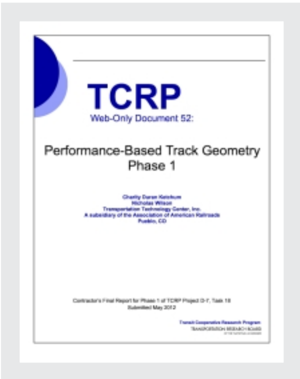
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Performance-Based Track Geometry
Phase 1

Performance-Based Track Geometry, Phase 1

DETAILS

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EXECUTIVE SUMMARY

Poor vehicle dynamic performance and poor ride quality frequently occur at track locations that do not exceed track geometry or safety standards, such as curve entry or exit, special trackwork, and track misalignments that promote yaw instability or hunting. Poor ride quality may not be an indicator of unsafe operation, but it may point to an area of track or a vehicle that needs maintenance to prevent further degradation. Conversely, track geometry locations that exceed track geometry or safety standards often do not cause poor ride quality or poor vehicle performance. To optimize transit system maintenance, methods need to be developed to identify vehicle conditions and track locations that actually cause poor ride quality or vehicle performance.

Track geometry measurements alone are not always an indicator of how a vehicle behaves. Predicting the vehicle dynamic response can help address the following issues:

- Prioritizing maintenance
- Identifying problem locations that do not exceed normal track geometry standards
- Identifying problems as they arise rather than waiting for scheduled maintenance
- Identifying car designs and car component wear issues that can contribute to poor vehicle performance and poor ride quality

To improve and advance the current track geometry inspection practice and standards, Transportation Technology Center, Inc. (TTCI) developed a track inspection method known as performance-based track geometry (PBTG). Trained neural networks in the PBTG system relate the complex dynamic relationships that exist between vehicles and track geometry to vehicle performance. They also identify track segments that may generate unwanted vehicle responses. PBTG is now in use by three North American freight railroads and one international railroad.

A transit agency can use PBTG to optimize maintenance of the track and fleet. Onboard accelerometers on the fleet and a PBTG neural network can be used to identify track locations that need work and do not require direct measurement of the track geometry. This permits monitoring of track condition between scheduled track geometry measurements. PBTG can also be used to identify cars that are beginning to deteriorate. If all cars in the fleet are equipped with PBTG accelerometers, they can be used to build a database of information for monitoring the condition of the cars and the track over time.

Also, PBTG uses measured track geometry and the PBTG neural network to predict vehicle performance on existing track. This helps to identify locations in the track likely to cause poor ride quality or other issues related to vehicle performance, which is the way PBTG is currently being applied by North American freight railroads.

An indirect benefit of implementing the PBTG system can be making validated vehicle dynamics models available to a transit agency. The models can be used for many other purposes such as investigating dynamic performance problems, evaluating vehicle modifications, evaluating vehicle performance over proposed new track routes and alignments, and optimizing wheel and rail profile maintenance.

In support of the Transit Cooperative Research Program (TCRP) D-7 research program, TTCI is conducting research to develop methods for evaluating track geometry that will account for transit system vehicle performance and passenger ride quality using a combination of PBTG and NUCARS®[1] modeling techniques and on-track measurements. These studies will form the basis for determining improvements in track geometry and track maintenance practices. The overall objective for the project is to demonstrate the use of PBTG techniques for improving the ride quality of transit systems. The project is being conducted with the cooperation of Dallas Area Rapid Transit (DART). Specific deliverables of this multiphased project include:

- Proof of Concept: Determine if PBTG will work to predict ride quality for the transit industry
- Trained PBTG neural net algorithms for DART and one other transit system
- Methodology and recommendations for implementing PBTG techniques on other transit systems

This report addresses Phase I of this work, which consisted of the following items:

- Ride Quality Literature Survey (Appendix)
- Vehicle Characterization and On-track Ride Quality Testing
- Track Geometry Measurements
- NUCARS Modeling
- Comparison of NUCARS simulations to on-track test results to determine whether the vehicle performance and ride quality can be linked to specific track geometry features

Phase II of the project will use the NUCARS simulations and data collected on transit systems during Phase I to train PBTG neural networks and the PBTG model's ability to predict ride quality. Phase II tasks include (1) using the Phase I NUCARS simulations and on-track test results to train PBTG neural networks to predict ride quality and (2) identifying track locations where track geometry maintenance could improve ride quality. Phase II will also include similar on-track tests, NUCARS simulations, and PBTG analyses for another transit authority using another vehicle type.

1 NUCARS is a registered trademark of Transportation Technology Center, Inc.

Four ride quality standards used to evaluate passenger comfort on rail transit vehicles were reviewed in Phase 1:

- International Organization for Standardization (ISO) 2631 Mechanical Vibration and Shock
- European Standards (ENV) 12299:1999 Railway Applications
- International Union of Railways (UIC) 513
- Sperling Index

All four standards require similar measurements. Therefore, the following ride quality measurements were identified for use in this study:

- Tri-axial accelerometers located
    a. Over bogie centers (both ends of vehicle)
    b. On center of vehicle
    c. On floor in operator's cabin
- Lateral accelerometers located
    a. On each axle of bogie so yaw can be calculated and location of curve accurately pinpointed
- Roll rate gyrometer

Based on the literature review, TTCI recommended that ride quality during the tests be calculated using the ISO 2631standards, because it was the most comprehensive.

TTCI has often found that actual vehicle characteristics as assembled vary considerably from the published design and measured individual components. In order to ensure an accurate NUCARS model of the Dallas Area Rapid Transit (DART) Super Light Rail Vehicle (SLRV), tests were conducted to measure suspension characteristics and carbody inertial and resonance characteristics, including:

- Characterization of the elastic elements of the primary and secondary suspension
- Determination of the center of gravity of the railcar
- Determination of the resonance frequencies of rigid body degrees of freedom of the railcar

All vehicle characterization and ride quality testing was performed on DART property located in Dallas, Texas, using a DART SLRV. DART's operating conditions provided a variety of track structures and a wide range of operating speeds.

Track geometry measurements were taken by Holland on DART Red Line in both directions. No measurements were taken in the tunnel, because of size restrictions. The tunnel had direct fixation track, and therefore, it was assumed that track geometry measurements could be used.

This research determined there is a correlation between ride quality and track geometry. Locations on the DART Red Line that had ride quality issues were identified from the ride quality test performed, as Table 1 shows.

Table 1. Ride Quality Issues Identified on DART Red Line

Direction	Stations	Lateral Ride Quality Index	Description
Northbound	Dallas Zoo to 8th & Corinth	0.661	Fairly uncomfortable
Northbound	Walnut Hill to Forest Lane	0.763	Fairly uncomfortable
Northbound	LBJ/Central to Spring Valley	0.651	Fairly uncomfortable
Northbound	Galatyn Park to Bush Turnpike	0.681	Fairly uncomfortable
Southbound	Plano Center to Bush Turnpike	0.845	Uncomfortable
Southbound	Spring Valley to LBJ/Central	0.640	Fairly uncomfortable
Southbound	Cedars to 8th & Corinth	1.056	Uncomfortable

The southbound section of track between Cedars and 8th & Corinth stations contained lateral alignment deviations with a wavelength of 94 feet, corresponding to a frequency of 1 Hertz (Hz) at the speed the train was traveling. This resulted in a vehicle yaw response of 1 Hz resulting in an "uncomfortable" ride quality index of 1.056. Although these track geometry deviations did not exceed any safety criteria, they clearly affect passenger ride quality. To show this correlation between ride quality and track geometry, it was imperative to take track geometry measurements at the same time as ride quality measurements.

These results indicated it should be possible to identify the effect of track geometry deviations on vehicle ride quality response during Phase II of the project. However, there is still some work required to improve the vehicle model to correctly predict this response. Identifying the influence of the following factors on vehicle response is important to accurately model and determine track geometry triggers:

- Wheel/rail interface, including profile shapes and contact geometry
- Vehicle speed
- Understanding and identifying rigid body vibration modes of the vehicle

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1.0 INTRODUCTION

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To improve and advance the current track geometry inspection practice and standards, Transportation Technology Center, Inc. (TTCI) developed a track inspection method known as performance-based track geometry (PBTG). Trained neural networks in the PBTG system relate the complex dynamic relationships that exist between vehicles and track geometry to vehicle performance.[2] They also identify track segments that may generate unwanted vehicle responses. PBTG is now in use by three North American freight railroads and one international railroad.

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2 Li, D., A. Meddah, K. Hass, and S. Kalay. March 2006. "Relating track geometry to vehicle performance using neural network approach." *Proc. IMECHE Vol. 200 Part F: J. Rail and Rapid Transit, 220 (F3), 273-282*.

An indirect benefit of implementing the PBTG system can be making validated vehicle dynamics models available to a transit agency. The models can be used for many other purposes such as investigating dynamic performance problems, evaluating vehicle modifications, evaluating vehicle performance over proposed new track routes and alignments, and optimizing wheel and rail profile maintenance.

In support of the Transit Cooperative Research Program (TCRP) D-7 research program, TTCI is conducting research to develop methods for evaluating track geometry that will account for transit system vehicle performance and passenger ride quality using a combination of PBTG and NUCARS®[3] modeling techniques, and on-track measurements. These studies will form the basis for determining improvements in track geometry and track maintenance practices. The overall objective for the project is to demonstrate the use of PBTG techniques for improving the ride quality of transit systems. The project is being conducted with the cooperation of Dallas Area Rapid Transit (DART). Specific deliverables of this multiphased project include:

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3 NUCARS is a registered trademark of Transportation Technology Center, Inc.

1.1 Ride Quality Literature Survey

In Phase I of this work, TTCI conducted a literature survey to identify how other transit authorities around the world measure and assess passenger ride quality and passenger ride comfort. Although this project is primarily concerned with rail passenger ride quality, the survey included a review of automobile passenger ride quality analysis techniques. The research addressed passenger ride quality and comfort on transit authorities for a range of passenger rail operations, from light right systems to typical intercity transportation. Therefore, the literature survey encompassed a wide range of possible conditions related to passenger ride quality. The appendix contains the literature survey.

1.2 Vehicle Characterization and Ride Quality Testing

TTCI partnered with Dallas Area Rapid Transit (DART) to participate in this research. DART provided support to the project by providing a test vehicle for TTCI to perform characterization and ride quality tests.

A typical passenger rail vehicle operating on the DART system was selected and fully characterized. The data obtained from the characterization studies was used to develop a NUCARS model representing the vehicle. The characterized vehicle was equipped with instrumentation to collect passenger ride quality data using accelerometers and various displacement transducers. Track geometry measurements were collected within two weeks of ride quality measurements and used as comparisons with predictions from the NUCARS model and for future PBTG neural network training.

1.3 NUCARS Modeling

NUCARS is a general multibody rail vehicle dynamics computer simulation model. It is designed to simulate the dynamic interaction of any rail vehicle with any track. The user may select any number of bodies, degrees of freedom, and connection elements to describe a vehicle and track system.

NUCARS can be used to analyze the dynamic interaction of rail vehicles and track to predict stability, ride quality, vertical and lateral dynamics, and steady state and dynamic curving response. The program includes detailed nonlinear models of wheel/rail interaction and suspension response, with wheel/rail interaction based on Kalker's complete nonlinear creep theory.[4]

Applications of NUCARS include vehicle design, safety performance evaluation, rail vehicle and track research, derailment investigation, and general simulation of mechanical systems. Simulations of any type of freight, passenger, transit, and locomotive rail vehicles are possible. Track simulations may include hypothetical track geometries or measured track supplied by the user, including turnouts and guard rails.

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4 Kalker, J.J., 1967. "On the Rolling Contact of Two Elastic Bodies in the Presence of Dry Friction," Doctoral Thesis, Delft University, The Delft, Netherlands.

1.4 PBTG

PBTG inspection is a new technology that can be implemented on conventional track geometry inspection vehicles. This technology relates measured track geometry to vehicle performance on a real-time basis. The technology can also be used on historic track geometry data in an office environment to post-process the data to evaluate the effect of track geometry deviations on vehicle performance.

The PBTG inspection technology was developed by TTCI under the Association of American Railroads' Strategic Research Initiatives Program. The technology has been demonstrated successfully on the test tracks at the Transportation Technology Center, as well as in revenue service. The BNSF Railway and the Union Pacific Railroad have implemented this technology on their track geometry inspection cars.

PBTG inspection is an improvement over the traditional track geometry inspection method. Track geometry defects identified using traditional methods do not always cause undesirable vehicle performance.

TTCI's PBTG inspection technology identifies track segments that may produce undesirable vehicle performance and generates recommended track geometry maintenance actions on a real-time or on a post-processed basis. Implementation of this technology allows transit authorities to prioritize track maintenance based upon vehicle performance. As such, transit authorities can expect to reduce the potential for derailment incidents and improve vehicle ride quality by improving vehicle/track interaction.

2.0 LITERATURE SURVEY

There are many ride quality standards available to evaluate passenger comfort on trains. The following four standards were reviewed:

1. ISO 2631 Mechanical Vibration and Shock — Evaluation of human exposure to whole-body vibration
2. ENV 12299:1999 Railway Applications — Ride comfort for passengers – Measurement and Evaluation
3. UIC 513 — Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles
4. Sperling Index

Table 2 summarizes the ride quality standards that were reviewed.

Table 2. Ride Quality Standards Comparison

Standard	ISO 2631	ENV 12299	UIC 513	Sperling Index
Effect of movement	• Health (0.5 to 80 Hz) • Comfort/Perception (0.5 to 80 Hz) • Motion Sickness	• Health (0.5 to 80 Hz) • Comfort/Perception (0.5 to 80 Hz) • Motion Sickness	• Health (0.5 to 80 Hz) • Comfort/Perception (0.5 to 80 Hz) • Motion Sickness	• Health (0.5 to 80 Hz) • Comfort/Perception (0.5 to 80 Hz) • Motion Sickness
Transmission	• Whole body through interfaces	• Whole body through interfaces	• Whole body through interfaces	• Whole body through interfaces
Position of passenger	• Standing • Seated • Recumbent	• Standing • Seated	• Standing • Seated	
Type of vehicle	• ISO 10056 – Railway vehicles	• Railway vehicle designed for carrying passengers	• Railway vehicle designed for carrying passengers	
Measurement type	• Translational	• Translational • Rotational	• Translational	
Analysis methods	• Basic Method • Running RMS (root-mean-square) method • Fourth Power Vibration Dose Method	• Simplified Mean Comfort • Complete Mean Comfort • Comfort on Discrete Events • Comfort in Curves	• Simplified Method • Full Method	
Persons	Not applicable	Not applicable	Two persons • 114.54 lb (52kg) • 198.42 lb (90kg)	

The literature survey determined what measurements and analysis method should be used to accurately correlate ride quality to track geometry. The data collected will eventually be used to help develop a PBTG method to predict the effects of track geometry on ride quality.

Not all issues that can affect passenger ride quality were addressed by the standards reviewed. Discrete events were also important in correlating track geometry to ride quality.

All the ride quality standards reviewed in this study required similar measurements. TTCI identified the following measurements needed to quantify the relationship between track geometry and ride quality:

1. Tri-axial accelerometers located
   a. Over bogie centers (both ends of vehicle)
   b. Center of vehicle
   c. Floor in operator's cabin
2. Lateral accelerometers located
   a. Each axle of bogie to calculate yaw and accurately pinpoint location of curves
3. Roll rate gyrometer located
   a. Under operator's seat

Based on the literature review, TTCI recommended that ride quality during the tests be calculated using ISO 2631. The data was filtered post-process for ISO 2631.

3.0 VEHICLE CHARACTERIZATION AND ON-TRACK TESTS

All testing was performed on DART property located in Dallas, Texas. DART's operating conditions provided a variety of track structures and a wide range of operating speeds. The following is a summary of the variety of conditions that were tested on the DART system:

- Tunnel 3.5 miles in length with direct fixation track
- Ballasted track with concrete ties
- Direct fixation track
- Embedded track
- Curvature range from 2 degrees (2,800 feet radius) to 20 degrees (300 feet radius)
- Overhead catenary system
- Operating speed 25 to 60 mph
- Rail profile 115 pound/yard rail

Figure 1 shows a map of the DART rail system. The testing took place on the entire Red Line from Westmoreland Station to Parker Road Station (7 o'clock to 1 o'clock on the graphic).

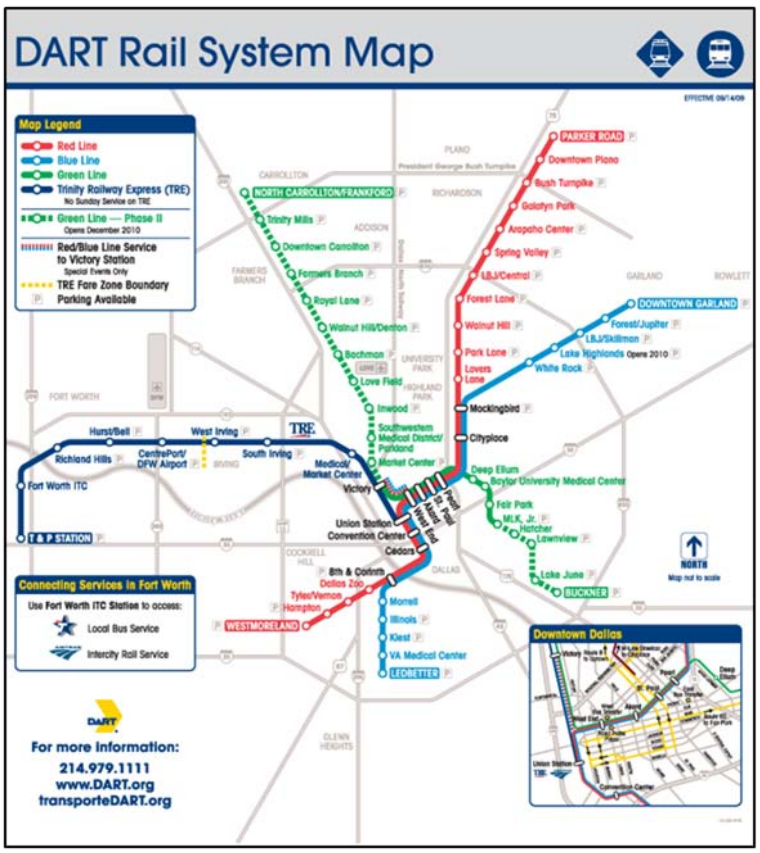


Figure 1. DART Rail System Map

DART's Super Light Rail Vehicle (SLRV) was used for testing. The SLRV is a three-section vehicle that can accommodate up to 150 seated and standing passengers. The vehicle is manufactured by Kinkisharyo. Figure 2 shows a picture and a schematic of the SLRV. Table 3 summarizes some of the design specifications of the vehicle.

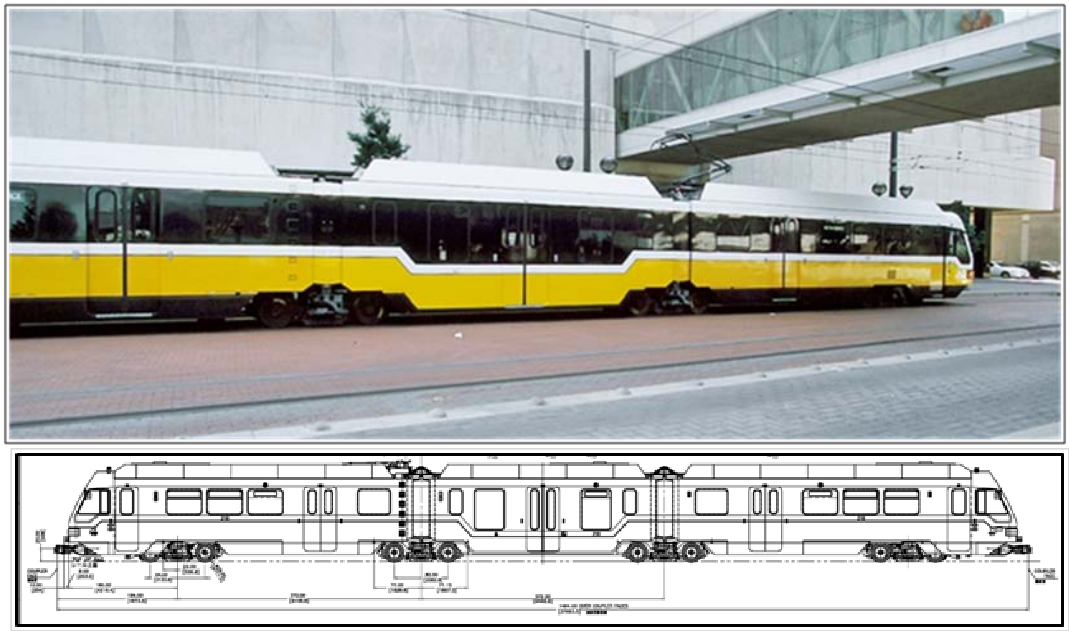


Figure 2. DART's SLRV

Table 3. SLRV Design Specifications

DART Super Light Rail Vehicle		
Weight		
AWO Empty 140,500 pounds	AW1 Full seated load 100 passengers 155,900 pounds	AW2 Full seated and standing load 150 passengers 163,900 pounds
Length	**Width**	**Height**
123 feet	106 inches	Lockdown Height 156.0 inches Operating Height 13 feet 6 inches to 22 feet 6 inches
Primary Suspension System		Chevron
Secondary Suspension System		Airbag
Wheel Profile		DART-HP02

3.1 Vehicle Characterization Tests

TTCI has often found that actual vehicle characteristics as assembled can vary considerably from the published design and measured individual components. In order to ensure an accurate NUCARS model of the DART SLRV, tests were conducted to measure suspension characteristics and carbody inertial and resonance characteristics. Testing included the following:

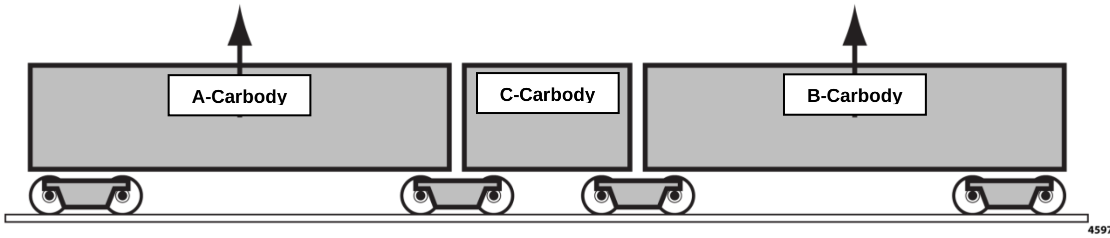
- Characterization of the elastic elements of the primary and secondary suspension
- Determination of the center of gravity of the railcar
- Determination of the resonance frequencies of rigid body degrees of freedom of the railcar

Results of the characterization tests were used to update and verify the preliminary NUCARS model.

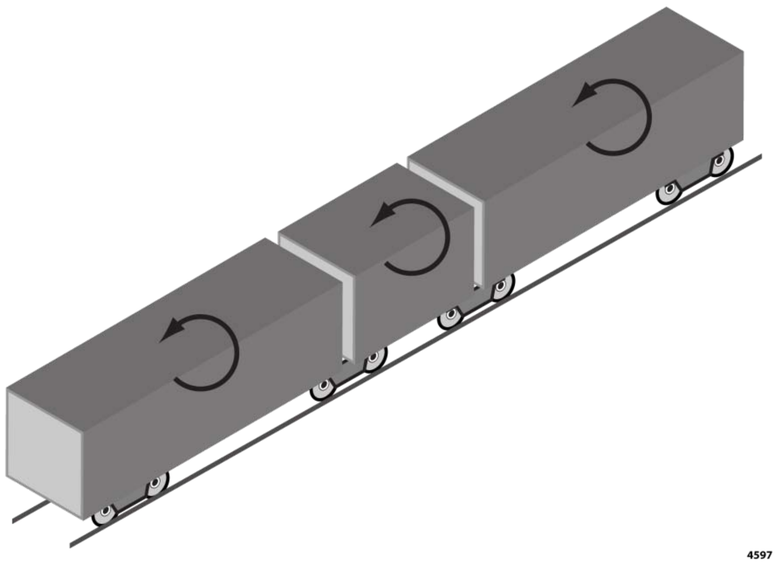
3.1.1 Carbody Resonance Tests

Carbody resonance testing was conducted to determine the rigid body modes of vibration of the SLRV. Figure 3 shows an example of the rigid body modes that were excited during the test.

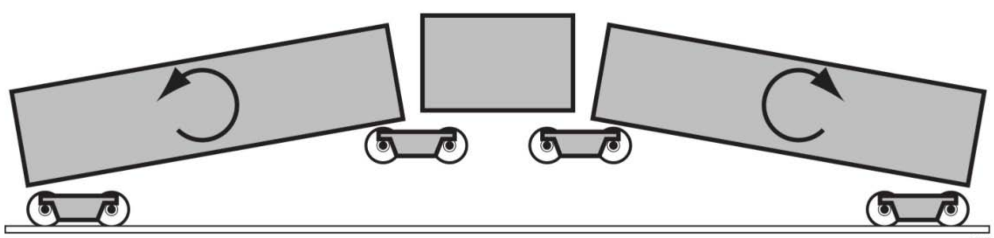
The SLRV was instrumented with accelerometers. Figure 4 shows the locations of the instrumentation and Table 4 describes the type of accelerometer used in the test. The rigid body modes of vibration were each excited by hand by two TTCI engineers with assistance from two transit authority employees. Figure 5 shows how the car can be excited by hand.



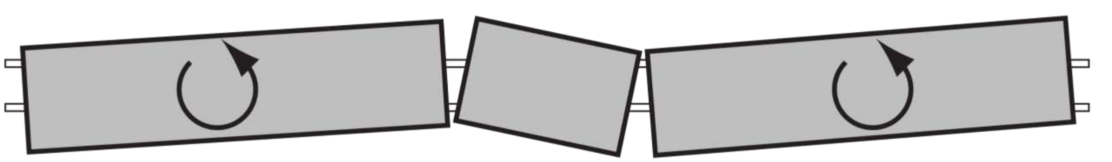
Bounce
(All bodies in phase)



Upper and Lower Center Roll
(All Bodies in Phase)



U-Shaped Pitch
(A and B bodies out-of-phase)



Zig-Zag Yaw
(A and B bodies in phase)

Figure 3. Illustration of Measured Rigid Body Vibration Modes

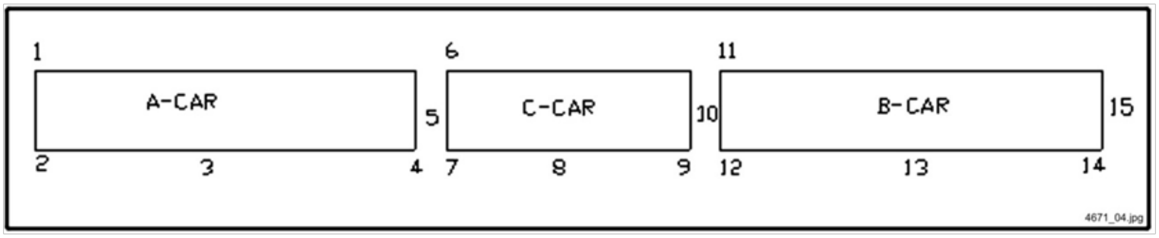


Figure 4. Location of Carbody Resonance Test Instrumentation (plan view)

Table 4. Carbody Resonance Instrumentation Description

Location No.	Description
1	Vertical Accelerometer
2	Vertical and Lateral Accelerometer
3	Lateral (top) Accelerometer
4	Lateral Accelerometer
5	Vertical Accelerometer
6	Vertical Accelerometer
7	Vertical and Lateral Accelerometer
8	Lateral Accelerometer
9	Lateral (top) Accelerometer
10	Vertical Accelerometer
11	Vertical Accelerometer
12	Vertical and Lateral Accelerometer
13	Lateral (top) Accelerometer
14	Lateral Accelerometer
15	Vertical Accelerometer

Figure 5. Using a Crowbar to Excite Carbody Yaw Vibration Mode

3.1.2 Bogie Resonance

Bogie and primary suspension resonance tests were performed using a load cell hammer and accelerometers placed on the bogie frame. The bogie frame is impacted by the load cell hammer. The accelerometers measure the response of the bogie frame and traction motor mounts. The test was performed on both a motor and trailer truck. The trucks tested were rolled out from under a carbody. Figure 6 shows this type of test. Figure 7 illustrates where the accelerometers were located for this test. The accelerometers were positioned to take longitudinal, lateral, and vertical measurements. Bogie suspension characteristics were estimated from the results of these resonance tests.

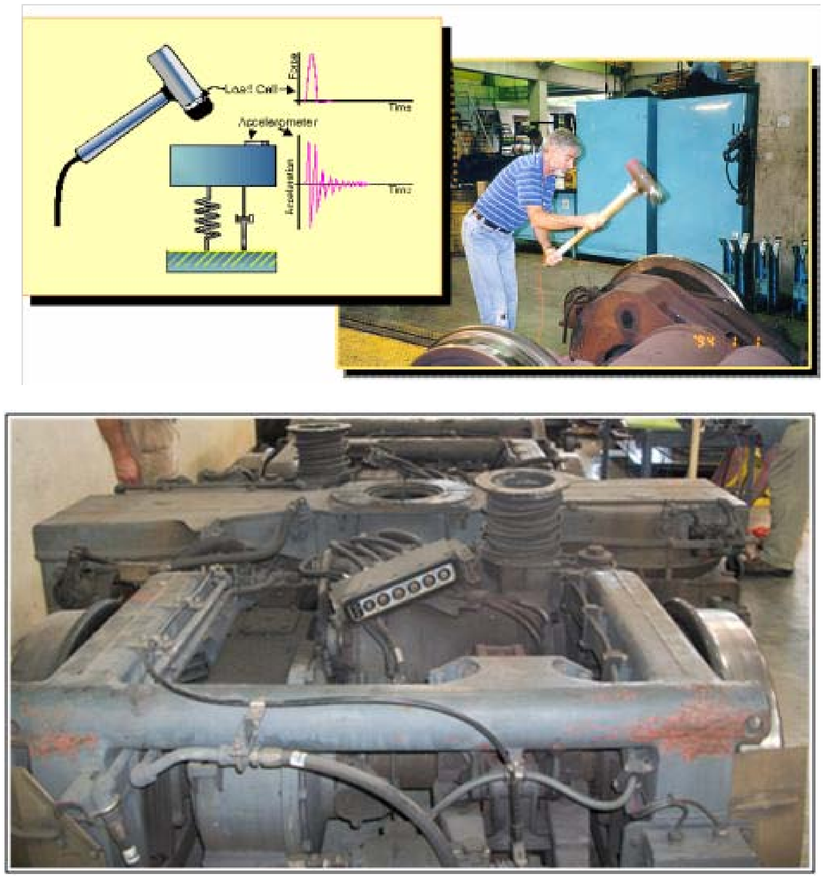


Figure 6. Hammer Test and SLRV Motor Truck

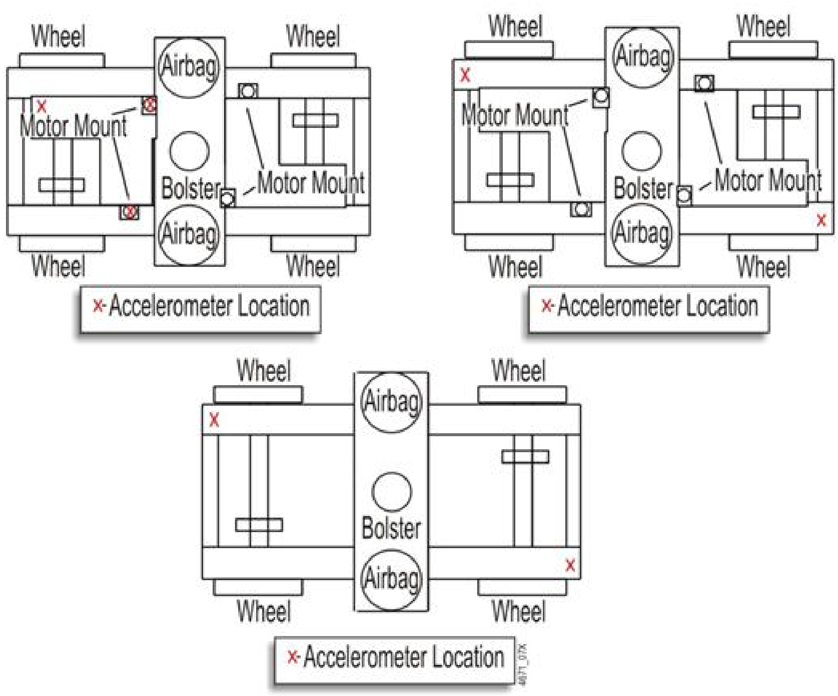


Figure 7. Accelerometer Locations for Motor Truck (top)
Accelerometer Locations for Trailer Truck (bottom)

3.1.3 Suspension Stiffness

In the suspension stiffness test, the longitudinal, lateral, and vertical stiffnesses of the primary and secondary suspension were measured. A force was applied across the suspension. The force was measured with a load cell and displacements were measured with dial indicators on magnetic bases.

DART had equipment that is used to straighten carbodies. This equipment was used for the lateral and longitudinal pull tests. It was anchored into the floor and provided a fixed point to pull against the suspension. Figure 8 shows the equipment setup for the longitudinal pull test. A similar reaction frame installation was used for the lateral suspension stiffness tests.

Figure 8. Setup of Longitudinal Pull Test

The vertical suspension was measured utilizing the lifts at DART. Load cells were placed under the wheels of the truck being measured. Figure 9 shows the load cells in place. The lift was used to raise the carbody off of the suspension in order to measure the stiffness of the suspension system. Figure 10 shows a photograph of the SLRV on the lift.

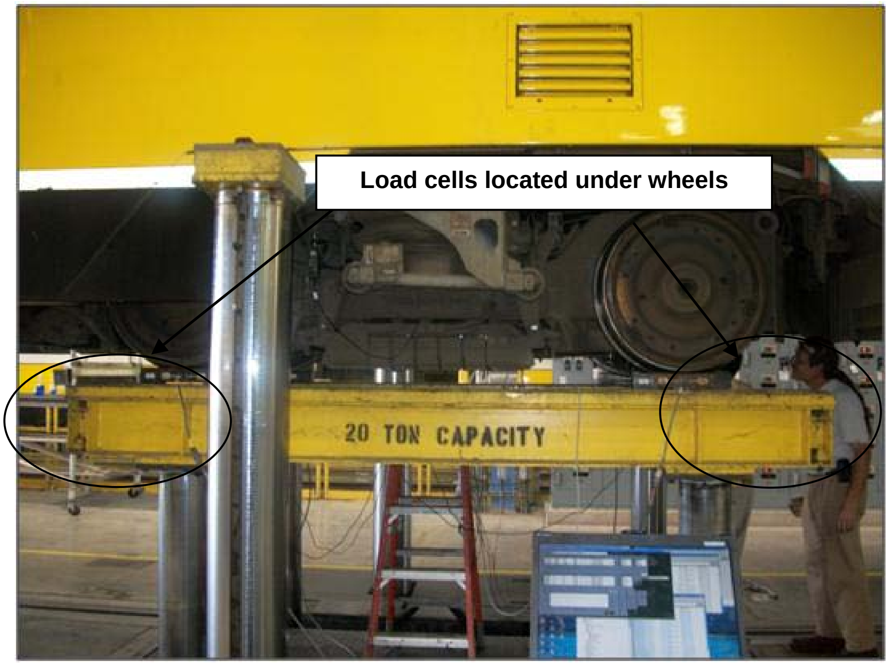


Figure 9. Wheel Load Cells

Figure 10. SLRV on Vertical Lift

3.2 Track Inspection and Track Geometry Measurements

A track inspection was done on the DART Red Line. Miniprof™[5] profiles where taken at locations where problems were known to have occurred. Representative rail profiles were also taken in curves, curve transitions, and tangent track. Track issues and locations were documented to be compared with ride quality data.

Figures 11 and 12 show examples of Miniprof profiles taken in a curve and on tangent track. Figure 13 shows some of the track geometry issues documented during inspection. Overall, the track was in good condition. There were several areas where rail corrugations, sun kinks, and ballast migration were evident. At the time of the inspection, the weather was very hot (110°F), and sun kinks were developing and being corrected on a regular basis.

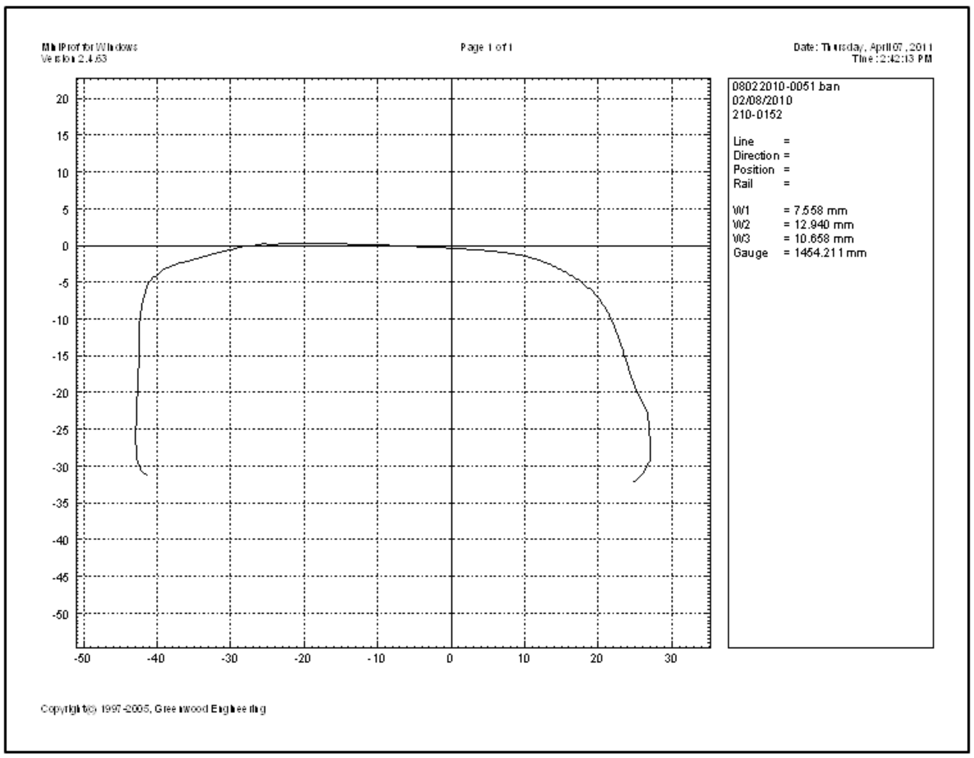


Figure 11a. Curve Rail Profiles High Rail

5 Miniprof is a portable piece of equipment by Greenwood Engineering that measures wheels, rails, and brake discs

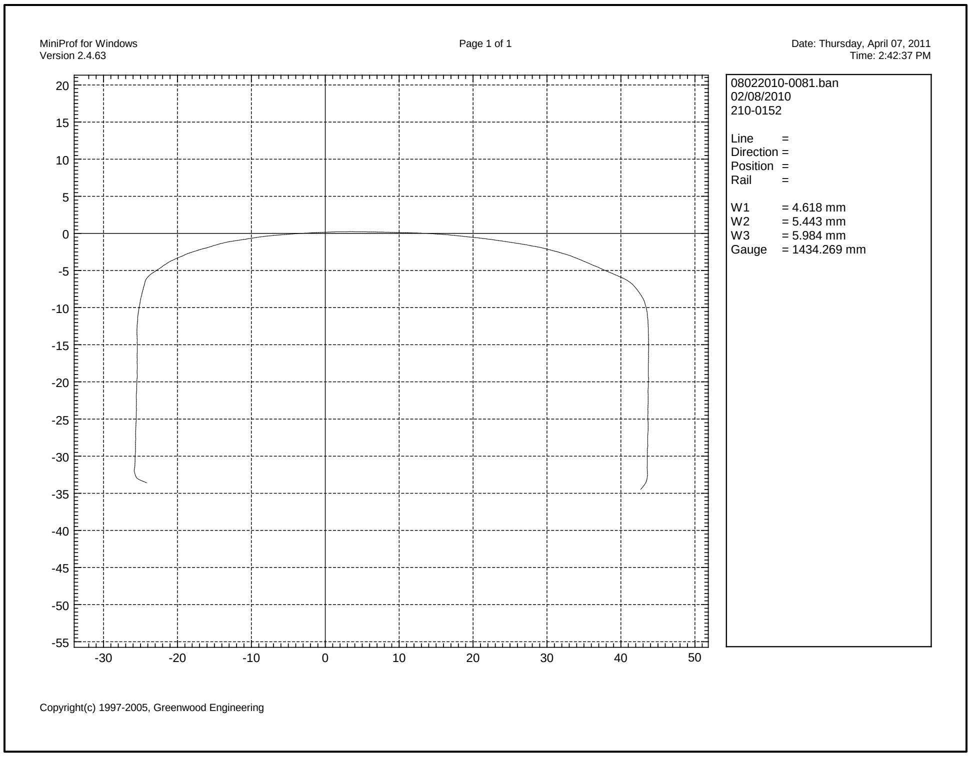


Figure 11b. Curve Rail Profiles Low Rail

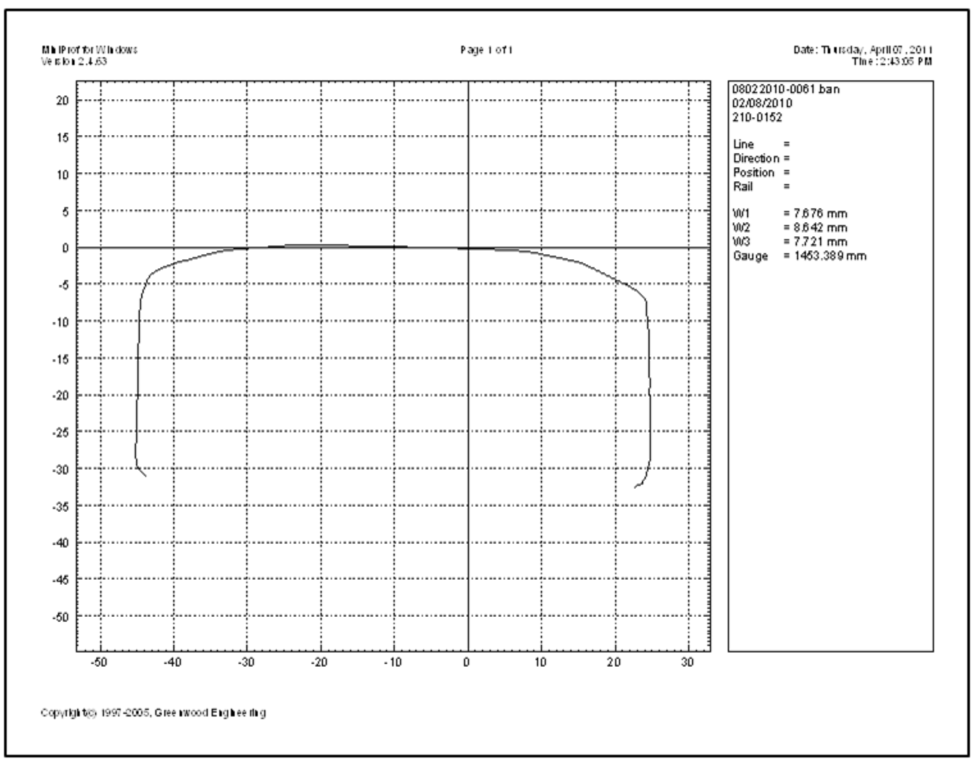


Figure 12. Tangent Rail Profiles

Figure 13. Track Geometry Issues

Track geometry measurements were taken by Holland August 13 and 14, 2010, on DART Red Line in both directions. Measurements were taken with Holland's TrackSTAR® system (Figure 14). It is a heavy, high rail track testing unit that provides track measurement of geometry, rail wear, and track gauge strength using a noncontact inertial and laser optical measurement system. The truck weighs approximately 55,000 pounds, and testing speeds range from 10 to 35 mph. No measurements were taken in the DART tunnel (between Pearl and Cityplace) because of a size restriction in the tunnel. Data from a previous track geometry run was used for the tunnel. The tunnel has direct fixation track; and therefore, it was assumed that track geometry changes in the time since the previous run was negligible.

Figure 14. Holland's TrackSTAR Vehicle

The data provided by Holland was in space curve format. Mid-chord offset data (MCO), while useful for track maintenance purposes, can filter out important information needed for input to simulation models and PBTG analyses.[6] Figure 15 shows an example of how a signal amplitude may be reduced using MCO data. Certain wavelengths are completely filtered out and cannot be reconstructed. Space curve data is the best option to investigate the correlation between track geometry and ride quality. Figure 16 shows the information that is needed to describe the track geometry.

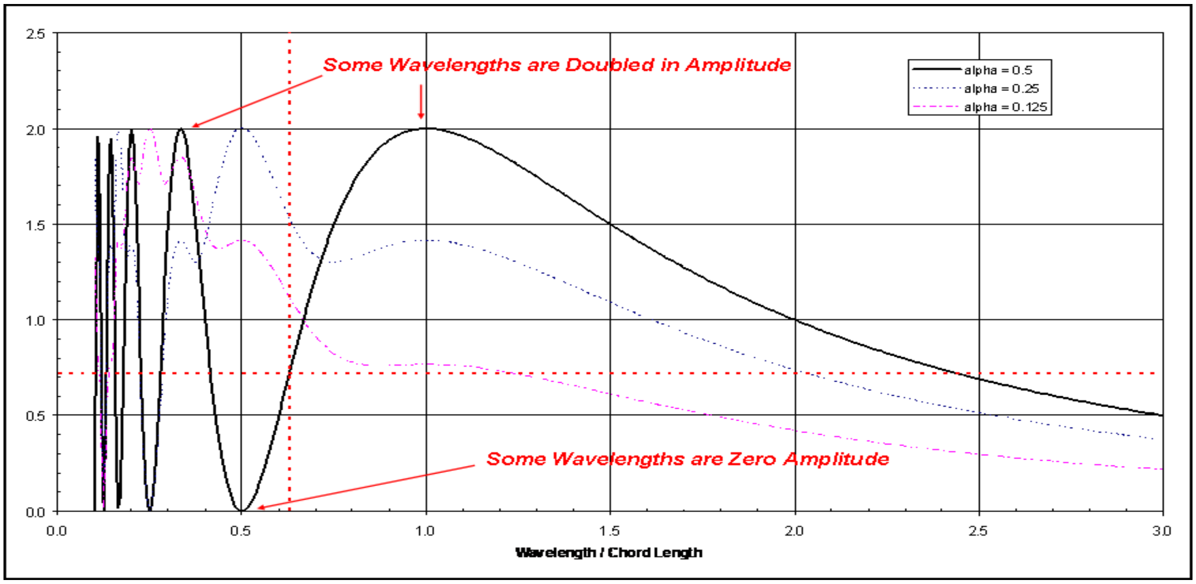


Figure 15. MCO Measurement Issue

6 Cohen, A. and W.A. Hutchens. 1970. "Methods for the reconstruction of rail geometry from mid-chord offset data." *ASME, 70-Tran-24.*

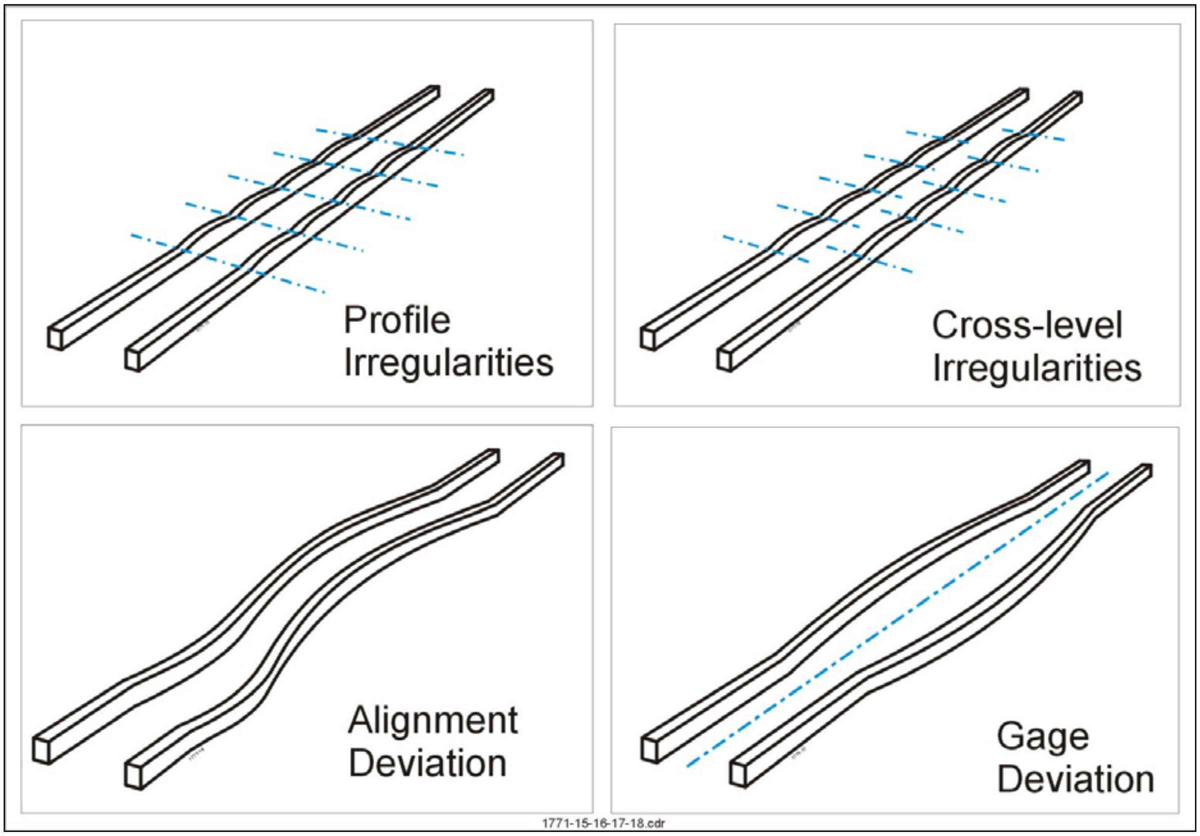


Figure 16. Required Track Geometry Information

3.3 Ride Quality Test

A ride quality test was conducted on DART's Red Line. The test conditions were similar to typical revenue service operations. Tri-axial accelerometers were placed on the floor under the operator's seat, on the floor over the bogie, and on the center of the vehicle. The accelerometers measured the vehicle's response to operating conditions and inputs from the track structure. A gyrometer was also placed on the floor under the operator's seat. The gyrometer was used to measure carbody rotation to correlate the effect of curves and curve transitions on ride quality. This information will be used to correlate ride quality issues with track geometry. Figure 17 shows an example of the instrumentation and data acquisition system. Figure 18 is a schematic of the instrumentation location. Table 5 is a description of the accelerometers at each location.

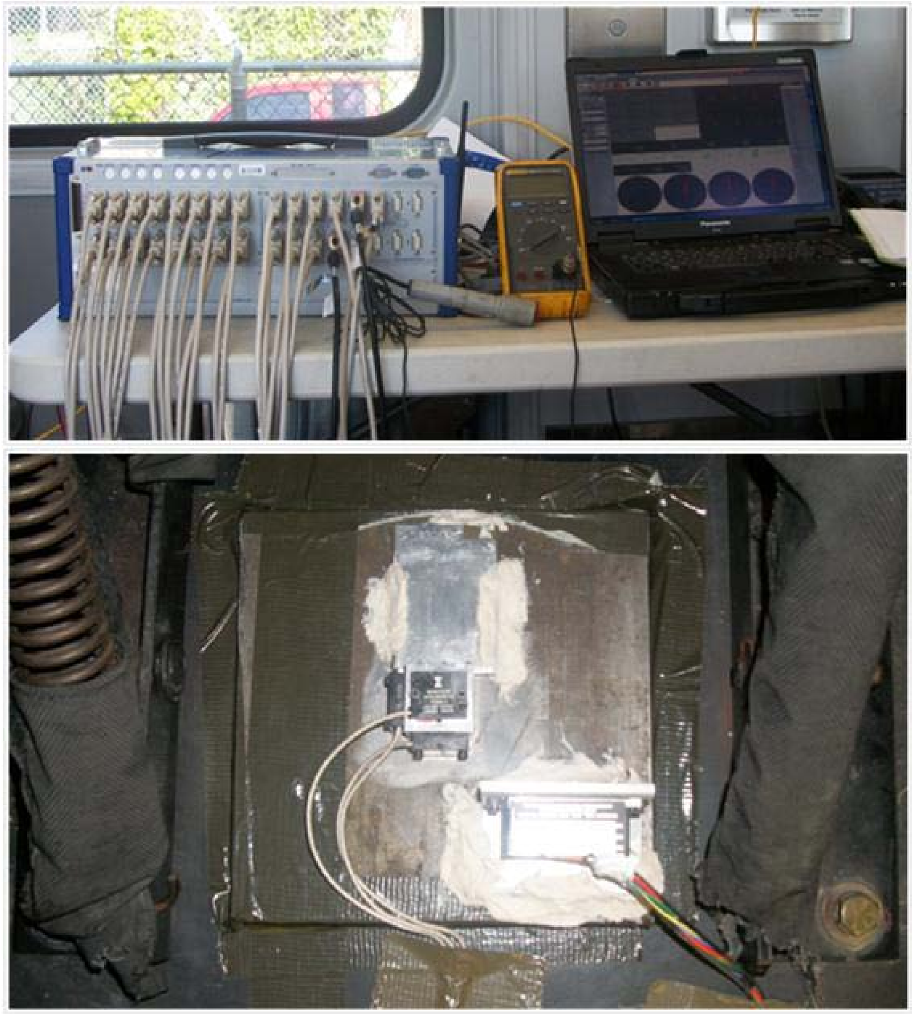


Figure 17. Ride Quality Instrumentation

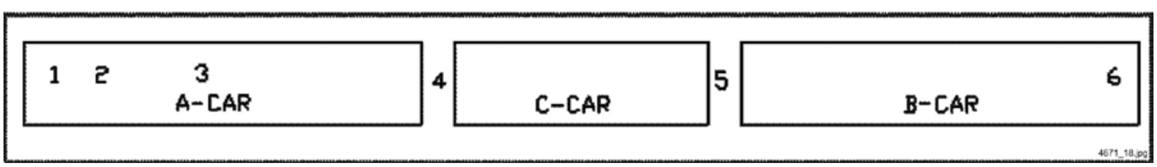


Figure 18. Location of Ride Quality Instrumentation (plan view)

Table 5. Instrumentation Description

Location	Description
1	Lateral, Longitudinal, Vertical Accelerometers under operator's seat on floor. Gyrometer under operator's seat.
2	Lateral, Longitudinal, Vertical Accelerometers on cabin floor over bogie.
3	Lateral, Longitudinal, Vertical Accelerometers on cabin floor in center of A-car.
4	Lateral Accelerometer between A-Car and C-car.
5	Lateral Accelerometer between C-Car and B-car.
6	Lateral, Longitudinal, Vertical Accelerometers under operator's seat on floor. Gyrometer under operator's seat.

4.0 VEHICLE CHARACTERIZATION DATA ANALYSIS

The data collected during vehicle characterization testing was used to make the NUCARS model a more accurate representation of the DART SLRV.

4.1 Carbody Resonance Test

During the carbody resonance test, accelerations were measured at locations described in Figure 4 and Table 4. These accelerations were analyzed to determine the frequency content and type of resonance excited. Figure 19 shows an example of raw acceleration data taken during the carbody resonance test. The data was processed to determine which rigid body motion was excited.

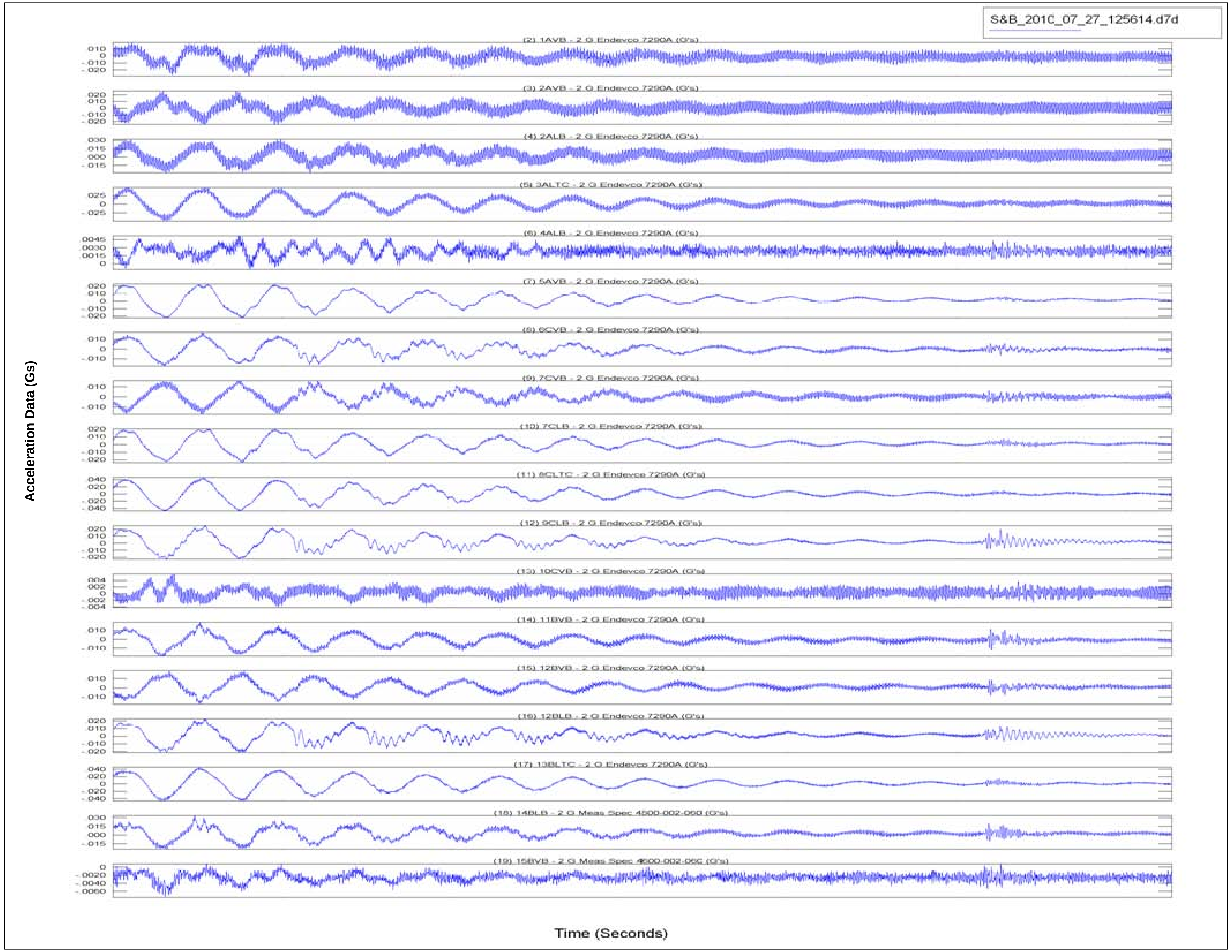


Figure 19. Raw Acceleration Data from Carbody Resonance Test

Figure 20 shows the result. A fast Fourier transform (FFT) calculation was done to determine the frequency of the lower center roll mode. The frequency is approximately 0.5 Hz. Figure 21 shows the FFT for this particular data. All three sections of the vehicle carbodies were in phase.

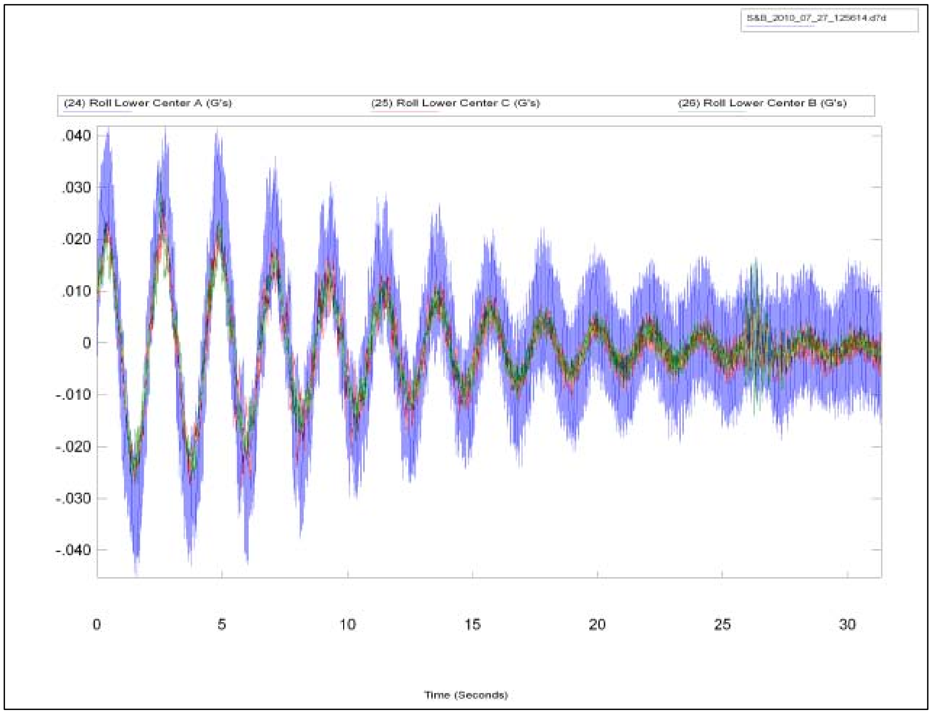


Figure 20. Lower Center Roll Rigid Body Vibration Mode

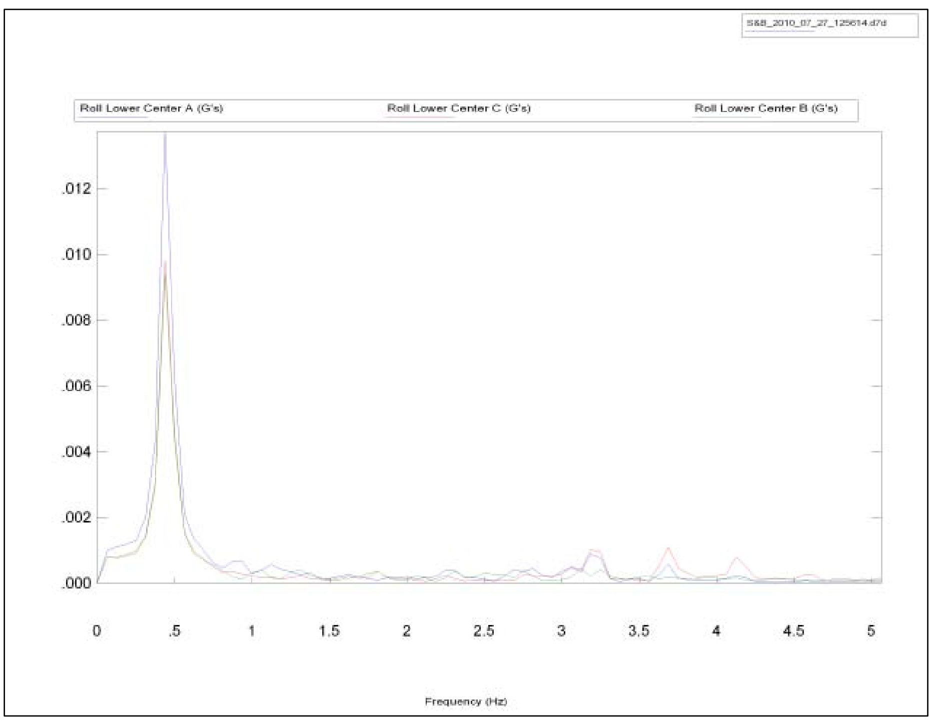


Figure 21. Lower Center Roll Vibration Mode Frequency

Each of the rigid body modes excited during the test were analyzed and their frequencies determined. Table 6 describes all the observable rigid body modes and the respective frequencies. This information was used to update the NUCARS model.

Table 6. Rigid Body Vibration Modes and Measured Frequencies

Rigid Body Mode	Frequency (Hz)	NUCARS Model Frequency (Hz)
Lower roll	0.50	0.50
Upper roll	2.00	2.02
Bounce	1.25	1.26
Pitch (all bodies in phase)		1.28
Pitch (u-shape)	1.50	1.50
Yaw (all bodies in phase)		1.42
Yaw (zigzag)	1.75	1.80
Yaw (u-shape)		1.57

This information was used in eigenvalue analysis to determine the values of air suspension characteristics, carbody moments of inertia, and carbody center of gravity. The measured resonance frequencies were compared to the calculated values of the NUCARS model. Adjustments were made to the model's suspension stiffness, center of gravity, and carbody inertias, and the resonance frequencies were recalculated. The model parameters were adjusted until the calculated values matched the measured values of the SLRV.

4.2 Bogie Resonance Test

The bogie resonance test was performed to characterize the stiffness and damping of the bogie frame and traction motor mounts. An instrumented hammer was used to impact the bogie and excite modes of vibration. Accelerometers were used to measure the response. Both a trailer and a motor truck were characterized.

The motor truck was characterized in longitudinal, lateral, and vertical directions. The traction motor is mounted to the truck at three points. Figure 22 shows the motor mount locations. The axle motor mount acts like a rigid connection. The pin mount and side frame mount effective stiffness and damping were characterized.

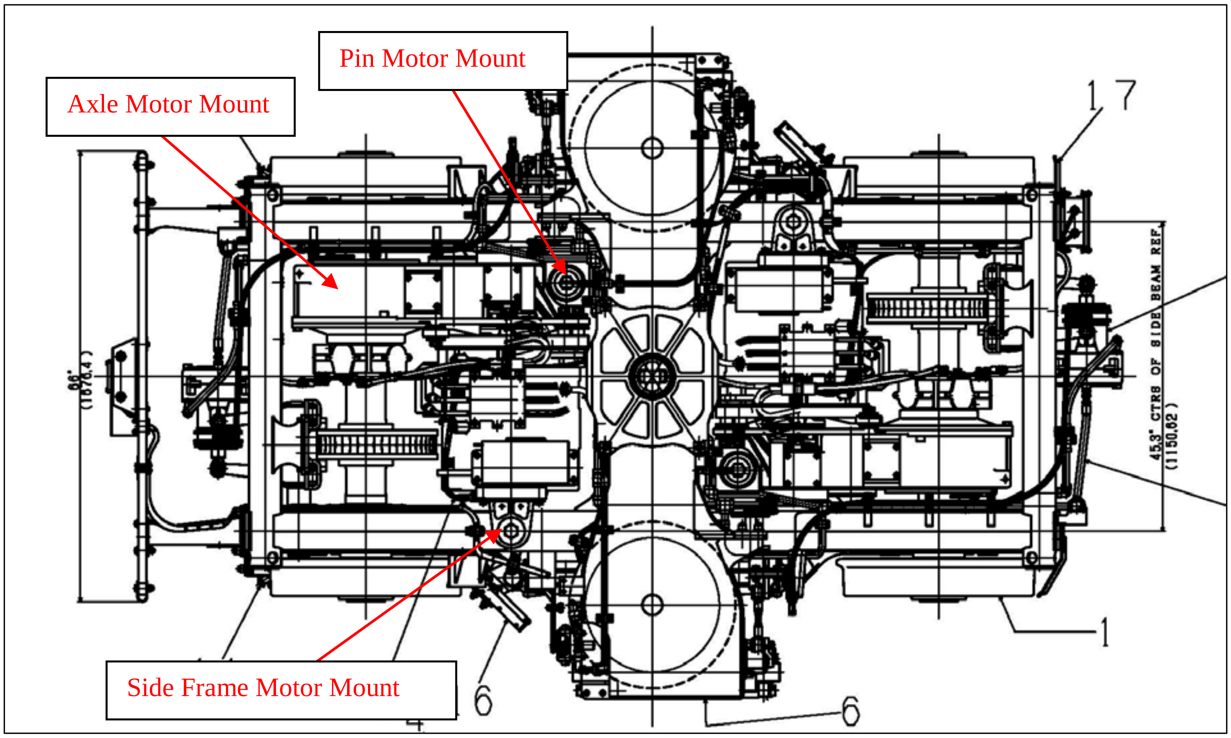


Figure 22. Traction Motor Mount Locations

Figure 23 shows the hammer input and output for the vertical directions of the traction motor mounts. The output from the pin and side frame mount were averaged to determine if a bounce mode existed and its frequency. The output from the pin and side frame mount were also subtracted to determine if a pitch mode existed and the frequency of that mode. Figure 24 shows the reduced data and frequency analysis.

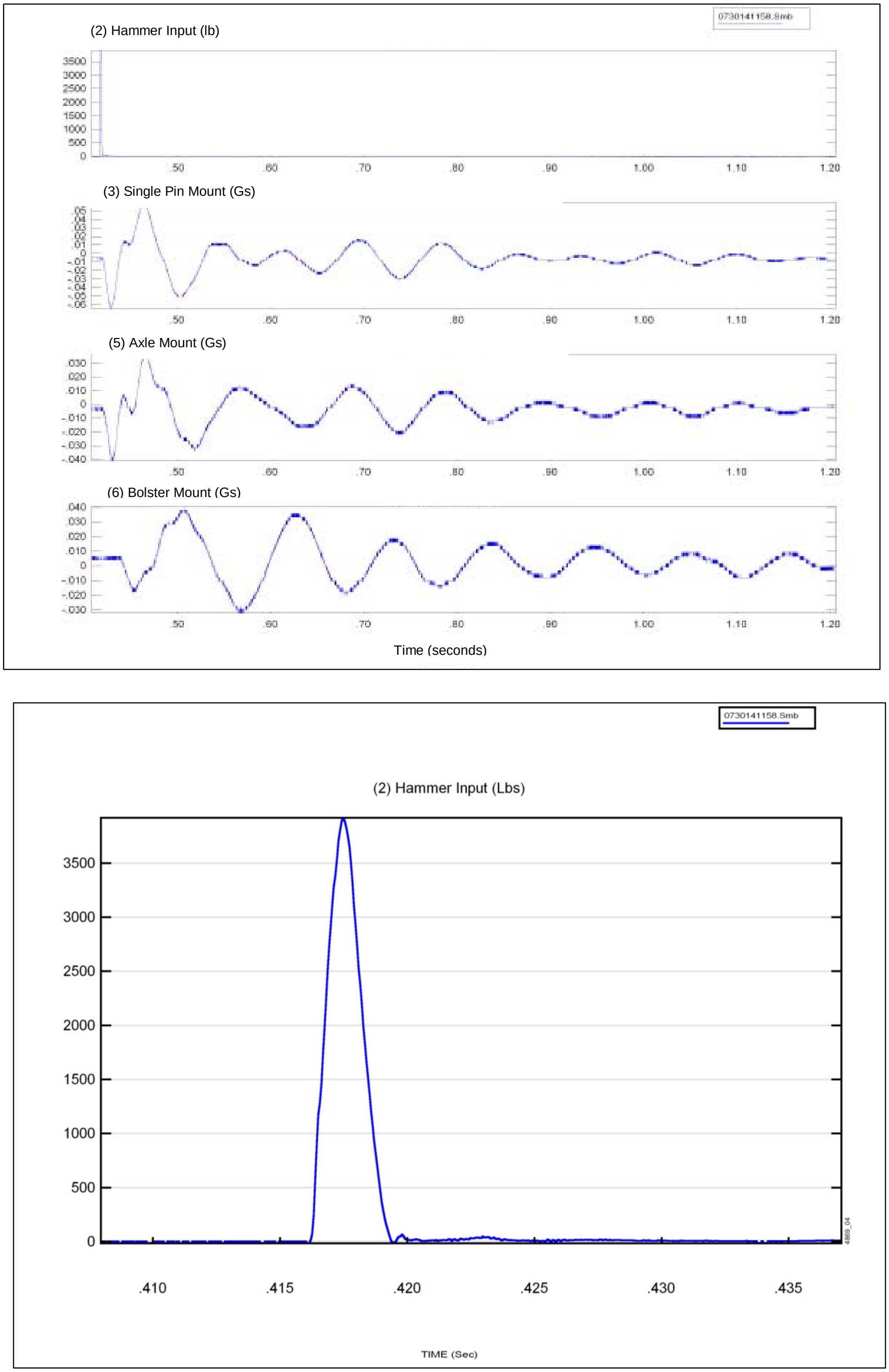


Figure 23. Hammer Input and Resulting Output — Vertical Direction

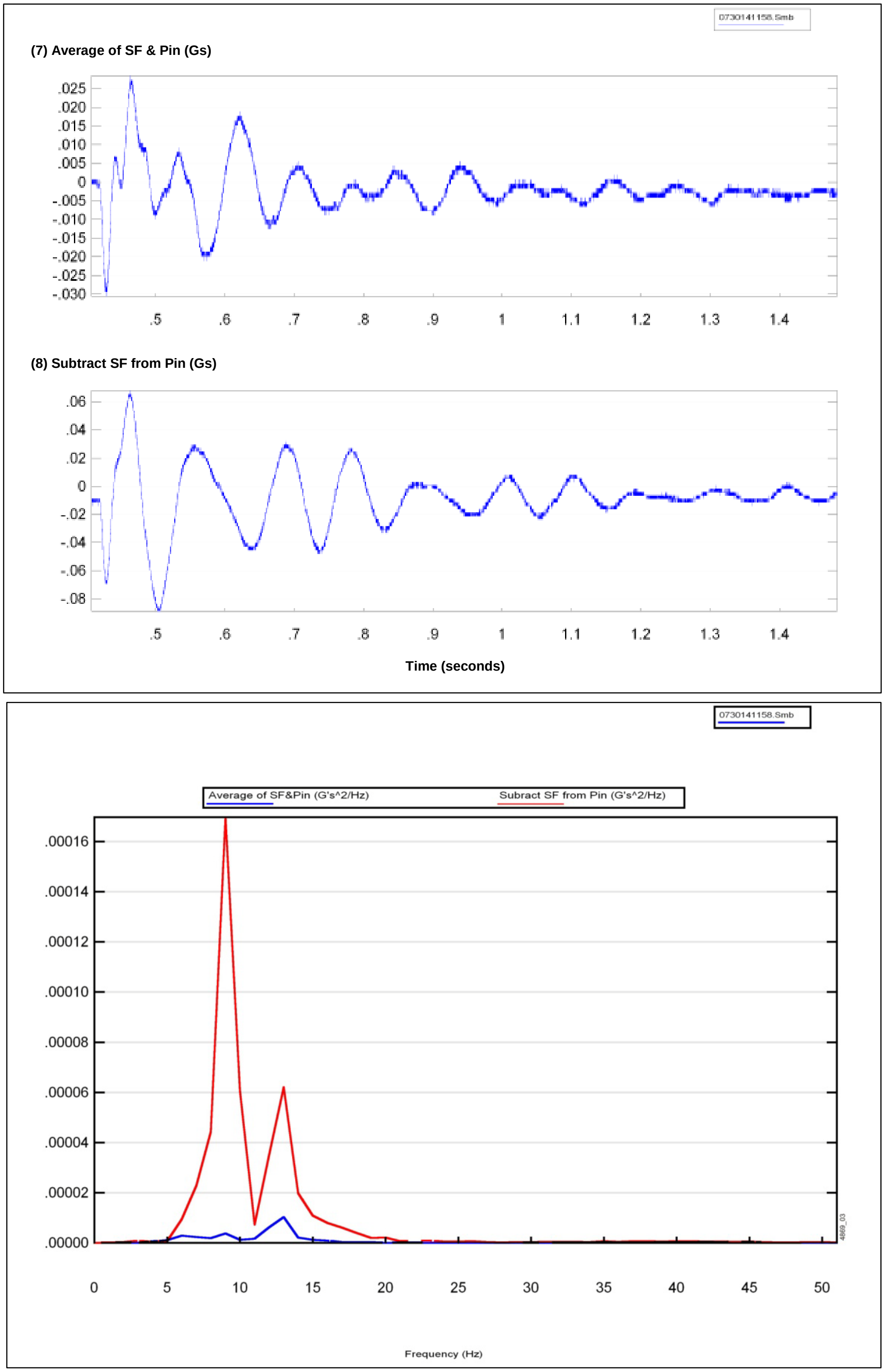


Figure 24. Time Domain Data and Frequency Content from Hammer Test

The bounce frequency of the motor mounts is approximately 12 Hz. The effective stiffness of the motor mounts can be calculated by the following equation:

Where:

K is stiffness
is the natural frequency
m is the mass of system

The effective stiffness for the motor mount is approximately 27,685 lb/in. The longitudinal and lateral directions were analyzed with the same procedure as the vertical for both the motor and the trailer.

The effective damping can be calculated from the decay of the vibration. The equation used is the following:

$$y = Ae^{-\alpha t}$$

Where:

A is a constant
$\alpha = c/2m$ (c is damping and m is mass)
t is period of decay

Figure 25 shows the decay of the vertical motor mount accelerations. The damping is 84 lb-sec/in. Table 7 summarizes the results.

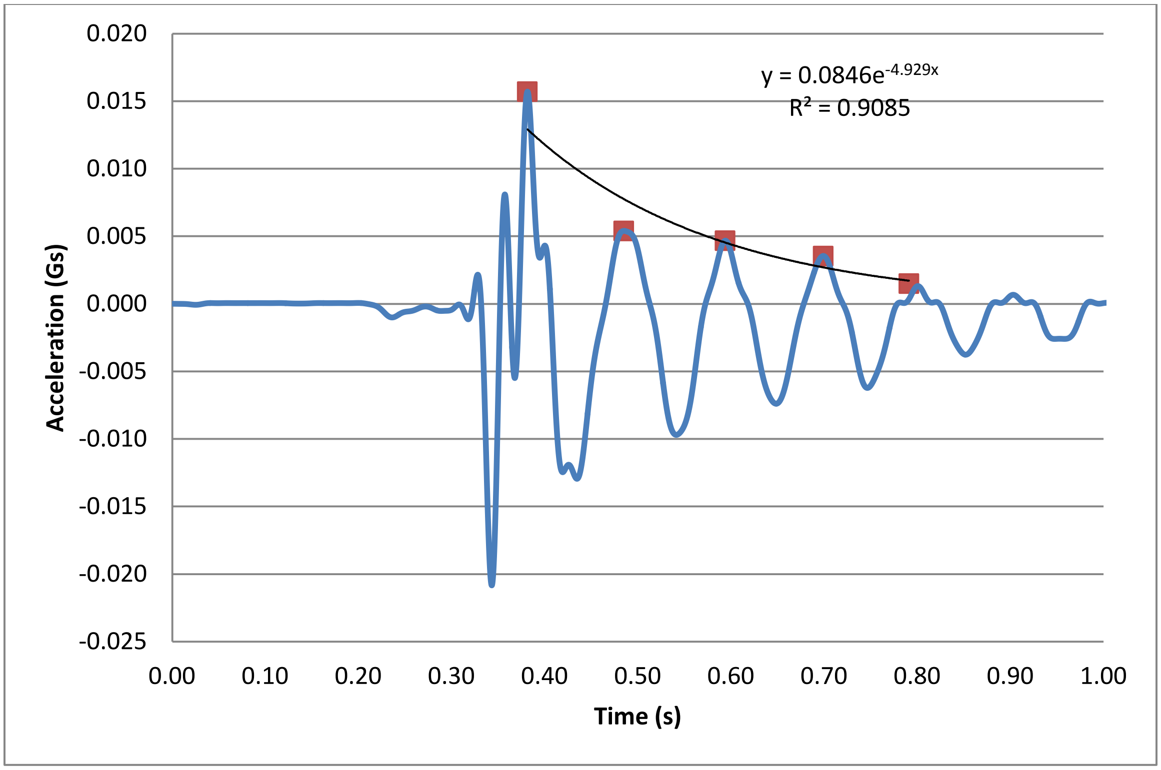


Figure 25. Decay Plot of Vertical Motor Mount Accelerations

Table 7. Bogie Resonance Test Summary

	Frequency (Hz)	Effective Stiffness (lb/in)	Effective Damping (lb-sec/in)
Motor Mounts Vertical	12	27,685	84
Motor Mounts Lateral	10	12,677	70
Motor Truck Side Frame Vertical	9	11,937	40
Motor Truck Side Frame Lateral	14	26,101	39
Trailer Truck Side Frame Vertical	9	19,730	47
Trailer Truck Side Frame Lateral	10	24,358	35

4.3 Longitudinal Stiffness Test

The longitudinal stiffness test was performed to determine the primary and secondary effective stiffness in the longitudinal direction. The DART maintenance facility was equipped with car frame straightening equipment. This equipment provided a reaction point for the load. Displacement measurements were taken across both the primary and secondary suspension systems.

Force-displacement slopes were calculated for the different runs. The calculated stiffness values for all runs were averaged to determine the effective stiffness of the primary suspension system. Figure 26 shows the displacement and load measured during the test. Figure 27 shows the force-displacement output and the calculated slope. The load was divided in half to account for the two chevrons in the system. Figure 28 shows the chevrons.

Table 8 shows the values determined from the test in comparison to the manufacturer specified values.

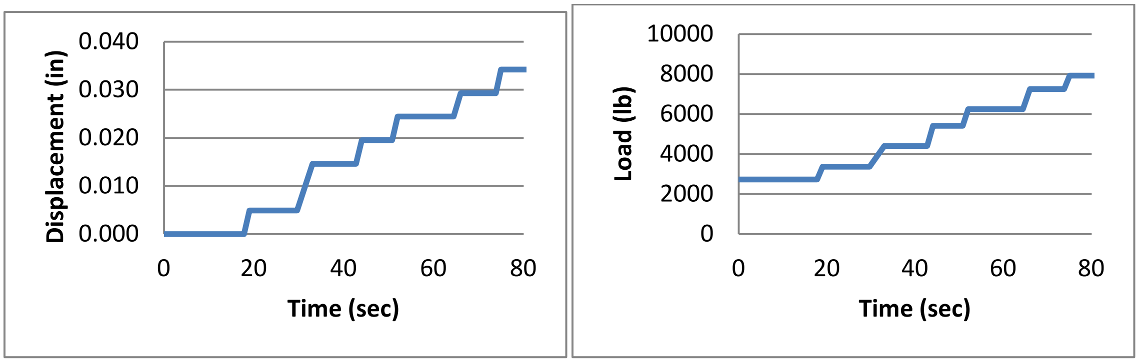


Figure 26. Longitudinal Displacement and Load Measurements

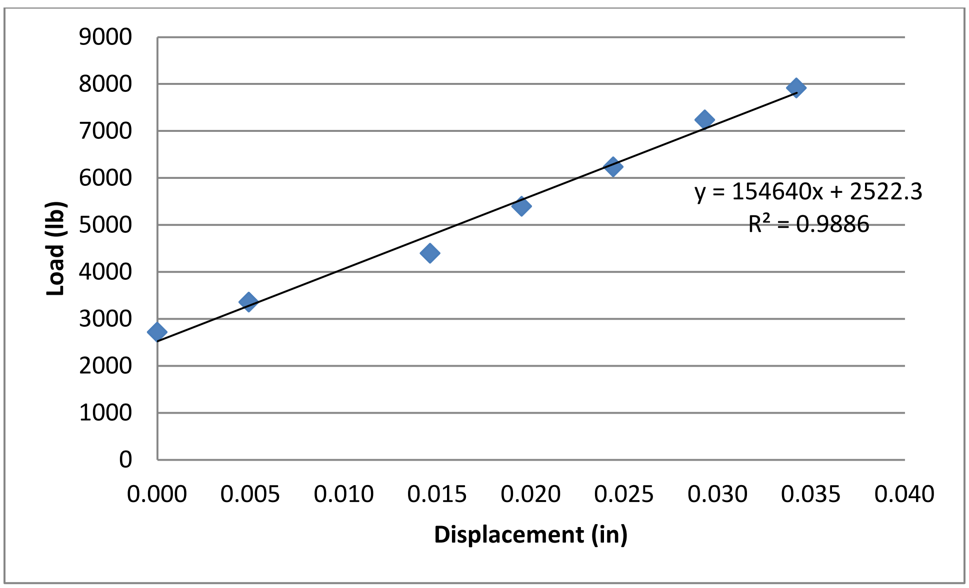


Figure 27. Force-Displacement Diagram and Calculated Slope

Figure 28. Primary Suspension System – Chevrons

Table 8. Longitudinal Primary Suspension Stiffness

Suspension Component	Manufacturer Value	Average Measured Value	Difference
Motor Primary Chevron	142,700 lb/in*	171,140 lb/in	19.9%
Trailer Primary Chevron	91,400 lb/in*	87,180 lb/in	4.6%

*Manufacturer's information was not available. Specifications of similar chevrons were used for preliminary model.

4.4 Lateral Stiffness Test

The lateral stiffness test was performed to determine the effective lateral stiffness for the primary and secondary lateral suspension systems. The frame straightening equipment was also used for this test. Force-displacement slopes were calculated for the different runs. The calculated stiffness values for all runs were averaged to determine the effective stiffness of the primary suspension system. Figure 29 shows the displacement and load measured during the test. Figure 30 shows the force-displacement output and the calculated slope. The load was divided in half to account for the two chevrons in the system.

Table 9 shows the primary suspension stiffness values determined from the test in comparison to the manufacturer's specified values. The secondary suspension stiffness was validated during the carbody resonance test and eigenvalue analysis.

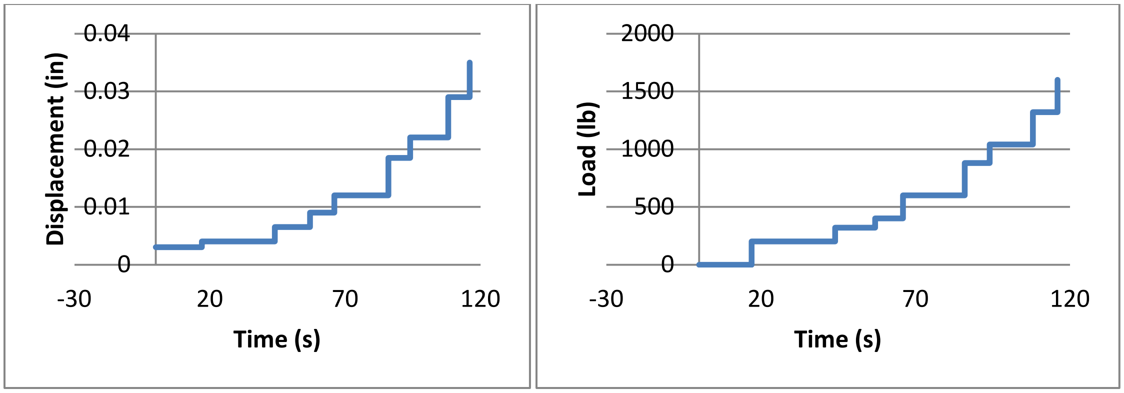


Figure 29. Lateral Displacement and Load Measurements

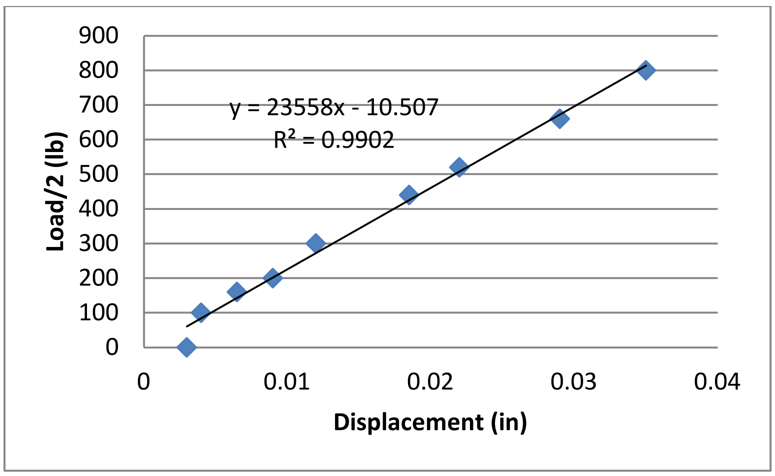


Figure 30. Force-Displacement Diagram and Calculated Slope

Table 9. Lateral Primary Suspension Stiffness

Suspension Component	Manufacturer Value	Measured Value	Difference
Motor	17,700 lb/in*	41,200 lb/in	132.0%
Trailer	20,500 lb/in*	22,700 lb/in	10.7%

*Manufacturer's information was not available. A specification of a similar chevron was used for preliminary model.

4.5 Vertical Stiffness Test

The vertical stiffness test was performed to determine the effective vertical stiffness for the primary and secondary lateral suspension systems. Load cells were placed under each wheel of a motor truck. The carbody was then slowly lifted off of the truck. The displacements of the suspension systems were measured. The calculated stiffness values for all runs were averaged to determine the effective stiffness of the primary suspension system. Figure 31 shows a typical primary suspension displacement and load measured during the test. Figure 32 shows the corresponding force-displacement output and the calculated slope. The load was divided in half to account for the two chevrons in the system. Table 10 shows the primary suspension stiffness values determined from the test in comparison to the manufacturer's specified values.

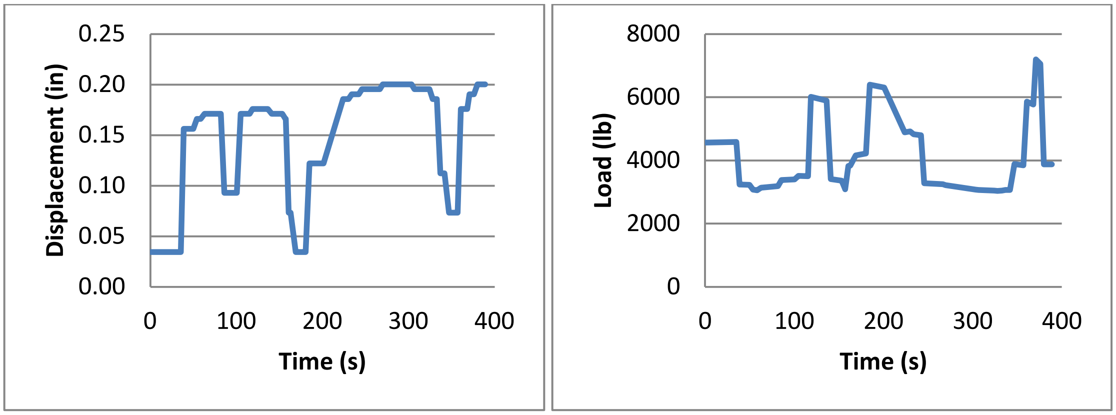


Figure 31. Vertical Displacement and Load Measurements

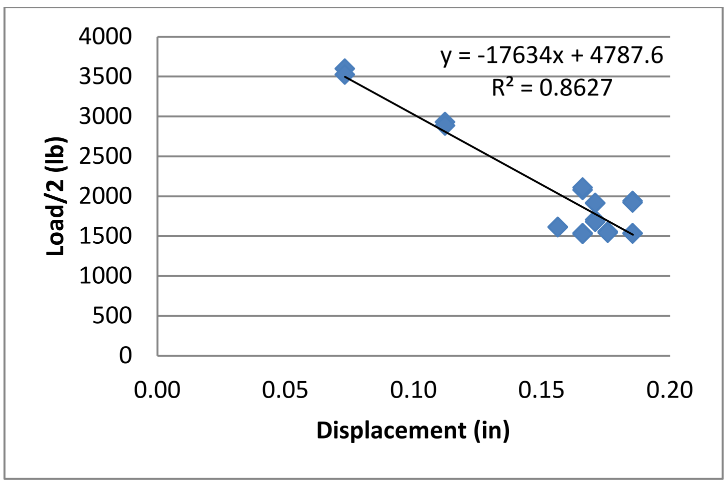


Figure 32. Force-Displacement Diagram and Calculated Slope

Table 10. Vertical Primary Suspension Stiffness

Suspension Component	Manufacturer Value	Measured Value	Difference
Motor	7,428 lb/in	10,500 lb/in	41.35%
Trailer	6,292 lb/in	7,400 lb/in	17.60%

5.0 RIDE QUALITY AND TRACK GEOMETRY DATA ANALYSIS

The data collected during the ride quality and track geometry tests were compared to determine if a correlation between the two was possible.

5.1 Ride Quality Test

Ride quality measurements were taken on DART's Red Line in both directions. The train was operated with typical operating conditions. Accelerations were measured on the floor at the following locations:

- A-end under operator's seat (lateral, vertical, and longitudinal)
- B-end under operator's seat (lateral, vertical, and longitudinal)
- A-end over bogie (lateral, vertical, and longitudinal)
- A-end center of car (lateral, vertical, and longitudinal)
- Lateral accelerometer between the A and C cars
- Lateral accelerometer between the C and B cars
- Lateral accelerometers at each axle

Gyrometers were also placed under the A-end and B-end operator's seats to measure the carbody roll angle as the vehicle traveled through the curves.

Figure 33 shows an example of ride quality data. It shows Westmoreland to Pearl Street Station and the accelerations measured under the operator's seat in the A-end of the SLRV. The data was analyzed between each station. Ride quality was determined according to ISO 2631-1997. Longitudinal, lateral, and vertical ride quality was determined between each station. The identified ride quality issues will be compared to track geometry to determine if there is a correlation.

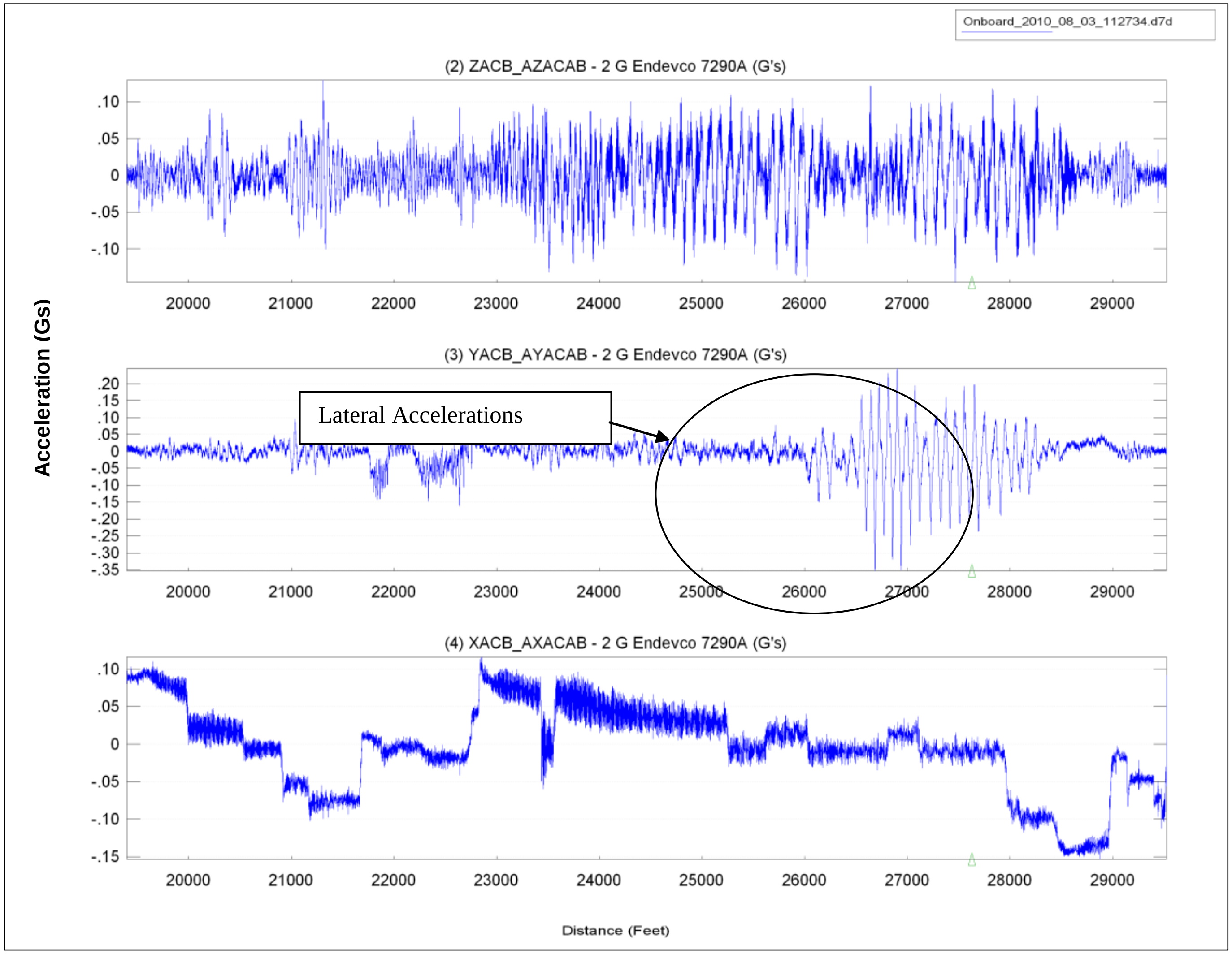


Figure 33. Example Ride Quality Data

Table 11 describes ISO 2631 ride quality index boundaries. Figure 34 (a, b) shows the crest factors calculated for each segment. The appendix contains the definitions of the parameters related to ride quality. There are some areas that have crest factors above 9; therefore, as required by ISO 2631, the running root-mean-square (RMS) Method was used to evaluate the ride quality. The vibration magnitude is defined as the maximum transient vibration value (MTVV). Figure 35 (a, b, c) shows the MTVV for vertical, lateral, and longitudinal accelerations.

Table 11. ISO 2631 Ride Quality Index Boundaries

Vibration Magnitude (meters/second^{2})	Comfort Level
$a_w<0.315$	Not uncomfortable
$0.315 \le a_w<0.63$	A little uncomfortable
$0.5 \le a_w<1$	Fairly uncomfortable
$0.8\le a_w<1.6$	Uncomfortable
$1.25\le a_w<2.5$	Very uncomfortable
$a_w\ge2$	Extremely uncomfortable

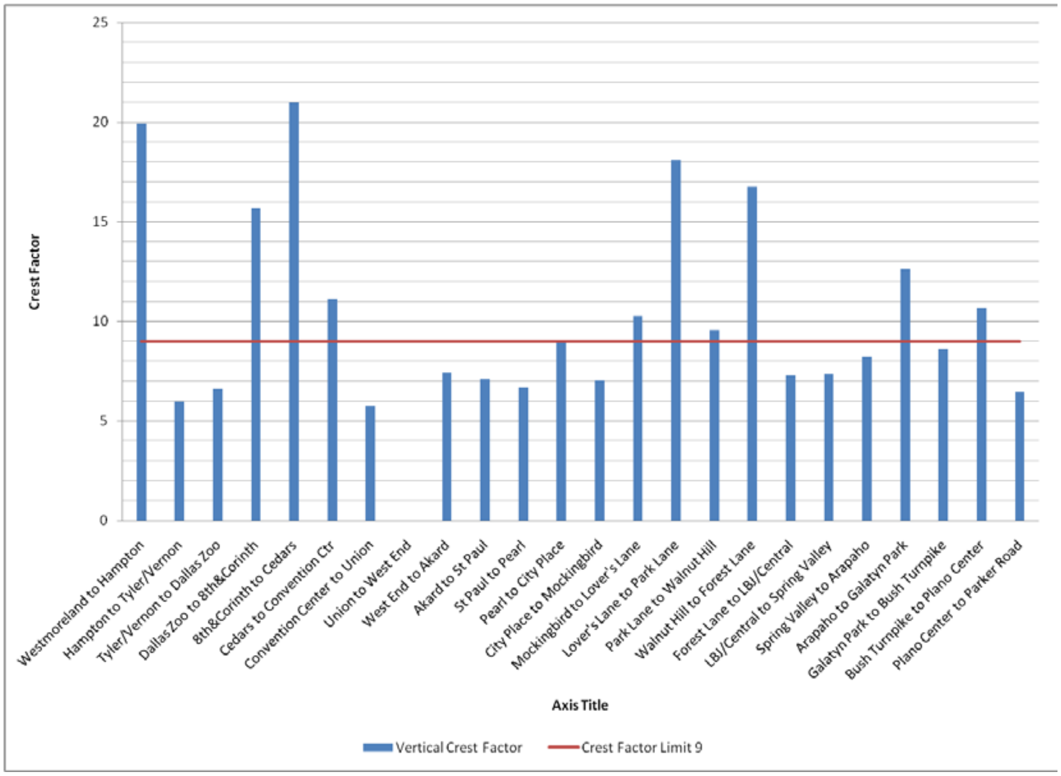


Figure 34a. Crest Factors for Vertical Accelerations

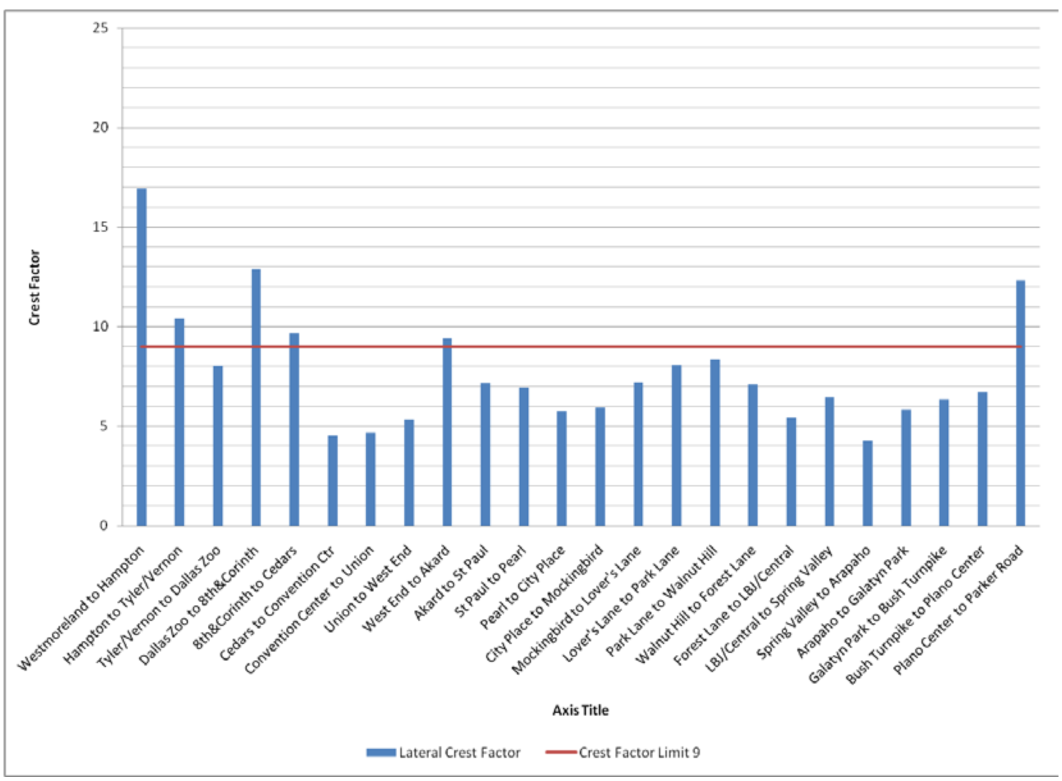


Figure 34b. Crest Factors for Lateral Accelerations

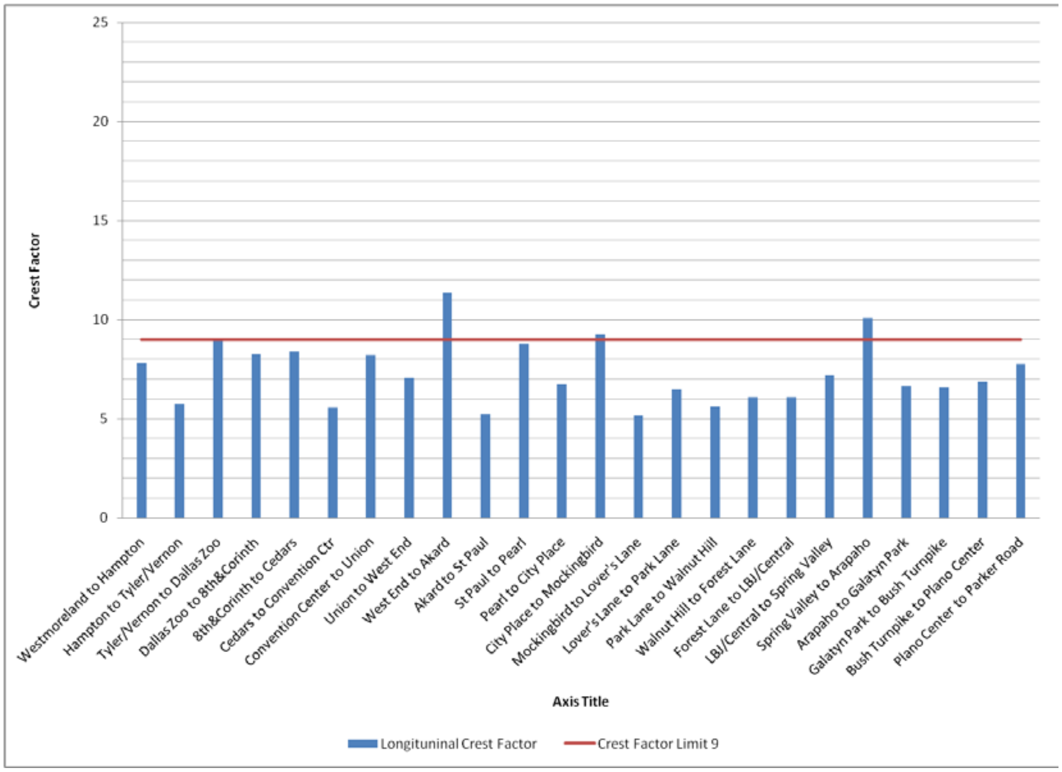
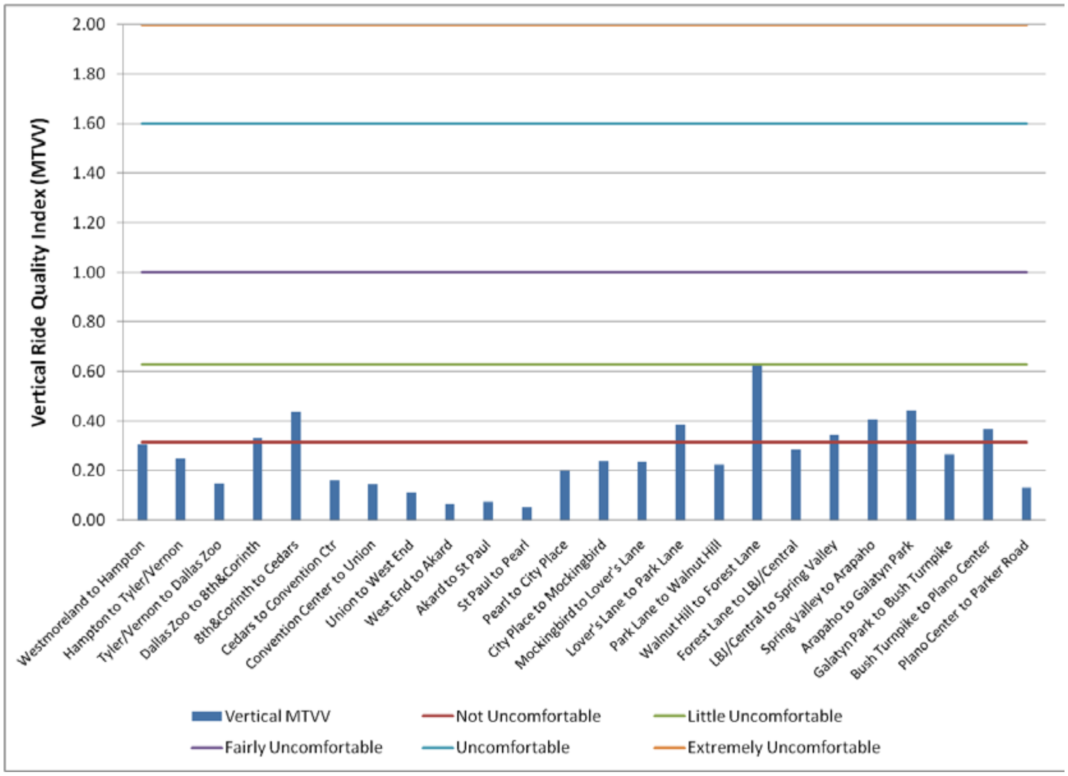


Figure 34c. Crest Factors for Longitudinal Accelerations



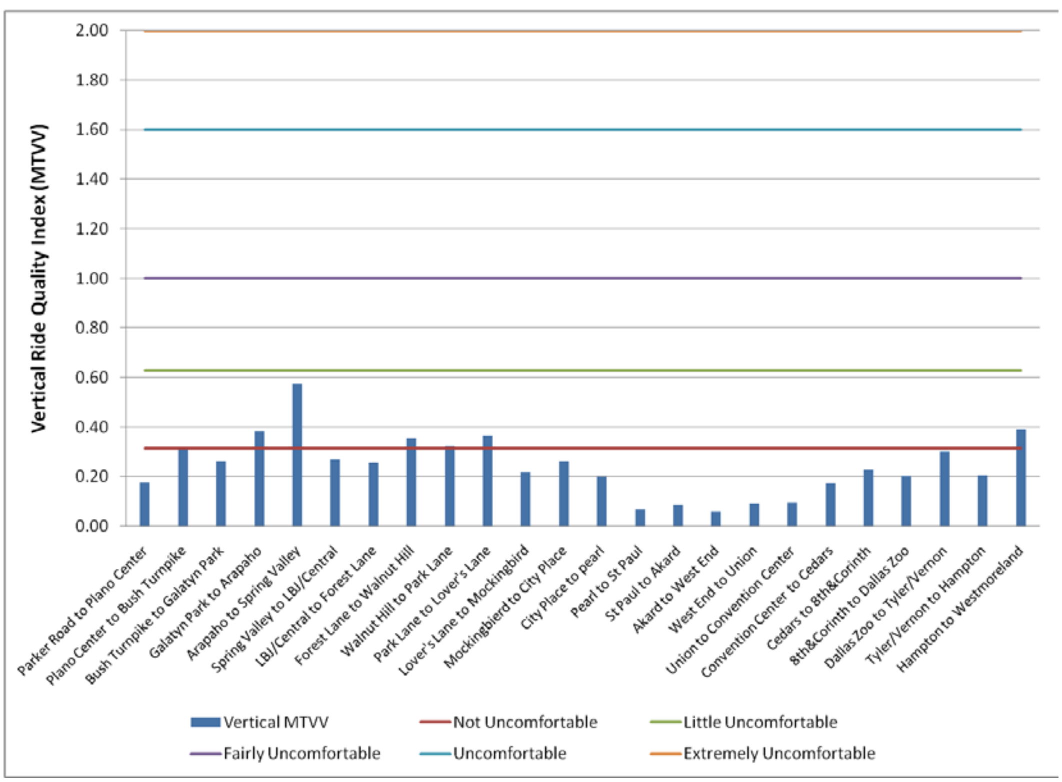
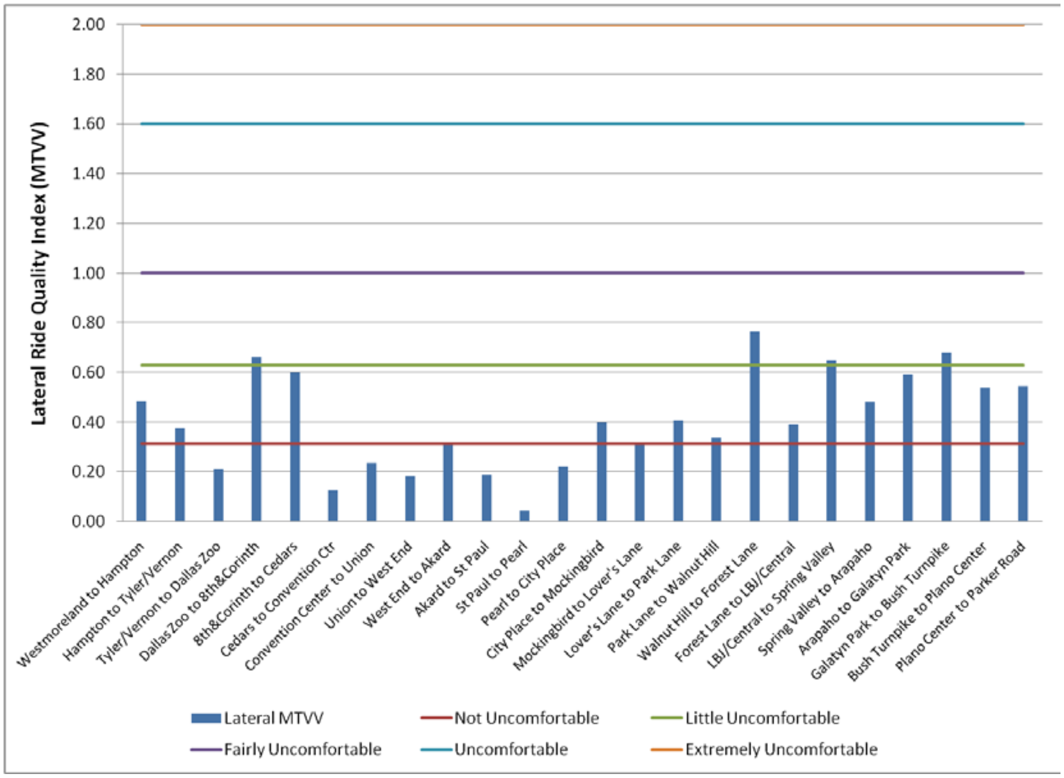


Figure 35a. MTVV Values for Vertical Accelerations



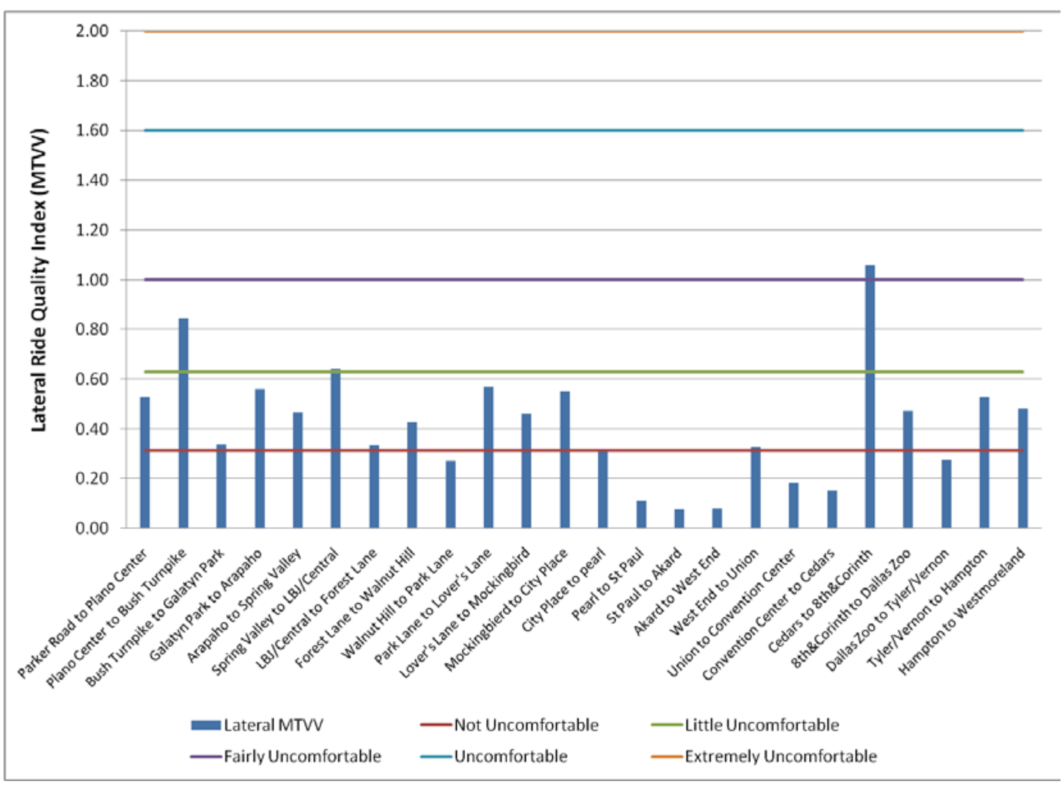


Figure 35b. MTVV Values for Lateral Accelerations

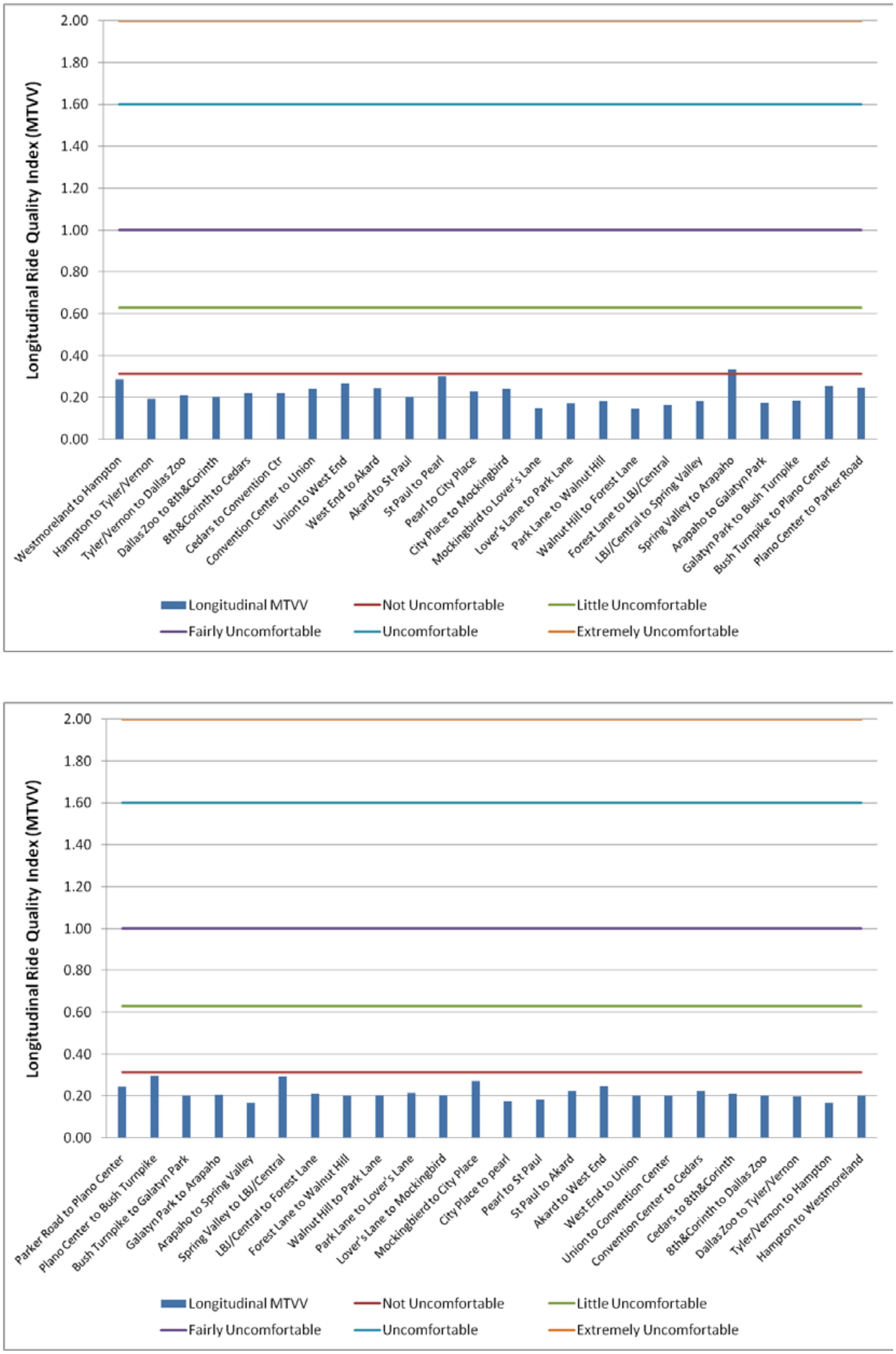


Figure 35c. MTVV Values for Longitudinal Accelerations

The ride quality for the longitudinal and vertical directions was in the “comfortable” to “not uncomfortable” range for both directions of travel. However, the lateral direction had areas with ride quality in the “little uncomfortable” to “fairly uncomfortable” range. Table 12 summarizes the areas with ride quality exceptions.

Table 12. Segments of Track with Ride Quality Exceptions

Direction	Stations	Lateral Ride Quality Index	Description
Northbound	Dallas Zoo to 8th& Corinth	0.661	Fairly uncomfortable
Northbound	Walnut Hill to Forest Lane	0.763	Fairly uncomfortable
Northbound	LBJ/Central to Spring Valley	0.651	Fairly uncomfortable
Northbound	Galatyn Park to Bush Turnpike	0.681	Fairly uncomfortable
Southbound	Plano Center to Bush Turnpike	0.845	Uncomfortable
Southbound	Spring Valley to LBJ/Central	0.640	Fairly uncomfortable
Southbound	Cedars to 8th& Corinth	1.056	Uncomfortable

The measured track geometry in these areas is evaluated in section 5.3 to determine if there is a correlation to the ride quality issues.

5.2 Track Geometry

Track geometry measurements were taken by Holland August 13-14, 2010, on DART Red Line in both directions. No measurements were taken in the tunnel because of a size restriction in the tunnel. Data from a previous track geometry run was used for the tunnel. The tunnel has direct fixation track, and therefore, it was assumed that track geometry changes in the time since the previous run were negligible.

Figure 36 shows an example of the measured track geometry. The tight gauge in the embedded track is evident.

The data was processed for use in the NUCARS simulations. High and low pass filters were applied to the data to ensure the long wavelength effects of curvature and entry spirals were removed from the short wavelength alignment data, and to ensure that long wavelength superelevation in curves was clearly separated from the short wavelength crosslevel deviations. In some areas, dropouts in the data were present due to the speed of the measurement vehicle dropping below a critical threshold. In these dropout locations, the curvature channel was filtered and a correction factor was determined. Figure 37 shows an example of the data processed for use in NUCARS.

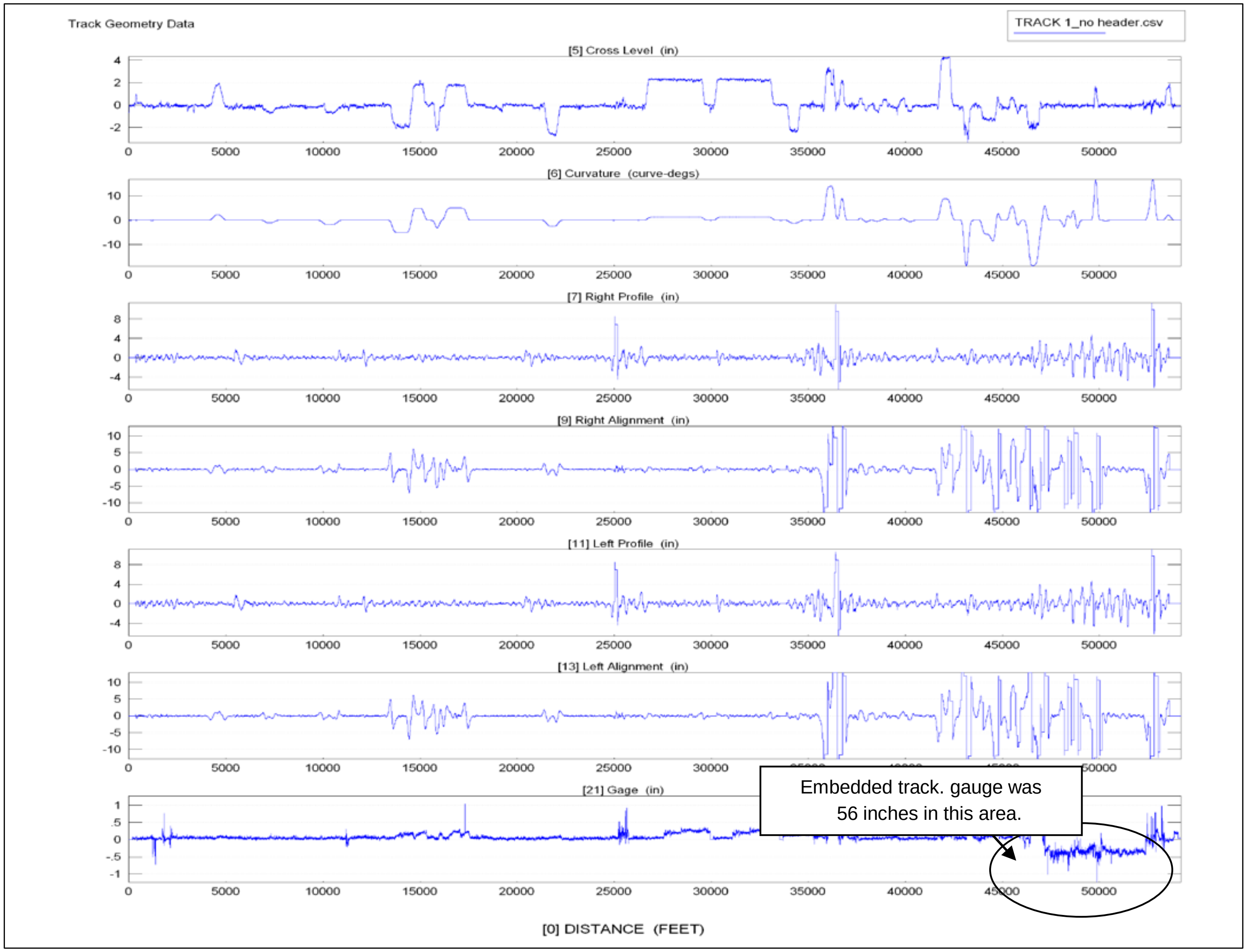


Figure 36. Raw Track Geometry Data
(from top graph down—Cross level (in); Curvature (degree); Profile, Alignment, Profile, Alignment, Gauge (in)

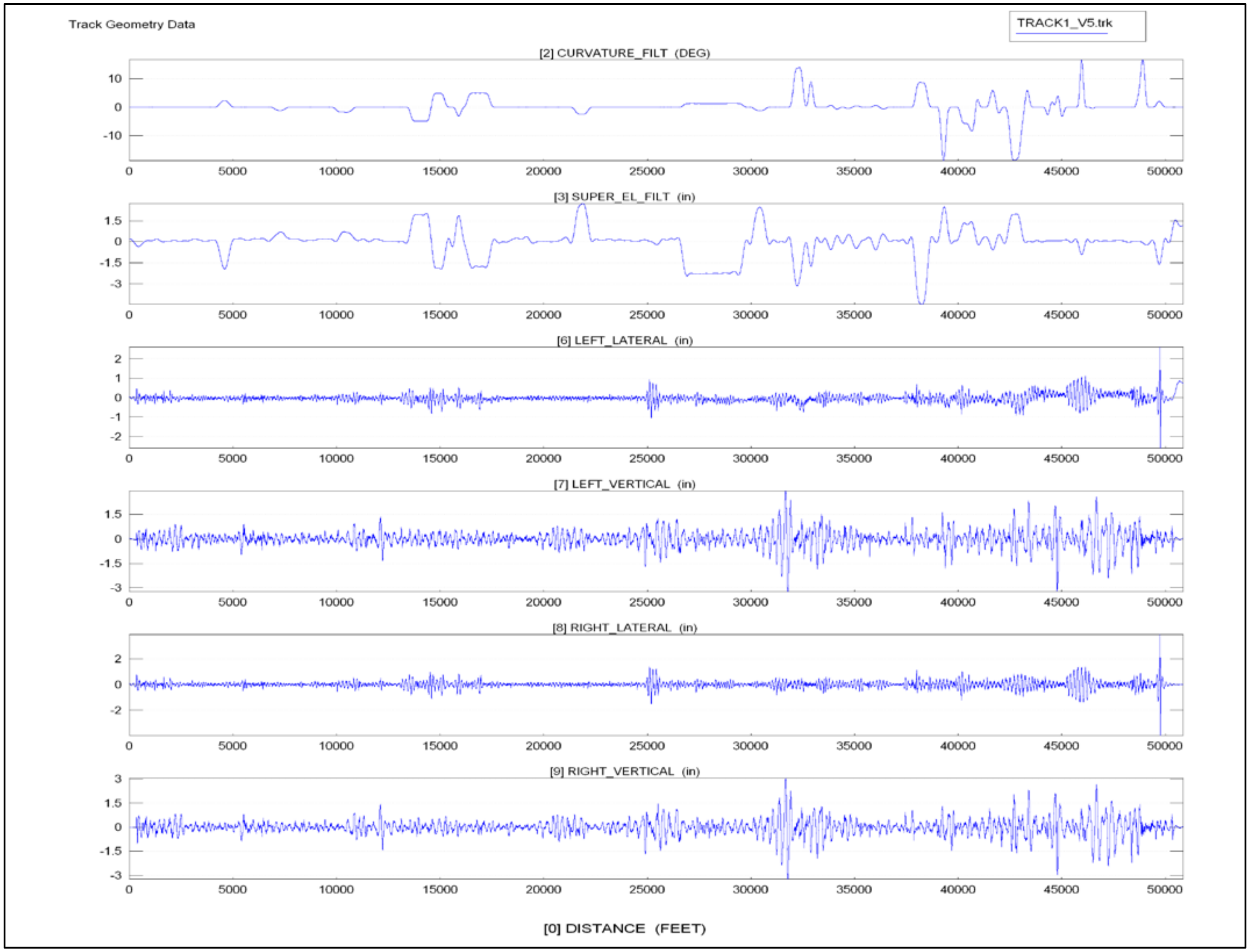


Figure 37. Processed Track Geometry Data for Use in NUCARS
[from top graph down—Curvature (degree); superelevation, left lateral, left vertical, right lateral, right vertical (in.)]

5.3 Ride Quality and Track Geometry Comparison

A major objective was to determine if there is a correlation between ride quality and track geometry. Places on the Red Line that had ride quality issues were identified from the ride quality test performed (section 5.1). The section of track that was fairly uncomfortable was located between Cedars and 8th & Corinth stations in the southbound direction. Figure 38 (top) shows the accelerations measured under the operator's seat in the leading end of the SLRV in this area. Figure 38 (bottom) shows the track geometry measured in the same area. The two-second peak-to-peak value is approximately 0.35 Gs. In the area where this occurs, there is a deviation in the lateral alignment.

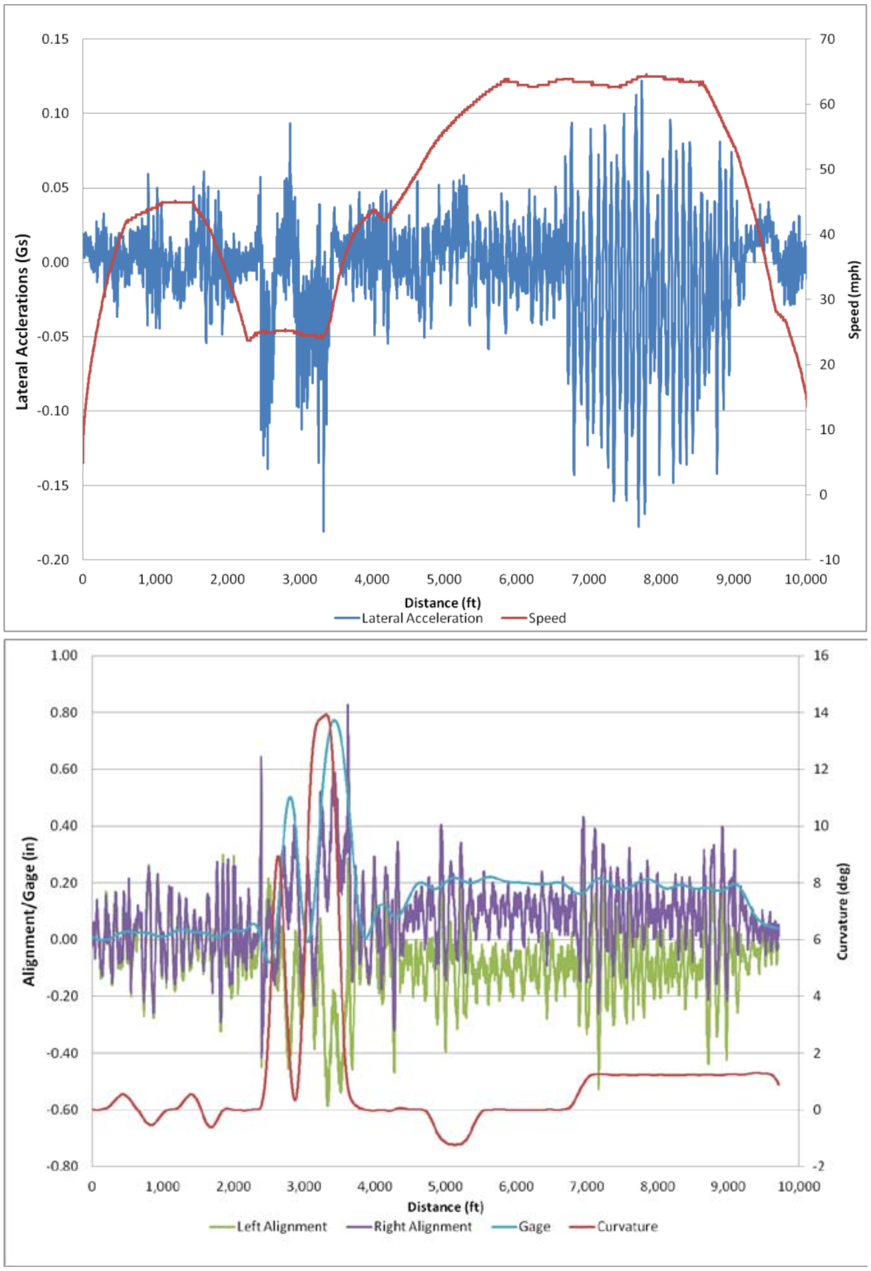


Figure 38. Measured Acceleration Data between Cedars and 8th & Corinth Stations (top), and Measured Track Geometry Data between Cedars and 8th & Corinth Stations (bottom)

Figure 39 shows the frequency content of the acceleration data and lateral alignment of the track geometry. There are peaks at approximately 1 Hz and 1.65 Hz in the lateral vehicle response. In the lateral alignment of the track geometry in this area there is also a 1 Hz peak corresponding to a wavelength of 94 feet. Figure 40 shows the acceleration data for the A-carbody and the B-carbody. The two carbodies are moving approximately 90 degrees out-of-phase. Its frequency content is approximately 1.63 Hz. There is also a 1 Hz response of the vehicle that correlates to the 1 Hz frequency content of the lateral alignment of the track in this area.

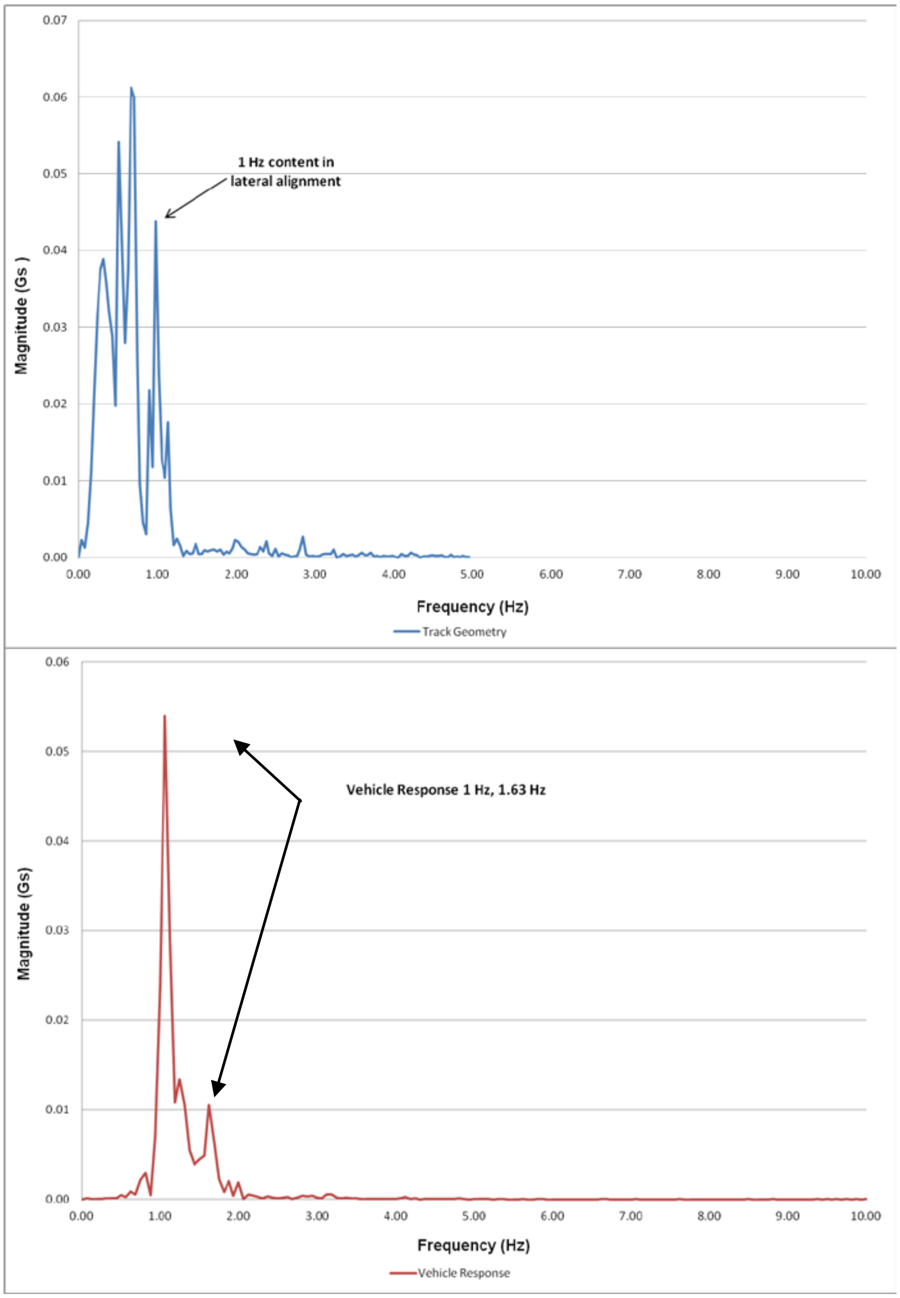


Figure 39. Frequency Content of Track Geometry (top), and Vehicle Response (bottom)

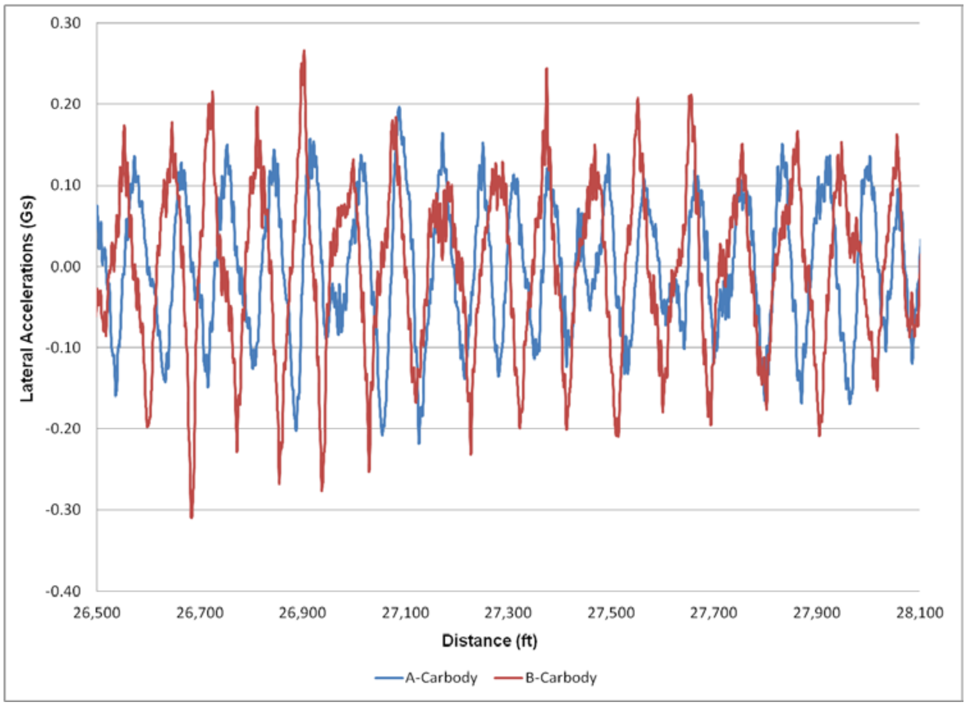


Figure 40. Yaw Acceleration Data for the A- and B-carbodies. Description of the U-shaped Yaw Vibration Mode (top)

It is possible to identify track geometry that can cause ride quality issues, such as the lateral deviations with the 94-foot wavelength between Cedars & 8th& Corinth Stations. These track misalignments cause a response in the vehicle. It is important to note that although these track geometry deviations do not exceed any safety criteria, they can affect passenger ride quality. In order to identify the track geometry issues that affect ride quality, it is imperative to take track geometry measurements at the same time as ride quality measurements.

Hunting may be triggered by a combination of lateral deviation, speed, and wheel/rail interaction. It will be important in the next phase of this project to investigate the potential triggers in more detail.

Figure 41 shows a sun kink that developed on the DART Red Line as a result of the extreme heat. Figure 42 shows the track geometry in the area. The sun kink is not evident in the measured track geometry, but it was present during the ride quality tests. The track geometry was taken at night a week after the ride quality test, and DART had already repaired it. The ride quality test does show some lateral acceleration in this area. DART was actively working to correct sun kinks as soon as possible after they occurred. This illustrates the importance of taking track geometry measurements at the same time as ride quality measurements, which will enhance the ability to correlate ride quality to track geometry.

Figure 41. Sun Kink Observed During Track Inspection

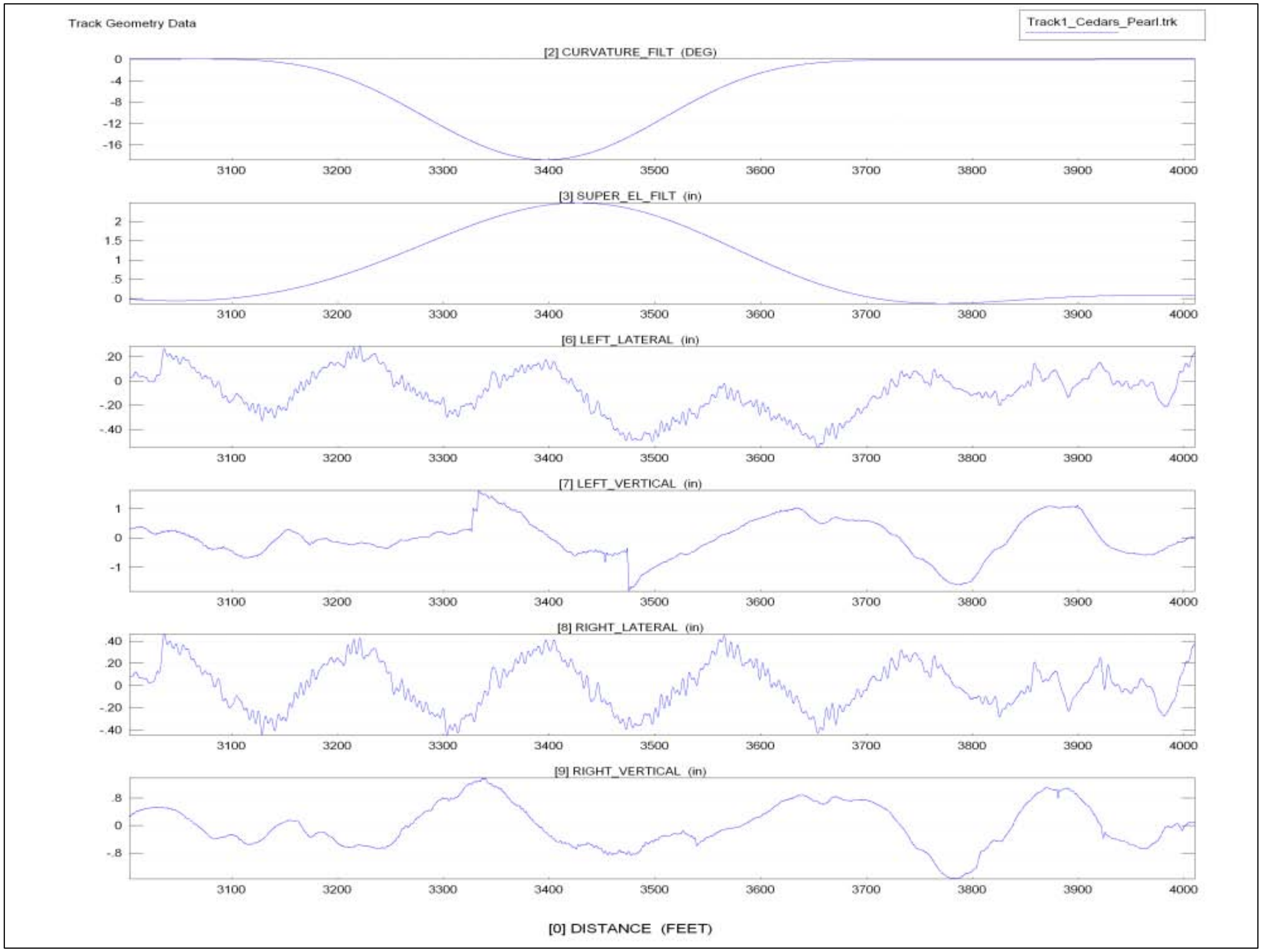


Figure 42. Measured Track Geometry in area of Observed Sun Kinks
[from top graph down—Curvature (degree); superelevation, left lateral, left vertical, right lateral, right vertical (in.)]

6.0 WHEEL AND RAIL PROFILES

Wheel and rail profile shapes can have a significant effect on vehicle dynamics and ride quality. Both wheel and rail profiles were measured. Rail profiles were taken on tangent and curved track. Profiles were also taken in places a track maintenance issue was identified by DART. Figure 43 shows both wheel and rail profiles. This information was used for input to the NUCARS simulations.

Figure 44 shows the wheel on a curved rail profile. The wheel and rail profiles are very conformal, which is a normal wear condition that may lead to high contact stresses.

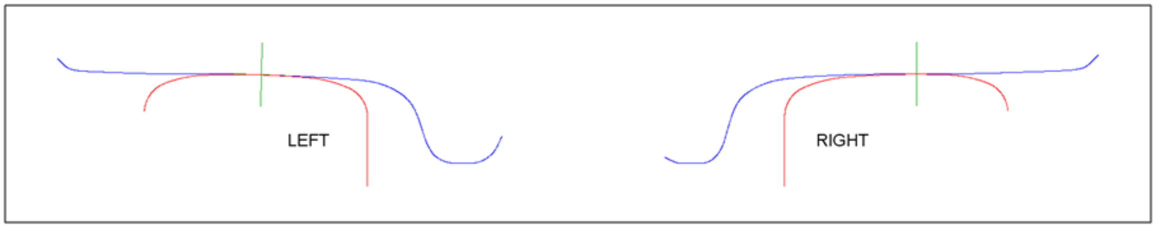


Figure 43. Wheel Profile Contacting Tangent Rail Profile

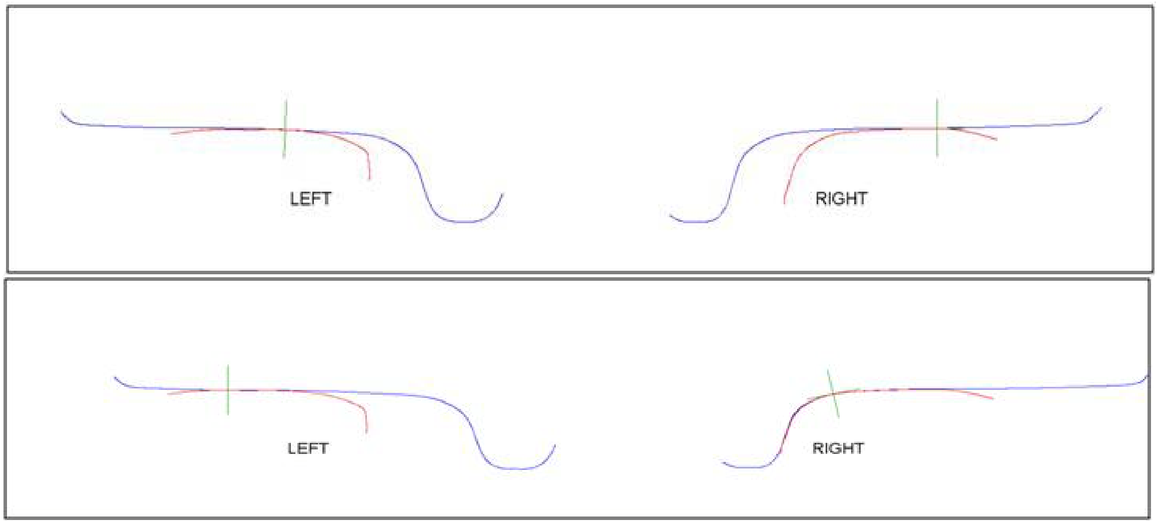


Figure 44. Wheel Profile Contacting Curved Rail Profile

7.0 NUCARS MODELING

A NUCARS model was built to represent the DART SLRV, using design data updated by the measured characteristics. The model includes a detailed representation of the articulation between the carbodies and a full nonlinear representation of the air suspension, including the effects of damping due to air flow in the orifices between the reservoirs and air bags.[7,8] The measured track geometry was used as input to the model.

7 Oda, N. and S Nishimura. 1970. "Vibration of Air Suspension Bogies and Their Design." Bulletin of the JSME Vol. 13, No. 55.
8 Berg, Mats. 1999. "A Three-Dimensional Airspring Model with Friction and Orifice Damping." Vehicle System Dynamics Supplement 33, pp. 528-539.

A simulation of the same conditions as the ride quality test was done to determine if the model accurately predicted the vehicle performance.

Figure 45 shows a plot of the actual test data and modeling results for the section of track between Cedars and 8th & Corinth stations. The plot shows data collected on the leading end of the vehicle. The accelerometer was placed on the floor under the operator's seat. In the NUCARS model, representative wheel and rail profiles were used. The NUCARS model predicted the same general trend as the actual ride quality data. The model showed the yaw response subsided more quickly than the test data. The model also under predicted the lateral acceleration amplitude in this area.

Figure 46 shows the vertical accelerations of the test and the model. The model accurately predicted the trend of the acceleration, but under predicted the amplitude.

Figure 47 shows the frequency content of the model and test data where yaw response/hunting occurred. Both the model and the test had a response at 1 Hz. This is a result of the 1 Hz frequency content in the lateral alignment. However, the model did not have the frequency response of 1.63 Hz.

The difference between the model and the test data may be due to a number of issues that will require further investigation. In the model, representative rail profiles were used in the curve and tangent. Wheel/rail interface issues may contribute to the response seen in the test. It will be necessary to use different rail profiles to determine the effect of the wheel/rail interface. In the carbody resonance test, the u-shaped yaw mode was not excited. It is evident in the ride quality test that it was excited. It will be important to review the model and update the parameters to assure the correct frequency can be simulated in the eigenvalue analysis.

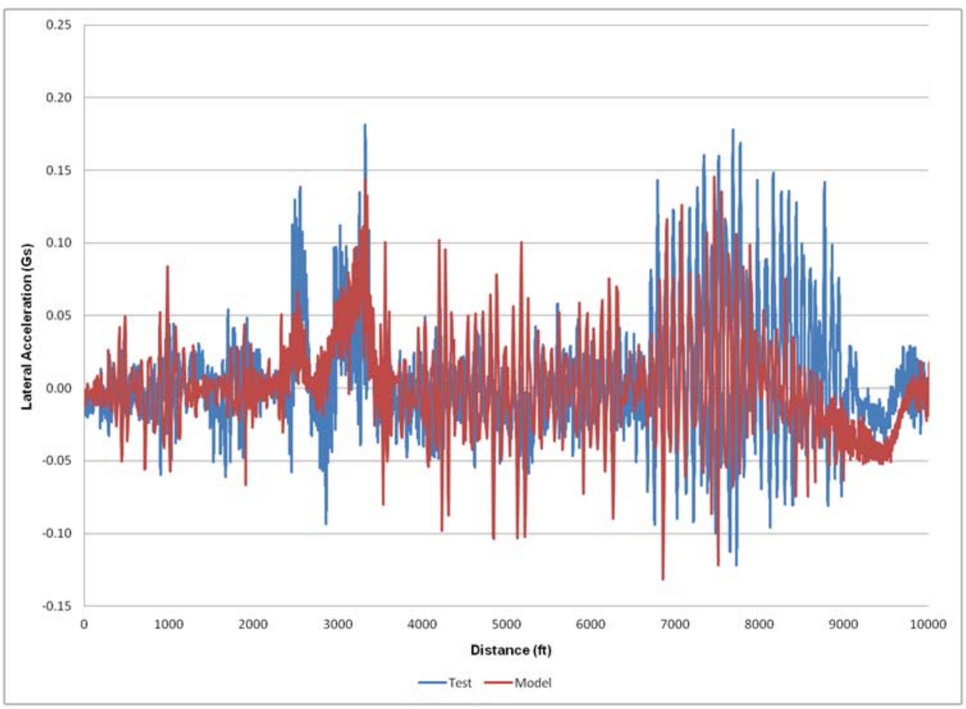


Figure 45. Measured Lateral Accelerations Compared to Predicted Lateral Accelerations

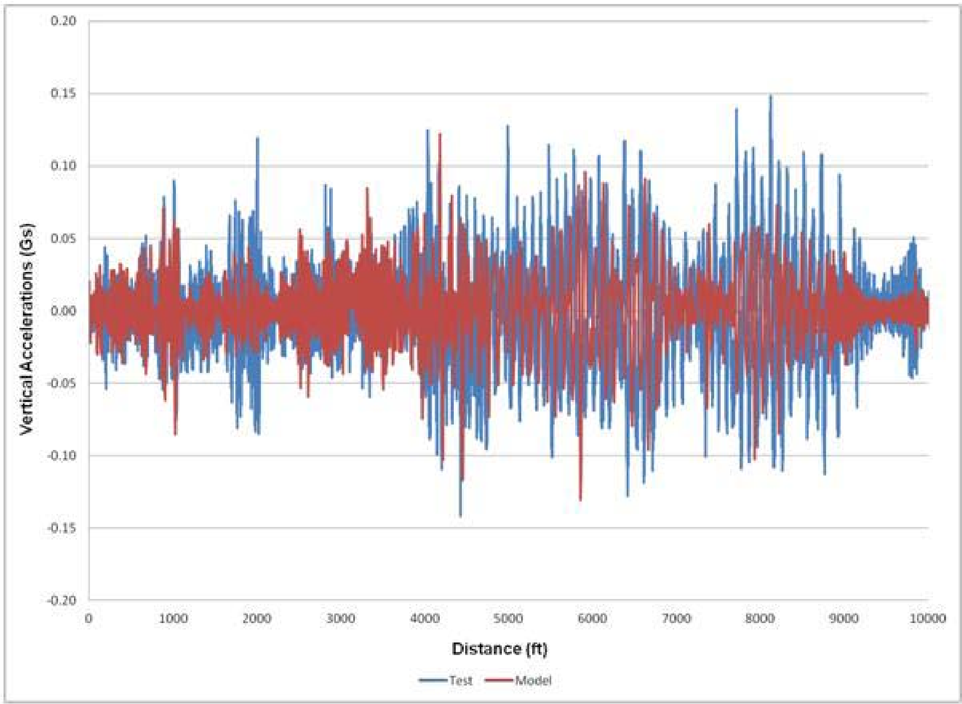


Figure 46. Measured Vertical Accelerations Compared with Predicted Vertical Accelerations

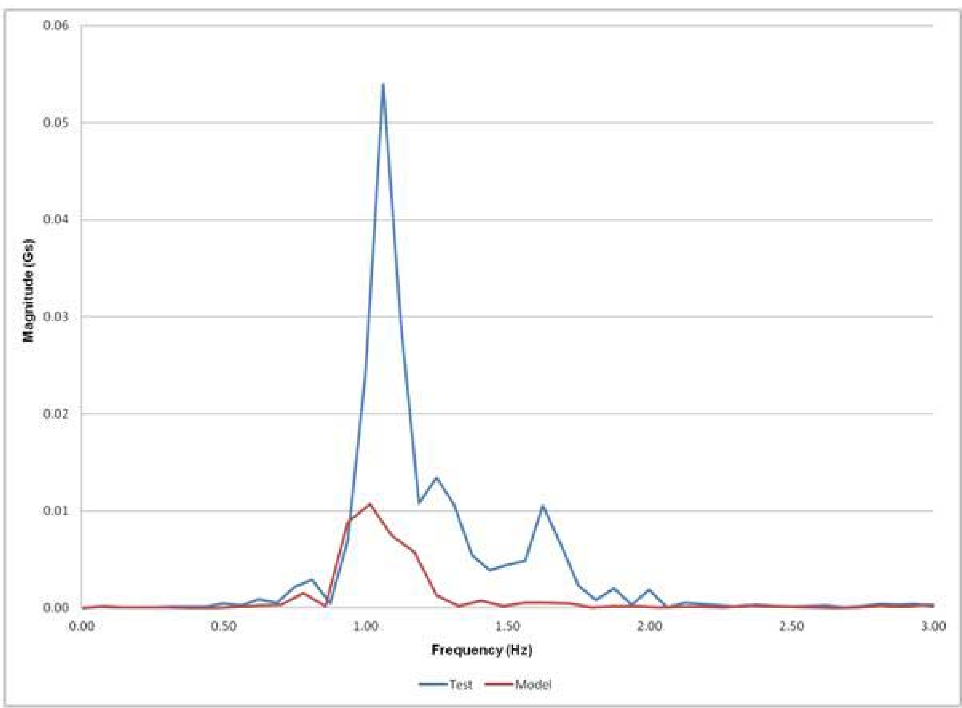


Figure 47. Measured Frequency Content Compared with Predicted Frequency Content

8.0 CONCLUSIONS

8.1 Ride Quality Standard Literature Review

All the ride quality standards reviewed in this study require similar measurements. TTCI identified the following measurements to be made in order to quantify the relationship between track geometry and ride quality:

1. Tri-axial accelerometers located
    a. Over bogie centers (both ends of vehicle)
    b. Center of vehicle
    c. Floor in operator's cabin
2. Lateral accelerometers located
    a. Each axle of bogie so yaw can be calculated and location of curve accurately pinpointed
3. Roll rate gyrometer

Based on the literature review, TTCI recommended that ride quality during the tests be calculated using ISO 2631, which was reviewed in the literature survey. The data was filtered post-process for ISO 2631.

8.2 Vehicle Characterization Testing

TTCI has often found that actual vehicle characteristics as assembled vary considerably from the published design and measured individual components. In order to ensure an accurate NUCARS model of the DART SLRV, tests were conducted to measure suspension characteristics and carbody inertial and resonance characteristics. All testing was performed on DART property located in Dallas, Texas. DART's operating conditions provided a variety of track structures and a wide range of operating speeds. DART's SLRV was used for testing. The SLRV is a three-section vehicle that can accommodate up to 150 seated and standing passengers.

Testing included the following:

- Characterization of the elastic elements of the primary and secondary suspension
- Determination of the center of gravity of the railcar
- Determination of the resonance frequencies of rigid body degrees of freedom of the railcar

The measured values for some of the suspension characteristics varied from the manufacturer's specifications; e.g., manufacturer specifications were given for a single component, but when the component is part of a suspension system, the effective stiffness may vary. All of the measured values were used to update the NUCARS model to represent the test vehicle as accurately as possible.

8.3 Track Geometry Measurements

Track geometry measurements were taken by Holland on August 13-14, 2010 on DART Red Line for southbound and northbound track. No measurements were taken in the DART tunnel (between Pearl and Cityplace) because of a size restriction in the tunnel.

Data from a previous track geometry run were used for the tunnel. The tunnel has direct fixation track; and therefore, it was assumed that track geometry changes in the time since the previous run were negligible.

8.4 Ride Quality and Track Geometry Comparison

A major objective of this research was to determine if there was a correlation between ride quality and track geometry. Places on the Red Line that had ride quality issues were identified from the ride quality test performed.

The southbound section of track between Cedars and 8th & Corinth stations was uncomfortable with a ride quality index of 1.056. This section of track contained lateral alignment deviations with a wavelength of 94 feet, which corresponds to a frequency of 1 Hz at the speed the train was running. This resulted in a vehicle yaw response of 1 Hz, clearly indicating a correlation between track geometry and vehicle response. It is important to note that although these track geometry deviations did not exceed any safety criteria, they clearly affected passenger ride quality. In order to identify the track geometry issues that affect ride quality, it is imperative to take track geometry measurement at the same time as ride quality measurements.

These results indicated it should be possible to identify the effect of track geometry deviations on vehicle ride quality response during Phase II of this project. However, there is still some work required to improve the vehicle model to correctly predict this response. Identifying the influence of the following factors on vehicle response will be important to accurately model and determine track geometry triggers:

- Wheel/rail interface, including profile shapes and contact geometry
- Vehicle speed
- Understanding and identifying rigid body vibration modes of the vehicle

This work will be continued in Phase II.

9.0 WHAT IS NEXT: PHASE II

The results of Phase I indicate it should be possible to identify the effect of track geometry deviations on vehicle ride quality response during Phase II of the project. However, there is still some work required to improve the vehicle model to correctly predict this response. Identifying the influence of the following factors on vehicle response is important to accurately model and determine track geometry triggers:

- Wheel/rail interface including profile shapes and contact geometry
- Vehicle speed
- Understanding and identifying rigid body vibration modes of the vehicle

After all the issues have been investigated, the track geometry and ride quality data collected during Phase I at DART will be used to train neural networks to predict ride quality. The validated DART vehicle NUCARS model will be used to run simulations at different speeds to generate additional neural network training data. The neural networks will then be used to predict ride quality over measured track not used in the training. The neural network output will be compared to NUCARS simulation predictions and measured ride quality to determine the accuracy of the neural network predictions.

If neural networks are determined to be a viable option for predicting ride quality, a different vehicle on a different transit system will be selected for additional investigation. Vehicle characterization and ride quality testing will be performed on the selected vehicle, and the data will be used to train and validate neural networks for the selected vehicle/system.

ACKNOWLEDGMENT

The authors thank DART for supporting the PBTG project, especially R.K. Rogers (assistant vice president, technical services), Michael Holbrook (senior manager, track & ROW), Darryl E. Spencer (director, fleet engineering), and Ron Foster (manager, rail fleet). TCRP D-7 panel members are Anthony Bohara, Steven Abramopaulos, Michael O. Brown, Michael K. Couse, James Dwyer, William H. Moorhead, Jeffrey G. Mora, James Nelson, Jerome M. Nery, Terrell Williams, Anne D. Aylward, Louis F. Sanders, Ann Purdue, and Stephan A. Parker (senior program officer). Dingqing Li is the TTCI TCRP program manager.

APPENDIX

RIDE QUALITY LITERATURE REVIEW

TCRP D-7 Track Geometry and Ride Quality Research

By C.D. Ketchum, Transportation Technology Center, Inc.

EXECUTIVE SUMMARY

There are many ride quality standards available to assess passenger comfort on trains. Transportation Technology Center, Inc. (TTCI) has conducted a literature survey to identify how transit authorities around the world measure and assess passenger ride quality and passenger ride comfort. While this project is primarily concerned with rail passenger ride quality, the survey also includes a review of other transport system passenger ride quality analysis techniques. The following four standards are reviewed:

1. ISO 2631 Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration
2. ENV 12299:1999 Railway applications — Ride comfort for passengers — Measurement and evaluation
3. UIC 513 — Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles
4. Sperling Index

One of the tasks of the literature review was to determine what measurements and analysis method should be used to accurately correlate ride quality to track geometry. The data collected will eventually be used to help develop a performance-based track geometry (PBTG) method to predict the effects of track geometry on ride quality.

There are many ride quality standards available to assess passenger comfort on trains. Not all issues that can affect passenger ride quality are addressed by the standards reviewed. Discrete events will be important in correlating track geometry to ride quality.

All the ride quality standards reviewed in this study require similar measurements. TTCI suggests the following measurements be made in order to quantify the relationship between track geometry and ride quality.

- Tri-axial accelerometers located
    a. Over bogie centers (both ends of vehicle)
    b. Center of vehicle
    c. Floor in operator's cabin
- Lateral accelerometers located
    a. Each axle of bogie (so yaw can be calculated and location of curve accurately pinpointed)
- Roll rate gyrometer

Ride quality will be calculated using all of the standards reviewed in this document. The data will be collected at a filter rate high enough to accommodate all calculation methods. The data will be filtered post-process for each method. This will help determine the best way to relate ride quality to different segments of track such as long tangents, curve entry/exit, embedded track, or separate right of way.

A1.0 INTRODUCTION

Typical track geometry design and maintenance standards address acceptable geometric restraints based on past safety acceptance levels, but disregard overall performance of various vehicle types and acceptable passenger ride quality standards. In support of the Transit Cooperative Research Program D-7 research program, TTCI is investigating the effect of current track design, geometry, and maintenance standards that will account for vehicle performance and passenger ride quality using a combination of PBTG and NUCARS®[9] modeling techniques.

In Phase I of this work, TTCI has conducted a literature survey to identify how transit authorities around the world measure and assess passenger ride quality and passenger ride comfort. Although this project is primarily concerned with rail passenger ride quality, the survey includes a review of automobile passenger ride quality analysis techniques. Part of the challenge of this research is to address passenger ride quality and comfort for transit authorities from tram systems on street level operations to typical intercity rail transportation. Therefore, this research is intended to encompass a wide range of possible conditions related to passenger ride quality.

This report discusses four common ride quality standards. It highlights similarities and differences among the four.

A2.0 BACKGROUND

A2.1 Components of Ride Quality

Ride quality is a dynamic characteristic of a rail vehicle. It is the effect of the ride environment on the passenger. The following factors can affect passenger perception of ride quality:

- Vibration — Human feelings vary with frequency of vibration even if the amplitudes are equal. A frequency weighting factor is used to evaluate ride comfort.
- Transient motions transmitted from the vehicle to the passenger and crew
- Lighting
- Temperature
- Humidity
- Noise Level — Noise generated by the vehicle, wheel/rail interface, discrete events

There are many standards available to analyze ride quality. Most standards address vibration measurements and effects. This study focuses on vibration and transient motions that are related to track inputs.

According Forstberg,[1] human reaction to the dynamic characteristics can be divided into different categories:

- Average ride comfort level — based on translational accelerations in longitudinal, lateral, and vertical directions with a frequency interval from 0.5 to 80 Hz. The comfort level can be evaluated by different scales, which are provided by ride quality standards such as Sperling, ISO 2631, and ENV 12299.
- Estimated ride comfort — based on how human subjects rate the ride comfort.

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*NUCARS is a registered trademark of Transportation Technology Center, Inc.

- Comfort disturbances due to motions such as high horizontal acceleration, jerks, and jolts. These disturbances can be due to discrete events that may have both high- and low-frequency content. Discrete events may occur due to transition through a turnout, alignment irregularity, or the combined effect of high lateral forces in circular curves and track irregularities. Comfort disturbances may also result from high lateral acceleration or lateral jerks while negotiating transition curves.
- Motion sickness or kinetosis is due to prolonged exposure to low-frequency translational and angular motion. The frequency content related to motion sickness is usually less than 0.5 Hz.

A2.2 Factors Affecting Ride Quality

The following parameters can affect the motion-caused components of ride quality:

- Vehicle suspension — The properties of the vehicle suspension affect the frequency and magnitude of vibration the passenger may feel
- Vibration properties of the vehicle/passenger interface
  - Seat, tables, floor
- Wheel/rail contact properties — These contact forces are nonlinear functions of displacement and velocity can produce vibrations in the vehicle
- Wheel condition — wheel flats (generate inputs)
- Vertical and lateral track misalignments
- Degree of curvature and cant deficiency
- Rail corrugations
- Superelevation or cross level (Track Cant) irregularities
- Gauge irregularities
- Transition curves and superelevation ramps (spirals)
- Rail joints, welds
- Turnouts
- Stiffness transitions (bridges)

Vibration is transmitted to the passenger through interfaces such as floor, seat, and tables depending on the position of the passenger. Whole-body vibrations are quantified using the basicentric axes of the human body. Figure A1 shows the axes.[2] Table A1 summarizes the passenger interfaces.

Table A1. Passenger/Vehicle Interfaces

Position	Interface
Standing	• Floor/feet
Seated	• Seat-supporting surface • Seat back • Floor/feet
Recumbent	• Surface supporting the pelvis, back, and head

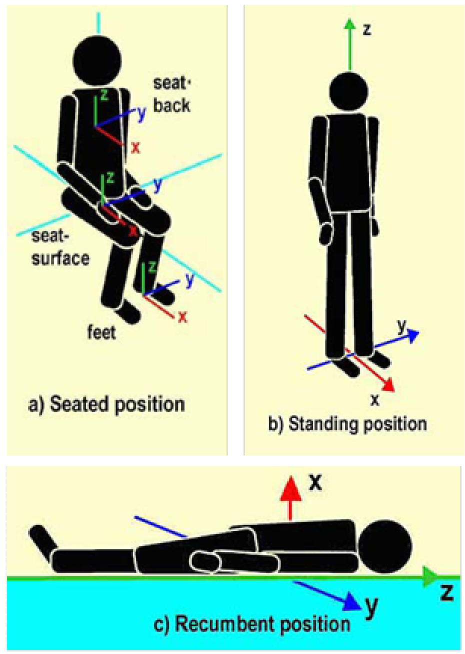


Figure A1. Basicentric Axes of the Human Body

A3.0 STANDARDS

There are many standards available for quantifying ride quality. This report is not all inclusive. In this literature review several of the predominately used standards are presented.

A3.1 ISO 2631 Mechanical Vibration and Shock — Evaluation of Human Exposure to Whole-body Vibration [2,3,4] (Cross-reference ANSI S2.72)

ISO 2631 is well recognized and widely used to quantify ride quality. The standard defines methods for quantifying whole-body vibration and effects on human health and comfort, probability of vibration perception, and incidence of motion sickness. The following types of vibrations are covered in this standard:

- Periodic vibration is oscillatory motion whose amplitude pattern repeats after fixed increments of time.
- Random vibration is instantaneous and not specified at any instant of time.
- Transient vibration is short duration and caused by mechanical shock.

Frequency content, direction, and amplitude of the vibration determine the effect on the passenger. Frequencies of the same amplitude will have different effects on passenger comfort and health. Frequency weightings are required to correctly correlate vibration content to ride quality. Different frequency weightings are used for different axes of vibration. Frequency weighting curves have developed over years with experiments using human subjects. Figure A2 shows the ISO 2631 frequency weightings.

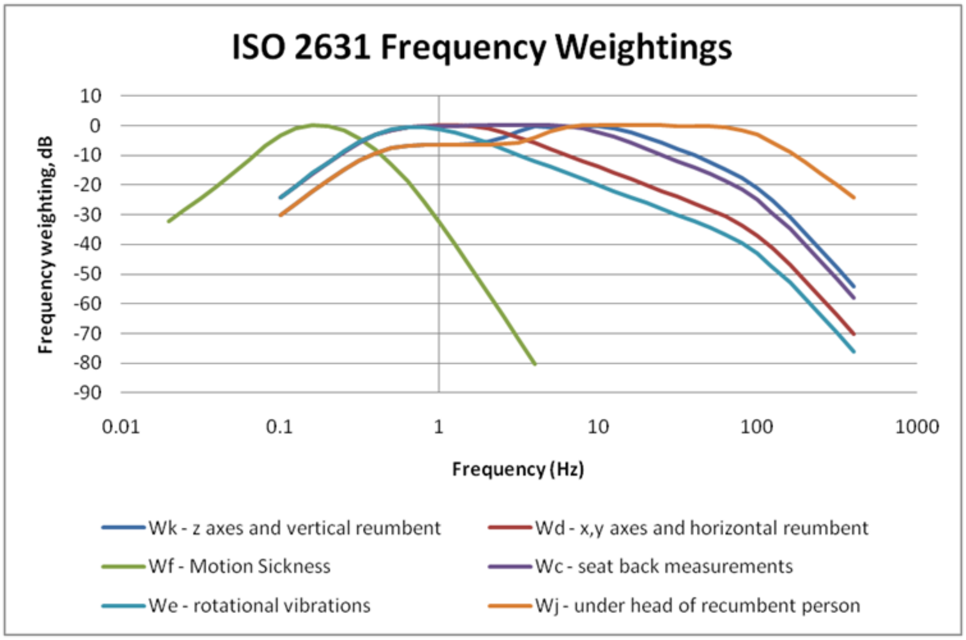


Figure A2. ISO 2631 Frequency Weightings

For example, the frequency weighting for motion sickness (W_f) shows that the lower frequency vibrations have greater potential to cause motion sickness.

ISO 2631 provides several analysis methods for measured accelerations. The following is a summary of the methods and details can be found in Appendix AA.

- Basic method is used for a general evaluation of ride quality. If a more in-depth analysis is required, one of the other methods should be used. A weighted root-mean-square (RMS) acceleration method is used when the crest factor is less than 9.
  - Crest factor is the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its RMS value
- Running RMS method is used to evaluate vibration with occasional shocks and transient vibration.
- Fourth power vibration dose method is more sensitive to peaks.

Once the weighted acceleration has been calculated, the ride quality effects on health, comfort perception, and motion sickness can be determined. Figure A3 shows vertical vibration exposure criteria curves defining fatigue decreased proficiency boundaries. ISO 2631 provides contours, as Figure A3 shows, for ride quality measures including reduced comfort, fatigue decreased proficiency, and exposure limit. The weighted acceleration can be plotted on the graph to determine if ride quality exceeds the health and comfort boundaries.

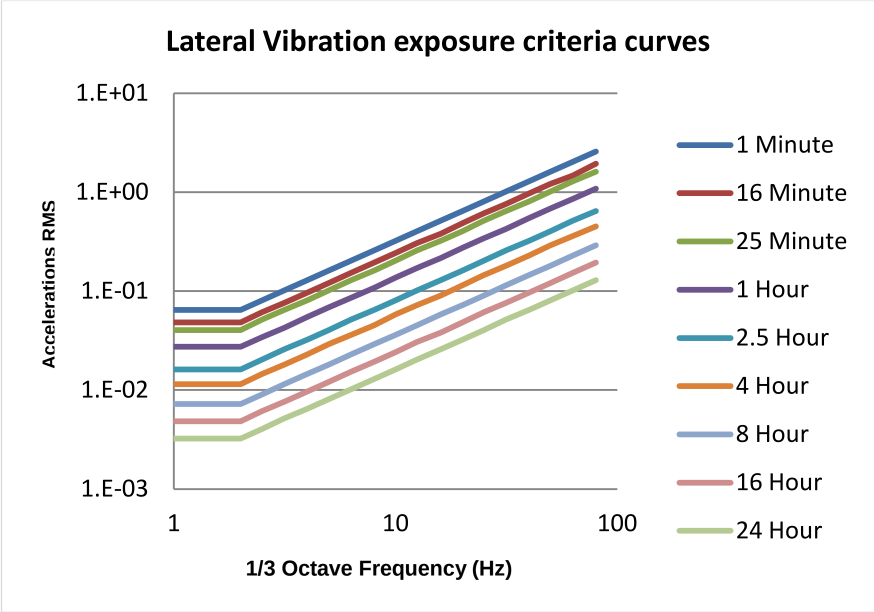


Figure A3. Lateral Exposure Criteria Curves showing Reduced Comfort Boundaries

Table A2 shows how the weighted accelerations are related back to passenger comfort perception. There are two ways provided by the standard to quantify passenger comfort level.

1. A single number can be calculated for the vibration magnitude and related directly to a passenger comfort level described in Table 2.
2. The weighted RMS value of acceleration can also be plotted against the boundaries shown in Figure A3. See Appendix AA for details on the calculation of a_w. This allows the analyst to determine which frequency ranges of vibration are contributing most to the ride quality.

Table A2. Vibration Magnitude and Corresponding Comfort Level

Vibration Magnitude (meters/second^2)	Comfort Level
$a_w<0.315$	Not uncomfortable
$0.315 \le a_w < 0.63$	A little uncomfortable
$0.5 \le a_w < 1$	Fairly uncomfortable
$0.8 \le a_w < 1.6$	Uncomfortable
$1.25 \le a_w < 2.5$	Very uncomfortable
$a_w \ge 2$	Extremely uncomfortable

A3.1.1 Required Measurements

It is important to take measurements at the passenger interfaces. Measurements should be carried out at both ends and at the middle of the test vehicle. For a double-decker (multilevel) vehicle, measurements should be taken on both upper and lower decks (all levels).[4] ISO 10056 Mechanical vibration – Measurement and analysis of whole-body vibration to which passengers and crew are exposed in railway vehicles[5] is a supplement to ISO 2631 that describes ride quality measurements on a railway vehicle in detail.

Vibration accelerations can be characterized by translational and rotational components. However, in this standard it was assumed that for rotational vibration the center of rotation is large enough to consider the vibration as translational. Therefore, the physical parameters usually measured are the translational accelerations at the passenger interfaces.

Table 3 shows the equipment, measurement locations, and measurement directions needed to accurately measure accelerations.

Table A3. Summary of Measurement Requirements

<table>
<tr><th>Equipment</th><th>Measurement Locations</th><th>Measurement Directions</th><th>Notes</th></tr>
<tr><td>• Accelerometers
• Filters (band limitation and frequency weighting)
• Data Recorders</td><td>• Floor
– Over bogie centers
– Center of vehicle
– Vestibule floor (optional)
• Seat
– On and under seat at center of vehicle
– Both ends of vehicle (optional)
• Operator’s Cabin
– Near where seat is mounted
NOTE: Accelerometers should be mounted on the floor as close as possible (less than 100 millimeters if possible) to the vertical projection of the center of the seat pan, and on the vestibule floor when studying the standing position for local transport.</td><td>X-axis – longitudinal, along the direction of travel
Y-axis – Lateral at right angle to direction of travel
Z-axis – vertical, upwards perpendicular to floor</td><td>Measurements shall be collected for a duration of no less than 20 minutes, divided into representative sequences of 5 minutes each to assure statistical significance</td></tr>
</table>

A3.1.2 Report Format

ISO 10056[5] specifies that the following information shall be reported:

- Basic Aim of the test
- Evaluation Methods
- Test Conditions
    - Description of vehicle
        - Vehicle (railcar, coach, locomotive, etc.)
        - Type
        - Load Conditions

        - Structural arrangements (steel, aluminium, type of suspension, type of bogie, wheel profile)
    - Description of seat
        - Type (single, multiple, etc.)
        - Covering (synthetic, fabric)
        - Special features (arm-rest, foot-rest, foldaway table, reclined, etc.)
        - Position (in a row, face to face, location, and orientation in vehicle)
    - Description of occupant
        - In cases where the measurements are carried out at the man-seat interface, the height and mass of the occupant shall be indicated
        - Age and gender
    - Description of Track
        - Route section and geographical location
        - Type of track (gauge, sleeper type, rail-support system, rail profile)
        - Description of track quality
        - Detail of track (radius of curvature, turnouts, etc.)
    - Running Speed
        - Vehicle speeds during test
- Measurement Setup
- Measurement Results
    - Spectral Analysis
    - Statistical Results
        - RMS values of accelerations
            - Histogram and cumulative histogram
            - Width of class and number of classes
        - Evaluated statistical parameters
            - Mean value
            - Standard deviation
            - 95th percentile, etc.

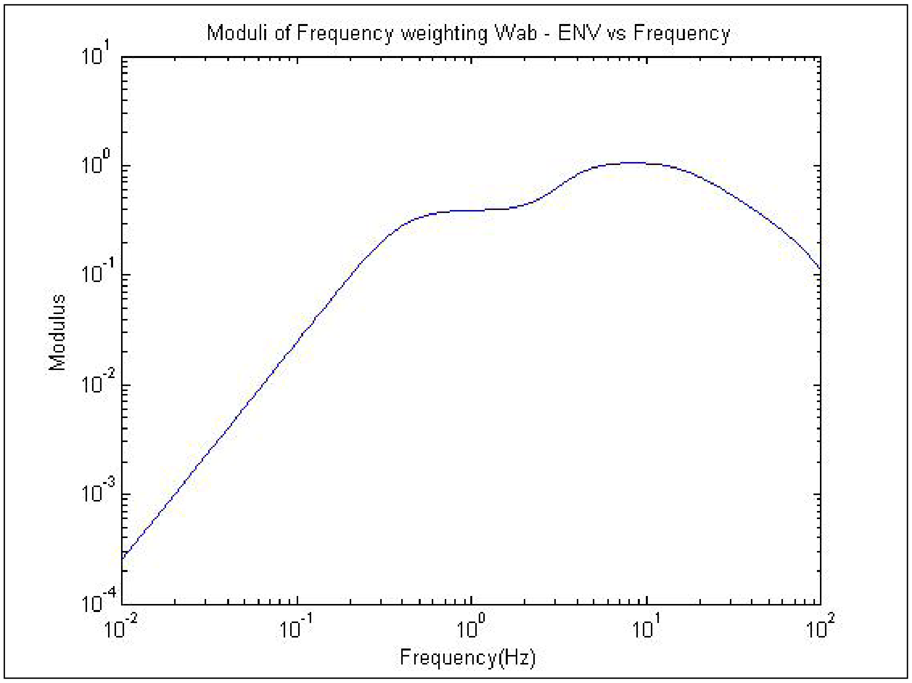
A3.2 ENV 12299:1999 Railway Applications — Ride Comfort for Passengers — Measurement and Evaluation[6]

ENV 12299:1999 is a European Standard with the status of a Swedish Standard. This standard is applied to passenger comfort influenced by the dynamic behavior of the vehicle. Discomfort associated with relatively low levels of acceleration is considered in this standard; however, health risk effects are not considered. Table 4 summarizes the applications for this standard.

Table A4. ENV 12299:1999 Railway Applications

Description	Included	Excluded
Effect of vibration	• Comfort	• Health • Activities
Transmission	• Whole body through passenger interface	• Single body part • Whole Surface • Vehicle Motion
Type of vehicle	• Railway vehicles designed for carrying passengers	• Other types of railway vehicle (e.g. locomotive)
Test Procedure	• Definitions • Reference System • Requirements • Measure and evaluation rules • Report Rules	• Limiting Values
Position of passenger	• Standing • Seated	• Lying • Performing specific actions, (e.g. writing)
Analysis Methods	• Indirect Measurements – Simplified Mean Comfort – Complete Mean Comfort – Comfort on Discrete Events – Comfort in Curve	• Direct Measurement • Combined Measurement

Figure A4 shows the frequency weightings applied in this standard.



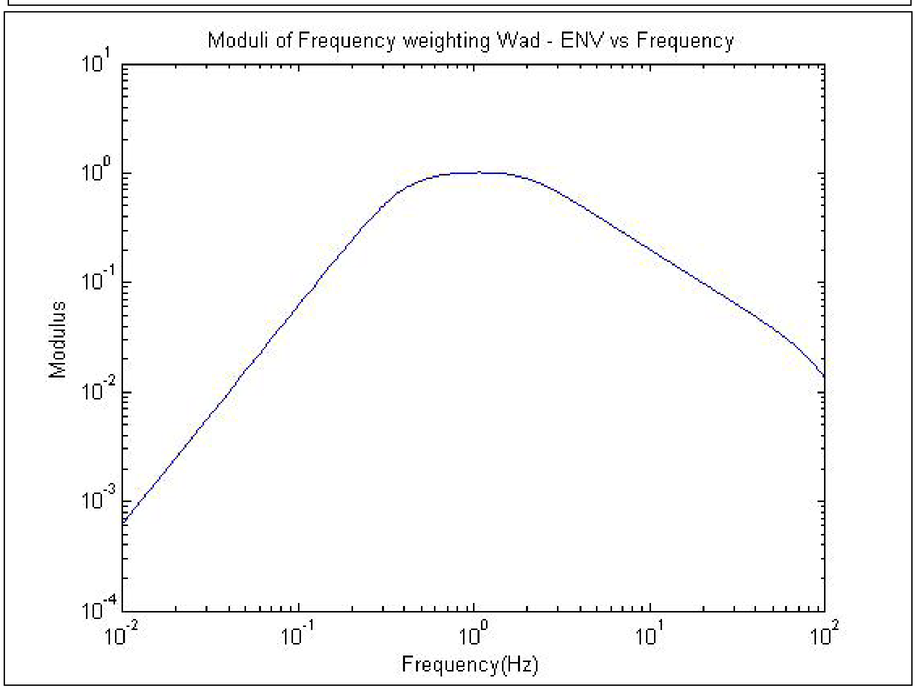


Figure A4. Frequency Weighting Curve for Weighting Factor W_{ab} and W_{ad}

Several analysis methods are provided for measured accelerations. The following is a summary of the methods, and details can be found in Appendix AB.

- Simplified Mean Comfort Method is based on measurements at the floor. This method is adequate for a general assessment of the ride quality.

- Complete Mean Comfort Method is based on measurements at the floor and seat interface. This method correlates better to passenger perception and is recommended to be used where practical.
- Comfort on Discrete Events Method is a measure of passenger comfort for individual discrete events such as local track irregularities without evaluation of cumulative effects.
- Comfort in Curves Method gives a measure of passenger comfort for an individual curve transition. It is a measure of a single event without evaluation of cumulative effects.

Once the weighted accelerations have been measured and analyzed by one of the methods above, it can be related to passenger comfort according to the scale shown in Table 5. The scale is only for the passenger comfort index calculated using the simplified or complex method. There is no scale for discrete events or curves. As a rule, the larger the discrete event values are, the poorer the ride quality. Appendix AC contains details of calculating comfort index N.

Table A5. Comfort Index Correlated to Passenger Perception

Comfort Index	Passenger Perception
$N<1$	Very Comfortable
$1\leq N<2$	Comfortable
$2\leq N<4$	Medium
$4\leq N<5$	Uncomfortable
$N\geq 5$	Very Uncomfortable

A3.2.1 Required Measurements

Translational accelerations are measured at the floor and interface between the passenger and the seat to quantify mean passenger comfort. Measurements should be taken in the center and at both ends of the vehicle. For a double-decker (multilevel) vehicle, measurements should be taken on both upper and lower decks (all levels) in the center of the vehicle.

Comfort in curve transitions is quantified by measuring lateral accelerations, carbody roll, speed, and tilting angle if applicable. Comfort on discrete events is quantified by measuring lateral accelerations and speed. The measurements are taken at the following locations for both curve transitions and discrete events:

- Center of carbody floor
- Above leading and trailing bogies
- Axle box lateral accelerations

A3.2.2 Report Format

The test report should include the test specification, the characteristics of the tested vehicle, the track characteristics, and a precise description of the actual test conditions; include necessary measurements, statistical results, and evaluation of comfort.

A3.3 UIC 513 Guidelines for Evaluating Passenger Comfort in Relation to Vibration in Railway Vehicles[7]

UIC 513 can be applied to vibrations normally encountered in the railway environment. This standard provides recommendations on measurements, analysis, and evaluations of vibrations to quantify passenger comfort. The evaluation of vibration comfort is based on the relationship, obtained over 5-minute periods, between the accelerations measured in the vehicle and the average of the vibration comfort ratings given by a representative group of passengers.

The evaluation methods in this standard are based on the following:

- Low level vibration
- Large part of energy contained below 3 Hz
- Physiological weightings have been made in particular in the frequency range of 0.5 to 5 Hz.
- Translational measurements are made at standard points of the vehicle and seat. Rotational accelerations are not measured because a minimal contribution to passenger comfort is assumed.
- Statistical evaluation method is based on the correlations between objective measurements and subjective impressions of passengers.
- Statistical evaluation is made with weighted RMS values calculated over 5-second periods.

Two methods of evaluation are presented in this standard.

1. Simplified method is based solely on the accelerations measured at the floor level.
2. Fuller method is based on accelerations measured at the floor level, seat pan, and seat back.

The measurements are conducted with two test persons weighing 114.64 pounds (52 kilograms) and 198.42 pounds (90 kilograms) to represent 5th percentile of women and the 95th percentile of men respectively. The test may also be conducted with two persons weighing 154.32 pounds (70 kilograms) each representative of the 50th percentile.

Once the weighted accelerations have been measured and analyzed according to one of the methods above, a comfort level can be determined according to the scale shown in Table 6.

Table A6. Comfort Index and Passenger Perception

Comfort Index	Passenger Perception
N<1	Very good comfort
1≤N<2	Good comfort
2≤N<4	Moderate comfort
4≤N<5	Poor comfort
N≥5	Very poor comfort

The weighting curves for UIC 513 are the same as those used in ENV 12299 (shown in Figure A4).

A3.3.1 Required Measurements

Translational accelerations are measured at the floor and seat/person interfaces. Measurements should be taken at the center and at both ends of the vehicle. For a double-decker (multilevel) vehicle, measurements should be taken on both upper and lower decks (all levels) in the center of the vehicle, and at each end of the lower deck. More measurement points may be selected depending on the objective of the test. Accelerometers, conditioning amplifier and filters, and data recorders will be needed to record specified measurements.

A3.3.2 Report Format

The following information should be reported according to UIC 513:

- Subject of the test
- Method of evaluation
  - Simplified
  - Full
- Test conditions
- Description of vehicle
  - Type of vehicle (motor car, passenger coach, locomotive, etc.)
  - Vehicle loading conditions
  - Structural details (steel, aluminium, type of suspension, etc.)
  - Wheel profiles and actual conicity
- Description of seat
  - Type
  - Covering
  - Special features
  - Position
- Description of seat occupant
  - Height
  - Weight
  - Age and sex
- Description of track
  - Geographical location and kilometer points of measurement
  - Track type (gauge, type of sleeper, type of rail, etc.)
  - Description of track quality
  - Special track features (curvature, turnouts, level crossings)
- Running speed
- Measuring chain
  - Example: Accelerations, filters, recorder
- Vibration characterization
- Spectral analysis
- Statistical results
- Comfort rating

A3.4 Sperling Index[8]

Sperling Index is one of the first methods developed for quantifying ride quality and comfort in railway vehicles. The Sperling method is based on a series of studies performed by the Rolling Stock Test Department of the Reischbahn at Berlin-Brunewald in 1941. In this standard, the estimate of ride quality is an evaluation of the vehicle itself, while ride comfort is the correlation of vehicle performance to perceived passenger comfort. The equations for expressing ride quality and ride comfort are the following:

- Ride quality $W_Z = 0.896(\frac{a^3}{f})^{1/10}$

- Ride comfort $W_Z = 0.896[(\frac{a^3}{f})F(f)]^{1/10}$

  a is the peak acceleration
  f is the oscillation frequency
  $F(f)$ is the weighting factor

The Sperling Index is calculated from measured data and can be evaluated using the following scales. Table 7 shows the ride index corresponding to vehicle ride quality, and Table 8 shows the ride index corresponding to ride comfort.

Table A7. Ride Index Corresponding to Vehicle Ride Quality

Ride Index W_Z	Ride Quality
1.00	Very good
2.00	Good
3.00	Satisfactory
4.00	Acceptable for running
4.50	Not acceptable for running
5.00	Dangerous

Table A8. Ride Index Corresponding to Passenger Ride Comfort

Ride index W_Z	Comfort (vibration sensitivity)
1.00	Just noticeable
2.00	Clearly noticeable
2.50	More pronounced but not unpleasant
3.00	Strong, irregular, but still tolerable
3.25	Very irregular
3.50	Extremely irregular, unpleasant, annoying, prolonged exposure intolerable
4.00	Extremely unpleasant, prolonged exposure harmful

Both lateral and vertical accelerations are evaluated at the carbody floor in the center and at both ends of the vehicle.

Figure A5 shows the frequency weighting curves for Sperling Ride comfort index.[9]

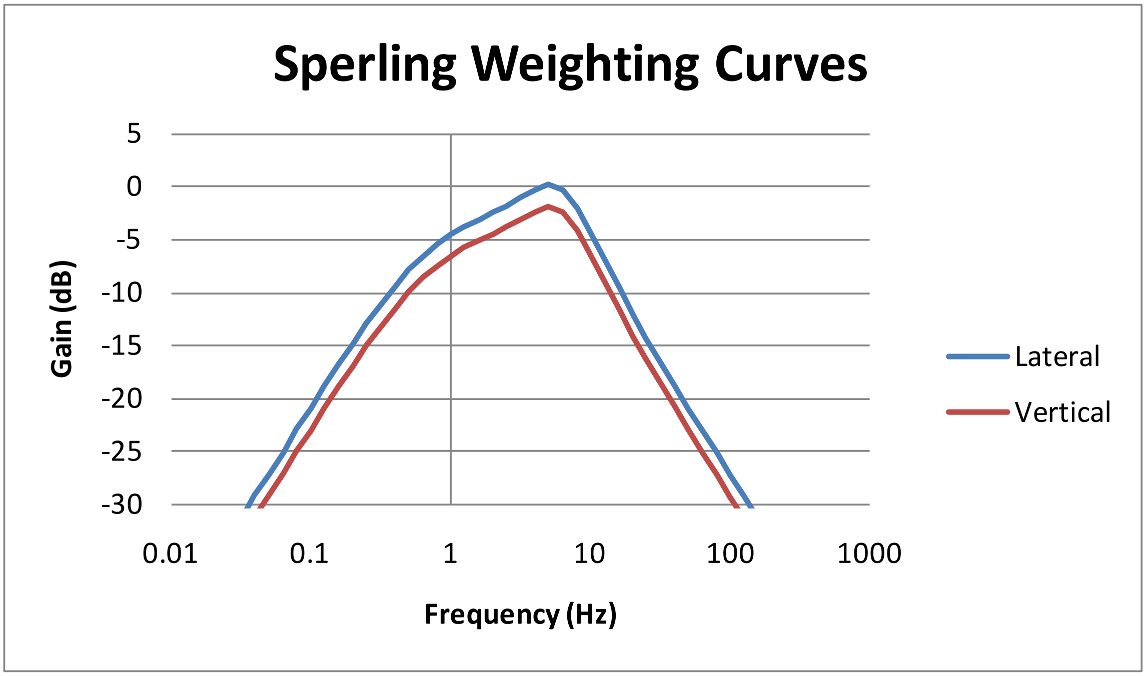


Figure A5. Sperling Frequency Weighting Curves

A4.0 STANDARD COMPARISIONS

Table 9 summarizes the standards reviewed in this literature review.

Table A9. Summary of Ride Quality Standards Reviewed

Standard	ISO 2631[2,3,4]	ENV 12299[6]	UIC 513[7]	Sperling[8]
Effect of movement	• Health (0.5 to 80 Hz) • Comfort/Perception (0.5 to 80 Hz) • Motion Sickness (0.1 to 0.5 Hz)	• Comfort (0.4 to 20 Hz)	• Comfort (0.5 to 40 Hz)	• Comfort (3-8 Hz**)
Transmission	Whole Body	Whole Body	Whole Body	Whole Body Vehicle Motion
Position of Passenger	• Standing • Seated • Recumbent	• Standing • Seated	• Standing • Seated	
Type of Vehicle	• ISO 10056 – Railway vehicles	• Railway vehicle designed for carrying passengers	• Railway vehicle designed for carrying passengers	• Railway vehicle designed for carrying passengers
Measurement Type	• Translational	• Translation • Rotational	• Translational	• Translational
Analysis Methods	• Basic Method • Running RMS method • Fourth Power Vibration Dose Method	• Simplified Mean Comfort • Complete Mean Comfort	• Simplified Method • Full Method	
Discrete Events Analyzed Separately	N/A	• Comfort on Discrete Events • Comfort in Curves	N/A	N/A
Persons	N/A	N/A	2 persons • 114.64 lb (52 kg) • 198.42 lb (90 kg)	N/A
Minimum Instrumentation Requirement	3 tri-axial accelerometers • Over bogie center • Center of vehicle • Floor in operator's cabin	3 tri-axial accelerometers • Both ends of vehicle • Center of vehicle Lateral accelerometer • Axle box accelerations Car body roll speed** Tilting angle if applicable Speed	3 tri-axial accelerometers • Over bogie center • Center of vehicle • Floor in operator's cabin	Biaxial accelerometer on vehicle floor

A5.0 STANDARDS AND PASSENGER PERCEPTION

Many passengers who commute on trains use the time read, write, or work on laptop computers. The rail vehicle, in many cases, becomes an extension of a person's office. The ability to perform some of these tasks may affect a person's perception of ride quality. Several studies have been done to assess the accuracy of standards in correlation with passenger perception.

A study was conducted on passenger trains in Sweden.[10] Vibration measurements and passenger surveys were conducted simultaneously on trains to determine the correlation between vibration and passenger activities. ISO 2631 and Sperling Ride Index were the standards used in this study to evaluate ride comfort.

Vibration measurements were taken at five locations: seat pan, backrest, floor, laptop, and table. The measurements on the laptop and table are not included in either standard, but were included to assess the vibrations at these locations. Accelerations were measured in x, y, z directions.

The passenger survey was conducted simultaneously on all trains at the same time vibration measurements were taken. The survey consisted of 30 questions divided into 6 parts:

1. General background of participants
2. Information about journey
3. Types of sedentary activities and time spent on each activity
4. Postural positions related to reported activity
5. Short typing test
6. Feeling from disturbances from noise, vibration, jerks, etc.

Evaluation of the questions did not show any significant difference between gender, age, or sitting positions in judgment of ride comfort.

An evaluation of the measured vibration using both standards showed reasonably good ride comfort. However, the passenger surveys indicated that a significant number of passengers had difficulties performing activities such as reading or working on a laptop computer. This indicates that the standards may not evaluate the effect on sedentary activities accurately. It also indicates that low levels of vibration may have an effect on passenger activities.

A similar study was conducted in India**.**[11] Vibration measurements and surveys were conducted simultaneously. The survey questions were categorized similarly to the study done in Sweden. However, the ENV 12299:1999 was used to analyze the accelerations and quantify the ride quality.

The ride quality measurements and assessment indicated a ride comfort in the medium to comfortable range. However, the surveys again indicated passengers were moderately affected by train vibrations while performing sedentary activities such as writing and working on a laptop computer. The motions that were reported to have the greatest effect were lateral vibrations and occasional jerk and vertical vibrations. The study also indicated that low levels of vibrations can affect passenger activities.

It may be necessary to look at discrete events individually to determine effects on ride quality. Some of the discrete events that may cause lateral vibration, jerk, and vertical vibrations are transition curves, turnouts, and corrugations to name a few. It will be important to quantify the vibrations caused by these events and to look at the contribution to passenger discomfort in detail.

A6.0 RIDE QUALITY AND TRACK GEOMETRY

Track geometry can affect ride quality. Typical track geometry design and maintenance standards address acceptable geometric restraints based on past safety acceptance levels, but usually disregard overall performance of various vehicle types and acceptable passenger ride quality standards. The following are parameters to consider when quantifying passenger ride quality:

- Vertical and lateral track misalignments
- Corrugations
- Cant irregularities
- Gauge irregularities
- Transition curves and superelevation ramps (spirals)
- Rail joints, welds
- Turnouts
- Stiffness transitions (bridges)

There are systems available to automatically measure track geometry and report exceptions to the safety standards. These systems give a report as to the size of defect and location, so it can be maintained as necessary. However, these systems do not usually take into account how the track geometry defects will affect passenger ride quality. Many of the current standards do not specifically quantify discrete events and relate them to ride quality.

A study on ride comfort of high-speed trains traveling over railway bridges was conducted.[12] The ride comfort was studied using the Sperling Comfort Index, and the maximum level of accelerations measured. Some of the objectives of this study are listed below:

- To investigate how rail roughness level influences ride comfort
- To investigate the influence of ballast stiffness on ride comfort
- To investigate the effects of train speed on ride comfort

A parametric study was done using a time domain model. Timoshenko beam theory was used to model the rail and bridge. Parallel damped springs and masses were used to model rail pads, sleepers, and ballast. A random, irregular vertical track profile was modeled. Figure A7 shows the vertical track profile and roughness index for each of the three different classes of track modeled. Nonlinear Hertz theory was used to model the wheel-rail contact. A 300-meter carriage type of Japan's Shinkansen (SKS) system was modeled. Three different types of suspension for this vehicle were modeled:

1. Linear primary and secondary suspension (base model)

2. Primary suspension is unchanged from base model and secondary suspension is modeled by a nonlinear rubber element
3. Primary suspension system is modeled, and nonlinear rubber springs and the secondary suspension are unchanged from the base model.

Results were calculated for train speeds from 0 to 250 miles per hour (400 kilometers per hour). Figure A6 shows the calculation procedure. Figure A7 shows track geometry deviations and roughness levels.

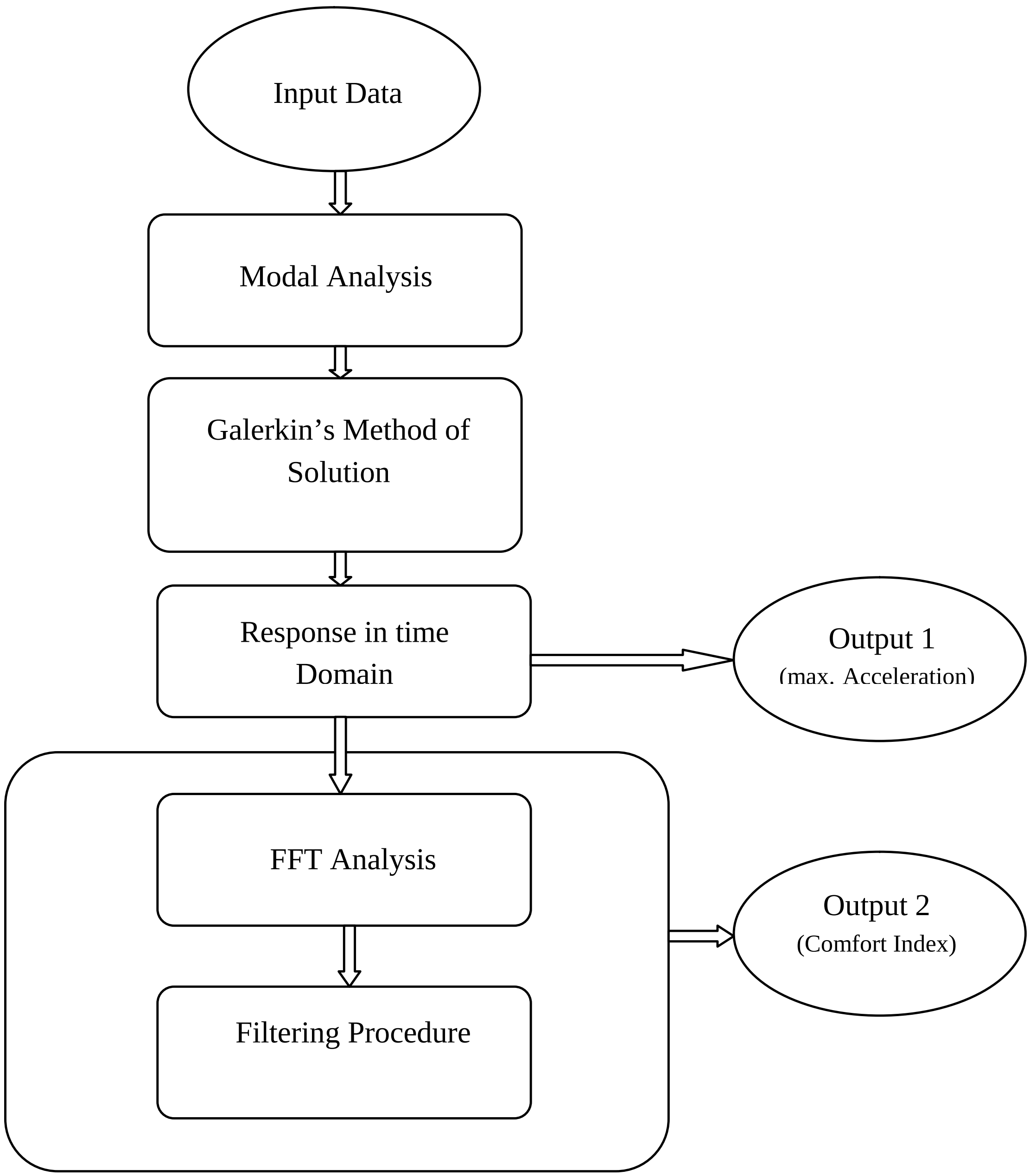


Figure A6. Calculation Procedure

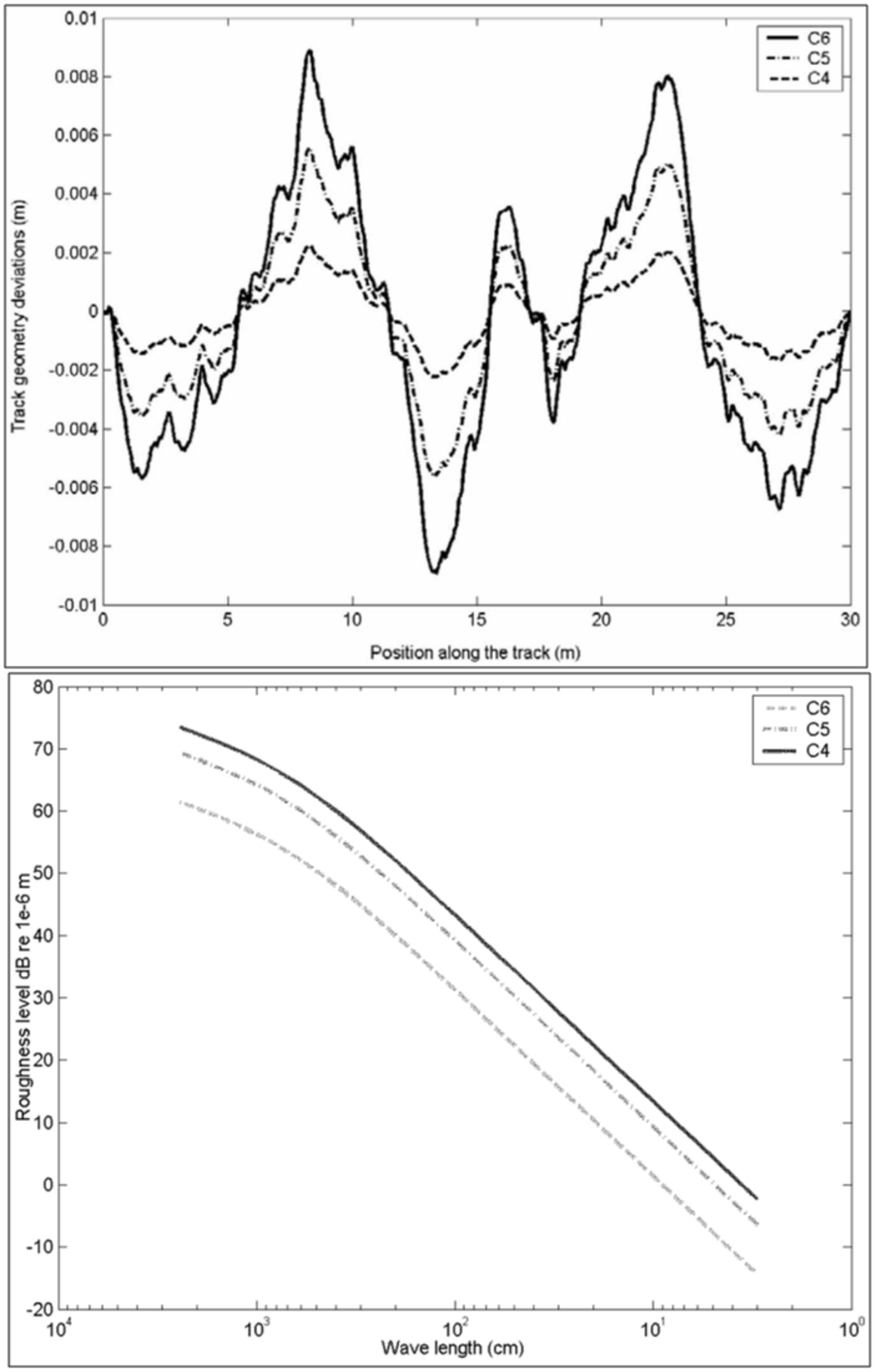
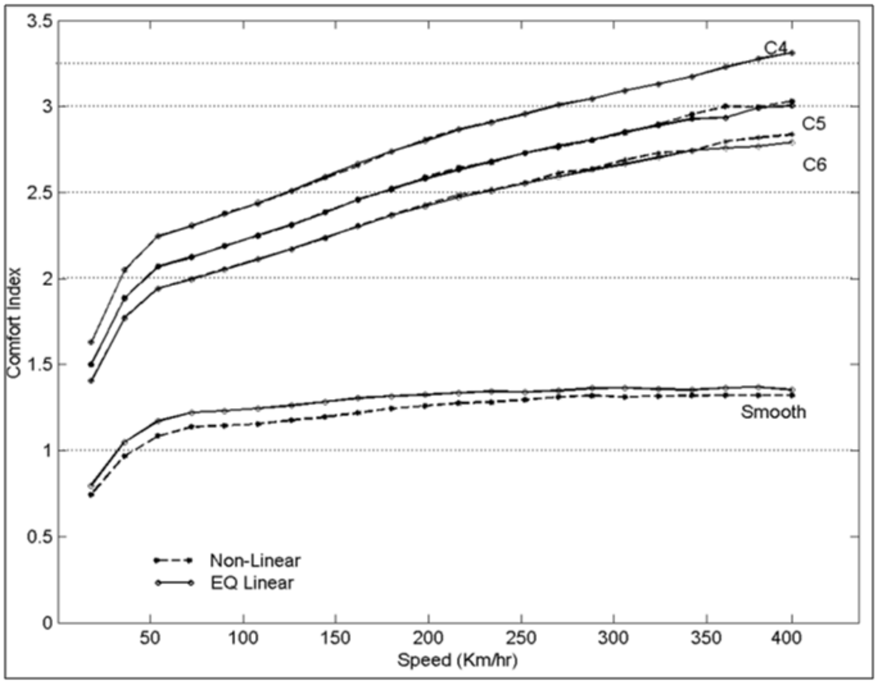


Figure A7. Track Geometry Deviations and Roughness Levels

Figure A8 shows the calculated ride comfort for different track roughness levels shown in Figure A7. For track with no irregularities (smooth), comfort index is independent of speed. However, as track roughness increases, the comfort index changes with speed. Track roughness also has a significant effect on ride quality.

Figure A9 shows comfort index related to ballast stiffness. ξ_B is the ratio between the actual ballast stiffness and the change in stiffness. The ballast stiffness has little effect on the comfort index.



FigureA8. Comfort Index Related to Track Roughness

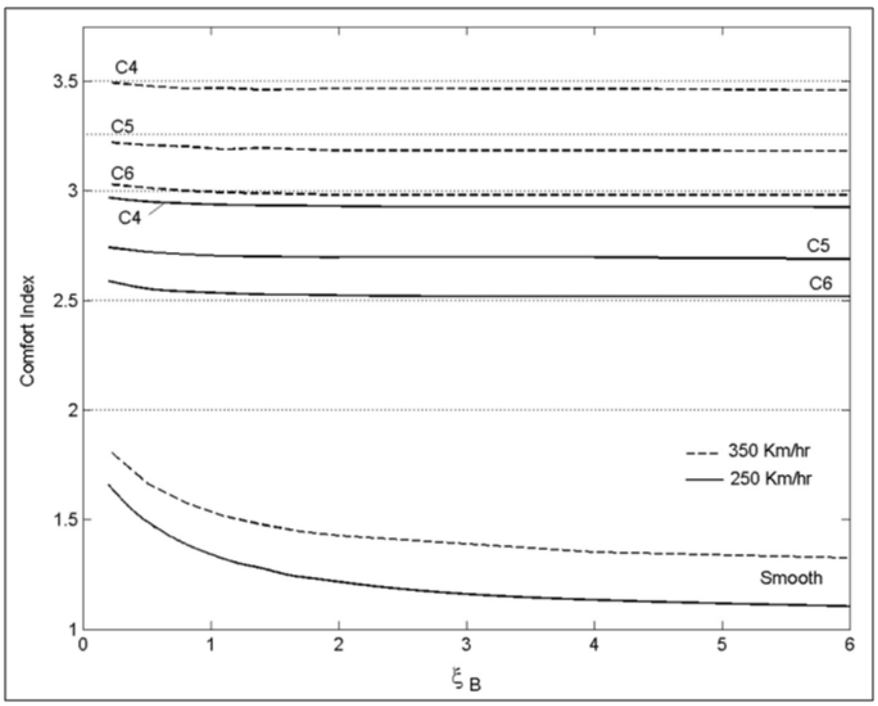


Figure A9. Comfort Index Related to Ballast Stiffness

Results of the study showed that ride comfort can be affected significantly by track roughness. Speed also has an effect on ride comfort. Ballast stiffness did not have a significant effect on track roughness.

The referenced study shows that track parameters can have a significant effect on ride quality. Most ride quality standards do not address discrete events separately. In order to understand specifically what the contributions of track roughness, corrugation, and track alignment are, it may be important to relate these specific events to ride comfort.

A7.0 OTHER TRANSPORT SYSTEMS

Other transportation modes also address ride quality and passenger comfort issues. The automotive industry also uses ISO 2631[13,14,15,16] to assess the effect of vibration on ride comfort. Studies have been done to determine the correlation between the subjective measure of passenger perception and the quantitative measure of vibration. One study indicated that overall, the correlation between fourth power method and passenger perception was good. The fourth power method is more sensitive to discrete events than the simplified or full methods in ISO 2631. This indicates the need to individually correlate discrete events to passenger comfort.

Marine transport systems also use ISO 2631 to quantify passenger comfort.[17] This transportation system is particularly interested in vibration effects on motion sickness. ISO 2631 is the only standard reviewed in this literature study that addresses motion sickness. In the study by Prince, the correlation between ISO 2631 and passenger perception was good in addressing whether or not motion sickness would occur, but not to the degree of motion sickness.

Aircraft transportation systems have recognized that airport pavement roughness does affect passenger comfort and safety during landing and takeoff.[18] The study looked at the relationship between pavement profile wavelengths and vertical vibrations. This study indicates there is a correlation between pavement profile wavelength and passenger safety and comfort. Uncomfortable and unsafe frequencies were identified. The evaluation index for highway pavement roughness, i.e., International Roughness Index (IRI), was determined to be unsuitable for this application.

Railways also have corrugations that develop in the running surface. The ride quality standards used to address railway ride comfort do not directly address the wavelength content of corrugations and the effect on passenger safety and comfort.

A8.0 CONCLUSIONS

There are many ride quality standards available to assess passenger comfort on trains. Not all issues that can affect passenger ride quality are addressed by the standards reviewed. Discrete events will be important in correlating track geometry to ride quality.

Passenger comfort is a subjective measure and the standards do not always correlate to passenger perception. This is especially true when passengers are performing sedentary activities. One reason for the discrepancy may be due to the vibrations from discrete events being averaged with the rest of the route. It may be necessary to analyze discrete events independently to get a more accurate picture of ride quality.

One of the objectives of the literature review was to determine what measurements and analysis method should be used to accurately correlate ride quality to track geometry. It will be important to quantify the overall ride quality and vibrations induced from discrete events. The data collected will eventually be used to help develop a PBTG method to predict the effects of track geometry on ride quality.

All the ride quality standards reviewed in this study require similar measurements. TTCI suggests the following measurements be made in order to quantify the relationship between track geometry and ride quality:

- Tri-axial accelerometers located
  - Over bogie centers (both ends of vehicle)
  - Center of vehicle
  - Floor in operator's cabin
- Lateral accelerometers located
  - Each axle of bogie so yaw can be calculated and location of curve accurately pinpointed
- Roll rate gyrometer

Ride quality will be calculated using all of the standards reviewed in this document. The data will be collected at a filter rate high enough to accommodate all calculations. Then, the data will be filtered according to the requirements for each method. This will help determine the best way to relate ride quality to different segments of track such as long tangents, curve entry/exit, embedded track, or separate right of way.

Bibliography

1. Förstberg, Johan. 2000. "Ride comfort and motion sickness in tilting trains." Doctoral thesis, TRITA-FKT Report 2000:28, ISSN 1103-470X, ISRN KTH/FKT/D—00/28—SE, Department of Vehicle Engineering, Royal Institute of Technology, Stockholm
2. International Organization for Standardization (ISO).1997. *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration Part 1: General requirements.* ISO 2631-1:1997 (E), Second edition corrected and reprinted 1997-07-15, Switzerland
3. International Organization for Standardization (ISO).1989. *Evaluation of human exposure to whole-body vibration Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz).* ISO 2631-2:1989 (E), First edition 1989-02-15, Switzerland
4. International Organization for Standardization (ISO).2001. *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems.* ISO 2631-4:2001 (E), First edition 2001-02-01, Switzerland

5. International Organization for Standardization (ISO). 2001. *Mechanical vibration — Measurement and analysis of whole-body vibration to which passengers and crew are exposed in railway vehicles.* ISO 10056:2001(E), First edition 2001-08-15, Switzerland
6. CEN. European Committee for Standardization. February 1999. *Railway applications — Ride comfort for passengers — Measurement and evaluation.* European Standard ENV 12299:1999 E, ICS 45.060.20, Brussels
7. International Union of Railways. 1995. *Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles.* UIC Code 513 R, 1st edition, 1.7.94, Paris, France
8. Sperling, E. and Ch. Betzhold. August 1957. "Contribution to the evaluation of comfortable running of railway vehicles." Bulletin-International Railway Congress
9. Kumar, Vivek and Vikas Rastogi. 2009. "Investigation of vertical dynamic behavior and modeling of a typical Indian Rail Road Vehicle through Bond Graph." *World Journal of Modeling and Simulation* Vol. 5 No. 2, pp 130-138
10. Narayanamoorthy, Ramasamy, Shafiquzzaman Khan, Mats Berg, Virendra Kumar Goel, V Huzur Saran, and S.P. Harsha. May 2008. "Determination of Activity Comfort in Swedish Passenger Trains," Paper 24112008 *Proceedings World Congress on Railway Research*, Seoul, Korea
11. Narayanamoorthy, R., V.K. Goel, and V.H. Saran. 2008. "Vibration Measurement — A Tool for Evaluating Activity Comfort in Trains." Research Paper 17112008, http://www.iitr.ac.in/outreach/web/CIRCIS/publication/Research%20Paper-moorthi-17112008.pdf
12. Kargarnovin, M.H., D. Younesian, D. Thompson, and C. Jones. March 2005. "Ride comfort of high-speed trains traveling over railway bridges." *Vehicle System Dynamics*, Vol. 43, No. 3, pp 173-199
13. Cann, Adam P., E. Kent Gillin, Alan W. Salmoni, Peter Vi, and Tammy R. Eger. 2005. "Transmissibility of Whole-body Vibration from Floor to Seat Experienced by Scraper Operators in the Construction Industry." http://www.nexgenergo.com/ergocenter/trends/20051305.pdf
14. Giacomin, J. and T.M. Hacaambwa. May 23-25, 2001. "Performance of ISO2631 and BS6841 Comfort Criteria for Evaluating Automobile Road Vibrations." Paper 01A1083. *ATA 7th International Conference on the Role of Experimentation in the Modern Automotive Product Development Process*, Florence, Italy.
15. Valasek, Michael, Jan Pelikan, Jaroslav Ulehla, Ondrej Vaculin, and Pavel Steinbauer. 2008. "Experimental Verification of Correlation between Objective and Subjective Evaluation of Passenger Car Vibration Comfort. *Bulletin of Applied Mechanics*, Vol. 4, Issue 15, pp 99-101.
16. Eger, Tammy, Martin Smets, Sylvain Grenier, and Vibration Research Group. 2005. "Whole-body Vibration Exposure Experienced during the Operation of Small and Large Load-Haul-Dump Vehicles." http://www.nexgenergo.com/ergocenter/trends/20051343.pdf

17. Price, Brian L., Mary Claire Froelich, Eric Pierce, Jeffrey Blankenship, Joseph LaBrecque, and Michael McCauley. 2008. “Motion Sickness Incidence (MSI) Results using Power Spectral Density (PSD) Technique.” *Proceedings International Maritime Conference,* Sydney, Australia. http://www.highspeedcraft.org/abcd.php
18. Chen, Yi-hsien and Chia-pei Chou. 2004. “Effects of Airport Pavement-Profile Wavelength on Aircraft Vertical Responses.” *Transportation Research Record: Journal of the Transportation Research Board*, No. 1889, TRB, National Research Council, Washington, D.C., pp 83-93.

Other References

19. AEA Technology Plc. June 7-8, 2004. “Derailment Prevention and Ride Quality.” Competitive and Sustainable Growth Programme, Light Rail Thematic Network, Prague, Czech Republic. <www.libertin.info>
20. American Public Transportation Association. 2007. “Standard for Definition and Measurement of Wheel Tread Taper.” 17. APTA SS-M-017-06, Volume V-Mechanical.
21. Andersson, Evert, Anneli Orvnäs, and Rikard Persson. August 2009. “On the Optimization of a Track-Friendly Bogie for High Speed.” *Proceedings of the 21st International Symposium on Dynamics of Vehicles on Roads and Tracks*, IAVDS'09, Stockholm.
22. Australian Rail Track Corporation Ltd. April 2007. *ARTC Track and Civil Code of Practice*. “Section 5: Track Geometry” Adelaide, South Australia.
23. Bamberg, Wolfgang and Hans Ludwig. 1979. “New Measuring Method for Ride Comfort in Transit Vehicles.” Vehicular Technology Conference, 1979. 29th IEEE.
24. Berggren, Eric G., Martin X. D. Li, and Jan Spannar. September 2006. “A New Approach to the Analysis and Presentation of Vertical Track Geometry Quality and Rail Roughness with Focus on Train-Track Interaction and Wavelength Content.” *Proceedings 7th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, Brisbane, Australia.
25. Clark, Jr., Alfred. 1989. “A Primer on Roller Coaster Dynamics, Part II — You Can Bank on Them.” *RollerCoaster!* Volume X, Issue 1, pp 32-37
26. Cleon, Louis-Marie and Guido Lauriks. May 1996. “Evaluation of Passenger Comfort in Railway Vehicles.” *Journal of Low Frequency Noise and Vibration*, Vol. 15 No. 2, pp 53-69
27. Donohew, B. and M.J. Griffin. July 2003. “Simulator for Optimizing Train Passenger and Crew Environment.” Rail Research UK Report: RRUK/C1/1, Railway Safety and Standards Board, UK
28. Dukkipati, Rao V. and Joseph R. Amyot. 1988. *Computer-Aided Simulation in Railway Dynamics.* New York: Marcel Dekker, Inc.
29. El-Sibaie, Magdy, et al. March 1997. “Engineering Studies in Support of the Development of High-Speed Track Geometry Specifications.” *IEEE/ASME Joint Railroad Conference*, Boston, MA

30. Esveld, Coenraad. 2001. *Modern Railway Track.* Second Edition. Zaltbommel: MRT-Productions
31. Fazio, A.E. and J.J. Cunningham. 1991. "An Analytic Approach to the Maintenance of High-Speed Track." *Proceedings of the 1991 IEEE/ASME Joint Railroad Conference*, St. Louis, MO
32. Förstberg, J., M. Griffin, and B. Donohew I. 15 March 2004. "Appearance of onset of nausea: Transfer of knowledge; suggestion of laboratory studies." ERRI/FACT/MM 16/17/02/04, Brussels
33. Förstberg, Johan. 2003. "Fast and comfortable trains (FACT)." Presentation for Nordic Rail 2003 by VTI, Sweden
34. Garg, Vijay K. and Rao V. Dukkipati. 1984. *Dynamics of Railway Vehicle Systems.* Academic Press Canada: Ontario
35. Hylén, Bertil. October 7-9, 2003. "EU Railway Research Presentation." VTI Conference 20 — VTI's fack- och monterseminarier vid Nordic Rail 2003, Sweden
36. ITTC — Recommended Procedures and Guidelines. 1999. "Testing and Extrapolation Methods High-Speed Marine Vehicles Excerpt of ISO 2631, Seasickness and Fatigue." *International Towing Tank Conference* 20th ITTC 1993, pp 384-392
37. Iwnicki, Simon, ed. 2006. *Handbook of Railway Vehicle Dynamics.* CRC Press, Taylor & Francis Group: Boca Raton
38. Jacobson, D., R.W. Barker, B.D. Pepler, and L.L. Vallerie. 1977. "Comparison of Passenger Comfort Models in Buses, Trains, and Airplanes." *Transportation Research Record* 646. Transportation Research Board: National Academy of Sciences, Washington, D.C.
39. Karakasis, Kleomenis, Dimitris Skarlator, and Tilemachos Zakinthinos. 2005. "A factorial analysis for the determination of an optimal train speed with a desired ride comfort."Applied Acoustics 66 (2005) 1121-1134, www.sciencedirect.com
40. Kazato, A. and S. Kamoshita. 2008. "Measures against high-frequency vibration for Next-Generation Tilt Control System." *Proceedings 8th World Congress on Railway Research*, Seoul, Korea
41. Kim, Y-G., H-B. Kwon, S-W. Kim, C-K. Park, and T-W. Park. 2003. "Correlation of ride comfort evaluation methods for railway vehicles." *Proceedings IMechE Conference* Vol. 217 Part F
42. Klauder, Jr., Louis T. June 20, 2007. "Roll-Guided Spirals for Railroad Tracks." *Proc. Railway Engineering – 2007 Conference*, London, UK
43. Klauder, Jr., Louis T. and Sherman A. Clevenson. 1975. "Evaluation of Ride Quality Measurement Procedures by Subjective Experiments using Simulators." *Proceedings of the 1975 Ride Quality Symposium*, NASA TM X-3295, Paper No. 11
44. Klauder, Jr., Louis T., Steven M. Chrismer, and John Elkins. 2002. "Improved Spiral Geometry for High-Speed Rail and Predicted Vehicle Response." *Transportation Research Record: Journal of the Transportation Research Board*, Volume 1785/2002, Washington, D.C.

45. Kufver, Björn. 2001. “Research on Track Geometry for High-speed Trains.” *Swedish National Road and Transport Research Institute (VTI)*, No. 2, pp 16-18
46. Kufver, Björn and Ola Rydell. June 24-25, 2009. “Certain Aspects of the CEN Standard for Alignments through Switches and Crossings.” *Proceedings 10th International Railway Engineering Conference*, London, UK
47. Kufver, Björn. October 2003. “Track/vehicle interaction and alignment design.” *Paper presented at seminar arranged by the VTI at Nordic Rail in Jönköping*
48. Kufver, Björn and Ola Rydell. October 2003. “Dynamic vehicle response on horizontal curves without transition curves, including turnout curves through Swedish UIC60 turnouts.” *Paper presented at seminar arranged by the VTI at Nordic Rail in Jönköping*
49. Luber, Bernd, Andreas Haigermoser, and Gerald Grabner. 2010. “Track Geometry Evaluation Method Based on Vehicle Response Prediction.” *Vehicle System Dynamics*. Vol. 48, Supplement, 2010, 157-173
50. MacMillan, Renata and Jingnan Guo. January 2009. “Reading — Assessment and Control of Whole-Body Vibration.” Safetyline Institute, www.worksafe.wa.gov.au/institute
51. Madejski, J. 2004. “Autonomous track geometry diagnostics system.” *Journal of Materials Processing Technology* 157-158 (2004) 194-202
52. Mancini, Giampaolo, Sergio Pelacchi, Monica Balli, and Alessandro Corbizi Fattori. 2008.“New developments with the Italian solution for tilting trains: optimization of tilting system on new generation of Pendolino trains.” *Proceedings 8th World Congress of Railway Research, Seoul, Korea* http://www.uic.org/cdrom/2008/11_wcrr2008/pdf/R.2.4.3.5.pdf
53. Mansfield, Neil J. 2006. “Literature Review on Low Frequency Vibration Comfort.” EU Asia-Link ASIE/2005/111000 CIRCIS
54. Mee, Brian, Brian Whitte, and Boris Neijikovsky. 1995. “Railway testing using a portable ride quality and vibration measurement system with GPS.” *Proceedings SPIE* Vol. 2458, pp 138-147
55. Mian, Zack. March 2009. “Wheel Inspection System Environment Qualification and Validation.” Report No. C-06-31 for the New York State Energy Research and Development Authority and New York State Department of Transportation, Albany, NY
56. Nakagawa, M. and M. Miwa. 2008. “Next-Generation Management of Ride Quality in the Tokaido Shinkansen.” *Proceedings 8th World Congress of Railway Research*, Seoul, Korea. http://www.uic.org/cdrom/2008/11_wcrr2008/pdf/I.3.4.1.4.pdf
57. Parkinson, H. and S. D. Iwnicki. 2004. “An Intelligent Track Monitoring System.” Manchester Metropolitan University, Manchester, UK http://www.railtechnologyunit.com
58. Picu, Ana. 2009. “An Investigation of the Human Sensation Induced by Wheel Hand Arm Vibration and Seat Whole-body Vibration using Single Axis and Tri-axial Methods — A Study using the Steven’s Power Law.” *Proceedings of the*

ACOUSTICS High Tatras 2009 34th International Acoustical Conference — EAA Symposium.

59. Popprath, S., C. Benatzky, C. Bilik, M. Kozek, A. Stribersky, and J. Wassermann. July 2006. "Experimental Modal Analysis of a Scaled Car Body for Metro Vehicles." *Thirteenth International Congress on Sound and Vibration*, Vienna, Austria.
60. Prem, Hans and Geoff Ayton. 2005. "Improved Techniques for Assessing Ride Quality on Concrete Pavements." Eighth International Conference on Concrete Pavements: Innovations for Concrete Pavement: Technology Transfer for the Next Generation, pp 733-754.
61. Presle, Gerard, Werner Hanreich, and Paul Mittermayr. 2000. "Austrian Track Testing and Recording Car EM 250, Source for Wheel-Rail Interaction Analysis." *Transportation Research Record: Journal of the Transportation Research Board*, 1713, Paper No. 00-0743, Transportation Research Board of the National Academies, Washington, D.C., pp 22-28.
62. Raymond, Gerald P. and Richard J. Bathurst. March 1994. "Repeated-load response of aggregates in relation to track quality index." Canada Geotech. J. 31, pp 547-554
63. Scharr, Richard L. and Raymond P. Owings. 1975. "Intercity Rail Passenger Car Ride Quality Test Program." *Proceedings of the 1975 Ride Quality Symposium*, NASA. pp 141-158
64. Schmidt, Tom. September 2005. "Why we need dynamic car-measurement tools." *Railway Age*
65. Sundström, Jerker. 2008. "Difficulties to Read and Write under Lateral Vibration Exposure: Contextual studies of train passengers' ride comfort." Doctoral thesis. Royal Institute of Technology, Stockholm, Sweden
66. Track Access. May 1998. "Track Geometry — Inspection and Assessment." *Track Access* Issue 2.3
67. Vermeij, David J. 2000. "Design of a high-speed track." HERON, Vol. 45, No. 1 (2000) ISSN 0046-7316
68. Winter, Theo, Peter A.J. Meijvis, Wijnand J.M. Paans, Michael J.M.M. Steenbergen, and Coenraad Esveld. 2007. "Track Quality Achieved on HSL-South." Project Organization HSL-Zuid. European Railway Review, Issue 3, pp 48-53
69. Yoo, Wan-Suk, Chang-Hwan Lee, Wui-Bong Jeong, and Sang-Hyun Kim. 2005. "Development and Application of New Evaluation System for Ride Comfort and Vibration on Railway Vehicles." *Journal of Mechanical Science and Technology*, Vol. 19, No. 7, pp 1469-1477
70. Zhou, Hinsong, Gang Shen, Hong Zhang, and Lihui Ren. 2008. "Application of modal parameters on ride quality improvement of railway vehicles." *Vehicle Systems Dynamics*, Vol. 46, Supplement, pp 629-641

Appendix AA – International Standard for Organization ISO 2631

The detail for the analysis methods included in ISO 2631 are given in this appendix.

AA1. The Basic Method

Basic evaluation method is weighted root-mean-square (RMS) acceleration for both translational and rotational vibration. The weighted RMS acceleration is calculated by:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)dt \right]^{\frac{1}{2}}$$

$a_w(t)$ is the weighted acceleration as a function of time (m/s^2 or rad/s^2)
T is the duration of the measurement (s)

AA2. The Running RMS Method

The running RMS method takes into account occasional and transient vibration by use of a short integration time constant.

$$a_w(t_0) = \{\frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)]^2 dt\}^{\frac{1}{2}}$$

$a_w(t_0)$	is the instantaneous frequency-weighted acceleration
τ	is the integration time for running averaging
t	is the time (integration variable)
t_0	is the time of observance (instantaneous time)

The maximum transient vibration value is defined as:

$$MTVV = \max[a_w(t_0)]$$

This is the highest magnitude of $a_w(t_0)$ read during the measurement period. It is recommended that τ is 1s in measuring MTVV.

AA3. The Fourth Power Vibration Dose Method

The fourth power vibration dose method is more sensitive to peaks than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging.

$$VDV = \{\int_0^T [a_w(t)]^4 dt\}^{\frac{1}{4}}$$

VDV is the fourth power dose value in m/s $^{1/4}$ or rad/s $^{1/4}$
$a_w(t)$ is the instantaneous frequency-weighted acceleration

T is the duration of measurement

Note: When the vibration exposure consists of two or more periods of different magnitudes, the vibration dose value for the total exposure should be calculated from the fourth root of the sum of the fourth power of individual dose values:

$$VDV_{total} = (\sum_i VDV_i^{\,4})^{\frac{1}{4}}$$

AA4. Ratios Used for Comparing Basic and Additional Methods of Evaluation

Additional methods other than the basic method should be used if the following ratios are exceeded.

$$\frac{MTVV}{a_w} = 1.5$$

$$\frac{VDV}{a_w T^{\frac{1}{4}}} = 1.75$$

AA5. Frequency Weighting

Frequency content of the vibration determines the effect on the passenger. Frequencies of the same amplitude will have different effects on passenger comfort and health. Frequency weightings are required to correctly correlate vibration content to ride quality. Different frequency weightings are used for different axes of vibration. Table A1 summarizes the application of the frequency weighting curves.

Table AA1. Summary of Frequency Weighting Curves

Frequency Weighting	Health	Comfort	Perception	Motion Sickness
W_k	z-axis, seat surface	z-axis, seat surface, standing, vertical recumbent (except head) x,y,z axes, Feet (sitting)	z-axis, seat surface, standing, vertical recumbent (except head)	N/A
W_d	x-axis, seat surface y-axis, seat surface	x-axis, seat surface y-axis, seat surface x,y-axes, standing, horizontal recumbent y,z axes, seat back		N/A
W_f	N/A	N/A	N/A	Vertical
W_c	x-axis, seat back	x-axis, seat back	x-axis, seat back	N/A
W_e	N/A	r_x,r_y,r_z-axes, seat surface	r_x,r_y,r_z-axes, seat surface	N/A
W_i	N/A	Vertical recumbent (head)	Vertical recumbent (head)	N/A

AA6. Combining Vibrations in More Than One Direction

The following equation is the total value of weighted RMS acceleration for vibrations in more than one direction:

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{\frac{1}{2}}$$

a_{wx}, a_{wy}, a_{wz} are the weighted RMS accelerations with respect to the orthogonal axes

k_x, k_y, k_z are multiplying factors

AA7. Multiplying Factors

Table AA2. Multiplying Factor for Seated Persons – Seat Surface

Effect of Movement	x-axis	y-axis	z-axis	r_x-axis	r_y-axis	r_z-axis
Health	W_d, k=1.4	W_d, k=1.4	W_k, k=1			
Comfort	W_d, k=1	W_d, k=1	W_k, k=1	W_e, k=0.63 m/rad	W_e, k=0.4 m/rad	W_e, k=0.2 m/rad
Perception	W_d, k=1	W_d, k=1	W_k, k=1			

Table AA3. Multiplying Factor for Seated Persons – Back Rest

Effect of Movement	x-axis	y-axis	z-axis
Health			
Comfort	W_c,k=0.8	W_d, k=0.5	W_d, k=0.4
Perception			

Table AA4. Multiplying Factor for Seated Persons –Feet

Effect of Movement	x-axis	y-axis	z-axis
Health			
Comfort	W_k,k=0.25	W_k,k=0.25	W_k,k=0.4
Perception			

Table AA5. Multiplying Factor for Standing Persons

Effect of Movement	x-axis	y-axis	z-axis
Health			
Comfort	W_d, k=1	W_d, k=1	W_k, k=1
Perception	W_d, k=1	W_d, k=1	W_k, k=1

Table AA6. Multiplying Factor for Recumbent Persons: Under Pelvis

Effect of Movement	Horizontal Axes	Vertical Axes
Health		
Comfort	W_d, k=1	W_k, k=1
Perception	W_d, k=1	W_k, k=1

APPENDIX AB – EUROPEAN STANDARD ENV 12299:1999

The detail for the analysis methods included in European Standard ENV 12299:1999 are given in this appendix.

AB1. Mean Comfort – Simplified Method

Comfort Index Calculation for Simplified Method:

$$N_{MV} = 6 * \sqrt{((a_{XP95}^{Wad})^2 + (a_{YP95}^{Wad})^2 + (a_{ZP95}^{Wab})^2)}$$

W is the weighted frequency value

Wab: vertical direction = Wa * Wb

Wad: lateral direction= Wa*Wd

a is the RMS acceleration

subscripts x,y,z indicate direction

p indicates floor interface

95 indicates 95 percentile RMS value

AB2. Mean Comfort – Complete Method

Seated comfort index

$$N_{VA} = 4 * (a_{ZP95}^{Wab}) + 2 * \sqrt{(a_{YA95}^{Wad})^2 + (a_{ZA95}^{Wab})^2} + 4 * (a_{XD95}^{Wac})$$

Standing comfort index

$$N_{VD} = 3 * \sqrt{(16 * (a_{XP50}^{Wad})^2 + 4 * (a_{YP50}^{Wad})^2 + (a_{ZP50}^{Wab})^2)} + 5 * (a_{YP95}^{Wad})$$

Weightings

$W_{ab} = W_a*W_b$

$W_{ac} = W_a*W_c$

$W_{ad} = W_a*W_d$

Acceleration RMS

a_{XD}: Seat back level

a_{YA}, a_{ZA}: Seat pan level

a_{XP}, a_{YP}, a_{ZP}: Floor level

AB3. Comfort on Curve Transitions

The comfort index gives a measure of passenger comfort for an individual curve transition, referred to as single events without an evaluation of cumulative effects. This measure is applicable to conventional and tilting vehicles at any speed and at medium or high levels of uncompensated lateral acceleration.

This index is based on the relationship between the relevant magnitudes of lateral jerk, body roll speed, variation of lateral acceleration level, and the average value of the comfort information given.

Comfort Index on Curve Transitions

$$P_{CT} = (A * \ddot{y} + B * \dddot{y} - C) + D * \dot{\vartheta}^{E}$$

A, B, C, D, E are constants

Condition	A	B	C	D	E
In rest – standing	28.54	20.69	11.1	0.185	2.283
In rest – seated	8.97	9.68	5.9	0.120	1.626

P_{CT} – Comfort Index on curve transitions
$\ddot{y}$ - Maximum value of lateral acceleration in the carbody averaged on 1s base shifting (1/10) s, in the interval between the beginning of the entry or reverse transition and the end +1.6s
$\dddot{y}$ - maximum jerk, evaluated as maximum variation of two subsequent values of lateral acceleration scaled of 1s, in the time interval 1s before the beginning of the entry or reverse transition and the end of the same.
$\dot{\vartheta}^{E}$ - maximum absolute value of carbody roll speed $\dot{\varphi}_1$ averaged on 1 s base shifting by (1/10)s from the beginning to the end of the transition

Location of Measurements
Lateral accelerations – center of carbody floor and above the leading axle (and trailing if possible)
Non-compensated lateral accelerations at the axlebox
Carbody roll speed in a suitable location on carbody
Tilting angle
Speed

AB4. Comfort on Discrete Events

Comfort Index of discrete events is a measure of passenger comfort resulting from the interaction of the rail vehicle and local track irregularities.

$$P_{DE} = a * \ddot{y}_P + b * \ddot{y}_m - c$$

P_{DE}- Comfort index for discrete events within 2 s intervals shifting by (1/10)s
a,b,c – constants

Condition	a	b	c
In rest – standing	16.62	27.01	37.0
In rest – seated	8.46	13.05	21.7

$\ddot{y}_P$ - difference between maximum and minimum value of lateral accelerations measured within an interval of 2 s
$\ddot{y}_m$ - average value of the lateral acceleration in the same 2 s interval

APPENDIX AC – UIC 513

The detail for the analysis methods included in UIC 513 are given in this appendix.

AC1. Simplified Method for Seating or Standing Position

$$N_{MV} = 6\sqrt{(a_{XP95}^{Wd})^2 + (a_{YP95}^{Wd})^2 + (a_{ZP95}^{Wd})^2}$$

- N_{MV} is the simplified method comfort index
- a is the effective value of acceleration
- Wd is the frequency weighting in the horizontal direction
- P indicates floor
- 95 indicates 95th percentile

AC2. Full Method in Seated Position

$$N_{VA} = 4*(a_{ZP95}^{Wb}) + 2*\sqrt{(a_{YA95}^{Wd})^2 + (a_{ZA95}^{Wb})^2} + 4*(a_{XD95}^{Wc})$$

N_{VA} is the full method comfort index for seated position

- a is the effective value of acceleration
- Wb is the frequency weighting in the vertical direction
- Wc is the frequency weighting for the seat back
- Wd is the frequency weighting in the horizontal direction
- A indicates seating surface
- D indicates seat back
- P indicates floor
- 95 indicates 95th percentile

AC3. Full Method in Standing Position

$$N_{VD} = 3*\sqrt{16*(a_{XP50}^{Wd})^2 + 4*(a_{YP50}^{Wd})^2 + (a_{ZP50}^{Wb})^2} + 5*(a_{YP95}^{Wd})$$

N_{VD} is the full method comfort index for standing position

- a is the effective value of acceleration
- Wb is the frequency weighting in the vertical direction
- Wd is the frequency weighting in the horizontal direction
- P indicates floor
- 95 indicates 95th percentile
- 50 indicates 50th percentile