U.S. Department
of Transportation

**Federal Railroad
Administration**

Letter Report – Distributions of Dynamic Wheel/Rail Forces Under Heavy Axle Loads

Office of Research and
Development
Washington, D.C. 20590

DOT/FRA/ORD-

December 1998
Letter Report

02-Track-Train Dynamics

1. Report No.
FRA

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Distributions of Dynamic Wheel/Rail Forces Under Heavy Axle Loads

5. Report Date
December 1998

6. Performing Organization Code

7. Authors
D. Li, D. White, M. Ahmadian, and M. El-Sibaie

8. Performing Organization Report No.

9. Performing Organization Name and Address
Association of American Railroads
Transportation Technology Center, Inc.
P.O. Box 11130
Pueblo, CO 81001

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Railroad Administration
Office of Research and Development
400 Seventh Street, SW
Washington, DC 20590

13. Type of Report or Period Covered

14. Sponsoring Agency Code

15. Supplemental Notes

16. Abstract

Under the Heavy Axle Load (HAL) program funded by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA), a test activity was initiated in 1997 to study the relationships between dynamic vehicle responses and track geometry conditions. As a first step, analyses were performed on the vast test records of wheel/rail forces and track geometry parameters measured on the High Tonnage Loop (HTL) of the Transportation Technology Center, Pueblo, Colorado. These records were obtained for more than 600 MGT traffic accumulation and were the results of various tests conducted under the HAL program.

This paper summarizes the statistical characterization of dynamic wheel/rail forces based on existing HAL measurement records. Dynamic variations of force magnitudes, as well as force distributions in frequency domain are given as a function of track curvature, subgrade support, truck type, wheel position, and traffic accumulation. The results of wheel/rail forces are also compared to the vehicle/track interaction safety standards proposed by FRA.

17. Key Words
Dynamic Wheel/Rail Forces, Heavy Tonnage Loop, Heavy Axle Loads (39-ton)

18. Distribution Statement
This document is available through National Technical Information Service, Springfield, VA 22161

19. Security Classification (of the report)

20. Security Classification (of this page)

21. No. of Pages
23

22. Price

EXECUTIVE SUMMARY

Under the Heavy Axle Load (HAL) program funded by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA), a test activity was initiated in 1997 to study the relationships between dynamic vehicle responses and track geometry conditions. As a first step, the vast test records of wheel/rail forces and track geometry parameters as measured on the High Tonnage Loop (HTL) of FRA's Transportation Technology Center, Pueblo, Colorado, were examined by Transportation Technology Center, Inc. (TTCI), a subsidiary of the AAR. These records were obtained for more than 600 million gross tons (MGT) traffic accumulation and were the results of various tests conducted under the HAL program.

This paper summarizes the statistical characterization of dynamic wheel/rail forces based on existing HAL measurement records. Dynamic variations of force magnitudes, as well as force distributions in frequency domain are given as a function of track curvature, subgrade support, truck type, wheel position, and traffic accumulation. The results of wheel/rail forces are also compared to the vehicle/track interaction safety standards proposed by FRA.

In the tangent sections, the mean values of vertical wheel force obtained at various MGT levels were not affected by subgrade support and truck type. However, dynamic variation of vertical forces in the forms of standard deviation and 90th percentile (a magnitude larger than 90 percent of the measured forces) was higher for the soft subgrade than for the stiff subgrade.

In the case of the standard trucks in a 6-degree curve, as an average over all the measurements, the leading wheels measured lateral wheel force approximately 9 kips (mean) and 11 kips at the 90th percentile. A 1-degree increase in track curvature generally equated to an increase of more than 1 kip in lateral wheel force. Use of the improved suspension trucks reduced lateral forces to the leading wheels by more than 50 percent (mean values) and by more than 20 percent (at the 90th percentile). Lateral wheel forces measured in the trailing wheels were generally much lower than in the leading wheels, and did not show reductions as a result of improved suspension truck use.

In the HTL curves, vertical wheel forces were always higher on the high rail than on the low rail because of cant deficiencies at the nominal train speed of 40 mph. However, similar magnitudes of lateral wheel forces were experienced on both rails.

A comparison with the FRA proposed safety standards for preventing potential derailments indicated that the wheel/rail forces generated on the HTL in the course of more than 600 MGT of HAL traffic accumulation were far below the vehicle/track interaction safety limits.

Within the range from 0.25 to 50 Hz, distributions of dynamic vertical and lateral forces at various frequencies were not affected by track curvature and subgrade support. Traffic accumulation was not found to have a consistent effect on the frequency characteristics of forces. However, use of the improved suspension trucks significantly attenuated the vertical force components higher than 5 Hz; this may explain the significant reduction of rail end and weld batter under improved suspension trucks. For all the measurements considered, lateral wheel forces were mainly concentrated in frequencies lower than 5 Hz.

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1.0 INTRODUCTION

Since the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA) initiated the Heavy Axle Load (HAL) test program in 1988, many measurements of wheel/rail forces and track geometry conditions have been collected. This data has been obtained by the Transportation Technology Center, Inc. (TTCI), a subsidiary of the AAR, through various HAL tests at FRA's Transportation Technology Center's (TTC) High Tonnage Loop (HTL), Pueblo, Colorado. Dynamic vertical and lateral wheel/rail forces have been measured at accumulated levels of traffic using AAR's instrumented wheel sets under HAL traffic (39-ton axle loads). Track geometry conditions have been regularly recorded on the HTL using a track geometry car EM-80 (via mid-chord measurements).

In 1997 and 1998, a new activity aimed at studying vehicle/track interactions has been initiated under the HAL program. The objective is to study the relationships between dynamic vehicle responses and track geometry conditions under the HAL test environment. As a first step, the vast test records since 1988 of wheel/rail force and track geometry measurements were examined. The purpose of these efforts include: (1) obtaining magnitude and frequency distributions of wheel/rail forces and track geometry deviations, as a function of track and vehicle conditions; and (2) examining the relationships between wheel/rail forces and corresponding track geometry conditions.

This paper summarizes the statistical characterization of wheel/rail forces, measured over more than 600 million gross tons (MGT) on the HTL, as a function of track curvature (0 to 6 degrees), subgrade support (stiff versus soft), truck type (standard versus improved), and traffic accumulation. Comparisons are also made between measured dynamic wheel/rail forces and the vehicle/track interaction safety standards proposed by the FRA.

Past track geometry records from HTL testing are currently under analysis by AAR and will be discussed in a later report. It is expected that some of the wheel/rail force characteristics shown in this paper will be related to track geometry characteristics and some relationships between these two sets of results will be established.

2.0 WHEEL/RAIL FORCE MEASUREMENTS

Since the inception of HAL testing on the HTL, AAR's instrumented wheel sets have been used to measure wheel/rail forces under 39-ton axle load test vehicles utilizing 125-ton gondola cars for various projects. Table 1 lists the measurements included in this analysis. At each MGT level, vertical and lateral forces were recorded and lateral/vertical (L/V) ratios were calculated for the entire track loop. Forces were measured for all four instrumented wheels under one truck. The analyzed records were for the test speed of 40 mph, which is the nominal train operation speed on HTL.

Table 1. Instrumented Wheel Set Records Used for Analysis

	Standard Trucks, Stiff Subgrade					Standard Trucks, Soft Subgrade in Section 29							Improved Trucks, Soft Subgrade in Section 29			
Date	3/90	4/90	1/91	3/91	5/91	12/91	1/92	7/92	4/93	5/93	7/93	5/94	5/95	2/96	2/96	11/96	1/97
MGT	138	159	161	175	195	212	222	257	310	326	338	376	460	513	522	614	628

Many track and vehicle characteristics determine and affect wheel/rail forces. In this study, the track conditions considered include track curvature and subgrade support. Figure 1 illustrates these HTL sections for various conditions including: Section 3, 5-degree curve; Section 7, reverse 5-degree curve; Section 25, 6-degree curve; Section 29, tangent with soft subgrade started in September 1991; and Section 33, tangent with stiff subgrade. The vehicle conditions considered are truck type (standard versus improved suspension trucks) and wheel positions. Both standard and improved trucks are three-piece trucks. However, the improved trucks have enhanced suspension characteristics.[1] The improvements may include frame bracing, primary suspension shear pads, and/or hydraulic dampers with the secondary suspension. Use of the improved trucks started in November 1995.

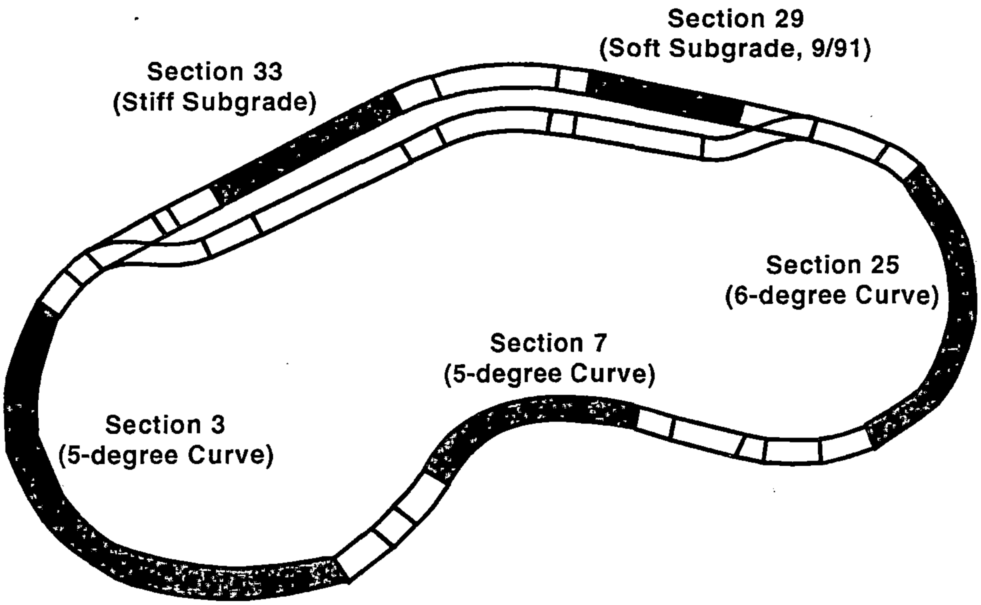


Figure 1. HTL Sections Analyzed for Various Curvatures and Subgrade Supports

3.0 MAGNITUDE DISTRIBUTIONS

A thorough understanding of the statistical distributions of dynamic wheel/rail forces will help to determine safety levels of HAL train operations as well as degradation rates of track and vehicle components. Essentially, the potential for train derailment is dependent upon vertical and lateral forces occurring at the wheel/rail interface. In this section, distributions of vertical, lateral, and L/V ratios are given to illustrate the effects of track and vehicle conditions discussed previously. Also, measured dynamic wheel/rail forces are compared with the vehicle/track interaction safety standards proposed by the FRA.

3.1 EFFECT OF SUBGRADE SUPPORT

As mentioned earlier, the soft subgrade was installed in the tangent Section 29 in September 1991. The resulting track modulus was approximately 2,000-2,500 lbs./in./in., as compared to 4,000-6,000 lbs./in./in. for Section 33, which was built on a stiff subgrade (typical at TTC). Since installation, track geometry degradation in the soft subgrade test zone generally has been rapid and substantial, requiring track surfacing every 10 to 30 MGT.[2] To examine how subgrade support affects wheel/rail forces, a comparison was made between Sections 29 and 33 for the measurements under the standard trucks. This comparison is given in Figure 2, which shows the effects of subgrade support on dynamic vertical forces at various traffic levels. Note that the soft subgrade force measurements selected for this figure were not obtained under poor geometry conditions; therefore, they do not indicate the effects on dynamic wheel/rail forces of excessive subgrade deformations. In this figure, the 90th percentile indicates an amplitude larger than 90 percent of all the measured forces. Along with standard deviation values, this percentile is used to indicate dynamic load variations. As can be seen, the effect of subgrade support was mainly on the dynamic variation of vertical forces. The soft subgrade section generally exhibited higher values at the 90th percentile and had higher standard deviations than did the stiff subgrade section. On the other hand, the mean values of the vertical forces were not influenced by subgrade support, as shown by the similar mean values for these two sections.

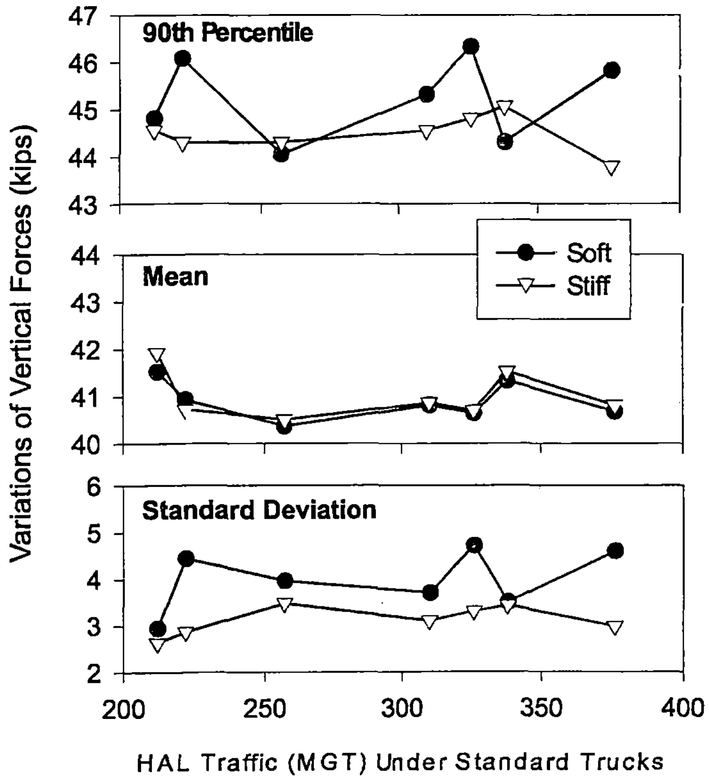


Figure 2. Effects of Subgrade Support on Vertical Forces

Over a series of 17 measurements at various MGT indicated in Table 1 (138 to 628 MGT), the mean value of the vertical forces levels ranged from 39 to 42 kips in the two tangent sections at or slightly above the nominal static wheel loads (39 kips).

3.2 EFFECT OF TRACK CURVATURE

Lateral wheel forces measured on the HTL varied greatly depending upon conditions such as wheel position, track curvature, truck type, and rail lubrication. Figure 3 shows an example of the variation of mean values for lateral wheel forces measured in Section 25. As can be seen, the mean values varied greatly, even for the same track section and for the same wheel.

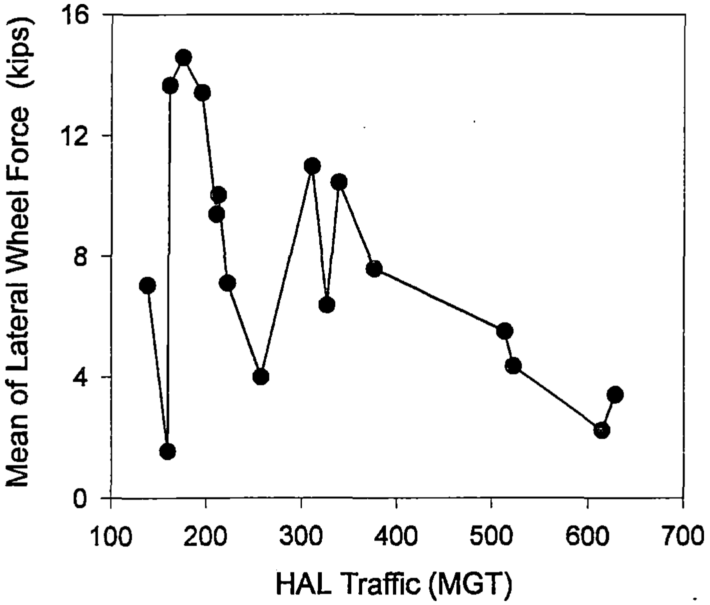


Figure 3. Variation of Lateral Wheel Force with MGT (Section 25, Leading Wheel on High Rail)

As expected, the two leading wheels always measured higher lateral forces than the two trailing wheels in the negotiation of curves. Figure 4 gives the mean and 90th percentile of lateral forces averaged over all the MGT measurements as a function of track curvature for the leading wheel on the high rail. As shown, an increase in track curvature led to large increases in both the mean value and 90th percentile of the lateral forces. As an average, a 1-degree increase in track curvature equated to a 1,300-pound increase in lateral wheel force.

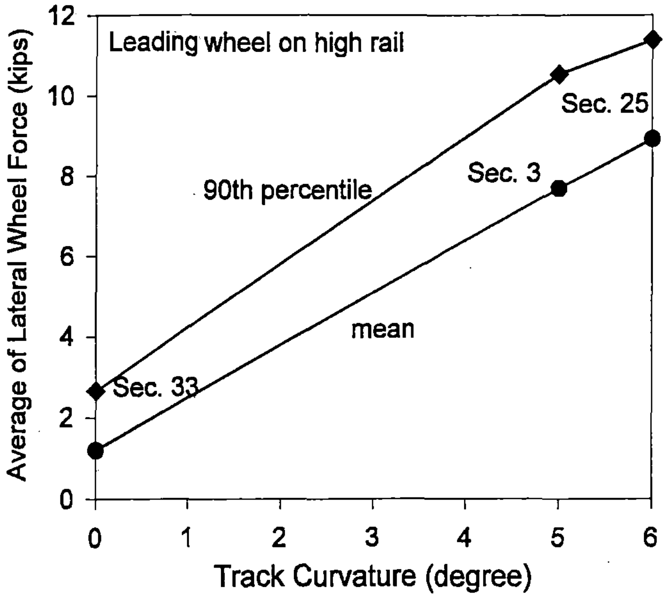


Figure 4. Effect of Track Curvature on Lateral Forces (Average over all MGT under Standard Trucks)

In the curves, high rail vertical wheel forces were always larger than those measured on the low rail because of cant deficiencies. For example, the balance speed is approximately 34 mph for Section 3 (5-degree curve with a 4-inch superelevation); consequently, more train weight is carried by the high rail than by the low rail at the nominal train speed of 40 mph. Figure 5 gives a comparison of mean vertical forces measured between the high and low rails in Section 3. Vertical forces measured on the high rail were consistently higher than those measured on the low rail.

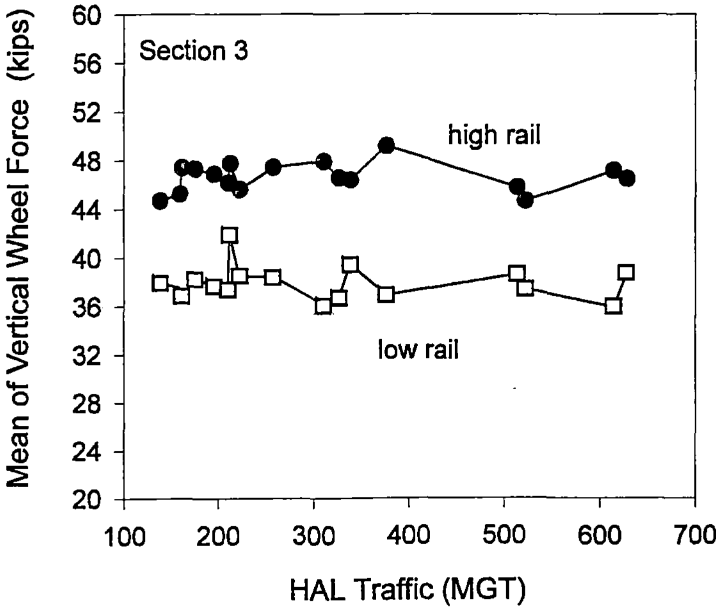


Figure 5. Comparison of Vertical Wheel Forces between High and Low Rails at 40 mph

Figure 6 gives a comparison of lateral wheel forces measured in Section 3. The mean values obtained at each MGT level showed similar magnitudes between the high and low rails. Note that a positive lateral force on either rail indicates the direction away from the track center line. Therefore, positive lateral wheel forces on both rails indicate a gage widening interaction in the curve.

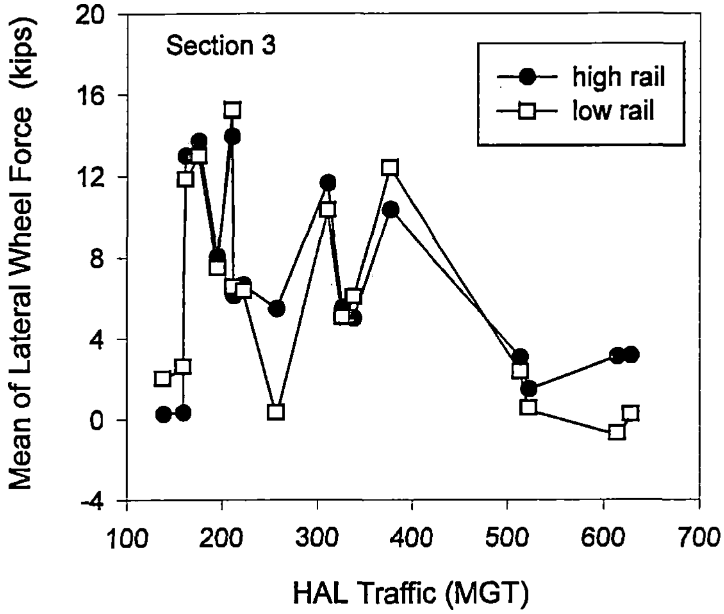


Figure 6. Comparison of Lateral Wheel Forces between High and Low Rails on a 5-degree Curve

3.3 EFFECT OF TRUCK TYPE

Use of the improved suspension trucks greatly reduced lateral wheel forces under the leading wheels. Based on a comparison of the measurements between the standard and improved trucks, the 90th percentile values showed a reduction of 20-50 percent. The reduction in mean value was even more prominent, having a range of 50-90 percent. However, the improved trucks did not reduce lateral wheel forces under the trailing wheels. The lateral forces generated by the trailing wheels also were not of the same magnitude as the leading wheels under the standard trucks. The effect of truck type on lateral wheel forces is illustrated in Figure 7, which shows a significant decrease in lateral forces under the leading wheels due to use of the improved trucks.

The effect of truck type on vertical forces is shown in Figure 8. The mean vertical force values were approximately 40 kips and were not significantly influenced by truck type. However, dynamic variations of vertical forces as indicated by the 90th percentile values were slightly higher under the improved trucks than under the standard trucks.

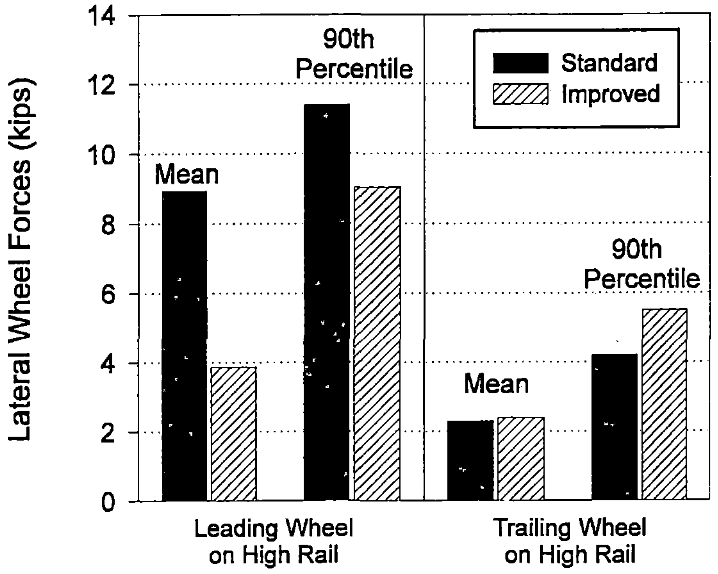


Figure 7. Effect of Truck Type on High Rail Lateral Forces in a 6-degree Curve (Section 25)

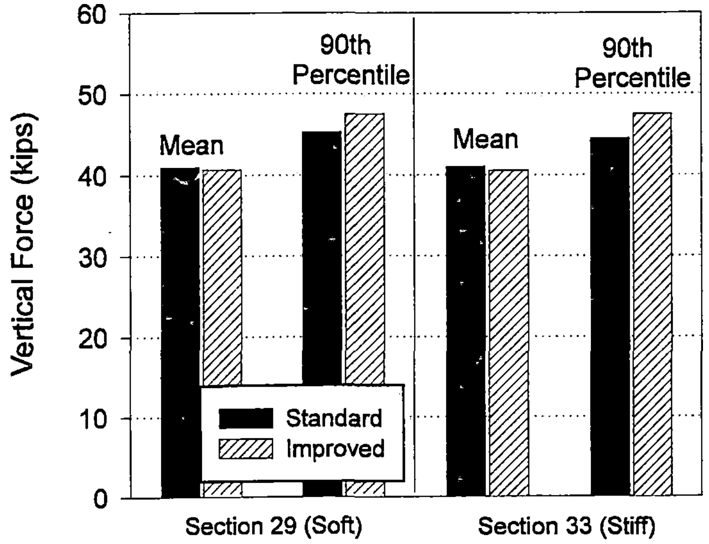


Figure 8. Effect of Truck Type on Vertical Forces in Tangent Track

3.4 COMPARISON WITH FRA PROPOSED SAFETY LIMITS

Lateral and vertical forces at the wheel/rail interface determine safety limits of train operations, as well as vehicle and track degradation rates and magnitudes. Controlling wheel/rail forces can reduce potential for various derailments (i.e., wheel unloading, flange climbing, track panel shifting, rail rollover).

To support the development of high-speed track geometry specifications, the FRA has conducted studies on vehicle/track interaction and track geometry effects as related to train operation safety. As a result of these studies, the FRA has proposed high-speed track geometry standards for track classes 6 through 9.[3] In addition, the FRA has proposed vehicle/track interaction safety standards, based on the limits of wheel/rail forces and accelerations of the car body and truck. Unlike the proposed high-speed track geometry standards, the vehicle/track interaction standards are not related to track class. These standards are applicable to any track class, for either passenger or freight service. Table 2 gives the FRA proposed limits of wheel/rail forces for minimizing the potential for derailments.

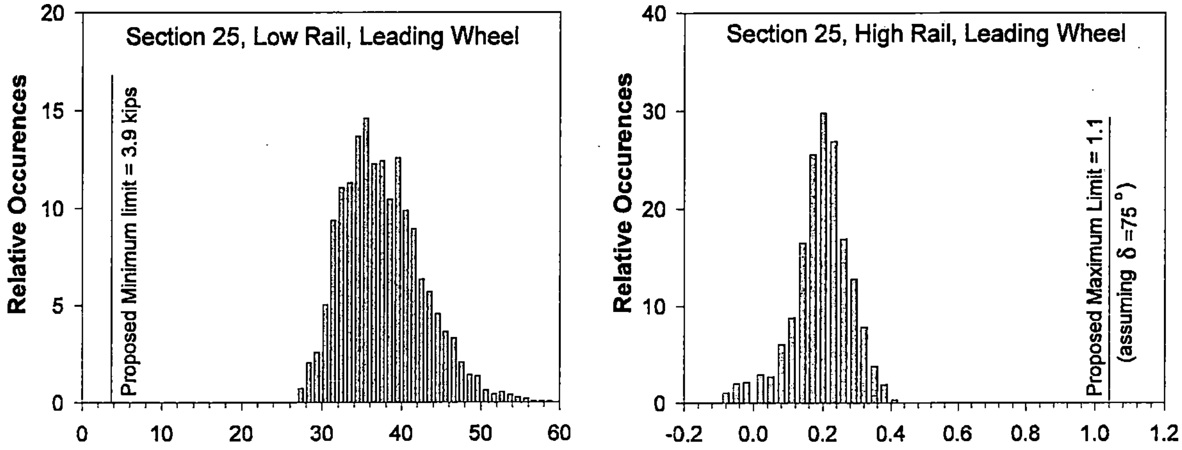
Table 2. FRA Proposed Vehicle/Track Interaction Limits for all Track Classes (Wheel/Rail Forces)

Parameters	Safety Limit	Filter / Window
Single Wheel Vertical Load Ratio	≥ 0.1	25 hertz, 5 feet
Single Wheel L/V Ratio	$\leq (\tan\delta - 0.5)/(1 + 0.5\tan\delta)$	25 hertz, 5 feet
Net Axle L/V Ratio	≤ 0.5	25 hertz, 5 feet
Truck Side L/V Ratio	≤ 0.6	25 hertz, 5 feet

δ - flange angle

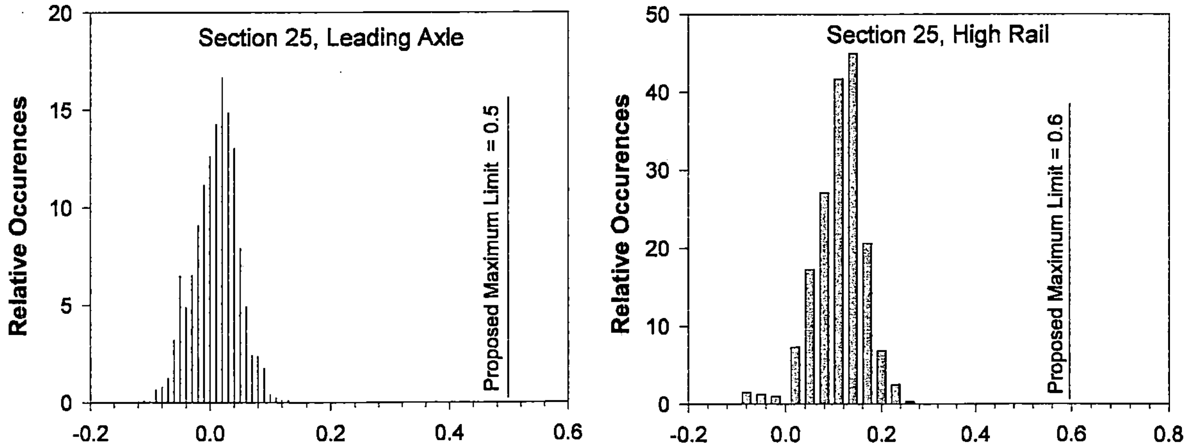
As a comparison between the FRA proposed safety limits and measured wheel/rail forces under HAL, Figure 9 shows the distributions of vertical wheel force, single wheel L/V ratio, net axle L/V ratio, and truck side L/V ratio under the standard trucks. As discussed earlier, improved suspension trucks reduced lateral wheel forces under the leading wheels and had less effect on the magnitude of vertical forces. Therefore, the data from these (better behaving) trucks is not included for comparison with the proposed safety limits. In Figure 9, the data shown was selected based on specific wheel positions and track section in order to represent the worst cases measured relative to the FRA proposed limits.

As can be seen in Figure 9a-d, the measured wheel/rail forces throughout all the MGT levels were far below the safety limits proposed by the FRA, indicating safe HAL train operations on the HTL.



(a) Vertical Wheel Force (kips)

(b) Single Wheel L/V Ratio



(c) Net Axle L/V Ratio

(d) Truck Side L/V Ratio

Figure 9. Comparison between Wheel/Rail Force Histograms under Standard Trucks and FRA Proposed Safety Standards (Relative Occurrences Indicating the Likelihood of such Amplitudes)

4.0 FREQUENCY DISTRIBUTIONS

The analysis of forces in the frequency domain gives an indication of the frequencies at which large dynamic wheel/rail forces are generated and the possible causes of these large forces. For this purpose, power spectral density (PSD) results of wheel/rail forces were obtained for each measurement on the HTL. In the PSD analysis, forcing energy below 0.25 Hz was removed X a practice designed to remove the near static load components that may hinder subsequent interpretation. Thus, the results shown represent dynamic variations in the forcing frequencies from 0.25 to 50 Hz. The upper limit of frequency is due to the instrumented wheel set that measures valid wheel/rail forces up to 50 Hz.

Results of force distribution in the frequency domain were obtained as a function of track curvature, subgrade support, truck type, and traffic accumulation. For each of the five HTL sections and for each truck type, it was found that the traffic accumulation did not consistently influence the frequency distributions of either vertical or lateral forces. Therefore, PSD results given here were averaged over all the MGT measurements for each of the track and vehicle conditions. In addition, 95 percent confidence intervals around the mean PSD results were also derived to show the PSD variation due to measurements at various MGT.

4.1 DYNAMIC VERTICAL FORCES

Figure 10a shows the frequency components (or energy distribution) of vertical force measured in Section 29 for the right leading wheel of the standard truck. As shown, dynamic vertical forces were generated primarily at five distinctive frequency bands (0.5, 2.8, 6, 12, and 18 Hz). In addition, there may be one more component above but closely coupled with 0.5 Hz. The distribution pattern shown in this figure was consistent for all five HTL sections, indicating that track curvature and subgrade support did not significantly affect the frequency characteristics.

Figure 10b shows the frequency components of vertical force as a result of the improved truck design. Dynamic vertical force was distributed primarily at two frequencies while higher frequency components that existed under the standard trucks were attenuated. Again, the pattern shown in this figure was consistent, with no significant influence from track curvature and subgrade support.

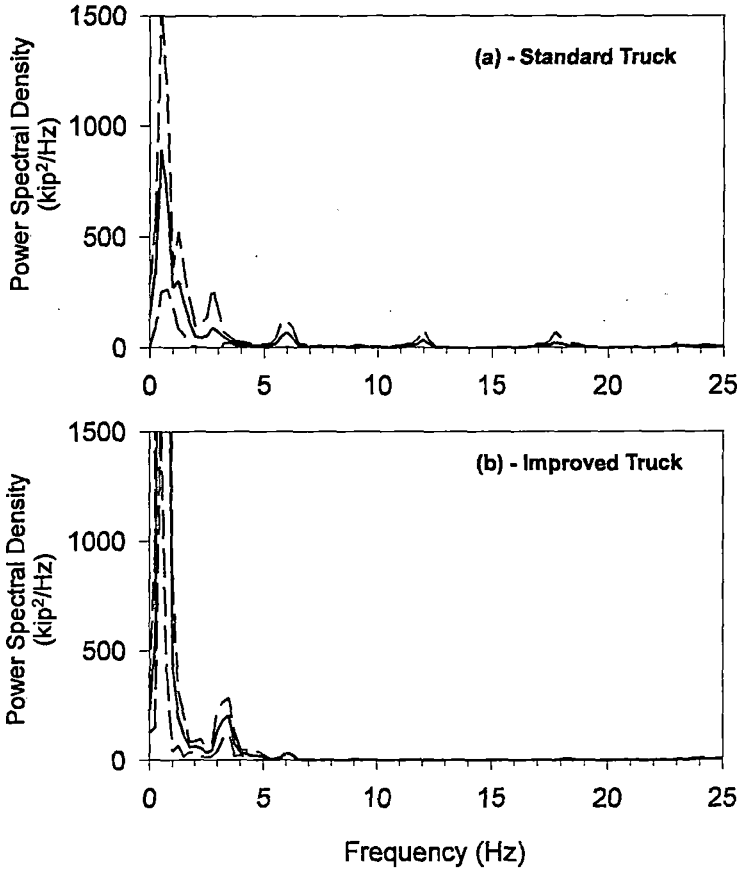


Figure 10. Frequency Distributions of Vertical Wheel Forces (Average with 95 Percent Confidence Intervals, Right Leading Wheel, Section 29)

The attenuation of higher frequency components of vertical wheel/rail forces can be attributed to improvements in the truck primary suspension characteristics. This attenuation of higher frequency vertical forces may explain the significant reduction of rail end and weld batter observed on the HTL as a result of the improved truck use.[1] Rail end and weld batter are considered to be defects caused by higher frequent vertical forces.

Figure 11 gives the same comparison of the averages shown in Figure 10 using a logarithmic scale for the force energy (PSD). Again, use of the improved truck design can be seen to attenuate the energy levels between 5 to 25 Hz.

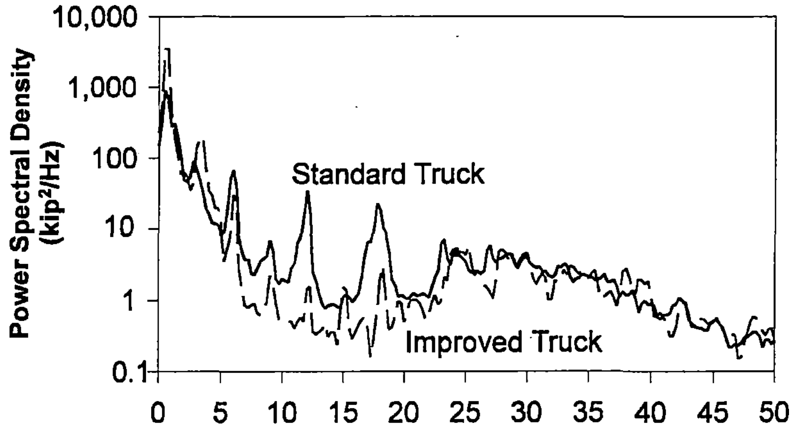


Figure 11. Comparison of Frequency Distributions of Vertical Wheel Forces (Average PSD for Right Leading Wheel, Section 29)

4.2 DYNAMIC LATERAL FORCES

Figure 12 gives an example of frequency distribution of lateral wheel forces. As can be seen, the energy of lateral wheel forces was primarily concentrated at two frequency bands X 0.6 Hz and 2.4 Hz. The second band, however, did not appear significant in most measurements.

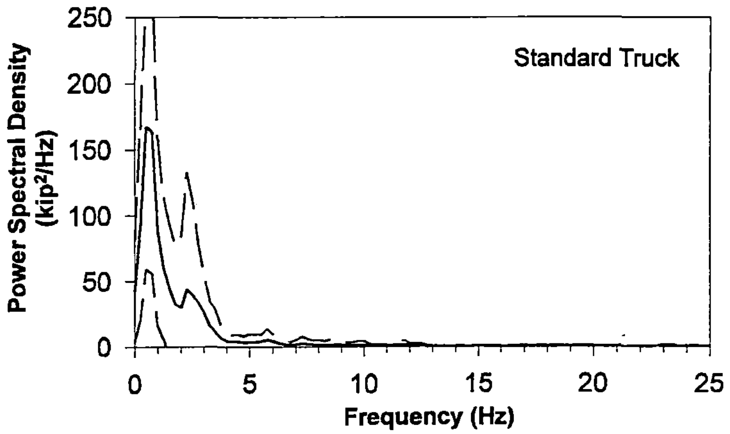


Figure 12. Frequency Distributions of Lateral Wheel Forces (Average with 95 Percent Confidence Intervals, Left Leading Wheel, Section 25)

The concentration of dynamic lateral wheel forces at 0.6 Hz was found consistent, regardless of track curvature, subgrade support, and truck type. Improvements in truck suspension characteristics did not change the frequency characteristics of lateral wheel forces. Therefore, the reduction of lateral wheel/rail forces due to the use of improved trucks was primarily a result of the improvement of steering or negotiating capabilities of the leading wheels in the curves (decrease of angle of attack).

The frequency characteristics of dynamic vertical and lateral forces summarized above can be due to one or both of the vehicle and truck structural behavior and track/wheel irregularities. The analysis of track geometry records in frequency domain and analysis of resonant frequencies of the test vehicle and trucks will help to determine these characteristics.

5.0 CONCLUSIONS

The following main conclusions were derived based on the statistical analysis of existing wheel set records obtained under the nominal HTL test environment:

In the tangent sections, the mean values of vertical wheel force obtained at various MGT levels were not affected by subgrade support and truck type. However, dynamic variation of vertical forces in the forms of standard deviation and 90th percentile (a magnitude larger than 90 percent of the measured forces) was higher for the soft subgrade than for the stiff subgrade.

In the case of the standard trucks in a 6-degree curve, as an average over all the measurements, the leading wheels measured lateral wheel force approximately 9 kips (mean) and 11 kips at the 90th percentile. A 1-degree increase in track curvature generally equated to more than 1 kip increase in lateral wheel force. Use of the improved suspension trucks greatly reduced lateral forces to the leading wheels by more than 50 percent (mean values) and by more than 20 percent at the 90th percentile. Lateral wheel forces measured in the trailing wheels were generally much lower than in the leading wheels and did not show reductions as a result of improved truck use.

In the HTL curves, vertical wheel forces were always higher on the high rail than on the low rail because of the cant deficiencies at the nominal train speed of 40 mph. However, similar magnitudes of lateral wheel forces were experienced on both rails.

A comparison with the FRA proposed safety standards for minimizing potential derailments indicated that the wheel/rail forces generated on the HTL in the course of more than 600 MGT of HAL traffic accumulation were far below the proposed vehicle/track interaction safety limits.

Within the range from 0.25 to 50 Hz, distributions of dynamic vertical and lateral forces in various frequencies were not affected by track curvature and subgrade support. Traffic accumulation was not found to have a consistent effect on the frequency characteristics of forces. However, use of the improved suspension trucks significantly attenuated the vertical force components higher than 5 Hz; this may explain the significant reduction of rail end and weld batter under improved suspension trucks. For all the measurements considered, lateral wheel forces were mainly concentrated in frequencies lower than 5 Hz.

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Letter Report-Distributions of Dynamic Wheel/Rail Forces Under Heavy Axle Loads,
1998
US DOT, FRA, D. Li, D. White, M Ahmadian, M El-Sibaie