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Force Environment Evaluation of Stub Sills on Tank Cars Using Autonomous Over-the-Road Testing of the Instrumented Tank Car

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13. ABSTRACT (Maximum 200 words)

Fractures have been observed on stub sill tank cars for many years. Undetected and unattended, these fractures can develop into a variety of tank car failures. While tank car ruptures are rare, the potential for a catastrophic hazmat release has made this a critical issue within the industry. The FRA contracted with ENSCO, Inc., to instrument and run an instrumented tank car over the road in autonomous measurement mode. The instrumentation and data collection focused on assessing the load environment seen by tank cars in regular service under full load conditions. Testing was conducted to collect data from the instrumented tank car over approximately 3,700 miles in the United States. The following key conclusions and recommendations are inferred from testing and analysis: 1) The high magnitude events that seem to cause damage to the stub sill are observed in yards and are attributed to train handling. Track geometry, specifically short chord vertical profile, is a contributing factor causing high vertical coupler force events, but typically is not a contributing factor for high longitudinal coupler force events. 2) If the coupling speeds are limited, the forces imparted to the stub sills would be kept lower than the yield limit for steel, reducing the occurrence of fractures in stub sills on tank cars. 3) A low-cost system can be developed for measuring vertical and longitudinal coupler forces in service.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC		METRIC TO ENGLISH	
LENGTH (APPROXIMATE)		**LENGTH** (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)	1 millimeter (mm)	= 0.04 inch (in)
1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	= 0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (km)	= 0.6 mile (mi)
AREA (APPROXIMATE)		**AREA** (APPROXIMATE)	
1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
MASS - WEIGHT (APPROXIMATE)		**MASS - WEIGHT** (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)	1 gram (gm)	= 0.036 ounce (oz)
1 pound (lb)	= 0.45 kilogram (kg)	1 kilogram (kg)	= 2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)	1 tonne (t)	= 1,000 kilograms (kg)
			= 1.1 short tons
VOLUME (APPROXIMATE)		**VOLUME** (APPROXIMATE)	
1 teaspoon (tsp)	= 5 milliliters (ml)	1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)		**TEMPERATURE** (EXACT)	
[(x-32)(5/9)] °F	= y °C	[(9/5) y + 32] °C	= x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0			1		2			3		4			5
Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

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

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

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Executive Summary

The FRA contracted with ENSCO, Inc., to instrument and run a tank car over the road in a special consist in June and July 2008. Results from this study resulted in recommendations to conduct an autonomous test to provide accurate information on the force environment spectrum that a tank car experiences during routine operations. The tank car, provided by General Electric (GE) and instrumented by ENSCO, was routed through hazmat routes and different yards to capture force environment information. The instrumented tank car was run in autonomous mode collecting force environment data over approximately 3,700 miles.

The data was collected over a period of four months, between February 17, 2010, and June 22, 2010, on CSX track from Gettysburg, PA, to Florida, Alabama, and back to Pennsylvania. This report describes the instrumentation, calibration, testing, and analysis efforts conducted by ENSCO over this four-month period. It also documents and describes the results, conclusions and recommendations out of the testing conducted.

Key Tank Car Characteristics:

- Manufactured by Union Tank Car
- Under frame design UTLZBG stub sill with head brace
- Coupler SE60DE
- Draft gear E/F top and bottom shelf
- Test conducted with the tank filled with 22,132 gallons of water (184,000 pounds) to achieve the weight limit of the car
- Total car weight 263,000 pounds

Longitudinal Coupler Force (LCF) Events:

- Top 30 LCF events with magnitudes greater than 635 kip[1] were analyzed:
  - 19 occurred in flat switching yards with a maximum LCF of 1,800 kip
  - 10 occurred in hump yards with a maximum LCF of 900 kip
  - 1 occurred in normal operation with a maximum LCF of 880 kip
- All 3 events that exceeded the Association of American Railroads (AAR) Standard (AAR M-1002) of 1,000 kip occurred in flat switching yards
- Most events were based on compressive forces, with only 3 events having large positive forces
- Maximum speed of tank car at beginning of events was 8 mph.
- Amount of time spent was substantially longer in flat switching yards than in normal hump yards for this study.

[1] 1 kip = 1,000 pounds-force.

- Events exceeding 673 kip occurred approximately once every 4 days while in a switching yard.
- Events exceeding 1,000 kip occurred approximately once every 40 days while in a switching yard.

Vertical Coupler Force (VCF) Events:

- Top 20 VCF events with magnitudes between 26 kip and 42 kip were analyzed:
    - 6 events (30%) occurred on or very near road crossings (within 25 feet).
    - 6 events (30%) occurred in yard operations.
    - 2 events (10%) occurred near bridge starts/ends.
    - 2 events (10%) occurred near switches/sidings.
    - 4 events (20%) had no distinguishable track features.
- No events exceeded the AAR Standard (AAR M-1002) of 50 kip.
- Highest upward force observed was 42 kip, whereas the highest downward force was about 33 kip.

Analysis:

- Based on the coupler forces observed, the stress on the upper face of the stub sill near the tank structure was calculated. The maximum stress predicted was 66,600 psi. This large stress occurred as a result of a large 1,800-kip compressive LCF.
- Next maximum stress magnitude predicted was 37,700 psi.
- Yield stress of the stub sill (made out of A572-50 steel) was 50,000 psi.
- 1,000-kip LCF (AAR M-1002 standard) produced a stress of 32,500 psi.
- 50-kip VCF (AAR M-1002 standard) produced a stress of 13,140 psi.
- Track geometry exceptions had an effect on the vertical coupler force but did not seem to cause the highest magnitude events.
- The high-magnitude events that seemed to cause damage to the stub sill were observed in yards and attributed to train handling in yards.
- If coupling speeds are limited, stresses imparted to the stub sills should be less than the yield limit for steel, thereby reducing the occurrence of fractures in stub sills on tank cars.

Conclusions:

- Stub sill tank cars were being subjected to LCF exceeding the AAR design limits.
- The majority of LCF with large magnitudes occurred in switching yards.
- The tank car was subjected to VCF less than the AAR design limits.
- Short-wavelength surface track geometry deviations were correlated with many of the large VCF events.

- Stress in the stub sill exceeded the elastic limit of the stub sill material.

Recommendations:

- Low-cost methods to measure LCF and VCF at both ends of tank cars should be developed and employed on about 20 cars to further characterize the force environment for tank cars in regular service.
- Guidelines for operations in flat switching yards should be generated to limit coupling speed and the effective impacting mass.

1. Introduction

This report describes testing conducted by ENSCO, Inc., under the sponsorship of the Federal Railroad Administration (FRA), in which data was gathered on railroad tank car vehicle dynamics, test data was analyzed to improve understanding of tank car stub sill failures, environmental conditions that lead to tank car damage were identified, and further testing methods were discussed.

1.1 Background

Fractures have been observed on stub sill tank cars for many years. Undetected and unattended, these fractures can develop into a variety of tank car failures. While tank car ruptures are relatively rare, the potential for a catastrophic hazmat release has made this a critical issue for the industry. As a result of this concern, special requirements for the construction, inspection, and repair of tank cars have been implemented.

Research into the underlying causes of stub sill tank car cracking and propagation continues. It is believed by some that the fractures are initiated by discrete events resulting in high stresses. Multiple tests and models have focused on extreme loading events and their contribution to the development of the fatigue cracks. Furthermore, it is believed by some that the cracks are propagated by the stresses caused by regular over-the-road service.

Under direction of the Tank Car Operating Environment Task Force (TCOE-TF) and the Stub Sill Working Group (SSWG), a test program was initiated to develop a methodology for both the measurement and reporting of events approaching and exceeding stub sill tank car design specifications. The TCOE-TF and the SSWG represent cooperative efforts between FRA, the Association of American Railroads (AAR), the Railway Supply Institute (RSI), and Transport Canada (TC).

Phase I of this test program addressed the development and proof of a method to record vertical and longitudinal coupler forces by employing strain gauge-based transducers and instrumentation. Phase II of the test program was established to validate the approach developed in Phase I by instrumenting several tank cars with a minimal set of sensors and instrumentation and conduct over-the-road tests. The Transportation Technology Center, Inc., (TTCI) conducted the initial stages of Phase II on a single instrumented vehicle.

Following Phase II, FRA contracted ENSCO, Inc., to instrument and run a second instrumented tank car over the road during a special test. This testing was conducted in a special consist, with the intent to collect data from the instrumented tank car, instrumented wheelsets, and track geometry. This test effort took place in June and July 2008. Results from this study resulted in recommendations to conduct an autonomous measurement test that would provide accurate information on the force environment spectrum that a tank car experiences during routine operations of transportation of materials. The tank car that had been instrumented in the earlier phase by ENSCO was routed through hazmat routes and through different yards to capture force environment information. The tank car used for this effort was provided by GE and is shown in Figure 1. A detailed view of the end of the tank car with the stub sill attachment is shown in Figure 2.

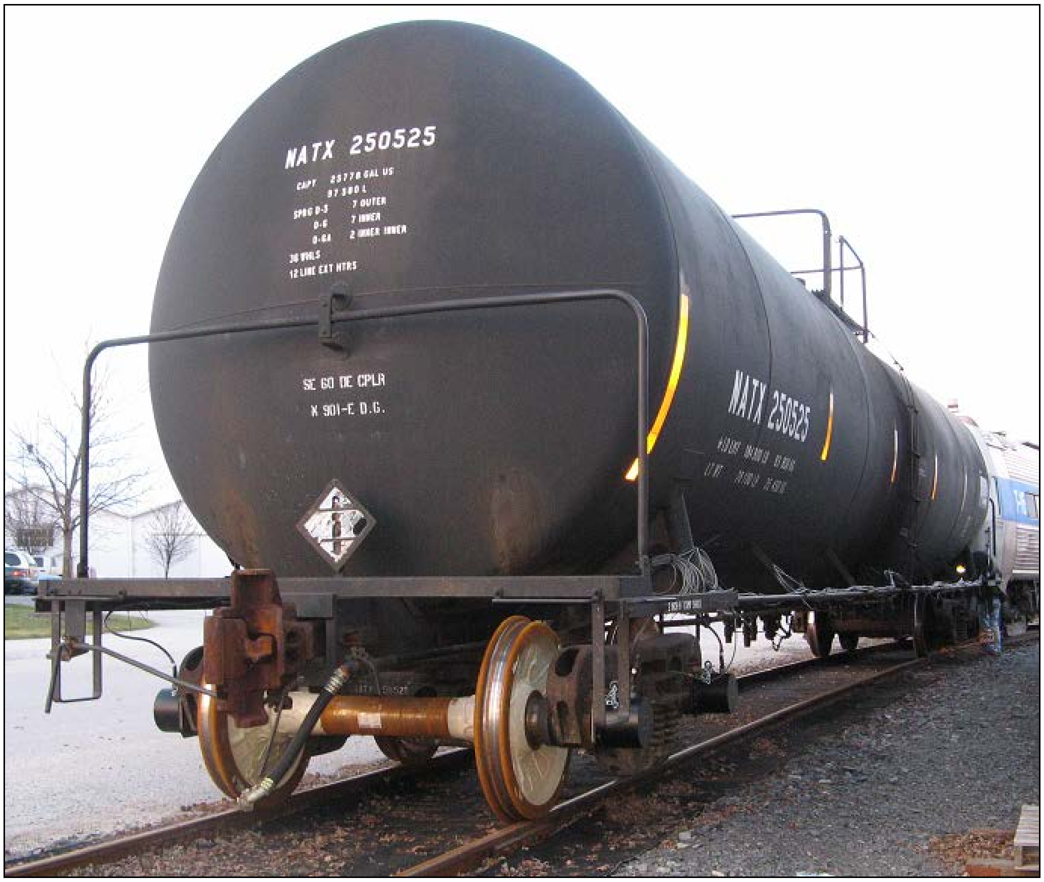

Figure 1. Tank Car Supplied by General Electric for Conducting Research

Figure 2. Detail View of the Stub Sill and Head Brace Attached to the Tank

Under the current effort, the instrumented tank car was run in autonomous mode, collecting force environment data over approximately 3,700 miles. The intent of this report is to document the results and findings of the test and the resultant analysis efforts. This report also describes the instrumentation, calibration, and testing efforts conducted by ENSCO.

Examples of fractures observed by CSX (Figure 3 and Figure 4) were provided to ENSCO. As can be seen, these fractures are catastrophic in nature for the stub sill. The industry has improved the design of the welds such that the weld between the head brace and stub sill should fail before the weld between the pad and tank.

Figure 3. Stub Sill Fracture Observed in Callahan, FL (December 2009)

Figure 4. Stub Sill Fracture Observed in Charleston, WV (January 2010)

1.2 Test Objectives and Approach

The objective of this effort is to better understand the operational environment and forces exerted on tank cars in over-the-road revenue service. The test used background information and placement of sensors based on results from the initial efforts conducted during Phase II of the TCOE-TF/SSWG research program.

It is anticipated that the results of this test effort will either (1) confirm the industry's current understanding of fracture initiation and propagation, or (2) reveal additional factors critical to the understanding of the phenomena. The testing will also make robust, real-world load environment data available for further research.

ENSCO installed five (5) types of sensors on the tank car: accelerometers, strain gauges, vertical load adapters, instrumented couplers, and a pressure transducer. The most critical environmental factors for the stub sill are the LCF and VCF. These two parameters have the biggest impact on the life of a tank car stub sill.

The tank car instrumented in the earlier phase was recalibrated during this phase to ensure up-to-date calibrations. CSX supported this effort by allowing the car to be tested on its routes between the cities requested by ENSCO and the FRA.

Key dates in the program timeline are provided in Table 1.

Table 1. Test Program Key Dates

Installation on tank car	December 2006 – November 2007
Calibration of sensors	August 2009
Low-speed test run	February 15, 2010
Over-the-road testing	February 16, 2010 – Jun 22, 2010
Draft report/Presentation	June 2010 to May 2011
Final report	Fall 2015

1.3 Organization of the Report

The test methodology is discussed in Section 2 and includes a review of the physical measurements recorded and the equipment used during testing. Section 2 also details the route on which the over-the-road testing was conducted. Section 3 presents the results of the test data analysis and includes observations for the respective analysis sections. Conclusions based on those observations are discussed in Section 4. Supplemental material is provided in Appendix A, "Correlation Plots of Track Geometry Exceptions and VCF Values on the Tank Car."

2. Test Methodology

A tank car was donated by GE for conducting this research supported by the FRA. Relevant details of the tank car are:

- Car manufacturer: Union Tank Car
- Under frame design: UTLZBG Stub Sill w/ Headbrace
- Coupler design: A End & B End: SE60DE
- Draft gear design: E/F Top & Bottom Shelf

Tank car instrumentation included a brake pressure sensor, eight strain gauge bridges, three single strain gauges, four vertical load adapters, five accelerometers, and two instrumented couplers. Thus, the systems simultaneously collected information about the features of the track, the tank car speed and location, the motion of the train, the dynamics of the tank car, and the forces and strains on the tank car's structural parts.

2.1 Instrumentation for Testing

The overall instrumentation layout is shown in Figure 5. Details for the sensors are provided in the following few paragraphs.

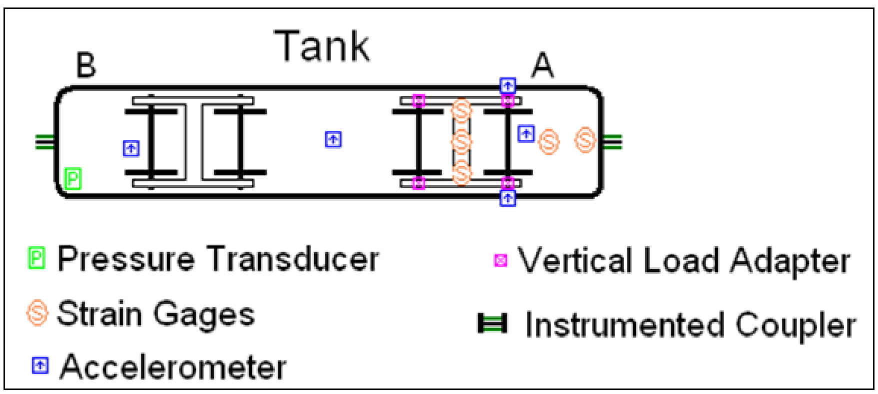

Figure 5. Instrumentation Layout for Over-the-Road Testing

The tank car was filled to its weight capacity of 184 kip with 22,000 gallons of water for the test. The weight of the car with an empty tank was 78 kip. The filling was done in five steps, using tanker trucks of approximately 6,000 gallon capacity (Table 2).

Table 2. Schedule for Filling Tank Car from Tank Trucks

Filling Status	Total Volume
Halfway through first tanker truck	3,238 gal
After first tanker	6,018 gal
After second tanker	12,210 gal
After third tanker	18,253 gal
After partial fourth tanker	22,132 gal

The filling was monitored, and strains on the bolster were measured before filling, halfway through the first tanker truck, and before the second tanker truck. Because the capacity was weight-based, the tank car's tank was not filled to the very top or 100% of the tank's volume. Because the test tank car was built for slurry, which is a lighter than water, the tank was partially empty. Table 2 shows the filling schedule used for the tank car loading from empty to loaded, based on the gauge table provided by GE.

To accurately calibrate the strains caused by loading at the measurement locations, steel blocks were used to control the load path of the carbody's weight to the truck. For example, blocks were set on the left side of the bolster such that the carbody was not touching the center or right contact point. A load cell placed in the load path between the carbody and truck, at left, right, or center contact points, measured the force.

Vertical coupler force sensors were tested using a device with a hydraulic ram and a load cell which applied upwards and downwards force loads to the coupler. This test correlated the vertical loading on the coupler to the strains measured in the vertical coupler load channel.

2.1.1 Coupler Forces

Coupler forces were measured between the tank car (A-end and B-end) and the rest of the train consist. A special coupler instrumented with strain gauge bridges was used to measure the longitudinal forces. To measure vertical forces, a pair of shear gauges were mounted on each side of the coupler channel, as shown in Figure 6.

The shear gauges were wired using a completion card to form a full bridge. A second set of gauges were mounted next to the original set as a spare (total 8 gauges, 4 on each side). The mounting process included grinding and polishing the coupler surface to provide a smooth area to which the strain gauges were adhered. To increase resolution after unsatisfactory initial testing, new gauges were applied at a location closer to the end of the car, but not beyond the points of contact between the coupler channel and the coupler. These shear gauges were applied only on the A-end of the instrumented tank car.

Figure 6. Shear Gauges Measuring Vertical Coupler Force
Left: Close-up of the installation. **Right:** New gauges on the right replaced gauges on the left (covered with sealant), which were then disconnected.

2.1.2 Bolster Forces

A second set of strain gauges were mounted on the truck bolster underneath the side bearing (Figure 7). One gauge was mounted on each side to form a half bridge. Bridge completion resistors were used to complete the bridge. A spare set of gauges were mounted adjacent to the main gauges. An identical set of gauges, mounted on the truck bolster on the other side of the vehicle, were used to measure the side bearing loads.

Figure 7. Strain Gauges Measuring Bolster Side Bearing Loads

A third set of strain gauges were mounted on the each side of the bottom center of the bolster (Figure 8). One gauge was mounted on each side to form a half bridge. Bridge completion resistors were used to complete the bridge. A spare set of gauges, mounted adjacent to the main gauges, were used to measure the bolster center bowl load.

Figure 8. Strain Gauges Measuring Bolster Center Bowl Load

2.1.3 Carbody and Axle Accelerations

Accelerometers were installed at several locations on the tank car. The first was a tri-axial accelerometer mounted on top of the carbody (Figure 9). The second and third accelerometers, mounted on the stub sill at each end of the car (Figure 10), measured accelerations in the vertical direction only. The fourth and fifth accelerometers, mounted on the bearing adapter on both sides of the first axle (Figure 11), measured accelerations on the axle in the vertical direction only.

Figure 9. Tri-axial Accelerometer Mounted on Top of Carbody

Figure 10. Vertical Accelerometer Mounted on the Stub Sill and Each End of the Car

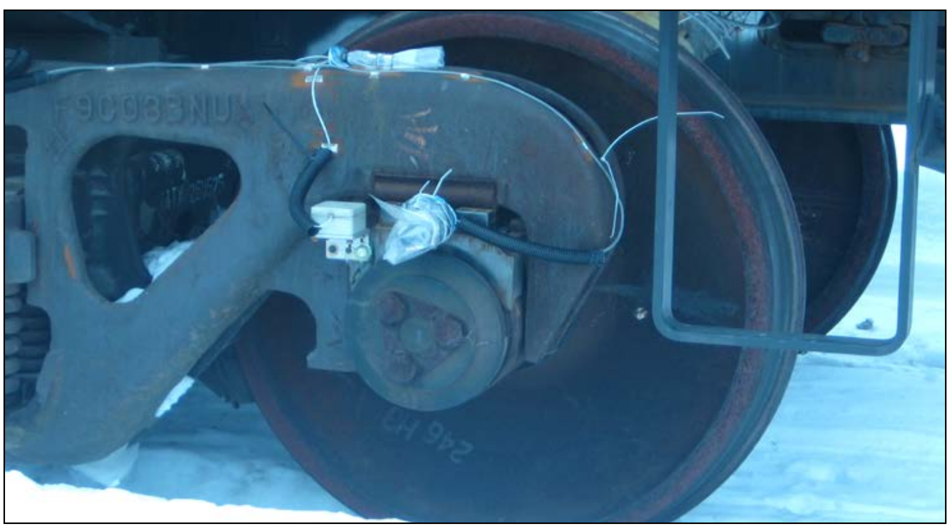

Figure 11. Vertical Accelerometer Mounted on the Axle on Both Sides of the Car

2.1.4 Vertical Loads

Vertical load adapters are modified bearing adapters used to measure vertical wheel forces. The vertical load adapters are made using strain gauges. After they are calibrated, they are used like any other load cells. Figure 12 shows a vertical load adapter mounted on the tank car. Four of these were mounted on the A-End of the tank car.

Figure 12. Vertical Load Adapter

2.1.5 Brake Pressure

Brake application data were gathered to correlate the force and strain data to the operation of the car. This measurement was achieved by using a pressure transducer to measure the brake cylinder pressure. Only one pressure transducer was needed. Figure 13 shows the installation of the brake pressure transducer with the wires connected before they were fully protected from moisture.

Figure 13. Brake Pressure Transducer

2.1.6 Strain Gauges

To measure the strains on the pad that attaches the tank to the stub sill and head brace, strain gauges were installed on the pad at the A-end. To determine principal stresses, three individual strain gauges were installed 45 degrees apart to form a rosette. Figure 14 shows the strain gauges after they were installed but before the weatherproofing was applied. The bottom three gauges were used during this testing. The top three gauges were installed so that the cabling could be switched to those gauges if necessary, but that was not done during this phase of testing.

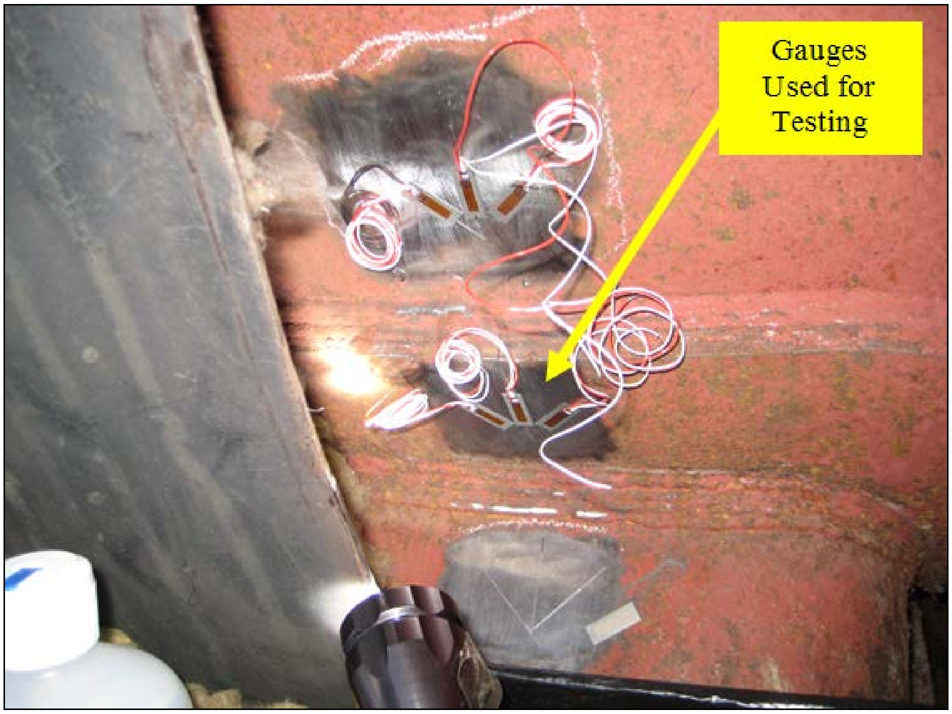

Figure 14. Individual Strain Gauges (Bottom Three Gauges Used)

2.1.7 Data Acquisition and Hardware Settings

Data acquisition was performed using a modified Vehicle/Track Interaction (V/TI) system. A V/TI system is an autonomous computer that incorporates signal conditioning and typically measures between two and six sensors, usually accelerometers. These V/TI systems generally are used by the industry to flag vehicle/track interaction issues. The V/TI is powered by train power or a small solar panel. It uses a cellular connection to transmit data back to the server and a GPS antenna for location and speed information.

The modified system collected 21 channels of data at a sample rate of 333 Hz. The low-pass anti-aliasing filters were set at 80 Hz, which meant that frequencies higher than 80 Hz were attenuated before being digitized. This helped in keeping signal noise at a low level and eliminated aliased frequencies on acceleration channels. Details of these channels are provided in the next section.

Signal conditioning unit outputs were passed through a filter card to a data acquisition card, both of which were in the computer. QNX-based software (an off-the-shelf real-time operating system) then acquired and recorded the data in real time. Figure 15 shows the modified V/TI (on right) and the junction box (on left).

Figure 15. Modified VTI and Junction Box

Four solar panels and a set of batteries were used to power the system. Figure 16 shows the solar panels and the battery box. The battery box also contains the electronics that control battery charging.

Figure 16. View of Solar Panels and Battery Box

2.1.8 Channel Assignments

Channel assignments and the respective descriptions are shown in Table 3.

Table 3. Input Channels for the Data Acquisition System

Channel	Channel Type	Channel Name
1	Acceleration	Acceleration Carbody Longitudinal
2	Acceleration	Acceleration Carbody Lateral
3	Acceleration	Acceleration Carbody Vertical
4	Acceleration	Stub Sill Vertical A
5	Acceleration	Stub Sill Vertical B
6	Acceleration	Acceleration Axle Left
7	Acceleration	Acceleration Axle Right
8	Pressure	Brake Pressure
9	Full bridge strain	Coupler 1 Longitudinal Force
10	Full bridge strain	Coupler 2 Longitudinal Force
11	Full bridge strain	Coupler Vertical Force
12	Half bridge strain	Bolster Left
13	Half bridge strain	Bolster Center
14	Half bridge strain	Bolster Right
15	Full bridge strain	Vertical Load Adapter Left Axle 1
16	Full bridge strain	Vertical Load Adapter Right Axle 1
17	Full bridge strain	Vertical Load Adapter Left Axle 2
18	Full bridge strain	Vertical Load Adapter Right Axle 2
19	Quarter bridge strain	Gauge A
20	Quarter bridge strain	Gauge B
21	Quarter bridge strain	Gauge C

2.2 Calibration of Sensors

All the instrumentation was calibrated prior to testing. Some of the more portable sensors were calibrated in the laboratory prior to installation on the vehicle. These included the accelerometers, pressure gauge, longitudinal coupler forces, and vertical load adapters. Manufacturer calibration procedures were followed for these sensors. The remaining sensors were strain gauges applied to the tank car in the field. These included the vertical coupler force, three bolster forces, and three strain gauges. The three strain gauges were used to measure the strain at a particular location and did not require additional calibration. However, the vertical coupler force and the three bolster forces that converted strains to forces required field calibration.

2.2.1 Calibration of Vertical Coupler Force

The vertical coupler force was calibrated in the field using a special load fixture, which consisted of a metal frame, a load cell previously calibrated in the lab, and a ram to apply the load. Figure 17 shows the calibration fixture when a downward vertical force was applied.

Figure 17. Vertical Coupler Force Calibration

The setup was then reversed so that an upward vertical force could be applied. The applied force and the two strain gauge bridges were measured at several points for both positive and negative loadings. Figure 18 shows a graph of the calibration results for both of the vertical coupler forces.

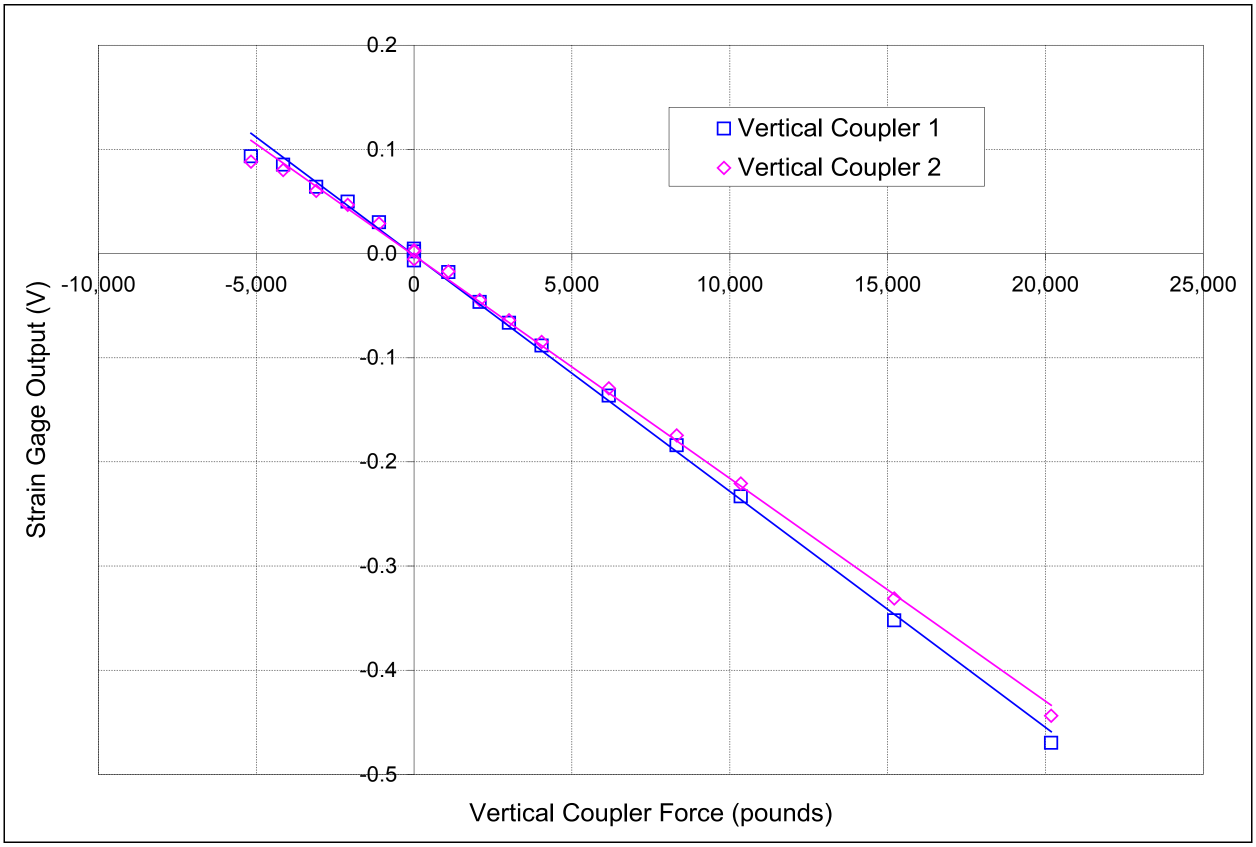

Figure 18. Vertical Coupler Force Calibration Graph

2.2.2 Bolster Forces Calibration

The three bolster loads were calibrated in the field using several load cells and a crane. The crane was used to lift the instrumentation end (A-end) of the tank car body during the calibration to insert the load cells in various positions. The crane was also used to take varying amounts of the load to achieve several load configurations as described below. Since the crane had the ability to measure the load it was carrying, these measurements were used to confirm the load cell readings.

The calibration consisted of three different configurations. In the first configuration, the car body was lifted completely off the A-end truck so that all three bolster loads were zero. In the second configuration, a load cell was inserted between both side bearers at the same time. (Initially, each side bearer was going to be done separately, but the vehicle was too unstable in this configuration.) Figure 19 shows the load cell inserted in one of the side bearers. In the third configuration, two load cells were inserted in the center bolster. Figure 20 shows the two load cells in this configuration.

Figure 19. Side Bolster Force Calibration

Figure 20. Center Bolster Force Calibration

Several load readings were taken for each of these configurations. Figure 21 shows the strain gauge readings versus the bolster loading for the center only. Figure 22 shows the same data for loading both sides. Both graphs show good linearity for the strain measurements.

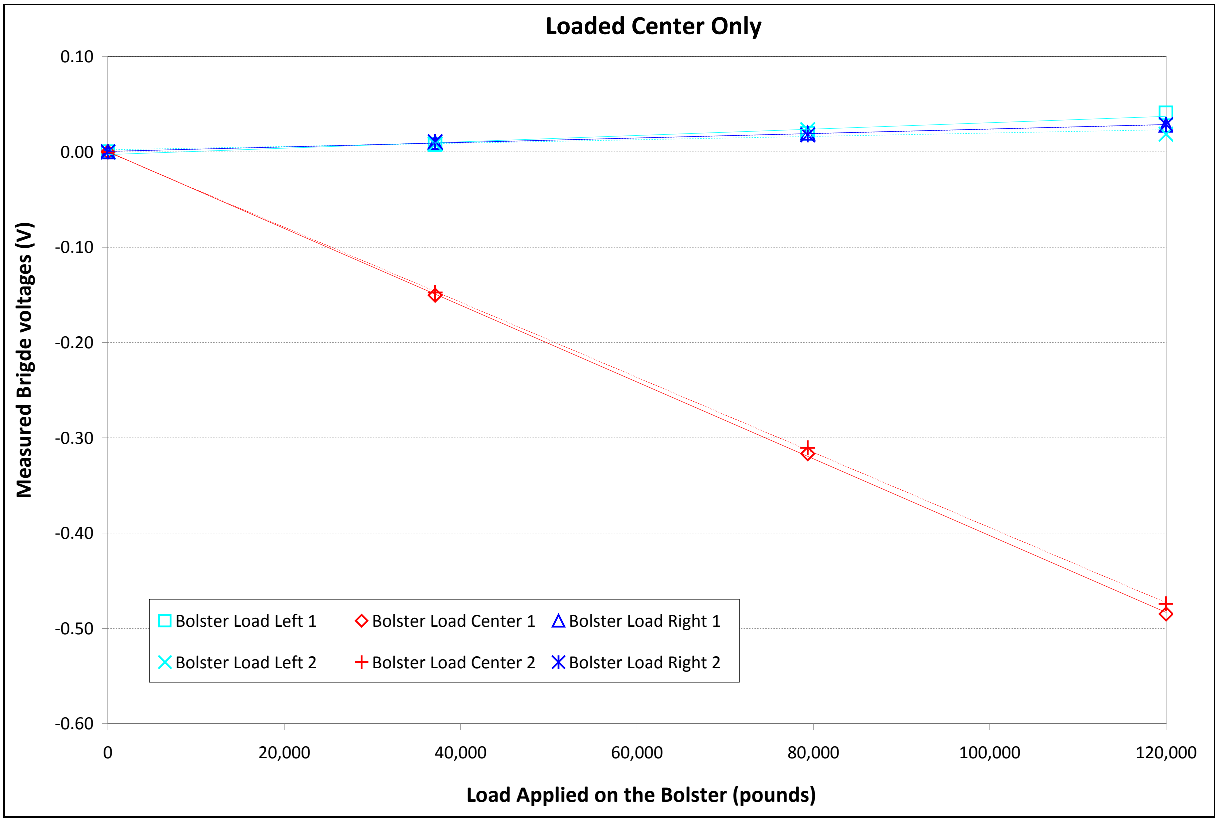

Figure 21. Bolster Loaded in Center Only

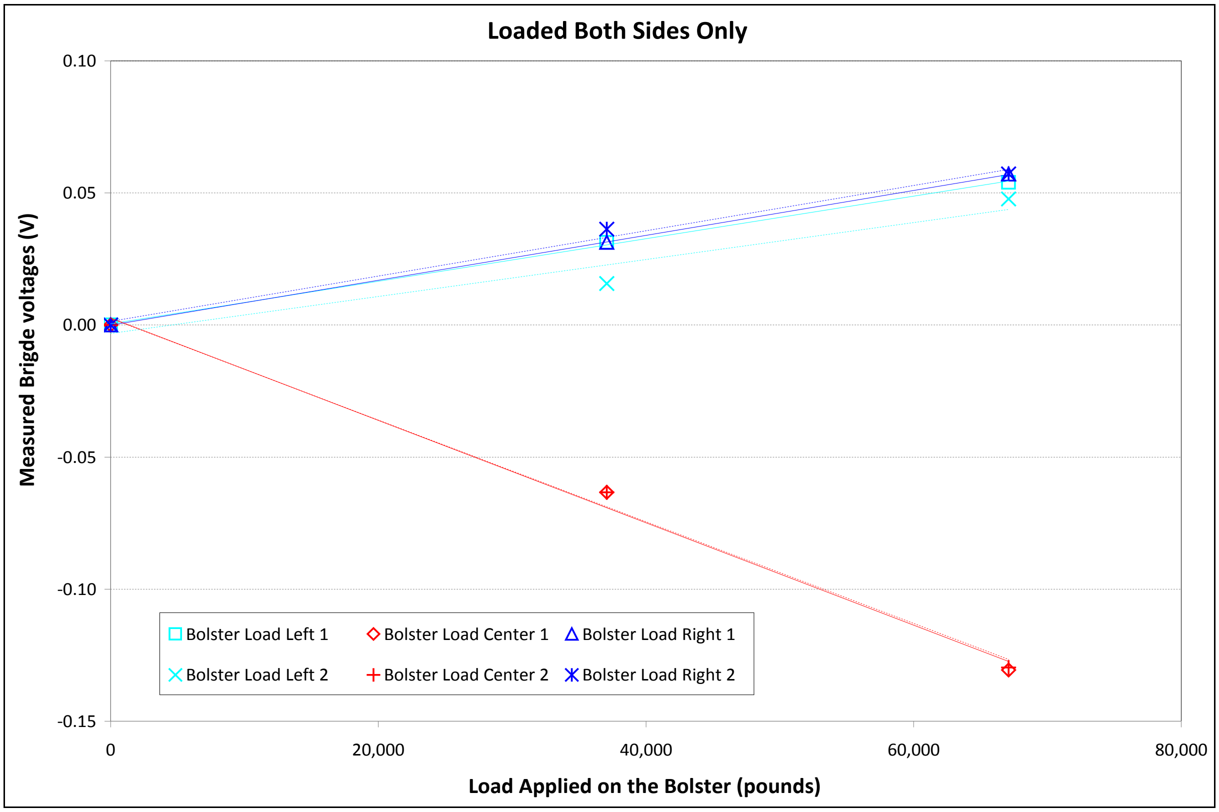

Figure 22. Bolster Loaded on Both Sides Only

To calculate the forces, a simple linear equation was used to sum the three strain outputs multiplied by three coefficients:

$$F = A\varepsilon_L + B\varepsilon_C + C\varepsilon_R \quad ,$$

where: $F = force$

$A, B, C = coefficients$

$\varepsilon = strain\,(left, right, and\ center)$

Table 4 shows the results of the bolster calibrations, comparing the measured forces from the load cell with the predicted forces based on the strain gauges on the bolster.

Table 4. Bolster Load Calibration Results

Bolster Load		Loading Condition (Pounds)					
		No Load	Center Only			Both Sides Only	
Center	Measured	0	37,100	79,360	120,000	0	0
	Predicted	0	38,010	79,400	122,730	-1,650	120
	Error	0	910	40	2,730	-1,650	120
Sides	Measured	0	0	0	0	37,080	67,100
	Predicted	0	-600	-30	-2,620	36,170	67,170
	Error	0	-600	-30	-2,620	36,170	67,170

2.3 Test Logistics

The test was conducted on CSX track between Pennsylvania, Florida, and Alabama from February 2010 to June 2010. Because the testing was autonomous, it was possible to test the tank car in regular freight service. This allowed the test tank car to experience the same conditions that any car would experience in normal transit. Data were collected continuously, with exceptions calculated in real-time. Trips were made to Jacksonville, FL, and Mobile, AL, to retrieve continuous data, inspect the system, and make any necessary repairs. Exceptions and vehicle locations were received automatically, using the cellular connection on the V/TI unit.

2.4 Test Route and Data Collected

Data were collected over a period of 4 months between February 17, 2010, and June 22, 2010, on CSX track from Pennsylvania (Gettysburg) to Florida, Alabama, and back to Pennsylvania (Table 5). Details of the geometry data collected over the test sections are provided in Section 2.5. A map of the route tested is shown in Figure 23. The instrumented tank was tested autonomously over approximately 3,764 miles during the entire period of testing. The car was left temporarily in Mobile, AL, for 94 days while it was awaiting further direction jointly from FRA and ENSCO.

Table 5. Testing Schedule for the Autonomous Testing

Test Leg	Start Location	End Location	Start Date	End Date	Number of Miles Tested
1	Gettysburg, PA	Jacksonville, FL	2/17/2010	2/23/2010	956
2	Jacksonville, FL	Tampa, FL	2/28/2010	3/2/2010	323
3	Tampa, FL	Waycross, GA, and back to Tampa, FL	3/4/2010	3/7/2010	502
4	Tampa, FL	Mobile, AL	3/10/2010	3/14/2010	743
5	Mobile, AL	Letterkenny, PA	6/09/2010	6/22/2010	1,240

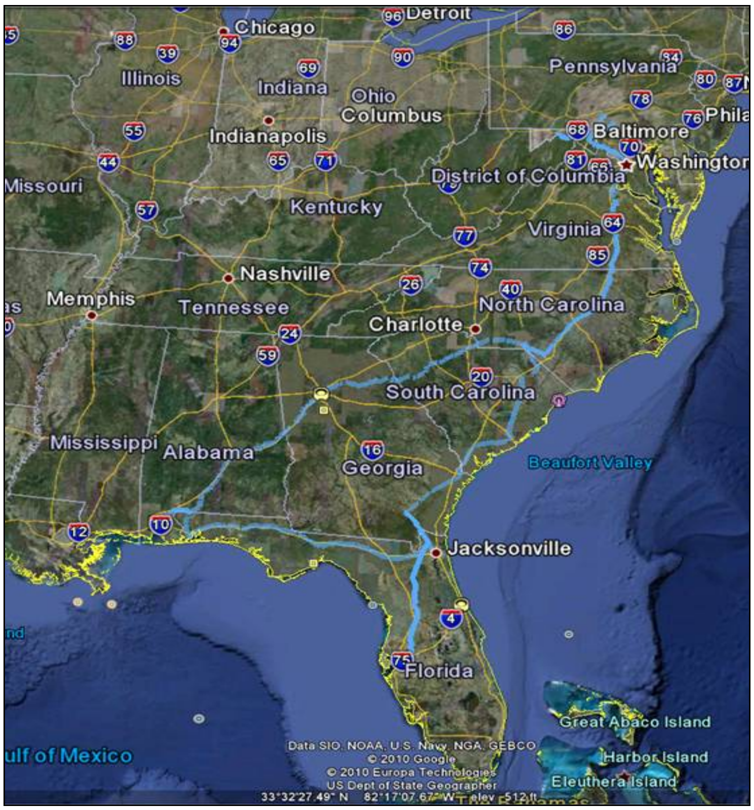

Figure 23. Map of Route Used for Testing the Tank Car (Highlighted in Blue)

2.5 Geometry Data Collected Over the Instrumented Tank Car Route

ENSCO tried to keep the tank car on the intended routes but could not control day-to-day railroad operations. The track database in the Automated Track Inspection Program (ATIP) provided track geometry data for the route that the tank car traveled on. The most recent survey data were used, but in some cases the data were dated. To locate the geometry data for a particular event, the GPS coordinates for the event on the tank car were located in the geometry data. In a few cases, the geometry data had been collected over two different runs for the section of track that the instrumented tank car was tested on. ENSCO intended to test the tank car over a route with recent track geometry data, such as the route from Washington, DC, to Jacksonville, FL. From that point on, the track geometry data were not very recent. The geometry data for the instrumented tank car route are provided in Table 6, along with the various sections of the tank car test route.

Table 6. Track Geometry Data for Instrumented Tank Car Routes

Tank Car			Track Geometry Surveys				
Start City	**End City**	**Date**	**Car**	**Start City**	**End City**	**File Name**	**Date**
Gettysburg, PA	Cumberland, MD	2/17/2010-2/23/2010	DOTX-217	Gettysburg, PA	Hagerstown, MD	2010033101	3/31/2010
Cumberland, MD	Washington, DC		DOTX-220	Cumberland, MD	Washington, DC	2009100902	10/9/2009
Washington, DC	Richmond, VA		DOTX-220	Washington, DC	Richmond, VA	2010030201	3/2/2010
Richmond, VA	Rocky Mount, NC		DOTX-220	Richmond, VA	Rocky Mount, NC	2010030401	3/4/2010
Rocky Mount, NC	Florence, SC		DOTX-220	Rocky Mount, NC	Florence, SC	2010030501	3/5/2010
Florence, SC	Savannah, GA		DOTX-220	Florence, SC	Savannah, GA	2010030801	3/8/2010
Savannah, GA	Jacksonville, FL		DOTX-220	Savannah, GA	Jacksonville, FL	2010030901	3/9/2010
Jacksonville, FL	Waycross, GA	2/28/2010-3/2/2010	DOTX-217	Jacksonville, FL	Charleston, SC	2011011201	1/12/2011
Waycross, GA	Baldwin, FL		DOTX-220	Baldwin, FL	Waycross, GA	2010032504	3/25/2010
Baldwin, FL	Tampa, FL		DOTX-219	Baldwin, FL	Tampa, FL	2009020601	2/6/2009
Tampa, FL	Waycross, GA	3/4/2010-3/7/2010	DOTX-220	Baldwin, FL	Waycross, GA	2010032504	3/25/2010
			DOTX-219	Baldwin, FL	Tampa, FL	2009020601	2/6/2009
Waycross, GA	Tampa, FL		DOTX-220	Baldwin, FL	Waycross, GA	2010032504	3/25/2010
			DOTX-219	Baldwin, FL	Tampa, FL	2009020601	2/6/2009
Tampa, FL	Waycross, GA		DOTX-220	Baldwin, FL	Waycross, GA	2010032504	3/25/2010
			DOTX-219	Baldwin, FL	Tampa, FL	2009020601	2/6/2009
Waycross, GA	Baldwin, FL	3/10/2010-3/14/2010	DOTX-220	Baldwin, FL	Waycross, GA	2010032504	3/25/2010
Baldwin, FL	Chattahoochee, FL		DOTX-220	Jacksonville, FL	Chattahoochee, FL	2009061001	6/10/2009
Chattahoochee, FL	Pensacola, FL		DOTX-220	Chattahoochee, FL	Pensacola, FL	2009061101	6/11/2009
Pensacola, FL	Mobile, AL		DOTX-220	Pensacola, FL	Mobile, AL	2009061201	6/12/2009
Mobile, AL	Montgomery, AL	6/11/2010-6/22/2010	DOTX-217	Mobile, AL	Montgomery, AL	2010121401	12/14/2010
Montgomery, AL	Atlanta, GA		DOTX-217	Montgomery, AL	Atlanta, GA	2011020901	2/9/2011
Atlanta, GA	Abbeville, SC		DOTX-217	Atlanta, GA	Columbia, SC	2009103001	10/30/2009
Abbeville, SC	Rockingham, NC[a]		DOTX-217	Charlotte, NC	Hamlet, NC	2009111301	11/13/2009
			DOTX-216	Hamlet, NC	Wilmington, NC	2008031401	3/14/2008
Rockingham, NC	Rocky Mount, NC		DOTX-220	Rocky Mount, NC	Florence, SC	2010030501	3/5/2010
Rocky Mount, NC	VA/NC State Line			VA/NC State Line	Rock Mount	2010091601	9/16/2010
VA/NC State Line	Washington, DC			Washington, DC	VA/NC State Line	2010091501	9/15/2010
Washington, DC	Letterkenny, PA		DOTX-217	Kurgan, PA	Hagerstown, MD	2009082402	8/24/2009
			DOTX-217	Hagerstown, MD	Cumberland, MD	2009082501	8/25/2009
			DOTX-220	Cumberland, MD	Washington, DC	2009100901	10/9/2009

[a]Track geometry between Abbeville, SC, and Monroe, NC, was not tested in the recent past, and that section was between Abbeville, SC, and Rockingham, NC, on the tank car route.

2.6 Issues Encountered During Testing

Several minor issues occurred during the autonomous testing:

- One of the bridge completion cards for one of the strain gauges was damaged by water. It was repaired in Jacksonville, FL, when the continuous data were retrieved.
- One of the longitudinal coupler channels on coupler A-End failed on March 12, 2010 It was switched to the backup channel in Mobile, AL, when ENSCO conducted a service repair visit on June 2. This channel also broke after a very large impact of 1.79 million pounds on the A-End on June 4.
- The backup coupler channel on the A-End stopped working on June 5. The B-End coupler channel had no issues and was operating accurately throughout the autonomous testing.

These were all minor issues and did not affect the overall test results.

3. Test Results

The purpose of this section is to provide an overview of the results determined from analysis of the data collected and events observed during the test program. At the start of the project, the hypothesis laid out for determining the cause of stub sill failures was that the damage causing events were ‘six-sigma” in nature. These events were hypothesized to be high-magnitude longitudinal coupler forces (LCF) or high-magnitude vertical coupler force (VCF) events, which would result in crack formation after multiple high-magnitude events. There is a desire to know where these high-magnitude events occur and the associated causes, in order to reduce stub sill cracking.

Each section below provides information about the various parameters studied during the over-the-road testing. Results obtained for longitudinal coupler force events are presented in Section 3.1, and results from the vertical coupler force data are presented in Section 3.2. In Section 3.3, the large force events measured during this test are compared with the AAR tank car design standards. Section 3.4 covers the analysis performed to estimate stress in critical regions, based on the measured forces obtained during the testing. Section 3.5 covers the effects of track geometry defects on the tank car force environment.

3.1 Longitudinal Coupler Force (LCF) Events

High LCF events were thought to occur during a rail car’s movement during material transportation. Typically, it is accepted that in-consist longitudinal pulling forces are much higher than the forces experienced by cars in yards, because of newer technology like retarders in hump yards. Testing conducted under this effort resulted in the test tank car traveling in consists and staying in yards for an extended time. The V/TI data acquisition system sent real-time data back to the Track IT website, including high-magnitude LCF events. After some filtering for bad data, the events were mapped to the database and made visible on the website. ENSCO mined the data files for the highest LCF events and identified the 30 largest events that the tank car saw over the entire route of testing. These large-magnitude events are listed in Table 7. For all testing conducted under this effort, the negative LCF events represent compression on the coupler, and positive events represent pulling on the coupler. High-magnitude LCF parameters were measured using high-pass filtered data from the actual coupler force measurements. The high-pass filter adjusts the data output to remove data bias.

Table 7. Large-Magnitude Events for the Longitudinal Coupler Force Parameter

Number	Speed (mph)	HPCpl1 Long (lb)	HPCpl2 Long (lb)	Latitude (degree)	Longitude (degree)	File Name	Location	Switching Type
1	8	-1797700	-7300	30.71957	-88.0491	06040834	Mobile, AL Yard	Flat
2	0	*NA	-1137600	30.7189	-88.0488	03141807	Mobile, AL Yard	Flat
3	0	*NA	-1092900	30.71858	-88.0489	05081736	Mobile, AL Yard	Flat
4	0	*NA	-988900	30.7189	-88.0488	03141807	Mobile, AL Yard	Flat
5	5	*NA	-897200	34.91667	-79.6615	06151104	Hamlet, NC Yard	Hump
6	5	-4500	-896200	31.17274	-82.4014	02221904	Waycross, GA Yard	Hump
7	0	-308000	880800	37.65615	-77.5062	02191305	Laurel, VA	Regular Operations
8	0	*NA	-876000	30.72151	-88.0496	05010040	Mobile, AL Yard	Flat
9	4	-3900	-871800	34.91674	-79.6602	02210405	Hamlet, NC Yard	Hump
10	5	-772200	-838400	31.17323	-82.4017	03111108	Waycross, GA Yard	Hump
11	0	-3800	-838200	27.95427	-82.3819	03071613	Tampa, FL Yard	Flat
12	0	-605000	-837800	30.71927	-88.0491	06041238	Mobile, AL Yard	Flat
13	0	-303800	-817600	31.17279	-82.4007	02282243	Waycross, GA Yard	Hump
14	6	28300	795100	30.72268	-88.0491	03141704	Mobile, AL Yard	Flat
15	5	-785000	-8400	27.95436	-82.3759	03031341	Tampa, FL Yard	Flat
16	0	-18200	-774600	30.72108	-88.0496	04130834	Mobile, AL Yard	Flat
17	4	-769200	-6600	27.95436	-82.376	03042135	Tampa, FL Yard	Flat
18	8	*NA	-740200	30.71926	-88.0491	06070704	Mobile, AL Yard	Flat
19	4	-717300	-485600	27.9544	-82.3749	03032216	Tampa, FL Yard	Flat
20	0	-711800	-479700	34.9167	-79.6603	02210824	Hamlet, NC Yard	Hump
21	4	-709900	-419000	39.62798	-78.7443	02181404	Cumberland, MD Yard	Hump
22	3	*NA	-701500	30.71531	-88.048	06101534	Mobile, AL Yard	Flat
23	0	-699900	-634800	31.1727	-82.4014	02221934	Waycross, GA Yard	Hump
24	0	*NA	-699900	30.71877	-88.049	06070704	Mobile, AL Yard	Flat
25	5	*NA	-699500	33.80856	-84.4543	06121004	Atlanta, GA Yard	Hump
26	0	688000	-1700	30.71228	-88.0472	03180004	Mobile, AL Yard	Flat
27	6	-682900	-629700	30.721	-88.0497	06040704	Mobile, AL Yard	Flat
28	0	*NA	-682100	30.71776	-88.0488	06052204	Mobile, AL Yard	Flat
29	5	*NA	-680800	39.62735	-78.7423	06180804	Cumberland, MD Yard	Hump
30	0	-673700	2000	30.71281	-88.0479	06030210	Mobile, AL Yard	Flat

*NA = Not available due to failed sensor.

The highest force value produced during the testing conducted under this project was 1.79 million pounds on the A-End of the tank car. This took place on the June 4 2010, at about 8:51 AM, as the instrumented tank car was being coupled into a standing set of cars (number of cars unknown). This was done by letting the instrumented tank car go from a speed of 9 mph into a switch and then coupling up to a standing set of cars. The acceleration measurement in the longitudinal direction on the instrumented tank car was recorded to be a maximum of 13.06 G in the negative direction. The longitudinal force measurements at both ends, the longitudinal acceleration measurement, and the speed of the car are shown in Figure 24. Because the car was released and was the impacting car, the measurement on the B-End was minor (near zero) as compared to the high force observed on the A-End of the car. Further field evaluation of this location revealed that there was a height difference of about 2.5 feet from the point at which the tank car was released at a speed of 8 mph to the point where the car came to rest, and the length of travel was about 250 feet.

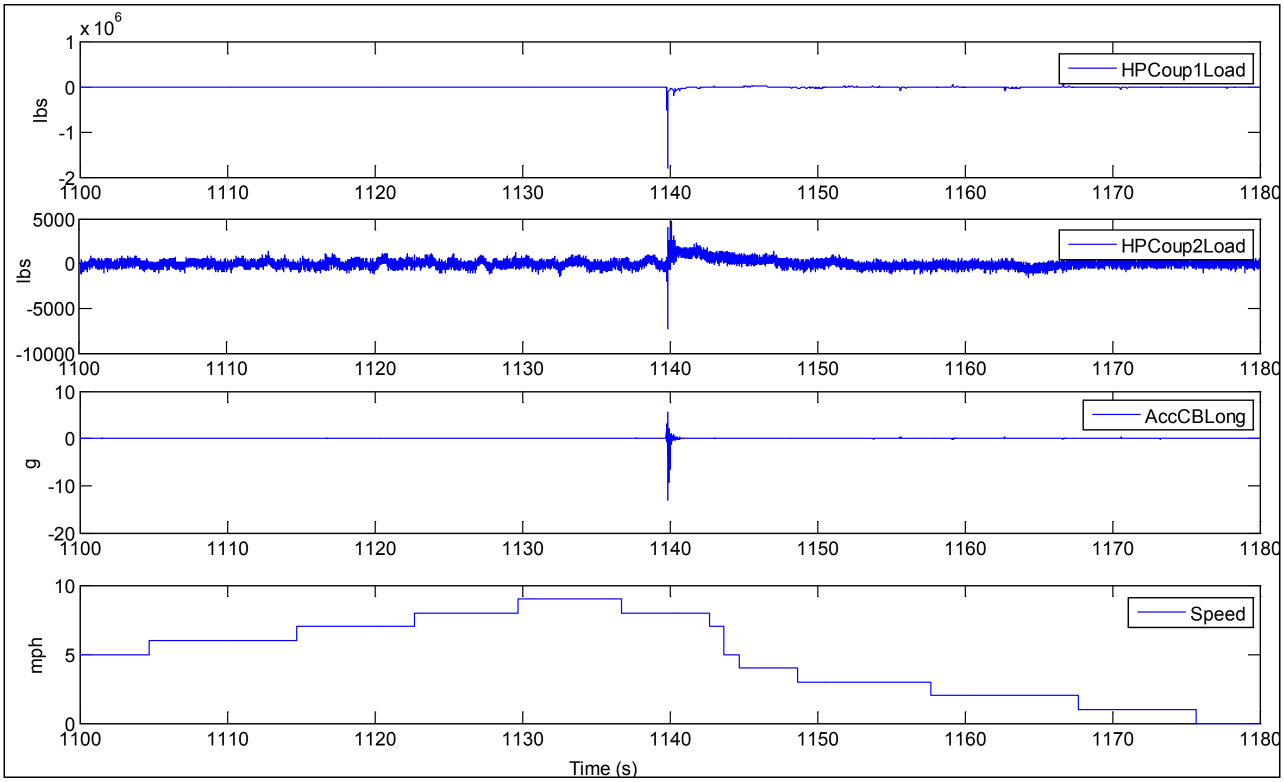

Figure 24. 1.79-Million-Pound Longitudinal Coupler Force Event Measured at the A-End of the Instrumented Car and Corresponding Data

The second maximum LCF measured, also experienced in the Mobile, AL, yard, was measured on the B-End of the tank car (Figure 25). In this case, the instrumented tank car was stationary and was impacted from a coupling operation on March 14, 2010, at about 8:07 AM local time. The A-End measurement was not working properly and hence is not shown in Figure 25.

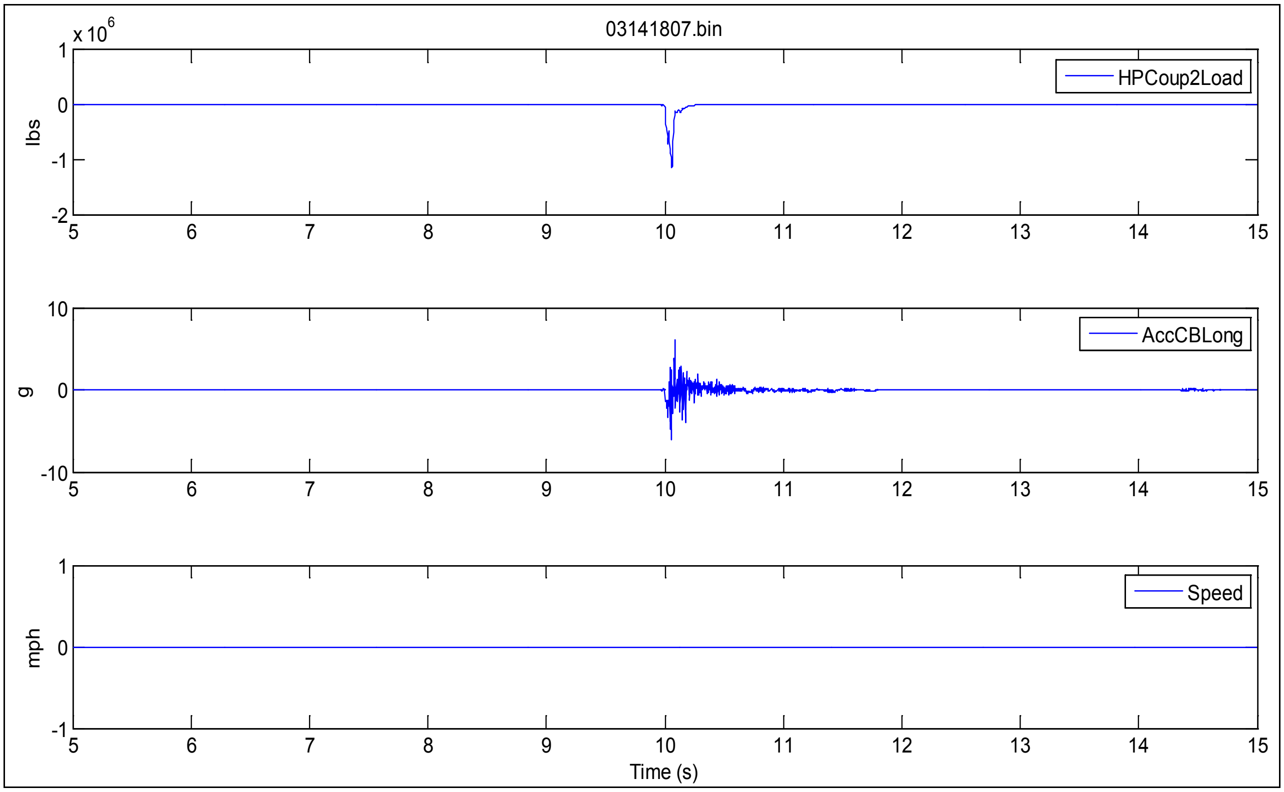

Figure 25. Second-Highest Longitudinal Coupler Force Event: March 3, 2010, in the Mobile, AL, Yard

Most of the large LCF events observed on the instrumented tank car were in the negative direction, corresponding to compression mode. There was one event in the positive direction (pulling on the coupler; no. 7 on the list in Table 7), which took place when the train was pulling from a stop. Using the consist information provided by CSX, it was determined that the car was 56th in the consist, which had a total of 64 cars with 40 cars loaded and 24 cars empty. The force was most likely generated due to pulling from the locomotive and some reaction from the cars moving to compress this car from the A-End at the release of the brakes. Speed started to increase 22 seconds after this event. The longitudinal acceleration also had a low frequency measurement of 0.5 G (Figure 26).

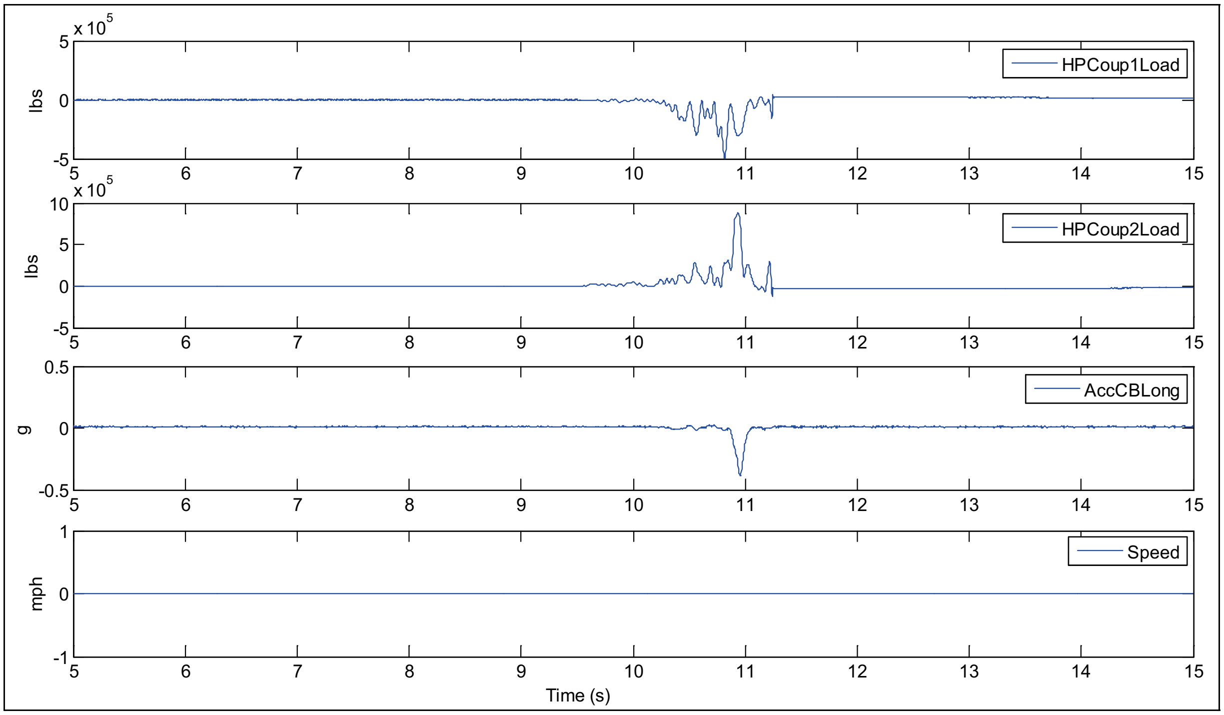

Figure 26. Characterization of the Only Positive High Longitudinal Coupler Force Event

3.1.1 Correlation of LCF Values With Respect to Speed of Impact

The LCF values measured for large impacts were plotted against speed (Figure 27). It should be noted that this plot also contains data from when the tank car was getting hit and was stationary before the impact; however, it is evident that even where the tank car was the hammer car, a strong correlation was not observed between the tank car speed and high LCF values. Some other factors are believed to be in play, such as the condition of the draft gears and the impacting and impacted masses during such an impact.

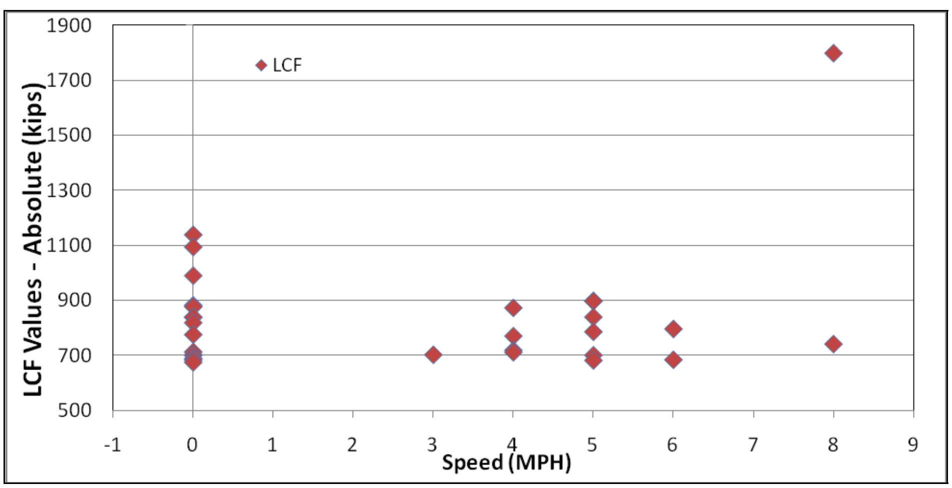

Figure 27. Characterization of the Top 30 Longitudinal Coupler Force Events with Respect to Speed

3.1.2 Characterization of the LCF Events With Respect to Switching Yard Classification

It has been believed that hump yards produce better coupling because of retarders and different shock-absorbing technology utilized in the yards. A comparison was conducted between the LCF values observed in hump and flat switching yards (Figure 28). It was observed that LCF impacts in hump yards lay in a tighter band as compared with those in flat switching yards.

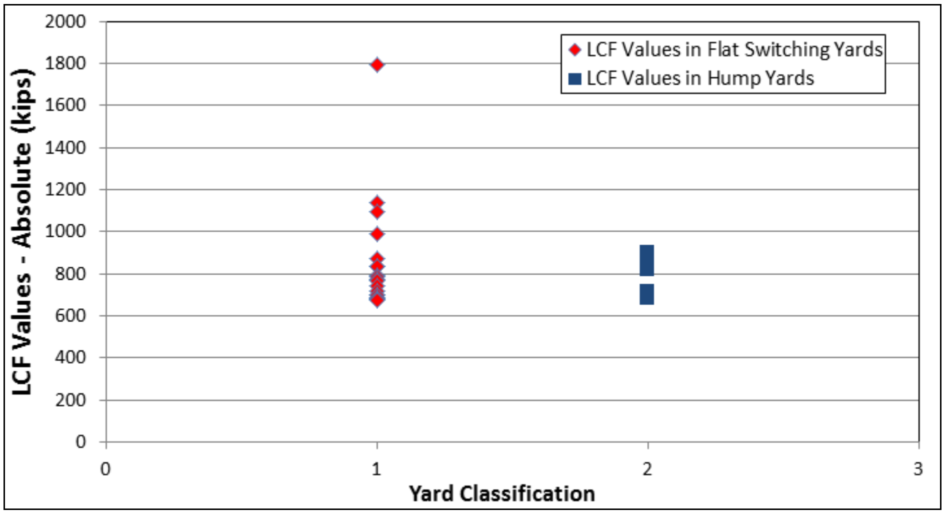

Figure 28. Comparison of Switching Yard Types

3.1.3 Correlation Between LCF and Longitudinal Carbody Accelerations

Comparisons were made between LCF values and the corresponding carbody accelerations in the longitudinal direction. Initially, this exercise was conducted to verify proper working of the instrumented couplers on both the ends. The analysis can be further used and developed to evaluate a low-cost system to capture environmental forces in combination with the low-cost VCF predictor approach described further in this report. An example of this analysis is shown using a high-LCF event that took place where the instrumented tank car was involved in coupling events on February 21, 2010, in the Hamlet, NC, yard (Figure 29).

Note that the instrumented tank in this situation was not moving and was in a consist with an unknown position. During this event, a car or a set of cars were being coupled to this consist from the A-end. The A-end LCF maximum value was 711 kip, and the B-end maximum value was 479 kip. The difference between the LCF traces at the two ends of the instrumented tank car was calculated, and the trace was filtered at 15 Hz. The trace was divided by 263,000 lb, which is the weight of the car, and then compared to the measured accelerations as shown in Figure 30. The accelerations were also filtered using a 15 Hz low pass 2 pole Butterworth filter.

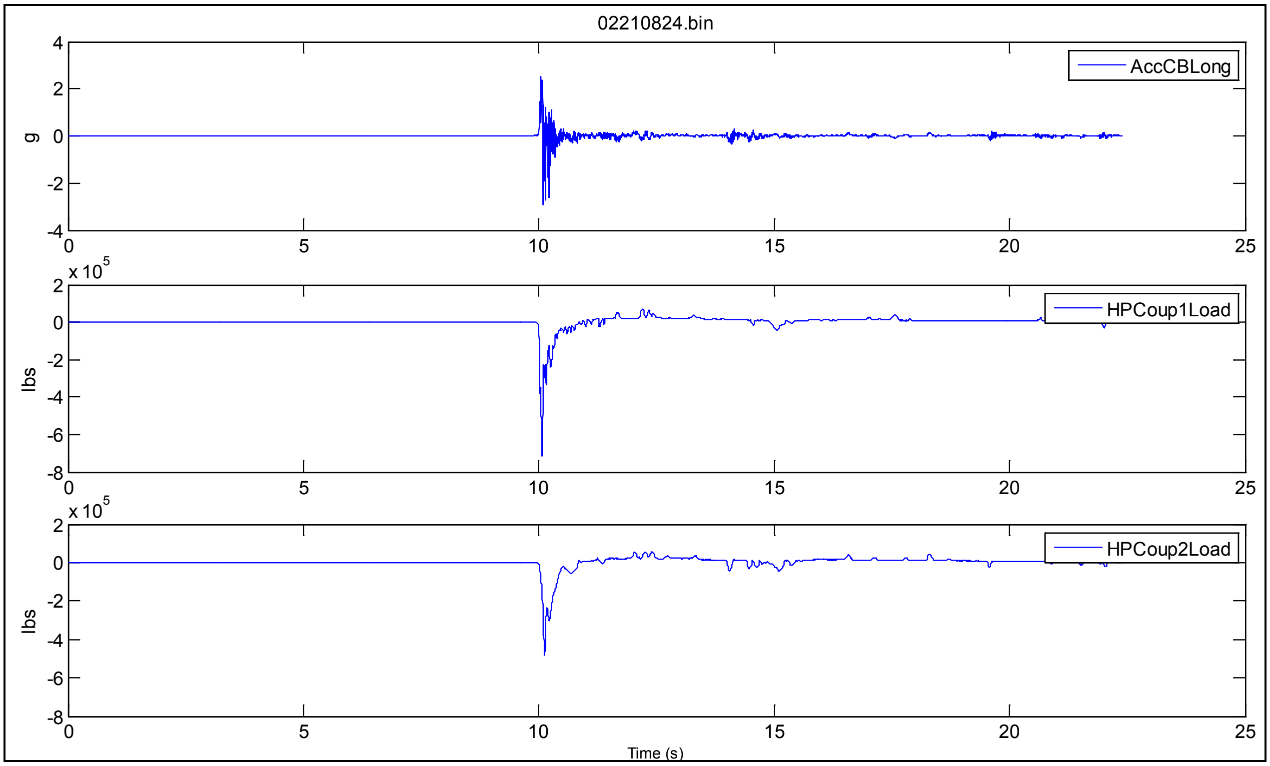

Figure 29. Longitudinal Accelerations and Longitudinal Forces at the A-End and the B-End

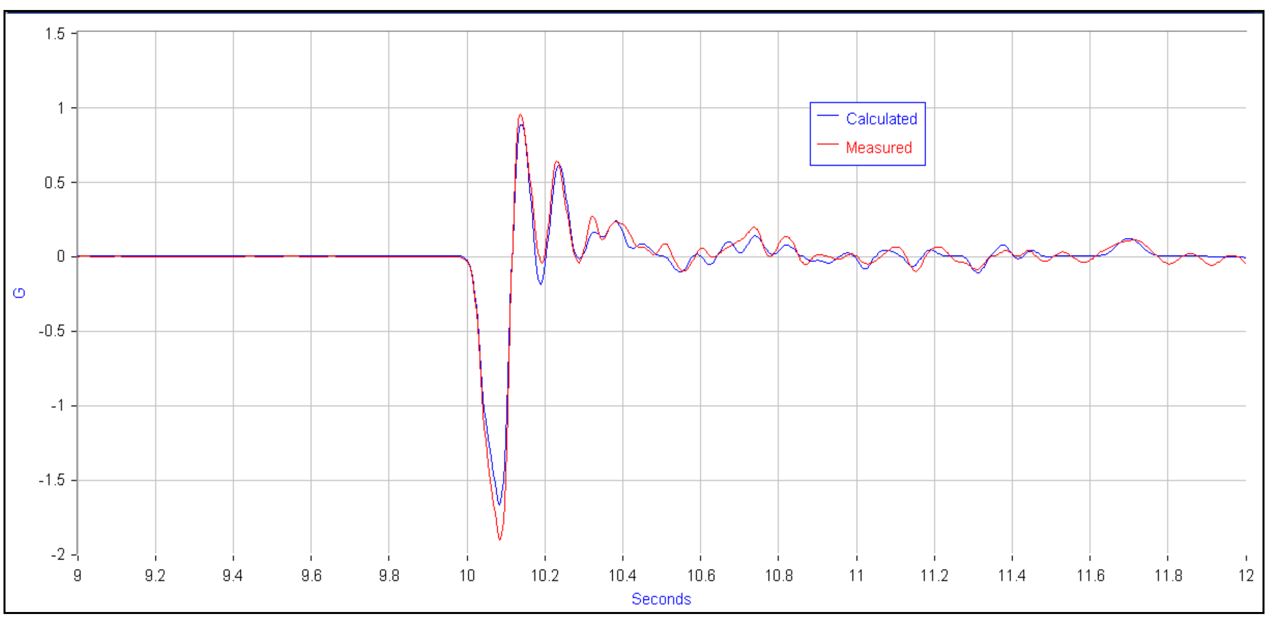

Figure 30. Comparison of Calculated Accelerations from LCF Values for Both Ends and Measured Accelerations

The measured accelerations and the calculated accelerations match very well. The comparison is shown for the difference and not the individual forces at the two ends of the car. With the given set of sensors it was not possible to derive individual LCF values from the longitudinal accelerations, but if there had been two or three accelerometers on the instrumented tank car, it might have been possible to arrive at the LCF values at the two ends of the car only from the longitudinal acceleration data from these sensors.

Certain observations can be made from the table and the data characterized above:

- All except one of the high-LCF events listed in Table 7 were observed in yards. It can be inferred that damage due to the LCF events most often takes place in yards during consist formation operations. In the case where it happened on the main line, the consist of 56 cars was starting from a resting position, and a large pull was produced on the instrumented tank car.
- The speeds of coupling were not known when the instrumented tank car was impacted. There does not seem to be a correlation between speed of coupling and the force measured on the instrumented couplers in the longitudinal direction.
- Testing indicates the rolling consist mass and tank car position in the consist influences the impacting forces exerted on the cars.
- Hump yard events have a much tighter band of values compared to the flat switching yards encountered during this testing. Note that the amount of time the instrumented tank car was in flat switching yards was substantially more than the time it was in hump switching yards.
- Further classification of yards was not conducted under this study conducted by ENSCO.
- On a statistical average, the car was in yards for about 112 days. During that time, at least 30 hits with magnitude above 673 kip were observed. This would equate to approximately 1 hit every 4 yard-days, with a value of more than 673 kip.
- It may be possible to arrive at the LCF value estimates from measured longitudinal accelerations. Further research would have to be conducted to develop an algorithm and could involve the use of train dynamics simulation models. Once achieved, it would provide an inexpensive method for measuring LCF values based on measured accelerations.

3.2 Vertical Coupler Force (VCF) Events

High-VCF events were thought to be a significant contributor to tank cracking, especially when the forces were in the downward direction. The downward forces represent an opening crack mode if a crack was present between the stub sill and the carbody. For the data collected during this effort, negative VCF events represent hits in the upward direction and positive values represent downward hits. Similar to the LCF events, the V/TI data acquisition system sent back data events with high VCF values to the Track IT website in real time. ENSCO mined the data files for the highest vertical coupler force events and identified the 20 largest events that the tank car saw over the entire route of testing (Table 8).

Table 8. Large-Magnitude Events for the Vertical Coupler Force Parameter

Number	Speed (mph)	Coupler VCF (lb)	Latitude (degree)	Longitude (degree)	File Name	Location
1	42	-42050	33.957877	-83.48026	06141634	Bogart, GA Regular Operations
2	0	-35840	30.718257	-88.049597	06040657	Mobile, AL Yard
3	41	-34940	33.947142	-83.548548	06141606	Bogart, GA Regular Operations
4	39	-33400	34.92335	-79.860257	06150604	Lilesville, NC Regular Operations
5	5	33010	31.17323	-82.401728	03111108	Waycross, GA Yard
6	28	-32010	34.172428	-82.376887	06142104	Abbeville, SC Regular Operations
7	7	-31960	34.912828	-79.667275	06152304	Hamlet, NC Yard
8	39	-31760	39.5327	-78.615835	06190434	Green Spring, WV Regular Operations
9	0	-30670	30.718257	-88.049598	06040657	Mobile, AL Yard
10	30	-30070	28.409163	-82.18356	03070434	Dade City, FL Regular Operations
11	39	-29480	34.852895	-80.909095	06150334	Catawba, SC Regular Operations
12	23	-28730	34.954275	-79.949998	06150534	Lilesville, NC Regular Operations
13	42	28460	33.957788	-83.480435	06141634	Bogart, GA Regular Operations Event #1 but other direction
14	0	28230	30.7189	-88.04877	03141807	Mobile, AL Yard
15	22	-28180	33.855288	-84.190815	06131504	Tucker, GA Regular Operations
16	43	-27840	28.047432	-82.12929	03020334	Plant City, FL Regular operations
17	25	-26930	39.645627	-77.599037	02171939	Smithsburg, MD Regular Operations
18	24	-26840	33.854762	-84.182787	06131504	Stone Mountain, GA Regular Operations
19	2	-26760	31.1725	-82.40233	03061504	Waycross, GA Yard
20	23	-26660	33.854992	-84.18627	06131504	Stone Mountain, GA Regular Operations

In Table 8, most of the forces took place on the mainline track during transportation operations. Most of the top VCF events are negative values, indicating that the coupler was pushed up. Upward and downward events contribute to the same stress value if the magnitude is the same in either direction, as long as a crack is not present.

3.2.1 Additional Analysis of Specific Events

The events listed in Table 8 were looked into for any common characteristics that could be observed. The highest magnitude VCF event, with a value of -42 kip (Figure 31), took place at a road crossing near Bogart, GA.

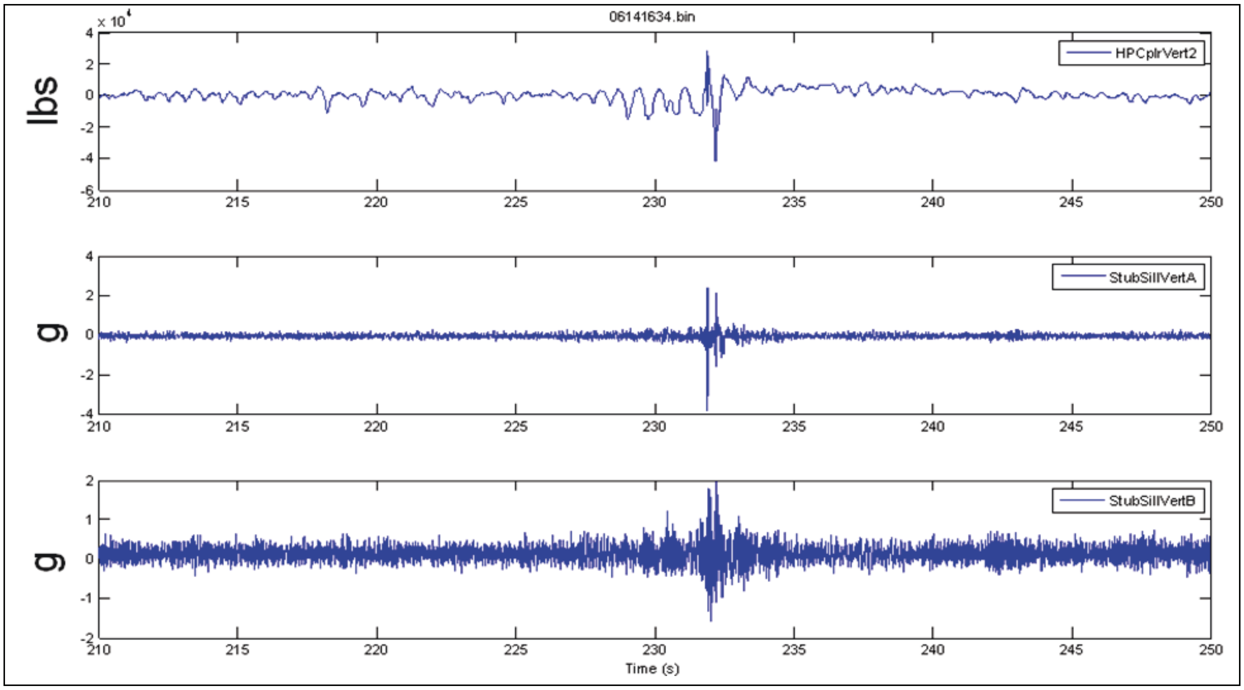

Figure 31. Highest VCF Event, at a Road Crossing Near Bogart, GA

The event is a sharp event, with an initial downward force of 28 kip and then an upward reaction at 42 kip. This may have been caused by the leading car going over a vertical perturbation of the right magnitude and frequency to cause the downward hit, and then the instrumented tank car going over the same perturbation and causing the opposite reaction as an upward hit. The road crossing was located on Google maps (Figure 32). The tank car was traveling at a constant speed of 42 mph. This high-VCF event was accompanied by a mildly high LCF value of about 300 kip.

Figure 32. Road Crossing at Bogart, GA, Attributed to the Highest VCF Event

The second-highest VCF event took place in the Mobile, AL, yard. It was a 35-kip hit that seemed to have occurred when the brakes were released and the car started to pull forward. It was accompanied by a large 500-kip LCF event (Figure 33). This event was one of the events which show that combined large LCF and large VCF events do take place and may produce a large stress event that could be detrimental to the life of a stub sill.

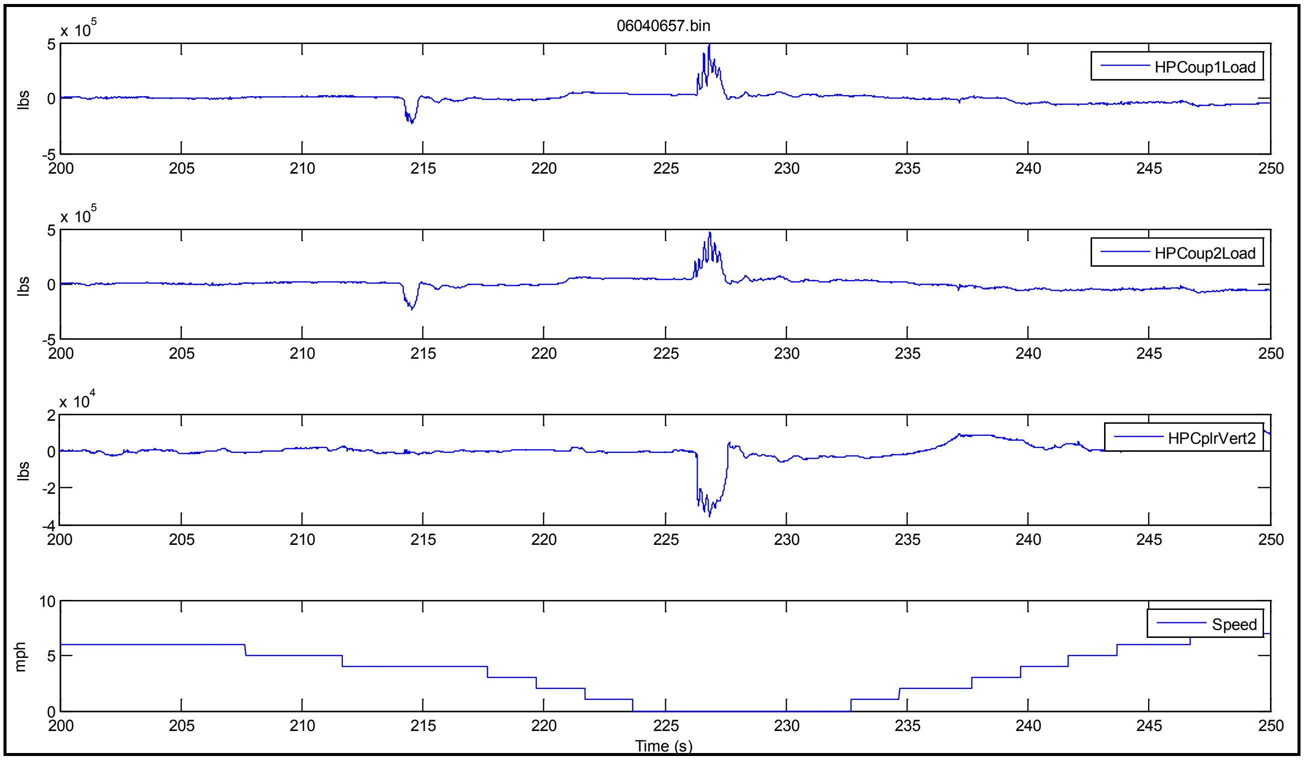

Figure 33. Second-Highest VCF Event (in the Mobile, AL Yard)

The fifth largest event of the top twenty was a positive (downward force) event that took place in the Waycross, GA, yard on the way from Tampa, FL, to Mobile, AL. A few of the parameters are shown in Figure 34. Note that a large LCF event of 834 kip accompanied the high VCF value. This event is the same as LCF event #10 in Table 7.

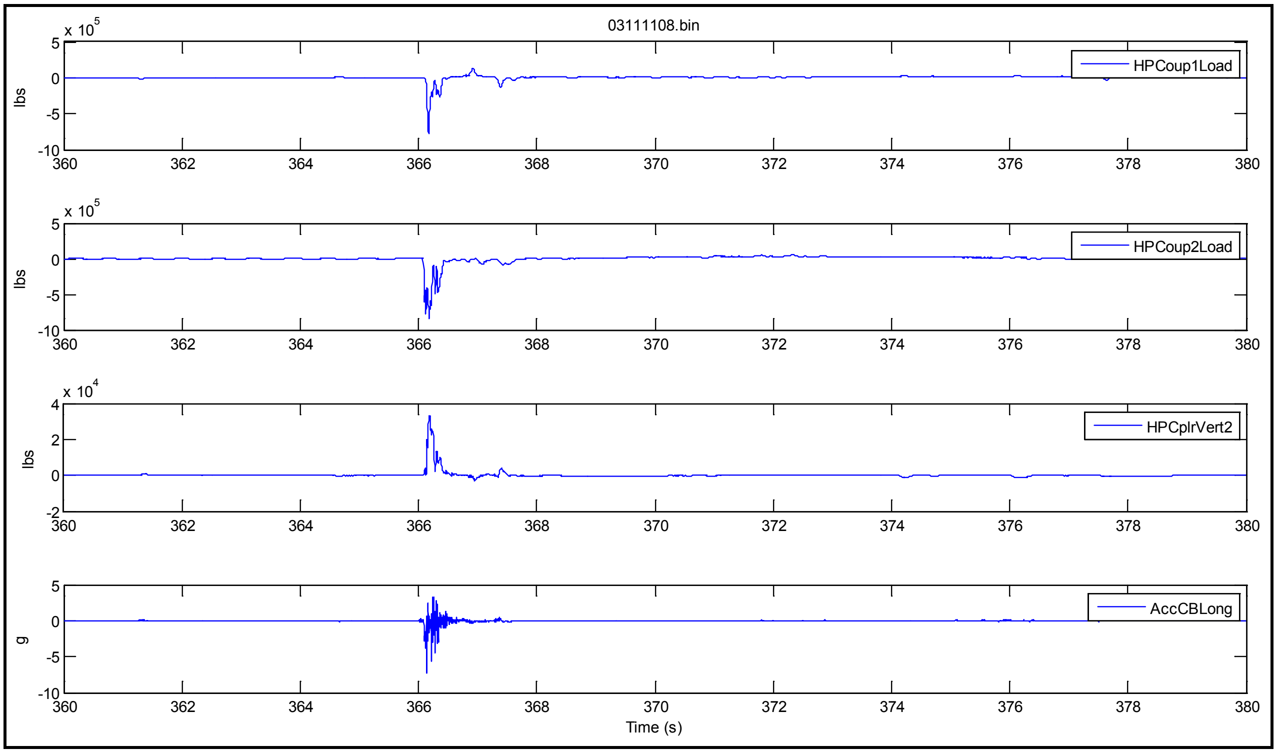

Figure 34. Fifth Largest VCF Event (with a Large Accompanying LCF Event)

3.2.2 Characterization of VCF Events

Further analysis of high-VCF events was conducted to find distinguishable features near the events in order to attribute causes for them. The events were characterized with respect to the location and other pertinent information, such as closest special track features (Table 9). Of the top 20 events, 14 took place on mainline operations, and 6 took place in yards during consist formation operations. The highest force observed during all testing conducted on the instrumented tank car was an upward force of 42 kip, which occurred at a road crossing in Bogart, GA, and was accompanied by a large downward force of 28 kip at the same location. The second highest VCF event took place in the Mobile, AL, yard with an upward force of 35 kip.

Table 9. Characterization of High-VCF Events

Number	Coupler VCF (lb)	Location	Pertinent Information
1	-42050	Bogart, GA Regular Operations	At road crossing
2	-35840	Mobile, AL Yard	Yard - Consist Formation
3	-34940	Bogart, GA Regular Operations	No distinguishable features
4	-33400	Lilesville, NC Regular Operations	Switch and Bridge Approach about 50 feet away
5	33010	Waycross, GA Yard	Yard - Consist Formation
6	-32010	Abbeville, SC Regular Operations	Bridge start about 40 feet away from GPS coordinates
7	-31960	Hamlet, NC Yard	Yard - Consist Formation
8	-31760	Green Spring, WV Regular Operations	Many Switches in Area
9	-30670	Mobile, AL Yard	Yard - Consist Formation
10	-30070	Dade City, FL Regular Operations	At dirt road crossing within 25 feet
11	-29480	Catawba, SC Regular Operations	Dirt road crossing within 50 feet
12	-28730	Lilesville, NC Regular Operations	At siding - may be a switch - image not clear
13	28460	Bogart, GA Regular Operations	Same event as the Event 1 - Positive swing
14	28230	Mobile, AL Yard	Yard - Consist Formation
15	-28180	Tucker, GA Regular Operations	No distinguishable features
16	-27840	Plant City, FL Regular Operations	On a road crossing
17	-26930	Smithsburg, MD	Crossing within 27 ft to East
18	-26840	Stone Mountain, GA Regular Operations	No distinguishable features
19	-26760	Waycross, GA Yard	Yard - Consist Formation
20	-26660	Stone Mountain, GA Regular Operations	No distinguishable features

Analysis of the data in Table 9 shows that high VCF events occurred at locations with the following characteristics:

- 6 (30%) on or very near road crossings (within 25 feet)
- 6 (30%) in yard operations
- 2 (10%) near bridge starts/ends
- 2 (10%) near switches/sidings
- 4 (20%) no distinguishable track features around the events.

Based on the number of test days the tank car travelled, it was observed that high VCF events (greater than 26 kip) occurred on an average of once every 2.5 days or approximately every 270 miles.

3.2.3 Effect of Track Geometry on VCF Events

Because most high VCF events identified during the test took place during routine operations, analysis was conducted to see what factors caused these events. All the events occurred at constant speeds, thereby ruling out train handling issues. Abnormal longitudinal accelerations (e.g., jerking) were not observed for these events. This left track geometry as a possible causal factor. These events were therefore analyzed for vertical perturbations, using track geometry data collected over the test route.

The top VCF event of 42 kip is shown again in Figure 35, and the corresponding track geometry data are shown in Figure 36. The track geometry data were collected by DOTX-217 on 10/30/2009 and were not an exception by current FRA Track Safety Standards (TSS) for surface deviations. Although the 62' surface parameters seem to be below the FRA TSS, the 31' profile parameters shown in the bottom part of Figure 36 show the same signature but with a significantly higher magnitude. Although the location was not a defect at the time the geometry car was tested (10/30/2009), it may have deteriorated by 06/14/2010, when the tank car traveled on the same route.

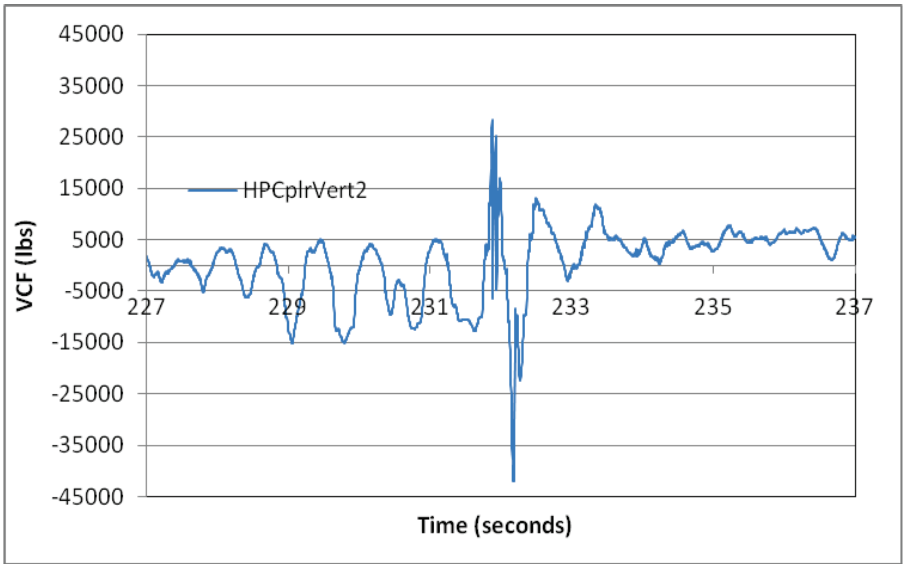

Figure 35. Snapshot of the Top VCF Event: 42 kip at a Road Crossing Near Bogart, GA

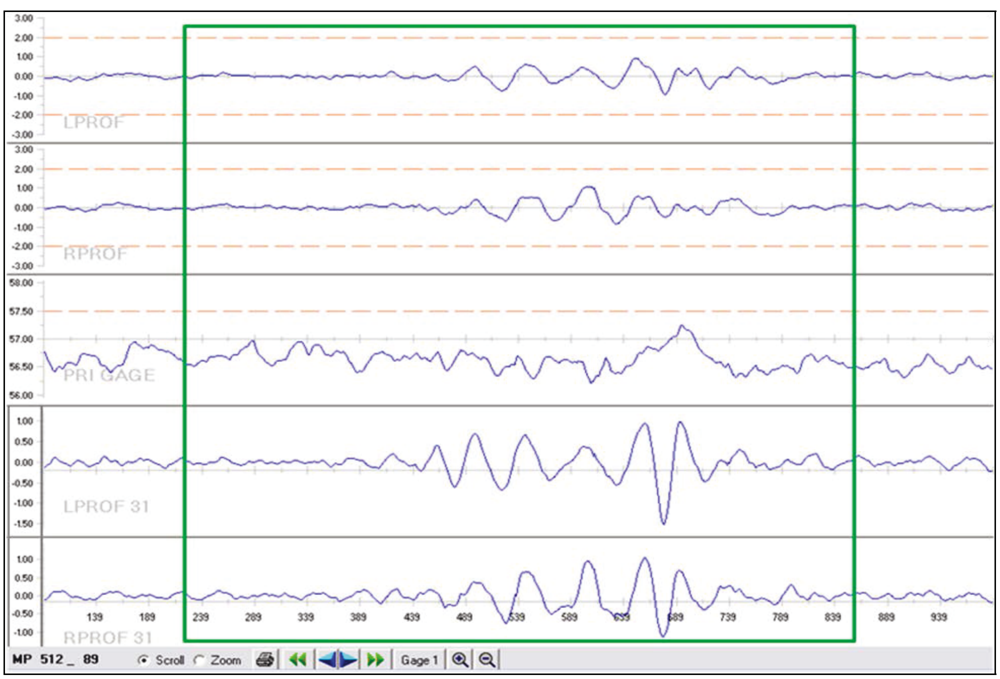

Figure 36. Track Geometry Data for the Section of Track Corresponding to Figure 35

The second-highest VCF event (on mainline track—yards excluded) was also similarly tied to short chord (31') vertical profile geometry, as shown in Figure 37 and Figure 38.

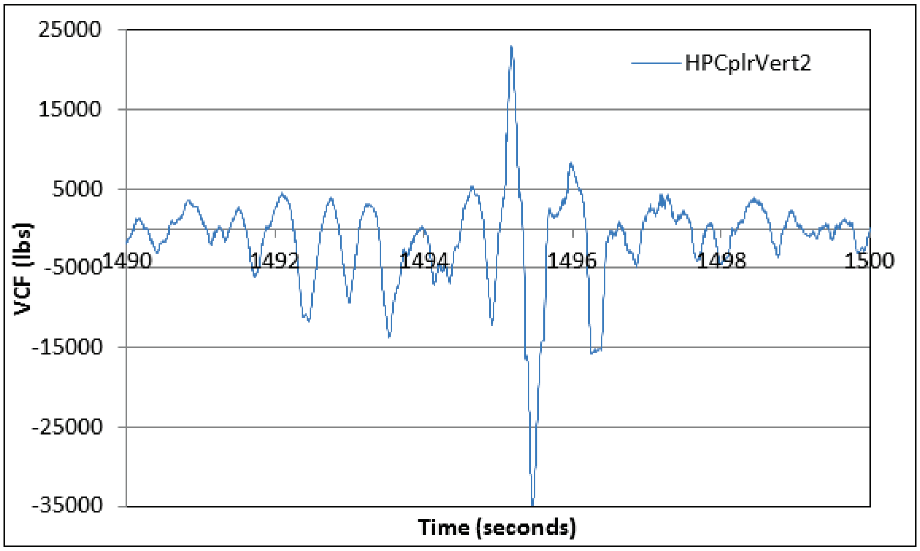

Figure 37. Second Highest VCF Event on Mainline Track: 35 kip Near Bogart, GA

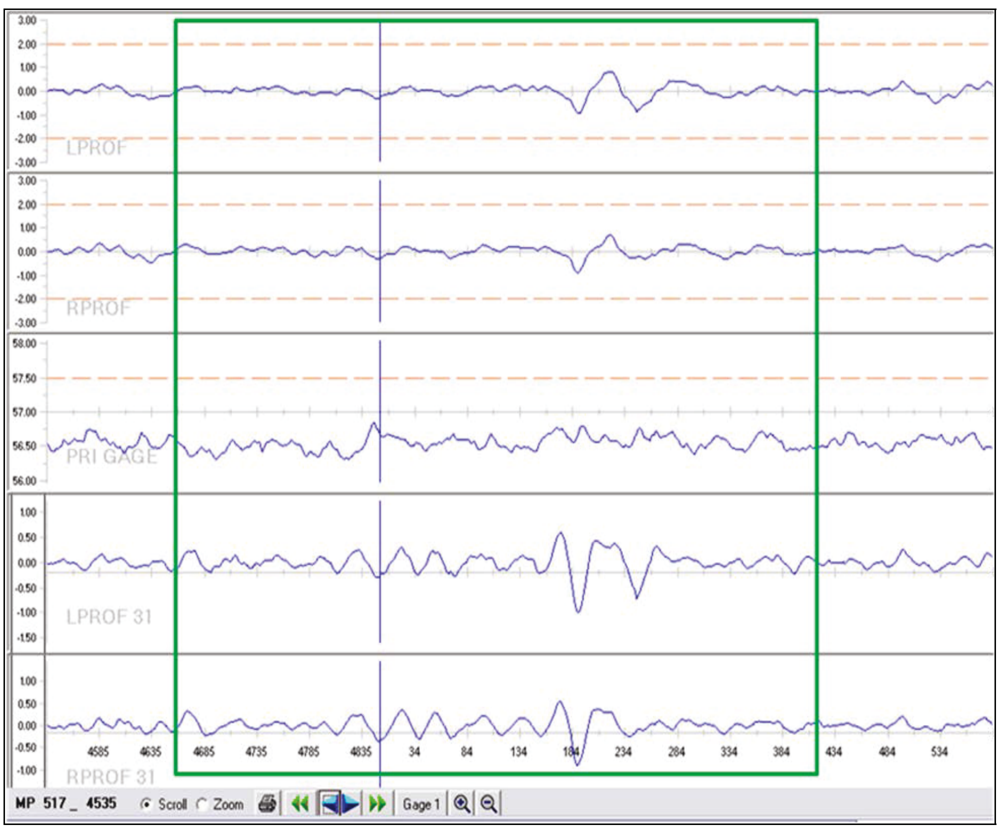

Figure 38. Track Geometry Data for the Section of Track Corresponding to Figure 37

Track geometry data was analyzed for all the top VCF events in the form of peak-to-peak values for left and right profile measurements at the respective locations. The data are shown in Table

10, along with the dates the geometry data were collected. It can be seen clearly that all these locations have high 31’ chord values. For reference, the 31’ chord profile measurement threshold to maintain track for Class 6 is 1” (Class 6 is for operating trains up to 110 mph).

Table 10. Peak-to-Peak Values for 31’ Chord Profile Measurements at High-Magnitude VCF Events on Mainline Track

Number	Coupler VCF (lb)	Location	Geometry Data Collected Date	Left Profile 31' Pk to Pk	Right Profile 31' Pk to Pk	Average Profile 31' Pk to Pk
1	-42050	Bogart, GA Regular Operations	10/30/2009	2.53	2.19	2.36
3	-34940	Bogart, GA Regular Operations	10/30/2009	1.64	1.46	1.55
4	-33400	Lilesville, NC Regular Operations	11/13/2009	1.58	1.88	1.73
6	-32010	Abbeville, SC Regular Operations	10/30/2009	1.71	0.98	1.345
8	-31760	Green Spring, WV Regular Operations	10/9/2009	2.21	2.06	2.135
10	-30070	Dade City, FL Regular Operations	2/6/2009	2.36	2.42	2.39
11	-29480	Catawba, SC Regular Operations	No track geometry data collected near this location			
12	-28730	Lilesville, NC Regular Operations	11/13/2009	1.25	1.33	1.29
13	28460	Bogart, GA Regular Operations Same Event but other direction	10/30/2009	2.53	2.19	2.36
15	-28180	Tucker, GA Regular Operations	10/30/2009	1.37	1.33	1.35
16	-27840	Plant City, FL Regular operations	No Track Geometry data collected. Track Geometry vehicle traveled on different tracks near this location.			
17	-26930	Smithsburg, MD	3/31/2010	2.89	1.7	2.295
18	-26840	Stone Mountain, GA	10/30/2009	1.69	1.44	1.565
20	-26660	Stone Mountain, GA	10/30/2009	1.85	2.19	2.02

3.2.4 Calculation of 10’ and 31’ Profile Mid Cord Offset Values Using Axle Accelerometers on Instrumented Tank Car

ENSCO has developed an algorithm for calculating rail profile (track surface) mid chord offset (MCO) from axle-mounted accelerometers. The algorithm has been tested and developed for the V/TI Monitor product that ENSCO produces. The algorithm essentially uses the fact that at a constant speed each acceleration measurement can be interpreted as a very short MCO, where the length is dependent on the speed, which is determined by GPS. A simple finite impulse response (FIR) weighted filter can be applied to the data to convert a short MCO measurement to a longer MCO measurement. If a 10’ MCO is desired, then it is assumed that the speed is essentially constant for 10 feet and the FIR filter is 10 feet in length.

This method is efficient and accurate. Good results have been generated for 10’ MCOs and 31’ MCOs. It is necessary to perform a mean-removal high-pass filter on the acceleration data before the short-to-long chord filter to prevent errors. Calculations are accurate only if the vehicle is moving at sufficient speed, i.e. over approximately 10 mph.

3.2.5 Comparison of the Calculated 31’ Mid Cord Offset to Top VCF Events

It appears that many high-VCF events can be correlated to significant deviations in the rail profile. The following are three examples of this correlation.

This first example is from 6/14/2010 on CSX track near Bogart, GA. The tank car was traveling north at 41 mph and experienced a VCF of approximately 35 kip. The 31’ profile MCO (Figure 39) was 1.27” on the left and 1.12” on the right. The 10’ profile MCO was 0.266” on the left and

0.222” on the right. The measured 31’ profile MCO at this location by the geometry car on 10/30/2009 was 1.64” and 1.46” on the left and right sides, respectively. Although the geometry data were generated about 8 months before the tank car passed through this location, it shows that the calculated values of the MCOs (tank car test) and the measured values (track geometry survey) are comparable. The signatures of the short chord MCOs and the vertical coupler force have a good correlation, too.

The second example is from 6/14/2010 on CSX track at a road crossing between Bogart, GA, and Athens, GA. The tank car was traveling north at 42 mph and experienced a vertical coupler force of approximately 42 kip. The 31’ profile MCO (Figure 40) was 1.88” on the left and 1.34” on the right. The 10’ MCO was 0.370” on the left and 0.228” on the right. The 31’ profile MCO at this location, measured by the geometry car on 10/30/2009, was 2.53” on the left side and 2.19” on the right side. Although the geometry data were generated about 8 months before the tank car passed through this location, it shows that the calculated (tank car test) and measured (track geometry survey) values of the MCOs are comparable. The correlation between signatures of the short chord MCOs and the VCF, especially the 10’ profile MCO retaining some parts of the high-frequency data that also shows up in the VCF data.

The third example is from 3/7/2010 on CSX track near Dade City, FL. The tank car was traveling south at 30 mph and experienced a vertical coupler force of approximately 30 kip. The 31’ profile MCO peak value (Figure 41) was 1.38” on the left and 1.34” on the right. The 10’ profile MCO peak value was 0.249” on the left and 0.244” on the right. The 31’ profile MCO measured at this location by the geometry car on 2/6/2009 was 2.36” and 2.42” on the left and right sides, respectively. Because the geometry data were generated about 1 year and 4 months before the tank car passed through this location, a comparison may not be valid.

These examples indicate that large tank car VCF can be correlated to rail profile calculated from axle accelerometer data when high forces are experienced during routine operations. This method could be used to further develop a low-cost approach where strain gauges may not be needed to measure the VCF, and less costly accelerometer sensors may be employed to provide the same measurements. Further algorithm development would have to be conducted to arrive at a method that would predict the VCF values from the accelerations.

This idea can be implemented in the case of the tank car, because the axle accelerometers are present, and the tank car project uses a modified V/TI for data collection. Currently, because the software has not been modified to do the calculation on board, it must be post-processed.

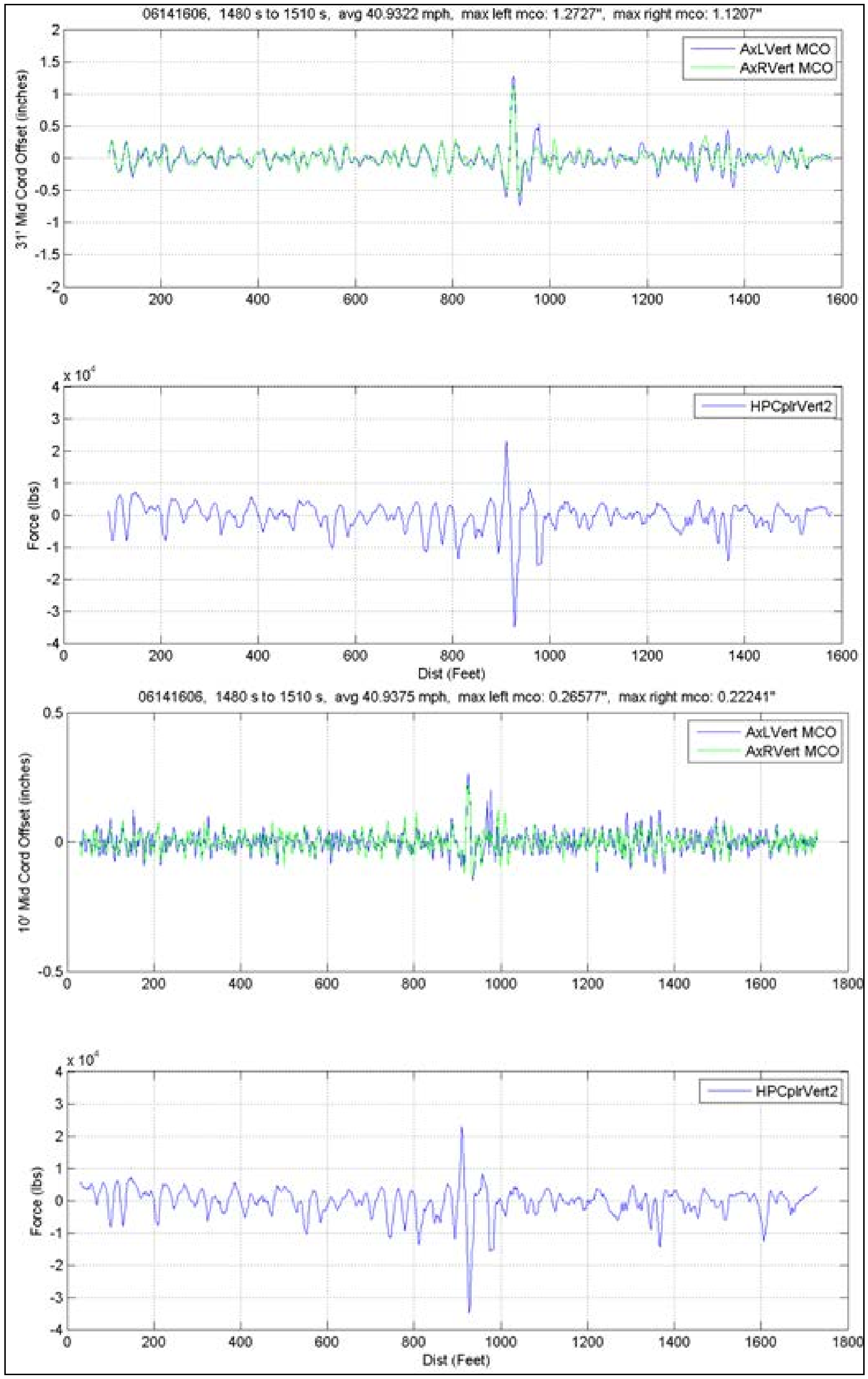

Figure 39. Comparison of VCF Event #3 with Calculated 31' and 10' Profile MCO Values

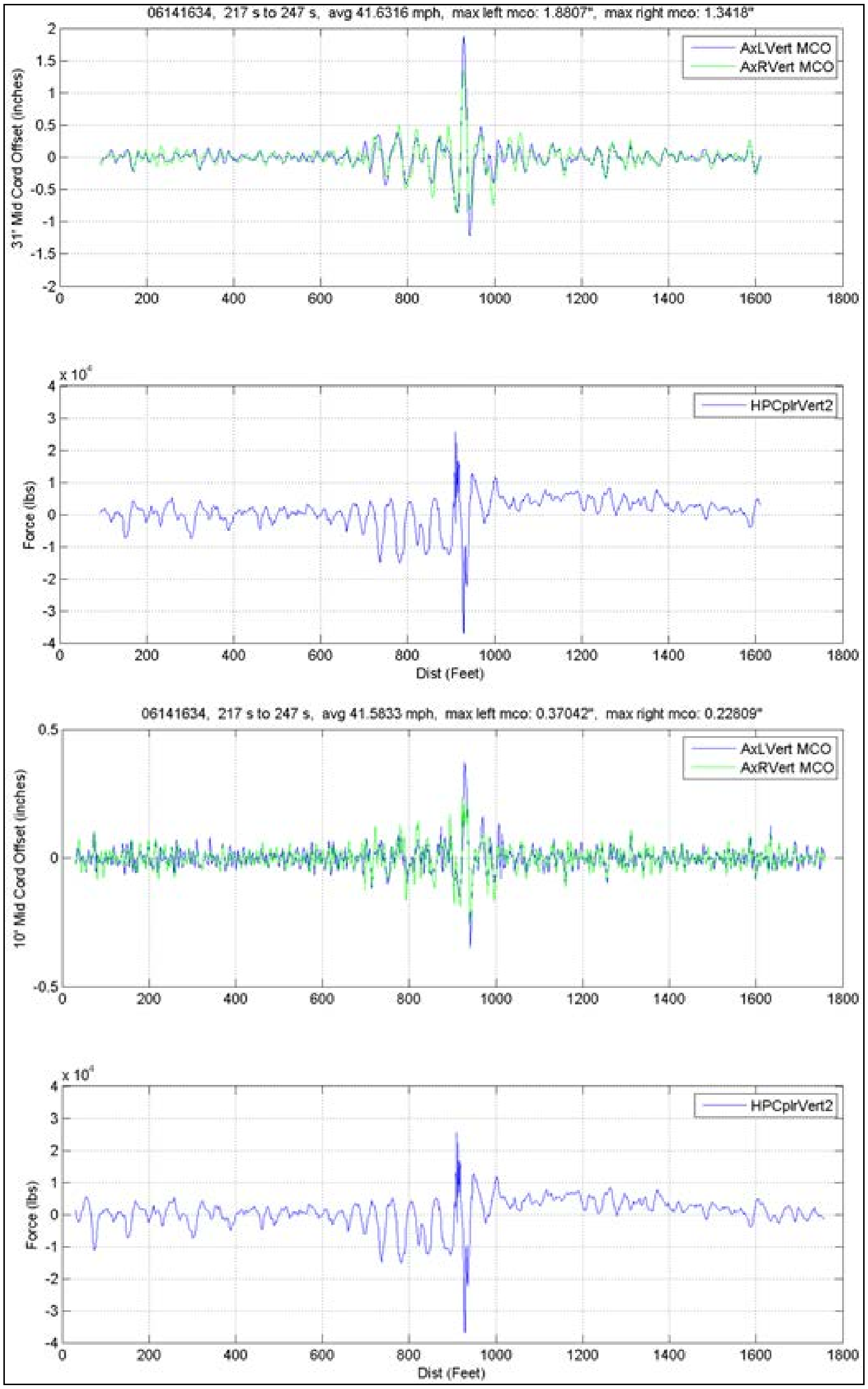

Figure 40. Comparison of VCF Event #1 with Calculated 31' and 10' Profile MCO Values

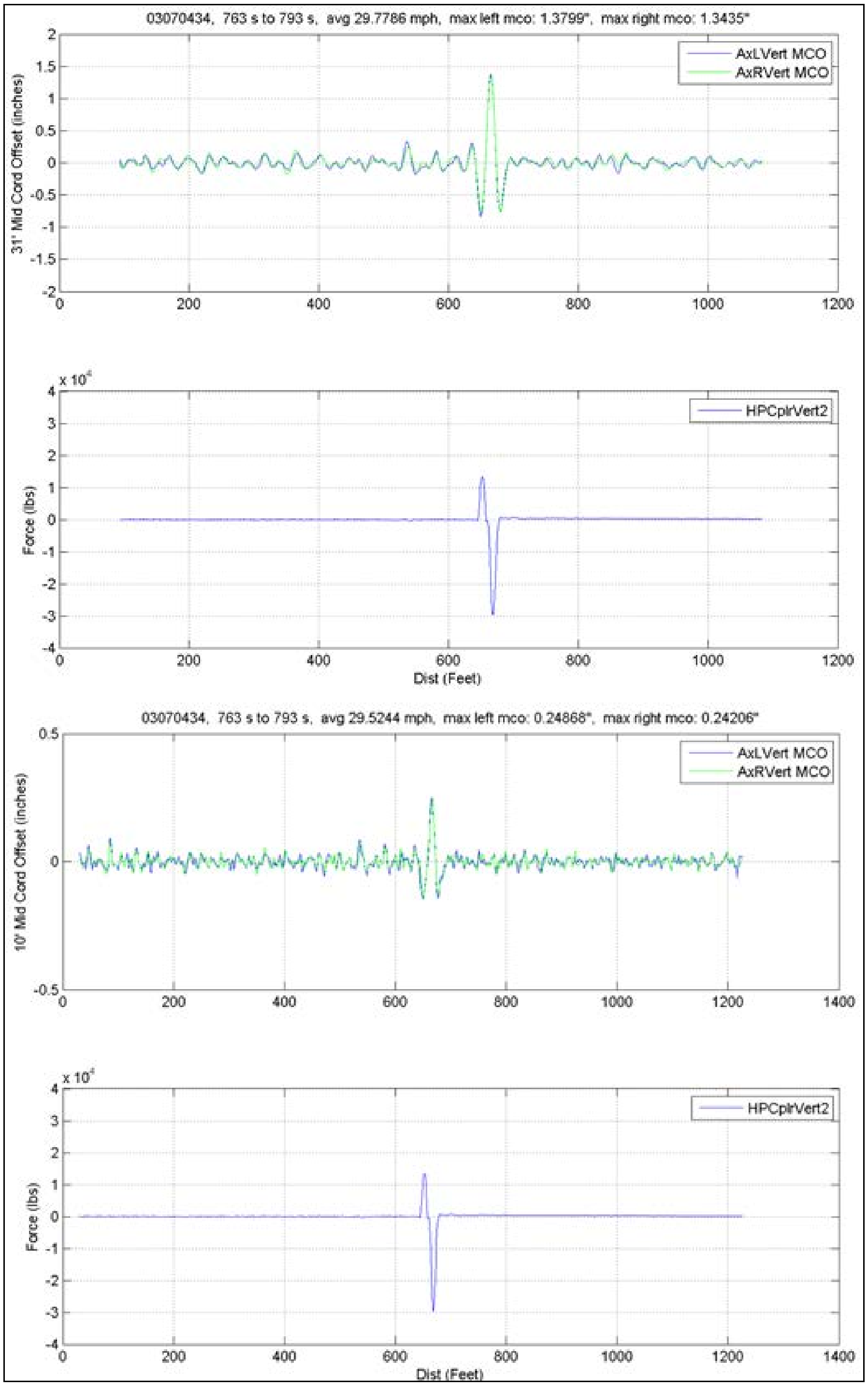

Figure 41. Comparison of VCF Event #6 with Calculated 31' and 10' Profile MCO Values

3.2.6 Mild Correlation of VCF Events with Respect to Speed

The high VCF events were plotted against the speed of the instrumented tank car when the events happened. It was observed that, for the events that took place on the mainline, there was a mild linear correlation with an R^2 value of 0.4. The values of VCF against the train speed are shown in Figure 42. The data seems to indicate that the VCF values are dependent not only on the vehicle speed, but also on the magnitude and frequency of the vertical perturbations on the track, such as road crossings, bridge transitions, etc.

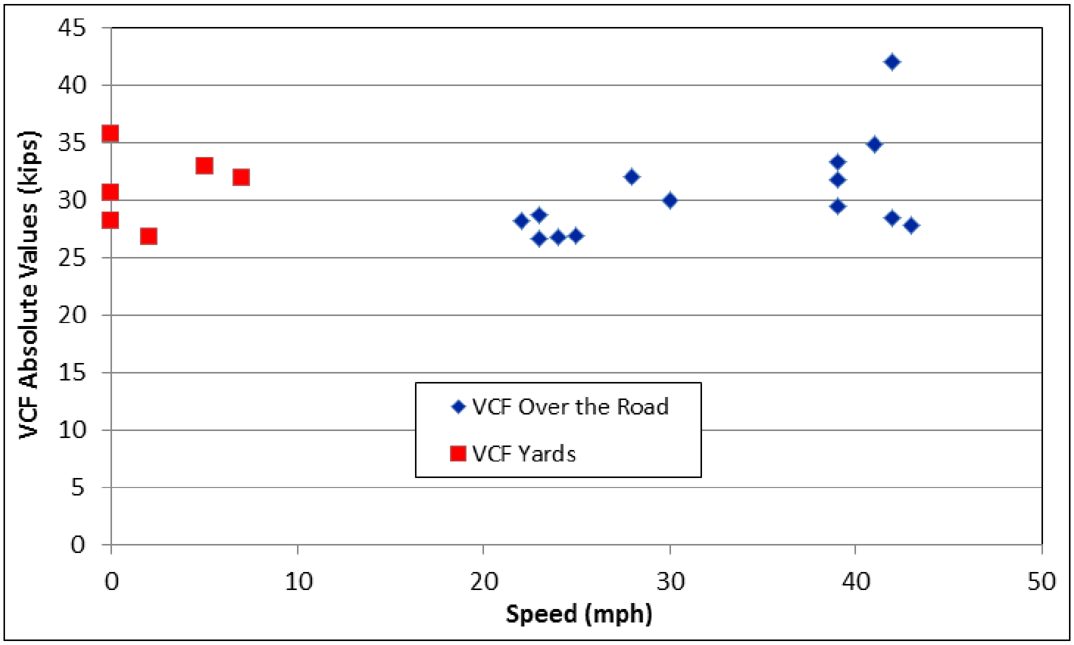

Figure 42. Mild Correlation of Train Speed and VCF Over the Road (Blue)

3.2.7 VCF Summary

Based on the analysis conducted on the VCF events, the following observations can be made:

- Most of the high VCF events take place on mainline track during regular transportation operations.
- A few high VCF events take place during consist formation operations in yards, often accompanied by high LCF events.
- A mild correlation with train speed is seen for VCF values but is insufficient to infer any trends.
- On a statistical average, a high VCF event (above 26 kip) is seen approximately every 270 miles.
- For the high VCF events observed on mainline track, track geometry seems to be the causal factor. Vertical perturbations of short chord nature shown by 31' profile measurements made during track geometry surveys seem to be the most important parameter.
- Special track features—such as crossings, bridge transitions, and switches—seem to be causing high VCF events.
- There is a strong possibility that a low-cost VCF value predictor could be developed by using calculated MCO values from axle acceleration measurements that were conducted during the over the road testing. The algorithm used in this analysis is based on the use of two

accelerometers on an axle of the tank car. A similar algorithm could be developed to predict LCF using two longitudinal accelerometers at the two ends of the car.

3.3 Comparison of High Stress Events with AAR Standards for Tank Cars

Upon observation of the high forces experienced during the instrumented tank car effort, the measured forces in the longitudinal and vertical directions were compared to the AAR standards for the manufacture and acceptance of stub sills for tank cars (AAR M-1002):

- Stub sills are designed for 1 million pounds of compressive or tensile longitudinal forces, such that stress values do not exceed yield stress limits for steel.
- Stub sills should be able to withstand vertical coupler force values of 50,000 pounds in both directions, and stresses should not exceed yield stress limits for steel.

Measured forces in the longitudinal direction exceeded 1 million pounds on the instrumented tank car test three (3) times in a duration of 112 days while in yards. The vertical coupler force did not exceed the AAR M-1002 limits during the testing conducted under this effort.

The combined longitudinal and vertical coupler force events observed could easily exceed the tank car design limits. As with a previous study, a 300-kip LCF event would generate 9,367 psi (Von Mises) stress at the critical region, as defined in DOT/FRA/ORD-07/22 (TTCI).[2] The same report estimated and validated the stress value for a 40-kip VCF event to generate 10,500 psi stress at the critical region. Under the current effort, stresses estimated by ENSCO for the stub sill on an instrumented tank car were evaluated for the tank car's stub sill design. The cross-section for the UTLZBG design for the NATX-250525 was obtained from the drawings of the tank car and simplified to estimate the stresses using a cantilever beam approach. This simplified cross-section is shown in Figure 43.

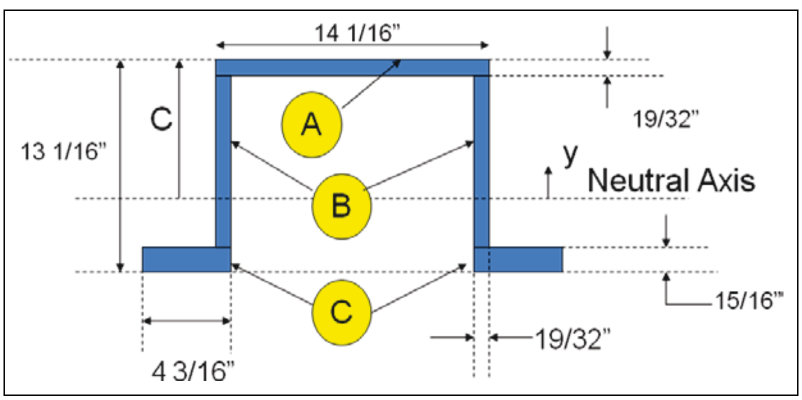

Figure 43. Simplified Cross-Section of the UTLZBG Stub Sill on NATX-250525

The moment of inertia and the neutral axis location were determined from the cross-section, using the following equations:

$$I = \int y^2 dA = 688.36 in.^4 \quad ,$$

[2]Kevin Koch, *Tank Car Operating Environment Study–Phase I*, DOT/FRA/ORD–07/22 (October 2007), http://permanent.access.gpo.gov/gpo20642/ord0722.pdf.

$$\text{Neutral Axis} = \int ydA = 6.76in.$$

The stress estimates, calculated by assuming that the stub sill is a simple cantilever beam with the above geometry, were calculated using the following equation, where *P* is the load applied at the end of the stub sill, and *x* is the distance from the end of the stub sill at which stress is being estimated:

$$\sigma = \frac{Mc}{I} = \frac{Pxc}{I} \quad .$$

The stress estimate variation with the distance from the end of the stub sill is shown in Figure 44. The distance from the end of the stub sill to the start of the head brace is 27.25" for this stub sill. At that distance, the stress is estimated to be 10,986 psi—very close to the values presented in the TTCI report mentioned above.

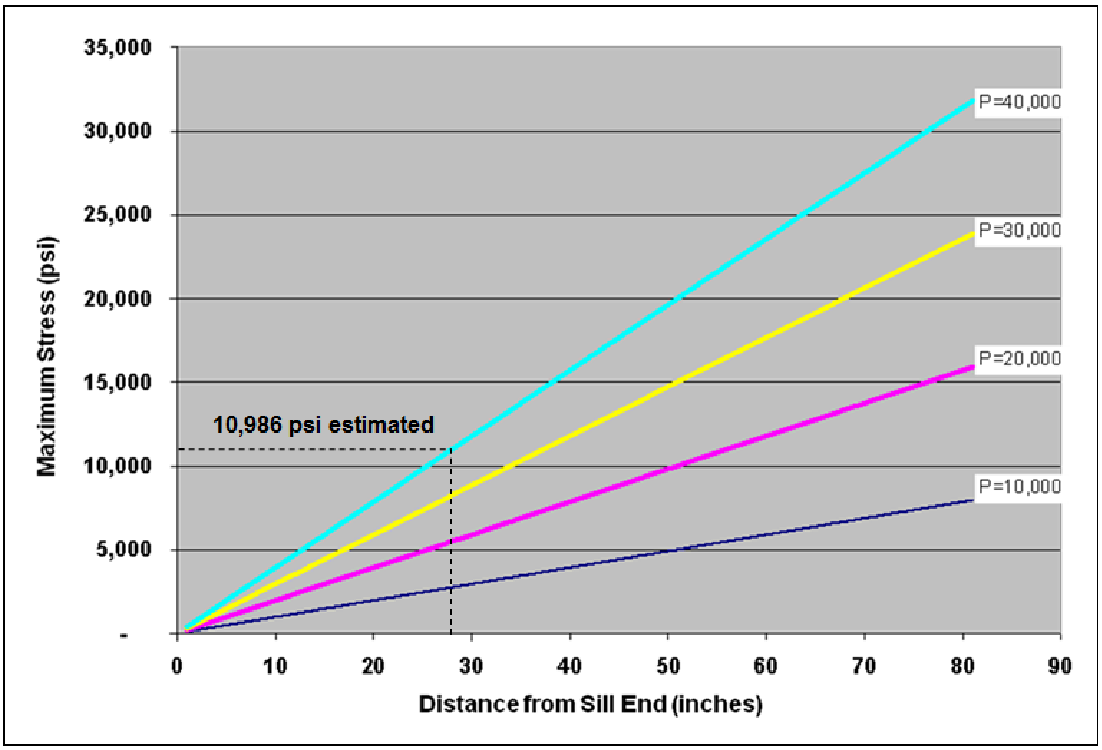

Figure 44. Estimate of Stress as a Relation to Distance from Striker Plate of Stub Sill Towards the Bolster

3.4 Stress Estimates Using Forces Observed During This Testing

Linear addition of stresses due to combinations of VCF and LCF was evaluated in this analysis as the worst-case scenario. Ideally, we would have to take the directions of the stress into consideration to account for the combinations of the compressive/tensile LCF forces and upward/downward VCF forces. Data show that many cases of high LCF in yards are accompanied by high values of VCF. Stress estimates as a linear addition for the magnitudes of the LCF and VCF values are listed in Table 11 for the travel from Gettysburg, PA, to Mobile, AL, for the top five (5) event locations.

Table 11. Locations of Top High Stress Events: Gettysburg, PA to Mobile, AL

	Event Location				
	1	2	3	4	5
Speed (mph)	0	5	0	5	0
A-End LCF (lb)	-888,000	-772,200	-699,900	-785,000	-711,800
B-End LCF (lb)	-1,137,600	-838,400	-634,800	-8,400	-479,700
A End VCF (lb)	28,230	33,010	-24,730	-10,070	-20,670
Stress Estimate (psi)	37,691	34,757	30,288	29,833	29,753
Latitude (degrees)	30.7189	31.17323	31.1727	27.95436	34.9167
Longitude (degrees)	-88.04877	-82.40173	-82.40145	-82.37594	-79.66025
Location	Mobile, AL Yard	Waycross, GA Yard	Waycross, GA Yard	Tampa, FL Yard	Hamlet, NC
File Name	03141807.bin	03111108.bin	02221934.bin	03031341.bin	02210824.bin

It should be noted that there were other locations where the B-end had much higher forces; but because the VCF measurement was not made at the B-end, the stress was not estimated for the B-end.

The stress estimates as a linear addition of the magnitudes of the LCF and VCF values are listed in Table 12 for the travel from Mobile, AL, to Letterkenny Army Depot near Chambersburg, PA, for the top five (5) event locations.

Table 12. Locations of Top High Stress Events: Mobile, AL to Letterkenny, PA

	Event Location				
	1	2	3	4	5
Speed (mph)	8	0	0	0	0
A-End LCF (lb)	-1,797,700	-569,300	498,400	-605,000	-486,200
B-End LCF (lb)	-73,000	-439,000	477,100	-837,800	-329,500
A End VCF (lb)	15,850	27,620	-35,840	12,340	15,930
Stress Estimate (psi)	66,631	26,393	25,837	24,065	20,747
Latitude (degrees)	30.71957	30.71647	30.71826	30.71927	30.71694
Longitude (degrees)	-88.04914	-88.04916	-88.0496	-88.04909	-88.04932
Location	Mobile, AL Yard	Mobile, AL Yard	Mobile, AL Yard	Mobile, AL Yard	Mobile, AL Yard
File Name	06040834.bin	06032233.bin	06040657.bin	06041238.bin	06040009.bin

The stub sill for this car was made out of A572-50 and had a minimum yield limit of 50 kilo-pounds per square inch (ksi). It can be seen from the two tables above that there was only one location that exceeded the specified yield limit of the steel used for the instrumented tank car. It should be noted that the instrumented coupler sensor at the A-end broke on 06/05/2010, and the tank car started traveling from Mobile, AL, to Letterkenny, PA, on 06/09/2010. Hence, there are no stress estimates after 06/05/2010 on the return trip. Also, as mentioned before, a few high forces were also observed on the B-end, where the instrumented coupler was working, but no measurement of VCF was made. As a result, there were no stress estimates on the B-end. Also, it should be noted that stress analysis should be conducted with better methods, such as Finite Element Analysis (FEA) considering the geometry of the stub sill and other integral components (weld elements, reinforcements, etc.).

3.5 Effects of Track Geometry Defects

The effect of track geometry was analyzed using available data collected closest to the tank car's travel dates. One section that was tested by geometry survey immediately after the tank car had been tested was between Washington, DC, and Jacksonville, FL, with the geometry survey conducted between the dates of 03/02/2010 and 03/09/2010. The corresponding tank car testing was conducted between 02/19/2010 and 02/23/2010. This section was used to flag five (5) profile deviations with their corresponding track classes. The exceptions are listed in Table 13, and the corresponding tank car VCF values are listed in Table 14.

Table 13. List of Exceptions Found by Geometry Car Surveys Immediately After the Tank Car Testing

Number	Geometry Data Date	Exception Parameter	Value (Inches)	Latitude	Longitude	Milepost and Foot Marker
1	3/8/2010	Left Profile 62'	-2.75"	32.92685	-80.0262	383-3941
2	3/9/2010	Right Profile 62'	-1.52"	31.97272	-81.2528	503-969
3	3/9/2010	Left Profile 62'	-1.45"	31.97252	-81.2532	503-1115
4	3/9/2010	Left Profile 62'	-1.37"	31.86313	-81.4593	517-2464
5	3/9/2010	Left Profile 62'	-1.40"	31.75973	-81.6531	530-4877

Table 14. VCF Peak Values for Profile Exception Locations Listed in Table 13

Number	Location in the Tank Car Files			Tank Car Speed (mph)	VCF Values (lb)
1	746 seconds	into	02212104.bin	45	8,000
2	684 seconds	into	02220618.bin	42	5,000
3	685 seconds	into	02220618.bin	43	Same as 2
4	854 seconds	into	02220634.bin	37	1,800
5	480 seconds	into	02220704.bin	39	1,800

These exceptions and the corresponding tank car data were plotted in order to allow conclusions to be drawn from the similarities, if any. Examples are shown in Figure 45 and Figure 46, where the profile measurement is 2.75" and the VCF value at this location is approximately 8,000 lb. These examples suggest that high VCF values are governed by short MCO values (such as 31') as opposed to the 62' chord measurement. This is also suggested by the various plots shown in Section 3.2.3.

3.6 Post-Test Stub Sill Inspection

After testing with the car was finished, a visual inspection was conducted on the A-end stub sill by an NDT inspector from GE Railcar Services. The visual inspection was conducted over a small section near the head brace, using the GE XL Go videoscope. More typical NDT methods, such as ultrasonic testing or dye penetration, were not performed because the car was not in a workshop where these tests could be performed.

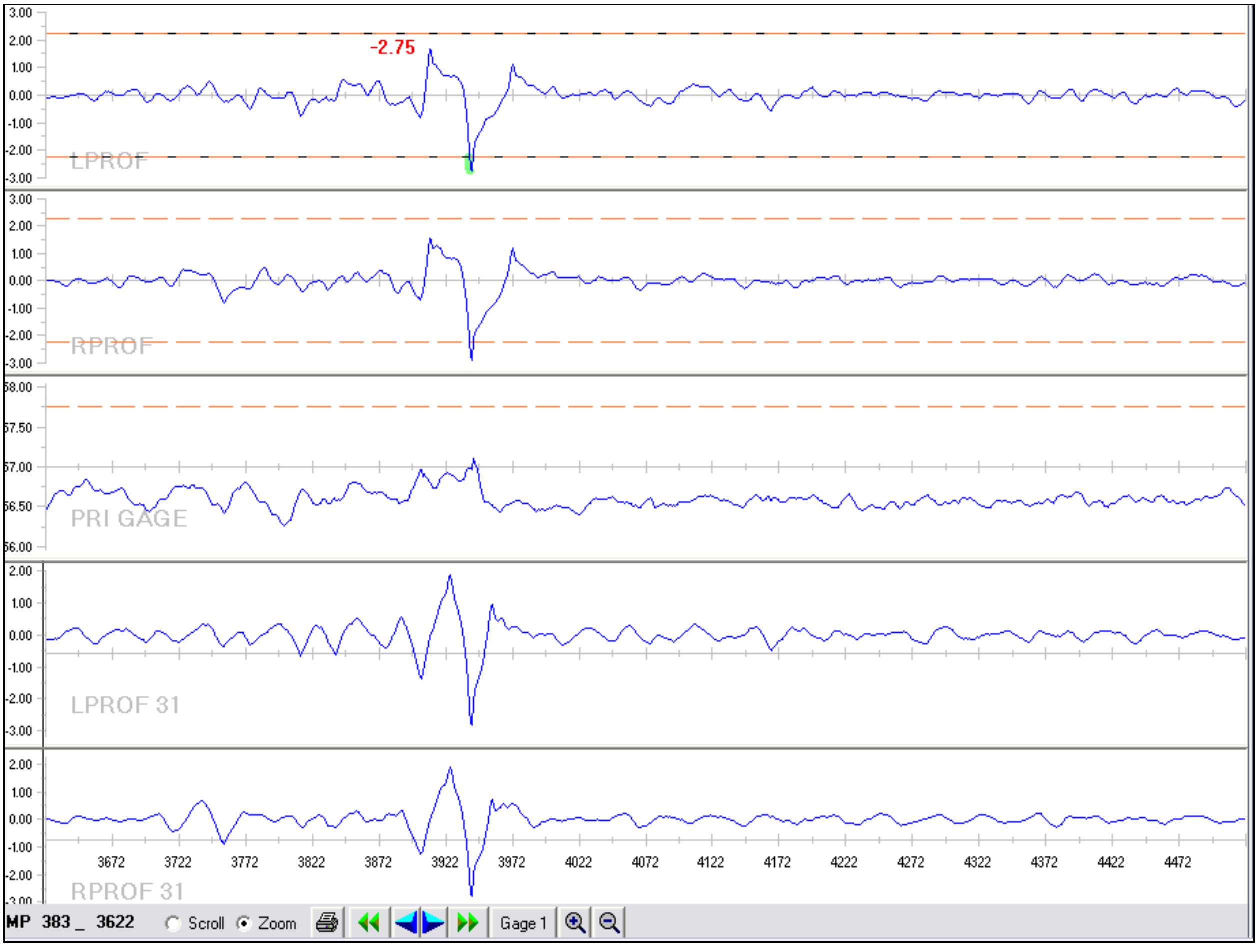

Figure 45. Exception on Left Profile 62' Chord Measurement (#1 Listed in Table 12)

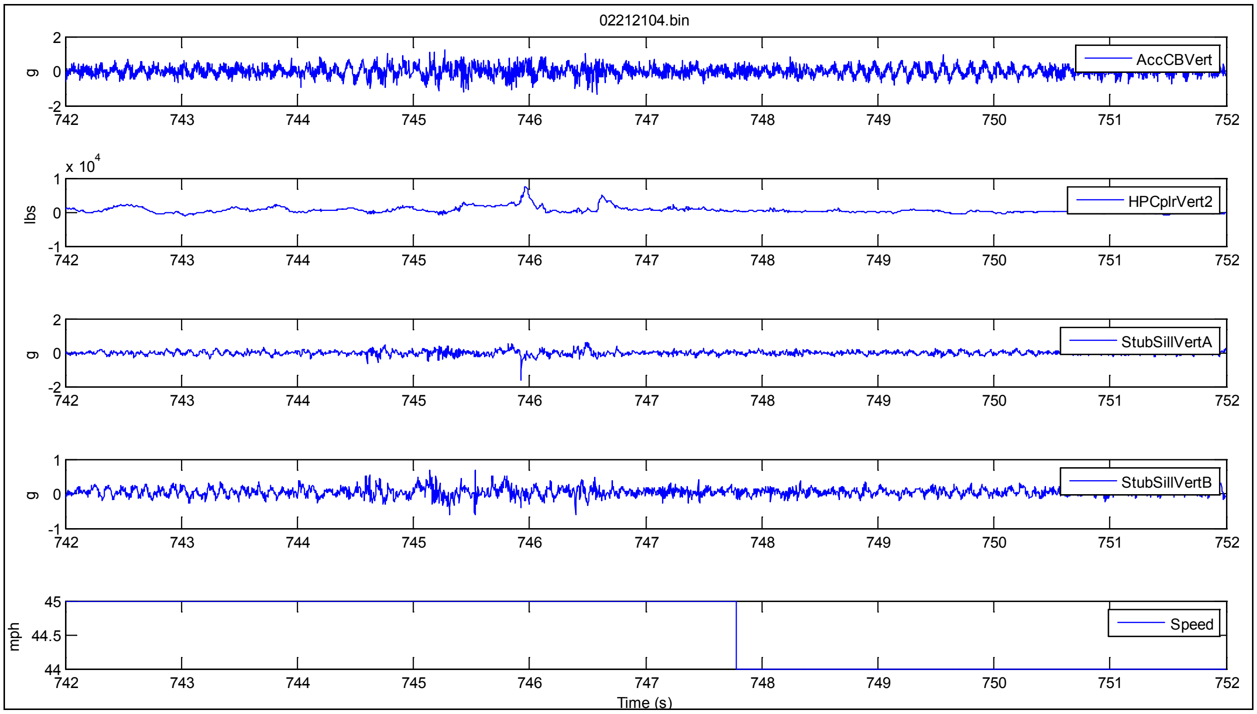

Figure 46. Tank Car Data Showing About 8,000 lbs VCF at the Profile Exception Location

4. Conclusion

The test effort in this study focused on capturing data from which the load environment and contributing factors associated with tank car operations on a hazmat route could be determined. The instrumentation on the tank car included a brake pressure sensor, eight strain gauges, four vertical load adapters, five accelerometers, and two instrumented couplers. A modified V/TI® monitoring system was used for autonomous data acquisition, collecting data during regular mainline transportation operations and in multiple yards. The data acquisition system collected information about speed and location, the motion of the train, the dynamics of the tank car, and the forces and strains on the tank car's structural parts. In addition to the collected instrumented tank car test data, geometry data collected on the test sections was also documented and used to derive pertinent information for the top VCF events.

The following conclusions can be drawn:

1. **Stub sill tank cars were being subjected to LCF exceeding AAR design limits.** Three times during the testing program, the LCF exceeded the AAR design limit of 1,000,000 pounds. One event involved a 1,800,000-pound LCF. The other events had LCF levels of 1,118,000 pounds and 1,093,000 pounds. Stress levels in the stub were associated with the largest LCF were greater than the yield stress of the A- steel. The vast majority of large-magnitude LCF were compressive forces.
2. **The majority of LCF with large magnitude occured in switching yards.** All three LCF that exceeded the AAR limit of 1,000,000 pounds occurred in a flat switching yard. Of the 30 LCF with the largest magnitude:
   - 19 occurred in a flat switching yard
   - 10 occurred in hump switching yards
   - 1 occurred in normal operations during startup.
3. **The tank car was subjected to VCF less than AAR design limits.** The largest magnitude VCF observed during testing was 33,000 pounds. Only 20 times did the magnitude of the VCF exceed 26,000 pounds. The majority of large-magnitude VCF occurred in normal operation conditions and showed a slight trend with operation speed.
4. **Short-wavelength surface track geometry was correlated with many large VCF.** For high-VCF events observed on mainline track, track geometry seemed to be the causal factor. Vertical perturbations of short-chord nature shown by 31' profile measurements made during track geometry surveys seem to be the most important parameter.
5. **Stress in the stub sill exceeded the elastic limit of the stub sill material.** The stress generated by the combined LCF and VCF was estimated based on a simple beam model. The largest stress was in compression of 66,000 psi. The elastic limit is 50,000 psi.

5. Recommendations

The following are recommended for further study of the tank car environment:

- Low-cost methods to measure VCF and LCF at both ends of tank cars should be developed and employed on about 20 cars, to further characterize the force environment for tank cars in regular service.
- Guidelines for operations in flat switching yards should be generated to limit coupling speed and the effective impacting mass.

Appendix A. Correlation Plots of Track Geometry Exceptions and VCF Values on the Tank Car

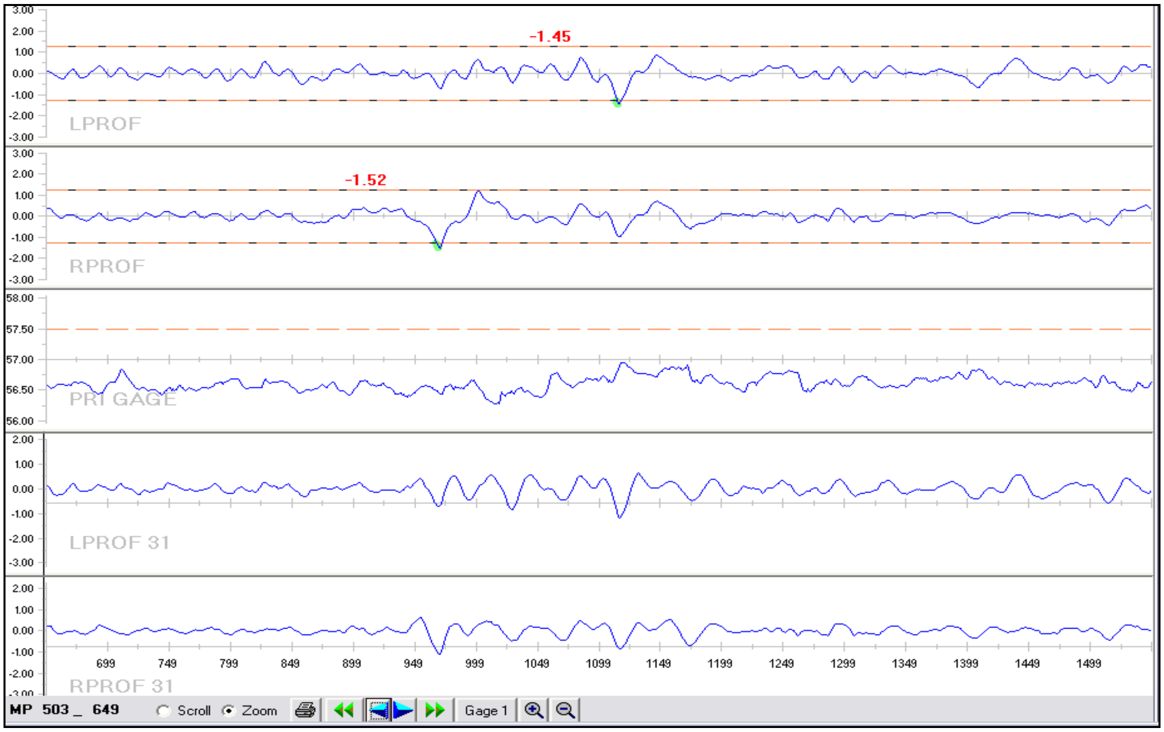

Figure A1. Geometry Data at MP503 and Feet 969 for Right Profile Exception, and Feet 1165 for Left Profile Exception, near Savannah, GA

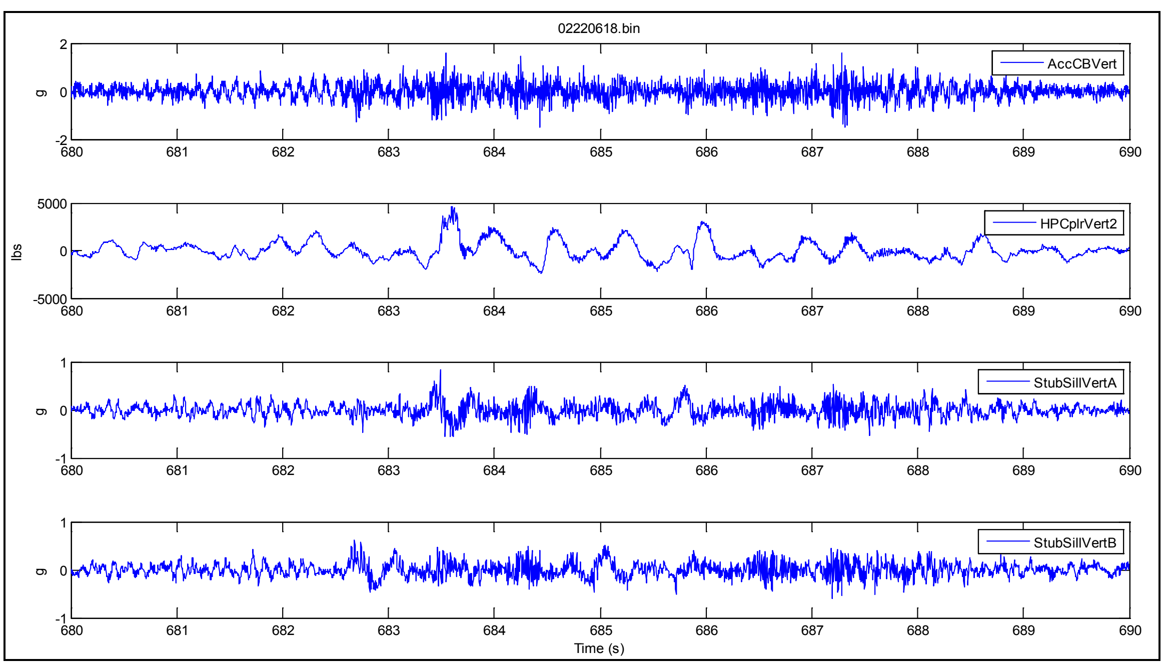

Figure A2. Corresponding Tank Car Data with VCF Values up to 5,000 lbs

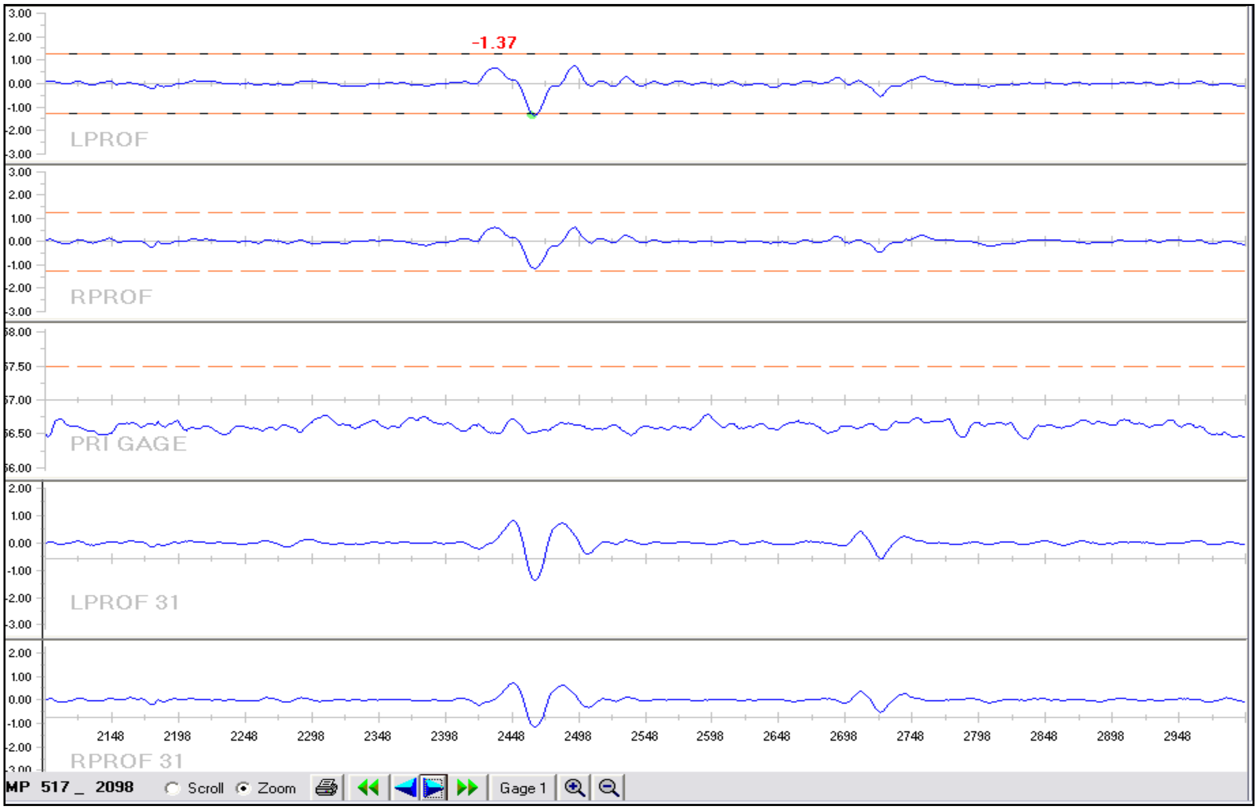

Figure A3. Geometry Data at MP517 and Feet 2464 for Left Profile Exception near Hinesville, GA

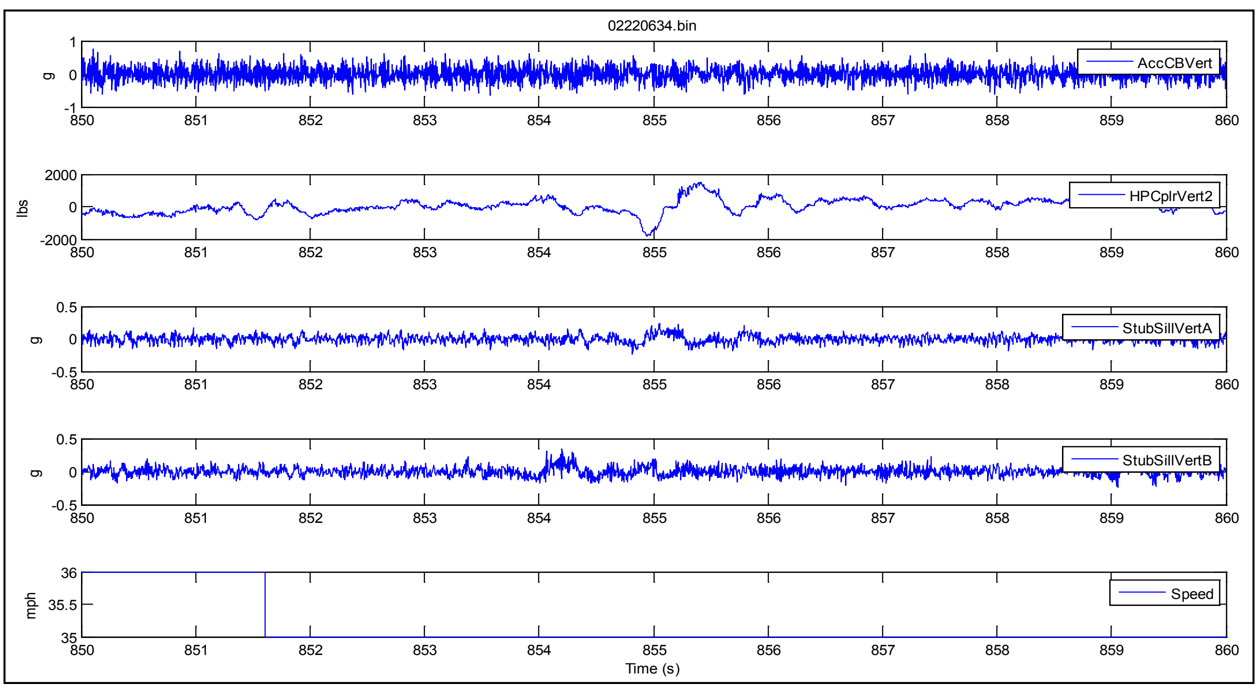

Figure A4. Corresponding Tank Car Data with VCF Values up to -1,800 lbs

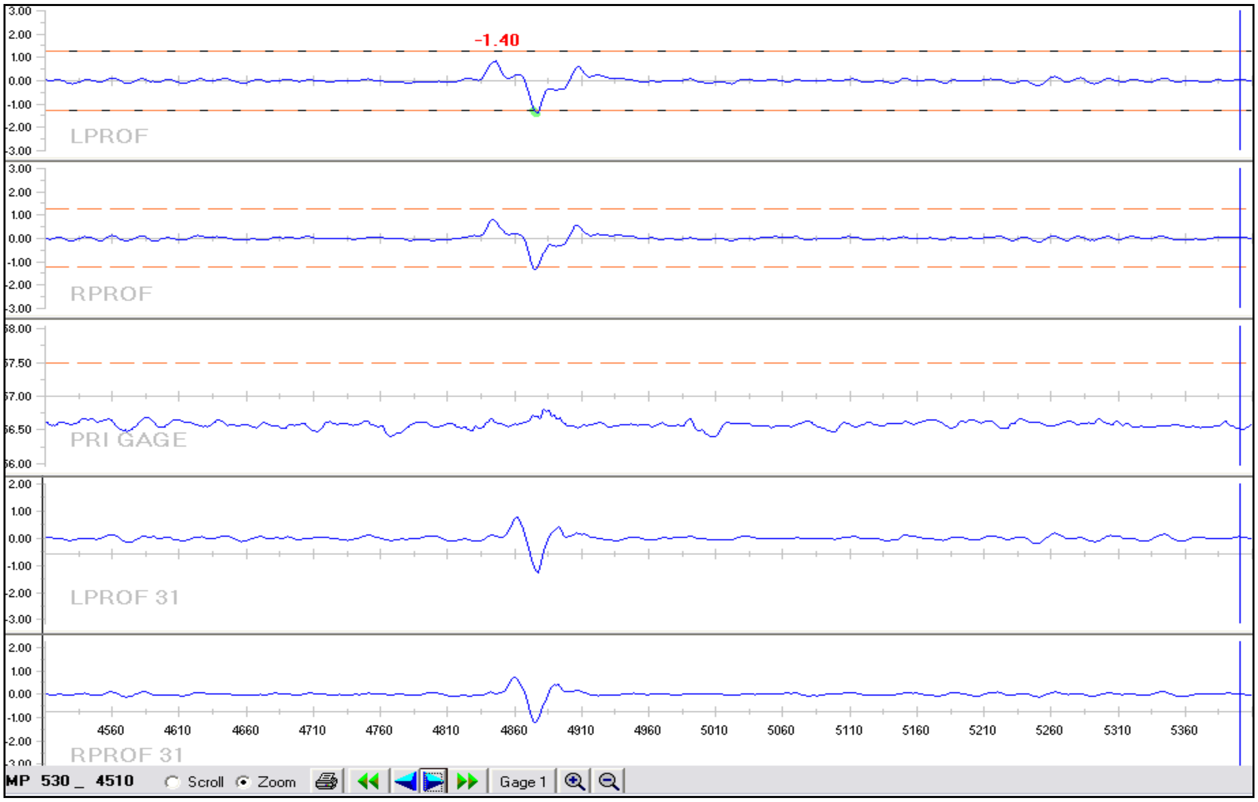

Figure A5. Geometry Data at MP539 and Feet 4877 for Left Profile Exception near Allenhurst, GA

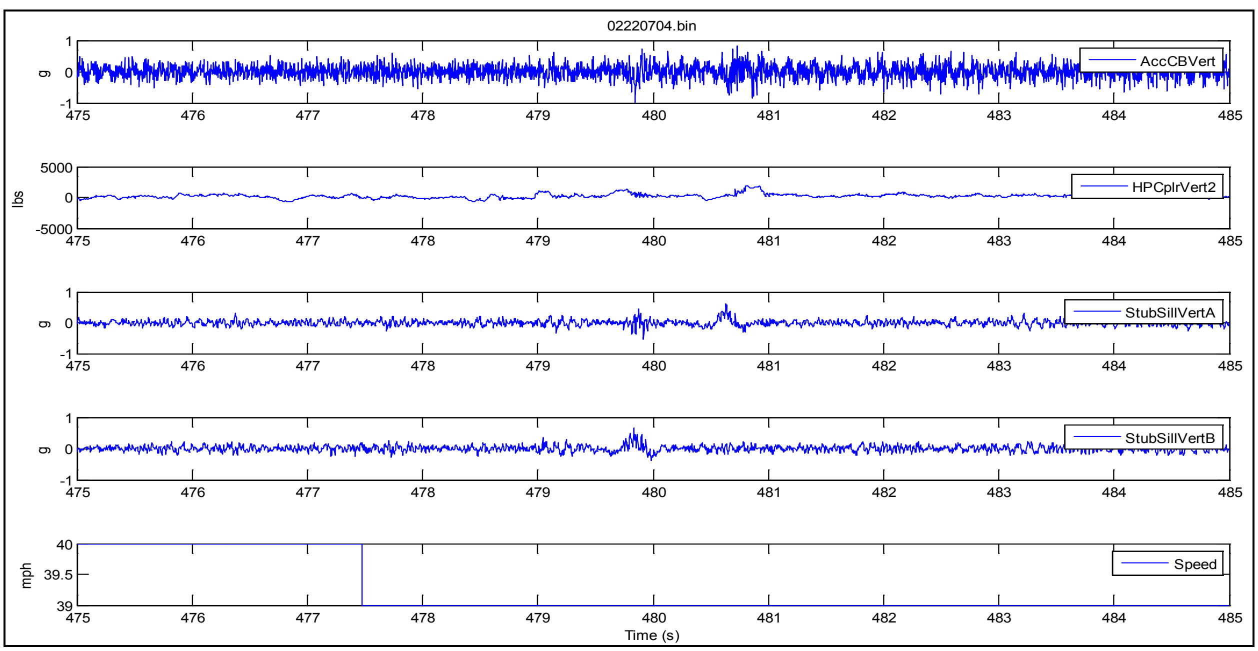

Figure A6. Corresponding Tank Car Data with VCF Values up to -1,800 lbs

Abbreviations and Acronyms

AAR	Association of American Railroads
ATIP	Automated Track Inspection Program
BLE	Brotherhood of Locomotive Engineers
FIR	finite impulse response
FRA	Federal Railroad Administration
GE	General Electric
hazmat	hazardous materials
kip	1,000 pounds-force
lb	pound
LCF	longitudinal coupler force
MCO	mid chord offset
mph	miles per hour
RSI	Railway Supply Institute
SSWG	Stub Sill Working Group
TC	Transport Canada
TCOE-TF	Tank Car Operating Environment Task Force
TSS	Track Safety Standards
TTCI	Transportation Technology Center, Inc.
UTU	United Transportation Union
V/TI	Vehicle/Track Interaction System
VCF	vertical coupler force