QUANTIFYING LATERAL WHEEL LOADING VARIATION USING TRUCK PERFORMANCE DETECTORS

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SUMMARY
As railroads continue to take advantage of their inherent efficiencies, axle loads have increased, placing greater demand on the infrastructure and its components. As loading conditions have become more demanding, an increased number of failures have been noted, particularly in curves where high lateral wheel loads occur. The magnitude of lateral wheel loads used in the current design procedure for concrete crossties and elastic fastening systems may not be reflective of all types of current train operations. In order to improve upon the design of the concrete crosstie and fastening system components these loads need to be quantified, to provide accurate input when determining the loading demand on the system. Researchers at the University of Illinois at Urbana-Champaign (UIUC) have used truck-performance detectors (TPDs) to gather lateral wheel load data from multiple locations throughout the United States. UIUC has used these data to characterize the magnitude and distribution of lateral wheel loads, which can then be used to update to the design lateral wheel loads. The effect of car type, degree of curvature, speed, cant deficiency, high versus low rail, and leading versus trailing axles was analyzed to determine what has the most significant impact of the magnitude of lateral wheel loads. This paper will discuss the current trends of lateral wheel loads across the United States and will investigate any variability in the magnitude of these loads.

INTRODUCTION
Historically, track superstructure components have been designed through a process that uses practical experience rather than actual input loads that are being applied to the system. In order to develop a mechanistic design process that is driven by actual loading conditions, the input loads to the system need to be quantified. Mechanistic design is a process that uses measured forces in track structure and the properties of materials to withstand or transfer them. The responses of the system, such as contact pressure and relative displacement can be used to optimize component geometric design, material selection, and system-level requirements.

Previous research by the University of Illinois at Urbana-Champaign (UIUC) was conducted to quantify the magnitude and distribution of vertical wheel loads. In order to quantify all input loads and develop a mechanistic design process, the magnitude and distribution of lateral wheel loads are also required. This is especially important because a large percentage of track superstructure failures occur in areas of high curvature. These areas tend to have higher lateral wheel loads compared to tangent track, where lateral loads are typically negligible as compared to vertical loads. To address these unknowns, and further the state-of-the-art in lateral load design for concrete crossties and fastening systems, UIUC has used data from truck performance detectors (TPDs) to quantify lateral wheel loads in North America and evaluate sources of variation.

METHOD FOR QUANTIFYING LATERAL LOAD
There are several options for evaluating the magnitude of lateral wheel loads at the wheel-rail interface. One option is to use an instrumented wheel set (IWS). An IWS is an independent wheel set that measures the vertical, lateral, and longitudinal forces as the wheel set travels over a route. These forces are measured through the use of strain gauges that are attached to the wheel, which allow strains to be measured and resolved into forces. IWS technology allows for an
in-depth understanding of the forces on a single wheel in a continuous manner. However, in order to develop an understanding of a variety of car types, the number of IWSs and the volume of data required would be cost prohibitive. For that reason, and to best answer the questions that are of interest to track component designers, a wayside measurement technology was pursued.

The primary wayside detector that can be used to measure lateral wheel loads is a truck performance detector (TPD). TPDs are typically used to evaluate the curving performance of a railcar truck, and can identify bad-acting trucks that need to be repaired or replaced. TPDs are located in a segment of track that contains a reverse curve, with two sets of strain gauges located on both rails in the two curves as well as in the tangent section (Figure 1). Each of the three locations has two instrumented cribs on the foot and web of the rail that are used to measure the magnitude of vertical and lateral loads at the wheel rail interface (Figure 1). A TPD site also includes equipment that records information such as car type and train speed. The loads measured are peak loads for the portion of the wheel’s rotation that is sampled, but each measurement site does not capture a full rotation of each wheel. The degree of curvature and superelevation for the reverse curves is not standardized, and vary among TPD locations. This allows the effect of degree of curvature on the magnitude of lateral wheel loads to be analyzed based on data collected from multiple TPD sites. All TPDs were located on concrete crosstie track.

SOURCES OF LOAD VARIATION

Lateral wheel loads that are imparted into the track may vary due to a variety of factors including car type and weight, speed of the vehicle, curvature, lateral load versus high rail, geographic location, and superelevation. TPDs facilitate the quantification and evaluation of variation. There are additional factors that can cause lateral wheel loads to vary, such as lead versus trailing axle or truck, angle-of-attack, truck type, wheel/rail profile, rail lubrication, grade, track modulus, and wheel/rail contact patch. These factors will not be discussed in this paper, but will be examined in future studies.

Six different locations were selected for data collection within the United States rail network (Figure 2). Two of the locations had multiple tracks instrumented, giving a total of eight unique TPD installations. Table 1 provides the names of each TPD location, as well as information on the degree of curvature and superelevation for each curve. All TPDs were located on concrete crosstie track.

Figure 1: Typical Layout Of Truck Performance Detector (TPD) Site

Figure 2: TPD Locations Selected For Further Evaluation

Car Type and Weight

The primary cause of variation in lateral wheel load is static car weight. Different car types have different static vertical loads, which result in higher lateral forces as the railcars traverse curves.
### Table 1. TPD Site Information

<table>
<thead>
<tr>
<th>Location</th>
<th>Curvature</th>
<th>Superelevation (in)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argyle 1, IA</td>
<td>4° 5'</td>
<td>Curve 1 3.63 Curve 2 3.39</td>
</tr>
<tr>
<td>Argyle 2, IA</td>
<td>4° 5'</td>
<td>Curve 1 3.63 Curve 2 3.39</td>
</tr>
<tr>
<td>Elmira, ID</td>
<td>4° 23'</td>
<td>Curve 1 3.63 Curve 2 3.63</td>
</tr>
<tr>
<td>Joppa, MT</td>
<td>4° 30'</td>
<td>Curve 1 2.06 Curve 2 1.25</td>
</tr>
<tr>
<td>Ludlow 1, CA</td>
<td>4° 5'</td>
<td>Curve 1 3.63 Curve 2 3.63</td>
</tr>
<tr>
<td>Ludlow 2, CA</td>
<td>4° 7'</td>
<td>Curve 1 3.63 Curve 2 3.63</td>
</tr>
<tr>
<td>Ludlow, CO</td>
<td>5° 0'</td>
<td>Curve 1 2.77 Curve 2 3.72</td>
</tr>
<tr>
<td>Pomona, MO</td>
<td>3° 55'</td>
<td>Curve 1 3.48 Curve 2 3.12</td>
</tr>
</tbody>
</table>

*Determined from degree of curvature, allowable unbalance, and maximum train speed at TPD location.*

The magnitude of vertical load affects the value of centrifugal and centripetal forces, which dictate the magnitude of lateral load. Rail cars and locomotives that pass TPD locations were classified into four types: loaded freight, unloaded freight, intermodal, and freight locomotives. Table 2 lists the static vertical loads for these car types, as measured in previous research by UIUC using wheel impact load detector (WILD) data. A 95% load is a quantitative value for wheel load measured at the wheel-rail interface that is exceeded by only 5% of all wheel loads measured. The 100% level indicates the maximum recorded load for each of the respective categories, which represents a single wheel load and may not be indicative of the overall distribution. The negative loads refer to a lateral load towards the gauge side of either rail (i.e. toward the center line of track). These can be the result of a hollow worn wheel and usually are recorded on the low rail. The two heaviest types of traffic, loaded freight cars and locomotives, tend to have the highest lateral forces, as can be seen in Figure 3.

The data collected from TPD sites were used to develop a table that describes the lateral wheel load environment (Table 3). One critical difference between the Table 2 and Table 3 is that TPDs do not measure static loads, so the measurements in Table 3 are peak loads. However, since the TPD does not measure the full rotation of the wheel, it is not necessarily the absolute peak load for the wheel, but is the peak of the portion of the wheel that was measured. Based on Table 3 and Figure 3, it can be seen that as static vertical wheel load increases, lateral wheel load also increases. One exception are loads from freight locomotives compared to loaded freight cars. Even though freight locomotives have slightly lower static vertical wheel loads than loaded freight cars, they tend to have significantly higher lateral wheel loads. Based on TPD data, locomotives at the front of a freight consist show no difference in lateral wheel load distribution from locomotives at the middle or end of the consist. This suggests that the increased loading is solely due to the curving characteristics of the locomotives. Table 4 contains the distribution of lateral/vertical (L/V) load ratio from the TPD data. At high values of L/V, the wheel can climb over the rail, causing a derailment. For heavier cars, high L/V ratios can cause the rail to roll, leading to a derailment. Instability of the rail can start to occur at L/V ratios of 0.68, at 1.29 rollover is nearly assured. From the analysis of the data it can be seen that empty cars are the most prone to high L/V ratios (Table 4).

### Table 2. Distribution of Static Vertical Wheel Load

<table>
<thead>
<tr>
<th>Car Type</th>
<th>Mean</th>
<th>95%</th>
<th>97.5%</th>
<th>99.5%</th>
<th>100% (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Freight Car</td>
<td>29.4</td>
<td>42.7</td>
<td>48.9</td>
<td>60.5</td>
<td>66.7</td>
</tr>
<tr>
<td>Loaded Freight Car</td>
<td>148.6</td>
<td>175.7</td>
<td>178.8</td>
<td>184.2</td>
<td>202.4</td>
</tr>
<tr>
<td>Intermodal Freight Car</td>
<td>91.2</td>
<td>157.0</td>
<td>163.7</td>
<td>177.0</td>
<td>225.1</td>
</tr>
<tr>
<td>Freight Locomotive</td>
<td>149.5</td>
<td>162.8</td>
<td>165.5</td>
<td>171.3</td>
<td>193.5</td>
</tr>
</tbody>
</table>
Table 3 Distribution of Peak Lateral Wheel Loads

<table>
<thead>
<tr>
<th>Car Type</th>
<th>0% (Min)</th>
<th>Mean</th>
<th>95%</th>
<th>97.5%</th>
<th>99.5%</th>
<th>100% (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Freight Car</td>
<td>-82.7</td>
<td>4.9</td>
<td>19.6</td>
<td>23.1</td>
<td>30.7</td>
<td>99.6</td>
</tr>
<tr>
<td>Loaded Freight Car</td>
<td>-88.0</td>
<td>12.0</td>
<td>44.9</td>
<td>53.8</td>
<td>70.7</td>
<td>149.0</td>
</tr>
<tr>
<td>Intermodal Freight Car</td>
<td>-58.0</td>
<td>8.5</td>
<td>27.6</td>
<td>32.9</td>
<td>44.9</td>
<td>101.4</td>
</tr>
<tr>
<td>Freight Locomotive</td>
<td>-88.9</td>
<td>17.3</td>
<td>59.2</td>
<td>69.4</td>
<td>91.2</td>
<td>153.0</td>
</tr>
</tbody>
</table>

Table 4. Distribution of Lateral/Vertical Load Ratios

<table>
<thead>
<tr>
<th>Car Type</th>
<th>0% (Min)</th>
<th>Mean</th>
<th>95%</th>
<th>97.5%</th>
<th>99.5%</th>
<th>100% (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Freight Car</td>
<td>-4.0</td>
<td>0.15</td>
<td>0.44</td>
<td>0.50</td>
<td>0.64</td>
<td>3.23</td>
</tr>
<tr>
<td>Loaded Freight Car</td>
<td>-0.76</td>
<td>0.11</td>
<td>0.35</td>
<td>0.41</td>
<td>0.52</td>
<td>1.46</td>
</tr>
<tr>
<td>Intermodal Freight Car</td>
<td>-1.25</td>
<td>0.12</td>
<td>0.39</td>
<td>0.46</td>
<td>0.59A</td>
<td>1.61</td>
</tr>
<tr>
<td>Freight Locomotive</td>
<td>-0.56</td>
<td>0.11</td>
<td>0.38</td>
<td>0.44</td>
<td>0.56</td>
<td>0.81</td>
</tr>
</tbody>
</table>

**Degree of Curvature**

The degree of curvature likely impacts the magnitude of lateral load. In order to examine the effect of curvature, cars have been classified according to their type. For empty cars, the change in lateral load is negligible as degree of curvature increases (Figure 4). This is likely due to the relatively low weight of empty cars. The weight of an empty car does vary but this variation is small when compared to other car types. For other car types, there is a general increase in lateral load with increasing degree of curvature, but there are inconsistencies as can be seen in Figure 5. Three to four degree curves tend to have the lowest lateral loads, but lateral wheel loads in four to five degree curves do not differ much from five to six degree curves. Based on this information, degree of curvature alone cannot be used as a predictor of lateral wheel load magnitude. In order to predict these loads other sources of variation need to be considered.
Train Speed
As the speed of train traffic increases, it is expected that the lateral loads on the high rail will increase, while the lateral load on the low rail will decrease. Therefore, the analysis will be divided into a discussion of the low rail and the high rail. The balanced speed for a curve is the speed at which the force on the low and high rail are equal. This balanced speed depends on the degree of curvature and the amount of superelevation in the curve. At speeds below the balanced speed more force will be imparted to the low rail, while at speeds above the balanced speed more force will be imparted to the high rail.

Figure 6 depicts the lateral wheel loads measured on the high rail at TPD sites, while Figure 7 depicts the loads measured on the low rail. The data were classified according to the car types described previously. The linear trend lines for each car type provide an estimation of lateral wheel loads as speed increases, and show the general relationship for predicting load magnitude. For lateral wheel loads on the high rail, there is only a minimal increase in load as speed increases.
while on the low rail, loads slightly decrease with speed. However, due to the magnitude of this increase and decrease, and the overall variability of the loading environment, this decrease is likely not significant enough to provide a strong prediction of lateral wheel load magnitude.

**Cant Deficiency**

Cant deficiency combines the effects of degree of curvature, speed, and superelevation. It is a measure of the difference between equilibrium superelevation and actual superelevation of a curve. Equilibrium superelevation refers to the amount of superelevation that would cause a train with a given speed to be at balanced speed. A negative cant deficiency means that there is more cant than is required for the train to operate at balanced speed, while a positive cant deficiency means that additional superelevation is required. The equation to calculate cant deficiency is as follows:

![Figure 6: Lateral Load Variation With Speed: High Rail](image1)

![Figure 7: Lateral Load Variation With Speed: Low Rail](image2)
\[ h_d = \frac{2b_0}{g} \left( \frac{v^2}{1746.40/D} \right) \cdot h_t \]

where, \( h_d \) = cant deficiency (mm)
\( 2b_0 \) = distance between contact patches on a wheel set (assumed to be 1,500 mm)
\( g \) = acceleration due to gravity (9.81 m/s²)
\( v \) = vehicle speed (m/s)
\( D \) = degree of curvature
\( h_t \) = actual superelevation of curve (mm)

Cant deficiency combines the factors that are believed to provide the most significant contribution to lateral wheel load magnitude into one variable. This variable will allow the variation from multiple factors to be described with a single metric.

Figure 8 and Figure 9 depict the relationship between amount of cant deficiency and lateral load. A linear relationship has again been plotted in order to examine the relationship between lateral wheel loads and cant deficiency. For the high rail, there is a minimal increase in lateral loads as cant deficiency increases. For the low rail, there is a slight decrease in lateral loads as cant deficiency increases. Both of these trends are what would be expected, however the magnitude of the increase or decrease is quite small. Additionally, since the range of loading is quite wide, cant deficiency is not a good predictor of lateral wheel load. The fact that this variation is negligible even considering all other primary factors suggests that car weight is the primary cause of variation in lateral wheel loading.
High Rail Versus Low Rail
Another possible source of lateral load variation is whether the wheel is imparting load into the high rail or low rail. As a train travels through a curve above the balanced speed it imparts forces on the high rail due to centrifugal force and on the low rail due to centripetal force. At speeds less than the balanced speed centripetal force governs, while at speeds greater than the balance speed centrifugal force will govern. In order to examine this variation, TPD data were divided into two categories based on whether the car was operating above or below the balanced speed. Each distribution has been further divided into high and low rail categories in order to examine the effect on each rail independently. As seen in Figure 10, the data collected from TPD sites supports this initial hypothesis. For traffic that is below the balanced speed of a curve, the high rail tends to have a lower lateral force than the low rail. However, when the speed of traffic is above the balanced speed, the high rail bears the majority of the load. This finding further illustrates why certain types of damage is seen in the field, and leads to an ability to predict where wear and deteriorate can occur as a function of speed of traffic. Once the balanced speed and speed of traffic is known, it can be predicted which rail will experience higher loading, which can result in increased rail wear.

Leading Versus Trailing Axles
An additional factor that has the potential to affect lateral wheel load is whether a wheel is on a leading or trailing axle. A leading axle is the first axle on each train car, while a trailing axle is the remainder of the axles. Leading axles tend to impart higher lateral wheel loads than trailing axles. This is due to the car truck not being aligned for the curve, so when the first axle hits the curve, a more severe force is generated. The axles following the first axle will hit the curve at a less severe angle, since the truck will already be turning and aligned to the curve. The truck performance data collected was filtered to exclude the trailing axles, in order to compare the magnitude of the wheel loads. Figure 11 contains lateral wheel loads for unloaded freight cars and loaded freight cars. Leading axles for both unloaded and loaded freight cars consistently imparted higher lateral loads than the distribution containing all wheel loads.

It was theorized that by only including leading axles, factors that showed little effect on lateral wheel load magnitude with all wheels might show a stronger relationship with the leading axle distribution. Figure 12 contains the magnitude of lateral wheel loads for the leading axles of loaded freight cars with varied degree of curvature. While the all axle distribution discussed in Figure 5 showed an inconsistent change as degree of curvature increased, the leading axles show that as degree of curvature increased, lateral wheel load increased. By only using the leading axles of cars, it might be possible to use the variety of factors discussed in this paper to more accurately and precisely predict lateral wheel loads. These loads will tend to be the highest loads, which will be the most critical when considering the design of the crosstie and fastening system.
CONCLUSIONS
Based on the TPD data collected and analyzed, it has been found that the most significant predictor of lateral wheel load is car weight. The magnitude of the vertical wheel load has a large effect on the typical magnitude of lateral wheel load. Since each type of car has a different average weight, the resultant lateral forces are also different.

97.5% of loaded freight cars have 133% higher lateral wheel loads than unloaded freight cars. Also, loaded freight cars have 64% higher lateral wheel loads than intermodal freight cars. Freight locomotives have 29% higher lateral wheel loads than unloaded freight cars.
loads than loaded freight cars, primarily due to the poor curving characteristics of locomotives. Other factors evaluated have some effect on lateral load, but their effects are quite small compared to car type. Based on the amount of variation experienced, it appears that solely using car type to predict design loads is a viable option. For example, if a designer was using the 97.5% threshold for the input load, the input lateral wheel loads would range from 23.1 kN (5.2 kips) for an unloaded freight car to 91.2 kN (20.5 kips) for a freight locomotive. The design of the system would depend on the type of traffic expected and the relevant wheel loads for the respective vehicles. Table 5 could be used alongside the vertical wheel loads developed in previous research by UIUC to determine the demands on the system to create an appropriate design for the concrete crosstie and fastening system and its components. These loads could also be used for maintenance purposes, to predict where severe lateral loads are more likely to occur, and prioritize those areas for maintenance procedures.

Another factor that was found to impact lateral wheel loads was leading versus trailing axles. Leading axles tend to impart higher lateral loads than the rest of the wheels, and also are more consistently affected by factors such as degree of curvature. By using this information, a more accurate lateral wheel loads prediction could be developed.

In the future, data will be collected from curves with higher degree of curvature. The degree of curvature studied in this report only reached up to 6 degrees, which is not the maximum for mainline track in the US. It is possible that more severe curves could cause lateral loads to increase, and change the way lateral wheel loads should be estimated. Additionally, TPD data from passenger trains will be measured and added to the lateral loading table for use as input loads for design. Further analysis that only includes leading axles will be conducted, examining the same factors discussed in this paper to determine whether this can provide a better prediction of lateral wheel load for use in design.

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