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Measurement of Wheel Load Environment of AAR M-976 Approved Truck

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13. ABSTRACT (Maximum 200 words)

Measurement of Wheel Load Environment of AAR M-976 Approved Truck study (FRA Task Order 319) is the continuation of the Measurement of Wheel Load Environment of a 3-piece Truck study (Task Order 245) completed in November 2010 that increased understanding of the conditions under which wheel rolling contact fatigue (RCF) damage accumulates. In this study the AAR M-976 approved truck had better steering truck performance, in terms of developing less RCF, than the 3-piece truck used in the previous study. Wheel load environment data was collected from a car operating in revenue service and analyzed using shakedown theory to assess the predicted wheel RCF damage. No track inspection was conducted and the study did not include parameters such as track conditions, rail age, and wheel-rail interface friction management applications. Statistical results from the study showed that a 3-piece truck had approximately four times higher probability of developing RCF than an AAR M-976 truck at 5-degree or tighter curves. For both trucks, RCF was predicted at sharp curves and underbalance speed (cant deficiency), such as yard entrance and exit curves, as well as mine and power plant turnaround loops. Recommendations for reducing wheel and rail RCF damage include controlling the wheel-rail coefficient of friction where track curvature is 4 degrees or tighter.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

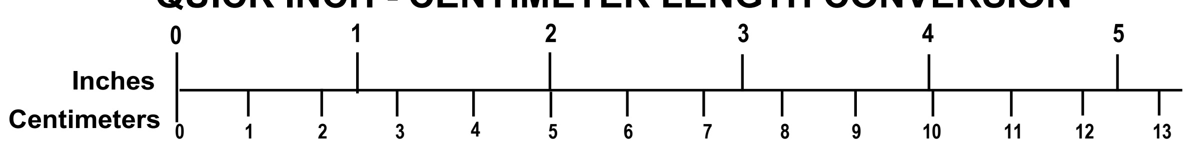
VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°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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The authors wish to express their gratitude for the valuable comments and support provided by Program Manager John Punwani of FRA's Office of Research, Development and Technology, TTCI Engineering Director Carmen Trevizo, AAR Chief of Technical Standards and Inspection David Cackovic, and TTCI Chief of Government Programs Dingqing Li.

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Executive Summary

Transportation Technology Center, Inc. (TTCI) conducted research funded by the Federal Railroad Administration (FRA) in 2014 to increase understanding of the conditions under which wheel rolling contact fatigue (RCF) damage accumulates. Wheel load environment data was collected from a car equipped with an Association of American Railroads (AAR) M-976 approved truck operating in revenue service. The data was analyzed using the shakedown theory to assess the predicted wheel RCF damage. It was then compared with load environment data collected from a car equipped with a 3-piece truck in a previous study completed in 2010 [1]. This study showed that based on shakedown theory, the AAR M-976 had better steering truck performance in terms of developing less RCF than the 3-piece truck used in the previous study.

Conclusions from this research are as follows:

- Track curvature significantly contributed to wheel and rail RCF damage. Nearly all significant RCF predicted locations were in curves of at least 5 degrees.
- The AAR M-976 truck performed significantly better in terms of developing less predicted RCF. Studies predicted four times more RCF for a 3-piece truck than for an AAR M-976 truck at 5-degree and tighter curves.
- The AAR M-976 truck and 3-piece truck traveled 0.03 percent and 0.15 percent, respectively, above the shakedown limit for all trips. This represents an 80% reduction in RCF damage.

Recommendations for reducing wheel and rail RCF damage include controlling the wheel-rail coefficient of friction when track curvature is 4 degrees or tighter, and reducing superelevation in curves where operating speeds are well below balance speed.

1. Introduction

The Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI) to evaluate root causes of wheel tread fatigue damage by collecting wheel load environment data from a railcar equipped with an Association of American Railroads (AAR) M-976 truck running in revenue service. The data was analyzed to assess the predicted rolling contact fatigue (RCF) damage in revenue service. In 2010, a similar study had been conducted using a 3-piece truck [1]. This subsequent study conducted in 2014 showed that based on shakedown theory, the AAR M-976 had better steering truck performance in terms of developing less RCF than the 3-piece truck used in the previous study. In the 2010 study, a track inspection team was dispatched to several critical sites to record relevant information but no track inspection was carried out for the 2014 study. To the degree possible, information about the predicted RCF damage was obtained from track charts and satellite pictures.

1.1 Background

Wheel tread damage is the primary cause of railcar wheelset replacement in North America [2]. Tread damage is commonly manifested as high-impact wheels identified through the use of wheel impact load detector systems. Voids in the wheel tread surface result in radial run-out, which in turn can produce impact loads each time the portion of the wheel with the radial deviation contacts the rail. Large impact loads increase the probability of a wheel developing a shattered rim failure.

The lateral traction forces generated at the low-rail wheel of the leading wheelset of a car negotiating a curve create the conditions necessary for RCF [3]. These lateral traction forces are a result of a high angle of attack (AOA), which is a function of many parameters including truck warp, wheel-rail profiles, wheel-rail friction, and excess track superelevation.

Shelling is a fatigue-based process and one mechanism by which large voids can be left in the running surface of a wheel. Many cycles of high stress create surface cracks in the wheel tread through the process of RCF. Frequently, bands of these cracks will form on the wheel tread surface. Figure 1 shows a wheel with a band of RCF cracks. As the cracks propagate and grow, they can connect and dislodge a patch of wheel tread, creating a void in the process.

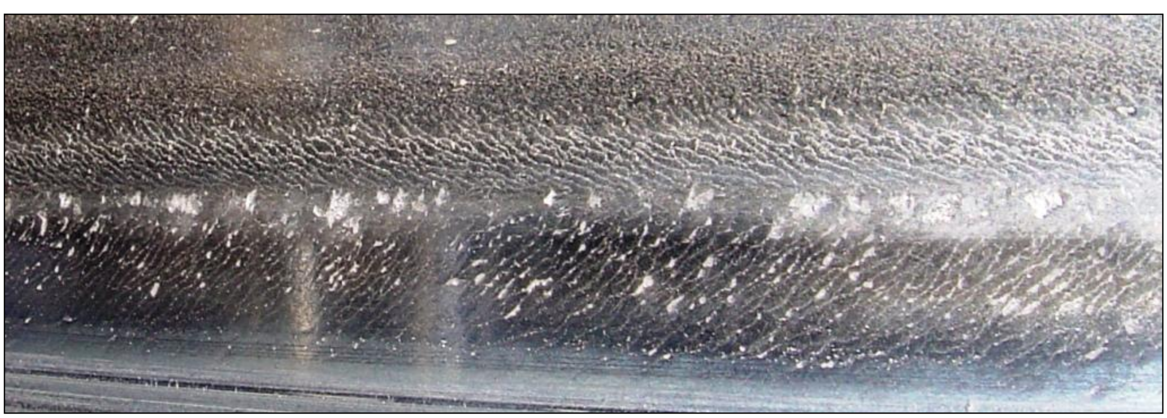

Figure 1. Wheel Tread Surface with RCF Cracks

The magnitude of the contact forces between the wheel and rail determines the fatigue damage incurred from each contact cycle. Thus, measuring the load environment of a wheel in revenue service allows researchers to investigate the conditions present when RCF damage occurs.

1.2 Objective

TTCI researchers measured the wheel load environment of AAR M-976 approved trucks to understand the conditions under which wheel RCF damage accumulates according to shakedown theory, and to compare steering AAR M-976 and nonsteering 3-piece trucks.

1.3 Overall Approach

The load environment of wheelset data in a revenue service coal car was collected via instrumented wheelset (IWS). The car was equipped with an unattended data collection system (UDAC), which automatically transmitted summary data to identify specific track locations where RCF was predicted to occur. Track charts of the identified track locations were examined to obtain degree of curvature, chart speed, superelevation, and grade of the track. Also, Global Positioning System (GPS) data was utilized to lay out the overall route, find the right track charts provided by the railroads, determine shakedown exceedance distribution along the route, and obtain pictorial information about RCF locations, such as coal mine, yard, special trackwork (i.e., diamond crossings or turnouts), tangent or curve track, and the turnaround loop of the power plant.

1.4 Scope

This study was carried out under Task Order 319 as a collaborative effort between TTCI, the Wheel Defect Prevention Consortium, and FRA. The scope of work for the task order included instrumentation of the car with a UDAC system, two revenue service data collection trips, removal of the test equipment from the car, data analysis, and the final report on this study.

1.5 Organization of the Report

The report is organized into the following sections: description of the procedures used, analysis of wheel-rail force data, and conclusions drawn from the study. Most of the sections note the results of the previous work conducted in 2010 with 3-piece trucks to compare performance with better steering AAR M-976 trucks.

2. Procedure

This section of the report describes the instrumentation used to record the data and the methodology for predicting RCF damage.

2.1 Test Vehicle

An aluminum body rotary dump coal gondola was used as the test vehicle. The car had a stenciled light weight of 43,900 pounds (lb) and a stenciled load limit of 242,100 lb. The car was equipped with standard AAR M-976 approved trucks, constant contact side bearings, and truck mounted brakes. The brakes were disabled on the A-end of the car to eliminate heat input into the IWS installed in the truck. An FRA waiver was obtained to run the car in revenue service for a limited number of trips on specific routes with a partially disabled brake system.

2.2 Instrumentation

The instrumentation installed on the railcar included an instrumented (load measuring) wheelset and a GPS receiver.

2.2.1 Instrumented Wheelset

For nearly 20 years, TTCI has designed and constructed high accuracy load measuring IWS to measure wheel-rail interaction values including:

- Vertical loads,
- Lateral loads,
- Longitudinal loads, and
- Lateral position of the contact patch relative to the wheel taping line.

An IWS was installed in the test vehicle in position 4 (A-end of the car). The vehicle was always oriented with the A-end of the car leading, so that the IWS was in the leading position of the leading truck. Largest curving forces are typically expected in the lead axle of the car. The orientation of the car was also checked with trackside data collection systems (via Automatic Equipment Identification) to ensure that it was always lead axle first.

Wheel-rail force at the contact patch can be divided into several components. When the plane of contact is approximately parallel to the ground, the normal force can be approximated as the vertical force, and the tangential force can be approximated as the vector sum of the lateral and longitudinal forces. In a situation where the wheel is flanging, these approximations are not accurate because the plane of contact is not parallel to the ground. Further complicating matters in a flanging situation is the possibility of more than one contact point between the wheel and rail.

From the available IWS measurements, the tangential force was calculated whenever the lateral contact position was no more than 0.5 inch inboard from the tapeline, effectively excluding any less accurate tangential force calculations because of wheel flange contact with the rail. Figure 2 shows the contact positions considered in the analysis. The exclusion of tangential forces near the flange should be an acceptable simplification, based on the fact that RCF damage on wheels is most intense outboard of the tapeline [4]. This simplification also means that all shakedown exceedances in curves described in this report are related to the low-rail wheel, because the contact patch of the high-rail wheel is located in the flange root where tangential forces are not calculated.

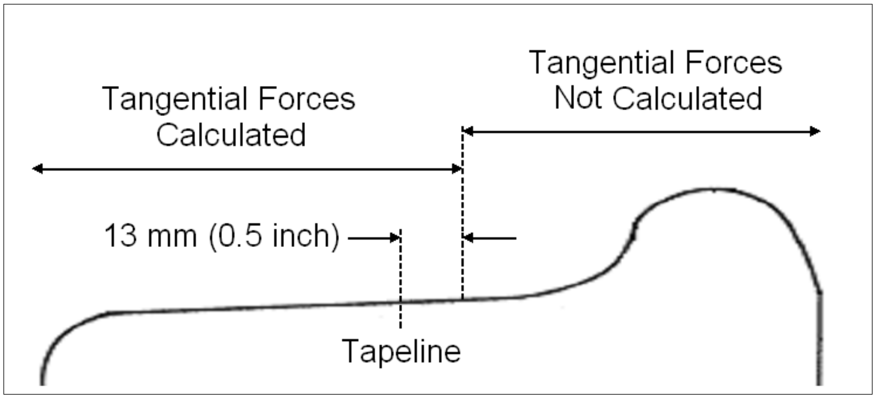

Figure 2. Wheel Profile Showing Contact Zone Considered in the Analysis

2.2.2 GPS Receiver

A GPS receiver was used to collect the following information about the test vehicle:

- Latitude
- Longitude
- Speed
- Heading

The latitude and longitude readings allowed TTCI to match the data with the track charts provided by the railroad. Street maps and satellite photos of the latitude and longitude of important track locations were used to identify nearby towns, road crossings, bridges, and curves, which then allowed for positive identification of the mileposts associated with important track locations. The heading data from the GPS receiver allowed for an estimate of the track curvature at all locations. The curvature estimates from important track locations were compared with the curvature data listed on the track charts and generally found to be accurate within one half of one degree.

2.2.3 Data Collection System

TTCI has developed ruggedized UDAC systems that have repeatedly proven reliable for collecting data in the vibration environment of freight railroading. The UDAC system used for this test consists of a low power usage computer and low power usage signal conditioning. Two generator bearings were installed on the wheelset in position 3 (same truck as the IWS) to charge a bank of batteries. One of the generator bearings belonged to FRA and the other generator bearing belonged to TTCI. To minimize power usage while the car was not moving, the UDAC system shut down whenever the car sat stationary for more than 15 minutes; it rebooted whenever the car resumed travel. The UDAC was equipped with a means to transmit basic information back to TTCI via cellular telephone signal. Data from the IWS was collected at 128 samples per second and low-pass filtered at 15 Hz.

2.3 Prediction of Rolling Contact Fatigue

Shakedown theory can be used to estimate how repeated rolling contact will affect a material. Stresses produced by rolling contact might produce purely elastic strains, subsurface plastic strains, or surface plastic strains. Initial rolling contacts might produce plastic strains that result in residual stresses. These residual stresses may form such that further rolling contacts produce stresses that when combined with the residual stresses no longer exceed the elastic limit. This process is called shakedown. Contact conditions can exist such that the residual stresses will not prevent plastic deformation with repeated contact. Plastic deformation leads to fatigue damage.

Figure 3 shows the shakedown diagram. The contact stress for the rolling contact (Po) is divided by the material's shear yield stress (K) and plotted against the traction coefficient (ratio of tangential force (T) and normal force (N)). Traction coefficient values can range from zero to the wheel-rail coefficient of friction. The shakedown limit is the limit for continuous deformation under repeated loading. This limit is calculated to be slightly different, depending upon assumptions made regarding the contact conditions. The shakedown limits under full-slip conditions for pure lateral and pure longitudinal loading are plotted on the axes [5]. The exact location of the shakedown limit line is a subject of some debate. In fact, it may be more accurate to identify it as a shakedown limit zone, rather than a line. The area below this zone represents conditions when only elastic deformation is likely to take place. The area above this zone represents conditions where plastic deformation is likely to take place. Regions where the plastic deformation occurs below the surface or on the surface are labeled. Contact conditions far beyond shakedown may result in wear instead of RCF damage.

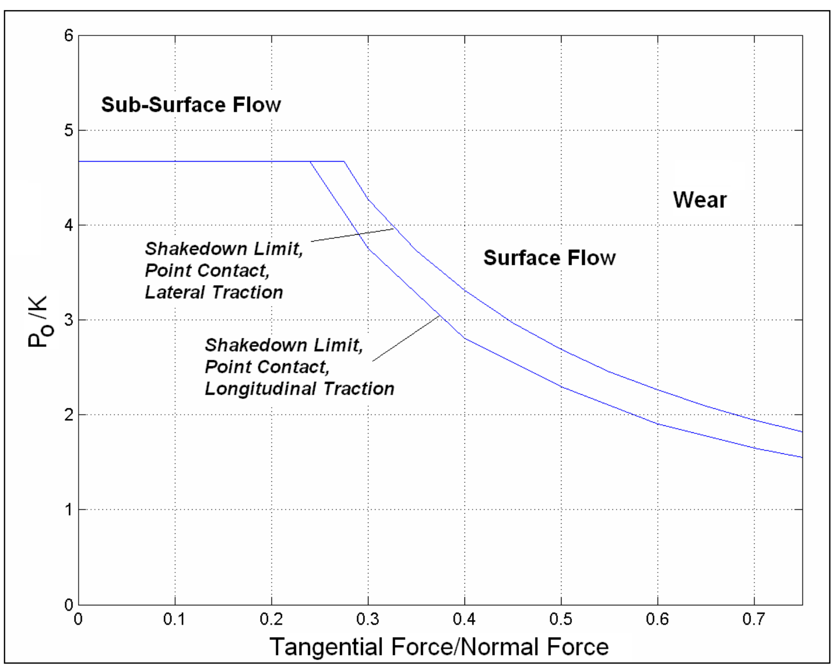

Figure 3. Shakedown Diagram

All shakedown plots were calculated assuming Hertzian contact between a 36-inch diameter wheel with a non-hollow transverse profile in the contact region and a rail with 14-inch crown radius. The shear yield stress was assumed to be 65,000 lb. per square inch, based on a tensile yield stress of 113,000 lb. per square inch for AAR Class C wheel material at room temperature. Thus, the shakedown plots indicate predicted RCF damage to the wheels. The shear yield stress of rail steel may be slightly different from that of wheel steel; therefore, the predicted RCF damage to the rails is expected to be slightly different.

To be consistent with the previous report, locations where RCF is predicted for at least 100 feet were found for this report's research study. There were 24 specific locations where RCF was predicted for at least 100 feet of track in the 3-piece truck study. The AAR M-976 truck, on the contrary, traveled over only six locations longer than 100 feet with shakedown exceedances.

3. Wheel Load Environment

The load environment experienced by a wheelset in revenue service was measured with an IWS installed in the leading position of the leading truck of a revenue service coal gondola. Data was analyzed for the two trips from the mine to the power plant.

3.1 First Trip

The first loaded trip began May 25, 2013, at the mine and concluded May 29, 2013, at the power plant. A total of 1,325 miles of data were recorded with the car in the loaded condition between the mine and the power plant. Figures 4 through 6 contain histograms of the vertical, lateral, and longitudinal wheel-rail forces, respectively. Figure 7 contains a histogram of the train speed, and Figure 8 is a histogram of the left and right traction ratios.

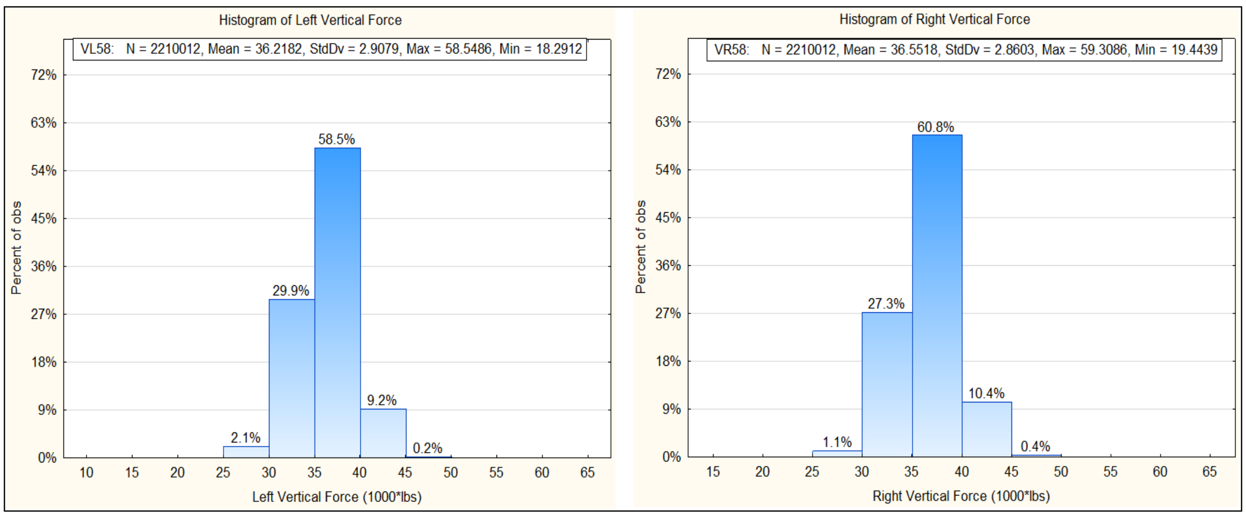

Figure 4. Histogram of Vertical Wheel-Rail Loads

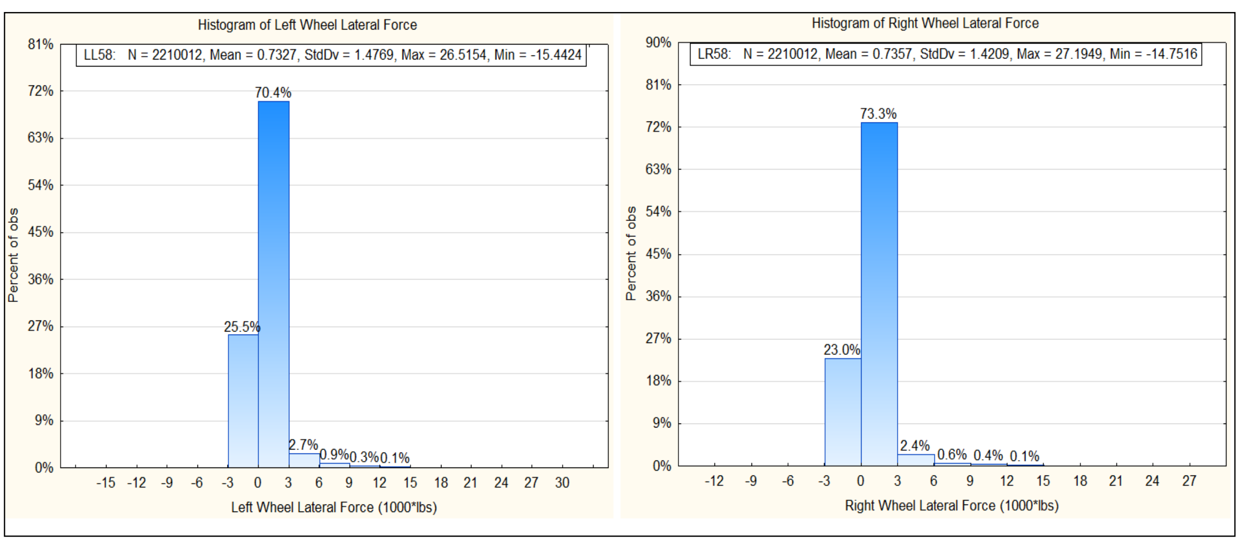

Figure 5. Histogram of Lateral Wheel-Rail Loads

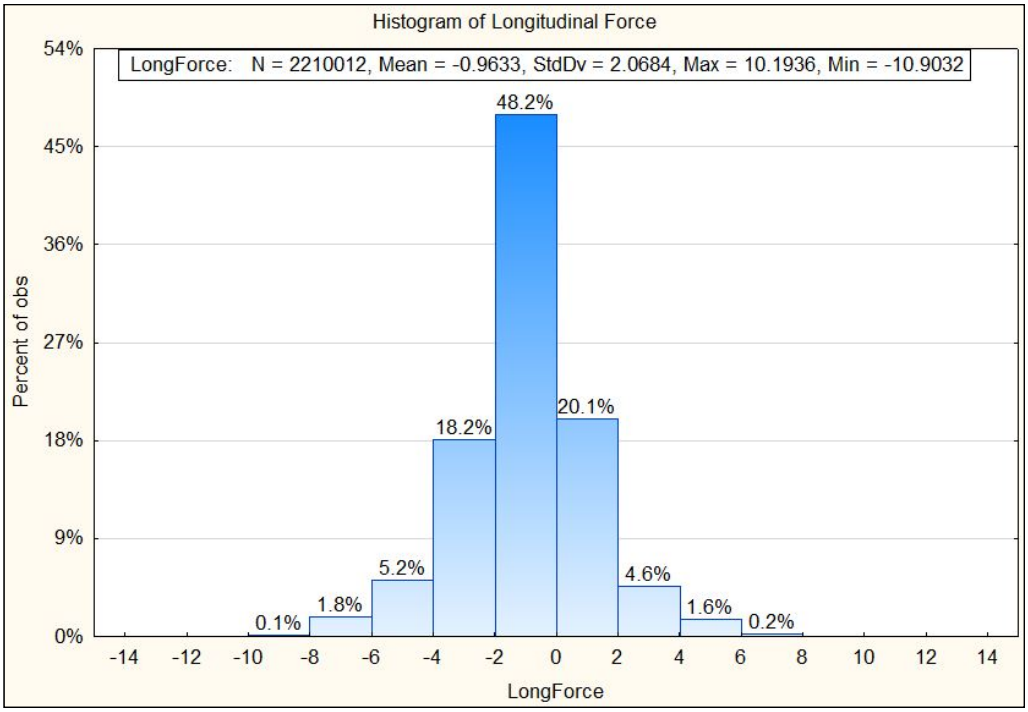

Figure 6. Histogram of Longitudinal Wheel-Rail Loads (1000*lb)

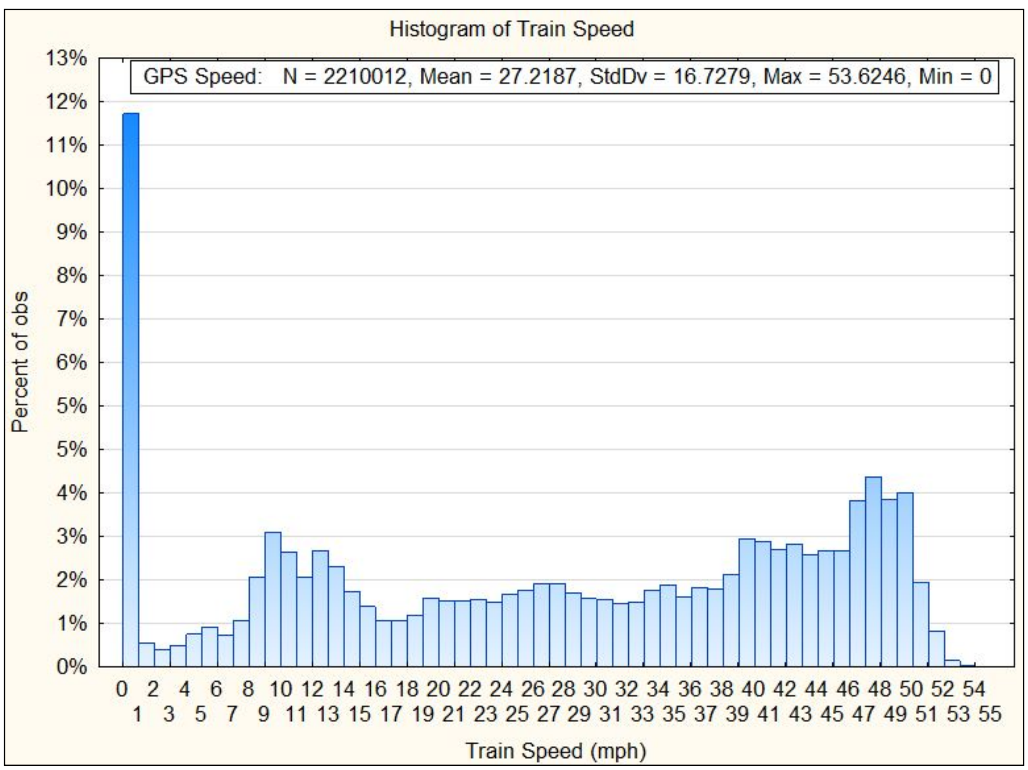

Figure 7. Histogram of Train Speed

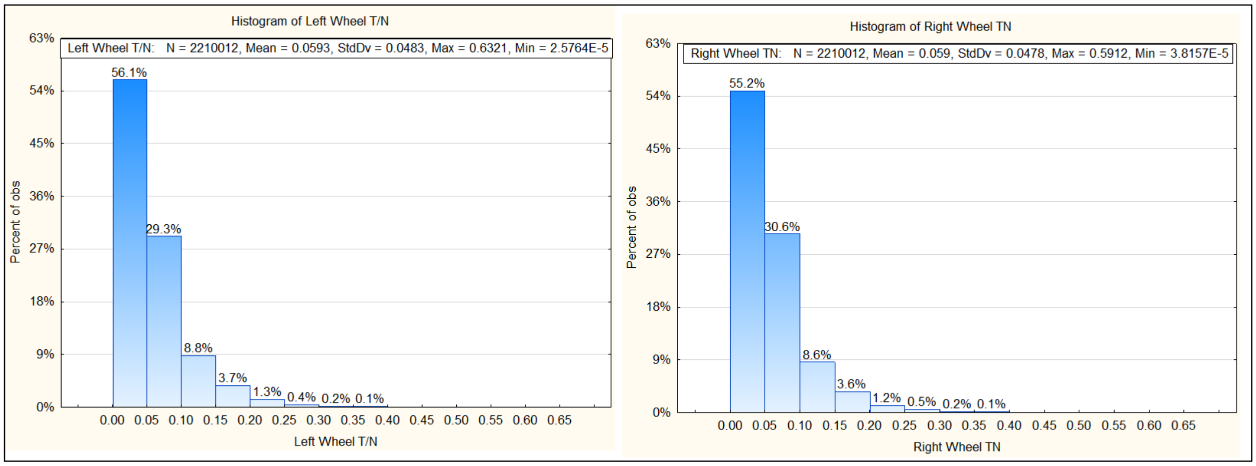

Figure 8. Histogram of Left and Right Traction Ratio

3.1.1 Shakedown Exceedances

The AAR M-976 truck traveled 2,300 feet at conditions exceeding the shakedown limit. This represents approximately 245 wheel revolutions (fatigue cycles) and 0.03 percent of the loaded trip. In the previous study, the 3-piece truck traveled 8,785 feet (932 wheel revolutions) and 0.15 percent of its loaded trip above the shakedown limit. The shakedown criteria were exceeded mainly on entrance and exit curves at yards, turnaround loops at the power plant and coal mine, and at curves tighter than 5 degrees on the route. There are six specific locations where shakedown limit was exceeded for more than 100 feet. The longest distance traveled above the shakedown criteria at a specific track location was 500 feet. This location is near a main yard terminal with an extremely sharp curve (calculated degree of curve goes up to 18 degrees), and the train traveled at an average speed of 5 mph along the curve. The vertical load difference between the high and low wheels went up to 20 kips.

The second and fourth most shakedown exceedances occurred at the same yard, but on different curves. When the train travelled on the yard entrance track, which is a 5-degree-30-minute curve at 20 mph track chart speed, the shakedown limit was exceeded by approximately 35 feet. This location is not included in the six specific locations because it was less than 100 feet. The train then traveled at 8 mph on a 5-degree curve in the yard and the shakedown limit was again exceeded for approximately 300 feet. This curvature was calculated via GPS data because detailed curvature information could not be found in the track chart. However, there is a high likelihood that the car was moving at a significant cant deficiency. Vertical load difference between the right and left wheel was averaging 5 kips and in some sections increased up to 10 kips. Leaving the yard, the train exceeded the shakedown limit for 230 feet at an estimated 5-degree curve. In this curve, the vertical load difference also averaged 5 kips and increased to 10 kips.

The third most shakedown exceedance occurred at another yard entrance curve. This was a 6-degree-30-minute curve, 1.75 inch superelevation, and a balance speed of 20 mph, with a track chart speed of 10 mph. The train travelled at 1.5 inches cant deficiency over 276 feet of track with a shakedown exceedance over this section. The vertical load difference between wheels was as high as 15 kips.

The fifth and sixth locations were 4-degree- and 5-degree-40-minute curves. The train traveled at a 0.5-inch deficiency at the fifth location and a 1.2-inch cant excess at the sixth location. The shakedown limit was also exceeded at the power plant and coal mine turnaround loops inconsistently and for no more than 100 feet in Trip 1.

Figure 9 shows the six specific track locations ranked in descending order by distance traveled above the shakedown limit and curvature information. The shakedown limit was exceeded at a total of 64 specific track locations. In the previous study, nonsteering trucks exceeded the shakedown limit at 157 specific locations.

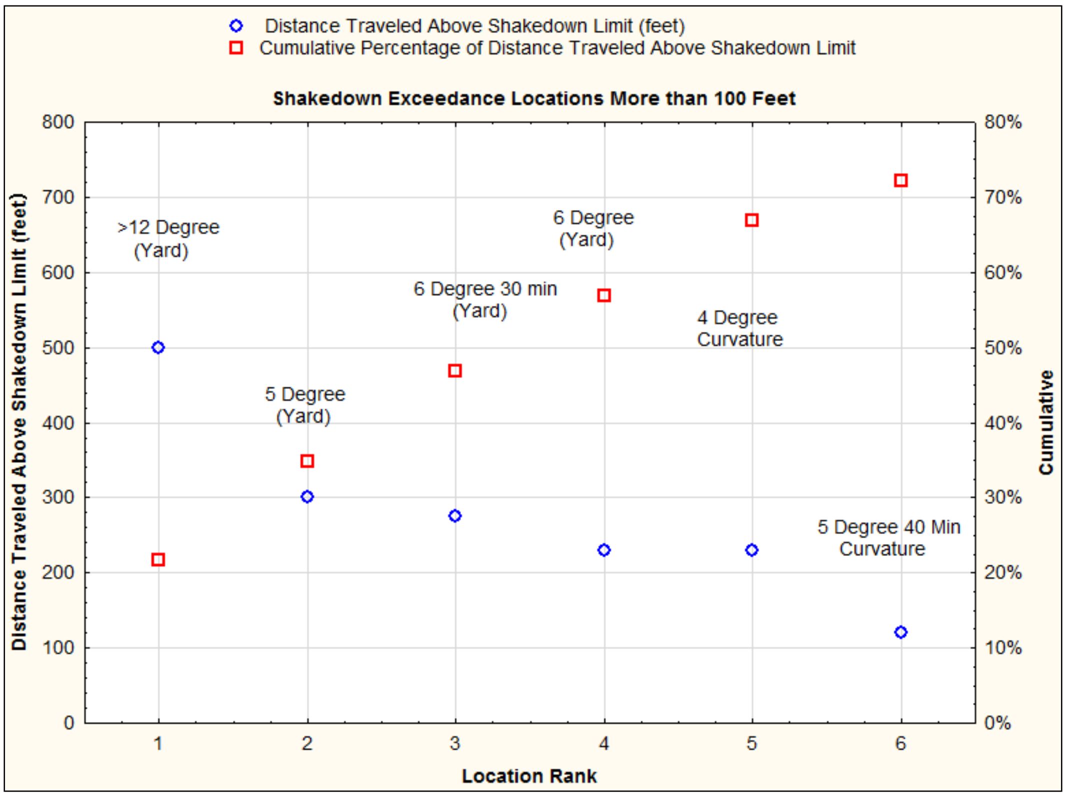

Figure 9. Distance Traveled per Top Shakedown Exceedance Location

Figure 10 shows the distance traveled at each curvature, as well as the distance traveled at that curvature exceeding the shakedown limit. While the route consists mainly of tangent track (75 percent of all trip) and shallow curves (total length of 4-degree and greater curvatures is about 1 percent of all trip), the majority of the distance traveled in excess of the shakedown limit occurred where the track curvature was 5 degrees or greater (60 percent of shakedown exceedance that occurred). In fact, 5-degree curves alone accounted for 21 percent of the total distance traveled above the shakedown limit. Figure 11 shows the percent of the total distance traveled at conditions exceeding the shakedown limit for each degree of curvature. Figure 12 shows the percent of distance traveled at each degree of curvature that exceeded the shakedown limit. Figure 12 shows that on 5-degree and tighter curves, approximately 5 percent of the distance traveled exceeds the shakedown limit. Note that some curvature information needed to be calculated via GPS data due to unavailability of track charts; for example, in yards. While +/-1 degree calculation error bands are accounted for these cases, the 7-degree column may belong to one lower or higher category. In the previous study, non-steering trucks showed a significant RCF probability at 4 and greater degrees of curvatures. Also, non-steering trucks showed more than 20 percent shakedown exceedance probability, whereas the AAR M-976 truck showed approximately 5 percent.

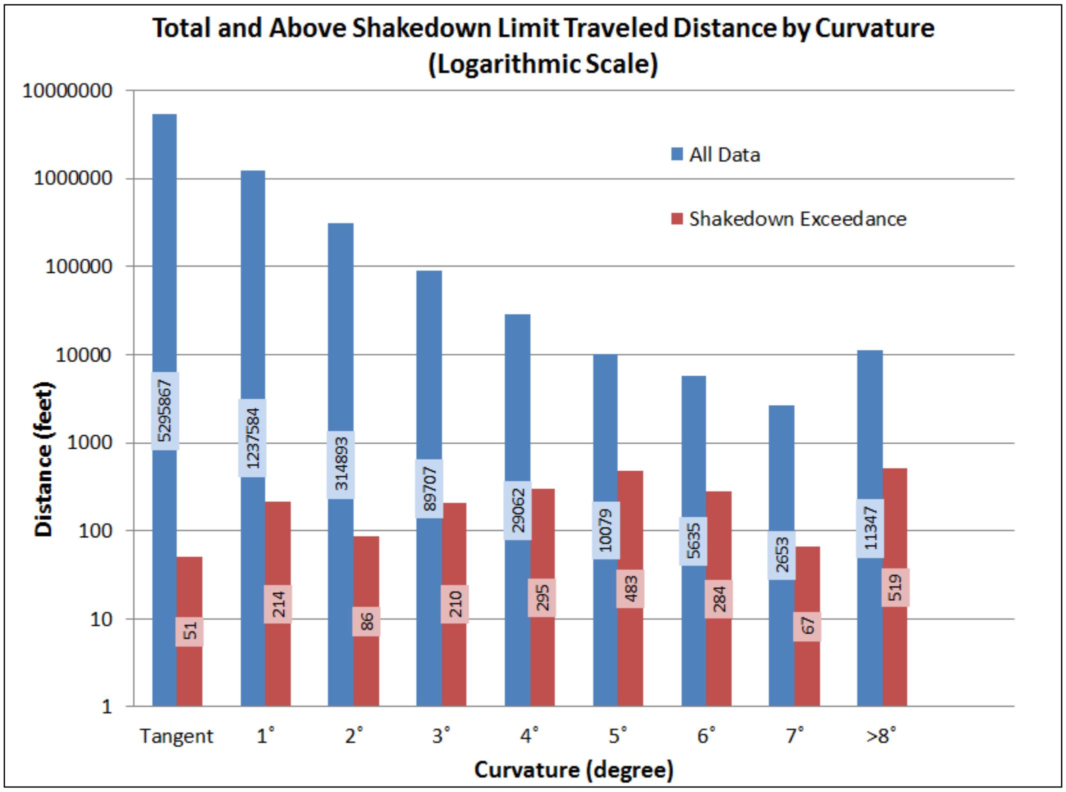

Figure 10. Distance Traveled by Track Curvature

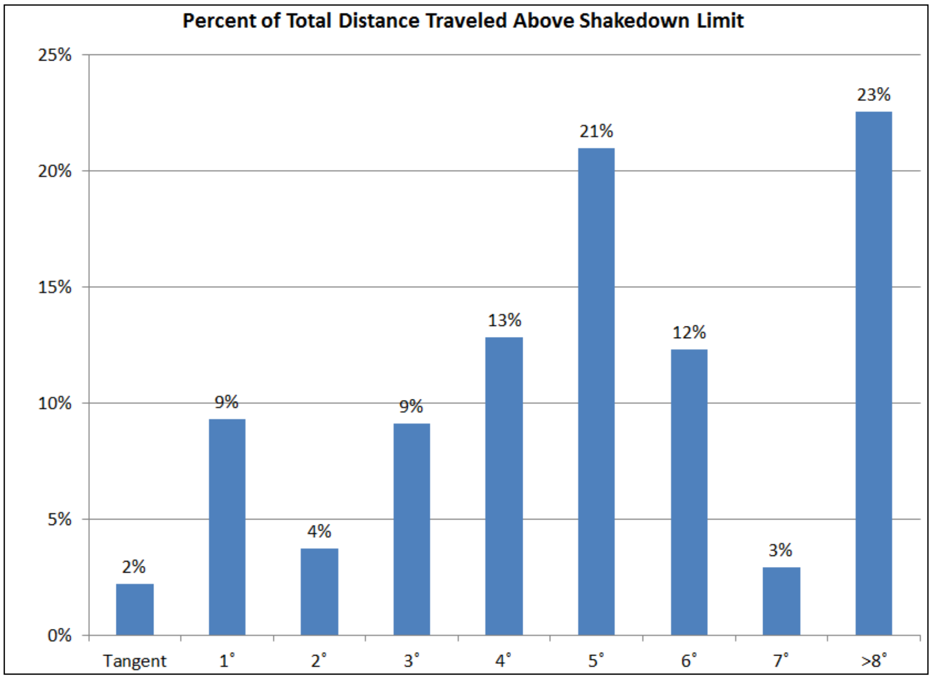

Figure 11. Relative Distribution of Track Curvature at Shakedown Exceedance Locations

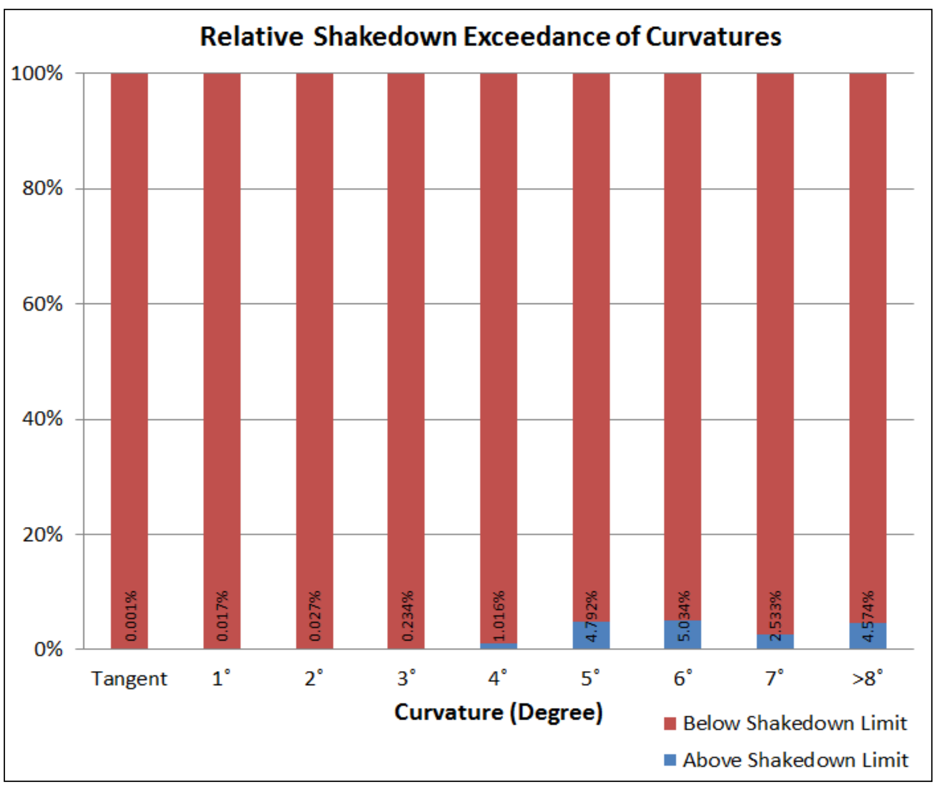

Figure 12. Percentage of Distance Traveled Above Shakedown Limit by Curvature

3.2 Second Trip

A second loaded trip over the same route began June 3, 2013, at the mine and concluded June 5, 2013, at the power plant. A total of 1,252 miles of data were recorded during the second trip. This data was mainly used as a check of the repeatability of the readings from the first trip.

In general, wheel-rail forces had good repeatability at individual curves when comparing the first and second trips. The predominant shakedown exceedance locations in both trips were sharp entrance or exit of yards. Fewer notable shakedown exceedance cases occurred in Trip 2 than in Trip 1, highlighting the effect of unbalance speed on RCF development.

In Trip 1, the test car traveled through a 4-degree-30-minute curve with 4 inches superelevation and 35 mph balance speed at 44 mph (Figure 13). No RCF was predicted.

In Trip 2, the test car traveled through the same curve at 11 mph with 3.6 inches cant deficiency and the shakedown limit was exceeded (Figure 14). The Figure 14 shakedown plot shows greater exceedances than the one in Figure 13.

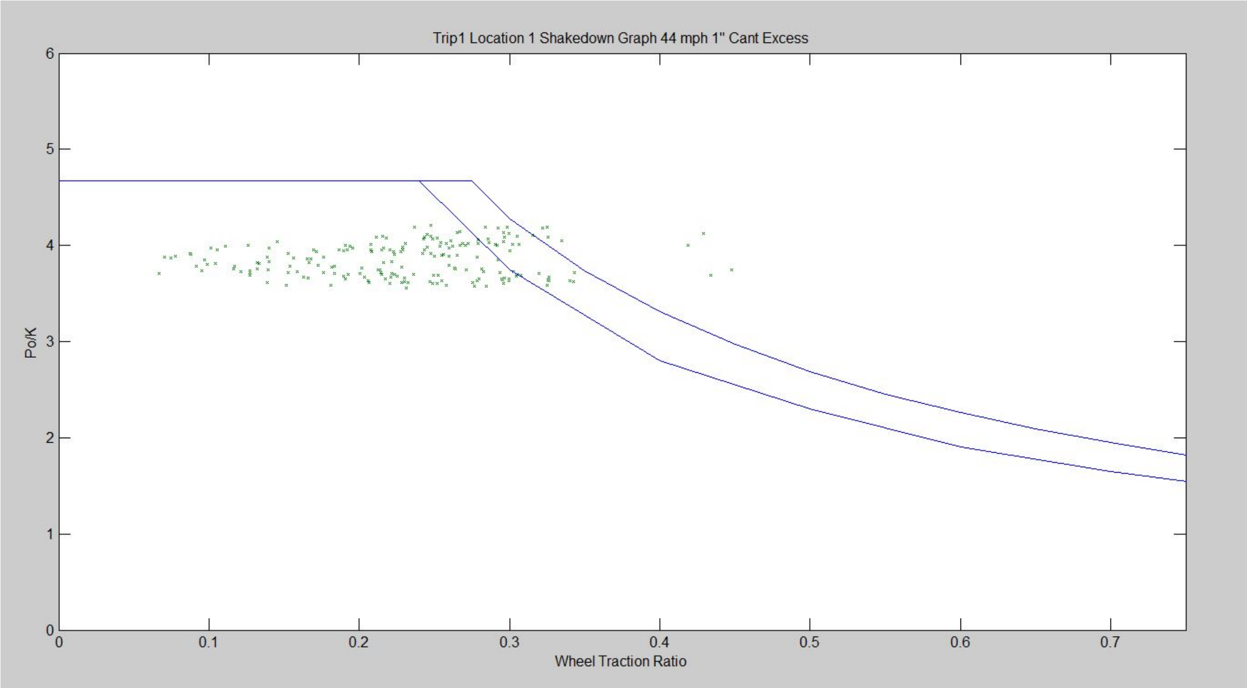

Figure 13. Shakedown Data at a 4-Degree-30-Minute Curve, Trip 1, 1-Inch Excess Cant

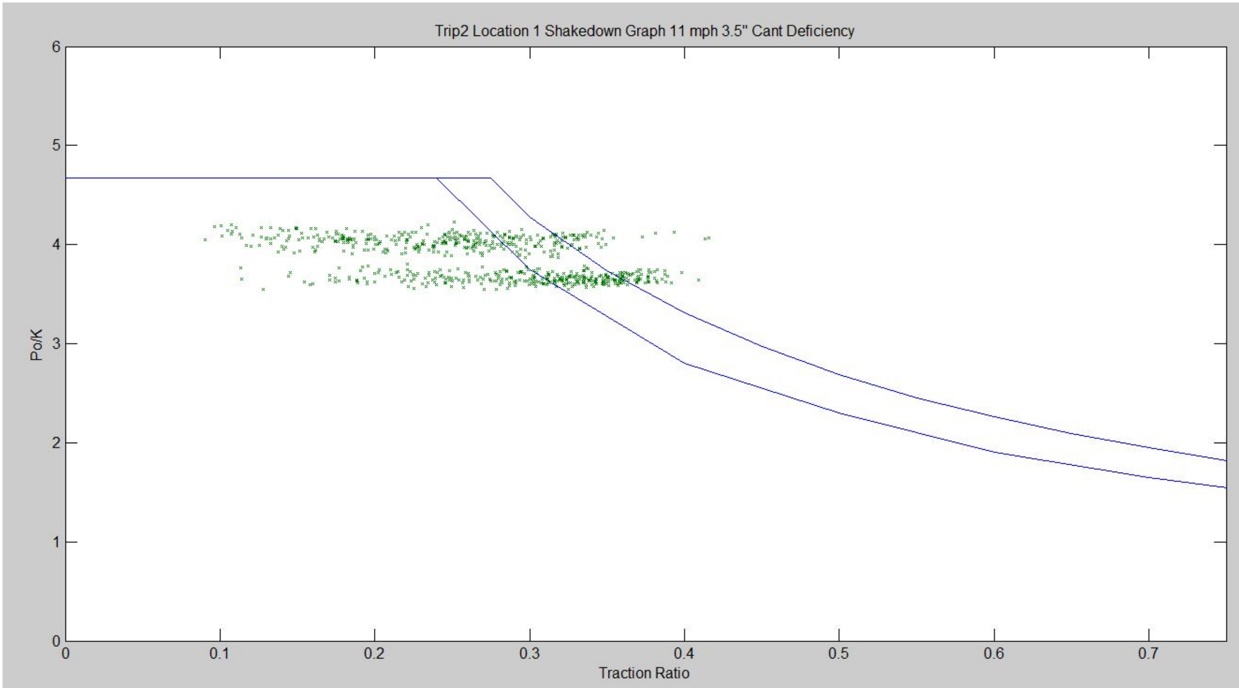

Figure 14. Shakedown Data at the Same 4-Degree-30-Minute Curve, Trip 2, 3.6 Inches Cant Deficiency

The data in the 4-degree-30-minute curve provides an example of the potential influence of train speed and track superelevation. Superelevating the outside rail in a curve is done to counteract some of the centripetal forces generated by the fastest train allowed on a particular curve. Many times, the fastest train on a curve will be a passenger train. Freight trains typically operate at lower speeds and thus do not need as much superelevation in curves to balance the smaller centripetal curving forces. Excess superelevation results in increased AOA and higher lateral wheel-rail forces. Larger AOA values produce higher tangential wheel-rail forces, which can produce conditions exceeding the shakedown limit and accumulate RCF damage.

4. Conclusion

Conclusions from the measurement of wheel load environment on a railcar equipped with Association of American Railroads (AAR) M-976 trucks study are listed below:

- The AAR M-976 truck was less likely to develop rolling contact fatigue (RCF) than the conventional 3-piece truck. Statistical results obtained in the two loaded trips showed that the 3-piece truck had approximately four times higher probability of developing RCF than the AAR M-976 truck on 5-degree or tighter curves.
- The AAR M-976 truck traveled 0.03 percent of its entire trip above the shakedown limit compared with the 3-piece truck, which traveled 0.15 percent of its whole trip in 2010 exceeding the shakedown limit.
- The AAR M-976 truck had six specific locations where it exceeded the shakedown limit for at least 100 feet of track. In the previous study, the 3-piece truck had 24 locations where it exceeded the shakedown limit for at least 100 feet.
- Most occurrences of shakedown exceedance for the current study were at the entrance or exit curves of yards, turnaround loops of the power plant, and curves at the coal mine. In general, extreme excess superelevation at 4-degree and tighter curves were at RCF predicted locations.
- Track curvature was highly influential in determining wheel and rail RCF damage for both truck types. Nearly all significant shakedown exceedances for the AAR M-976 truck were recorded on curves of at least 5 degrees.
- Curvature, track superelevation, and train speed were important factors in RCF for both truck types. This finding is illustrated by the significant difference in performance at one curve. When operated at 11 mph and 3.6 inches of excess elevation, the wheel-rail forces produced a significant exceedance of the shakedown limit. A week before, at 44 mph and 1 inch of excess cant, the shakedown limit was not exceeded.

Recommendations for reducing wheel and rail RCF damage include controlling the wheel-rail coefficient of friction when track curvature is 4 degrees or tighter, and reducing superelevation in curves within yards, terminals and loading facilities where operating speeds are well below balance speed. TTCI researchers recorded and analyzed data from two loaded trips of a coal car operating on a ~1,300-mile route. Using this data, they predicted that RCF damage would occur at 64 specific track locations for a total distance of less than 0.43 mile. Most of these locations were at very sharp curves near yards—5- to 7-degree curves or tighter.

In general, wheel-rail forces had good repeatability at individual curves when comparing the first and second trips. A notable exception occurred at one 4-degree-30-minute curve: when operated at 11 mph and 3.6 inches of cant deficiency, significant RCF was predicted. A week before, the car had been pulled through the same curve at 44 mph and 1 inch of excess superelevation, and this had resulted in no predicted RCF. It was therefore determined that large cant deficiency could contribute to higher predicted RCF.

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5. References

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Abbreviations and Acronyms

AAR	Association of American Railroads
AOA	Angle-Of-Attack (of an axle relative to the track)
FRA	Federal Railroad Administration
GPS	Global Positioning System
IWS	Instrumented Wheelset
RCF	Rolling Contact Fatigue
TTCI	Transportation Technology Center, Inc.
UDAC	Unattended Data Acquisition Computer