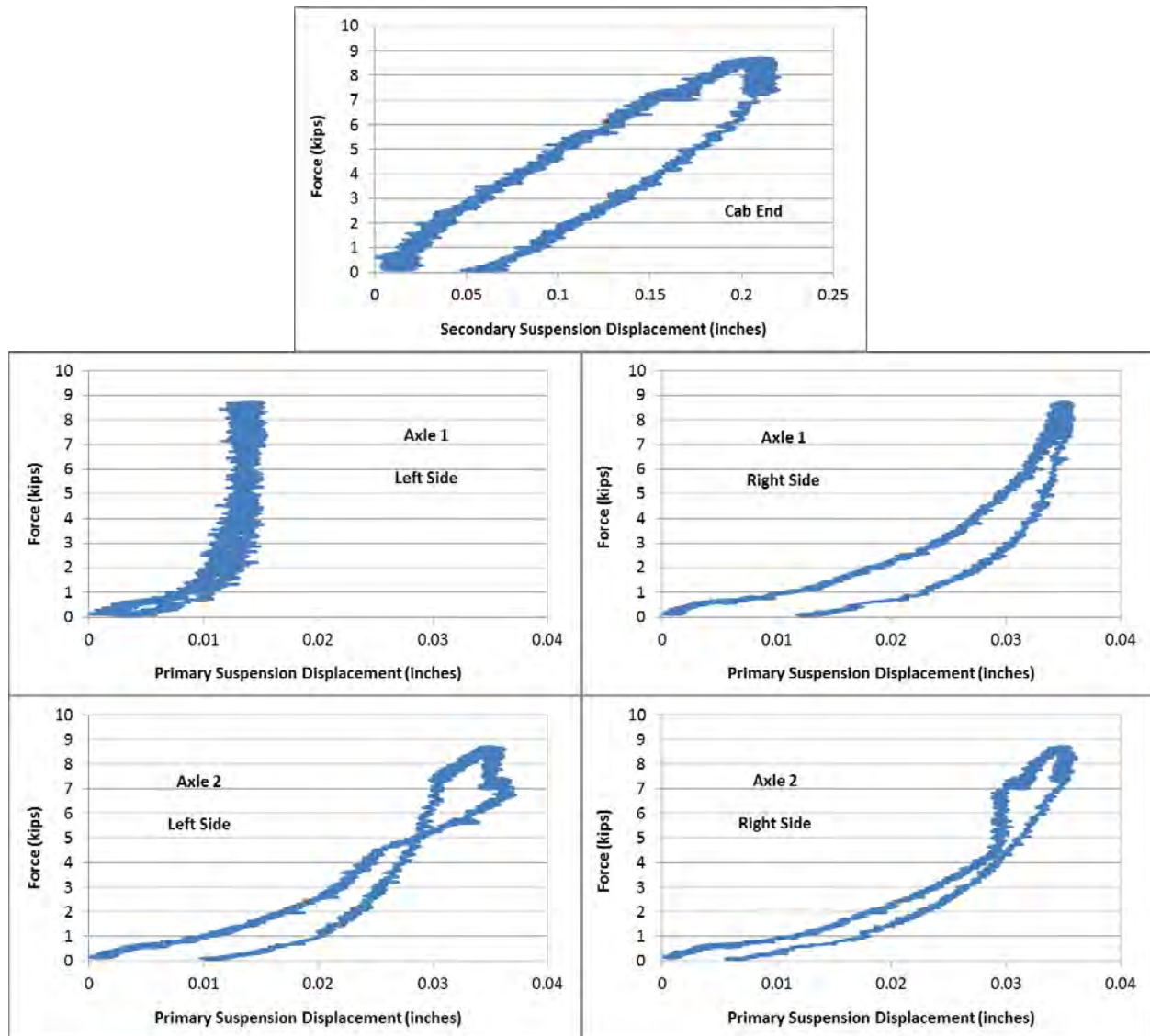


Figure A32. 8.75-Kip Load – Longitudinal Suspension Stiffness Test Axle 1 Chocked

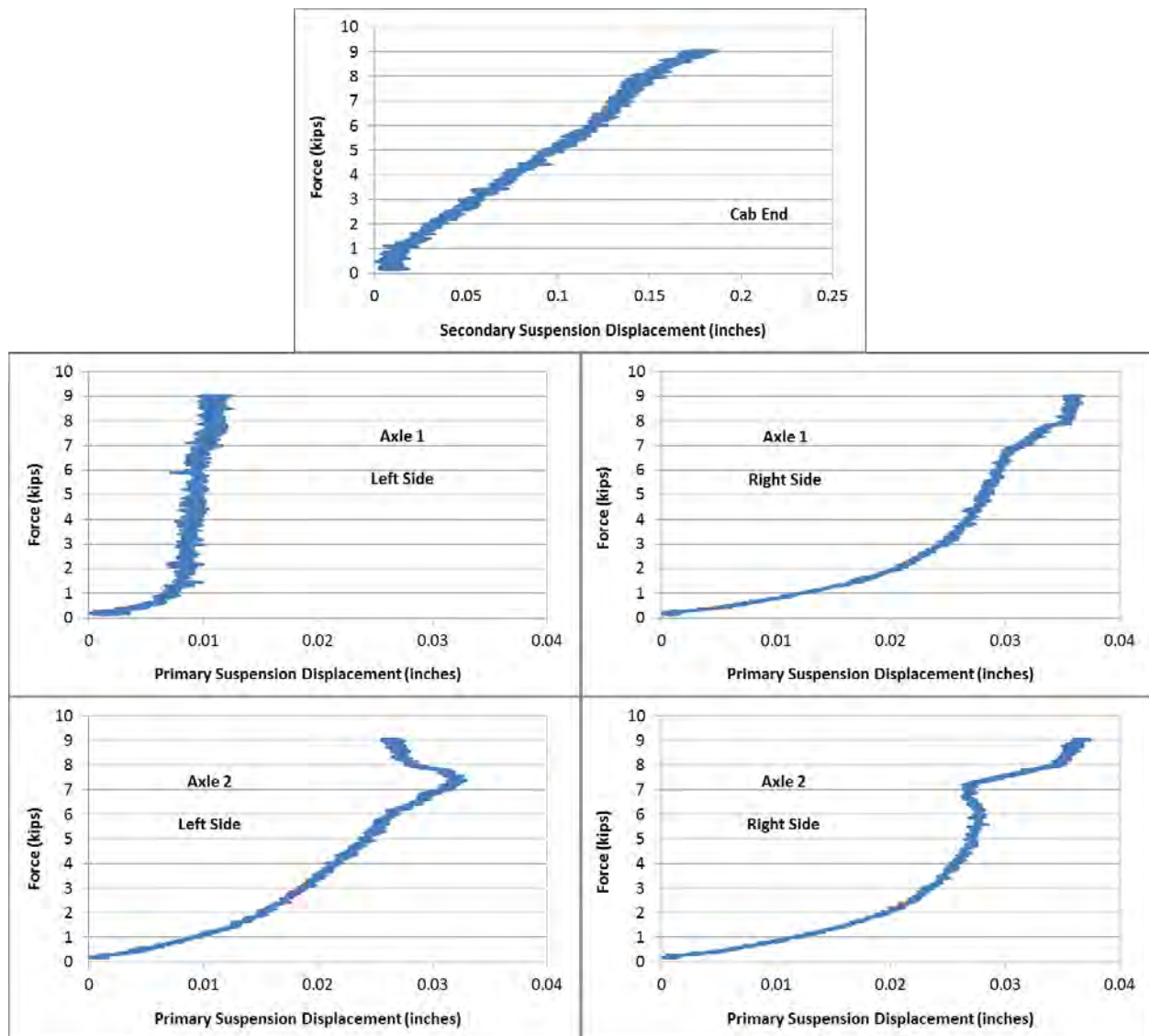


Figure A33. 9-Kip Load – Longitudinal Suspension Stiffness Test Axle 1 Chocked

Longitudinal Suspension Stiffness Test – Chocked Axle 2

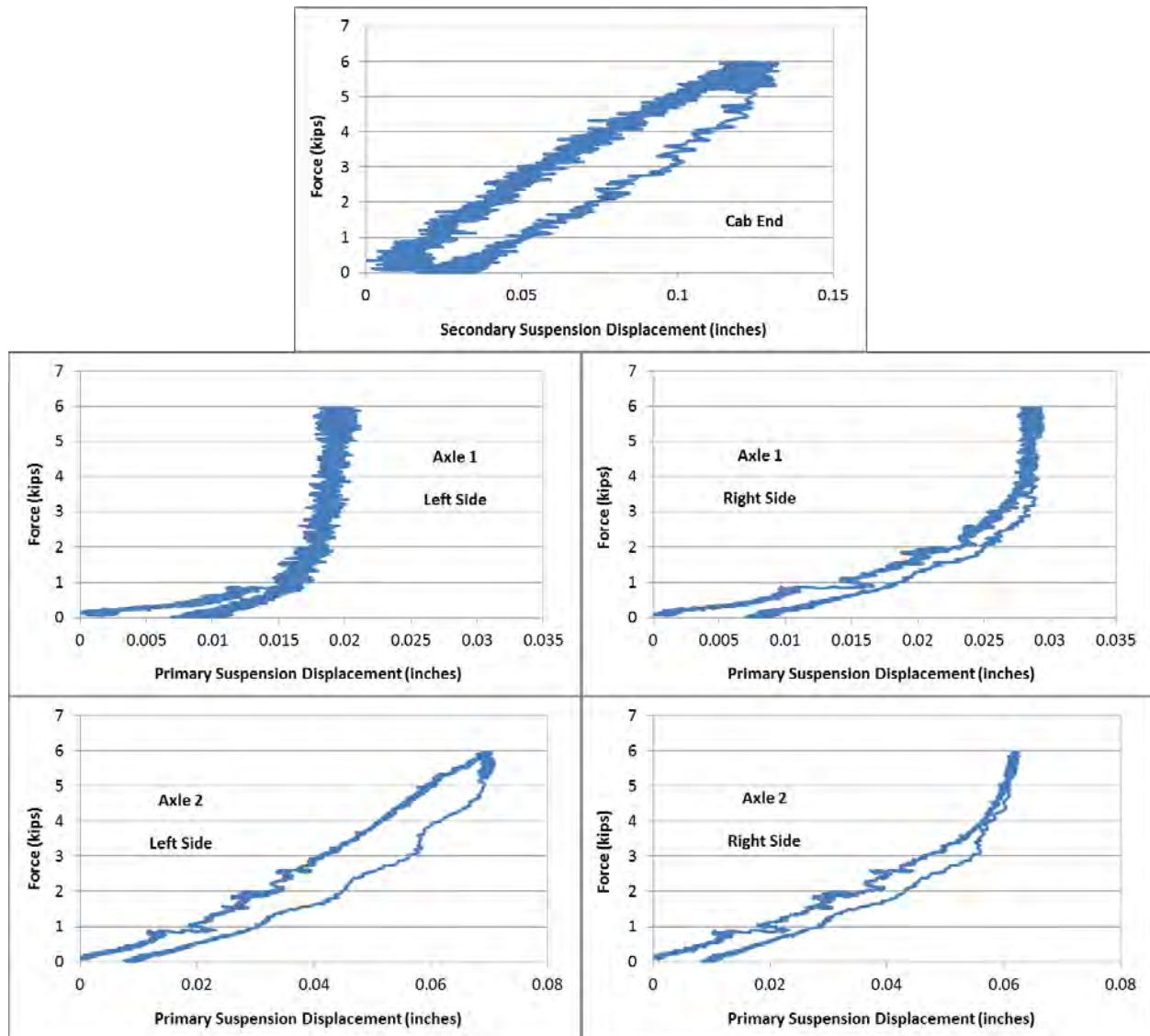


Figure A34. 6-Kip Load – Longitudinal Suspension Stiffness Test Axle 2 Chocked

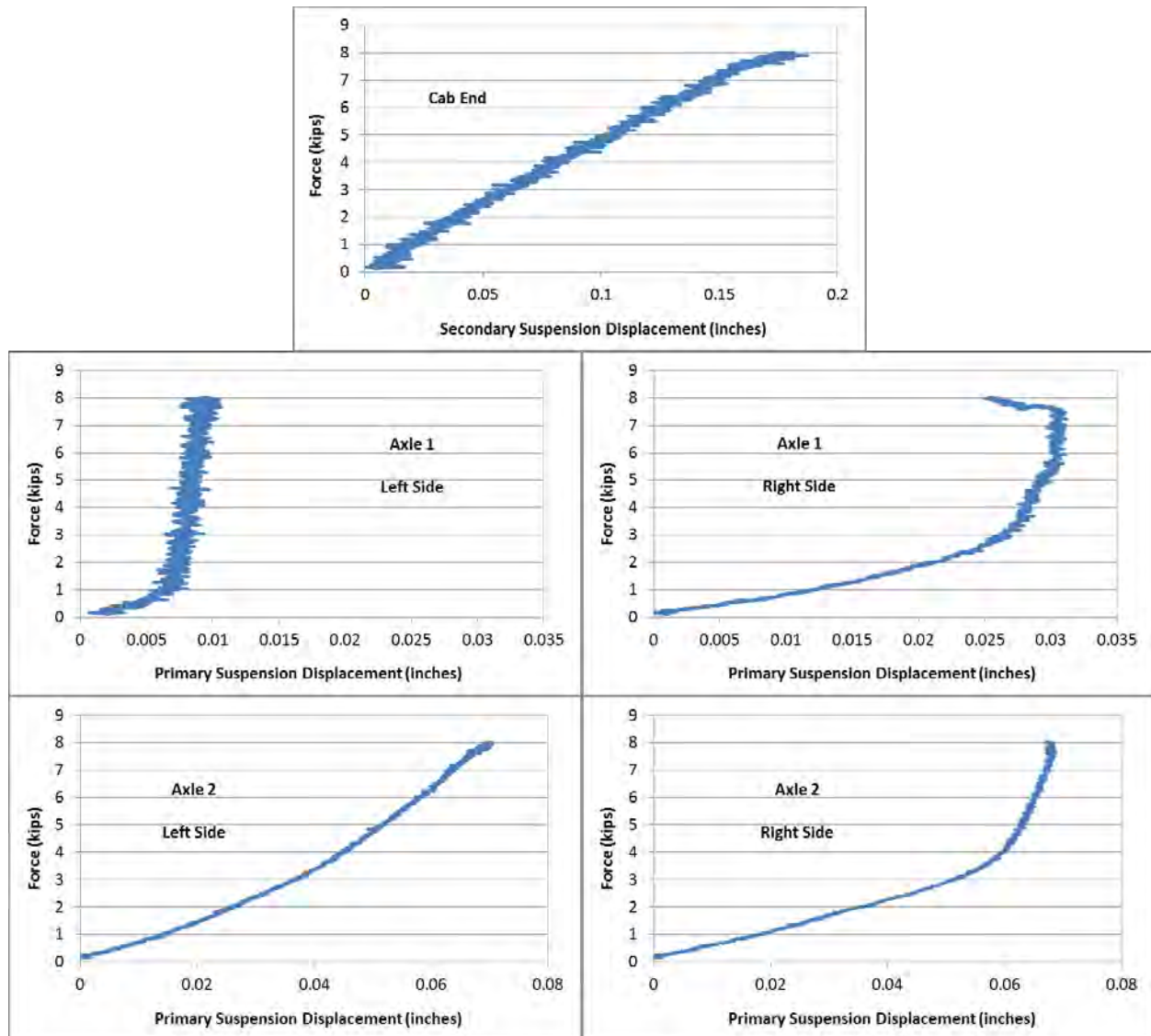


Figure A35. 8-Kip Load – Longitudinal Suspension Stiffness Test Axle 2 Chocked

Lateral Suspension Stiffness Test – without Traction Rods

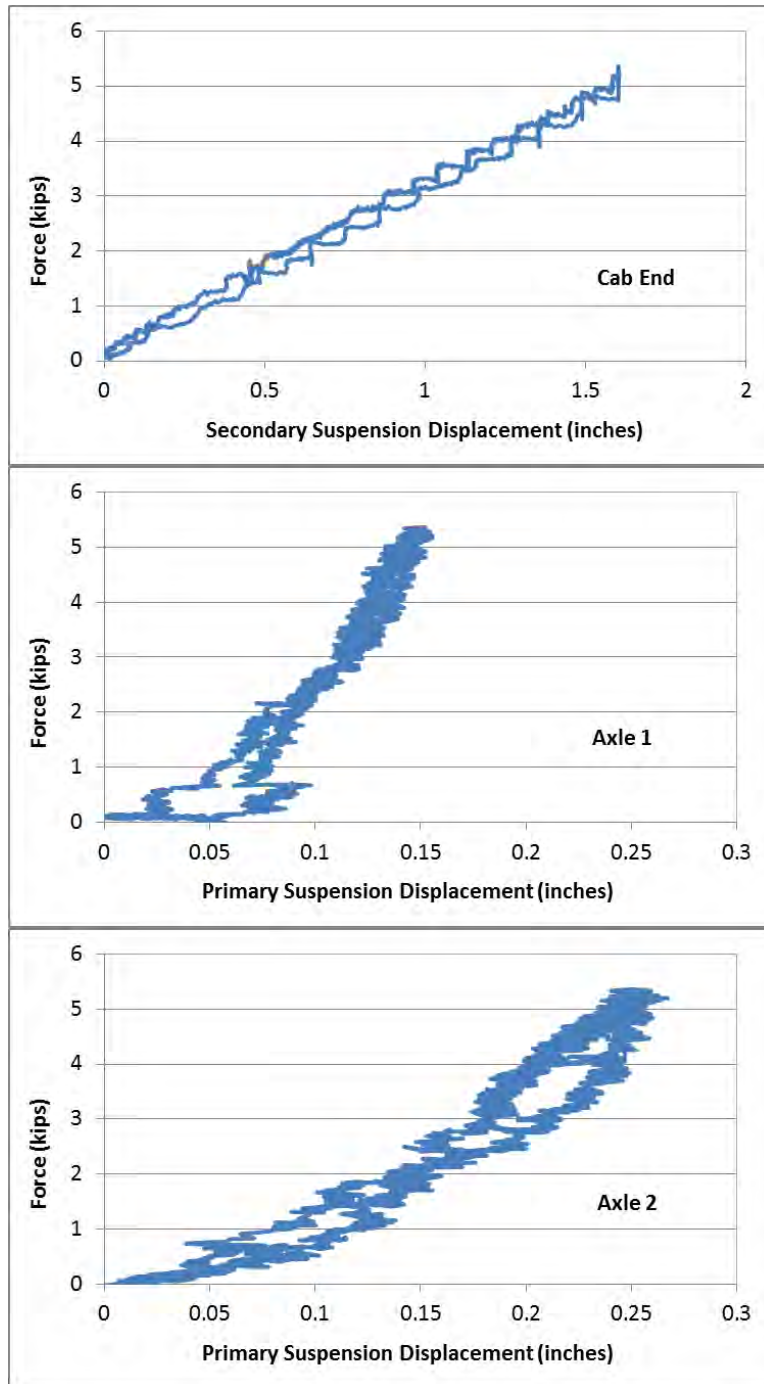


Figure A36. 5-Kip Load Trial 1 – Lateral Suspension Stiffness Test without Traction Rods

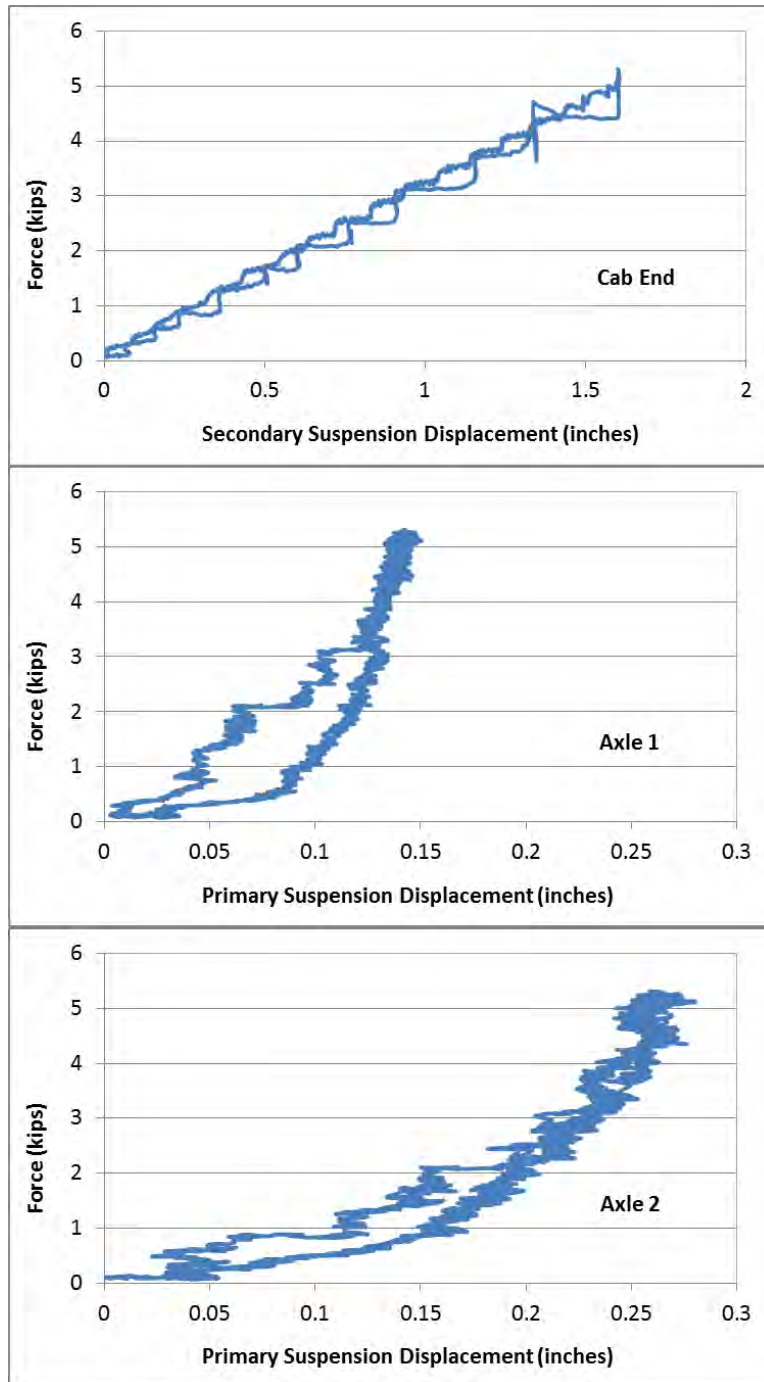


Figure A37. 5-Kip Load Trial 2 – Lateral Suspension Stiffness Test without Traction Rods

Lateral Suspension Stiffness Test – with Traction Rods

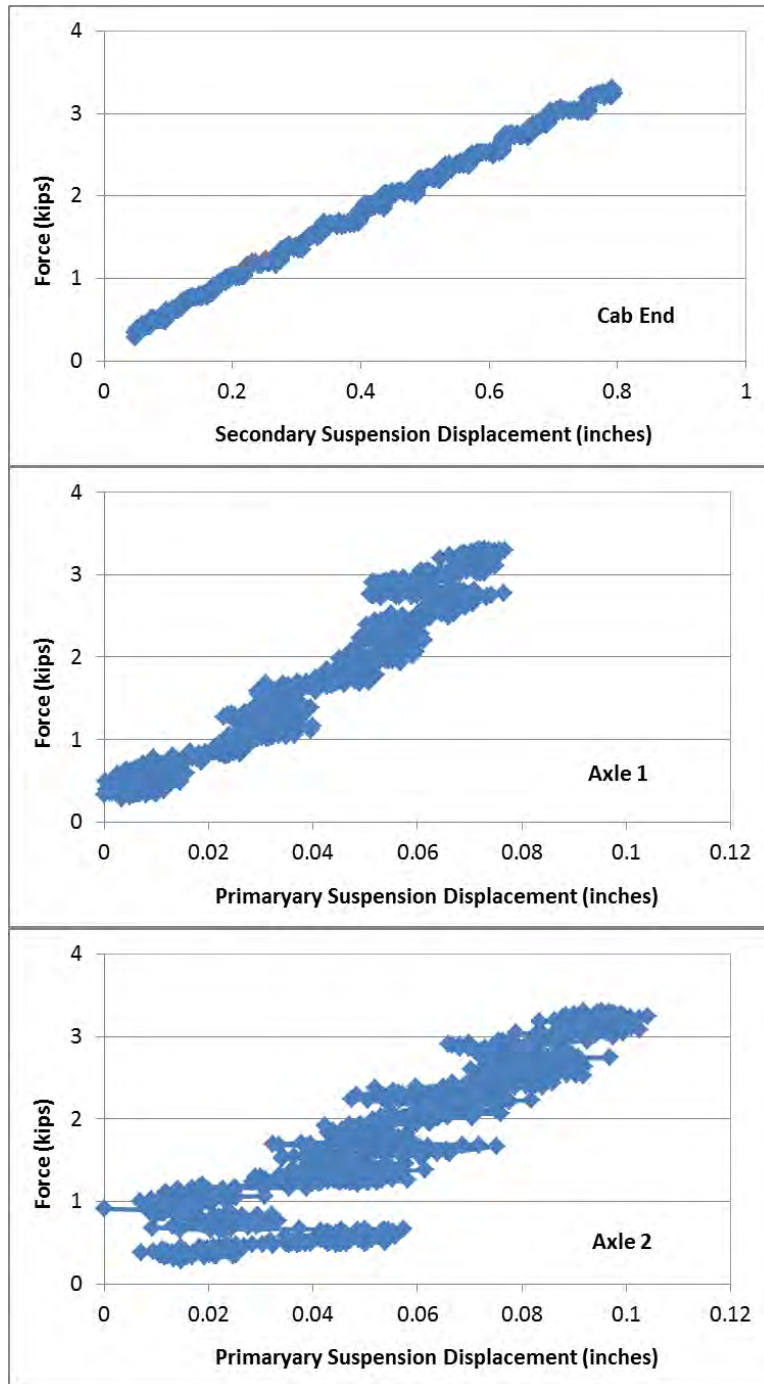


Figure A38. 3-Kip Load – Lateral Suspension Stiffness Test with Traction Rods

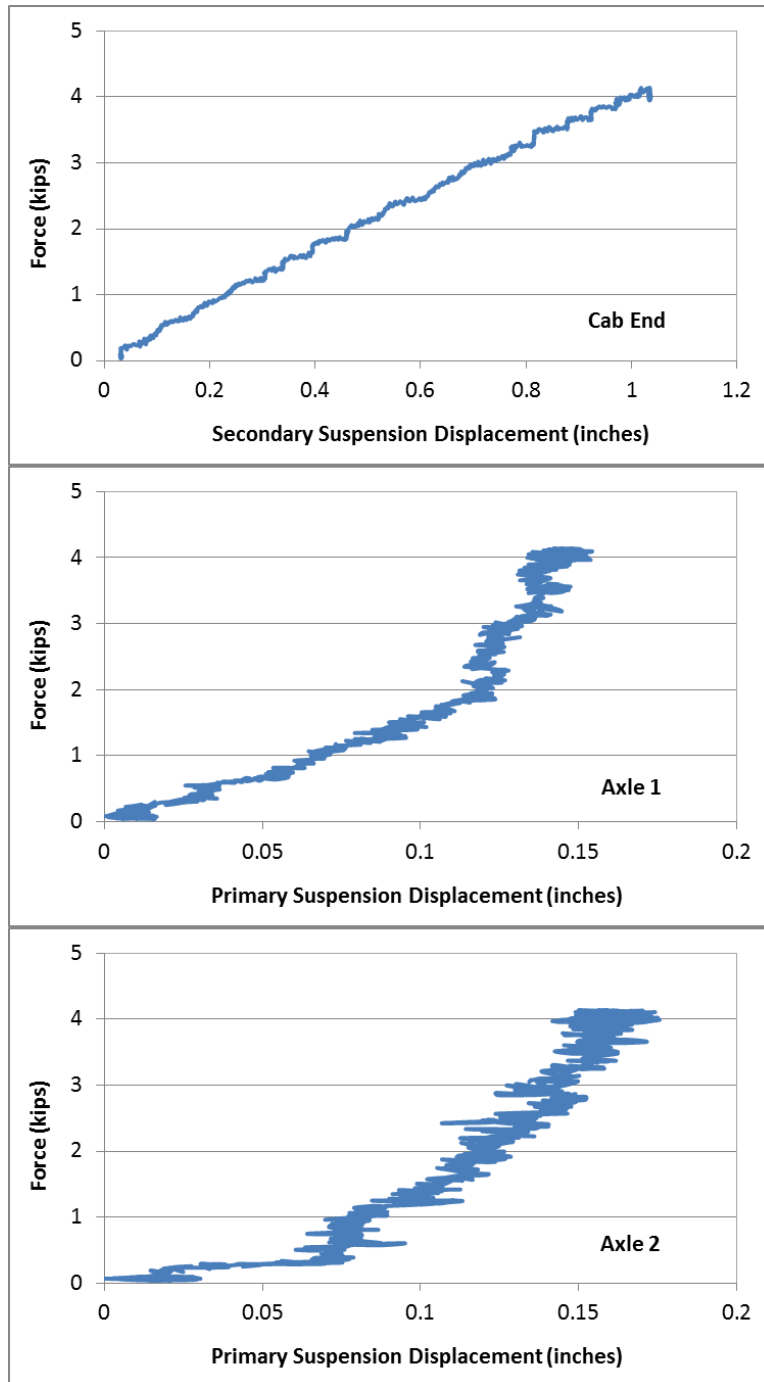


Figure A39. 4-Kip Load – Lateral Suspension Stiffness Test with Traction Rods

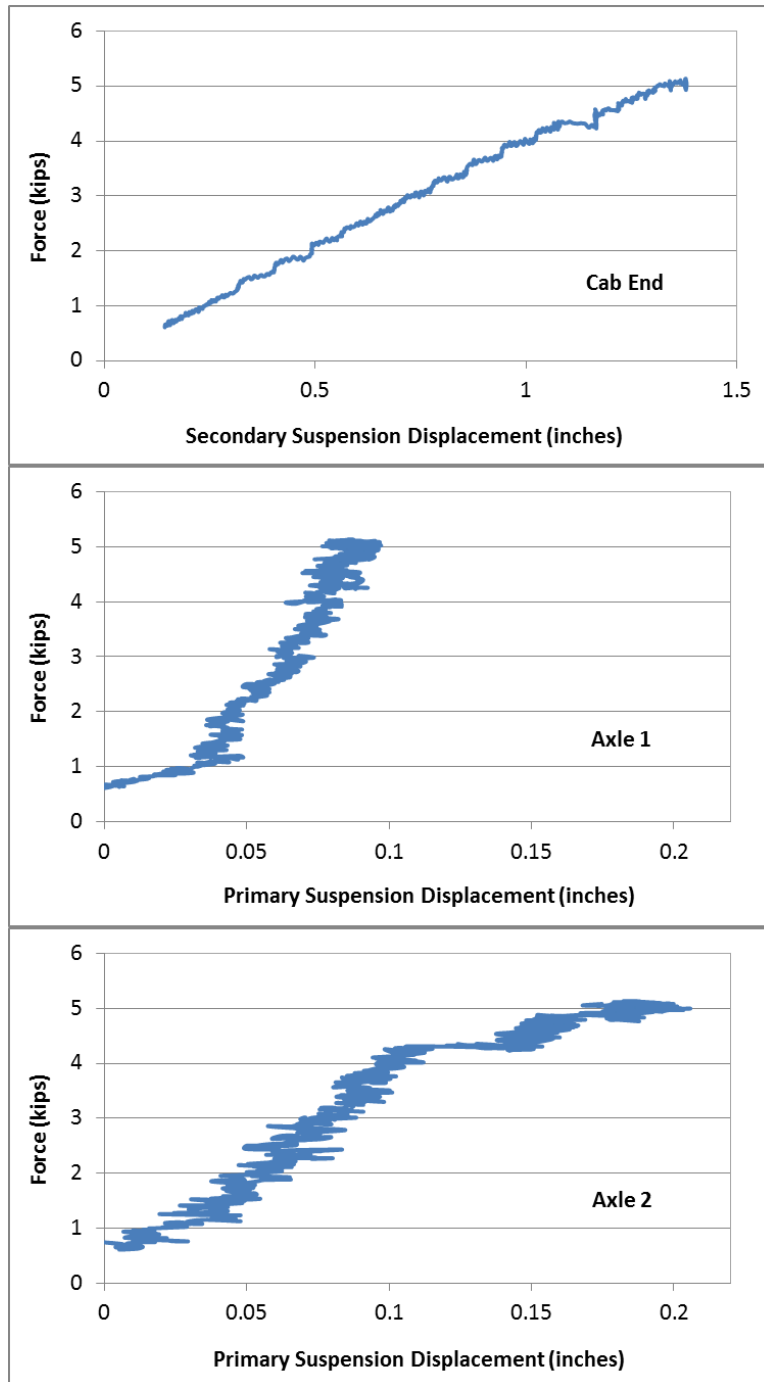


Figure A40. 5-Kip Load – Lateral Suspension Stiffness Test with Traction Rods

Vertical Suspension Stiffness Test – without Traction Rods

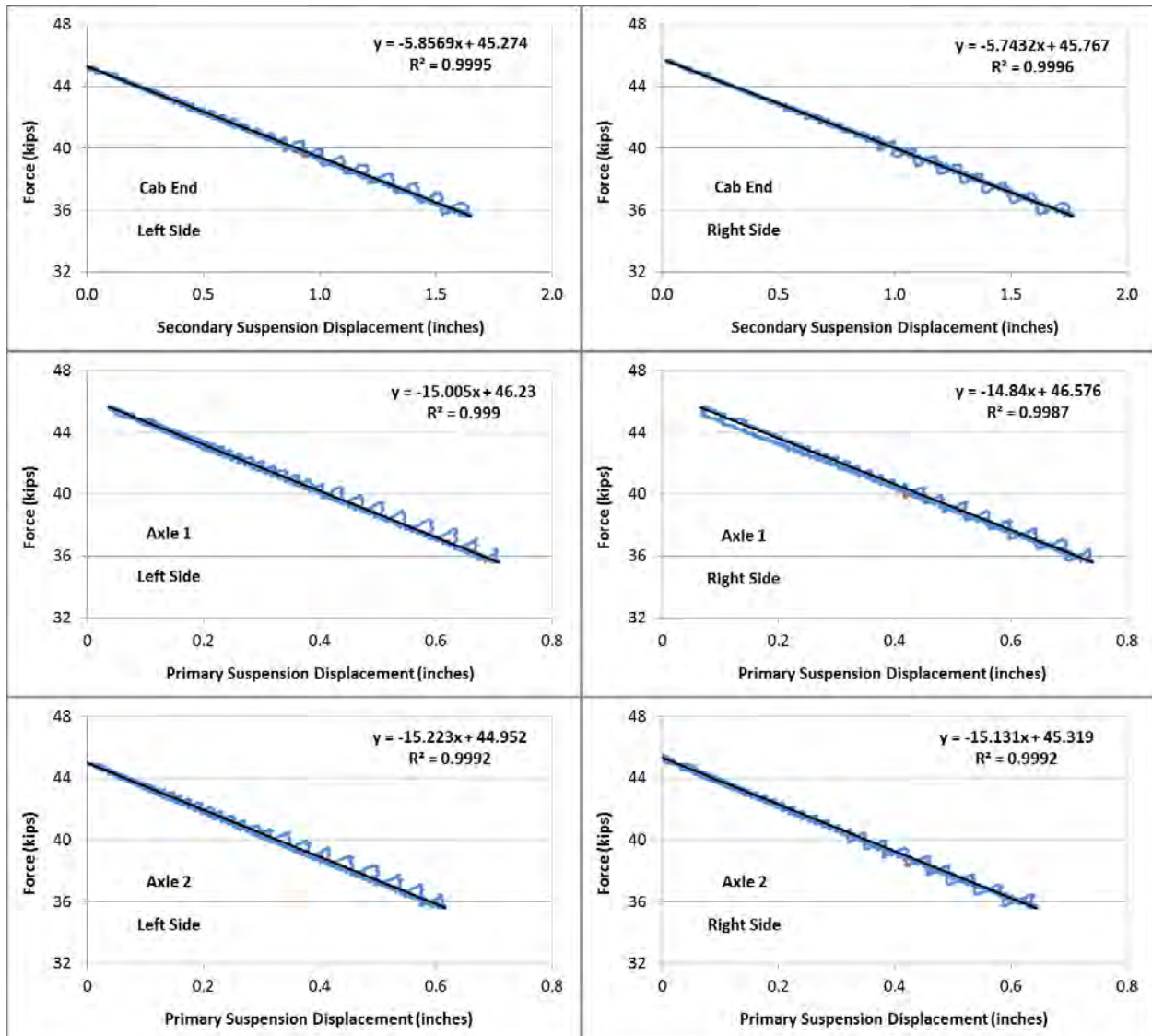


Figure A41. Trial 1 – Vertical Suspension Stiffness Test without Traction Rods

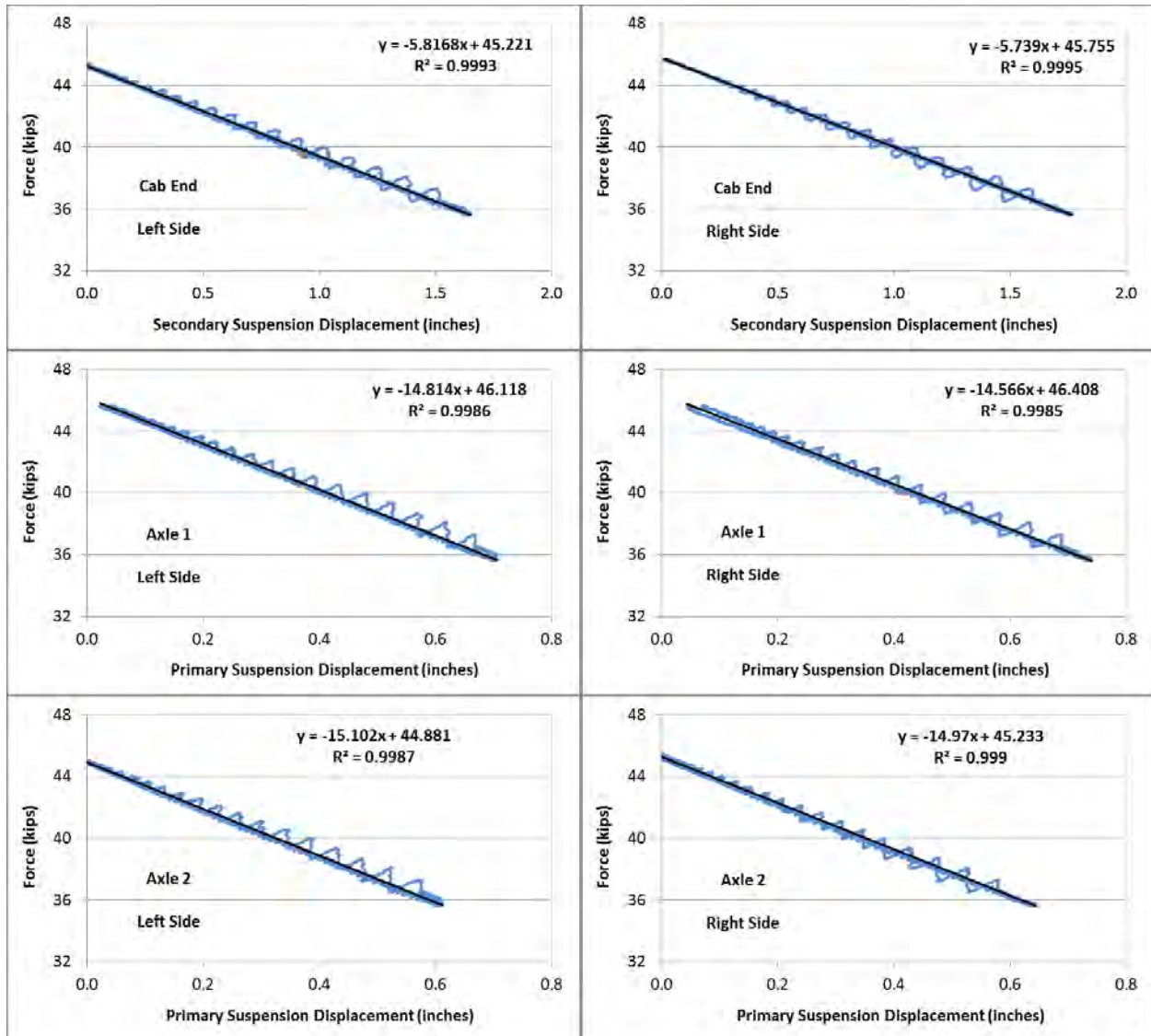


Figure A42. Trial 2 – Vertical Suspension Stiffness Test without Traction Rods

Vertical Suspension Stiffness Test – with Traction Rods

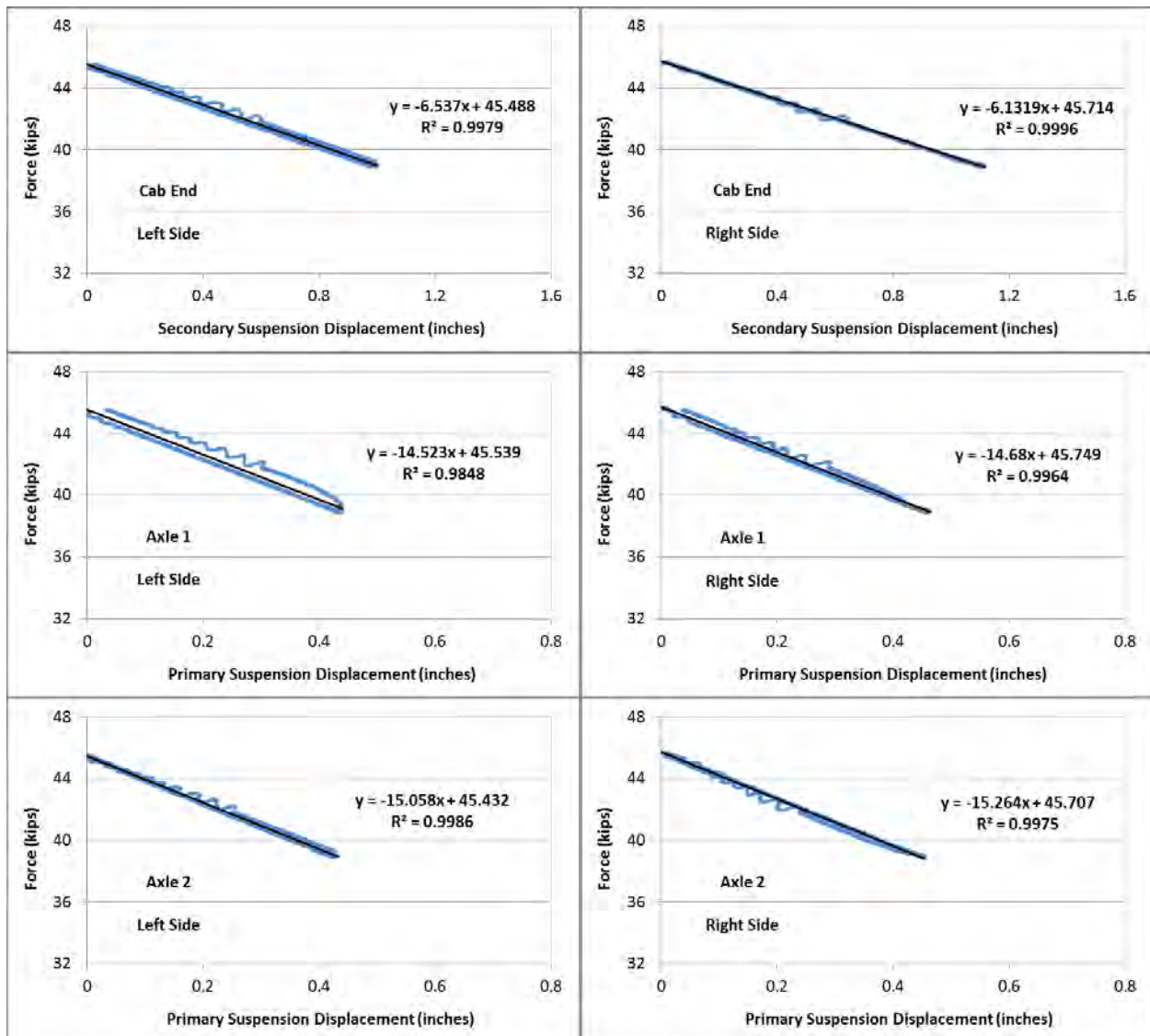


Figure A43. Trial 1 – Vertical Suspension Stiffness Test with Traction Rods

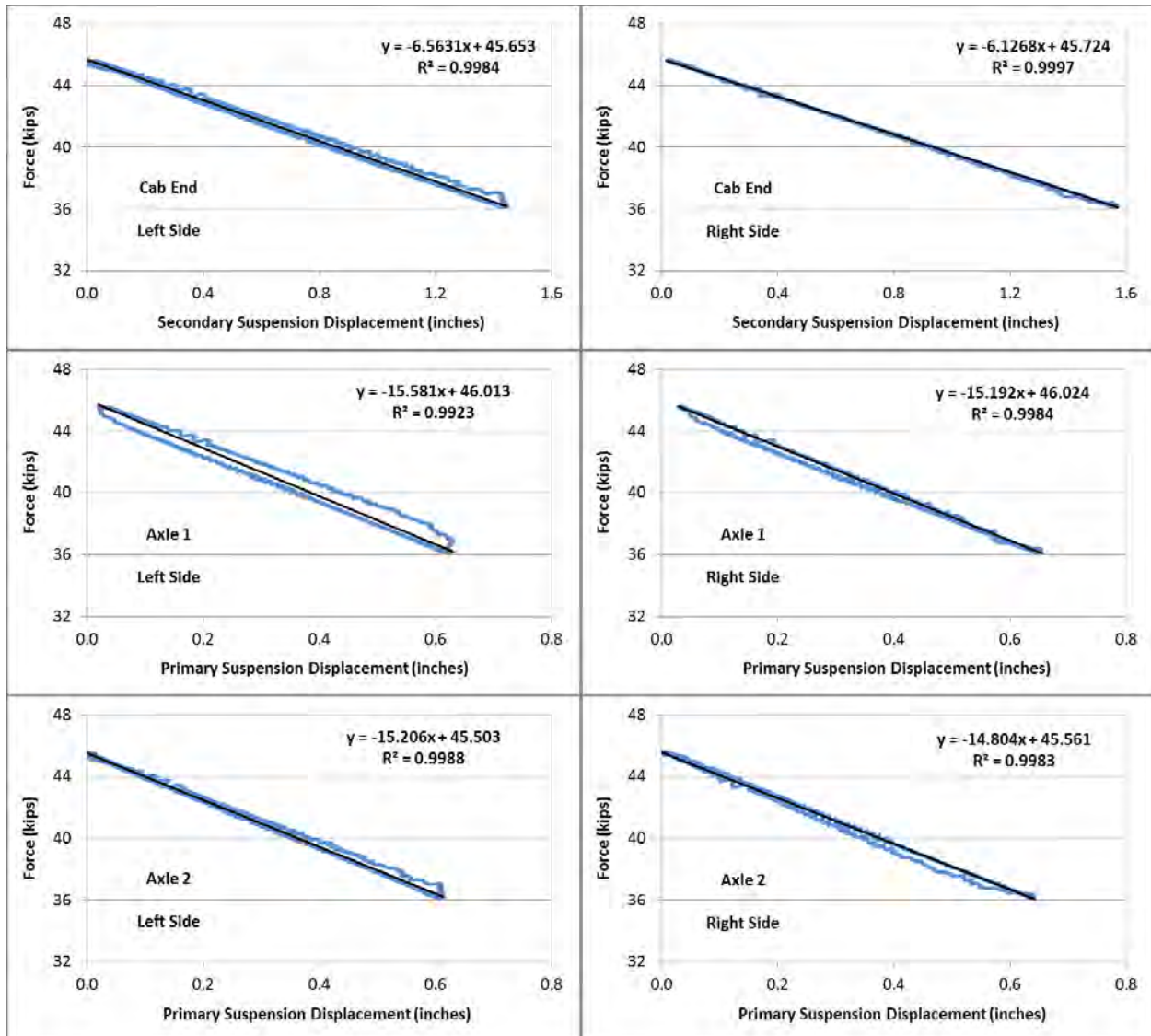


Figure A44. Trial 2 – Vertical Suspension Stiffness Test with Traction Rods

Spring Stiffness Measurements

Primary Springs

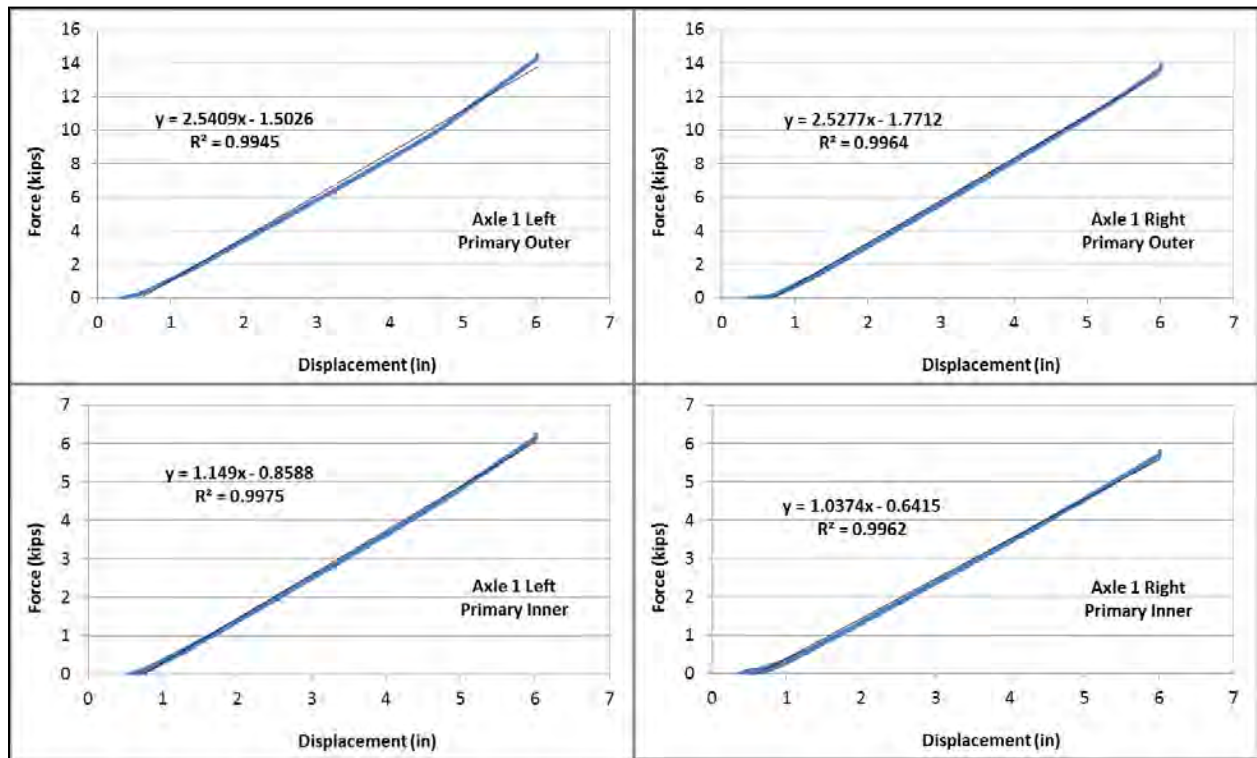


Figure A45. Primary Spring Force Displacement Plots

Secondary Springs

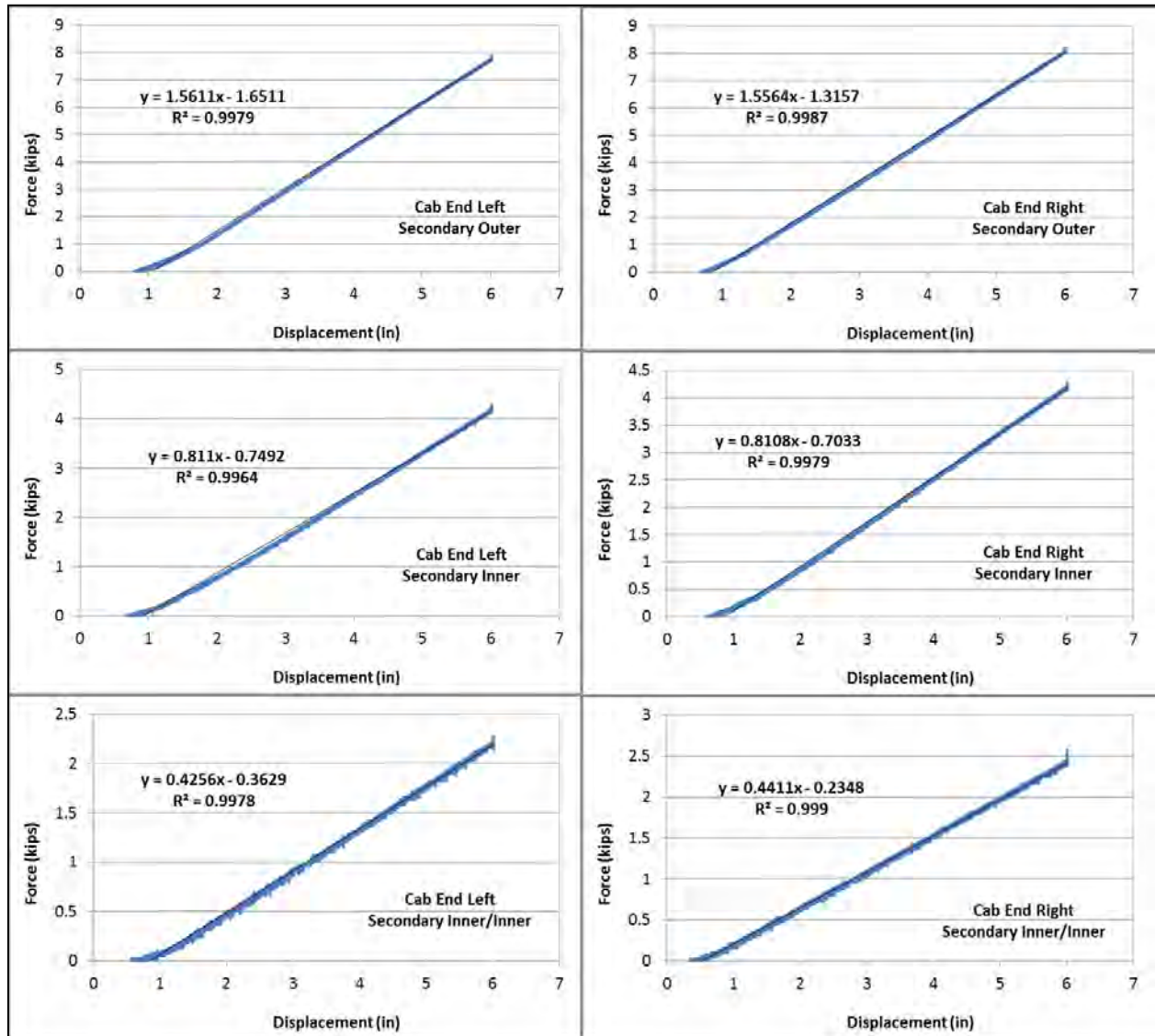


Figure A46. Secondary Spring Force Displacement Plots

Truck Resonance Test

Lateral Hammer Impact at Truck Center – Lateral and Yaw Mode Excitations

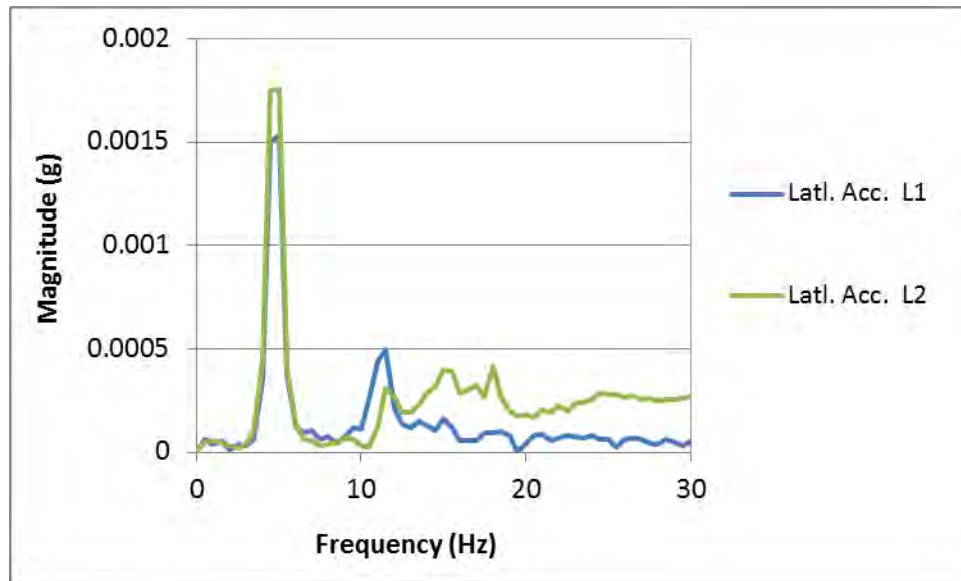


Figure A47. Truck Response to Lateral Hammer Impact (Magnitude)

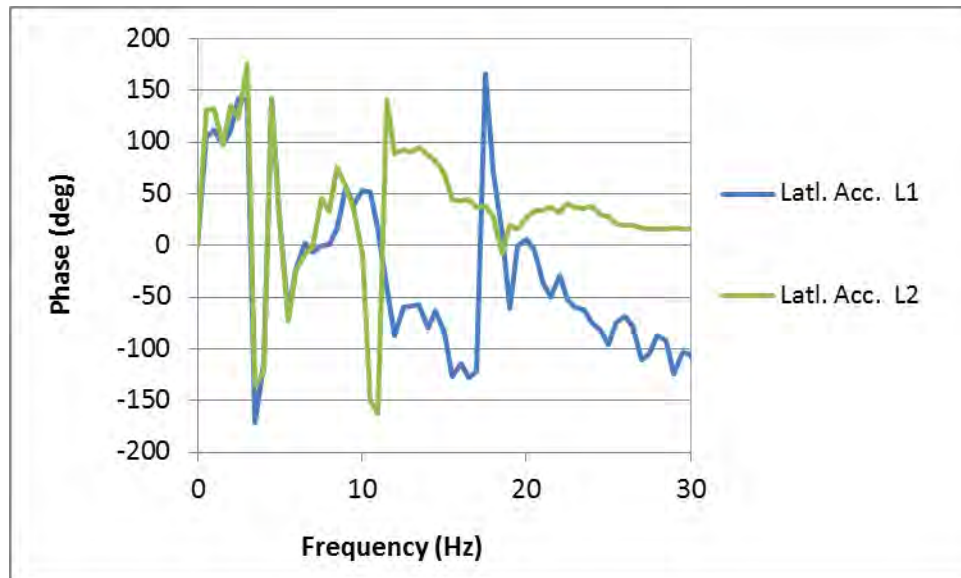


Figure A48. Truck Response to Lateral Hammer Impact (Phase Angle)

Longitudinal Hammer Impact at Truck Center – Pitch Mode Excitation

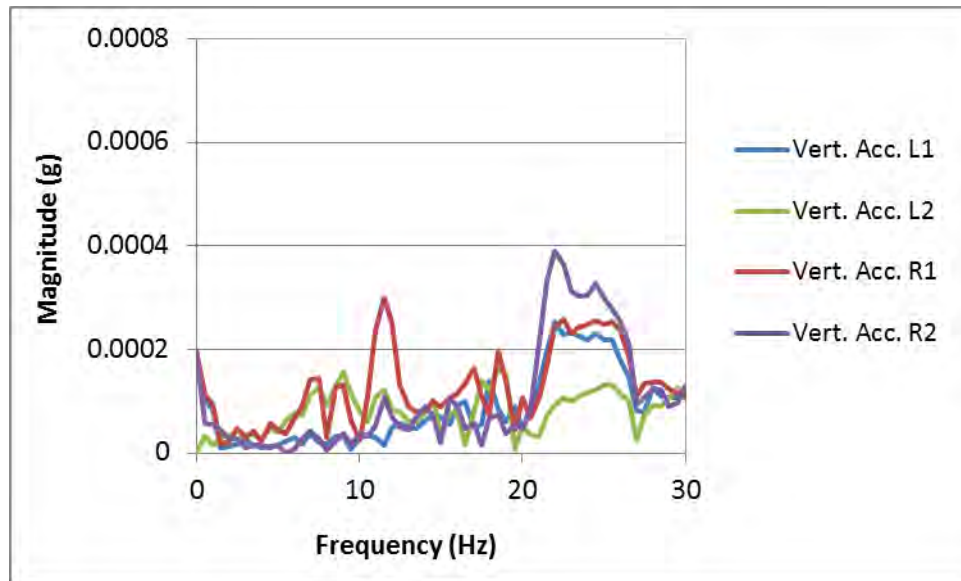


Figure A49. Truck Response to Longitudinal Hammer Impact (Magnitude)

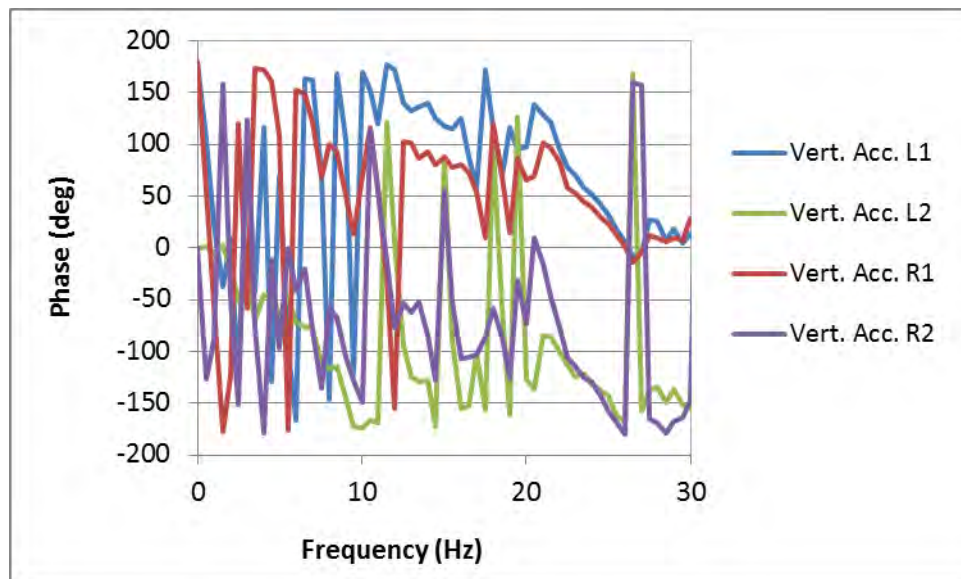


Figure A50. Truck Response to Longitudinal Hammer Impact (Phase Angle)

Vertical Hammer Impact at Truck Center – Bounce Mode Excitation

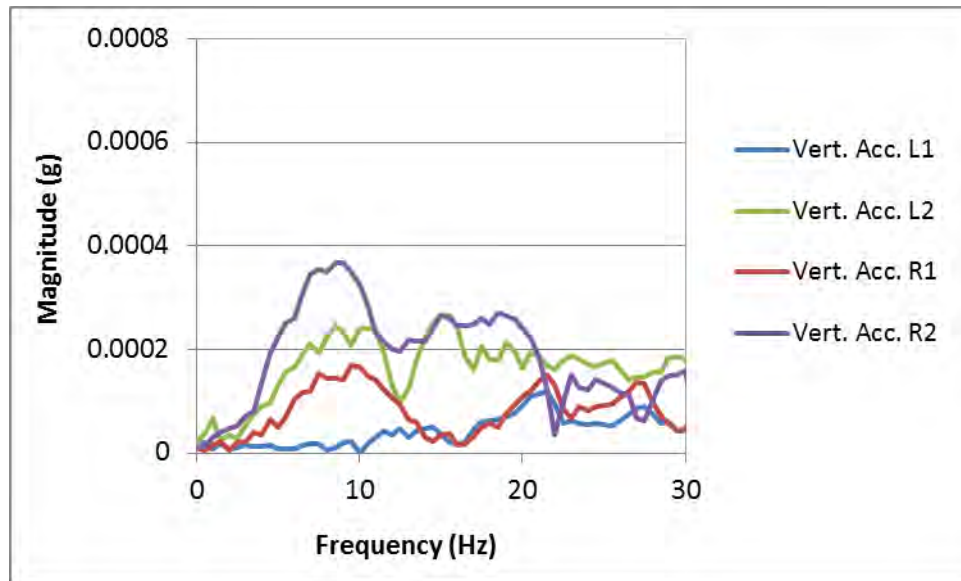


Figure A51. Truck Response to Vertical Hammer Impact at the Truck Center (Magnitude)

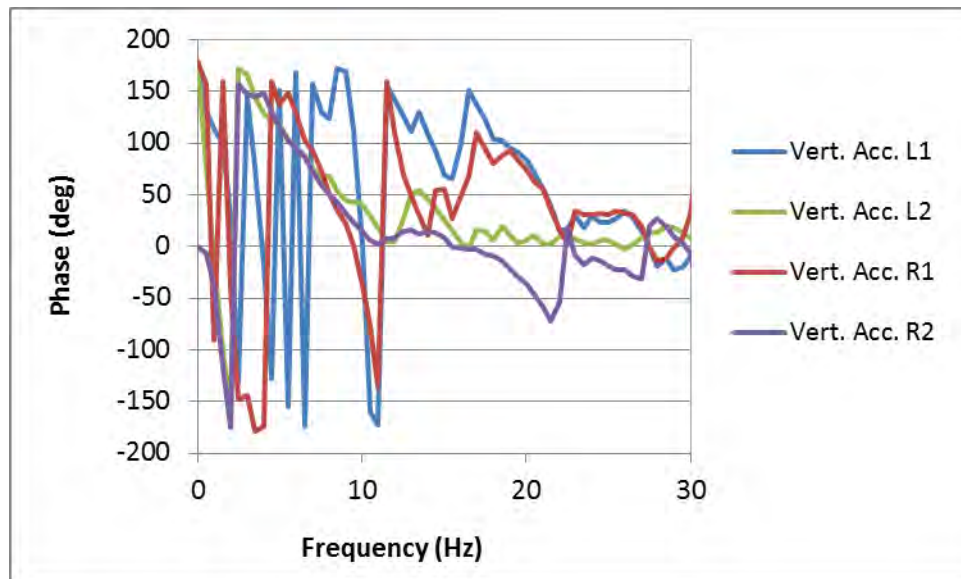


Figure A52. Truck Response to Vertical Hammer Impact at the Truck Center (Phase Angle)

Vertical Hammer Impact at Right Side of Truck – Roll Mode Excitation

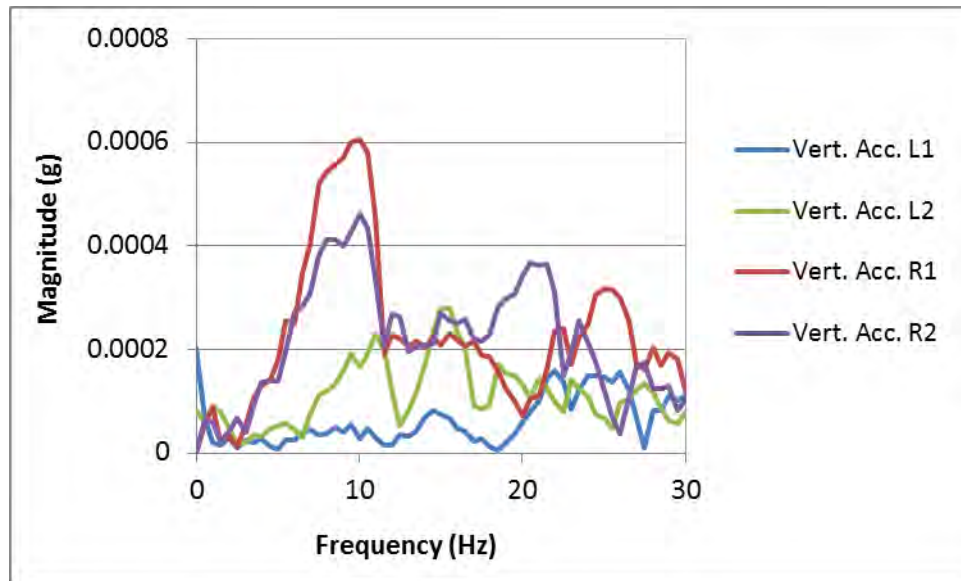


Figure A53. Truck Response to Vertical Hammer Impact at Right Side of Truck (Magnitude)

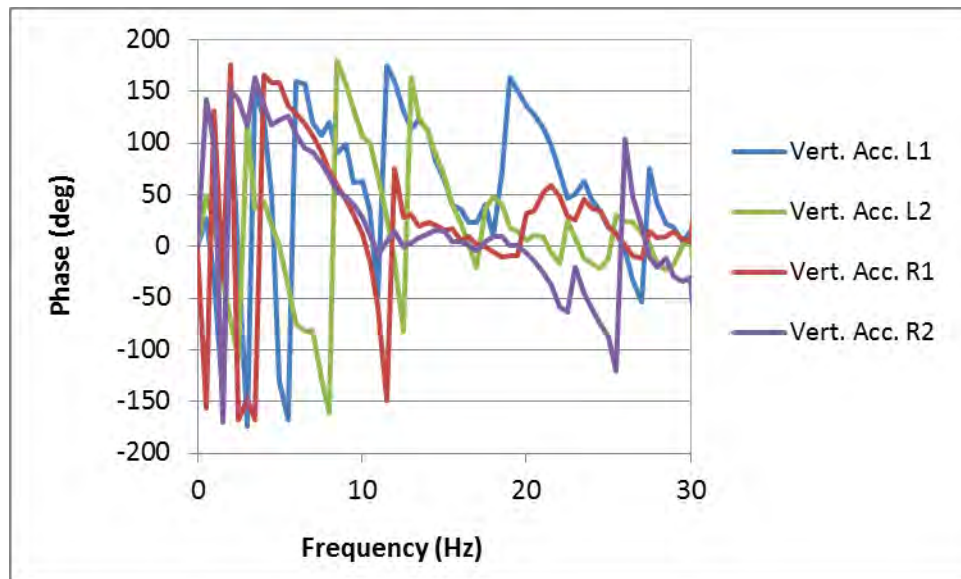


Figure A54. Truck Response to Vertical Hammer Impact at Right Side of Truck (Phase Angle)

Damper Characterization

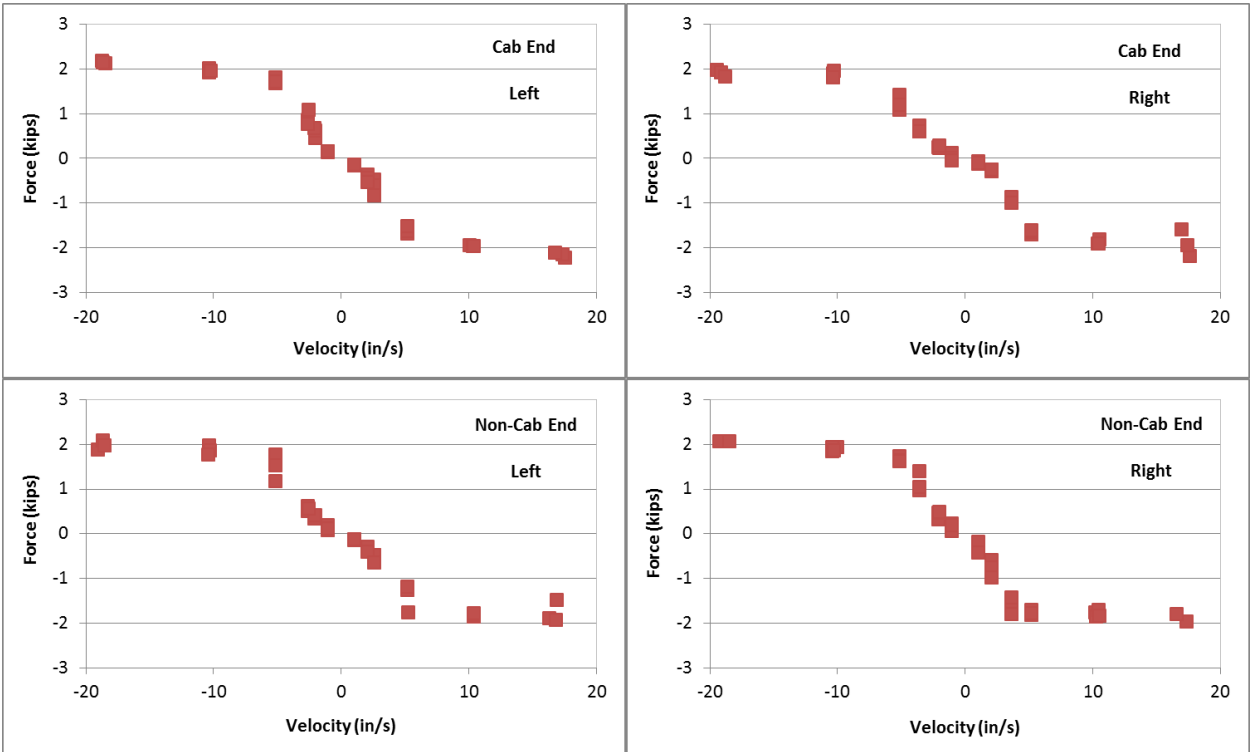


Figure A55. Lateral Damper Characteristics

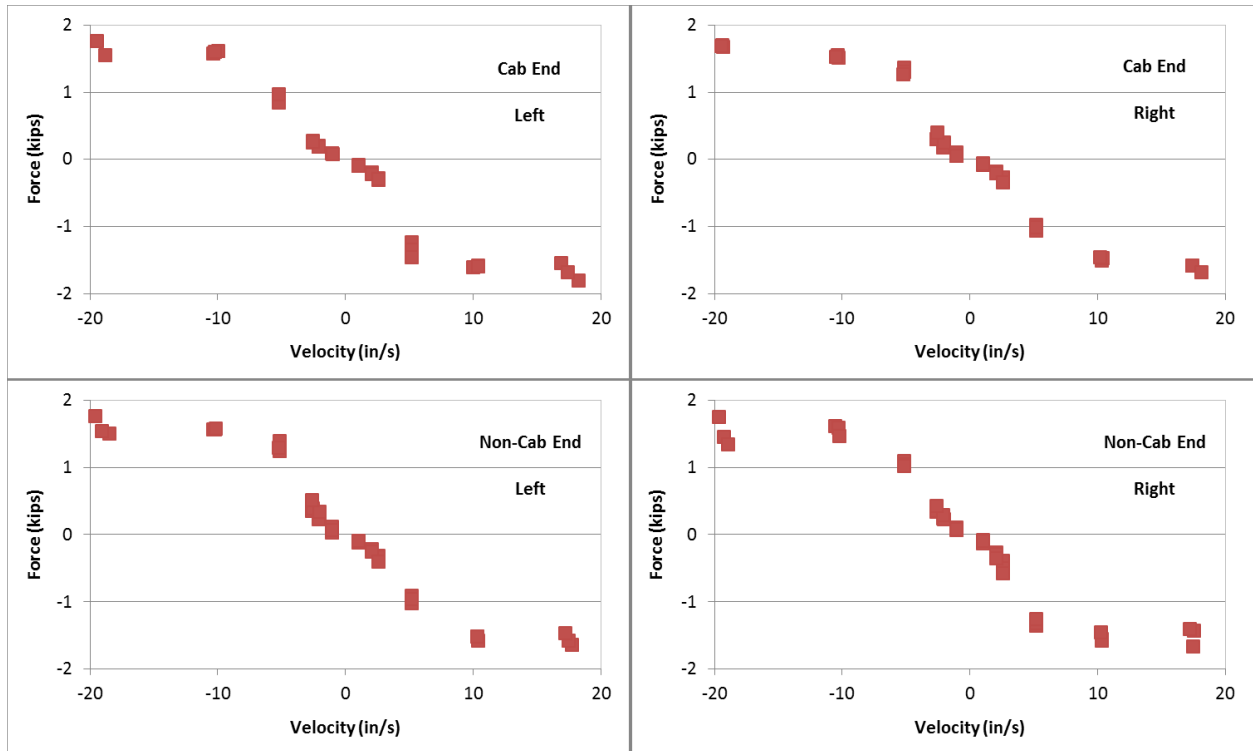


Figure A56. Vertical Damper Characteristics

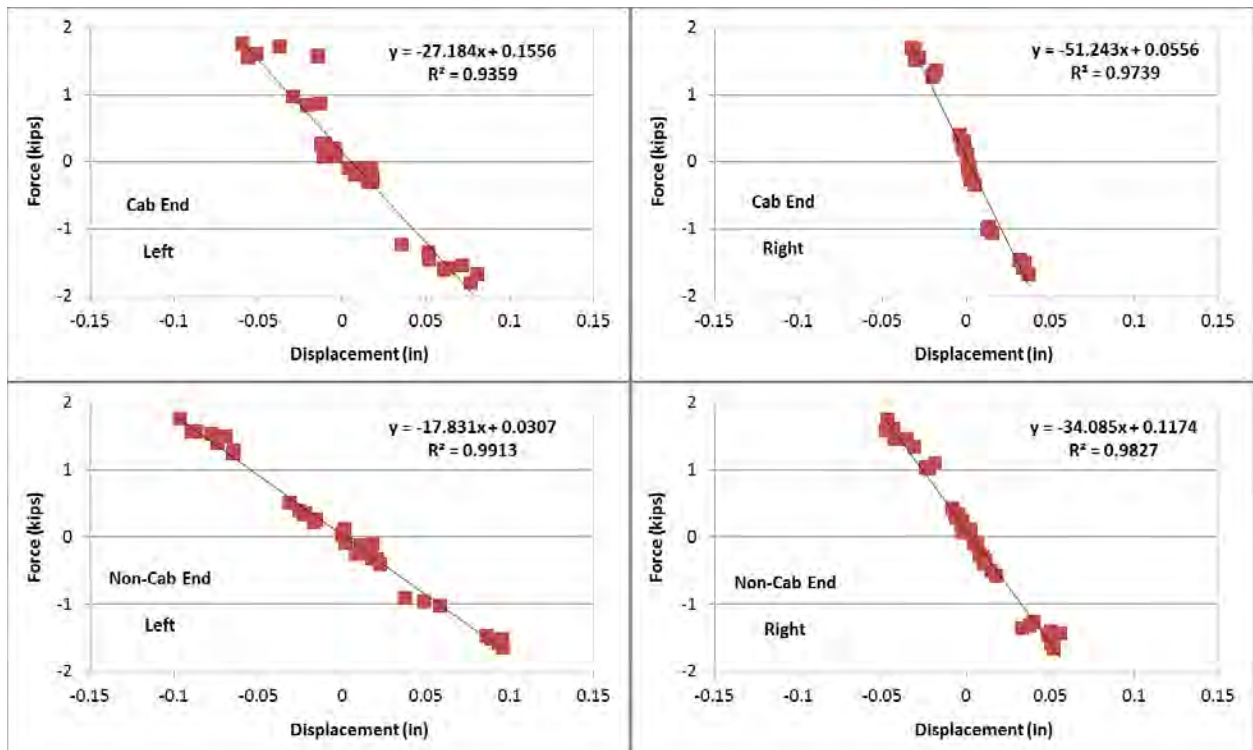


Figure A57. Vertical Damper Bushing Stiffness

Truck Resistive Torque Test

Cab End

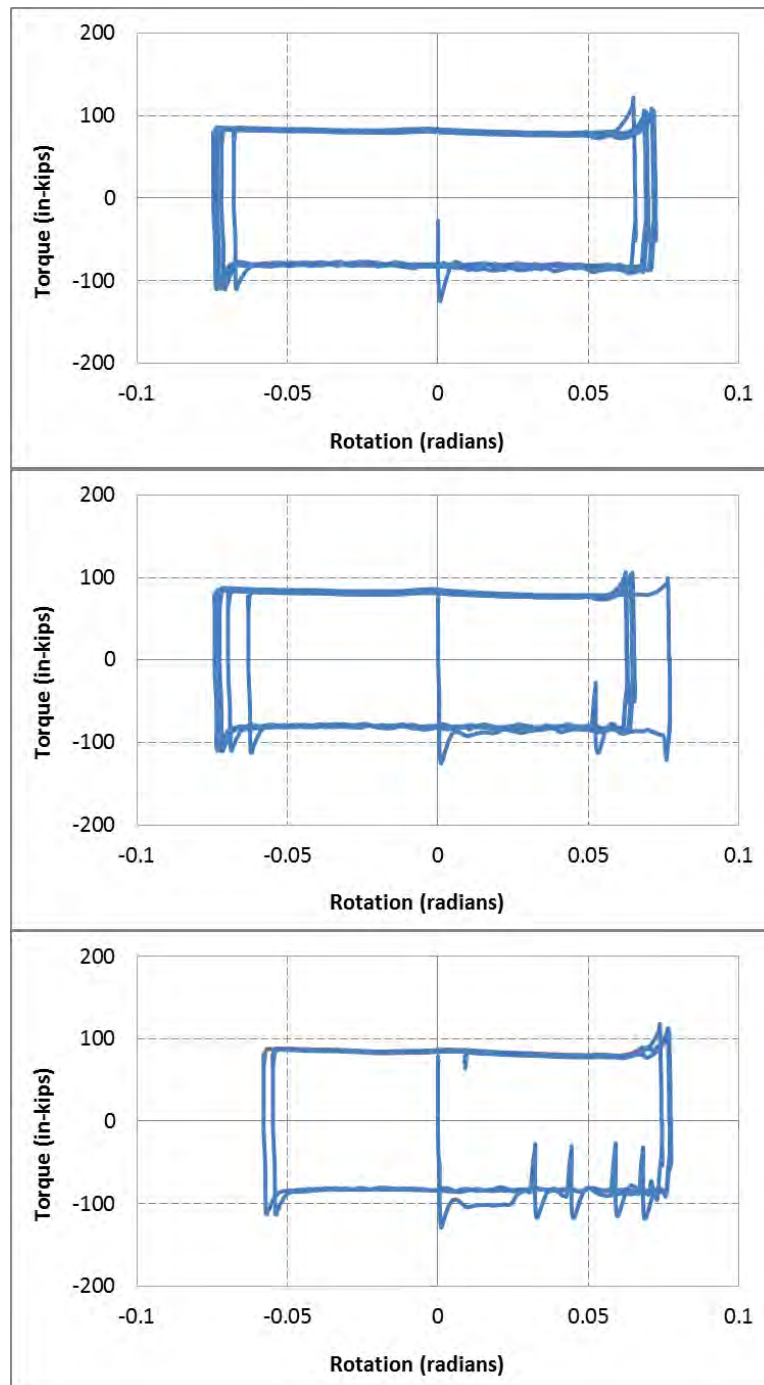


Figure A58. Cab End Truck Rotations

Non-Cab End

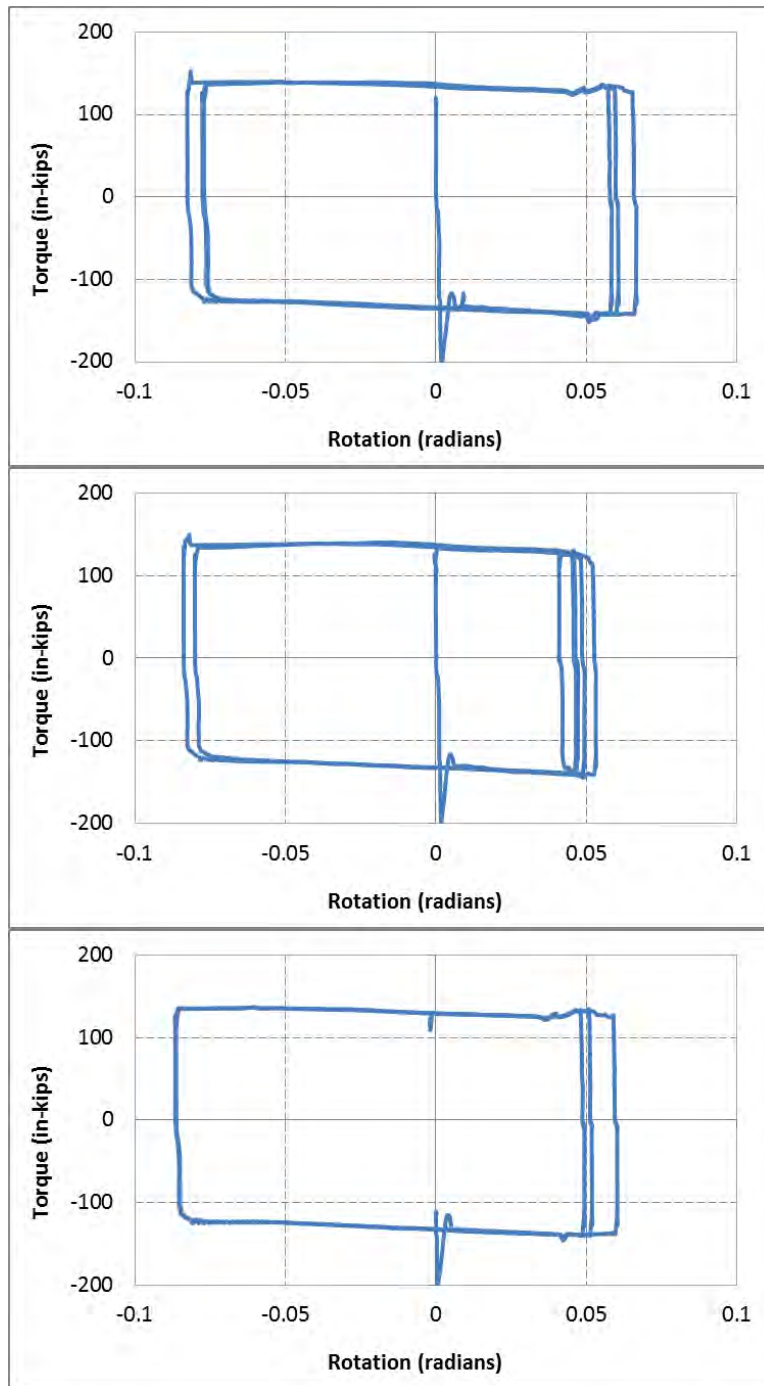


Figure A59. Non-Cab End Truck Rotations

Truck Load Equalization Test

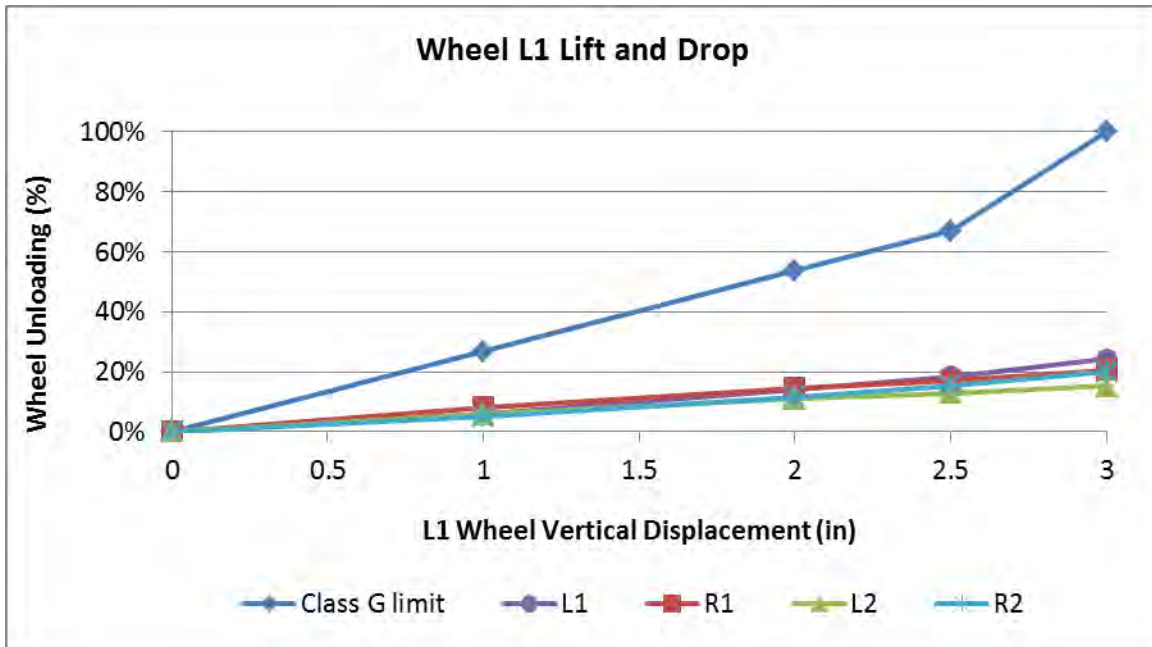


Figure A60. L1 Lift and Drop – Average Wheel Unloading at the Cab End Truck

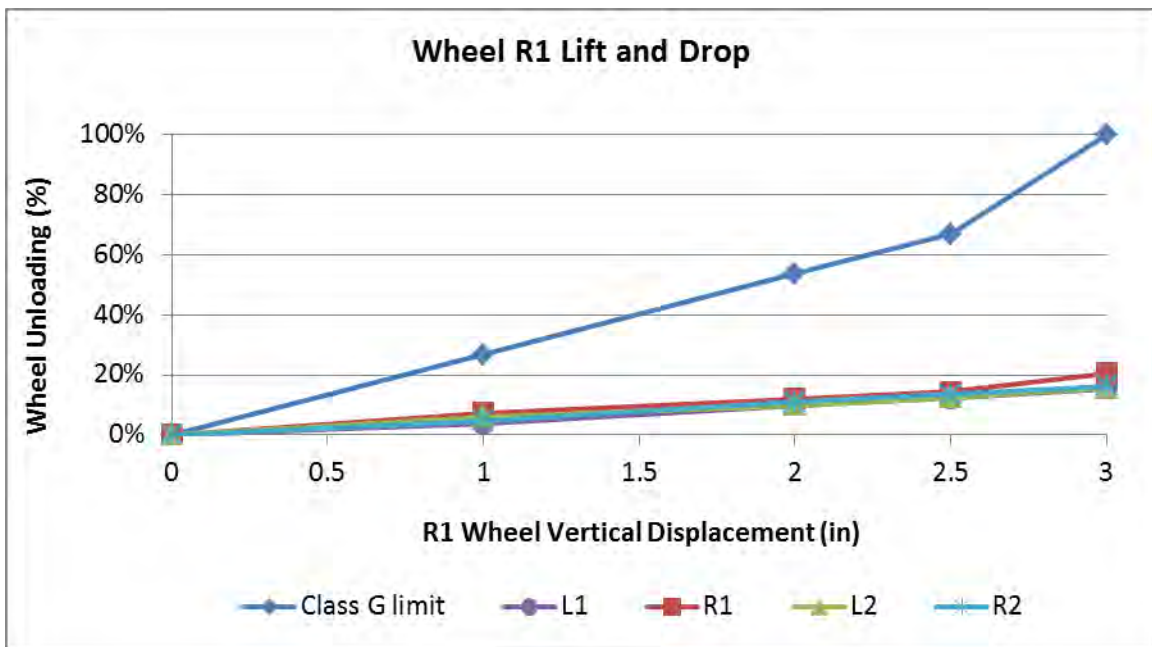


Figure A61. R1 Lift and Drop – Average Wheel Unloading at the Cab End Truck

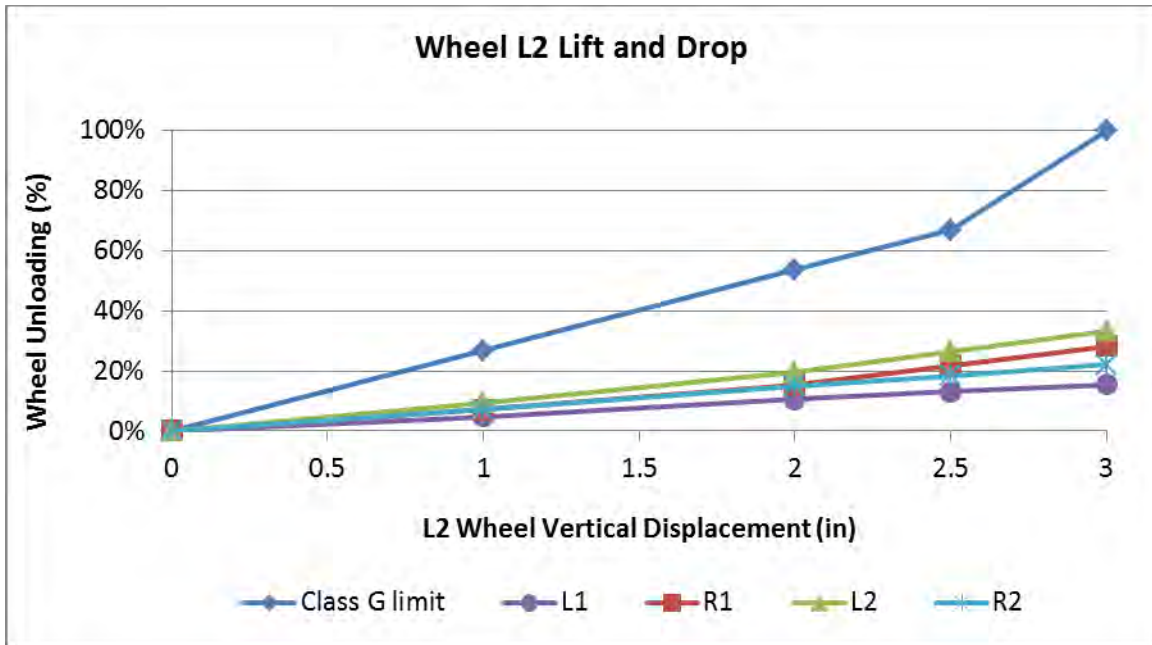


Figure A62. L2 Lift and Drop – Average Wheel Unloading at the Cab End Truck

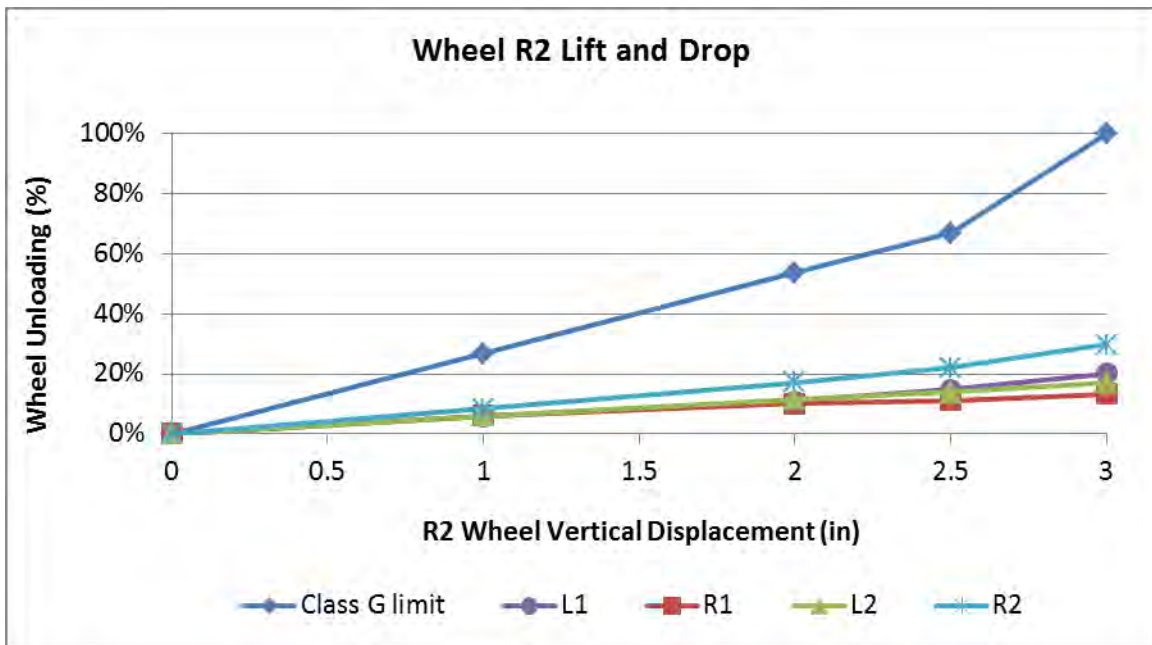


Figure A63. R2 Lift and Drop – Average Wheel Unloading at the Cab End

Lean Test Results

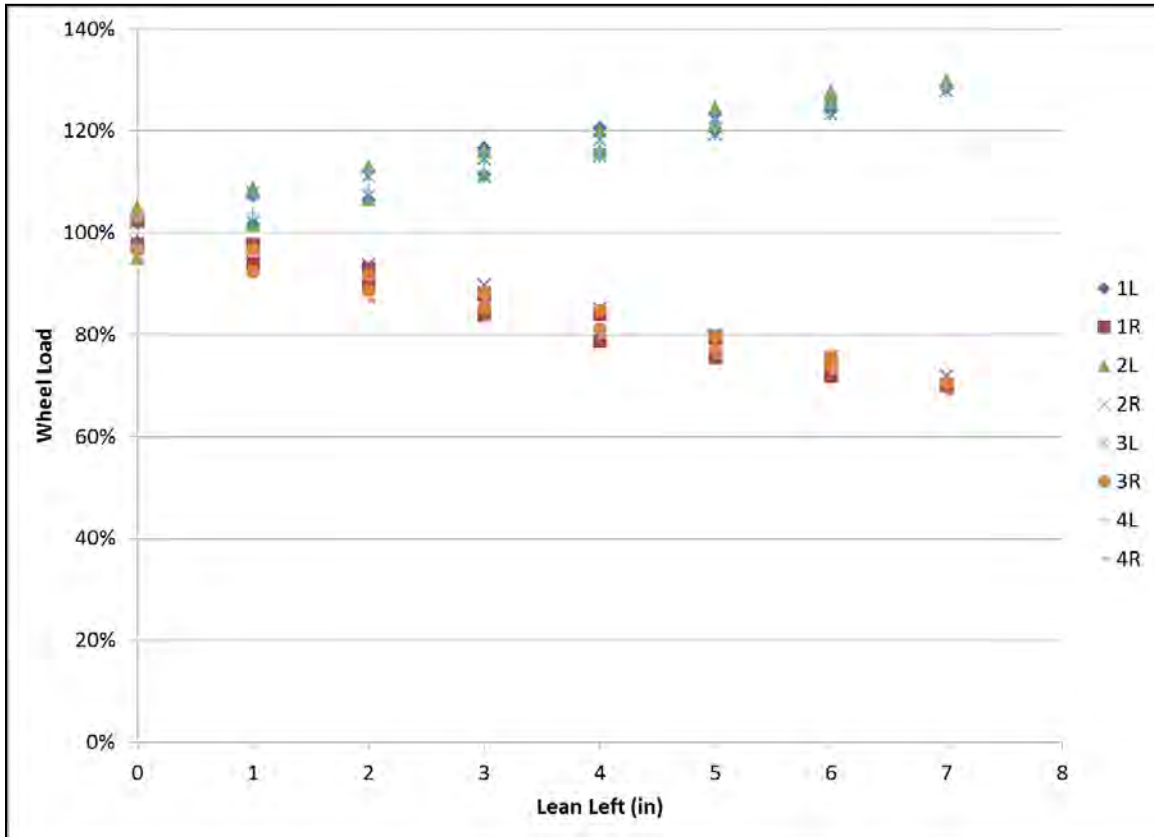


Figure A64. Lean Left Wheel Unloading

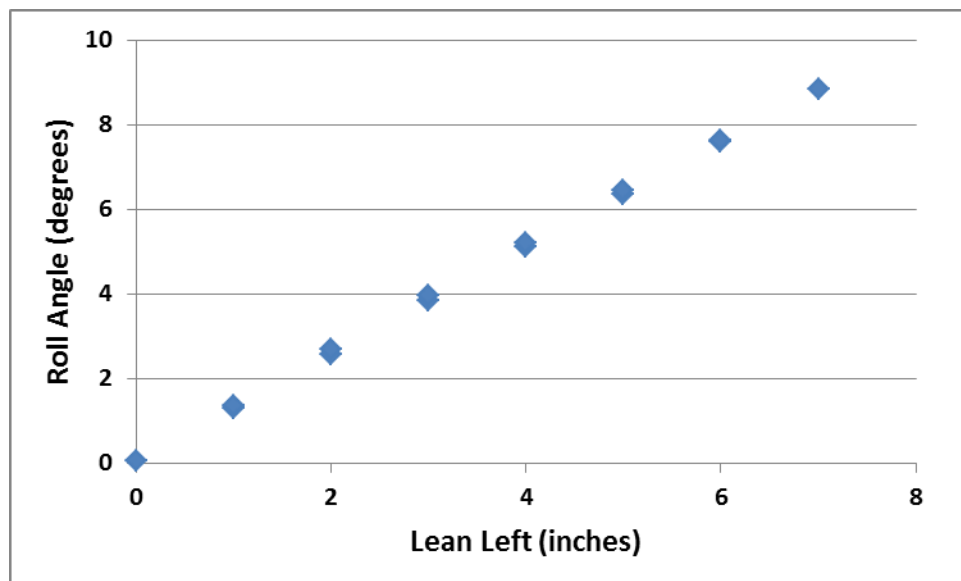


Figure A65. Lean Left Roll Angle

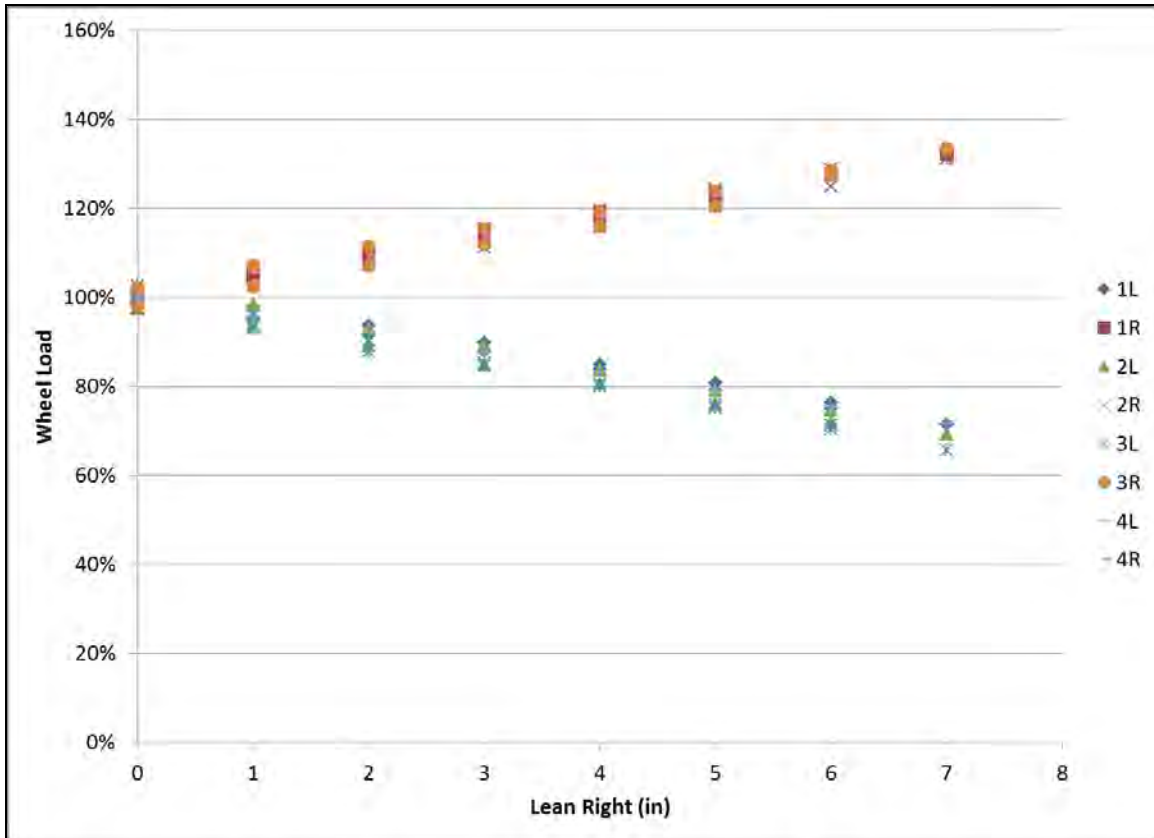


Figure A66. Lean Right Wheel Unloading

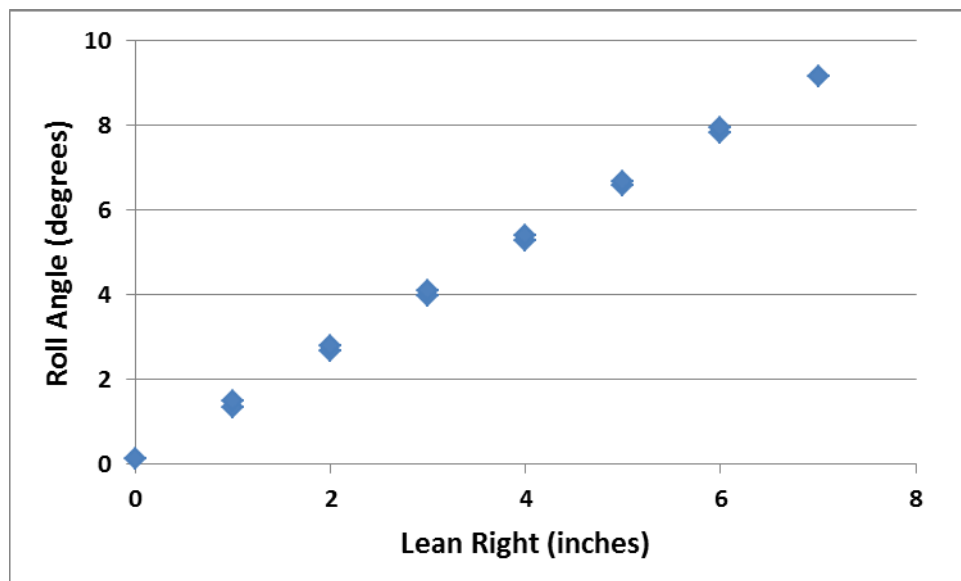


Figure A67. Lean Right Roll Angle

Appendix B. NUCARS Model System Files

DOTX-216 Observation End Leading Model

\System Title

T-16 Car Observation End Lead T16_ObsLead.sys

\Body Data

13

! Car body X Y Z #DOF

1	'Car Body'	-426.96	1.26	73	6	1	2	3	4	5	6	
		246.952783	800000	23000000	21500000							
2	'Ld Bolster'	-51	0	18	6	1	2	3	4	5	6	
		6.423372789	6530	268	6614							
3	'Tr Bolster'	-771	0	18	6	1	2	3	4	5	6	
		6.423372789	6530	268	6614							
4	'Ld Truck Frame'	-51	0	18	6	1	2	3	4	5	6	
		16.83545287	17291	33951	33951							
5	'Tr Truck Frame'	-771	0	18	6	1	2	3	4	5	6	
		16.83545287	17291	33951	33951							
6	'LdL Eqlzr Beam'	-51	39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
7	'LdR Eqlzr Beam'	-51	-39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
8	'TrL Eqlzr Beam'	-771	39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
9	'TrR Eqlzr Beam'	-771	-39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
10	'Axle 1'	0	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
11	'Axle 2'	-102	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
12	'Axle 3'	-720	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
13	'Axle 4'	-822	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							

!End of body data

\Flexible Modes

```

6 1 -51 102 600000000 0 0 0.2 0 0
7 1 -51 102 600000000 0 0 0.2 0 0
8 1 -771 102 600000000 0 0 0.2 0 0
9 1 -771 102 600000000 0 0 0.2 0 0

```

\Connection Data

120

!Connections	Name	Type	Bdy1	Bdy2	X Locn	Y Locn	Z Locn	#DOF	CH#
--------------	------	------	------	------	--------	--------	--------	------	-----

!Couplers

1	'Ld Coupler'	1.3	0	1	99	0	33.8125	3	1	2	6	1	2	2
2	'Tr Coupler'	1.3	1	0	-921	0	33.8125	3	1	2	6	1	2	2

!Carbody to Truck Bolster Secondary Springs

3	'LL SecSpr'	1.3	1	2	-51	53.25	39	3	2	3	4	3	4	5
4	'LR SecSpr'	1.3	1	2	-51	-53.25	39	3	2	3	4	3	6	5
5	'TL SecSpr'	1.3	1	3	-771	53.25	39	3	2	3	4	3	7	5
6	'TR SecSpr'	1.3	1	3	-771	-53.25	39	3	2	3	4	3	8	5

!Traction Rod

7	'LL TracRod'	1.1	1	2	-51	53.5	20.75	3	1	2	3	9	10	11
8	'LR TracRod'	1.1	1	2	-51	-53.5	20.75	3	1	2	3	9	12	13
9	'TL TracRod'	1.1	1	3	-771	53.5	20.75	3	1	2	3	9	14	15
10	'TR TracRod'	1.1	1	3	-771	-53.5	20.75	3	1	2	3	9	16	17

!Lateral bump stop

11	'L1 Lat Bump Stp'	1.2	2	1	-41.75	26	42	2						18
12	'R1 Lat Bump Stp'	1.2	1	2	-41.75	-26	42	2						19
13	'L2 Lat Bump Stp'	1.2	2	1	-60.25	26	42	2						20
14	'R2 Lat Bump Stp'	1.2	1	2	-60.25	-26	42	2						21
15	'L3 Lat Bump Stp'	1.2	3	1	-761.75	26	42	2						22
16	'R3 Lat Bump Stp'	1.2	1	3	-761.75	-26	42	2						23
17	'L4 Lat Bump Stp'	1.2	3	1	-780.25	26	42	2						24
18	'R4 Lat Bump Stp'	1.2	1	3	-780.25	-26	42	2						25

!Vertical Bump Stops

19	'L1 Vert Bmp Stp'	1.2	1	2	-41.75	34	42	3						26
20	'R1 Vert Bmp Stp'	1.2	1	2	-41.75	-34	42	3						27
21	'L2 Vert Bmp Stp'	1.2	1	2	-60.25	34	42	3						28
22	'R2 Vert Bmp Stp'	1.2	1	2	-60.25	-34	42	3						29

23	'L3 Vert Bmp Stp'	1.2	1	3	-761.75	34	42	3		30	
24	'R3 Vert Bmp Stp'	1.2	1	3	-761.75	-34	42	3		31	
25	'L4 Vert Bmp Stp'	1.2	1	3	-780.25	34	42	3		32	
26	'R4 Vert Bmp Stp'	1.2	1	3	-780.25	-34	42	3		33	
!Lateral Dampers											
27	'LL HorizDamp'	2	1	2	-36	50.75	37.5	2		34	
28	'LR HorizDamp'	2	1	2	-36	-50.75	37.5	2		35	
29	'TL HorizDamp'	2	1	3	-786	50.75	37.5	2		36	
30	'TR HorizDamp'	2	1	3	-786	-50.75	37.5	2		37	
!Vertical damper											
31	'LL VrtDamp'	2	1	2	-31.5	49.625	35	3		38	
32	'LR VrtDamp'	2	1	2	-31.5	-49.625	35	3		39	
33	'TL VrtDamp'	2	1	3	-790.5	49.625	35	3		40	
34	'TR VrtDamp'	2	1	3	-790.5	-49.625	35	3		41	
!Center plate vertical connections											
35	'LdTrk CPZ Ld'	6.5	2	4	-39	0	18	3	1	2	42
36	'LdTrk CPZ Tr'	6.5	2	4	-63	0	18	3	1	2	42
37	'LdTrk CPZ Lf'	6.5	2	4	-51	12	18	3	1	2	42
38	'LdTrk CPZ Rt'	6.5	2	4	-51	-12	18	3	1	2	42
39	'TrTrk CPZ Ld'	6.5	3	5	-759	0	19	3	1	2	42
40	'TrTrk CPZ Tr'	6.5	3	5	-783	0	19	3	1	2	42
41	'TrTrk CPZ Lf'	6.5	3	5	-771	12	19	3	1	2	42
42	'TrTrk CPZ Rt'	6.5	3	5	-771	-12	19	3	1	2	42
!Center plate Rim connections											
43	'LdTrk CPX Ld'	6.2	4	2	-39	0	18	1	2		43
44	'LdTrk CPX Tr'	6.2	2	4	-63	0	18	1	2		43
45	'LdTrk CPY Lf'	6.2	4	2	-51	12	18	2	1		43
46	'LdTrk CPY Rt'	6.2	2	4	-51	-12	18	2	1		43
47	'TrTrk CPX Ld'	6.2	5	3	-759	0	19	1	2		43
48	'TrTrk CPX Tr'	6.2	3	5	-783	0	19	1	2		43
49	'TrTrk CPY Lf'	6.2	5	3	-771	12	19	2	1		43
50	'TrTrk CPY Rt'	6.2	3	5	-771	-12	19	2	1		43
!Side bearings											
51	'LL Side Bearing'	6.2	2	4	-51	40.4375	25.5	3	1		44
52	'LR Side Bearing'	6.2	2	4	-51	-40.4375	25.5	3	1		45
53	'TL Side Bearing'	6.2	3	5	-771	40.4375	25.5	3	1		46
54	'TR Side Bearing'	6.2	3	5	-771	-40.4375	25.5	3	1		47

!Primary suspension - Truck Frame to Equalizer Beam

55	'Ax1L PrimSp'	1.1	4	6	-22	39.5	18.1875	3	1	2	3	48	49	50
56	'Ax1R PrimSp'	1.1	4	7	-22	-39.5	18.1875	3	1	2	3	48	49	51
57	'Ax2L PrimSp'	1.1	4	6	-80	39.5	18.1875	3	1	2	3	48	49	50
58	'Ax2R PrimSp'	1.1	4	7	-80	-39.5	18.1875	3	1	2	3	48	49	51
59	'Ax3L PrimSp'	1.1	5	8	-742	39.5	18.1875	3	1	2	3	48	49	52
60	'Ax3R PrimSp'	1.1	5	9	-742	-39.5	18.1875	3	1	2	3	48	49	53
61	'Ax4L PrimSp'	1.1	5	8	-800	39.5	18.1875	3	1	2	3	48	49	52
62	'Ax4R PrimSp'	1.1	5	9	-800	-39.5	18.1875	3	1	2	3	48	49	53

! Equalizer Beam To Axle Box

63	'Ax1LEqBAxBxIn'	1.1	6	10	0	36.5	18	3	1	2	3	54	55	56
64	'Ax1LEqBAxBxOut'	1.1	6	10	0	42.5	18	3	1	2	3	57	55	56
65	'Ax1REqBAxBxIn'	1.1	7	10	0	-36.5	18	3	1	2	3	54	55	56
66	'Ax1REqBAxBxOut'	1.1	7	10	0	-42.5	18	3	1	2	3	57	55	56
67	'Ax2LEqBAxBxIn'	1.1	6	11	-102	36.5	18	3	1	2	3	54	55	56
68	'Ax2LEqBAxBxOut'	1.1	6	11	-102	42.5	18	3	1	2	3	57	55	56
69	'Ax2REqBAxBxIn'	1.1	7	11	-102	-36.5	18	3	1	2	3	54	55	56
70	'Ax2REqBAxBxOut'	1.1	7	11	-102	-42.5	18	3	1	2	3	57	55	56
71	'Ax3LEqBAxBxIn'	1.1	8	12	-720	36.5	18	3	1	2	3	54	55	56
72	'Ax3LEqBAxBxOut'	1.1	8	12	-720	42.5	18	3	1	2	3	57	55	56
73	'Ax3REqBAxBxIn'	1.1	9	12	-720	-36.5	18	3	1	2	3	54	55	56
74	'Ax3REqBAxBxOut'	1.1	9	12	-720	-42.5	18	3	1	2	3	57	55	56
75	'Ax4LEqBAxBxIn'	1.1	8	13	-822	36.5	18	3	1	2	3	54	55	56
76	'Ax4LEqBAxBxOut'	1.1	8	13	-822	42.5	18	3	1	2	3	57	55	56
77	'Ax4REqBAxBxIn'	1.1	9	13	-822	-36.5	18	3	1	2	3	54	55	56
78	'Ax4REqBAxBxOut'	1.1	9	13	-822	-42.5	18	3	1	2	3	57	55	56

!AxleBox to Truck Frame Connections - Longitudinal Stops

79	'Ax1L-TrkFrmX'	6.5	4	10	0	39.5	18.1875	1	2	3		58
80	'Ax1R-TrkFrmX'	6.5	4	10	0	-39.5	18.1875	1	2	3		59
81	'Ax2L-TrkFrmX'	6.5	4	11	-102	39.5	18.1875	1	2	3		60
82	'Ax2R-TrkFrmX'	6.5	4	11	-102	-39.5	18.1875	1	2	3		61
83	'Ax3L-TrkFrmX'	6.5	5	12	-720	39.5	18.1875	1	2	3		62
84	'Ax3R-TrkFrmX'	6.5	5	12	-720	-39.5	18.1875	1	2	3		63
85	'Ax4L-TrkFrmX'	6.5	5	13	-822	39.5	18.1875	1	2	3		64
86	'Ax4R-TrkFrmX'	6.5	5	13	-822	-39.5	18.1875	1	2	3		65

!AxleBox Connections - Lateral Stops

87	'Ax1L-TrkFrmY'	6.5	4	10	0	39.5	18.1875	2	1	3		66
----	----------------	-----	---	----	---	------	---------	---	---	---	--	----

88	'Ax1R-TrkFrmY'	6.5	10	4	0	-39.5	18.1875	2	1	3	67
89	'Ax2L-TrkFrmY'	6.5	4	11	-102	39.5	18.1875	2	1	3	68
90	'Ax2R-TrkFrmY'	6.5	11	4	-102	-39.5	18.1875	2	1	3	69
91	'Ax3L-TrkFrmY'	6.5	5	12	-720	39.5	18.1875	2	1	3	70
92	'Ax3R-TrkFrmY'	6.5	12	5	-720	-39.5	18.1875	2	1	3	71
93	'Ax4L-TrkFrmY'	6.5	5	13	-822	39.5	18.1875	2	1	3	72
94	'Ax4R-TrkFrmY'	6.5	13	5	-822	-39.5	18.1875	2	1	3	73

!Wheel/rail connections

95	'Ax1L-W/R'	4	10	0	29.75	0	1
96	'Ax1R-W/R'	4	10	0	-29.75	0	1
97	'Ax2L-W/R'	4	11	-102	29.75	0	2
98	'Ax2R-W/R'	4	11	-102	-29.75	0	2
99	'Ax3L-W/R'	4	12	-720	29.75	0	3
100	'Ax3R-W/R'	4	12	-720	-29.75	0	3
101	'Ax4L-W/R'	4	13	-822	29.75	0	4
102	'Ax4R-W/R'	4	13	-822	-29.75	0	4

!Dummy Connections for Stringpots

103	'DXSS1'	1	4	1	-51	53.5	10	1	74
104	'DXSS2'	1	1	5	-771	53.5	10	1	74
105	'DYSS1'	1	2	1	-61	60	39	2	74
106	'DYSS2'	1	3	1	-781	60	39	2	74
107	'DZSSL1'	1	1	2	-61	65	39	3	74
108	'DZSSR1'	1	1	2	-61	-65	39	3	74
109	'DZSSL2'	1	1	3	-781	65	39	3	74
110	'DZSSR2'	1	1	3	-781	-65	39	3	74
111	'DXPSL1'	1	4	10	6	44	18	1	74
112	'DXPSR1'	1	4	10	6	-44	18	1	74
113	'DXPSL2'	1	11	4	-108	44	18	1	74
114	'DXPSR2'	1	11	4	-108	-44	18	1	74
115	'DYPS1'	1	10	4	6	44	32	2	74
116	'DYPS2'	1	11	4	-108	44	32	2	74
117	'DZPSL1'	1	4	6	-22	47	18	3	74
118	'DZPSR1'	1	4	7	-22	-47	18	3	74
119	'DZPSL2'	1	4	6	-80	47	18	3	74
120	'DZPSR2'	1	4	7	-80	-47	18	3	74

!End of Connection Data

```

\CHARACTERISTIC DATA
!Coupler Longitudinal
1 1 2 1000000000 -1000000000
!Coupler Dummy Lateral and Vertical
2 0 0 0 0
!Secondary Spring Lateral
3 3 4 1000000000 -1000000000
!Secondary Spring Lead Left Vertical - Different offsets for each
!Secondary Spring to stabilize model
4 5 6 1000000000 -1000000000
!Secondary Spring Roll
5 7 8 1000000000 -1000000000
!Secondary Spring Lead Right Vertical - Different offsets for each
!Secondary Spring to stabilize model
6 9 10 1000000000 -1000000000
!Secondary Spring Trail Left Vertical - Different offsets for each
!Secondary Spring to stabilize model
7 11 12 1000000000 -1000000000
!Secondary Spring Trail Right Vertical - Different offsets for each
!Secondary Spring to stabilize model
8 13 14 1000000000 -1000000000
!Traction rod longitudinal characteristic
9 15 16 1000000000 -1000000000
!Traction rod lateral characteristic Cab End L
10 17 18 1000000000 -1000000000
!Traction rod vertical characteristic Cab End L
11 19 20 1000000000 -1000000000
!Traction rod lateral characteristic Cab End R
12 21 22 1000000000 -1000000000
!Traction rod vertical characteristic Cab End R
13 23 24 1000000000 -1000000000
!Traction rod lateral characteristic Non-Cab End L
14 25 26 1000000000 -1000000000
!Traction rod vertical characteristic Non-Cab End L
15 27 28 1000000000 -1000000000
!Traction rod lateral characteristic Non-Cab End R
16 29 30 1000000000 -1000000000

```

```

!Traction rod vertical characteristic Non-Cab End R
17 31 32 1000000000 -1000000000
!Lateral bump stop nearest axle 1L
18 33 0 1000 -1.75
!Lateral bump stop nearest axle 1R
19 33 0 1000 -1.75
!Lateral bump stop nearest axle 2L
20 33 0 1000 -1.75
!Lateral bump stop nearest axle 2R
21 33 0 1000 -1.75
!Lateral bump stop nearest axle 3L
22 33 0 1000 -1.75
!Lateral bump stop nearest axle 3R
23 33 0 1000 -1.75
!Lateral bump stop nearest axle 4L
24 33 0 1000 -1.75
!Lateral bump stop nearest axle 4R
25 33 0 1000 -1.75
!Vertical bump stop nearest axle 1L
26 34 0 1000 -2
!Vertical bump stop nearest axle 1R
27 34 0 1000 -2.5625
!Vertical bump stop nearest axle 2L
28 34 0 1000 -2.0625
!Vertical bump stop nearest axle 2R
29 34 0 1000 -2.5625
!Vertical bump stop nearest axle 3L
30 34 0 1000 -2.75
!Vertical bump stop nearest axle 3R
31 34 0 1000 -3.0625
!Vertical bump stop nearest axle 4L
32 34 0 1000 -2.375
!Vertical bump stop nearest axle 4R
33 34 0 1000 -2.9375
!Lead Left Lateral Damper
34 35 36 3.4 -3.4 1000000

```

```

!Lead Right Lateral Damper
35 37 38 3.4 -3.4 1000000
!Trail Left Lateral Damper
36 39 40 3.4 -3.4 1000000
!Trail Right Lateral Damper
37 41 42 3.4 -3.4 1000000
!Lead Left Vertical damper
38 43 44 4.3 -4.3 1000000
!Lead Right Vertical damper
39 45 46 4.3 -4.3 1000000
!Trail Left Vertical damper
40 47 48 4.3 -4.3 1000000
!Trail Right Vertical damper
41 49 50 4.3 -4.3 1000000
!Centerplate Vertical Connections
42 51 0 1000000 1000 0.3
!Centerplate rim connections
43 52 0 1000000 -1000000 0 1000000 1000 0.2
!Lead Left Side bearing connection
44 53 0 10000000000 -10000000000 0 1000000 1000 0.3
!Lead Right Side bearing connection
45 54 0 10000000000 -10000000000 0 1000000 1000 0.3
!Trail Left Side bearing connection
46 55 0 10000000000 -10000000000 0 1000000 1000 0.3
!Trail Right Side bearing connection
47 56 0 10000000000 -10000000000 0 1000000 1000 0.3
!Primary Coil Longitudinal
48 57 58 10000000000 -10000000000
!Primary Coil Lateral
49 59 60 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
50 61 62 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
51 63 64 10000000000 -10000000000

```

```

!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
52 65 66 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
53 67 68 10000000000 -10000000000
! Equalizer Beam To Axle Box Longitudinal (inside)
54 69 70 10000000000 -10000000000
! Equalizer Beam To Axle Box Lateral
55 71 72 10000000000 -10000000000
! Equalizer Beam To Axle Box Vertical
56 73 74 10000000000 -10000000000
! Equalizer Beam To Axle Box Longitudinal (outside)
!Zero stiffness to prevent excessive interaxle shear stiffness
57 0 0 0 0
!L1 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
58 75 0 1000000 1000 0.2
!R1 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
59 76 0 1000000 1000 0.2
!L2 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
60 77 0 1000000 1000 0.2
!R2 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
61 78 0 1000000 1000 0.2
!L3 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
62 79 0 1000000 1000 0.2
!R3 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
63 80 0 1000000 1000 0.2
!L4 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
64 81 0 1000000 1000 0.2

```

```

!R4 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
65 82 0 1000000 1000 0.2
!L1 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
66 83 0 1000000 1000 0.15
!R1 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
67 84 0 1000000 1000 0.15
!L2 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
68 85 0 1000000 1000 0.15
!R2 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
69 86 0 1000000 1000 0.15
!L3 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
70 87 0 1000000 1000 0.15
!R3 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
71 88 0 1000000 1000 0.15
!L4 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
72 89 0 1000000 1000 0.15
!R4 AxleBox Connections - Lateral Stops.
!One connection/side - only needs compression
73 90 0 1000000 1000 0.15
! Dummy characteristic for stringpots
74 0 0 1 -1
!End of Characteristic Data

```

```

\WHEEL/RAIL ELEMENT
100000 100 250000 250
10 18 .F. 0 0
11 18 .F. 0 0
12 18 .F. 0 0
13 18 .F. 0 0

```

\PWL DATA

!Coupler Longitudinal

!Connections

1 2 0 100000

0 1

2 2 0 600

0 1

!Secondary Spring Lateral

3 2 0 1600

0 1

4 2 0 13

0 1

!Secondary Spring Lead Left Vertical - Different offsets for each spring

5 3 -23344.21558 0 0

0 8.049729509 8.149729509

6 2 0 17

0 1

!Secondary Spring Roll

7 2 0 0

0 1

8 2 0 0

0 1

!Secondary Spring Lead Right Vertical - Different offsets for each spring

9 3 -22215.46044 0 0

0 7.660503599 7.760503599

10 2 0 17

0 1

!Secondary Spring Trail Left Vertical - Different offsets for each spring

11 3 -25457.53956 0 0

0 8.778461919 8.878461919

12 2 0 17

0 1

!Secondary Spring Trail Right Vertical - Different offsets for each spring

13 3 -24328.78442 0 0

0 8.389236008 8.489236008

14 2 0 17

0 1

```

!Traction rod longitudinal characteristic
15  2  0  24000
    0  1
16  2  0  39
    0  1
!Traction rod lateral characteristic Cab End L
17  2  0  500
    0  1
18  2  0  6
    0  1
!Traction rod vertical characteristic Cab End L
19  2  0  350
    0  1
20  2  0  5
    0  1
!Traction rod lateral characteristic Cab End R
21  2  0  500
    0  1
22  2  0  6
    0  1
!Traction rod vertical characteristic Cab End R
23  2  0  350
    0  1
24  2  0  5
    0  1
!Traction rod lateral characteristic Non-Cab End L
25  2  0  500
    0  1
26  2  0  6
    0  1
!Traction rod vertical characteristic Non-Cab End L
27  2  0  350
    0  1
28  2  0  5
    0  1

```

```

!Traction rod lateral characteristic Non-Cab End R
29  2  0  500
    0  1
30  2  0  6
    0  1
!Traction rod vertical characteristic Non-Cab End R
31  2  0  350
    0  1
32  2  0  5
    0  1
!Lateral bump stop nearest axle 1L
33  2  0  50000
    0  1
!Vertical bump stop nearest axle 1L
34  2  0  50000
    0  1
!Lead Left Lateral Damper
35  2  0  100000
    0  1
36  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20
!Lead Right Lateral Damper
37  2  0  100000
    0  1
38  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20
!Trail Left Lateral Damper
39  2  0  100000
    0  1
40  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20

!Trail Right Lateral Damper
41  2  0  100000
    0  1
42  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20

```

```

!Lead Left Vertical damper
43 2 0 32600
    0 1
44 5 -1400 -950 0 950 1400
    -20 -5 0 5 20
!Lead Right Vertical damper
45 2 0 32600
    0 1
46 5 -1400 -950 0 950 1400
    -20 -5 0 5 20
!Trail Left Vertical damper
47 2 0 32600
    0 1
48 5 -1400 -950 0 950 1400
    -20 -5 0 5 20
!Trail Right Vertical damper
49 2 0 32600
    0 1
50 5 -1400 -950 0 950 1400
    -20 -5 0 5 20
!Centerplate Vertical Connections
51 3 -12538.25 0 0
    0 0.01253825 0.02253825
!Centerplate rim connections
52 3 -100000 0 0
    -0.225 -0.125 1
!Lead Left Side bearing connection
53 3 -100000 0 0
    -0.35 -0.25 1
!Lead Right Side bearing connection
54 3 -100000 0 0
    -0.2875 -0.1875 1
!Trail Left Side bearing connection
55 3 -100000 0 0
    -0.1625 -0.0625 1

```

```

!Trail Right Side bearing connection
56 3 -100000 0 0
    -0.225 -0.125 1
!Primary Coil Longitudinal
57 2 0 8500
    0 1
58 2 0 29
    0 1
!Primary Coil Lateral
59 2 0 8500
    0 1
60 2 0 29
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
61 3 -13917.10779 0 0
    0 3.479276947 3.489276947
62 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
63 3 -13352.73022 0 0
    0 3.338182554 3.348182554
64 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
65 3 -14973.76978 0 0
    0 3.743442446 3.753442446
66 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
67 3 -14409.39221 0 0
    0 3.602348053 3.612348053
68 2 0 20
    0 1
! Equalizer Beam To Axle Box Longitudinal (inside)
69 2 0 500000
    0 1

```

```

70  2  0  100
    0  1
! Equalizer Beam To Axle Box Lateral
71  2  0  1000000
    0  1
72  2  0  100
    0  1
! Equalizer Beam To Axle Box Vertical
73  3  -7332.875  0  0
    0  0.007332875  0.107332875
74  2  0  100
    0  1
!L1 AxleBox to Truck Frame Connections - Longitudinal Stops.
75  3  0  0  50000
    0  0.0375  0.1375
!R1 AxleBox to Truck Frame Connections - Longitudinal Stops.
76  3  0  0  50000
    0  0.054  0.154
!L2 AxleBox to Truck Frame Connections - Longitudinal Stops.
77  3  0  0  50000
    0  0.0375  0.1375
!R2 AxleBox to Truck Frame Connections - Longitudinal Stops.
78  3  0  0  50000
    0  0.0615  0.1615
!L3 AxleBox to Truck Frame Connections - Longitudinal Stops.
79  3  0  0  50000
    0  0.05  0.15
!R3 AxleBox to Truck Frame Connections - Longitudinal Stops.
80  3  0  0  50000
    0  0.0635  0.1635
!L4 AxleBox to Truck Frame Connections - Longitudinal Stops.
81  3  0  0  50000
    0  0.044  0.144
!R4 AxleBox to Truck Frame Connections - Longitudinal Stops.
82  3  0  0  50000
    0  0.0425  0.1425

```

```

!L1 AxleBox Connections - Lateral Stops.
83  4  -100000  0  0  0
      -0.240625  -0.140625  0  1
!R1 AxleBox Connections - Lateral Stops.
84  4  -100000  0  0  0
      -0.240625  -0.140625  0  1
!L2 AxleBox Connections - Lateral Stops.
85  4  -100000  0  0  0
      -0.31875   -0.21875   0  1
!R2 AxleBox Connections - Lateral Stops.
86  4  -100000  0  0  0
      -0.31875   -0.21875   0  1
!L3 AxleBox Connections - Lateral Stops.
87  4  -100000  0  0  0
      -0.225     -0.125     0  1
!R3 AxleBox Connections - Lateral Stops.
88  4  -100000  0  0  0
      -0.225     -0.125     0  1
!L4 AxleBox Connections - Lateral Stops.
89  4  -100000  0  0  0
      -0.25625   -0.15625   0  1
!R4 AxleBox Connections - Lateral Stops.
90  4  -100000  0  0  0
      -0.25625   -0.15625   0  1

```

DOTX-216 Vestibule End Leading Model

\System Title

T-16 Car Observation End Trail T16_VestLead.sys

\Body Data

13

! Car body X Y Z #DOF

1	'Car Body'	-395.04	-1.26	73	6	1	2	3	4	5	6	
		246.952783	800000	23000000	21500000							
2	'Ld Bolster'	-771	0	18	6	1	2	3	4	5	6	
		6.423372789	6530	268	6614							
3	'Tr Bolster'	-51	0	18	6	1	2	3	4	5	6	
		6.423372789	6530	268	6614							
4	'Ld Truck Frame'	-771	0	18	6	1	2	3	4	5	6	
		16.83545287	17291	33951	33951							
5	'Tr Truck Frame'	-51	0	18	6	1	2	3	4	5	6	
		16.83545287	17291	33951	33951							
6	'LdL Eqlzr Beam'	-771	-39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
7	'LdR Eqlzr Beam'	-771	39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
8	'TrL Eqlzr Beam'	-51	-39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
9	'TrR Eqlzr Beam'	-51	39.5	18	7	1	2	3	4	5	6	7.01
		2.603020021	57	2674	2633							
10	'Axle 1'	-822	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
11	'Axle 2'	-720	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
12	'Axle 3'	-102	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							
13	'Axle 4'	0	0	18	5	1	2	3	4	6		
		10.47683183	7983	2500	7983							

!End of body data

\Flexible Modes

6	1	-771	102	600000000	0	0	0.2	0	0
7	1	-771	102	600000000	0	0	0.2	0	0
8	1	-51	102	600000000	0	0	0.2	0	0
9	1	-51	102	600000000	0	0	0.2	0	0

\Connection Data

120

!Connections	Name	Type	Bdy1	Bdy2	X Locn	Y Locn	Z Locn	#DOF	CH#
--------------	------	------	------	------	--------	--------	--------	------	-----

!Couplers

1	'Ld Coupler'	1.3	0	1	-921	0	33.8125	3	1	2	6	1	2	2
2	'Tr Coupler'	1.3	1	0	99	0	33.8125	3	1	2	6	1	2	2

!Carbody to Truck Bolster Secondary Springs

3	'LL SecSpr'	1.3	1	2	-771	-53.25	39	3	2	3	4	3	4	5
4	'LR SecSpr'	1.3	1	2	-771	53.25	39	3	2	3	4	3	6	5
5	'TL SecSpr'	1.3	1	3	-51	-53.25	39	3	2	3	4	3	7	5
6	'TR SecSpr'	1.3	1	3	-51	53.25	39	3	2	3	4	3	8	5

!Traction Rod

7	'LL TracRod'	1.1	1	2	-771	-53.5	20.75	3	1	2	3	9	10	11
8	'LR TracRod'	1.1	1	2	-771	53.5	20.75	3	1	2	3	9	12	13
9	'TL TracRod'	1.1	1	3	-51	-53.5	20.75	3	1	2	3	9	14	15
10	'TR TracRod'	1.1	1	3	-51	53.5	20.75	3	1	2	3	9	16	17

!Lateral bump stop

11	'L1 Lat Bump Stp'	1.2	2	1	-780.25	-26	42	2	18
12	'R1 Lat Bump Stp'	1.2	1	2	-780.25	26	42	2	19
13	'L2 Lat Bump Stp'	1.2	2	1	-761.75	-26	42	2	20
14	'R2 Lat Bump Stp'	1.2	1	2	-761.75	26	42	2	21
15	'L3 Lat Bump Stp'	1.2	3	1	-60.25	-26	42	2	22
16	'R3 Lat Bump Stp'	1.2	1	3	-60.25	26	42	2	23
17	'L4 Lat Bump Stp'	1.2	3	1	-41.75	-26	42	2	24
18	'R4 Lat Bump Stp'	1.2	1	3	-41.75	26	42	2	25

!Vertical Bump Stops

19	'L1 Vert Bmp Stp'	1.2	1	2	-780.25	-34	42	3	26
20	'R1 Vert Bmp Stp'	1.2	1	2	-780.25	34	42	3	27
21	'L2 Vert Bmp Stp'	1.2	1	2	-761.75	-34	42	3	28
22	'R2 Vert Bmp Stp'	1.2	1	2	-761.75	34	42	3	29
23	'L3 Vert Bmp Stp'	1.2	1	3	-60.25	-34	42	3	30
24	'R3 Vert Bmp Stp'	1.2	1	3	-60.25	34	42	3	31

25	'L4 Vert Bmp Stp'	1.2	1	3	-41.75	-34	42	3	32
26	'R4 Vert Bmp Stp'	1.2	1	3	-41.75	34	42	3	33
!Lateral Dampers									
27	'LL HorizDamp'	2	1	2	-786	-50.75	37.5	2	34
28	'LR HorizDamp'	2	1	2	-786	50.75	37.5	2	35
29	'TL HorizDamp'	2	1	3	-36	-50.75	37.5	2	36
30	'TR HorizDamp'	2	1	3	-36	50.75	37.5	2	37
!Vertical damper									
31	'LL VrtDamp'	2	1	2	-790.5	-49.625	35	3	38
32	'LR VrtDamp'	2	1	2	-790.5	49.625	35	3	39
33	'TL VrtDamp'	2	1	3	-31.5	-49.625	35	3	40
34	'TR VrtDamp'	2	1	3	-31.5	49.625	35	3	41
!Center plate vertical connections									
35	'LdTrk CPZ Ld'	6.5	2	4	-783	0	18	3	1 2 42
36	'LdTrk CPZ Tr'	6.5	2	4	-759	0	18	3	1 2 42
37	'LdTrk CPZ Lf'	6.5	2	4	-771	-12	18	3	1 2 42
38	'LdTrk CPZ Rt'	6.5	2	4	-771	12	18	3	1 2 42
39	'TrTrk CPZ Ld'	6.5	3	5	-63	0	19	3	1 2 42
40	'TrTrk CPZ Tr'	6.5	3	5	-39	0	19	3	1 2 42
41	'TrTrk CPZ Lf'	6.5	3	5	-51	-12	19	3	1 2 42
42	'TrTrk CPZ Rt'	6.5	3	5	-51	12	19	3	1 2 42
!Center plate Rim connections									
43	'LdTrk CPX Ld'	6.2	4	2	-783	0	18	1	2 43
44	'LdTrk CPX Tr'	6.2	2	4	-759	0	18	1	2 43
45	'LdTrk CPY Lf'	6.2	4	2	-771	-12	18	2	1 43
46	'LdTrk CPY Rt'	6.2	2	4	-771	12	18	2	1 43
47	'TrTrk CPX Ld'	6.2	5	3	-63	0	19	1	2 43
48	'TrTrk CPX Tr'	6.2	3	5	-39	0	19	1	2 43
49	'TrTrk CPY Lf'	6.2	5	3	-51	-12	19	2	1 43
50	'TrTrk CPY Rt'	6.2	3	5	-51	12	19	2	1 43
!Side bearings									
51	'LL Side Bearing'	6.2	2	4	-771	-40.4375	25.5	3	1 44
52	'LR Side Bearing'	6.2	2	4	-771	40.4375	25.5	3	1 45
53	'TL Side Bearing'	6.2	3	5	-51	-40.4375	25.5	3	1 46
54	'TR Side Bearing'	6.2	3	5	-51	40.4375	25.5	3	1 47

!Primary suspension - Truck Frame to Equalizer Beam

55	'Ax1L PrimSp'	1.1	4	6	-800	-39.5	18.1875	3	1	2	3	48	49	50
56	'Ax1R PrimSp'	1.1	4	7	-800	39.5	18.1875	3	1	2	3	48	49	51
57	'Ax2L PrimSp'	1.1	4	6	-742	-39.5	18.1875	3	1	2	3	48	49	50
58	'Ax2R PrimSp'	1.1	4	7	-742	39.5	18.1875	3	1	2	3	48	49	51
59	'Ax3L PrimSp'	1.1	5	8	-80	-39.5	18.1875	3	1	2	3	48	49	52
60	'Ax3R PrimSp'	1.1	5	9	-80	39.5	18.1875	3	1	2	3	48	49	53
61	'Ax4L PrimSp'	1.1	5	8	-22	-39.5	18.1875	3	1	2	3	48	49	52
62	'Ax4R PrimSp'	1.1	5	9	-22	39.5	18.1875	3	1	2	3	48	49	53

! Equalizer Beam To Axle Box

63	'Ax1LEqBAxBxIn'	1.1	6	10	-822	-36.5	18	3	1	2	3	54	55	56
64	'Ax1LEqBAxBxOut'	1.1	6	10	-822	-42.5	18	3	1	2	3	57	55	56
65	'Ax1REqBAxBxIn'	1.1	7	10	-822	36.5	18	3	1	2	3	54	55	56
66	'Ax1REqBAxBxOut'	1.1	7	10	-822	42.5	18	3	1	2	3	57	55	56
67	'Ax2LEqBAxBxIn'	1.1	6	11	-720	-36.5	18	3	1	2	3	54	55	56
68	'Ax2LEqBAxBxOut'	1.1	6	11	-720	-42.5	18	3	1	2	3	57	55	56
69	'Ax2REqBAxBxIn'	1.1	7	11	-720	36.5	18	3	1	2	3	54	55	56
70	'Ax2REqBAxBxOut'	1.1	7	11	-720	42.5	18	3	1	2	3	57	55	56
71	'Ax3LEqBAxBxIn'	1.1	8	12	-102	-36.5	18	3	1	2	3	54	55	56
72	'Ax3LEqBAxBxOut'	1.1	8	12	-102	-42.5	18	3	1	2	3	57	55	56
73	'Ax3REqBAxBxIn'	1.1	9	12	-102	36.5	18	3	1	2	3	54	55	56
74	'Ax3REqBAxBxOut'	1.1	9	12	-102	42.5	18	3	1	2	3	57	55	56
75	'Ax4LEqBAxBxIn'	1.1	8	13	0	-36.5	18	3	1	2	3	54	55	56
76	'Ax4LEqBAxBxOut'	1.1	8	13	0	-42.5	18	3	1	2	3	57	55	56
77	'Ax4REqBAxBxIn'	1.1	9	13	0	36.5	18	3	1	2	3	54	55	56
78	'Ax4REqBAxBxOut'	1.1	9	13	0	42.5	18	3	1	2	3	57	55	56

!AxleBox to Truck Frame Connections - Longitudinal Stops

79	'Ax1L-TrkFrmX'	6.5	4	10	-822	-39.5	18.1875	1	2	3	58
80	'Ax1R-TrkFrmX'	6.5	4	10	-822	39.5	18.1875	1	2	3	59
81	'Ax2L-TrkFrmX'	6.5	4	11	-720	-39.5	18.1875	1	2	3	60
82	'Ax2R-TrkFrmX'	6.5	4	11	-720	39.5	18.1875	1	2	3	61
83	'Ax3L-TrkFrmX'	6.5	5	12	-102	-39.5	18.1875	1	2	3	62
84	'Ax3R-TrkFrmX'	6.5	5	12	-102	39.5	18.1875	1	2	3	63
85	'Ax4L-TrkFrmX'	6.5	5	13	0	-39.5	18.1875	1	2	3	64
86	'Ax4R-TrkFrmX'	6.5	5	13	0	39.5	18.1875	1	2	3	65

!AxleBox Connections - Lateral Stops

87	'Ax1L-TrkFrmY'	6.5	4	10	-822	-39.5	18.1875	2	1	3	66
88	'Ax1R-TrkFrmY'	6.5	10	4	-822	39.5	18.1875	2	1	3	67

89	'Ax2L-TrkFrmY'	6.5	4	11	-720	-39.5	18.1875	2	1	3	68
90	'Ax2R-TrkFrmY'	6.5	11	4	-720	39.5	18.1875	2	1	3	69
91	'Ax3L-TrkFrmY'	6.5	5	12	-102	-39.5	18.1875	2	1	3	70
92	'Ax3R-TrkFrmY'	6.5	12	5	-102	39.5	18.1875	2	1	3	71
93	'Ax4L-TrkFrmY'	6.5	5	13	0	-39.5	18.1875	2	1	3	72
94	'Ax4R-TrkFrmY'	6.5	13	5	0	39.5	18.1875	2	1	3	73

!Wheel/rail connections

95	'Ax1L-W/R'	4	10	-822	-29.75	0	1
96	'Ax1R-W/R'	4	10	-822	29.75	0	1
97	'Ax2L-W/R'	4	11	-720	-29.75	0	2
98	'Ax2R-W/R'	4	11	-720	29.75	0	2
99	'Ax3L-W/R'	4	12	-102	-29.75	0	3
100	'Ax3R-W/R'	4	12	-102	29.75	0	3
101	'Ax4L-W/R'	4	13	0	-29.75	0	4
102	'Ax4R-W/R'	4	13	0	29.75	0	4

!Dummy Connections for Stringpots

103	'DXSS1'	1	4	1	-771	-53.5	10	1	74
104	'DXSS2'	1	1	5	-51	-53.5	10	1	74
105	'DYSS1'	1	2	1	-761	-60	39	2	74
106	'DYSS2'	1	3	1	-41	-60	39	2	74
107	'DZSSL1'	1	1	2	-761	-65	39	3	74
108	'DZSSR1'	1	1	2	-761	65	39	3	74
109	'DZSSL2'	1	1	3	-41	-65	39	3	74
110	'DZSSR2'	1	1	3	-41	65	39	3	74
111	'DXPSL1'	1	4	10	-828	-44	18	1	74
112	'DXPSR1'	1	4	10	-828	44	18	1	74
113	'DXPSL2'	1	11	4	-714	-44	18	1	74
114	'DXPSR2'	1	11	4	-714	44	18	1	74
115	'DYPS1'	1	10	4	-828	-44	32	2	74
116	'DYPS2'	1	11	4	-714	-44	32	2	74
117	'DZPSL1'	1	4	6	-800	-47	18	3	74
118	'DZPSR1'	1	4	7	-800	47	18	3	74
119	'DZPSL2'	1	4	6	-742	-47	18	3	74
120	'DZPSR2'	1	4	7	-742	47	18	3	74

!End of Connection Data

\CHARACTERISTIC DATA

```

!Coupler Longitudinal
1 1 2 1000000000 -1000000000
!Coupler Dummy Lateral and Vertical
2 0 0 0 0
!Secondary Spring Lateral
3 3 4 1000000000 -1000000000
!Secondary Spring Lead Left Vertical - Different offsets for each
!Secondary Spring to stabilize model
4 5 6 1000000000 -1000000000
!Secondary Spring Roll
5 7 8 1000000000 -1000000000
!Secondary Spring Lead Right Vertical - Different offsets for each
!Secondary Spring to stabilize model
6 9 10 1000000000 -1000000000
!Secondary Spring Trail Left Vertical - Different offsets for each
!Secondary Spring to stabilize model
7 11 12 1000000000 -1000000000
!Secondary Spring Trail Right Vertical - Different offsets for each
!Secondary Spring to stabilize model
8 13 14 1000000000 -1000000000
!Traction rod longitudinal characteristic
9 15 16 1000000000 -1000000000
!Traction rod lateral characteristic Cab End L
10 17 18 1000000000 -1000000000
!Traction rod vertical characteristic Cab End L
11 19 20 1000000000 -1000000000
!Traction rod lateral characteristic Cab End R
12 21 22 1000000000 -1000000000
!Traction rod vertical characteristic Cab End R
13 23 24 1000000000 -1000000000
!Traction rod lateral characteristic Non-Cab End L
14 25 26 1000000000 -1000000000
!Traction rod vertical characteristic Non-Cab End L
15 27 28 1000000000 -1000000000
!Traction rod lateral characteristic Non-Cab End R
16 29 30 1000000000 -1000000000
!Traction rod vertical characteristic Non-Cab End R

```

```

17 31 32 1000000000 -1000000000
!Lateral bump stop nearest axle 1L
18 33 0 1000 -1.75
!Lateral bump stop nearest axle 1R
19 33 0 1000 -1.75
!Lateral bump stop nearest axle 2L
20 33 0 1000 -1.75
!Lateral bump stop nearest axle 2R
21 33 0 1000 -1.75
!Lateral bump stop nearest axle 3L
22 33 0 1000 -1.75
!Lateral bump stop nearest axle 3R
23 33 0 1000 -1.75
!Lateral bump stop nearest axle 4L
24 33 0 1000 -1.75
!Lateral bump stop nearest axle 4R
25 33 0 1000 -1.75
!Vertical bump stop nearest axle 1L
26 34 0 1000 -2
!Vertical bump stop nearest axle 1R
27 34 0 1000 -2.5625
!Vertical bump stop nearest axle 2L
28 34 0 1000 -2.0625
!Vertical bump stop nearest axle 2R
29 34 0 1000 -2.5625
!Vertical bump stop nearest axle 3L
30 34 0 1000 -2.75
!Vertical bump stop nearest axle 3R
31 34 0 1000 -3.0625
!Vertical bump stop nearest axle 4L
32 34 0 1000 -2.375
!Vertical bump stop nearest axle 4R
33 34 0 1000 -2.9375
!Lead Left Lateral Damper
34 35 36 3.4 -3.4 1000000

!Lead Right Lateral Damper

```

```

35 37 38 3.4 -3.4 1000000
!Trail Left Lateral Damper
36 39 40 3.4 -3.4 1000000
!Trail Right Lateral Damper
37 41 42 3.4 -3.4 1000000
!Lead Left Vertical damper
38 43 44 4.3 -4.3 1000000
!Lead Right Vertical damper
39 45 46 4.3 -4.3 1000000
!Trail Left Vertical damper
40 47 48 4.3 -4.3 1000000
!Trail Right Vertical damper
41 49 50 4.3 -4.3 1000000
!Centerplate Vertical Connections
42 51 0 1000000 1000 0.3
!Centerplate rim connections
43 52 0 1000000 -1000000 0 1000000 1000 0.2
!Lead Left Side bearing connection
44 53 0 10000000000 -10000000000 0 1000000 1000 0.3
!Lead Right Side bearing connection
45 54 0 10000000000 -10000000000 0 1000000 1000 0.3
!Trail Left Side bearing connection
46 55 0 10000000000 -10000000000 0 1000000 1000 0.3
!Trail Right Side bearing connection
47 56 0 10000000000 -10000000000 0 1000000 1000 0.3
!Primary Coil Longitudinal
48 57 58 10000000000 -10000000000
!Primary Coil Lateral
49 59 60 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
50 61 62 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
51 63 64 10000000000 -10000000000

!Primary Coil Vertical LL - Different offsets for each pair of

```

```

!Primary Springs to stabilize model
52 65 66 10000000000 -10000000000
!Primary Coil Vertical LL - Different offsets for each pair of
!Primary Springs to stabilize model
53 67 68 10000000000 -10000000000
! Equalizer Beam To Axle Box Longitudinal (inside)
54 69 70 10000000000 -10000000000
! Equalizer Beam To Axle Box Lateral
55 71 72 10000000000 -10000000000
! Equalizer Beam To Axle Box Vertical
56 73 74 10000000000 -10000000000
! Equalizer Beam To Axle Box Longitudinal (outside)
! Zero stiffness to prevent excessive interaxle shear stiffness
57 0 0 0 0
!L1 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
58 75 0 1000000 1000 0.2
!R1 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
59 76 0 1000000 1000 0.2
!L2 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
60 77 0 1000000 1000 0.2
!R2 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
61 78 0 1000000 1000 0.2
!L3 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
62 79 0 1000000 1000 0.2
!R3 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
63 80 0 1000000 1000 0.2
!L4 AxleBox to Truck Frame Connections - Longitudinal Stops.
!One Connection/side - needs tension and compression
64 81 0 1000000 1000 0.2

!R4 AxleBox to Truck Frame Connections - Longitudinal Stops.

```

```

!One Connection/side - needs tension and compression
65 82 0 1000000 1000 0.2
!L1 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
66 83 0 1000000 1000 0.15
!R1 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
67 84 0 1000000 1000 0.15
!L2 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
68 85 0 1000000 1000 0.15
!R2 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
69 86 0 1000000 1000 0.15
!L3 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
70 87 0 1000000 1000 0.15
!R3 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
71 88 0 1000000 1000 0.15
!L4 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
72 89 0 1000000 1000 0.15
!R4 AxleBox Connections - Lateral Stops. One connection/side
!only needs compression
73 90 0 1000000 1000 0.15
! Dummy characteristic for stringpots
74 0 0 1 -1
!End of Characteristic Data

```

\WHEEL/RAIL ELEMENT

```

100000 100 250000 250
10 18 .F. 0 0
11 18 .F. 0 0
12 18 .F. 0 0
13 18 .F. 0 0

```

```

\PWL DATA

```

```

!Coupler Longitudinal
1 2 0 100000
  0 1
2 2 0 600
  0 1
!Secondary Spring Lateral
3 2 0 1600
  0 1
4 2 0 13
  0 1
!Secondary Spring Lead Left Vertical - Different offsets for each Spring
5 3 -23344.21558 0 0
  0 8.049729509 8.149729509
6 2 0 17
  0 1
!Secondary Spring Roll
7 2 0 0
  0 1
8 2 0 0
  0 1
!Secondary Spring Lead Right Vertical - Different offsets for each Spring
9 3 -22215.46044 0 0
  0 7.660503599 7.760503599
10 2 0 17
  0 1
!Secondary Spring Trail Left Vertical - Different offsets for each Spring
11 3 -25457.53956 0 0
  0 8.778461919 8.878461919
12 2 0 17
  0 1
!Secondary Spring Trail Right Vertical - Different offsets for each Spring
13 3 -24328.78442 0 0
  0 8.389236008 8.489236008
14 2 0 17
  0 1

!Traction rod longitudinal characteristic

```

```

15  2  0  24000
    0  1
16  2  0  39
    0  1
!Traction rod lateral characteristic Cab End L
17  2  0  500
    0  1
18  2  0  6
    0  1
!Traction rod vertical characteristic Cab End L
19  2  0  350
    0  1
20  2  0  5
    0  1
!Traction rod lateral characteristic Cab End R
21  2  0  500
    0  1
22  2  0  6
    0  1
!Traction rod vertical characteristic Cab End R
23  2  0  350
    0  1
24  2  0  5
    0  1
!Traction rod lateral characteristic Non-Cab End L
25  2  0  500
    0  1
26  2  0  6
    0  1
!Traction rod vertical characteristic Non-Cab End L
27  2  0  350
    0  1
28  2  0  5
    0  1

!Traction rod lateral characteristic Non-Cab End R

```

```

29  2  0  500
    0  1
30  2  0  6
    0  1
!Traction rod vertical characteristic Non-Cab End R
31  2  0  350
    0  1
32  2  0  5
    0  1
!Lateral bump stop nearest axle 1L
33  2  0  50000
    0  1
!Vertical bump stop nearest axle 1L
34  2  0  50000
    0  1
!Lead Left Lateral Damper
35  2  0  100000
    0  1
36  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20
!Lead Right Lateral Damper
37  2  0  100000
    0  1
38  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20
!Trail Left Lateral Damper
39  2  0  100000
    0  1
40  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20
!Trail Right Lateral Damper
41  2  0  100000
    0  1
42  5  -1850  -1400  0  1400  1850
    -20  -5  0  5  20

!Lead Left Vertical damper

```

```

43  2  0  32600
    0  1
44  5 -1400 -950  0  950 1400
    -20 -5  0  5  20
!Lead Right Vertical damper
45  2  0  32600
    0  1
46  5 -1400 -950  0  950 1400
    -20 -5  0  5  20
!Trail Left Vertical damper
47  2  0  32600
    0  1
48  5 -1400 -950  0  950 1400
    -20 -5  0  5  20
!Trail Right Vertical damper
49  2  0  32600
    0  1
50  5 -1400 -950  0  950 1400
    -20 -5  0  5  20
!Centerplate Vertical Connections
51  3 -12538.25  0  0
    0  0.01253825  0.02253825
!Centerplate rim connections
52  3 -100000  0  0
    -0.225 -0.125  1
!Lead Left Side bearing connection
53  3 -100000  0  0
    -0.35 -0.25  1
!Lead Right Side bearing connection
54  3 -100000  0  0
    -0.2875 -0.1875  1
!Trail Left Side bearing connection
55  3 -100000  0  0
    -0.1625 -0.0625  1

!Trail Right Side bearing connection

```

```

56 3 -100000 0 0
    -0.225 -0.125 1
!Primary Coil Longitudinal
57 2 0 8500
    0 1
58 2 0 29
    0 1
!Primary Coil Lateral
59 2 0 8500
    0 1
60 2 0 29
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
61 3 -13917.10779 0 0
    0 3.479276947 3.489276947
62 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
63 3 -13352.73022 0 0
    0 3.338182554 3.348182554
64 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
65 3 -14973.76978 0 0
    0 3.743442446 3.753442446
66 2 0 20
    0 1
!Primary Coil Vertical LL - Different offsets for each pair
67 3 -14409.39221 0 0
    0 3.602348053 3.612348053
68 2 0 20
    0 1
! Equalizer Beam To Axle Box Longitudinal (inside)
69 2 0 500000
    0 1

70 2 0 100

```

```

0 1
! Equalizer Beam To Axle Box Lateral
71 2 0 1000000
0 1
72 2 0 100
0 1
! Equalizer Beam To Axle Box Vertical
73 3 -7332.875 0 0
0 0.007332875 0.107332875
74 2 0 100
0 1
!L1 AxleBox to Truck Frame Connections - Longitudinal Stops.
75 3 0 0 50000
0 0.0375 0.1375
!R1 AxleBox to Truck Frame Connections - Longitudinal Stops.
76 3 0 0 50000
0 0.054 0.154
!L2 AxleBox to Truck Frame Connections - Longitudinal Stops.
77 3 0 0 50000
0 0.0375 0.1375
!R2 AxleBox to Truck Frame Connections - Longitudinal Stops.
78 3 0 0 50000
0 0.0615 0.1615
!L3 AxleBox to Truck Frame Connections - Longitudinal Stops.
79 3 0 0 50000
0 0.05 0.15
!R3 AxleBox to Truck Frame Connections - Longitudinal Stops.
80 3 0 0 50000
0 0.0635 0.1635
!L4 AxleBox to Truck Frame Connections - Longitudinal Stops.
81 3 0 0 50000
0 0.044 0.144
!R4 AxleBox to Truck Frame Connections - Longitudinal Stops.
82 3 0 0 50000
0 0.0425 0.1425

!L1 AxleBox Connections - Lateral Stops.

```

```

83  4  -100000  0  0  0
    -0.240625  -0.140625  0  1
!R1 AxleBox Connections - Lateral Stops.
84  4  -100000  0  0  0
    -0.240625  -0.140625  0  1
!L2 AxleBox Connections - Lateral Stops.
85  4  -100000  0  0  0
    -0.31875   -0.21875   0  1
!R2 AxleBox Connections - Lateral Stops.
86  4  -100000  0  0  0
    -0.31875   -0.21875   0  1
!L3 AxleBox Connections - Lateral Stops
87  4  -100000  0  0  0
    -0.225     -0.125     0  1
!R3 AxleBox Connections - Lateral Stops.
88  4  -100000  0  0  0
    -0.225     -0.125     0  1
!L4 AxleBox Connections - Lateral Stops
89  4  -100000  0  0  0
    -0.25625   -0.15625   0  1
!R4 AxleBox Connections - Lateral Stops.
90  4  -100000  0  0  0
    -0.25625   -0.15625   0  1

```

Appendix C. Comparisons of Model and Test Results

Wheel Load Equalization Test Comparisons

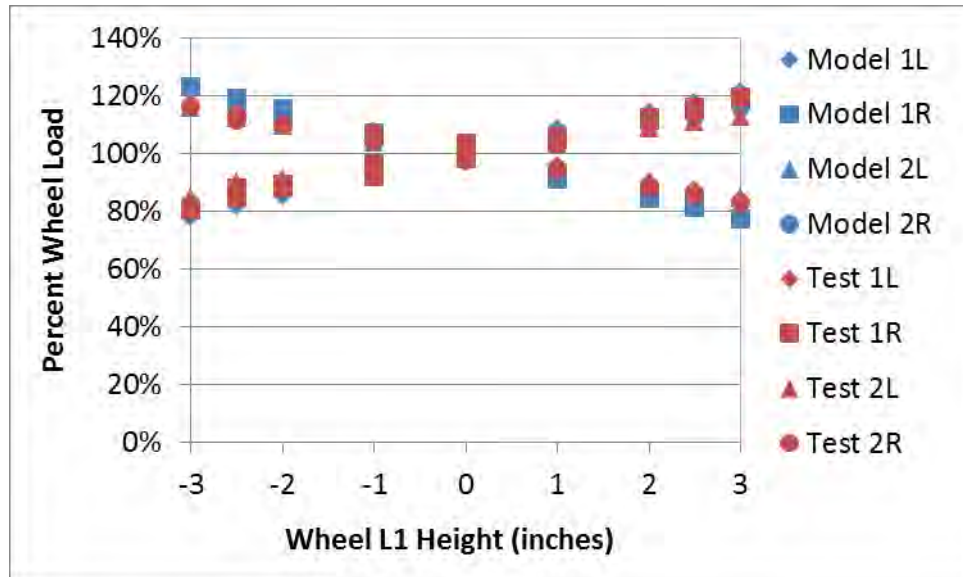


Figure C1. Wheel Load Equalization Comparison – Wheel L1 Lift and Drop

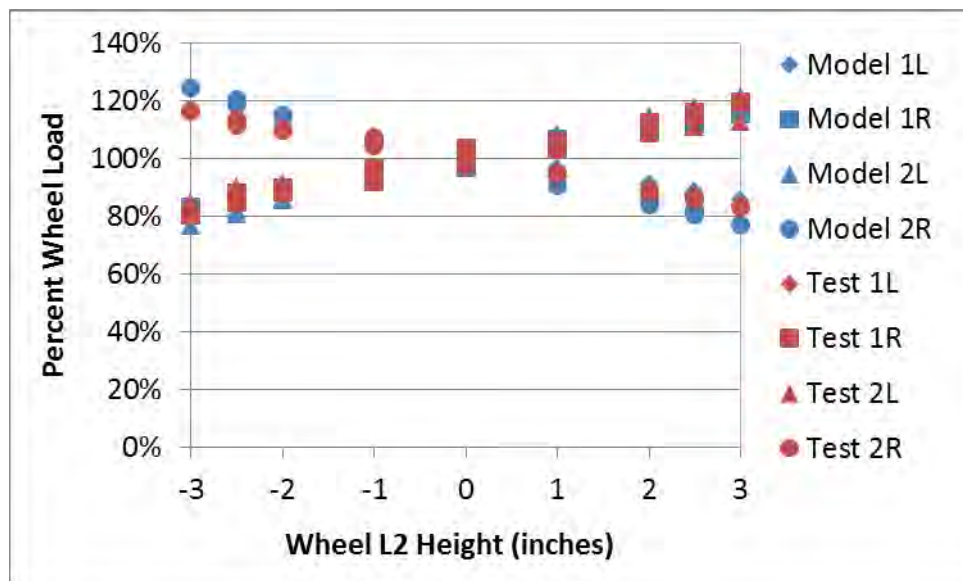


Figure C2. Wheel Load Equalization Comparison – Wheel L2 Lift and Drop

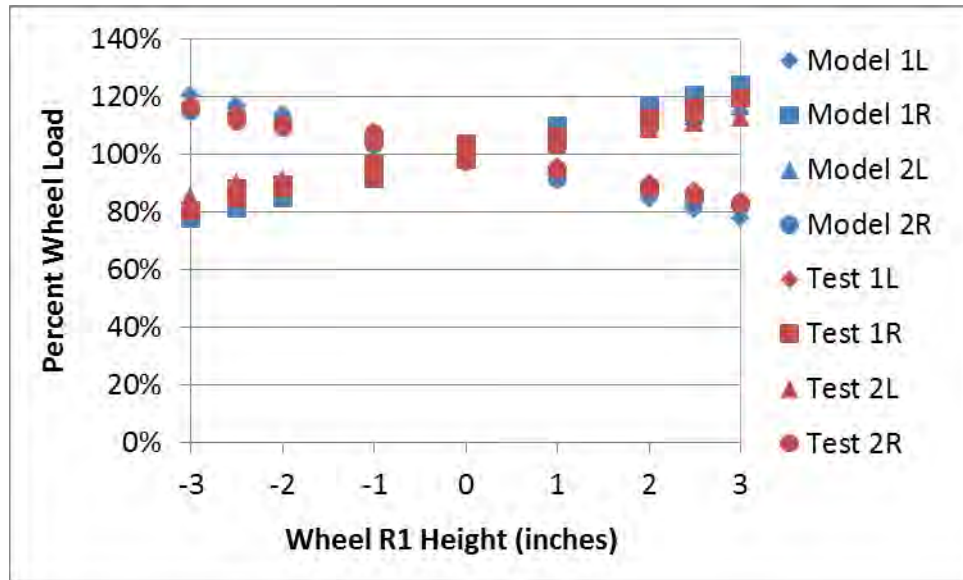


Figure C3. Wheel Load Equalization Comparison – Wheel R1 Lift and Drop

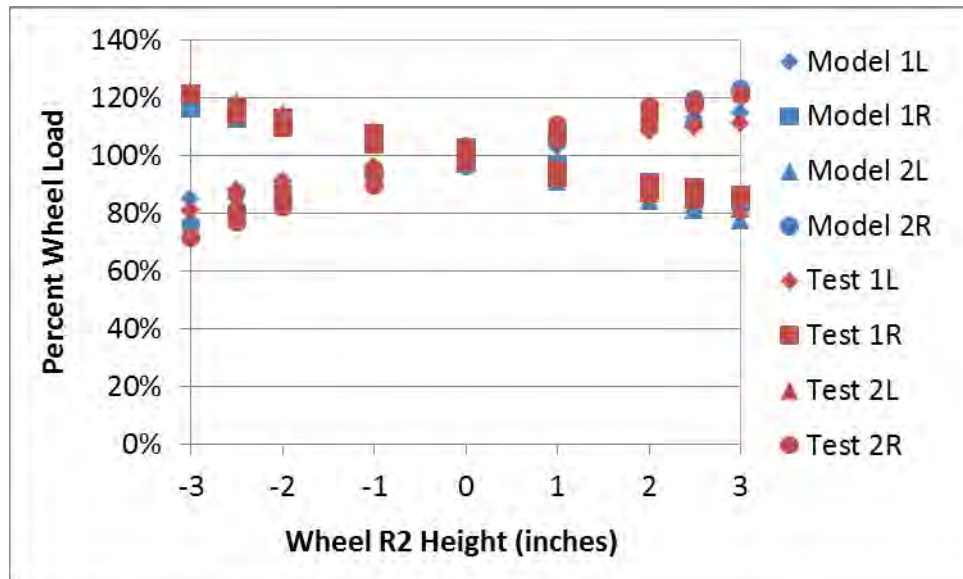


Figure C4. Wheel Load Equalization Comparison – Wheel R2 Lift and Drop

Lean Test Comparisons

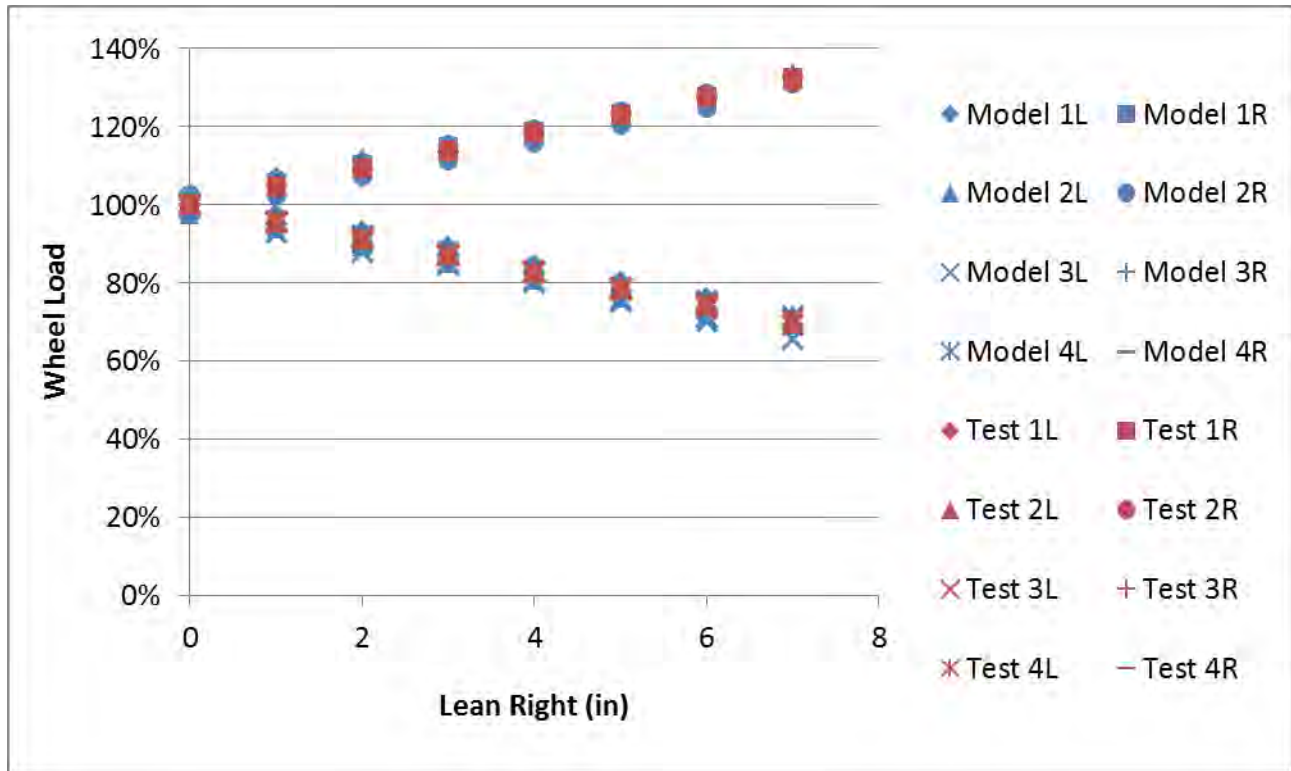


Figure C5. Lean Test Comparison – Lean Right

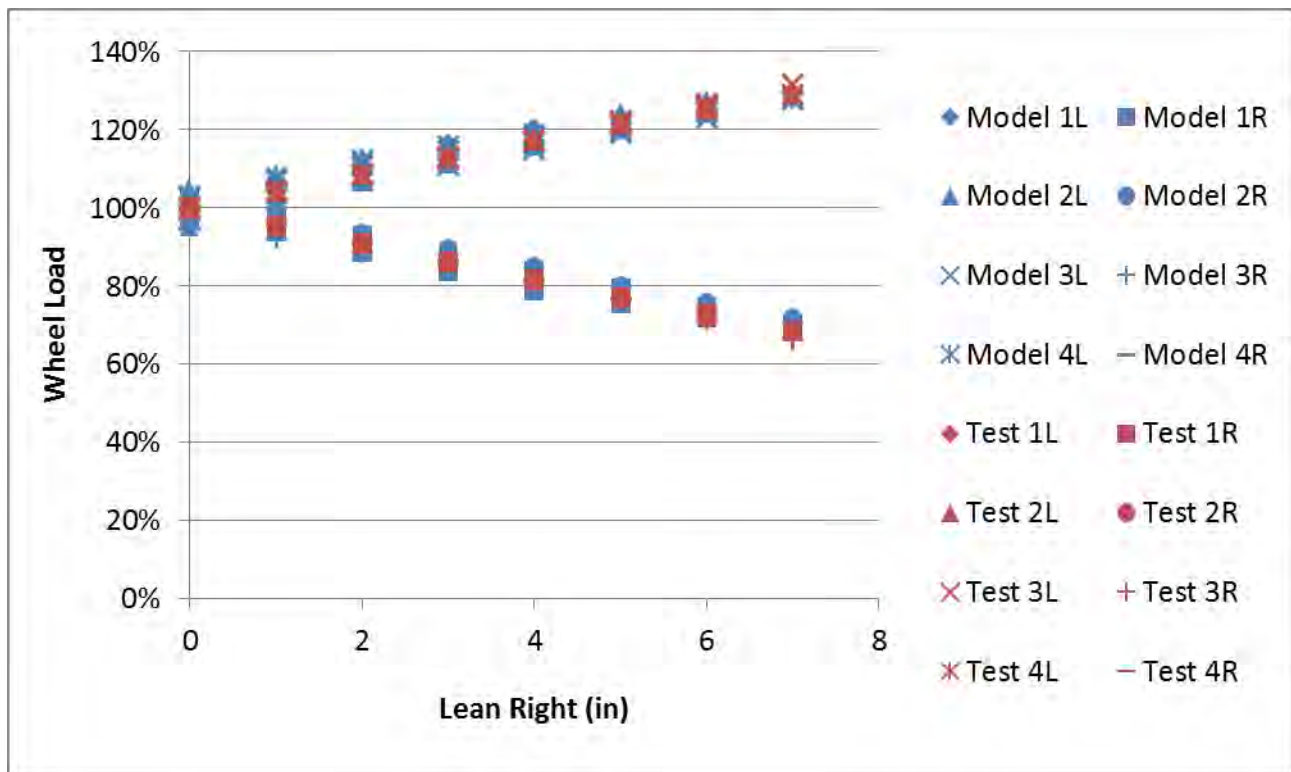


Figure C6. Lean Test Comparison – Lean Left

Resonance Test Comparisons

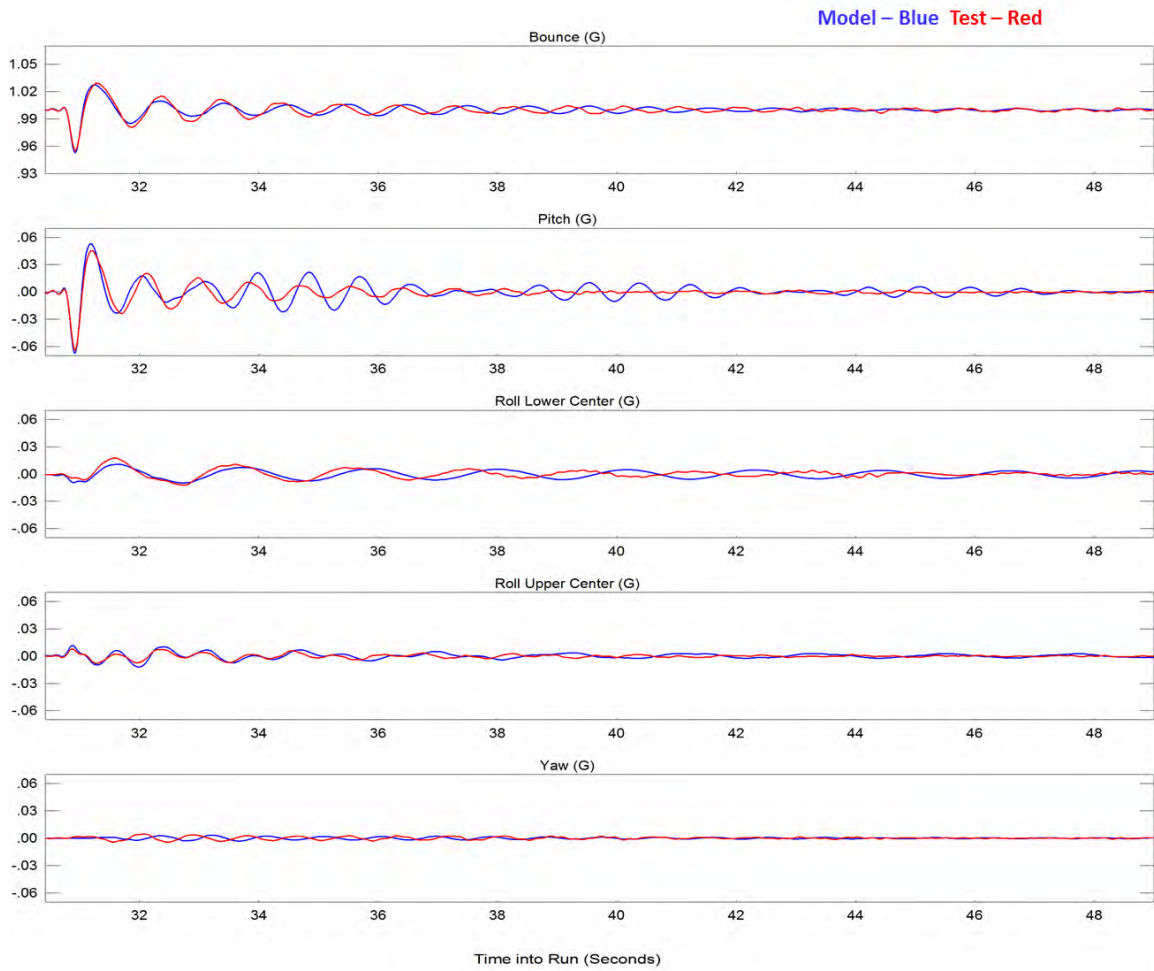


Figure C7. Comparison – Vertical Jack and Drop at Cab End on Left and Right Sides

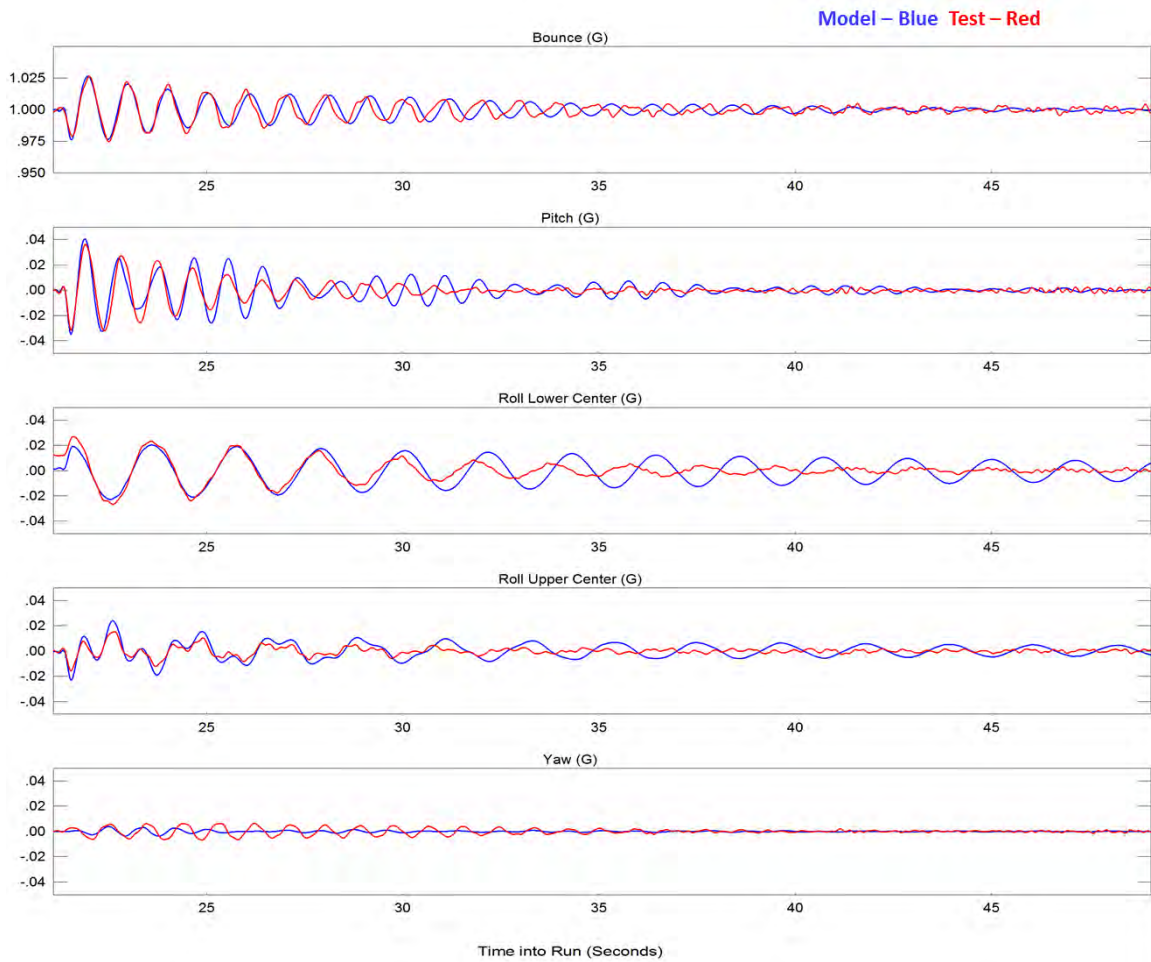


Figure C8. Comparison – Vertical Jack and Drop at Cab End on Left Side

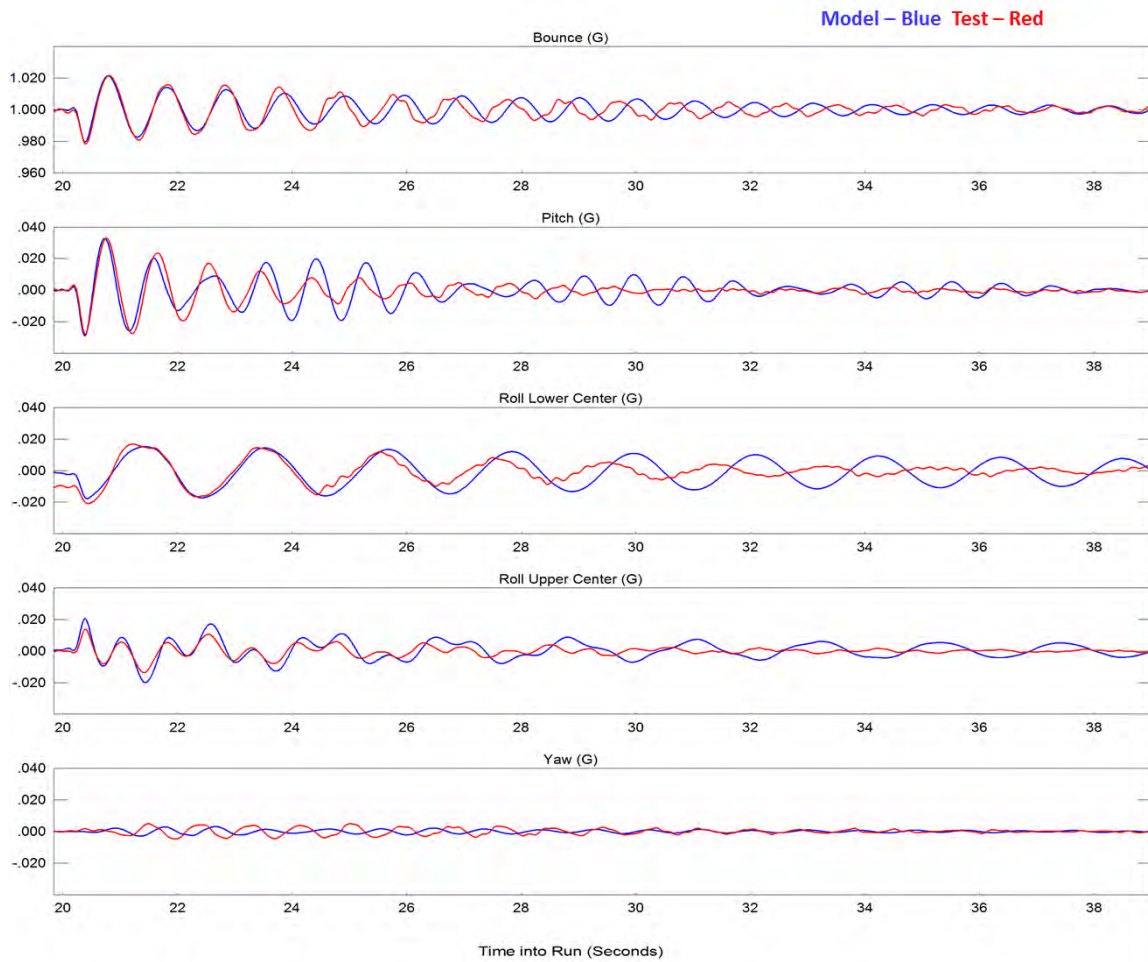


Figure C9. Comparison – Vertical Jack and Drop at Cab End on Right Side

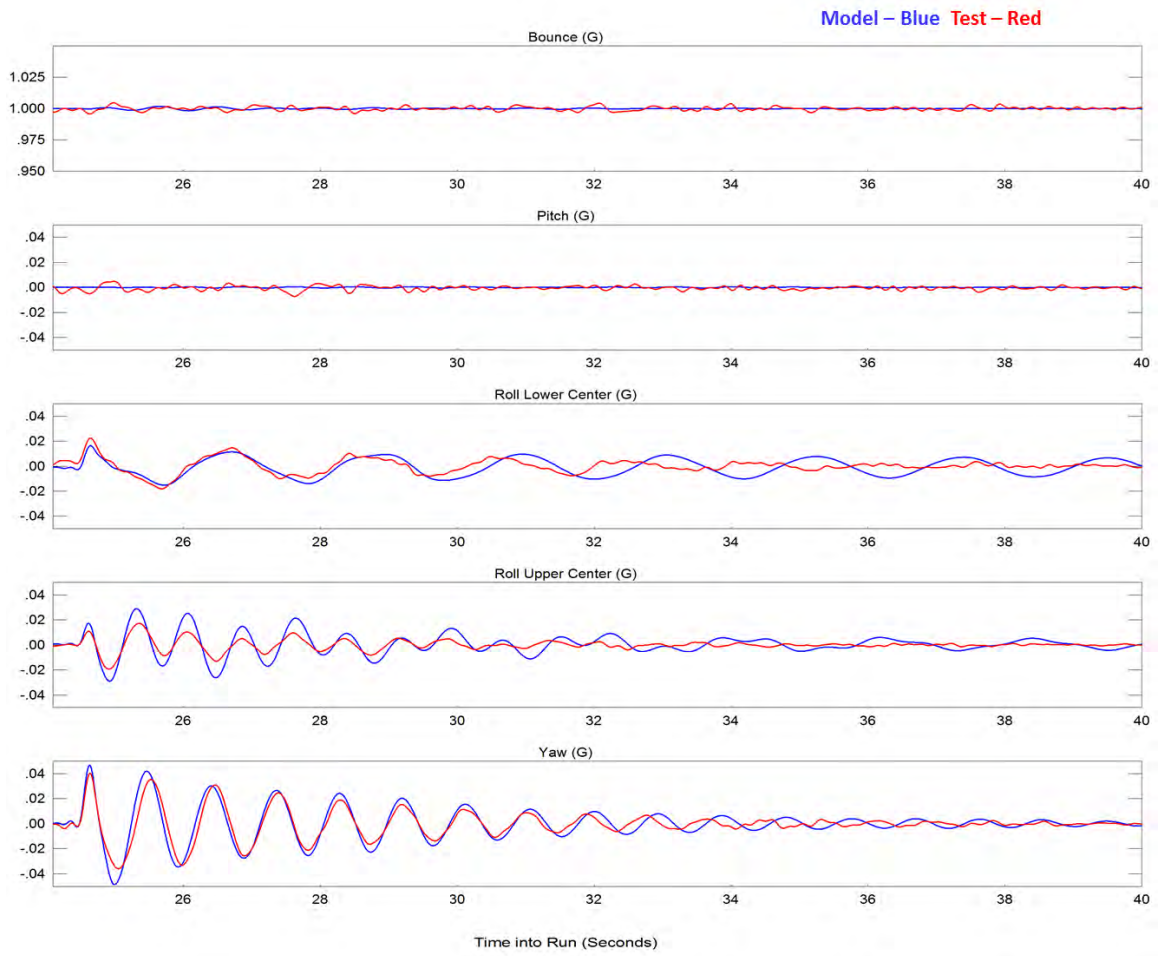


Figure C10. Comparison – Lateral Jacking at Cab End on Right Side

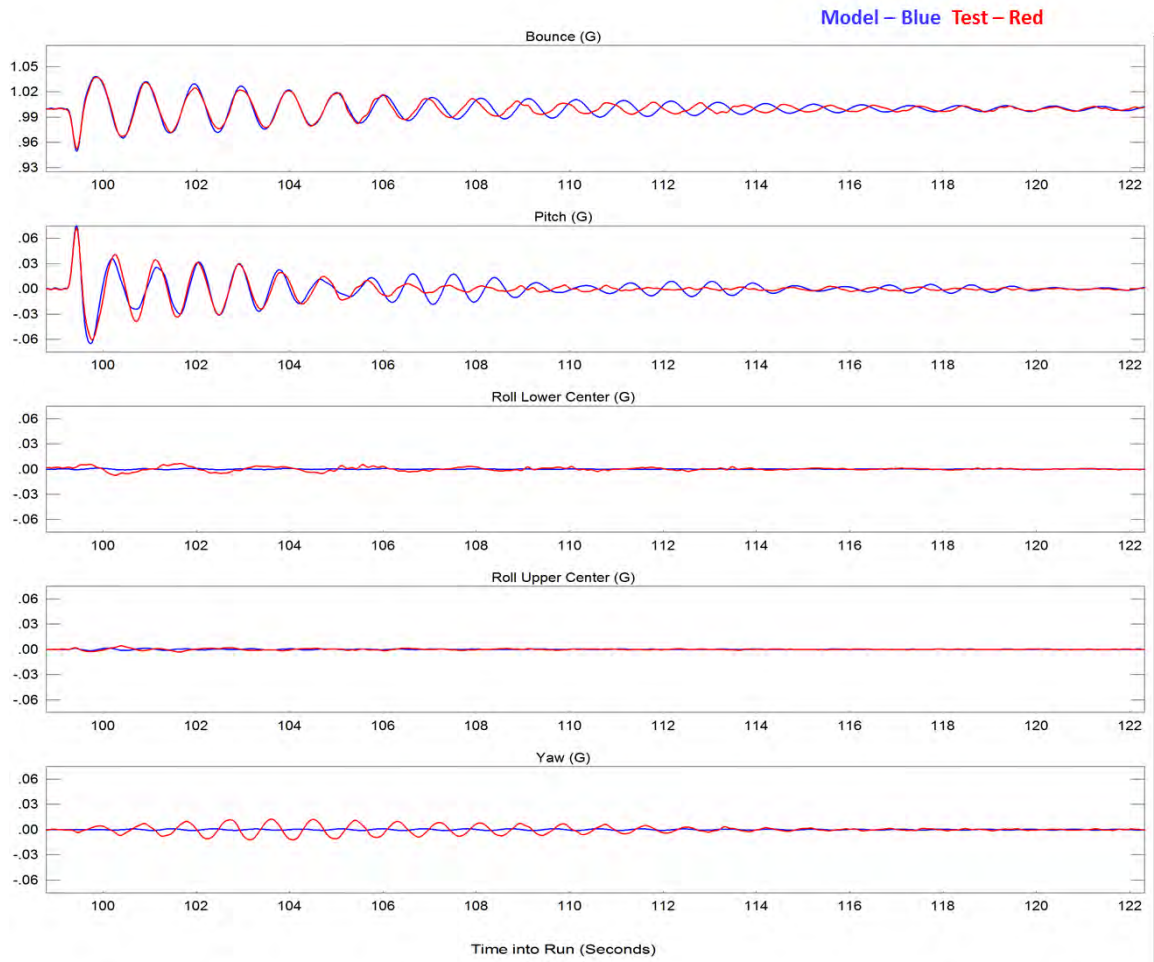


Figure C11. Comparison – Vertical Jack and Drop at Non-Cab End on Left and Right Sides

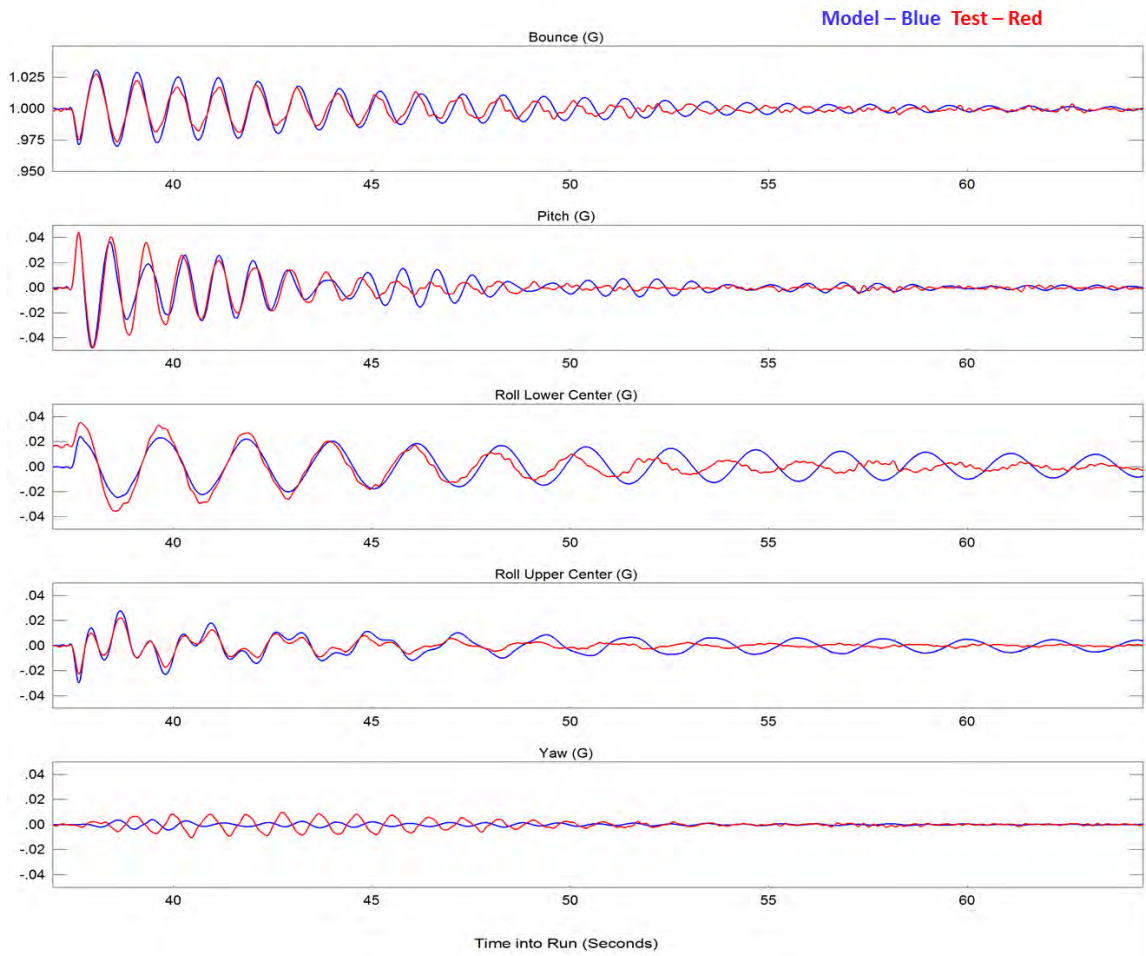


Figure C12. Comparison – Vertical Jack and Drop at Non-Cab End on Left Side

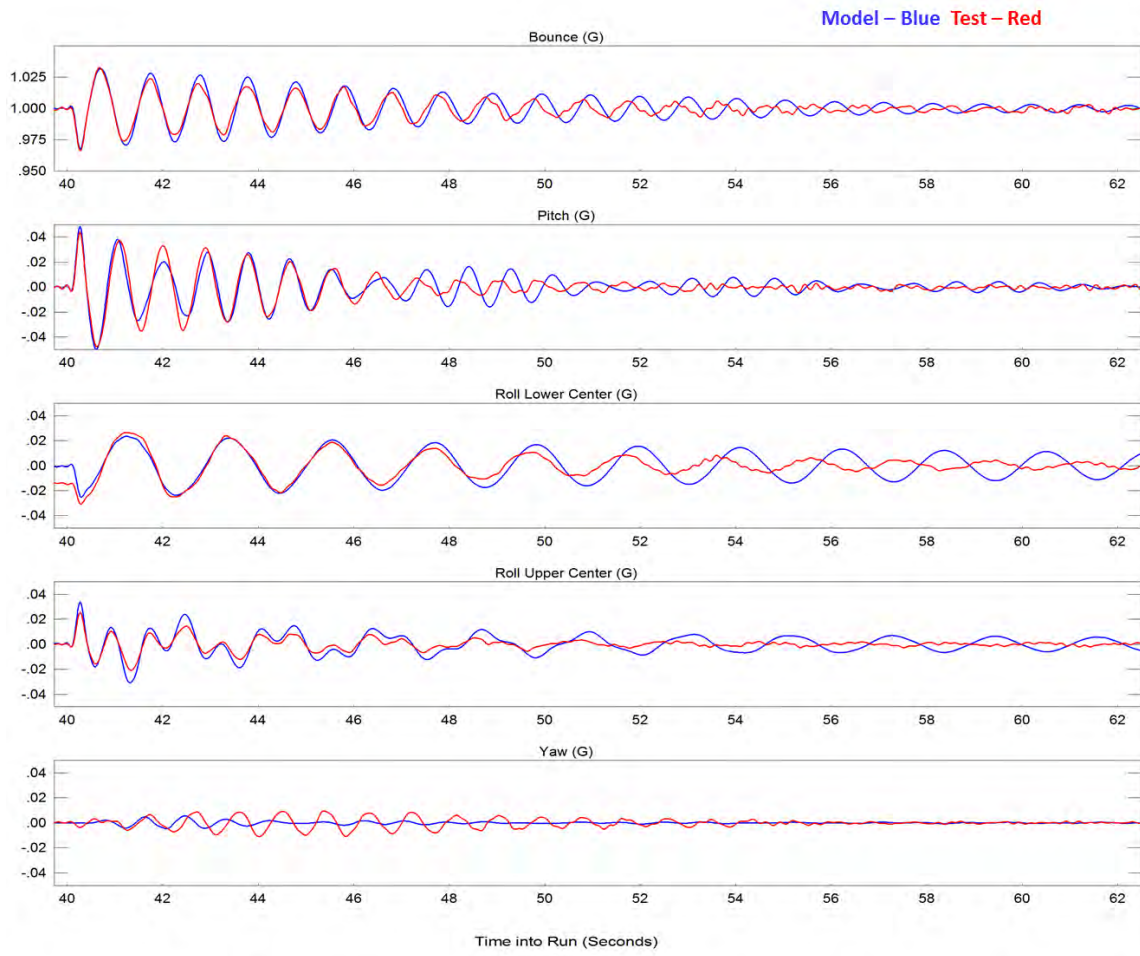


Figure C13. Comparison – Vertical Jack and Drop at Non-Cab End on Right Side

Abbreviations and Acronyms

Acronym	Definition
APTA	American Public Transportation Association
AAR	Association of American Railroads
CG	Center of gravity
CW	Clockwise
CFR	Code of Federal Regulations
CCW	Counterclockwise
FFT	Fast Fourier Transform
FRA	Federal Railroad Administration
IWS	Instrumented Wheelset
PSD	Power Spectral Density
PTT	Precision Test Track (at TTC)
RTT	Railroad Test Track (at TTC)
rms	Root Mean Square
TTT	Transit Test Track (at TTC)
TTC	Transportation Technology Center (the facility)
TTCI	Transportation Technology Center, Inc. (the company)
TSI	Truck Swivel Index
URB	Urban Rail Building (at TTC)
VTI	Vehicle Track Interaction
WRM	Wheel Rail Mechanisms Loop (at TTC)
L/V	Wheelset Lateral to Vertical Force Ratio