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RAIL FORCE MEASUREMENT AND FASTENER LOAD DEMAND AT HORSESHOE CURVE

SUMMARY

In 2022, the Federal Railroad Administration (FRA) and Association of American Railroads (AAR) completed short-term field experiments to measure the rail forces in steep grades and high-degree curvature on Norfolk Southern Railway (NS). This experiment was conducted to understand the rail stress distribution and fastener load demand by measuring the dynamic rail forces and the longitudinal rail forces due to temperature changes.

Transportation Technology Center, Inc. (TTCI) performed the field test at Horseshoe Curve, a three-track railroad curve near Altoona, PA (Figure 1). The team installed 12 rail circuit arrays for dynamic rail forces (lateral, longitudinal, and vertical) on all 3 main tracks (i.e., 2 rail circuits on each track). In addition, longitudinal rail force circuits were used along with thermocouples on each rail to measure the static longitudinal rail force changes due to temperature variation. Researchers collected measurements over a 24 hour period.

Figure 1. Test Location

The test showed that the number of consecutive locomotives and braking/tractive effort could affect the dynamic rail forces. This report provides the estimated spike loading using both the measured dynamic rail forces and load distributions from literature. The results showed that both lateral and longitudinal forces contribute to the loading, exceeding the spike fatigue limit and leading to fatigue failures.

BACKGROUND

Railroads have experienced a higher frequency of broken spikes in territories with steep grades and high-degree (i.e., greater than 4 degrees) curvatures. This is especially true when spikes are used in conjunction with elastic fastening systems. Typically, the spikes break 1 to 1.5 inches below the surface of the ties, making the break difficult to identify during inspections (Gao, McHenry, Brice, and Baillargeon, 2020). The railroad industry believes that the issue is a systemic problem due to the load transfer mechanism inherent in the elastic fastening systems, rather than a problem caused by a single spike or by weak material. Therefore, it is important to understand the load transfer path from rail into fasteners in order to provide appropriate solutions to the problem.

OBJECTIVES

The objective of the research was to investigate the influence of traffic, train makeup, and operations on the rail stress distribution and fastener demands. A secondary objective in this research was to identify how the rail temperature affects rail stress for future rail buckling analysis.

METHODS

Horseshoe Curve is approximately 2,375 feet long and 1,300 feet in diameter (9°25’ curvature) with a 1.8 percent grade. The curve has three main tracks with a history of broken spikes, especially on Main 3:

- Main 1: 18 inch elastic fastener plates with 4 cut spikes
- Main 2: 18 inch elastic fastener plates with 4 cut spikes and rail anchors
- Main 3: 18 inch elastic fastener plates with 4 cut spikes for the low rail and 18 inch elastic fastener plates with 4 lag screws for the high rail

The team collected dynamic rail forces (i.e., vertical, lateral, and longitudinal) on each of the three tracks using twelve rail circuits. The researchers installed four rail circuits on each track, two on the high rail and two on the low rail. The static longitudinal rail forces were measured every 15 minutes. In addition, the team installed thermocouples measuring ambient temperature and rail temperature for each rail.

Researchers collected rail force data over a period of 24 hours, during which they collected data on 55 trains. Main 1 traffic was mostly fully loaded freight trains descending the grade. Main 3 traffic was mostly empty freight trains climbing the hill. Main 2 traffic was a mix of loaded and unloaded freight trains and passenger trains with traffic in both directions.

RESULTS

Dynamic Rail Force Measurement

Analysts recorded the peak load at each wheel for the load distribution analysis. Figure 2 and Figure 3 show the distribution of dynamic vertical and lateral rail forces.

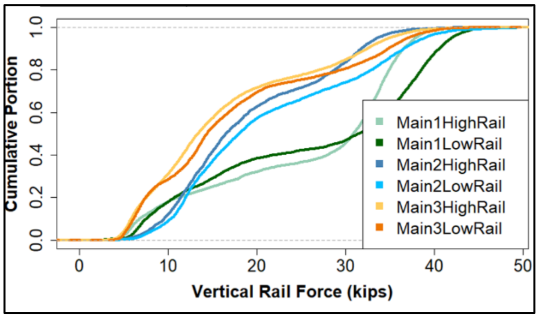

Figure 2. Distribution of dynamic vertical rail force

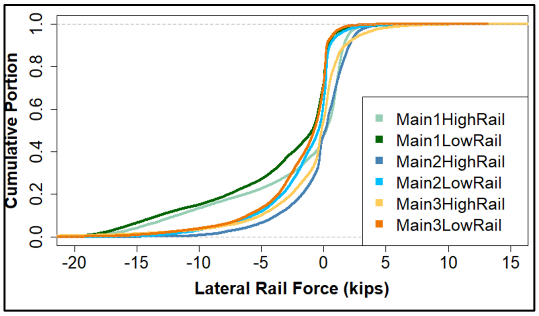

Figure 3. Distribution of dynamic lateral rail force

The traffic on Main 1 had higher vertical and lateral loads than those on the other two tracks. In addition, the trains were operating at an under-balance speed throughout the curve. This resulted in the low rail carrying slightly higher vertical loads for all tracks.

The ratio of lateral to vertical force, or “L/V ratio,” for the leading axles was larger for Main 3 than the other two tracks. In addition, the high rail of Main 3 had a larger L/V ratio than the low rail. Considering that the vertical loads could provide higher frictional resistance between tie fasteners to resist lateral loads, higher L/V ratios on the high rail of Main 3 may result in more lateral load being transferred into the fastening systems. In fact, the high rail of Main 3 had a history of broken cut spikes throughout the curve before the installation of lag screws.

Figure 4 shows an example of the dynamic longitudinal rail forces produced during this study. According to the measurements, the longitudinal rail forces had a longer influence length before train arrival, ranging from 60 to 250 feet. This is unlike the vertical and lateral wheel forces, which only influenced three to four ties under the wheel.

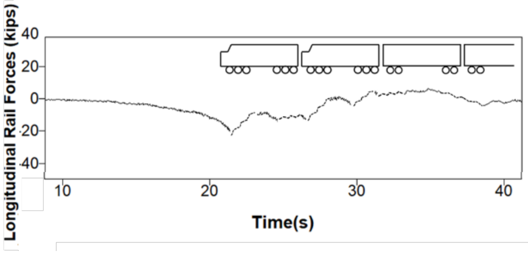

Figure 4. Dynamic longitudinal rail forces

The measurements also showed that the number of consecutive locomotives could also affect the maximum longitudinal forces. This is due to the superposition of the longitudinal rail forces (braking or pulling) from multiple locomotives. Two locomotives in a row resulted in higher longitudinal forces in rails than a single locomotive. Table 1 shows the maximum longitudinal forces from one and two locomotives.

Table 1. Peak longitudinal rail force by number of consecutive locomotives

Direction	1 Loco	2 Locos
Uphill	13 kips	22 kips
Downhill	7.5 kips	14 kips

Further, uphill trains (tractive forces) generated higher peak longitudinal rail forces than downhill trains (braking forces). This is to be expected since tractive effort is concentrated only at the locomotives for uphill movements. Downhill movements are slowed primarily by locomotive dynamic brakes, so the braking effort is once again concentrated at the locomotives.

The dynamic rail forces are important for understanding spike loading demand as rail forces are distributed to the lower track structure through rail fastening systems. Fastener loads (i.e., tie plate load and spike load) come from these rail forces; the higher the rail forces, the more likely the fastening system will experience a higher load.

Longitudinal Thermal Forces in Rail

Longitudinal rail forces are affected by the daily temperature swings. In this study, researchers measured a longitudinal rail force variation of about 120 kips for Main 1 within the 24 hour window. Table 2 presents the longitudinal rail force variation for all three tracks. Since the rail was not cut before the measurement, the rail neutral temperature was unknown.

Table 2. Longitudinal rail thermal force variation

Track	Force Variation (Max.-Min.)
Main 1	120 kips
Main 2	104 kips
Main 3	88 kips

Trains braking downhill could increase the rail temperature and, in turn, increase the longitudinal forces in the rail. Figure 5 shows the trend of increasing longitudinal rail forces and temperature when a downhill train passed.

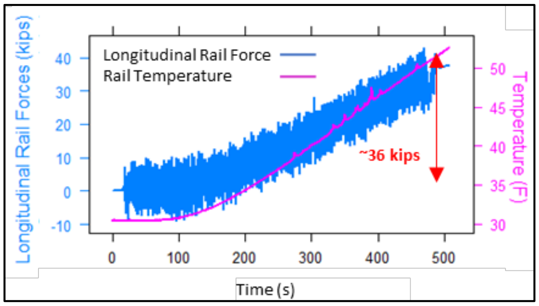

Figure 5. Longitudinal forces due to downhill trains

The longitudinal forces were initially around 0 kips and elevated to 36 kips after the train passed. The rail temperature rose approximately 20°F. This increase was found only on the downhill trains. The application of air braking heats the train wheels, which was likely a contributing factor to the rail temperature increase.

Fastener Load Demand

Researchers used the measured dynamic rail forces to estimate the loading level for spikes. These fastener load demand estimates do not consider the longitudinal thermal forces discussed in the previous section. Prior testing showed that spikes experienced the largest loading level when the wheel load was directly above the tie (Gao et al., 2020). Therefore, spike loading was estimated when the dynamic wheel forces were directly over the tie. Only lateral and longitudinal rail forces can transfer into spikes as spikes are mainly designed to resist shear forces.

The actual transfer mechanism from rails to spikes mainly consists of two paths:

- The portion of rail forces distributed to one individual fastening system, P_1
- The portion of P_1 distributed to spikes, P_2

To estimate P_1, the track is assumed to be a continuously supported structure. Therefore, using beam theory, the lateral rail forces typically distribute 25 to 50 percent to one individual fastening system (Zarembski, 1992). For the longitudinal rail forces, the individual fastening system receives 8 to 10 percent of the longitudinal rail forces (Marquis, Liu, and Stuart, 2020; Dersch, Trizotto, Edwards, and Lima, 2021).

P_1 has two main portions. First, the load is taken up by the frictional resistance of the tie plate and the tie. The remainder is resisted by spikes, or P_2. Based on the past study, spikes typically receive between 20 and 45 percent of P_1 (Zarembski, 1992). With that, the total spike load on one tie plate can be calculated.

Past research has shown that a single spike could carry 70 percent of the total spike load on one plate. Using the 99th percentile of dynamic lateral rail forces (19.0 kips) and longitudinal rail forces (26.7 kips) from the test, the estimated single spike load ranges are 0.7 to 2.6 kips in lateral and 0.3 to 0.8 kips in longitudinal. The resultant load on that spike ranges from 0.8 to 2.7 kips. This range indicates that the spike load could exceed the minimum load required to produce spike fatigue failures, roughly 2 kips (Gao et al., 2020; Dersch et al., 2021).

CONCLUSIONS

Based on the field investigation and data analysis, the following findings are presented:

- Tractive effort (concentrated at locomotives) generated higher longitudinal rail forces than braking effort (distributed through a train). Also, the number of consecutive locomotives could affect the maximum longitudinal rail forces, which could affect the load level in spikes.
- Thermal longitudinal rail forces were recorded with one track showing a 120 kip variation in a 24 hour window. Also, downhill heavy trains caused a 20 degree rail temperature change, generating 36 kips of longitudinal rail forces at the Horseshoe Curve. Therefore, the thermal-induced longitudinal rail forces can be affected by temperature changes as well as passing trains. This observation will be used for rail buckling analysis in the future.
- Spike load level was estimated through typical load transfer ratios from rail to fastening systems. Both lateral and longitudinal forces had a contribution to spike fatigue failure, while lateral forces contributed more.

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KEYWORDS

Rail force measurement, fastener load demand, spike breakage