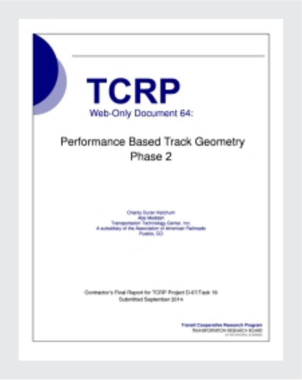

# Performance Based Track Geometry Phase 2

## DETAILS

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# Summary

In support of the Transit Cooperative Research Program (TCRP) D7 Task Order 19, Transportation Technology Center, Inc. completed Phase 2 of Performance Based Track Geometry (PBTG). The following tasks were completed during Phase 2:

- Vehicle Characterization and On-track Testing with Port Authority Trans-Hudson (PATH) System
- NUCARS® Modeling of PATH PA5 Car
- Comparison of NUCARS simulations to on-track test results
- PBTG Neural Network (NN) development for Dallas Area Rapid Transit (DART) and PATH systems
- Evaluation of the potential use of PBTG on transit systems (Proof of concept)

### Vehicle Characterization and On-track Testing with PATH System

### NUCARS Modeling of PATH PA5 Car

PATH PA5 car was selected and fully characterized and ride quality tests were performed. The NUCARS model of the PATH PA5 car was updated with information collected during vehicle characterization testing. Then, the NUCARS model was validated using test results from on-track testing on the PATH system. The simulation correctly predicted the frequency content and trends of lateral and vertical accelerations measured in the driver's cab during on-track testing. There was some deviation in the magnitudes. The differences may be due to the following:

- Dampers of the PA5 car were not measured. Damping rates from the manufacturer for new dampers were used.
- Representative rail profiles were used in the simulations. Actual wheel/rail interaction is influenced by the shapes of the wheels and rails.

### Comparison of NUCARS Simulations to On-track Test Results

On-track tests showed a strong correlation between passenger ride quality and track geometry on the PATH system. Further work needs to be done to identify what track anomalies or structures correspond to the wavelengths identified. The influence of entry/exit spiral (or lack of) will need to be investigated. The roll response due to curves can affect ride quality and will need to be studied in Phase 3.

### PBTG NN Development for DART and PATH Systems

Phase 2 results show that transit systems with a wide range of track geometry deviations and corresponding high vehicle dynamic response are well suited for using NNs to develop PBTG, whereas transit systems with very few track geometry deviations and relatively low vehicle dynamic response are not.

NNs were developed for both DART and PATH systems and showed the following:

- DART NNs predicted vehicle response to track geometry with confidence intervals of 0.1 percent and 0.25 percent based on point-by-point response and segment-based approach, respectively.
- The poor predictive performance on DART is due to what is known as overfitting. The track geometry had small deviations; therefore, there were no high dynamic events in the ride

quality data. The data used to train the NNs was seen as “patternless” noise; therefore, the NNs did not recognize a trend in the data.

- PATH NNs predicted vehicle response to track geometry with an 81 percent confidence interval using the segment-based approach. The data collected on PATH had significant dynamic events recorded in response to a wide range of track geometry deviations. These results show significant improvement compared to DART NNs, because PATH NNs recognized trends in the data.

**Evaluation of the Potential Use of PBTG on Transit Systems (Proof of concept)**

The NUCARS model was used to generate information to build the NNs for PBTG proof of concept.

Research from Phase 1 and Phase 2 shows there is potential for PBTG to be used on some transit systems to optimize maintenance and ride quality. Further research is needed to determine the viability of a PBTG system and to establish guidelines for implementation. The following tasks are recommended for Phase 3 research:

- Build a complete set of NNs for PATH using the data and NUCARS model of the PA5 Car.
- Use PBTG developed for PATH to predict areas in track that cause adverse ride quality. Once these areas are identified, a track inspection should be done to determine if the prediction is accurate and if it is in fact a deviation that can be maintained (slab track versus ballasted track, etc.).
- Maintain and correct deviations in the identified locations. Measure both track geometry and ride quality to determine if significant improvement is achieved.
- If significant improvement is achieved, modify the PBTG system that was developed for freight railroads to meet the transit agency needs.
- Write guidelines for implementation of PBTG for transit systems.

## CHAPTER 1

# Background

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, combinations of several track geometry deviations, special track work, and track misalignments that promote yaw instability or hunting. Poor ride quality may not be an indicator of unsafe operation, but may point to an area of track or a vehicle that needs maintenance to prevent further degradation. Conversely, track geometry locations that exceed some track geometry or safety limits may not cause poor ride quality or poor vehicle performance. To optimize transit system maintenance, methods need to be developed to identify vehicle conditions and locations in track that actually cause poor ride quality or vehicle performance.

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

- Prioritize track maintenance
- Identify problem locations that do not exceed normal track geometry standards
- Identify problems as they arise rather than waiting for scheduled maintenance
- Identify 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) has developed a track inspection method known as Performance Based Track Geometry (PBTG). Trained neural networks (NNs) in the PBTG system relate the complex dynamic relationships that exist between vehicles and track geometry to vehicle performance.[1] NNs also identify track segments that may generate unwanted vehicle responses.

A transit agency could use PBTG to optimize maintenance of the track and fleet, which allows monitoring of track conditions between scheduled track geometry measurements.

Also, PBTG uses measured track geometry and the PBTG NN to predict vehicle performance on existing track. These predictions help 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.

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1 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.

In support of the Transit Cooperative Research Program (TCRP) D7 Task 19 research program, TTCI completed Phase 2 of PBTG for the transit system research. The following tasks were completed during Phase 2:

- Vehicle Characterization and On-track Testing – Port Authority Trans-Hudson (PATH) System
- NUCARS®[2] Modeling of PATH PA5 Car
- Comparison of NUCARS simulations to on-track test results
- PBTG NN for Dallas Area Rapid Transit (DART) and PATH system
- Evaluation of the potential use of PBTG on Transit Systems (Proof of concept)

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2 NUCARS® is a registered trademark of Transportation Technology Center, Inc., Pueblo, Colo.

## CHAPTER 2

# Research Approach

## 2.1 Vehicle Characterization and Ride Quality Testing

TTCI partnered with PATH to participate in this research. PATH supported the project by providing a test vehicle for TTCI to perform characterization and ride quality tests.

A typical transit car operating on the PATH 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 revenue service passenger ride quality data using accelerometers and various displacement transducers. Track geometry measurements were collected and used as comparisons with predictions from the NUCARS model and for future PBTG NN training.

## 2.2 Vehicle Characterization Tests at PATH

Vehicle characterization testing was performed on PATH property located in Harrison, New Jersey. PATH's operating conditions provided a variety of track structures and a wide range of operating speeds for the ride quality testing. The following is a summary of the conditions that were tested on the PATH system:

- Tunnel
- Ballasted track with concrete ties
- Direct fixation track
- Curvature range from 1 (5279 feet) to 39 (150 feet) degrees
- Third rail system
- Rail profile 115 RE rail and 11 ARA-B rail

Figure 1 shows a map of the PATH rail system.

Figure 1. PATH Rail System Map

PATH's PA5 passenger car (with all axles powered) was used for testing. The vehicle is manufactured by Kawasaki. Figure 2 shows a photograph and a schematic of the PA5 car. Table 1 summarizes some of the design specifications of the vehicle.

Figure 2. PATH's PA5 Car

**Table 1. PATH Design Specifications**

| **PATH Railcar Design Specifications** | |
|---|---|
| Weight | Load Condition : AWO 72,450 pounds<br>Load Condition : AW3 95,330 pounds |
| Primary Suspension System | Chevron |
| Secondary Suspension System | Airbag |
| Wheel Profile | PATH Design Cylindrical Wheel |

TTCI has often found that actual vehicle characteristics as assembled may vary considerably from the published design and measured individual components. In order to ensure an accurate NUCARS model of the PATH PA5 car, 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 resonant 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.

### 2.2.1 Carbody Resonance Tests

Carbody resonance testing was conducted to determine the rigid body modes of vibration of the PATH PA5 Car. Figure 3 shows an example of the rigid body modes that were excited during the test.

The car was instrumented with accelerometers. Figure 4 shows the locations of the instrumentation and describes the accelerometers used in the test. The rigid body modes of vibration were each excited by hand by two TTCI engineers with assistance from PATH employees.

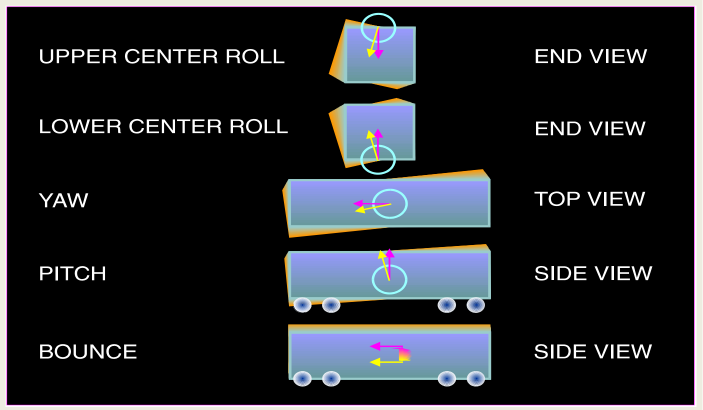
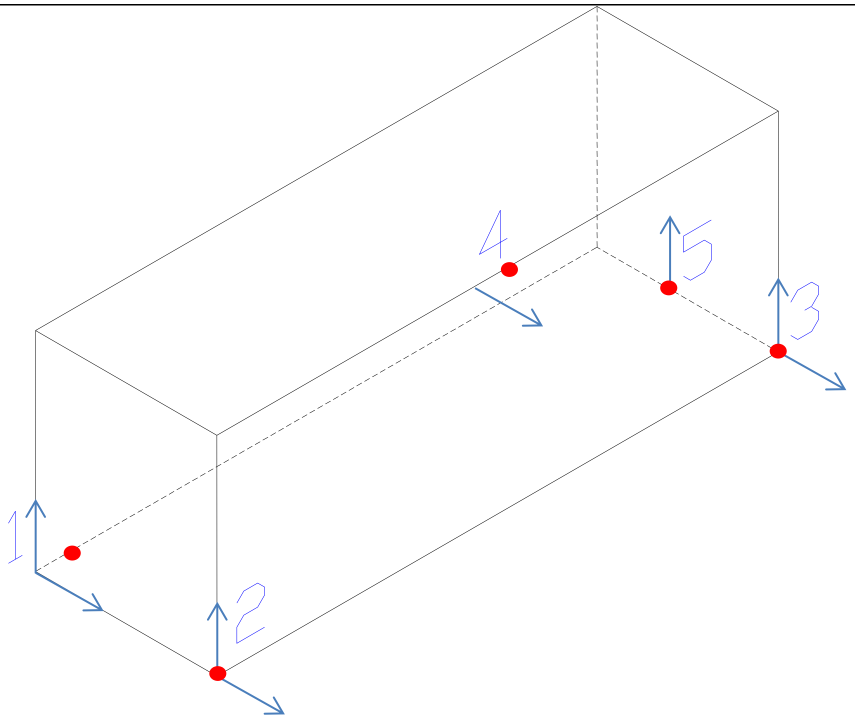


*Figure 3. Carbody Rigid Body Modes excited during Test*



| Location Number | Description |
|---|---|
| 1 | Vertical and Lateral Accelerometer |
| 2 | Vertical and Lateral Accelerometer |
| 3 | Vertical and Lateral Accelerometer |
| 4 | Lateral Accelerometer (top) |
| 5 | Vertical Accelerometer |

The following equations are used to determine carbody resonance for measured accelerations:

**Bounce** $\frac{\frac{a_{1v}+a_{2v}}{2}+a_{5v}}{2}$

**Pitch** $\frac{a_{1v}+a_{2v}}{2}-a_{5v}$

**Yaw** $\frac{a_{1l}+a_{2l}}{2}-a_{3l}$

**Roll** $a_{4l}-\frac{a_{1l}+a_{2l}+a_{3l}}{3}$

***Figure 4. Acceleration Placement and Description***

Figure 5 shows an example of raw acceleration data recorded during the test. These accelerations were analyzed by calculating a Fast Fourier Transform (FFT). The FFT results were used to determine what rigid body modes were excited. The model was tuned using the measured data. Moments of inertias, center of gravity locations, and suspension properties were updated accordingly. Table 2 shows the measured modes and the modes “tuned in” the model.

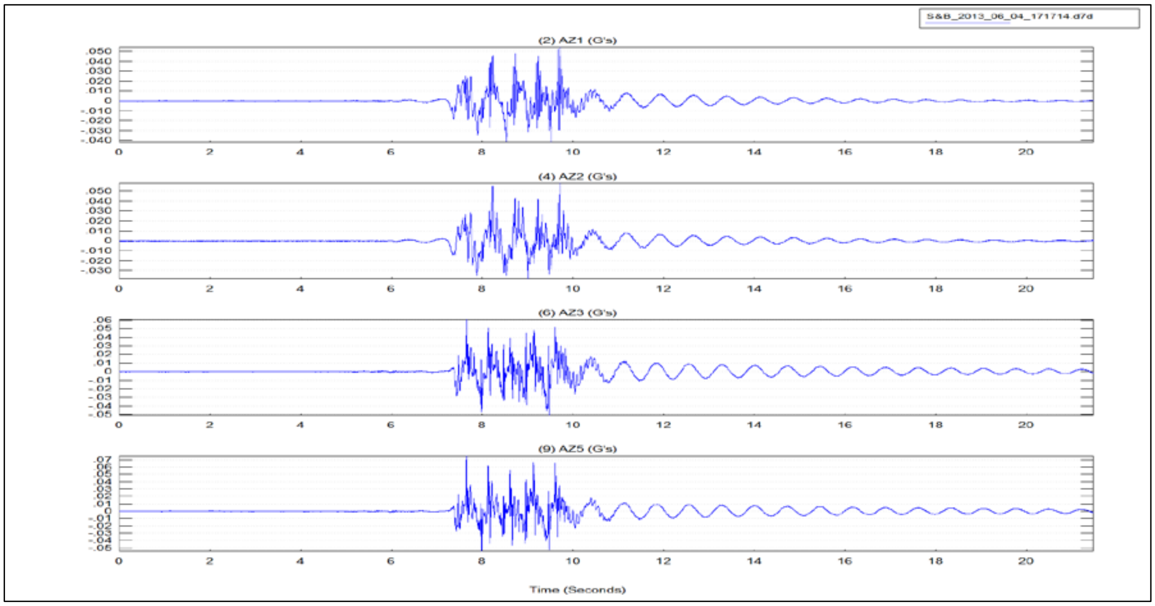


*Figure 5. Example of Carbody Resonance Data*

**Table 2. Measured Rigid Body Mode Frequencies Compared to Model**

| Rigid Body Mode | Measured Frequency | Model Frequency | Difference |
|---|---|---|---|
| Bounce | 1.34 | 1.38 | 3.0% |
| Pitch | 1.39 | 1.40 | 0.7% |
| Lower Center Roll | 0.48 | 0.49 | 2.1% |
| Yaw | 1.46 | 1.48 | 1.4% |
| UC Roll | 1.65 | 1.64 | -0.6% |

### 2.2.2 Suspension Stiffness Tests

Suspension stiffness tests were performed to measure the longitudinal, lateral, and vertical stiffness of the primary and secondary suspensions. A force was applied across the suspension system in the direction to be measured. The force was measured with a load cell. The displacement of the system was measured with a displacement transducer. A force/displacement graph can be generated to calculate the suspension stiffness.

#### *Longitudinal Stiffness Test*

The longitudinal stiffness test was performed to determine the primary and secondary effective stiffness in the longitudinal direction. A second PA5 car was placed on the same track directly in front of the test car with brakes applied. A hydraulic cylinder was connected between the two railcars to apply the load across the suspension. A load cell was used to determine the force needed to displace the suspension in the longitudinal direction. Displacement transducers were placed across both the primary and secondary suspension systems to measure the displacement resulting from the applied load. Figures 6 and 7 show the test setup.

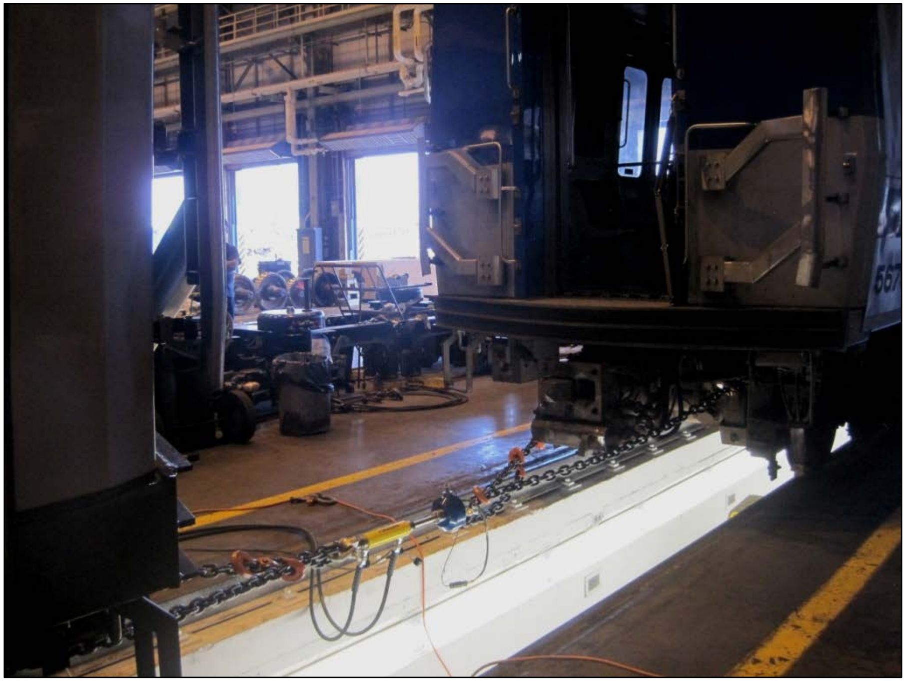


*Figure 6. Longitudinal Suspension Setup between Two Railcars*

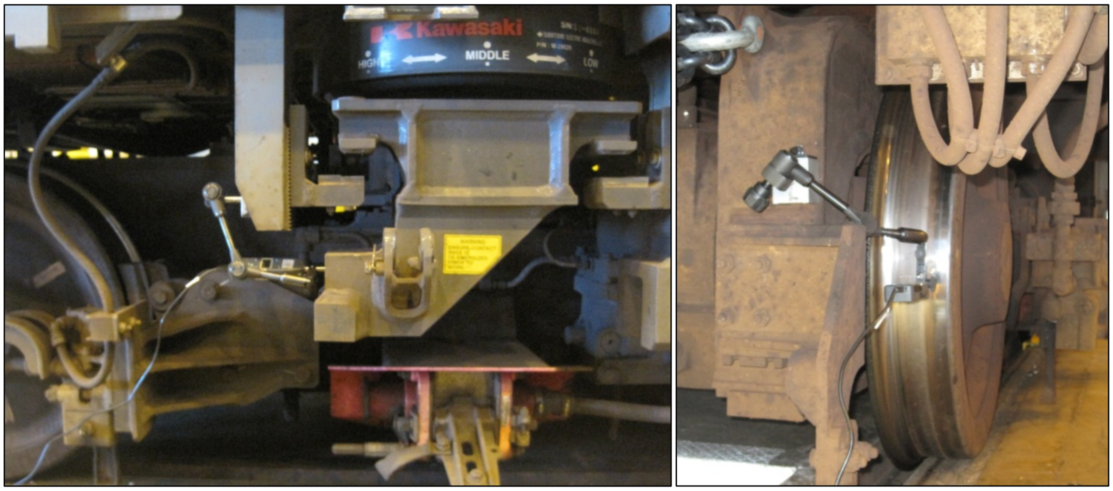


*Figure 7. Displacement Transducer for Longitudinal Suspension Test*

Force-displacement slopes were calculated for each run. The calculated stiffness values for all runs were averaged to determine the effective stiffness of the primary and secondary suspension systems. Figure 8 shows an example of the displacement and load measured during the test. Table 3 shows the values determined from the test in comparison to the manufacturer specified values.

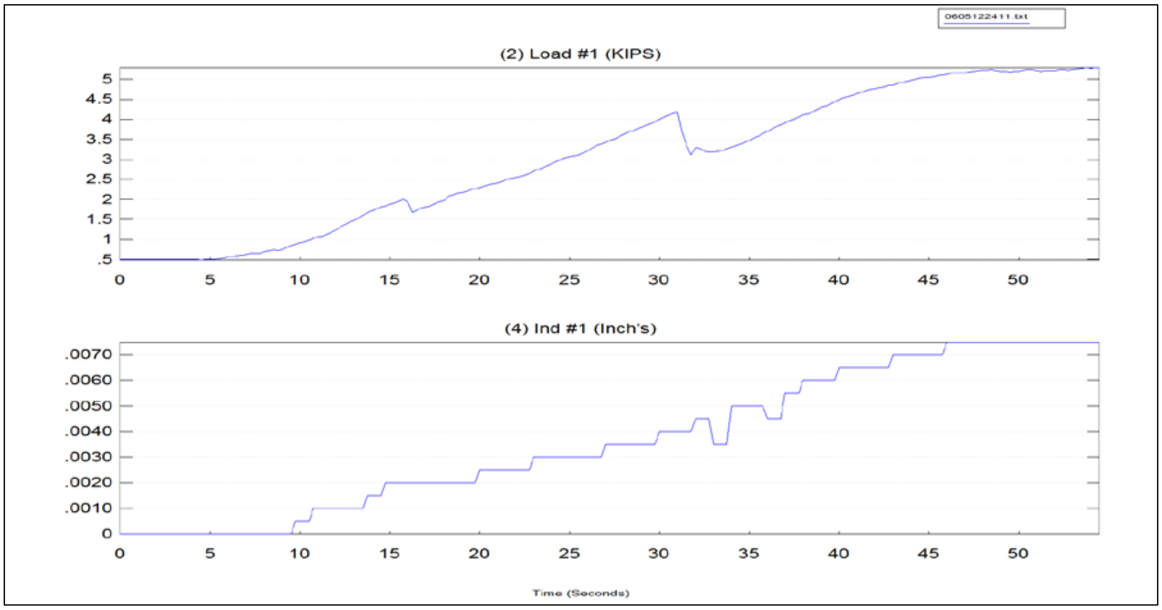


***Figure 8. Example of Longitudinal Stiffness Test Data***

**Table 3. Longitudinal Suspension Characteristics**

| Suspension Component | Manufacturer Value | Average Measured Value | Difference |
|---|---|---|---|
| Primary Suspension Stiffness per axle box (pair of chevrons) | 67,380 lb/in | 77,330 lb/in | +14.8% |
| Shear Stiffness of Airbag | No manufacturer data available | 1,625 lb/in | N/A |
| Traction Rod Stiffness in Longitudinal Direction | No manufacturer data available | 42,400 lb/in | N/A |

### *Lateral Stiffness Test*

The lateral stiffness test was performed to determine the effective lateral stiffness values for the primary and secondary lateral suspension systems. A forklift was placed next to the lead truck of the PA5 car. A hydraulic cylinder was connected between them to apply the load across the suspension. A load cell was used to determine the force needed to displace the suspension in the lateral direction. Displacement transducers were placed across both the primary and secondary suspension systems to measure the displacement resulting from the applied load. Figure 9 shows the test setup.

*Figure 9. Lateral Stiffness Test Setup*

Force-displacement slopes were calculated for each run. The calculated stiffness values for all runs were averaged to determine the effective stiffness of the primary and secondary suspension systems. Table 4 shows the values determined from the test in comparison to the manufacturer specified values.

**Table 4. Lateral Suspension Characteristics**

| Suspension Component | Manufacturer Value | Average Measured Value | Difference |
|---|---|---|---|
| Primary Suspension Stiffness per axle box (pair of chevrons) | 13,990 lb/in | 19,414 lb/in | +38.8 % |

### *Vertical Stiffness Test*

The vertical stiffness test was performed to determine the effective vertical stiffness for the secondary and primary lateral suspension systems.

#### Secondary Suspension System

The secondary suspension system of the PA5 car is an air suspension consisting of airbags and air reservoirs. The air suspension models used in NUCARS are based on the methods described by Oda and Nishimura[3] and Berg.[4]. Figure 10 shows how the airbag systems are represented in the NUCARS model. Note that because of the arrangement of the damping in the system, the

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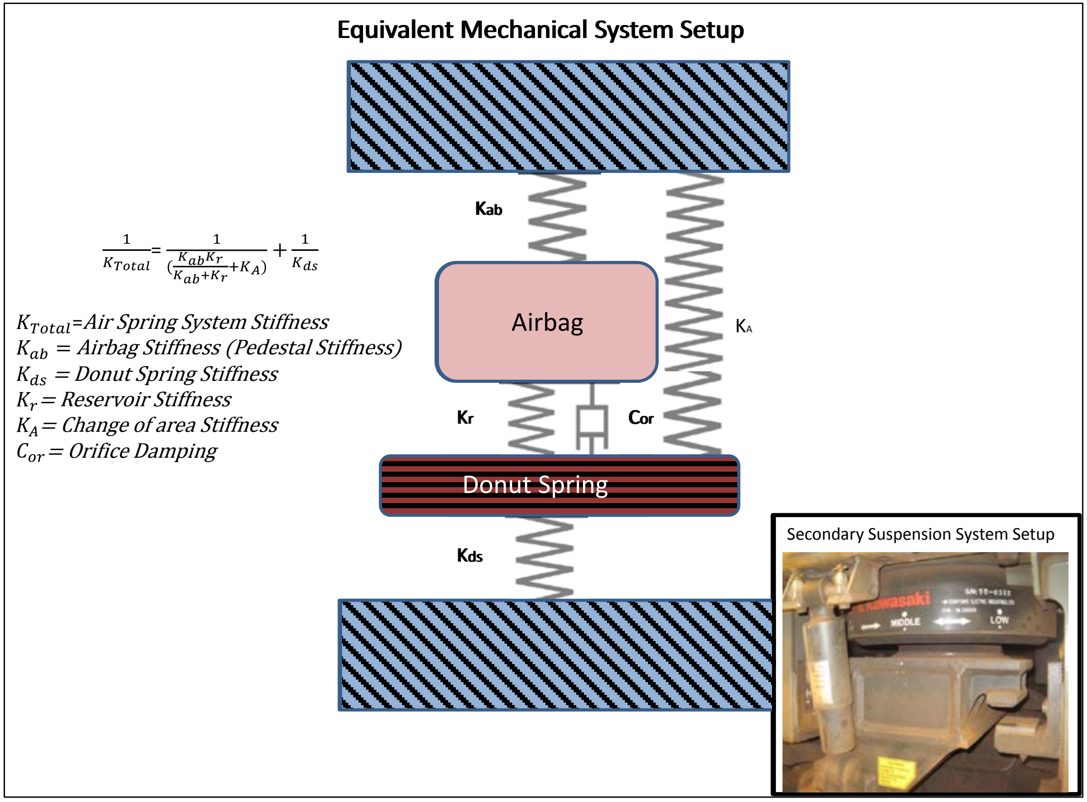
3 Oda, N. and S. Nishimura. 1970. “Vibration of Air Suspension Bogies and their Design.” *Bulletin of the JSME* Vol. 13, No. 55.

4 Berg, Mats. 1999. “A Three-Dimensional Airspring Model with Friction and Orifice Damping.” *Vehicle System Dynamics Supplement* 33, pp. 528–539.

effective vertical and shear stiffness are nonlinear. The donut spring is a safety spring that will support the load of the car if the airbag system deflates. This spring was included in the model to accurately represent the vertical response of the car.



$$\frac{1}{K_{Total}} = \frac{1}{\left(\frac{K_{ab}K_r}{K_{ab}+K_r} + K_A\right)} + \frac{1}{K_{ds}}$$

$K_{Total}$=*Air Spring System Stiffness*
$K_{ab}$ = *Airbag Stiffness (Pedestal Stiffness)*
$K_{ds}$ = *Donut Spring Stiffness*
$K_r$ = *Reservoir Stiffness*
$K_A$ = *Change of area Stiffness*
$C_{or}$ = *Orifice Damping*

***Figure 10. Air Suspension Equivalent Mechanical System***

Secondary suspension stiffness was measured by placing hydraulic cylinders under the jacking points of the carbody at lead truck locations. Transducers were placed across the airbag suspension system to measure the displacement resulting from the load. Figure 11 shows the setup to measure the secondary suspension stiffness. Table 5 shows the secondary suspension system vertical stiffness values measured during the test.

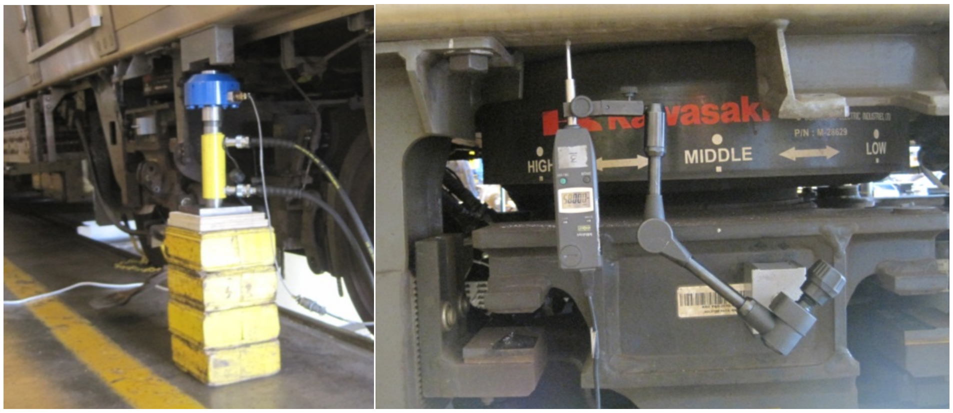


***Figure 11. Secondary Suspension Vertical Test Setup***

**Table 5. Secondary Suspension Vertical Stiffness**

| Suspension Component | Average Measured Value |
|---|---|
| Total Air spring System Stiffness | 3,066 lb/in |
| Donut Spring Stiffness | 18,351 lb/in |
| Airbag Stiffness | 8,525 lb/in |
| Reservoir Stiffness | 6,539 lb/in |

### Primary Suspension System

The primary suspension system consists of a pair of chevrons. Figure 12 shows a photograph of the system. The stiffness of the primary system was measured by placing the hydraulic actuators at the center of the truck. The actuators pushed up on the truck frame displacing the suspension. Displacement transducers were used to measure the displacement and a force/displacement curve was calculated. Figure 13 shows the test setup. Table 6 summarizes the results.

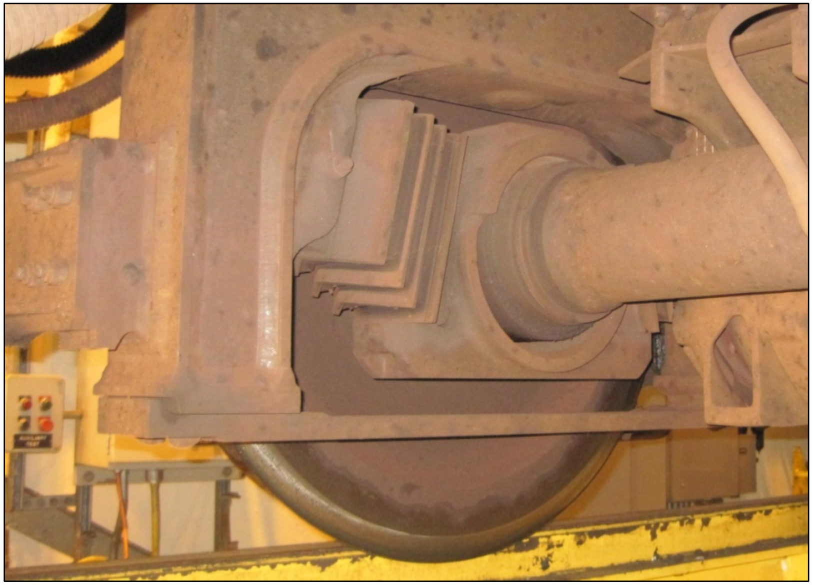


*Figure 12. Primary Suspension System – Chevron*

*Figure 13. Primary Suspension Vertical Test Setup*

**Table 6. Primary Suspension Stiffness**

| Suspension Component | Manufacturer Value | Average Measured Value | Difference |
|---|---|---|---|
| Primary Suspension Stiffness per axle box (pair of chevrons) | 67,380 lb/in | 77,330 lb/in | +14.8% |

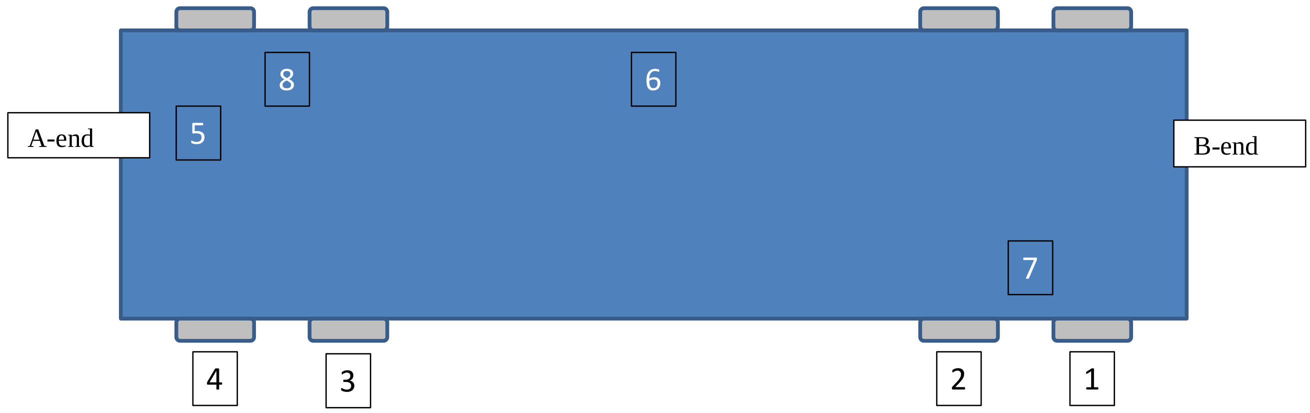
## 2.3 On-Track Tests

The goal of the on-track tests was to collect data to ascertain the ability of NUCARS and PBTG to properly predict vehicle performance and ride quality and to identify track geometry locations that need maintenance. The data collected was used to validate the NUCARS model output and build PBTG NNs.

PA5 Car 5746 was instrumented and put in service on June 3, 2013. Data was taken in both directions between Journal Square Station and 33rd St Station in the morning and in both directions between Newark/Penn Station and World Trade Center Station in the afternoon. Load conditions from AW0 to AW4 (crush load) were measured throughout the test. The PATH and TTCI test team was onboard the train to monitor test and equipment.

Accelerometers were mounted on the carbody and axle boxes. All accelerometers had to be placed outside of the carbody due to passengers being onboard during the time of testing. Table 7 summarizes the locations and types of accelerometers used during the test. Figures 14 to 18 show photographs of the instrumentation on the car.

**Table 7. Ride Quality Test Accelerometer Locations**



| | Description | Type of Measurements | Notes |
|---|---|---|---|
| 1 | Axle Acceleration | Longitudinal, Lateral, Vertical | |
| 2 | Axle Acceleration | Longitudinal, Lateral, Vertical | |
| 3 | Axle Acceleration | Longitudinal, Lateral, Vertical | |
| 4 | Axle Acceleration | Longitudinal, Lateral, Vertical | |
| 5 | Driver’s Cab Acceleration | Longitudinal, Lateral, Vertical | Accelerometer placed on floor under driver’s seat. |
| 6 | Center of Carbody Accelerations | Longitudinal, Lateral, Vertical | Accelerometer could not be placed in the center due to equipment mounted underneath the car. Accelerometer was mounted on a beam centered longitudinally and about 30 inches from the centerline of carbody. A beam was used instead of carbody skin to minimize noise. |
| 7 | Carbody at truck centerline Accelerations | Longitudinal, Lateral, Vertical | Accelerometer was mounted on a beam. A beam was used instead of carbody skin to minimize noise. |
| 8 | Carbody at truck centerline Accelerations | Longitudinal, Lateral, Vertical | Accelerometer was mounted on a beam. A beam was used instead of carbody skin to minimize noise. |

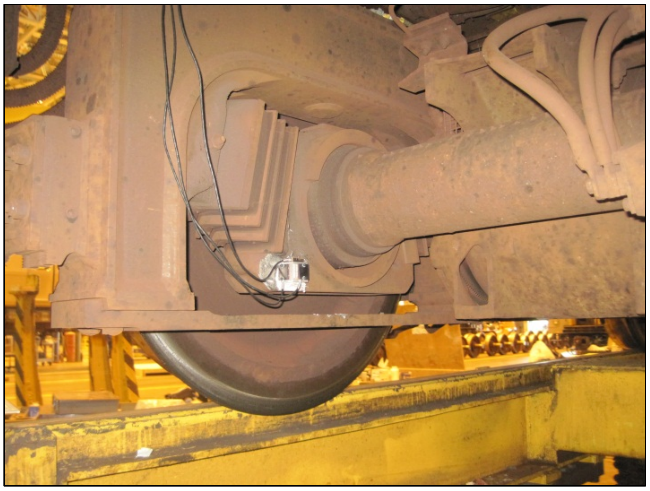


*Figure 14. Axle Box Accelerometer*

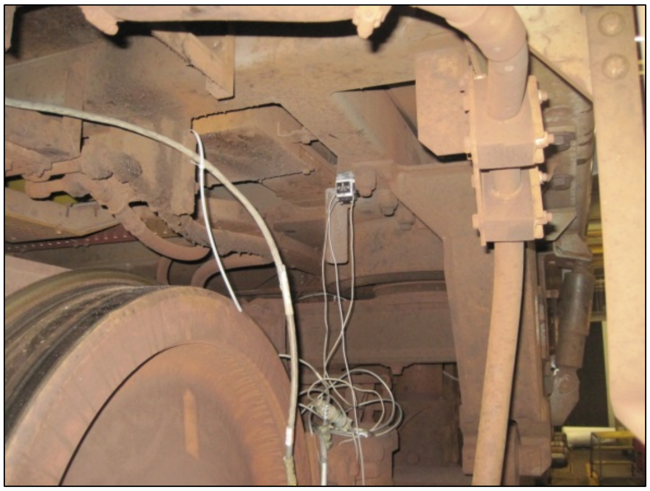


*Figure 15. Carbody Accelerometer at Truck Centerline*

*Figure 16. Carbody Accelerometer at Center of Car*

***Figure 17. Carbody Accelerometer in Driver's Cab***

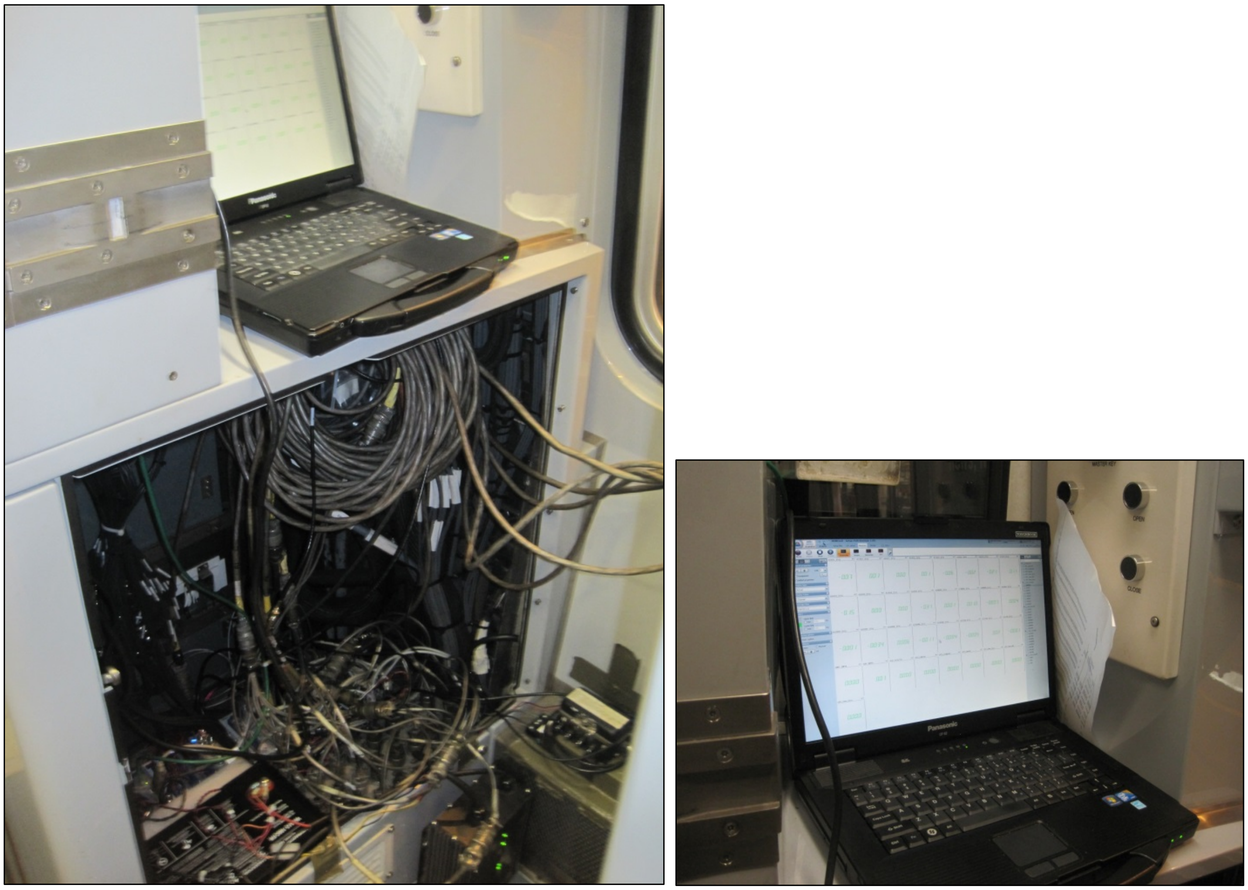


***Figure 18. Instrumentation Setup***

### 2.3.1 ISO 2631 Ride Quality Analysis Requirements

The well recognized and widely used ISO 2631 standard was used for analysis of the passenger ride quality.[5] 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.

Table 8 shows the ride quality index specified in ISO 2631. The following are ways to analyze passenger ride quality

- Basic method is used for general evaluation of ride quality. This method should only be used when the crest factor is less than nine.
  - Crest factor is ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its root-mean-square (RMS) value.
- Running RMS method is used to evaluate vibration with occasional shocks and transient vibration. This is the method that is typically used for a more in-depth look at passenger ride quality.
- Fourth power vibration dose (VDV) method is more sensitive to peaks in vibration. This method is used to look at the effect of discrete events on passenger ride quality.

In this study the fourth power VDV method is used to evaluate passenger ride quality. It allows for better correlation between track geometry deviations and ride quality.

**Table 8. Passenger Ride Quality Index**

| Weighted Vibration Magnitude (m/s$^2$) | Ride Quality Index |
|---|---|
| Less than 0.315 | Not uncomfortable |
| 0.315 to 0.63 | A little uncomfortable |
| 0.5 to 1 | Fairly uncomfortable |
| 0.8 to 1.6 | Uncomfortable |
| 1.25 to 2.5 | Very uncomfortable |
| Greater than 2 | Extremely uncomfortable |

### 2.3.2 Journal Square to 33rd Street

Figure 19 describes the location of test car 5746 in the train consist. The A-end of the car was leading from Journal Square to 33rd Street, and the B-end was leading from 33rd Street to Journal Square. Data was collected from 6 a.m. to approximately 11 a.m. on June 3, 2013. Load conditionsAW0 to AW4 (crush load) were measured during the test.

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[5] 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

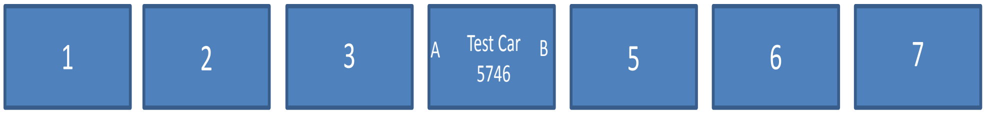

***Figure 19. Consist Setup***

The acceleration data in the driver's cab was analyzed in accordance with ISO 2631. Figures 20 and 21 show the fourth power VDV method. The VDV method is used to look at discrete events. This measure may be helpful when looking at a correlation between track geometry deviations and passenger ride quality. Between Pavonia-Newport and Christopher Street stations the VDV value was in the uncomfortable to very uncomfortable range. The measured values are summarized in Table 9.

**Table 9. VDV Values that exceeded Fairly Uncomfortable Ride Quality Index**

| Station | Measured VDV m/s$^{1.75}$ | Ride Quality Index |
|---|---|---|
| Pavonia-Newport to Christopher Street | Vertical 1.25 | Uncomfortable to Very Uncomfortable |
| | Lateral 1.31 | Uncomfortable to Very Uncomfortable |
| Christopher Street to Pavonia-Newport | Vertical 1.35 | Uncomfortable to Very Uncomfortable |
| | Lateral 1.06 | Uncomfortable to Very Uncomfortable |

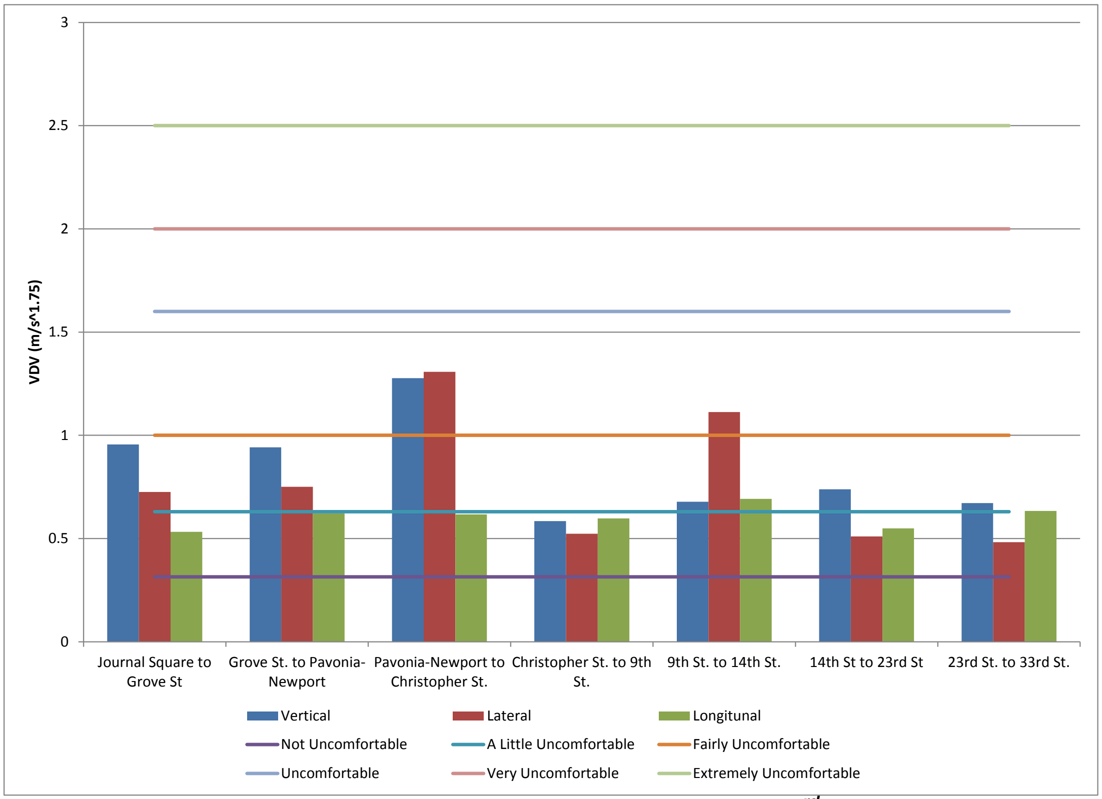

***Figure 20. VDV Ride Quality calculated for Journal Square to 33$^{rd}$ Street***

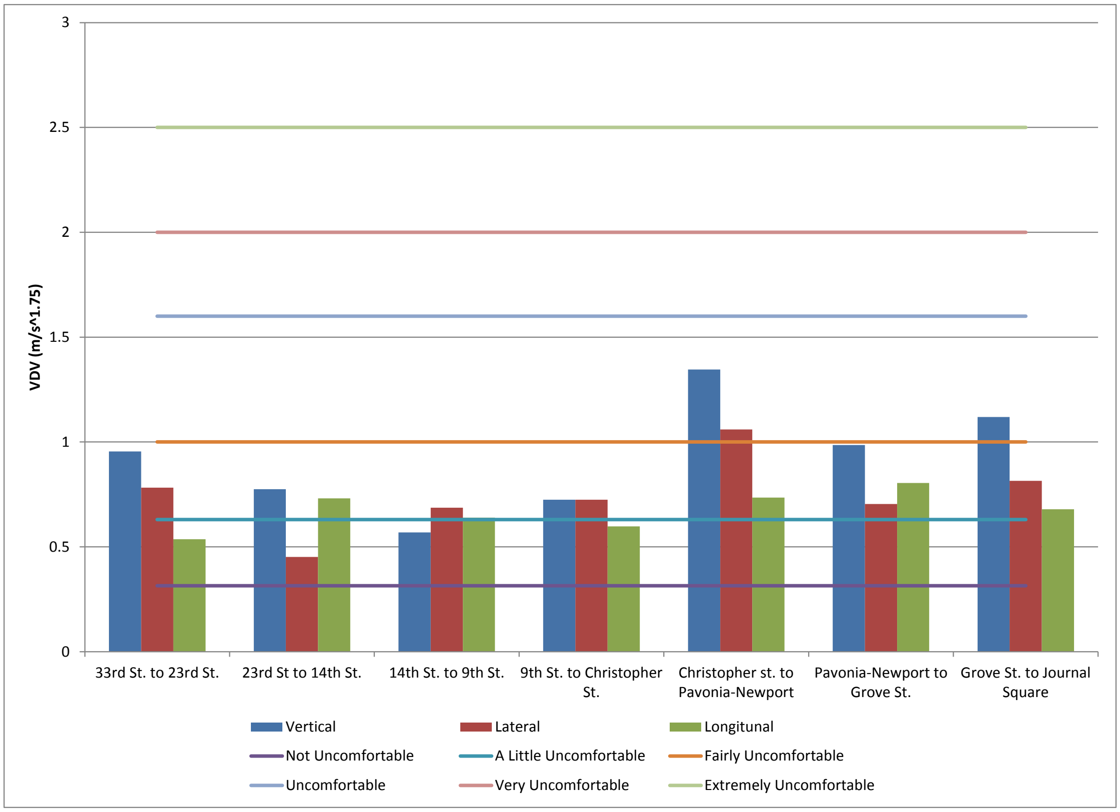

***Figure 21. VDV Ride Quality calculated for 33rd Street to Journal Square***

Figures 22 and 23 show the measured accelerations, speed, and track geometry between the stations. The vertical accelerations were excited between 4,000 and 8,000 feet. The maximum 2-second peak-to-peak is 0.37 g's. In this area, the track is mainly tangent with a shallow curve of 4,100-foot radius with a superelevation of 1 inch. The average speed is 38 mph. There are some cross-level deviations in the tangent track and profile deviations corresponding to the start of the increase in vertical accelerations (illustrated in Figure 22). The frequencies excited in the vehicle are approximately 0.9 Hz and 1.34 Hz (corresponds to bounce), 1.43 Hz (corresponds to upper center roll). In the vertical profile, there is a deviation that occurs approximately every 62 feet. The speed the vehicle was traveling through this segment of track corresponds to a frequency of 0.9 Hz.

The lateral accelerations are also excited in this section of track. Figure 23 illustrates the acceleration and corresponding alignment deviations. The maximum lateral 2-second peak-to-peak was 0.29 g's. The frequencies excited in the vehicle in this section of track are approximately 0.48 (corresponds to lower center roll) and 0.76 Hz. The horizontal alignment of the track in this segment has a deviation approximately every 74 feet, which corresponds to a frequency of approximately 0.76 at an average speed of 38 mph. Figure 24 and 25 show the frequency content of both the vehicle and track geometry in the lateral and vertical directions.

There appears to be a relationship between track geometry deviations and vehicle performance. PBTG NNs were developed to explore this relationship further. The results are discussed in Section 5.

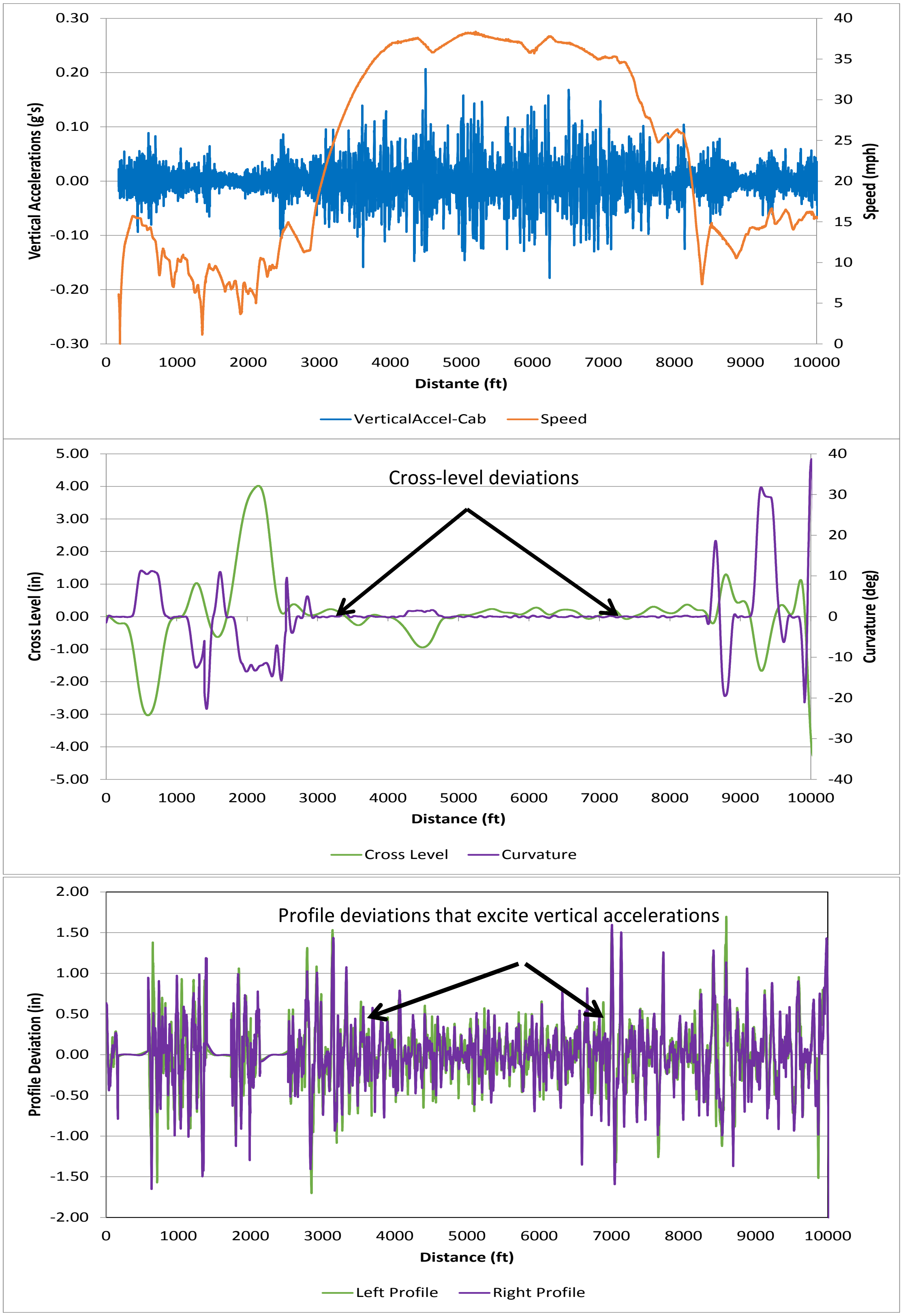

***Figure 22. Vertical Accelerations compared to Track Geometry***

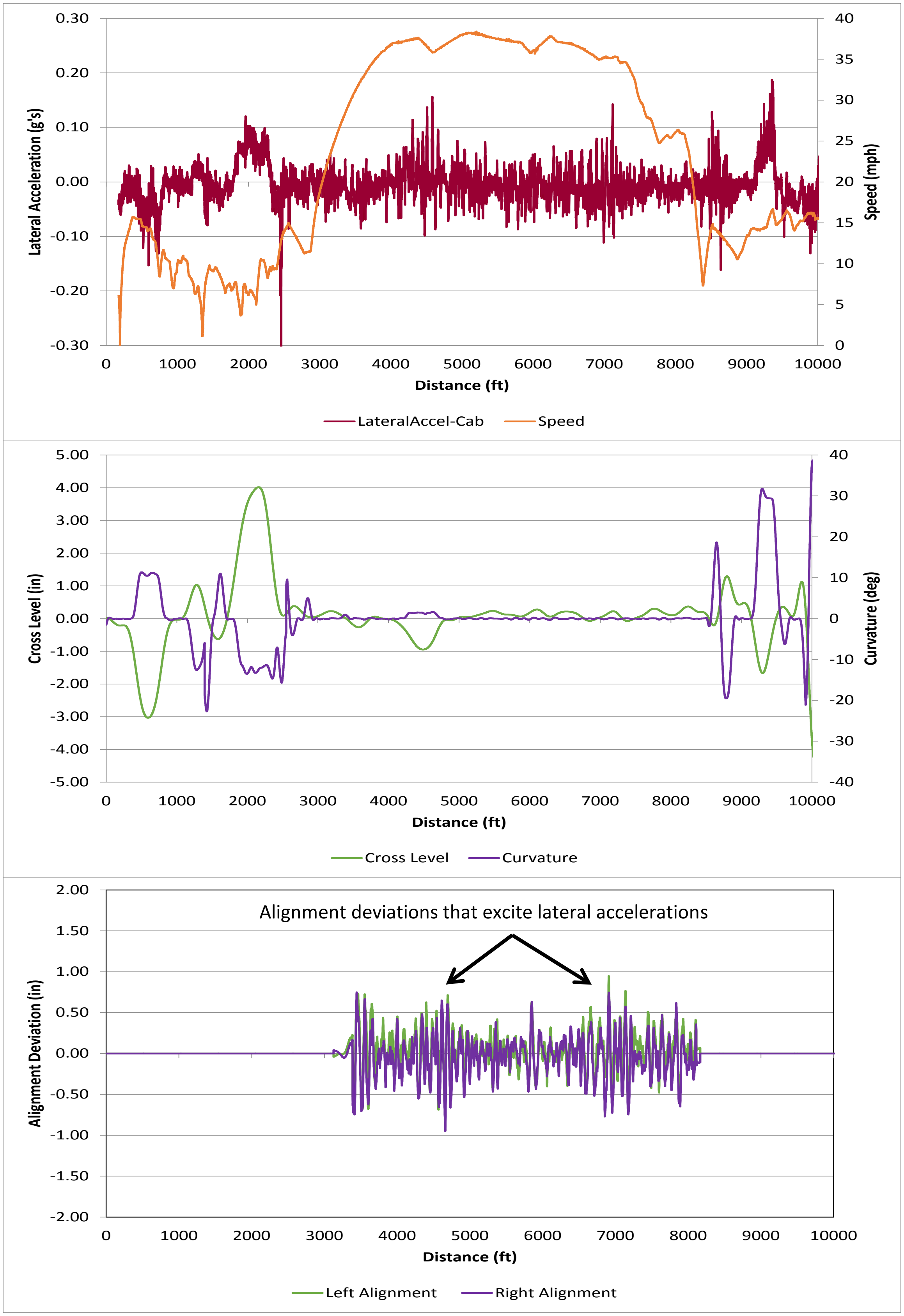

***Figure 23. Lateral Accelerations compared to Track Geometry***

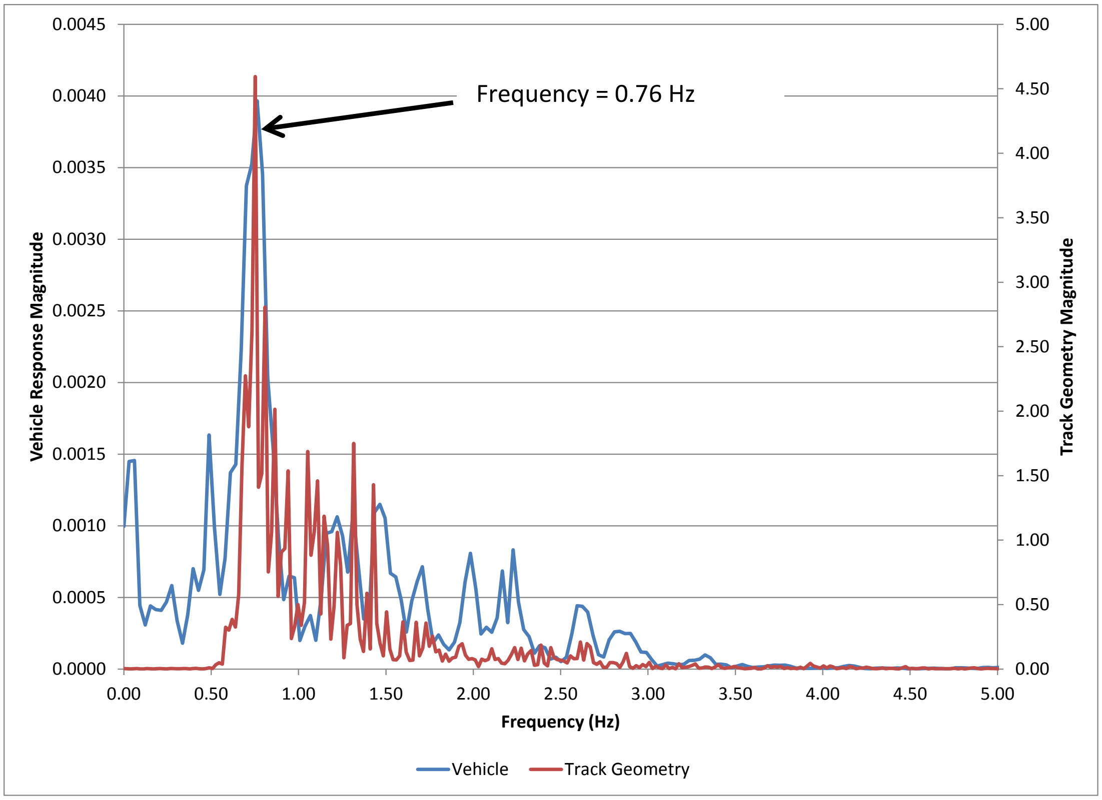

*Figure 24. Lateral Frequency Content*

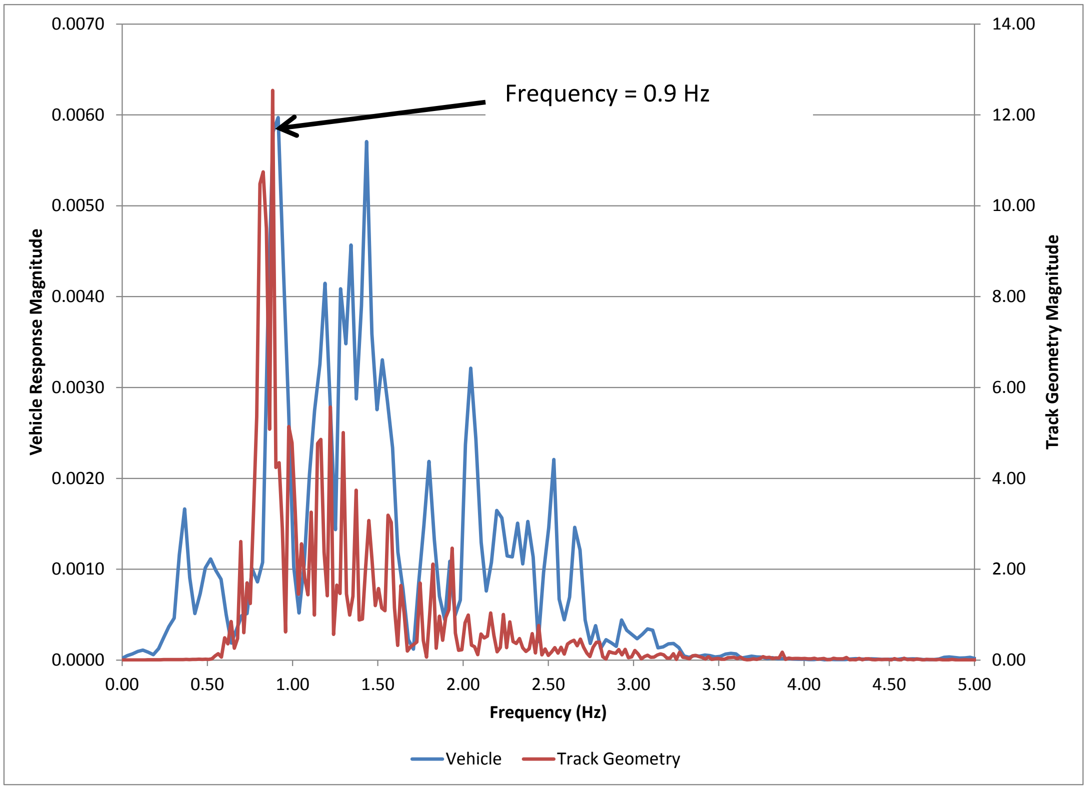

*Figure 25. Vertical Frequency Content*

### 2.3.3 Newark to World Trade Center

Figure 26 describes the location of test car 5746 in the train consist. The A-end of the car was leading from Newark to World Trade Center, and the B-end was leading in the other direction. Data was collected from 4:30 p.m. to approximately 7:15 p.m. on June 3, 2013. Load conditionsAW0 to AW4 (crush load) were measured during the test.

***Figure 26. Consist Setup***

Figures 27 and 28 show the ride quality measured and analyzed by the fourth power VDV method. Between Harrison and Journal Square stations the VDV value was in the fairly uncomfortable range. The measured values are summarized in Table 10.

**Table 10. VDV Values that exceeded Fairly Uncomfortable Ride Quality Index**

| Station | Measured VDV m/s$^{1.75}$ | Ride Quality Index |
|---|---|---|
| Harrison to Journal Square | Vertical 1.86 | Very Uncomfortable |
| | Lateral 1.24 | Uncomfortable |
| Journal Square to Harrison | Vertical 1.76 | Very Uncomfortable |
| | Lateral 1.00 | Uncomfortable |
| Grove Street to Journal Square | Vertical 1.23 | Uncomfortable |
| | Lateral 0.85 | Uncomfortable |

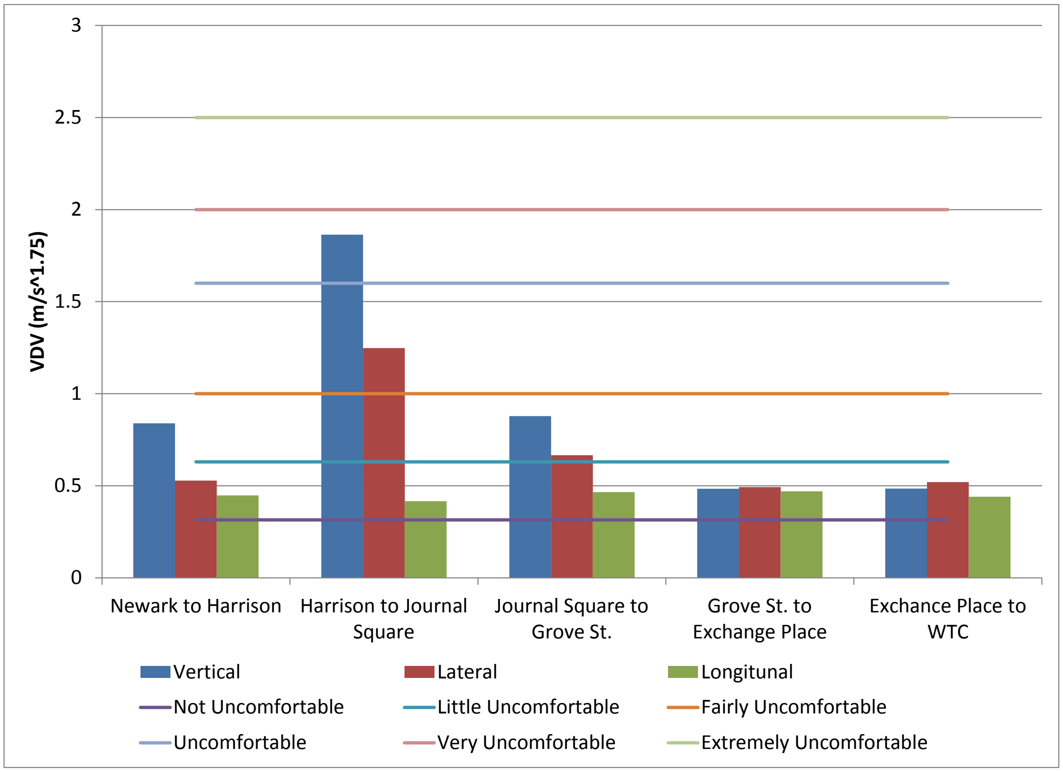

***Figure 27. VDV Ride Quality calculated for Newark to World Trade Center***

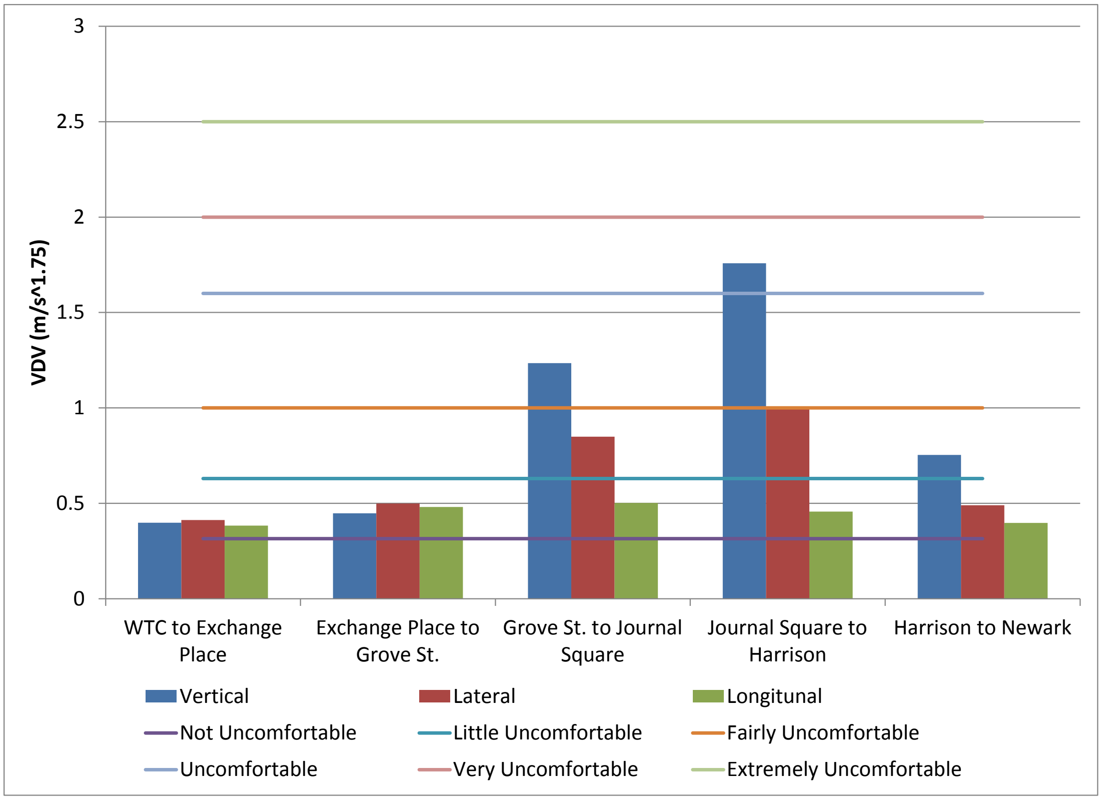

***Figure 28. VDV Ride Quality calculated World Trade Center to Newark***

Figures 29 and 30 show the measured accelerations, speed, and track geometry between the stations. The vertical accelerations are excited between 0 and 12,000 feet. The maximum 2 second peak-to-peak acceleration is 0.54 g’s. In this area, the track has three curves ranging from 3.5 to 1 degree, and two reverse curves ranging from 1 to 2.5 degrees. The average speed is 40 mph. There are profile deviations in this area. The frequencies excited in the vehicle are approximately 1.25 Hz and 1.59 Hz. In the vertical profile, there is a deviation that occurs approximately every 33 feet. The speed the vehicle was traveling through this segment of track corresponds to a frequency of 1.2 Hz.

The lateral accelerations are also excited in this section of track. Figure 30 illustrates the acceleration and corresponding alignment deviations. The maximum lateral 2 second peak-to-peak acceleration was 0.31 g’s. The frequency excited in the vehicle in this section of track is approximately 0.45 Hz (corresponds to lower center roll). In the horizontal alignment of the track in this segment, there is a deviation approximately every 130 feet. This corresponds to a frequency of approximately 0.45 at an average speed of 40 mph. Figures 31 and 32 show the frequency content of both the vehicle and track geometry in the vertical and lateral directions.

There appears to be a relationship between track geometry deviations and vehicle performance. PBTG NNs were developed to explore this relationship further. The results are discussed in Section 5.

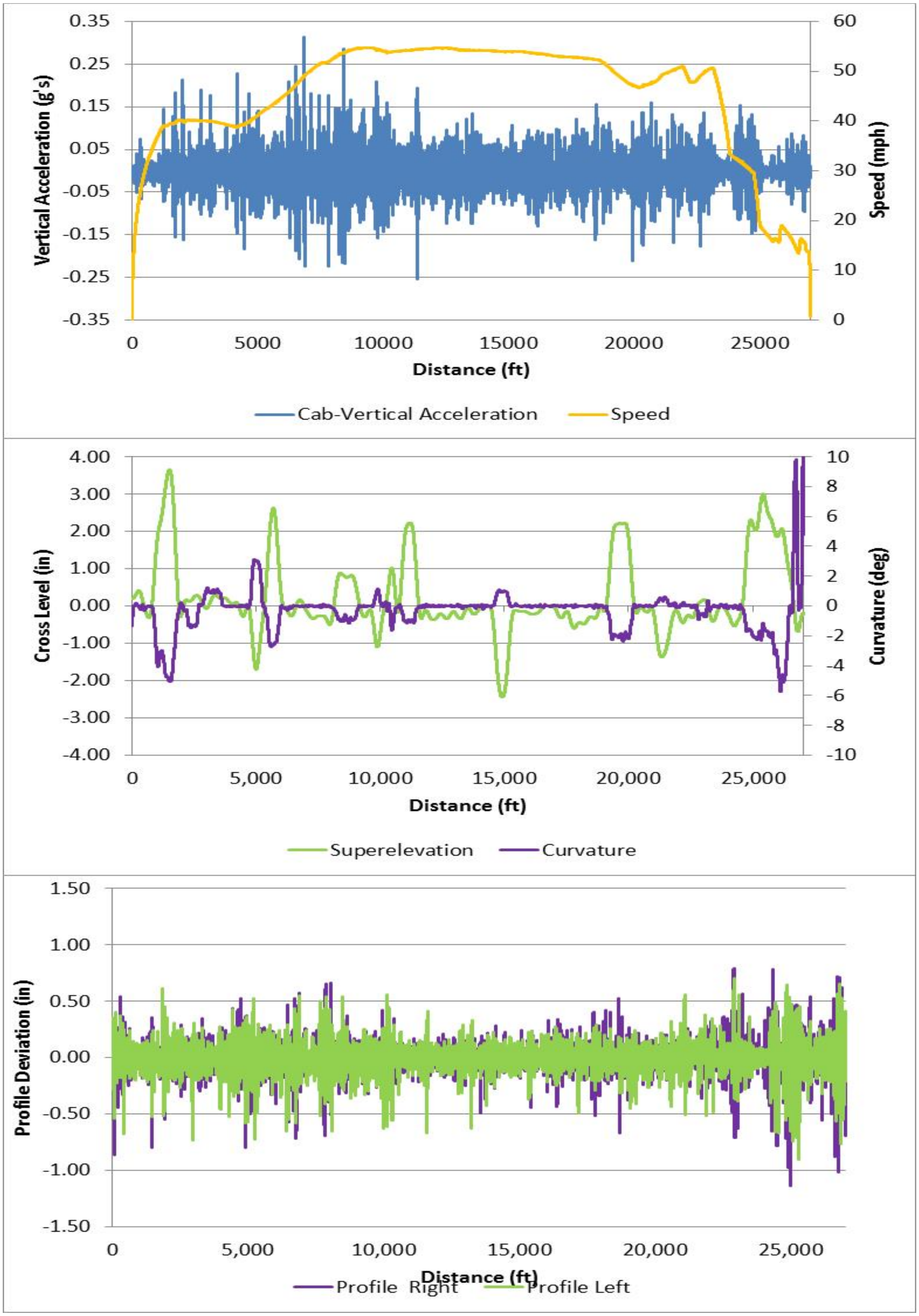

*Figure 29. Vertical Accelerations compared to Track Geometry*

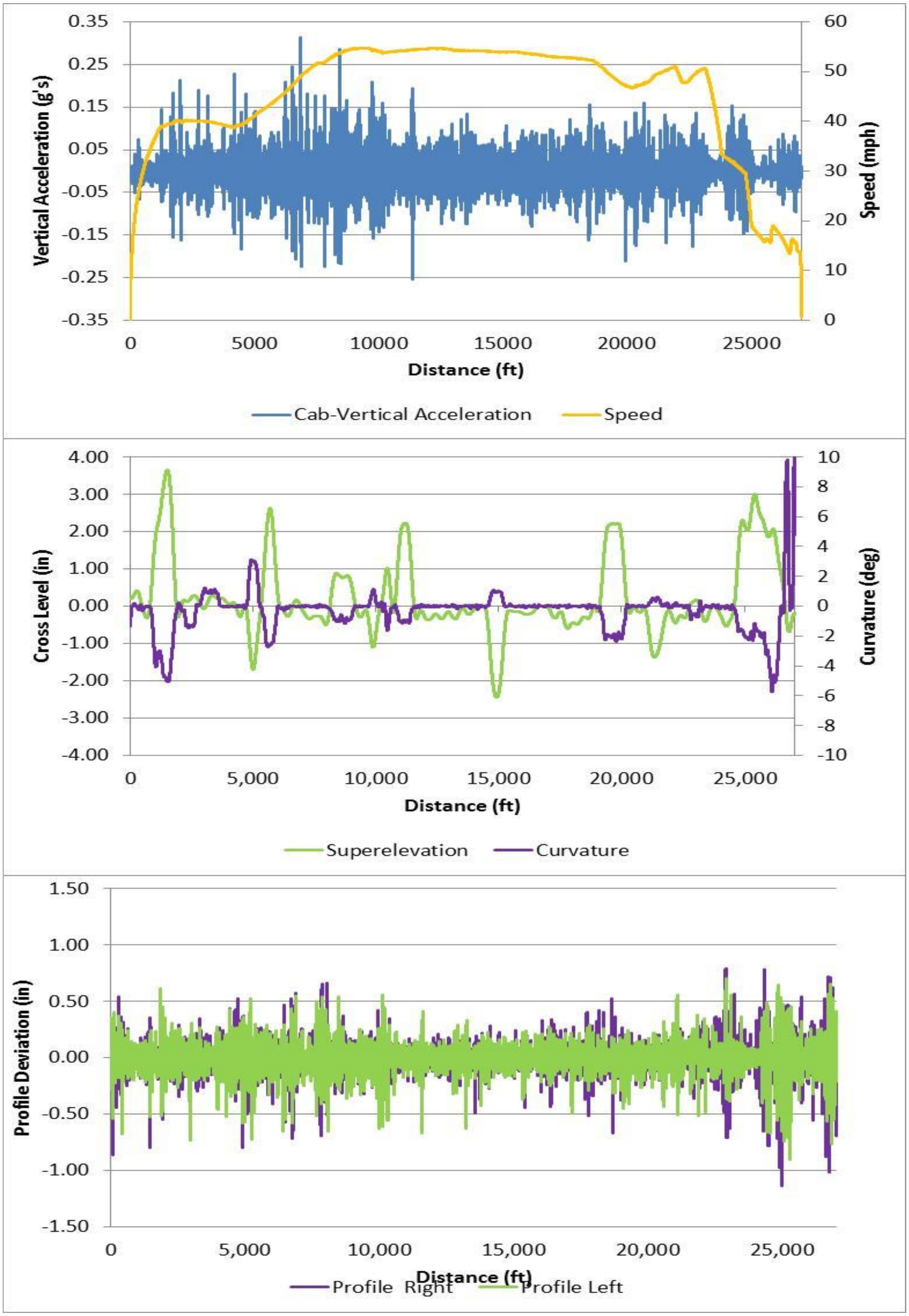

***Figure 30. Lateral Accelerations compared to Track Geometry***

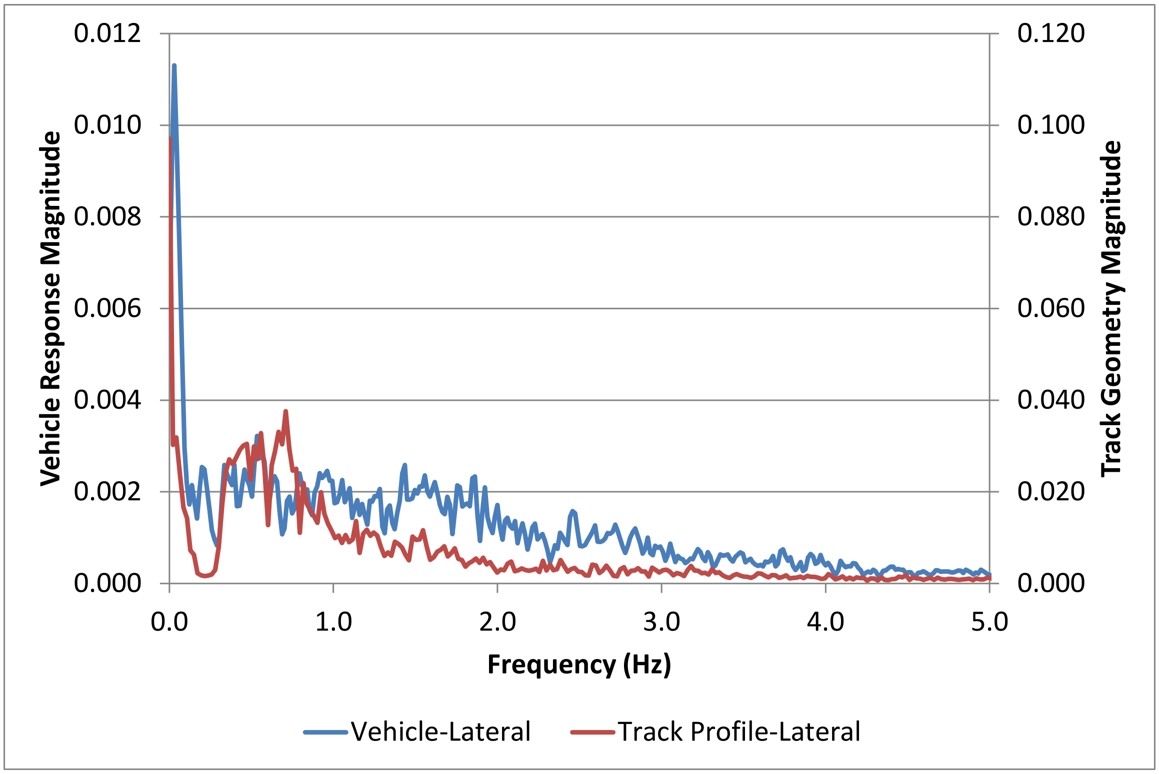

*Figure 31. Lateral Frequency Response*

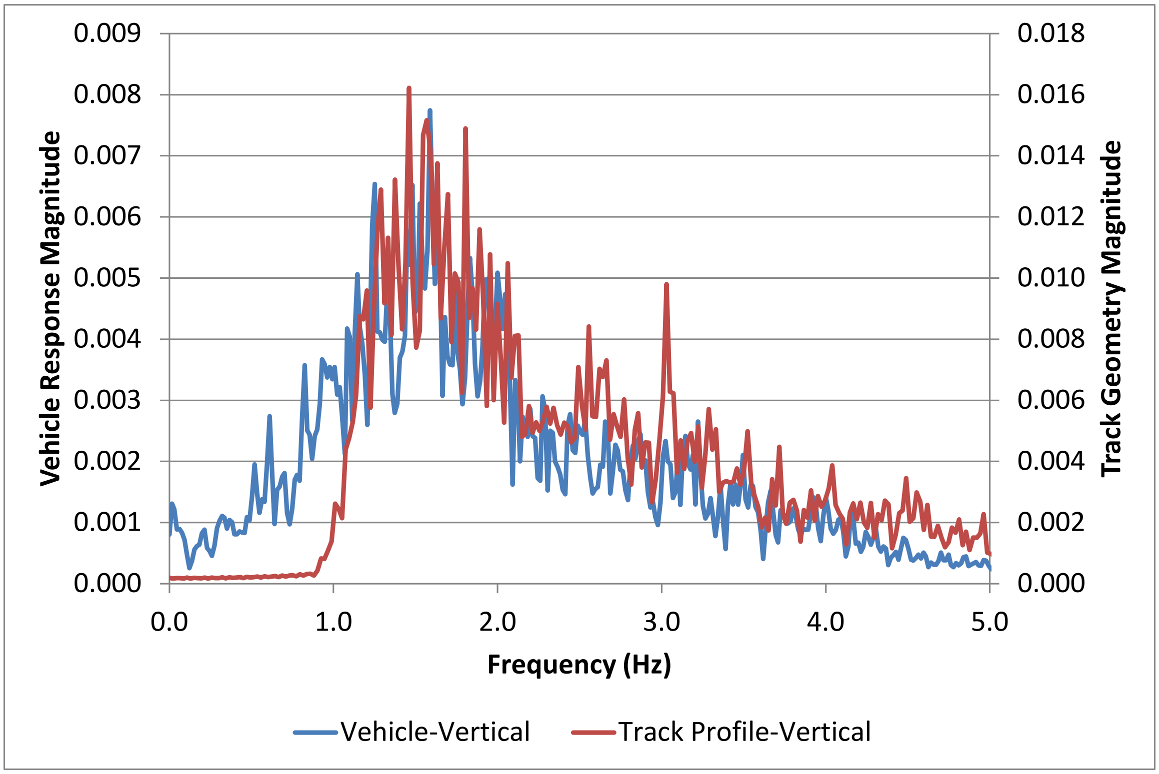

*Figure 32. Vertical Frequency Response*

CHAPTER 3

# Findings and Application

## 3.1 Model Validation

A NUCARS model was built to represent the PATH PA5 car, using design data updated by the measured characteristics. The model included a full nonlinear representation of the air suspension, including the effects of damping due to air flow in the orifices between the reservoirs and airbags. The measured track geometry was used as input to the model. A simulation of the same conditions as the ride quality test was done to determine if the model accurately predicted the vehicle performance.

Figures 33 and 34 compare the acceleration test data and modeling results for the section of track between Harrison and Journal Square stations. The plots show data collected on the floor in the driver's cab. In the NUCARS model, representative wheel and rail profiles were used. The NUCARS model predicted the same general trends as the actual measurement data.

Figure 33 shows vertical accelerations. The trends and amplitudes are similar between test data and modeling results. The difference in amplitudes may be due to the damping in the system. In the model, vertical dampers were assumed to be in new condition, and the damping properties were those provided by the damper manufacturer. The actual dampers on the car were not tested. This may contribute to the under prediction of vertical accelerations.

Figure 34 shows lateral accelerations. The model predicts the same trend as the test data; however, the magnitude is under predicted. The small differences in the magnitude may be due to the difference in the actual rail profiles and what was used in the simulation. A representative rail profile was used in the simulations. Wheel/rail interaction affects the lateral response of the car.

Figures 35 and 36 show the frequency content of the model and test data. Both the model and the test had a response similar frequency content for both lateral and vertical accelerations.

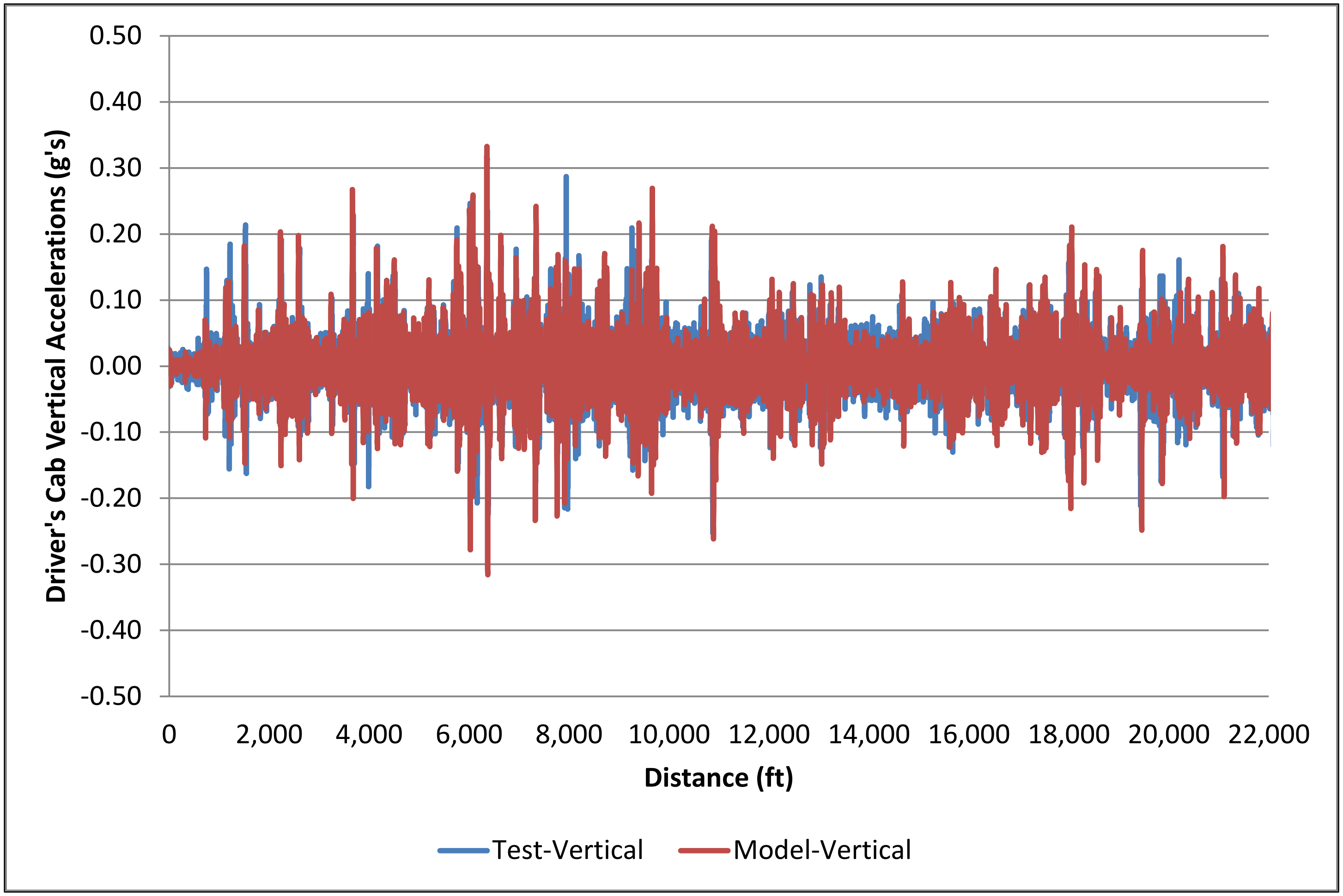

*Figure 33. Measured Vertical Accelerations Compared with Predicted Vertical Accelerations*

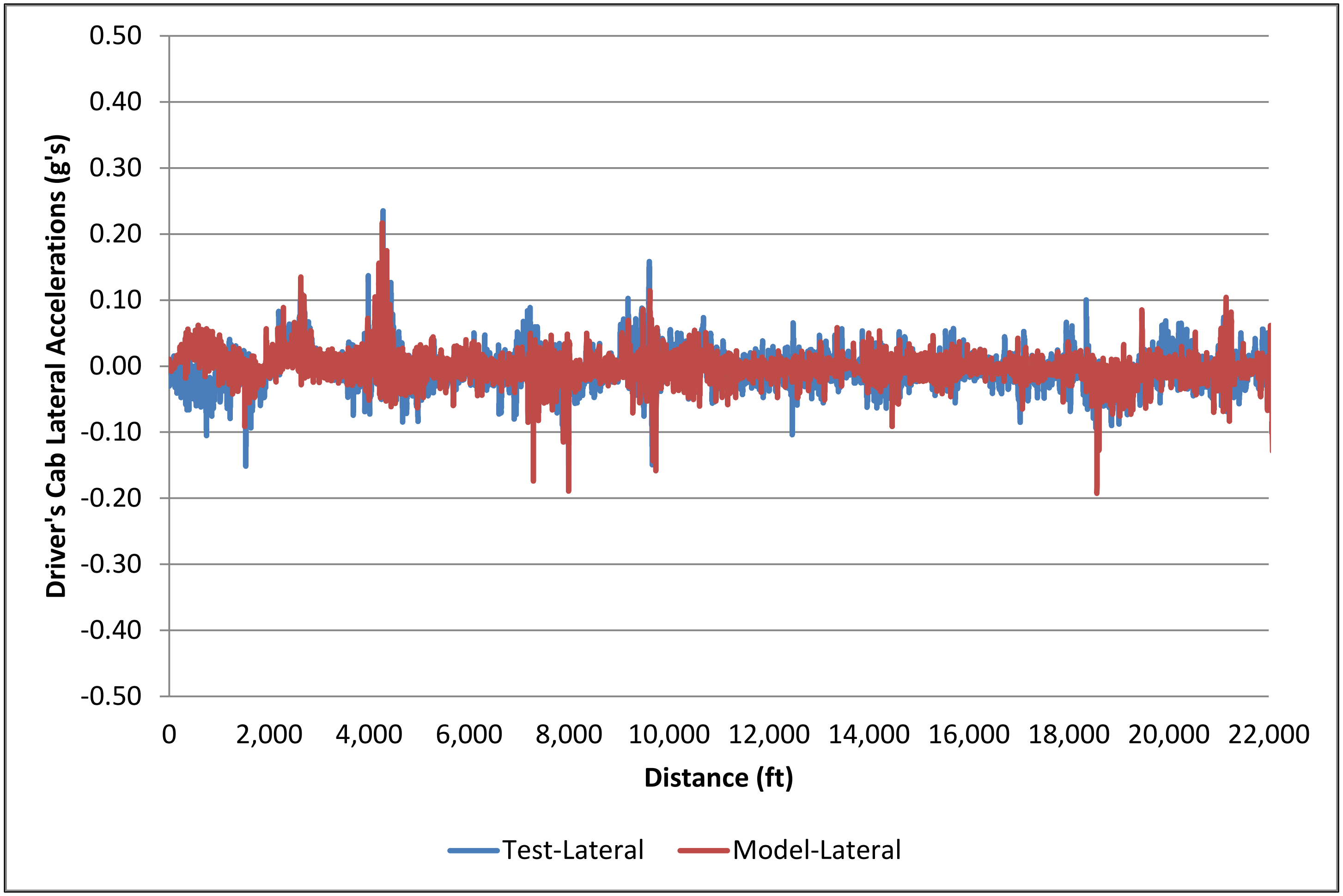

*Figure 34. Measured Lateral Accelerations Compared to Predicted Lateral Accelerations*

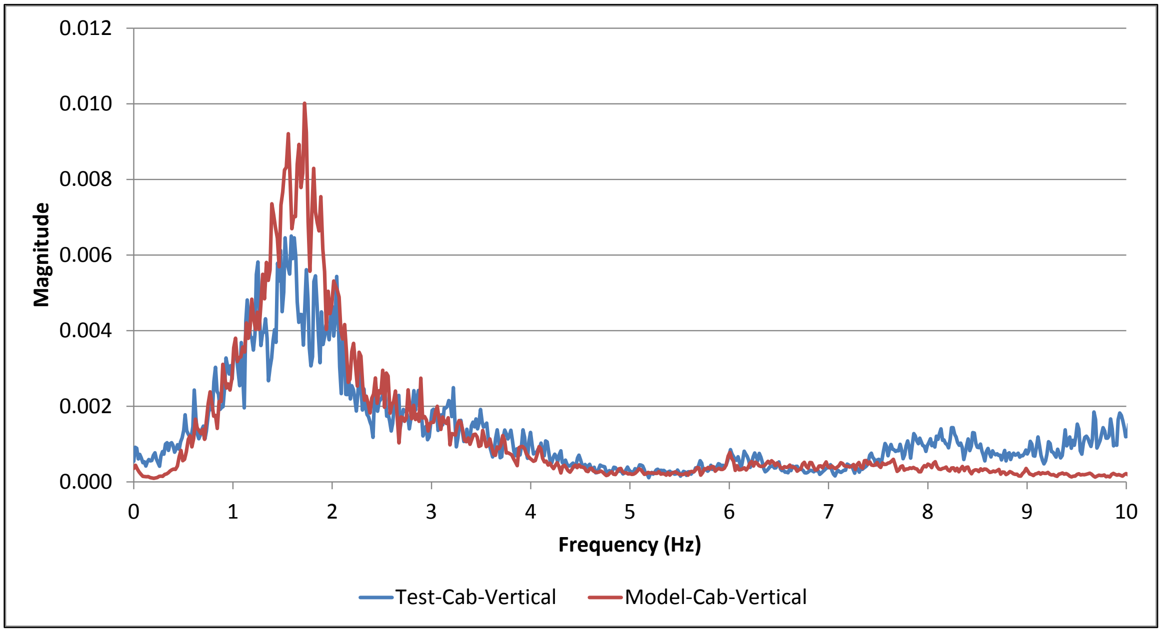

***Figure 35. Measured Vertical Acceleration Frequency Content Compared with Predicted Frequency Content***

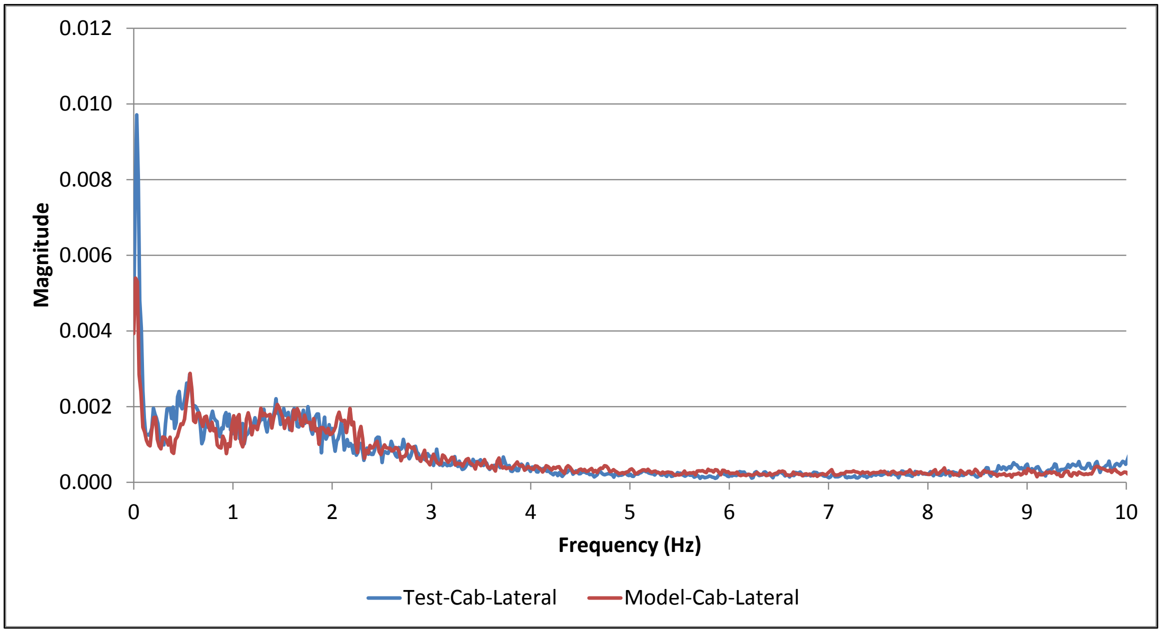

***Figure 36. Measured Lateral Acceleration Frequency Content Compared with Predicted Frequency Content***

## 3.2 Neural Net Development

A complex dynamic relationship exists between vehicle response and track geometry. PBTG inspection emphasizes that car dynamic response directly results from a combination of many track geometry variables acting together with vehicle operating conditions. Unwanted vehicle responses do not always result from individual track geometry defects, but from the dynamic interaction of the vehicle with all the track geometry parameters in the track segment where the unwanted response occurs. Use of NNs in the PBTG system allows all track geometry parameters and vehicle operating conditions to be related to vehicle performance.

NNs, such as the ones built under this task, are networks of artificial neurons or nodes consisting of many input paths and one output path. Figure 37 shows a simplified architecture of a NN.

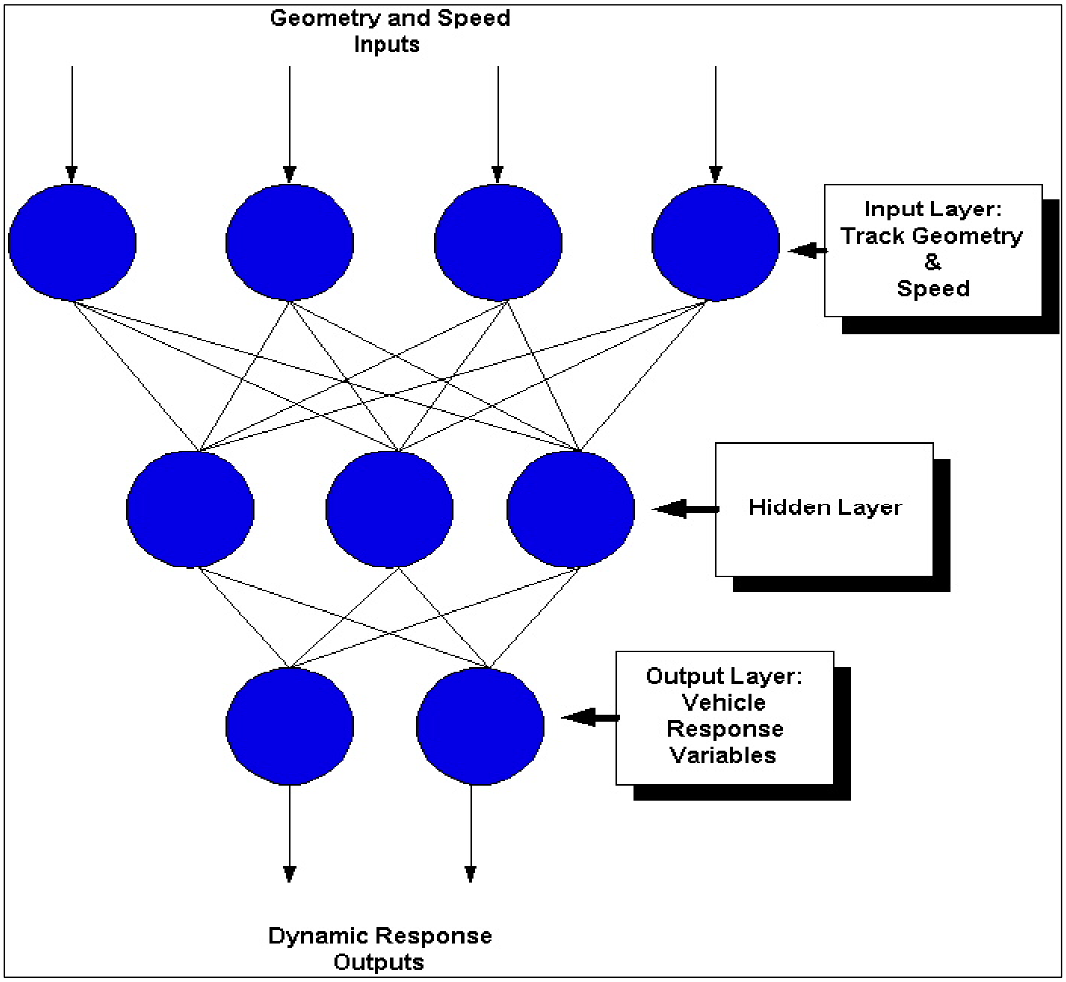

*Figure 37. NN Schematic*

The nodes in NNs can be connected in many ways. In this study, the architecture used to connect the nodes is multilayer perceptron (MLP). It consists of an input layer, two hidden layers, and an output layer. The input signal propagates through the network in a forward direction. To train an MLP, a back-propagation algorithm is used and is based on the error-correction learning rule. The rule applies forward passes and backward passes through all the network layers. In the forward pass, an input vector is applied to the nodes of the network, and the effect from applying that input vector propagates through the NN layers. Thus, an output is produced as an actual response of the network. If the network response is not adequately close to the desired response, a backward pass is used and the NN weights are iteratively adjusted based on an error-correction rule to fine-tune the response in order to move it closer to the desired response.

In addition, the number of nodes in the NN hidden layers is determined by the cascade learning method. In this method, one or more hidden nodes are added at a time until performance on an independent test set within the NN shows no additional improvement

The NNs are trained to learn and recognize patterns and relationships in vehicle/track interaction data. Once a NN is trained for a specific vehicle, it acquires the aptitude to predict the dynamic response of that particular vehicle. As a result, track segments that induce unwanted vehicle response can be identified. Two approaches were used to building the NNs:

- Point-by-point approach aligns the track geometry data with the measured vehicle response based on 1-foot increments.
- Segment-based approach uses the variable statistics, such as maximum, minimum, standard deviations and averages, from a 150-foot-long segment of track geometry. This information is related to the vehicle response over that segment of track.

### 3.2.1 DART NN Development

The NN was first developed under Phase 1 of this project, using a DART vehicle model and track geometry collected on the DART system in August 2010 to train the NNs.[6] Alignment, surface, gage, curvature, and superelevation were used. Operational speeds from the ride quality tests were also used in the NN training. Carbody and axle accelerations measured during the ride quality test in August 2010 were used to train and determine the effectiveness of the NNs to predict ride quality.

The first task was to align the track geometry and vehicle response data. The vehicle response data was shifted to align with the track geometry data. The location of the accelerometer, speed of vehicle, and a visual tool were used to align the data. Figure 38 shows the data before and after alignment.

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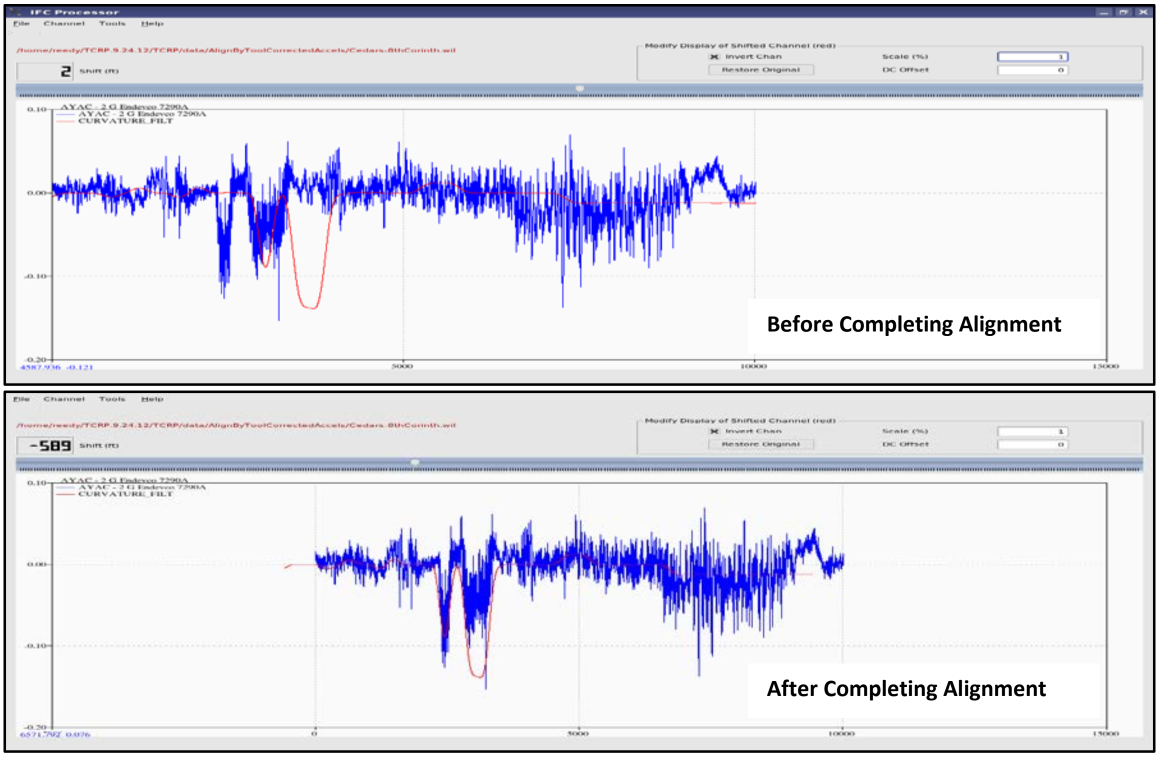
[6] Ketchum, C. and N. Wilson. *TCRP Web-only Document 52: Performance Based Track Geometry Phase 1*. Transportation Research Board of the National Academies, 2012. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_w52.pdf



/home/reedy/TCRP.9.24.12/TCRP/data/AlignByToolCorrectedAccels/Cedars-8thCorinth.wil

Shift (ft): 2

☒ Invert Chan

Scale (%): 1

DC Offset: 0

/home/reedy/TCRP.9.24.12/TCRP/data/AlignByToolCorrectedAccels/Cedars-8thCorinth.wil

Shift (ft): -589

☒ Invert Chan

Scale (%): 1

DC Offset: 0

***Figure 38. DART – Alignment of Ride Quality Data and Track Geometry Data***

The NNs were trained using a portion of the measured ride quality data. The trained NNs were then deployed to predict ride quality on a section of track not seen by them. This information is called validation data. It is an indicator of the accuracy of the trained NNs to predict ride quality for the DART SLRV on the DART red line.

Figure 39 shows a NN trained using the point-by-point approach on data collected between Walnut Hill and Forest Lane Stations. The blue line represents the lateral accelerations measured under the operator's seat at the A-end of the car. The red line represents the predicted accelerations from the training data.

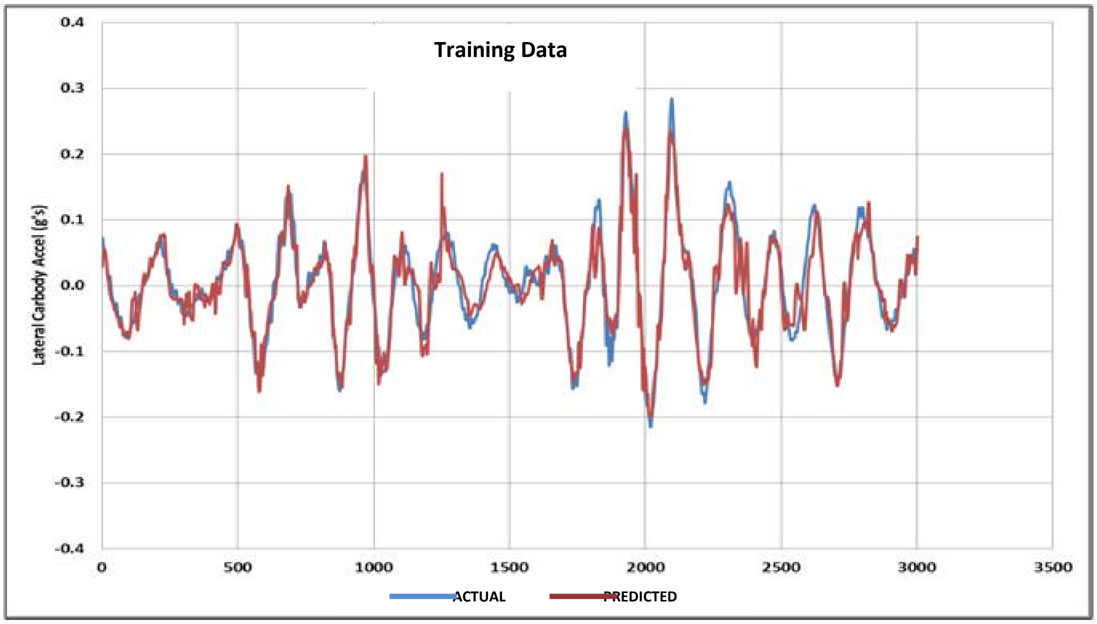


*Figure 39. DART – Neural Net Training Data for Point-by-Point Approach*

Figure 40 shows the trained NN deployed on LBJ station to Spring Valley Stations track geometry for validation. The NN predicted the lateral accelerations with 0.1 percent confidence. The NN model performed very poorly on the validation data, although it performed satisfactorily on the training data.

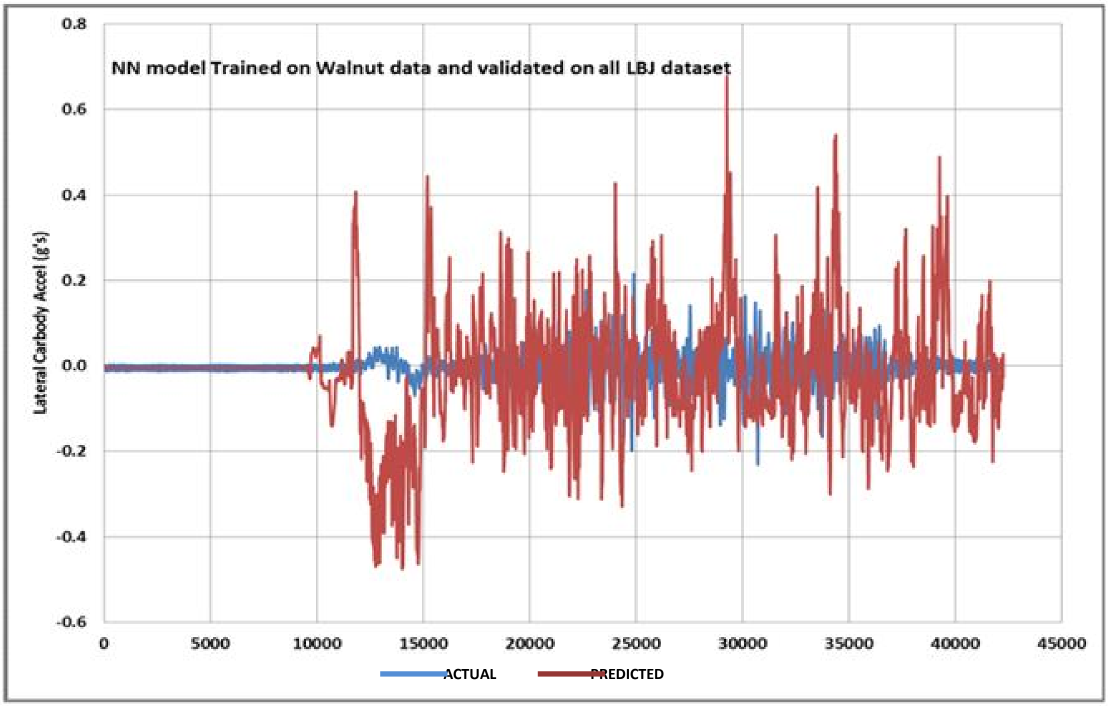


*Figure 40. DART – Point-by-Point Approach deployed on LBJ to Spring Valley Station Data*

Figure 41 shows NN training and validation data using a segment-based approach. The NN predicted the carbody vertical accelerations with 0.25 percent confidence. This NN model, too, presented a poor predictive performance on the validation data.

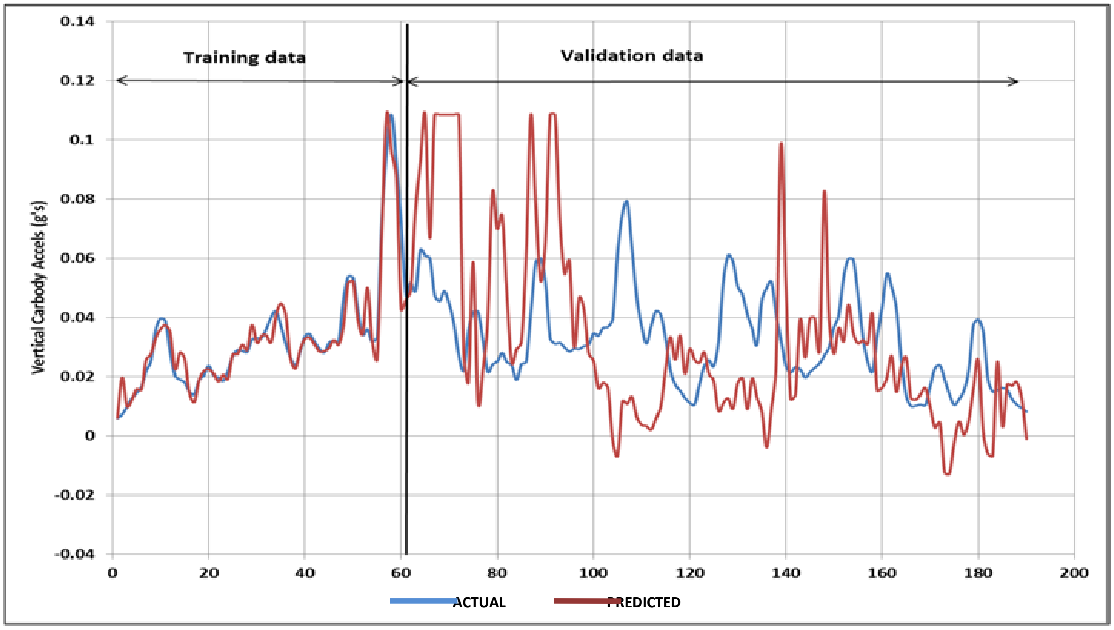


***Figure 41. DART – Segment-based Approach deployed on LBJ to Spring Valley Station Data***

Both models displayed a case of what is known as "overfitting," meaning, the NN models learned just to memorize the training data, but were unable to generalize from trending patterns present in the validation data. Lacking high dynamic events in the training data (and validation data as well), the data used to build the models may have been seen as patternless noise during the NN training process, which NN models tend not to recognize. From past experience, NN model performance would have been better if training data had contained a wide range of significant track geometry deviations and corresponding high dynamic events in terms of accelerations.

### 3.2.2 PATH NN Development

Data was selected and processed to build a synchronized database of ride quality and track geometry. The data was comprised of dynamic response of the PATH PA5 car to wide-ranging track and operating conditions. The database was used to build NN algorithms that relate the track geometry conditions to the likely ride quality accelerations of the PA5 car. The segment-based approach was used in this effort. Variable statistics, such as maximum, minimum, standard deviations and averages, from a 150-foot-long segment of track geometry were utilized the build the NN models. The following variables were used as input for developing the NNs:

- Track alignment
- Track surface
- Gage
- Curve and Superelevation
- Operating speed
- Centrifugal force (synthetic channel) created from curvature and speed

Carbody accelerations were the output variables the NN models were trained to predict. Figure 42 shows an example of a predicted front carbody vertical acceleration (in red) versus actual data (in blue). The validation data, as shown in the graph, is deployment data that was not used during the NN training. The correlation coefficient of 81 percent measured the strength of association between the NN predictions and actual response. Figures 43 and 44 show predicted carbody center and driver cab accelerations versus actual data. The correlation coefficients were 78 and 71 percent, respectively.

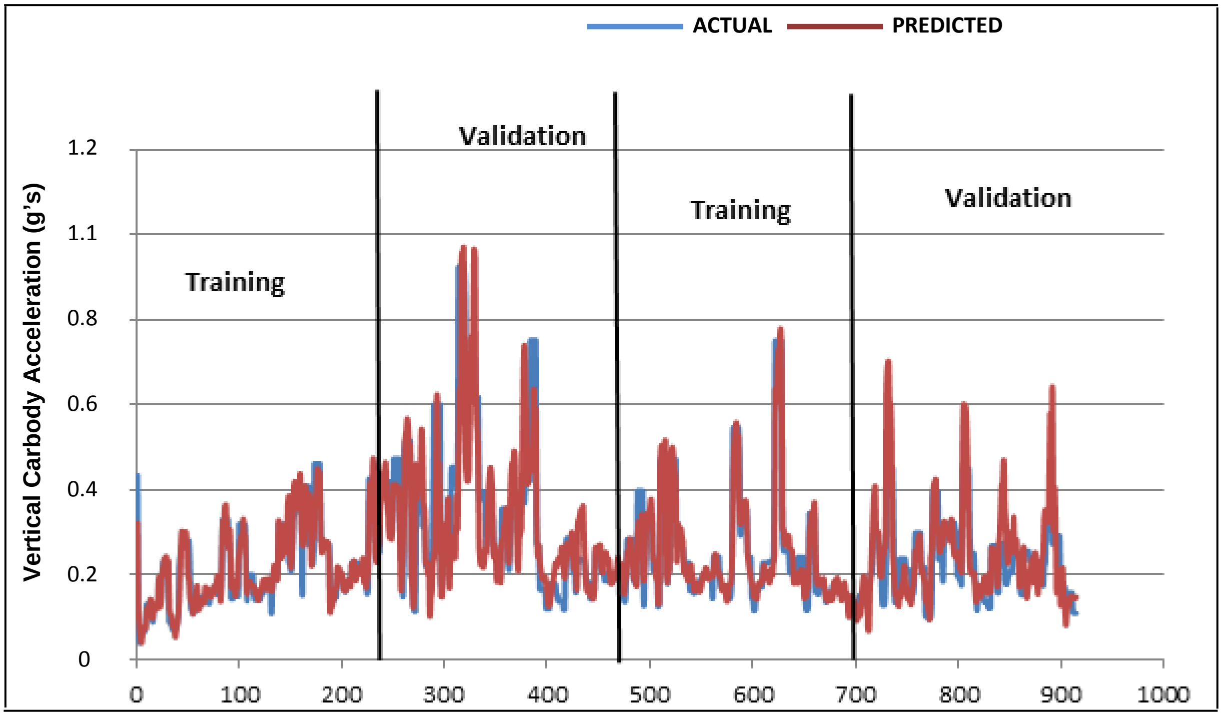


*Figure 42. PATH Training and Validation Data at Front Carbody Acceleration*

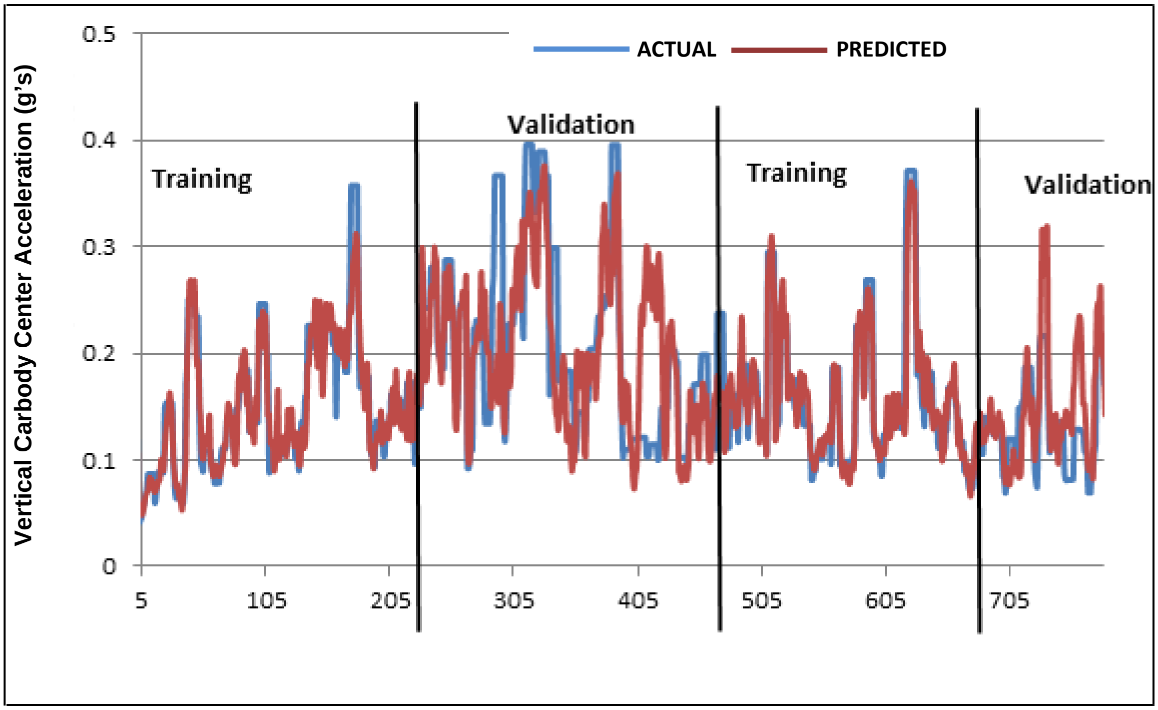


*Figure 43. PATH Training and Validation Data at Center Carbody Acceleration*

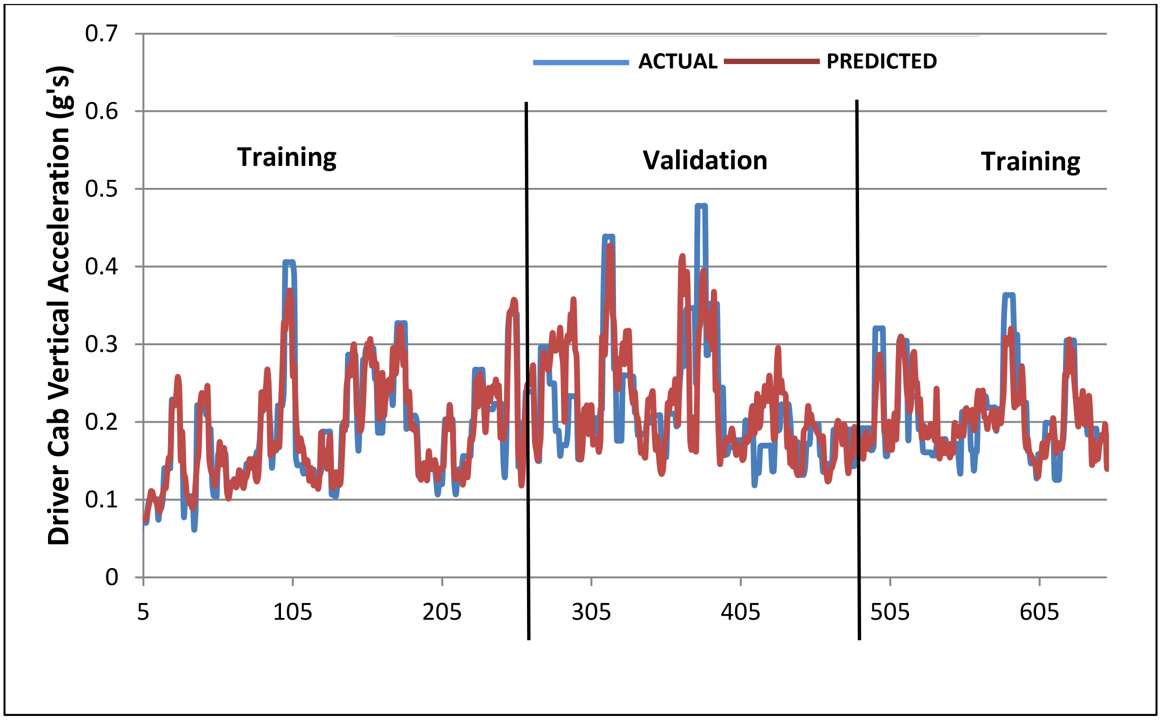


*Figure 44. PATH Training and Validation Data at Driver Cab Carbody Acceleration*

The predictions of these preliminary NN models were adequate and represent a significant improvement in comparison with the NN models built using the DART data, because of the following conditions:

- More track geometry deviations trends and corresponding high dynamic responses were present in the data collected on PATH tracks
- Geometry deviations and high dynamic responses are patterns that NN models are capable of recognizing reasonably well if available in the training data.

By contrast, good track conditions and low dynamic response are seen as patternless noise that the NNs tend not to recognize the trends or the patterns.

## CHAPTER 4

# Conclusions and Suggested Research

## 4.1 NUCARS Model Validation

The NUCARS model of the PATH PA5 car was updated with the information collected during the vehicle characterization testing. Simulations were performed using the track geometry that was measured on the PATH system in July 2013. Simulation results were compared to test data to determine whether the model accurately predicted vehicle response to track geometry input.

Lateral and vertical accelerations collected in the driver's cab were compared to the simulation results, which correctly predicted the trends and frequency content of the accelerations. There was some deviation in the magnitudes. The discrepancy may be due to the following:

- Dampers of the PA5 car were not measured. Manufacture damping information was used in the model. There can be some variation of actual properties and manufacturer data. In the model, it was assumed that the damper was in new condition. The vehicle had been in service, so it is likely that the dampers had some wear.
- Representative rail profiles were used in the simulations. Wheel/rail interaction is influenced by the shape of the wheels and rails. The difference between the actual rail profile and the representative profile can contribute to some of the deviations between test and modeling results.

To determine the extent of the influence of these parameters, more simulations would have to be run varying the damping and rail profiles. The frequency content and trend were accurately predicted. The magnitude had some deviations, but was well within an acceptable range. The model was used to generate information to build the NNs for PBTG proof of concept.

## 4.2 On-track Tests

A correlation between passenger ride quality and track geometry on the PATH system was identified. Table 11 shows a vehicle response frequency that correlated with a wavelength identified in the track geometry. Further work needs to be done to identify what track anomalies or structures correspond to the wavelengths identified. The influence of entry/exit spiral (or lack of) will need to be investigated. The roll response due to curves can affect ride quality and will need to be studied in Phase 3.

**Table 11. Frequency Response of Vehicle and Corresponding Wavelength in Track**

| Location | Acceleration Direction | Vehicle Frequency Response (g's) | Track Geometry Wavelength |
|---|---|---|---|
| Pavonia-Newport to Christopher Street | Vertical | 0.9 Hz | 62 ft |
| | Lateral | 0.76 Hz | 74 ft |
| Harrison to Journal Square | Vertical | 1.25 Hz | 33 ft |
| | Lateral | 0.45 Hz | 130 ft |

## 4.3 PBTG NN Development

NNs were built for both the DART System and the PATH system.

- DART NNs predicted vehicle response to track geometry with confidence intervals of 0.1 percent and 0.25 percent based on point-by-point response and segment-based approach, respectively.
- The poor predictive performance on DART is due to what is known as overfitting. The track geometry had small deviations; therefore, there were no high dynamic events in the ride quality data. The data used to train the NNs was seen as patternless noise; therefore, the NNs did not recognize a trend in the data.
- PATH NNs predicted vehicle response to track geometry with an 81 percent confidence interval using the segment-based approach. The data collected on PATH had significant dynamic events recorded in response to wide range of track geometry deviations. These results show significant improvement compared to DART NNs, which is due to the PATH NNs recognizing trends in the data.

The PATH and DART NNs show a potential for using PBTG on some transit systems:

- Transit systems with track structures that have significant track geometry deviations and corresponding dynamic response in the vehicle are potential candidates for using NNs to develop PBTG
- Transit systems with very few track geometry deviations and relatively low dynamic response are not well suited for using NNs to develop PBTG

Phase 2 showed that a correlation between track geometry and vehicle performance can be established. NNs can also be used to predict the vehicle response with a high degree of confidence. More in-depth study will need to be done to establish whether what was predicted by the NNs was accurate and if the track geometry deviation can be mitigated to improve ride quality.

## 4.4 Recommendation for Future Research: Phase 3

The work from Phase 1 and Phase 2 shows that there is potential for PBTG to be used on transit systems to optimize maintenance and ride quality. Further work will need to be done to determine the viability of a PBTG system and establish guidelines for implementation. The following are tasks that are recommended for Phase 3:

- Build a complete set of NNs for PATH using the data and NUCARS model of the PA5 Car.
- Use PBTG developed for PATH to predict areas in track that cause adverse ride quality. Once these areas are identified, a track inspection should be done to determine if the prediction is accurate and if it is in fact a deviation that can be maintained (slab track versus ballasted track, etc.).
- Correct deviations in the identified track locations. Measure both track geometry and ride quality to determine if significant improvement is achieved.
- If significant improvement is achieved, modify the PBTG System that was developed for freight railroads to meet the transit agency needs.
- Write guidelines for implementation of PBTG for transit systems.