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Quantifying Lateral Wheel Loading Variation Using Truck Performance Detectors

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ABSTRACT

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 geographic location 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 (*1*). 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 (*2*). 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.

METHODS FOR QUANTIFYING LATERAL LOADS

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 (*3*). The degree of curvature for the reverse curve is not standardized, so the superelevation can 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. TPDs allow for large amount of data to be collected in a short amount of time due to the fact that most installations are on high density corridors with multiple train types.

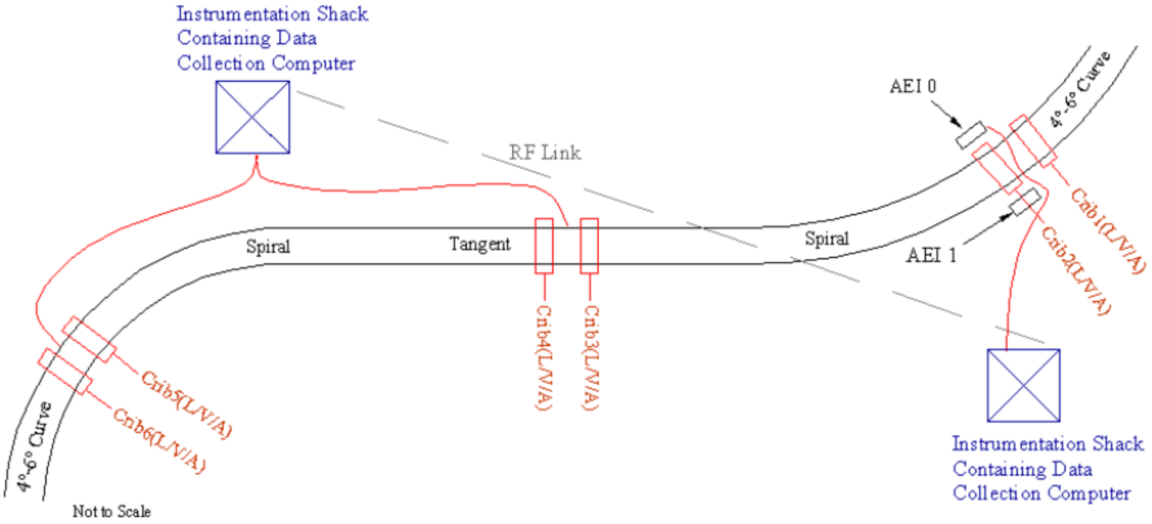

FIGURE 1 Typical layout of Truck Performance Detector (TPD) site.

SOURCES OF LOAD VARIATION

Lateral wheel loads that are imparted into the track may vary due to a variety of factors including car type, speed of the vehicle, curvature, low rail versus high rail, geographic location, and superelevation. While it is not easy to control these sources of variability, TPDs facilitate the quantification and evaluation of variation.

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 2 TPD locations selected for further evaluation.

TABLE 1 TPD Site Information

Location	Curvature		Superelevation (in)*	
	Curve 1	Curve 2	Curve 1	Curve 2
Argyle 1, IA	4° 5’	3° 4’	3.63	3.39
Argyle 2, IA	4° 5’	3° 4’	3.63	3.39
Elmira, ID	4° 23’	4° 9’	3.63	3.63
Joppa, MT	4° 30’	3° 36’	2.06	1.25
Ludlow 1, CA	4° 5’	4° 6’	3.63	3.63
Ludlow 2, CA	4° 7’	4° 19’	3.63	3.63
Ludlow, CO	5° 0’	6° 0’	2.77	3.72
Pomona, MO	3° 55’	4° 10’	3.48	3.12

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

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. 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 (*6*). 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**.

TABLE 2 Distribution of Static Vertical Wheel Loads (*6*)

	Nominal Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	6.6	9.6	11.0	13.6	15.0
Loaded Freight Car	33.4	39.5	40.2	41.4	45.5
Intermodal Freight Car	20.5	35.3	36.8	39.8	50.6
Freight Locomotive	33.6	36.6	37.2	38.5	43.5

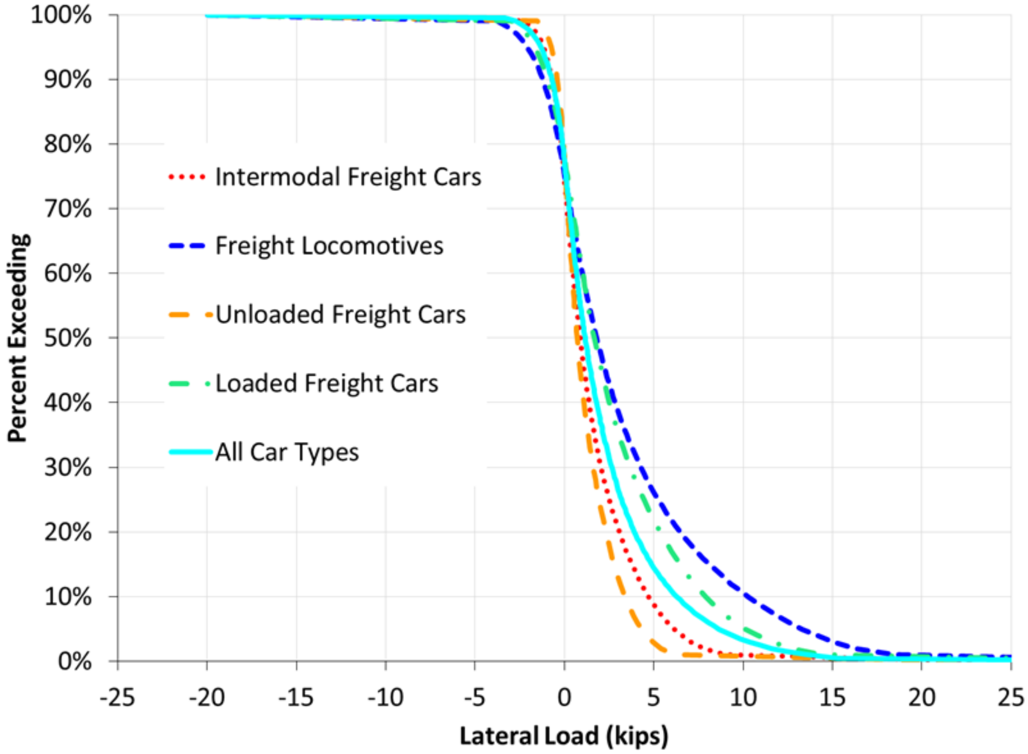

FIGURE 3 Lateral load variation with car type.

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. Instability of the rail can start to occur at L/V ratios of 0.68, at 1.29 rollover is nearly assured (*5*). 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 3 Distribution of Peak Lateral Wheel Loads

	Lateral Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	1.1	4.4	5.2	6.9	22.4
Loaded Freight Car	2.7	10.1	12.1	15.9	33.5
Intermodal Freight Car	1.9	6.2	7.4	10.1	22.8
Freight Locomotive	3.9	13.3	15.6	20.5	34.4

TABLE 4 Distribution of Lateral/Vertical Load Ratios.

	L/V				
Car Type	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	0.15	0.44	0.50	0.64	4.00
Loaded Freight Car	0.11	0.35	0.41	0.52	1.46
Intermodal Freight Car	0.12	0.39	0.46	0.59	1.61
Freight Locomotive	0.11	0.38	0.44	0.56	0.81

Degree of Curvature

The degree of curvature likely impacts the magnitude of lateral load (*2*). 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.

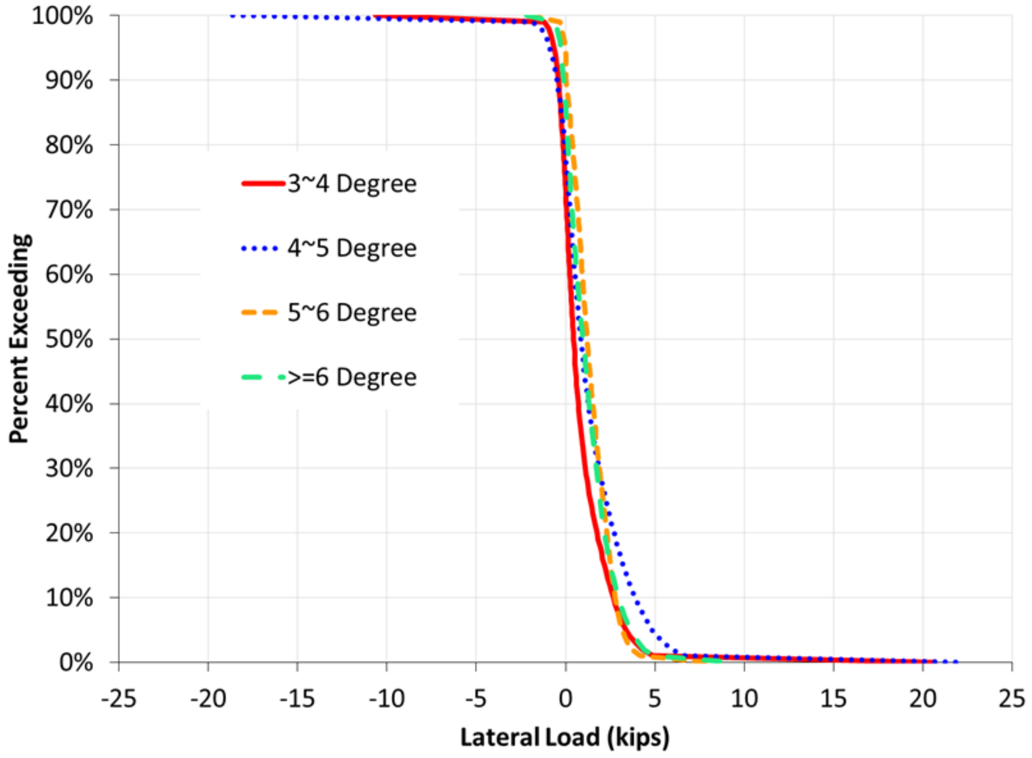

FIGURE 4 Lateral load variation with degree of curvature: unloaded freight cars.

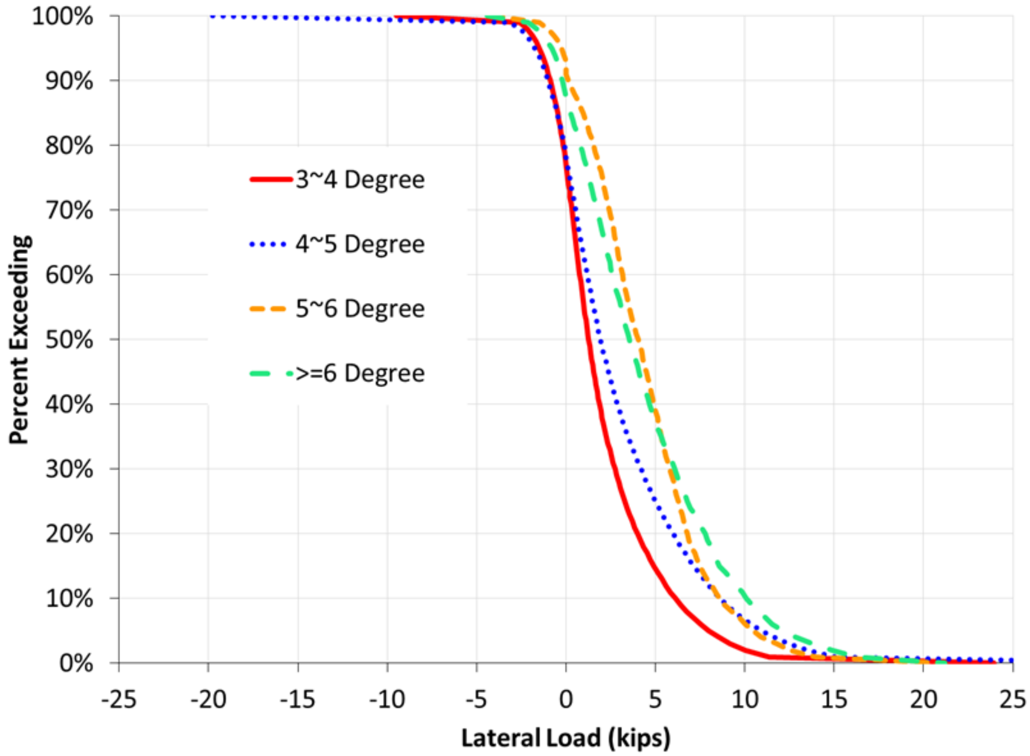

FIGURE 5 Lateral load variation with degree of curvature: loaded freight cars.

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 (*4*).

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.

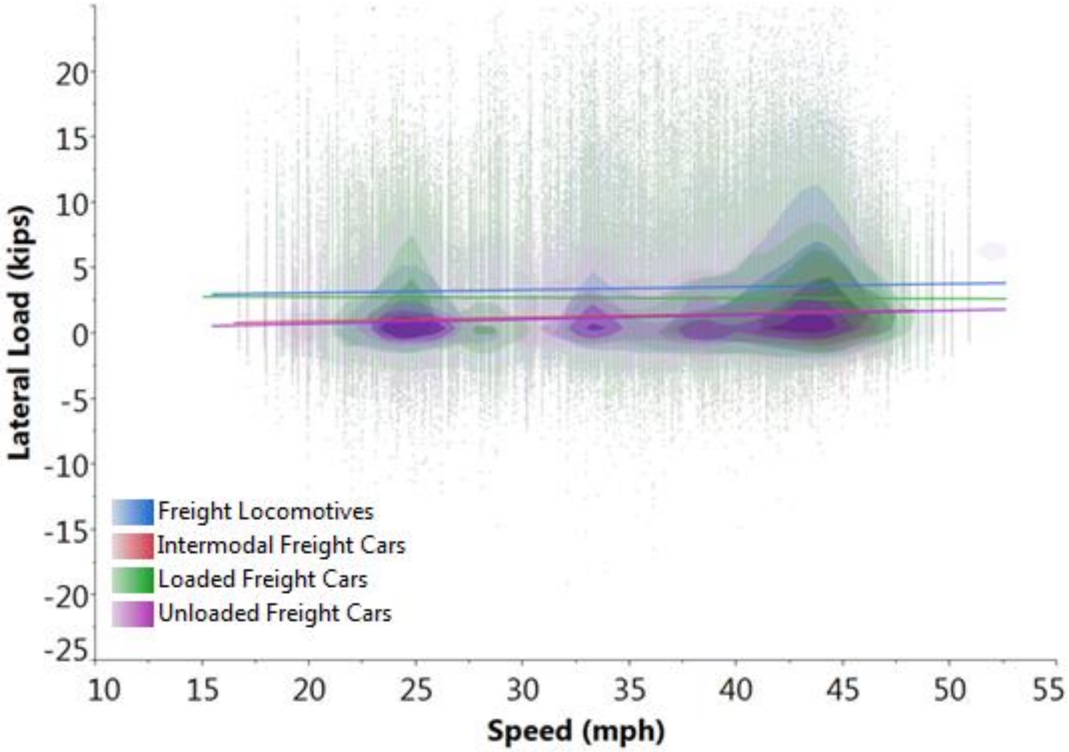

FIGURE 6 Lateral load variation with speed: high rail.

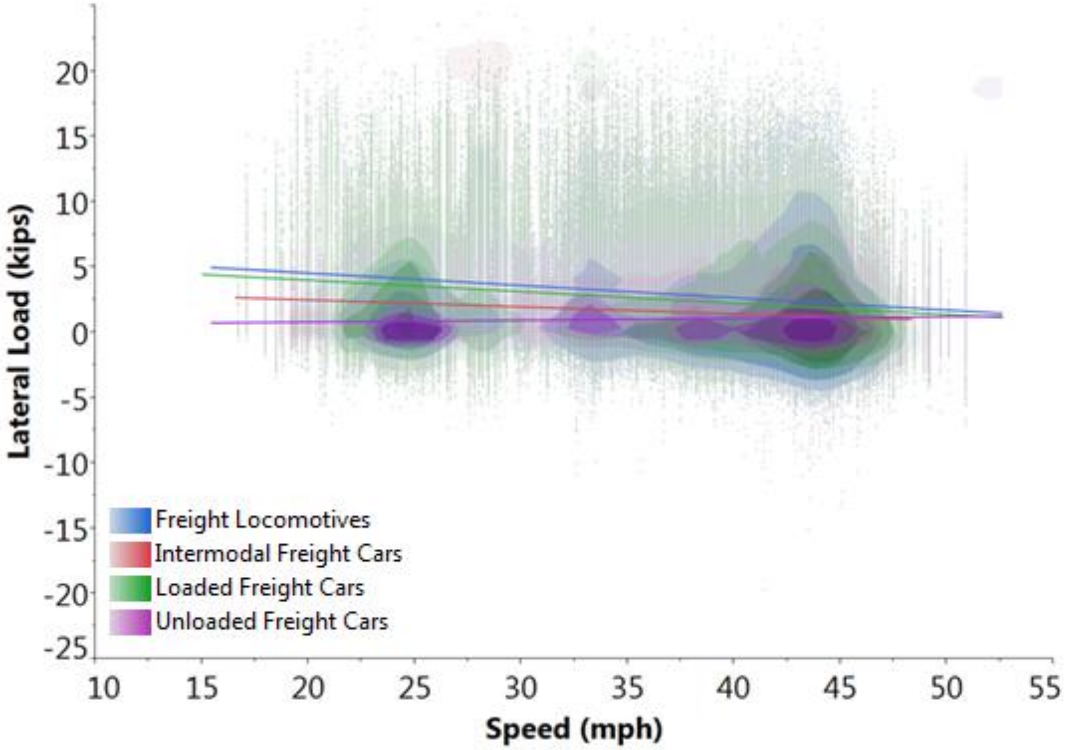

FIGURE 7 Lateral load variation with speed: low rail.

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 (*7*). 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:

$$h_d=\frac{2b_0}{g}\left(\frac{v^2}{1746.40/D}\right)-h_t$$

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/s^2)
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. 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.

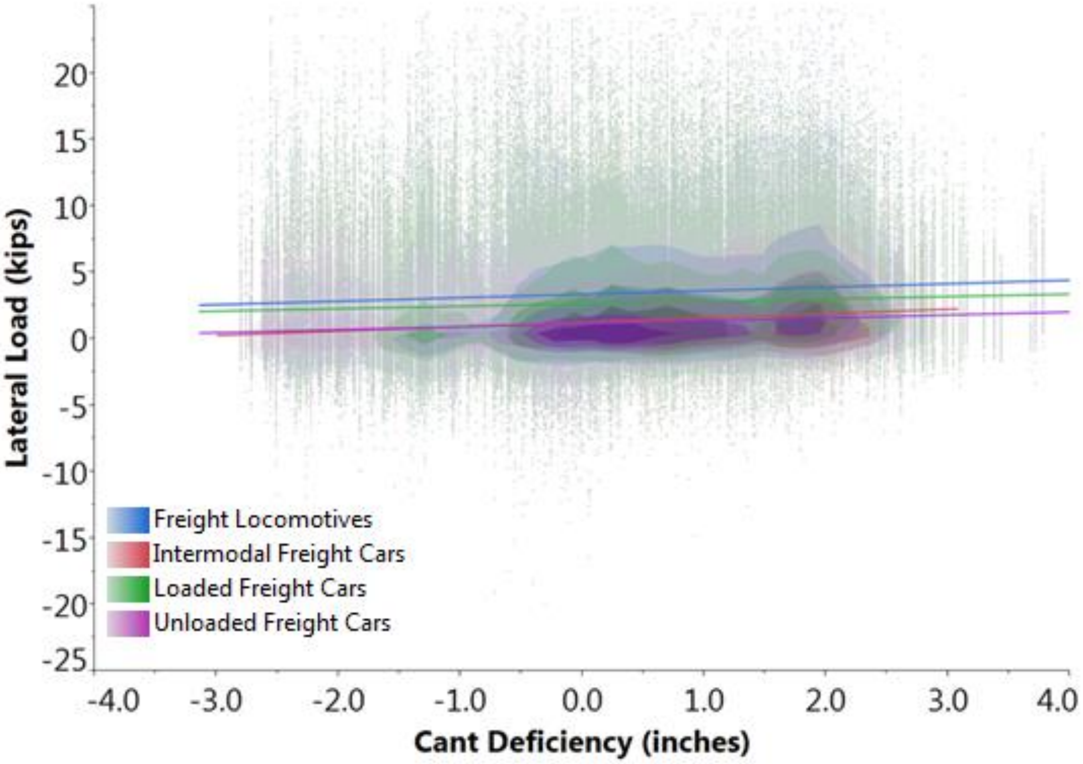

FIGURE 8 Lateral load variation with cant deficiency: high rail.

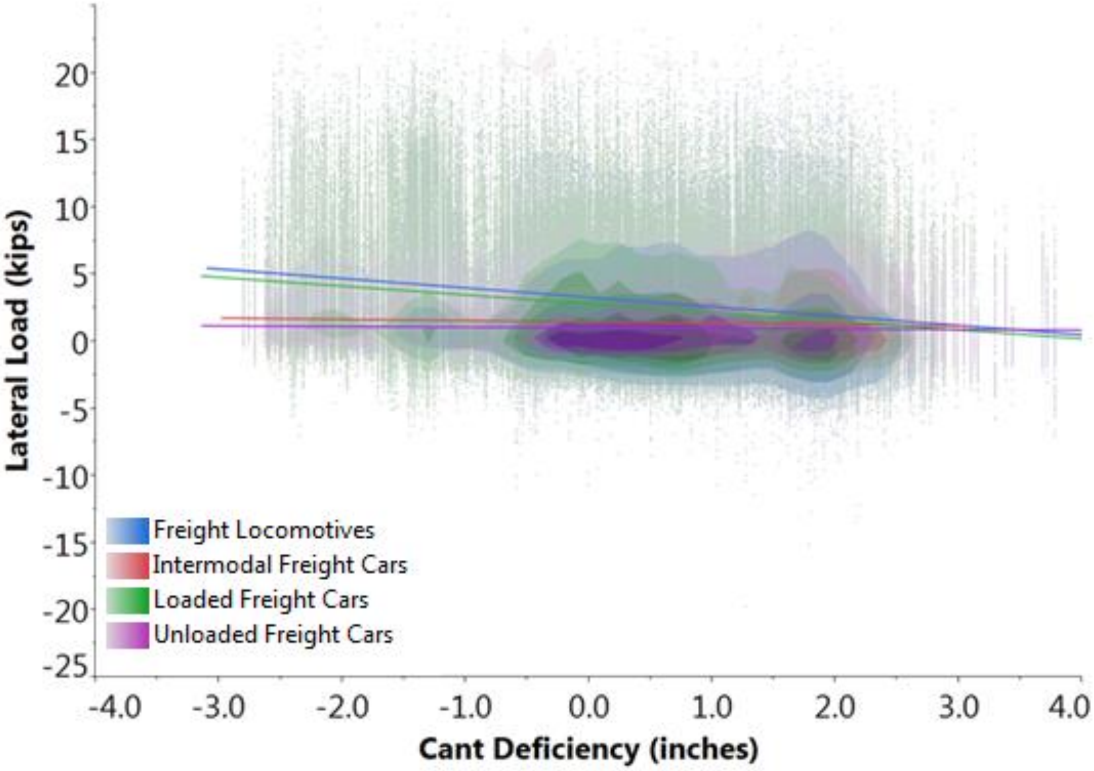

FIGURE 9 Lateral load variation with cant deficiency: low rail.

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 (*4*). 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.

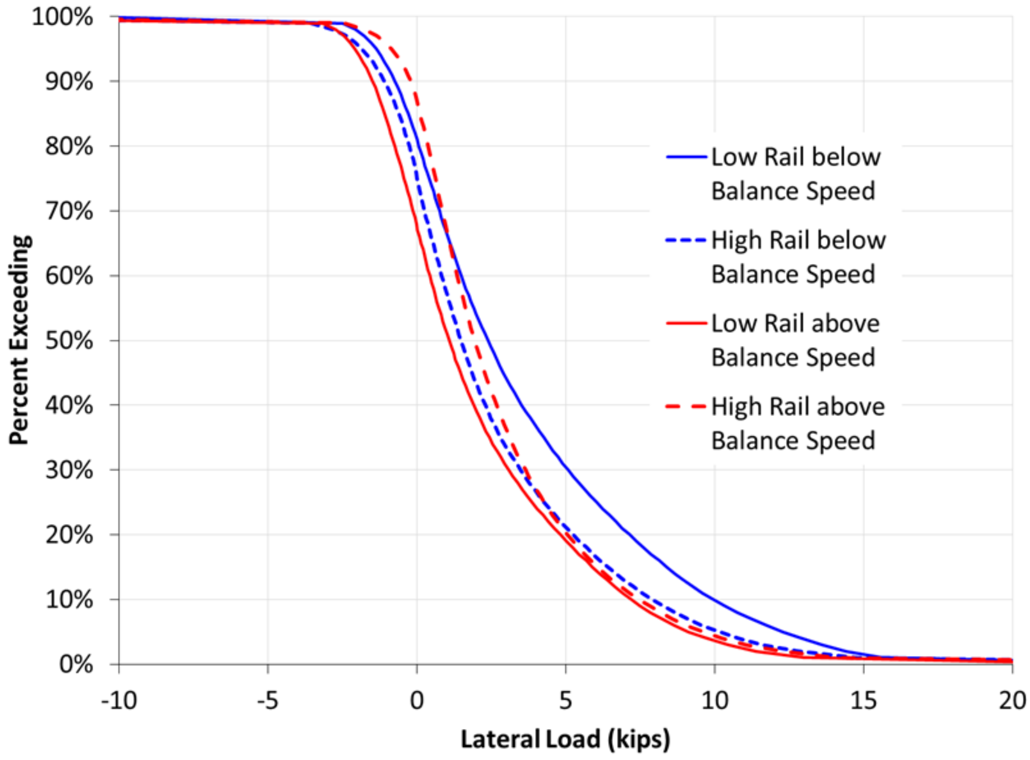

FIGURE 10 Low and high rail loading above and below balance speed.

Site Location

Due to traffic characteristics (i.e. variability in car type), TPD locations with approximately the same curve characteristics can have different lateral wheel load distributions. In **Figure 12**, all TPD locations with 3.6 to 4.5 degree curves have been plotted on the same axes to examine the differences in the distributions. The highest lateral loads tend to occur at Ludlow, CA, Main Track 1, while the lowest occur at Argyle_2. The distributions differ significantly, even within a specific car type. A possible cause of this variation is variability in the weight of cars within each category. A loaded freight car's vertical wheel load can range from 27,500 lb. to 39,375 lb. This weight significantly affects the lateral wheel load, as discussed earlier. Given the degree of variability identified, cars should be classified into categories with additional specificity to aid in predicting lateral wheel load variability.

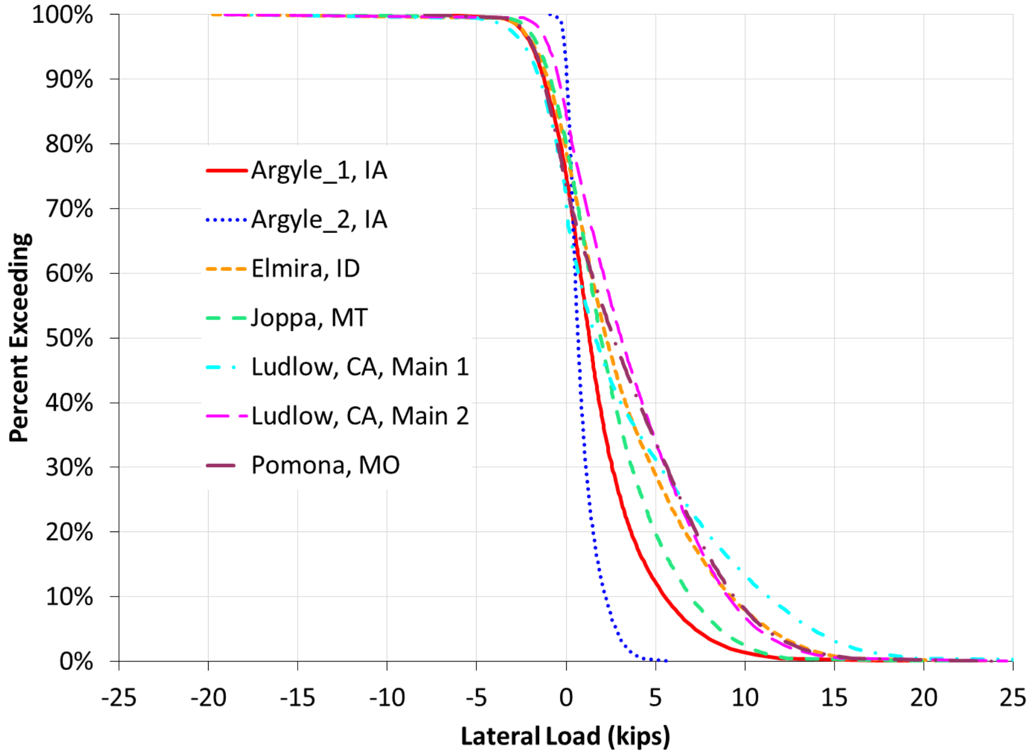

FIGURE 11 Lateral load variation with location: loaded freight cars.

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 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 5.2 kips for an unloaded freight car to 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 (*6*). 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.

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.

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