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Load Characterization Techniques and Overview of Loading Environment in North America

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ABSTRACT

In North America, many design guidelines for track components in shared-use railway infrastructure use historical wheel loads that may not necessarily be representative of those seen on rail networks today. Without a clear understanding of the nature of these loads, it is impossible to adequately evaluate the superstructure to make design improvements. Therefore, researchers at the University of Illinois at Urbana-Champaign (UIUC) are conducting research to lay the groundwork for an improved and thorough understanding of the loading environment entering the track structure. Wheel impact load detectors (WILDs) have been used in North America for decades to identify bad-acting wheels that could damage the rail infrastructure or result in a rolling stock failure. Information regarding loads obtained from the WILD can be used to identify trends that not only provide a clearer picture of the existing loading environment created by widely varied traffic characteristics, but can be used in future design and maintenance planning of infrastructure according to the anticipated traffic. This paper will discuss the current trends in wheel loads across the North American rail network while investigating the effects of speed and other sources of load variability. In addition to WILD data, instrumented wheel set (IWS) data have also been used to gain insight into loading conditions, and preliminary analyses of these data are included. Ultimately this work will lead to useful distinctions of loads for improved design methodologies that are specific to the intended type of traffic traversing a given route or network.

INTRODUCTION

Elements of the track superstructure in North America have historically been designed through a process that is generally based on practical experience, without a complete understanding of the loading environment causing particular failure mechanisms *(1)*. Improvements in the design process for track superstructure components may result in a more robust track structure if the loading environment can be adequately characterized.

The North American operating environment differs from that found throughout much of the rest of the world due to the prominence of heavy axle load rail freight transportation and shared infrastructure between heavy axle load freight and intercity passenger rail traffic. One of the challenges created by this operating environment is the design of critical infrastructure components under a widely varied loading spectrum.

To best determine how to describe the loads entering the track structure, one must explore possible causes of variation. This paper will use data, primarily from wheel impact load detectors (WILD), to identify sources of variation in the loading regime entering the track structure and test several hypotheses aimed at understanding trends between some of the most critical parameters. These hypotheses are that (a) the static load is the most reliable indicator of wheel load, (b) increased speed causes increased wheel loads, (c) conditions prevalent in the winter months result in higher wheel loads, and (d) site-based traffic composition has a significant influence on the distribution of loads at the wheel-rail interface. Instrumented wheel set (IWS) data will be used to explore the effect of curvature and cant deficiency on wheel load magnitudes. More thorough understanding of these relationships will lead to improved design effectiveness of critical infrastructure components.

METHODOLOGIES AND MEASUREMENT TECHNOLOGIES

There are several load quantification technologies, systems, and instrumentation strategies available to the rail industry for quantifying the performance of vehicles and track. Specifically, instrumented wheel sets (IWS) and wheel impact load detectors (WILD) monitor forces at the wheel-rail interface. These systems are used to monitor rolling stock performance and assess wheel and vehicle health, producing efficiencies in both predictive and reactive maintenance strategies. However, they can also be used by railway infrastructure engineers to provide insight into the magnitude and distribution of loads entering the track structure. A clear understanding of this loading spectrum provides a foundation for the analysis and design of critical infrastructure components.

Instrumented Wheel Set

The IWS is a wheel set that is instrumented with strain gauges on the axle and wheel. It can be deployed on any type of vehicle and provides information related to vertical, lateral, and tangential forces created by the wheel set, as well as the contact patch location on the head of the rail. The IWS measures numerous data channels at high frequencies (300 Hz) which, through the use of GPS referencing, can be combined with other measured and recorded track data (e.g. track geometry, curvature, grade, type of track structure, track stiffness). While the IWS data is primarily used to evaluate rolling stock component and system performance, it can also be used to determine that magnitude of the forces being imparted to the track. In the future, UIUC will further utilize IWS data from the Association of American Railroads (AAR) and TTX Company to provide insight into the effects of these track parameters on forces experienced at the wheel-rail interface.

Wheel Impact Load Detector

A WILD consists of strain gauges mounted on the rail over a series of cribs that measure vertical rail deflection to calculate wheel loads. The WILD site is over 50 feet in length, with crossties instrumented at various intervals to capture a single wheel's rotation five times, recording peak (impact) forces and average forces *(2)* by collecting data at 25 kHz. Using an algorithm that analyzes variability along the site, these average, or nominal, forces are filtered from the peak loads to obtain an estimate of static wheel load. The peak wheel load is simply the highest recorded measurement from the strain gauges along the length of the detector. While the WILD has traditionally been used by infrastructure and rolling stock owners to detect and identify poorly-performing wheels, it has also been proven to be a practical mechanism for producing reliable wheel load data, according to a study performed by the AAR in which they reviewed the variation of measurements produced by the detector *(3)*.

WILD sites are constructed on tangent track with concrete crossties, typically with premium ballast, and well-compacted subgrade (possibly with hot mix asphalt underlayment) to reduce sources of load variation within the track structure due to track geometry and support condition irregularities. Although loads experienced in other locations on the network may have higher magnitudes due to track geometry and support deviations, these data still provide representative loading information for networks throughout North America *(4)*.

Because WILDs are implemented to detect poorly-performing wheels and are, therefore, only located on tangent track where lateral to vertical load ratios (L/V) are typically much lower, the information regarding lateral loads may not be as useful as compared to data collected on curved track. Therefore, much of the analysis shown in this paper is derived from vertical loading data. Other measurement technologies may be useful for gathering loading data related to additional objectives. It is the intent of the UIUC research team to further develop our understanding of lateral loads through the use of other technologies, such as the IWS and Truck Performance Detector (TPD).

SHARED USE LOADING ENVIRONMENT IN NORTH AMERICA

The railroad operating and loading environment in North America is increasingly made up of shared corridors as expanded and improved passenger rail service is added to the existing freight network. Changes in freight railroad infrastructure, rolling stock, and operating practices involving the accommodation of passenger service have introduced many challenges *(5)*. One of these challenges is the design and performance of critical infrastructure components. Because of the diverse nature of the wheel loads and speeds on shared-use infrastructure, designing components within the track structure requires significant analysis. Most design decisions cannot be made without gaining a quantitative understanding of the entire load spectrum. Recent industry trends show an improving trend in terms of less severe wheel loads, but a more thorough analysis will provide additional insight into the nature of these loads (unpublished data; Mike Brown). To better understand the loads applied to the infrastructure, UIUC has acquired WILD data from Amtrak's Northeast Corridor (a shared corridor in operation for many decades) and the Union Pacific Railroad (UPRR) (Figure 1). Figure 2 illustrates how loads can vary on shared use infrastructure, even within particular vehicle types.

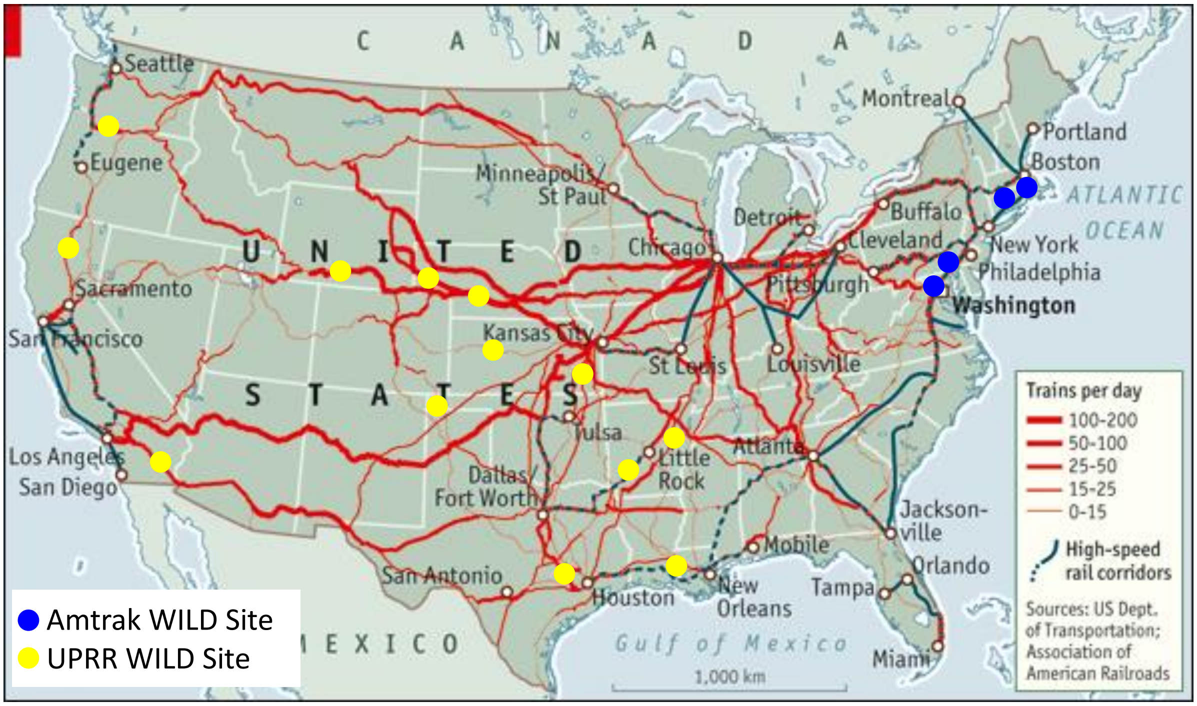


FIGURE 1 WILD data provided to UIUC by Amtrak and UPRR.

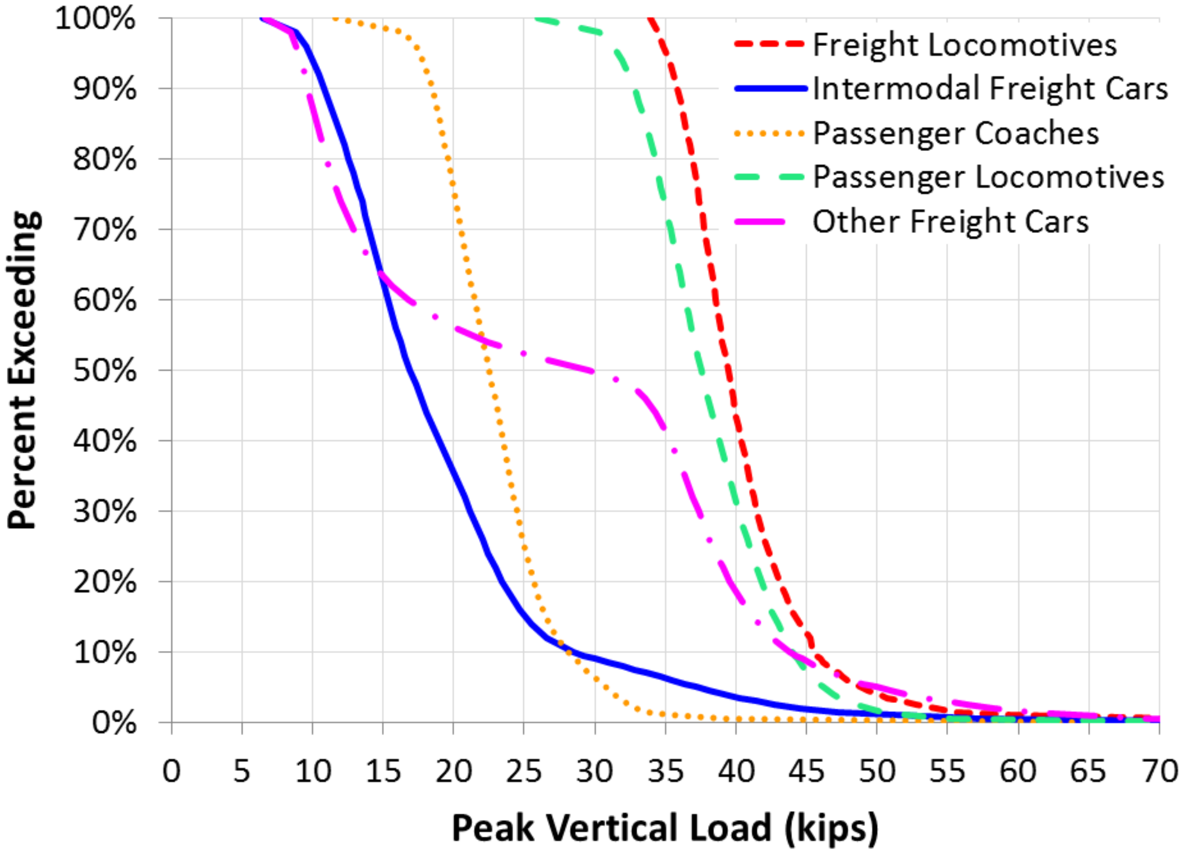


FIGURE 2 Percent exceeding particular peak vertical loads on Amtrak at Edgewood, Maryland (WILD data from November 2010) (1 kip = 4.45 kN).

Tables 1 and 2 provide tabular depictions of the static and peak load spectrums that represent the diverse rolling stock composition in North America. For the purposes of this summary and any following figures that reference them, "unloaded freight cars" include any non-intermodal freight car whose nominal wheel load is 15 kips or less.

Some statistical testing was performed to determine if one month was representative of the entire population of wheel loading. A series of Kolmogorov-Smirnov tests were performed to compare wheel load data from multiple months. When the entire data set was used (greater than 140,000 wheels per month), there was a statistically significant difference in months because the sample size effectively captured the entire population. When the sample size was reduced to about 2,000 random wheels per month (which still provided an adequate representation of the data), the month-to-month variation was not statistically significant. Therefore, one month's worth of data can be used to make broader generalizations of the wheel load data.

TABLE 1 Distribution of Static Wheel Loads (1 kip = 4.45 kN) (Freight data: UPRR; Gothenburg, Nebraska; January 2010. Passenger data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010.)

	Nominal Load (kips)								
Car Type	Mean	10%	50%	75%	90%	95%	97.5%	99.5%	100%
Unloaded Freight Car	6.6	5.2	6.2	7.2	8.5	9.6	11.0	13.6	15.0
Loaded Freight Car	33.4	24.3	34.8	37.1	38.7	39.5	40.2	41.4	45.5
Intermodal Freight Car	20.5	10.4	18.8	26.8	32.9	35.3	36.8	39.8	50.6
Freight Locomotive	33.6	31.4	33.6	34.8	35.9	36.6	37.2	38.5	43.5
Passenger Locomotive	27.0	23.3	26.1	28.4	33.5	35.8	37.2	39.3	42.6
Passenger Coach	15.0	12.7	14.7	16.4	17.7	18.3	19.0	20.1	45.4

TABLE 2 Distribution of Peak Wheel Loads (1 kip = 4.45 kN) (Freight data: UPRR; Gothenburg, Nebraska; January 2010. Passenger data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010.)

	Peak Load (kips)								
Car Type	Mean	10%	50%	75%	90%	95%	97.5%	99.5%	100%
Unloaded Freight Car	10.8	7.4	9.2	11.2	15.8	20.5	26.4	39.7	100.8
Loaded Freight Car	42.3	32.6	42.3	45.6	49.8	56.2	65.3	84.7	156.6
Intermodal Freight Car	27.5	15.2	24.8	34.6	41.9	46.8	54.3	74.8	141.9
Freight Locomotive	42.8	36.9	41.6	45.3	50.1	53.9	57.5	68.8	109.6
Passenger Locomotive	38.1	31.1	36.7	41.5	46.4	50.0	53.6	63.4	94.0
Passenger Coach	23.2	17.5	21.7	25.0	30.2	35.3	42.9	58.5	108.8

SOURCES OF LOAD VARIATION

Wheel loads vary due to many causes, including, but not limited to, static load, speed, temperature, location, position within the train, vehicle characteristics, track geometry and quality, curvature, and grade. Because WILDs are constructed on tangent track, and they are dispersed throughout the United States, they are able to capture many of these sources of variation.

Static Wheel Load

The nominal (static) wheel load is the best indicator of the load expected to enter into the track structure and is highly dependent on the type of vehicle passing over the WILD. Vehicles with higher nominal wheel loads produce higher peak wheel loads, as shown in Figure 3. Density contours are displayed to show areas of high data concentration. The wide distribution beyond the most highly concentrated data, however, suggests that there are other factors affecting the peak load entering the track structure.

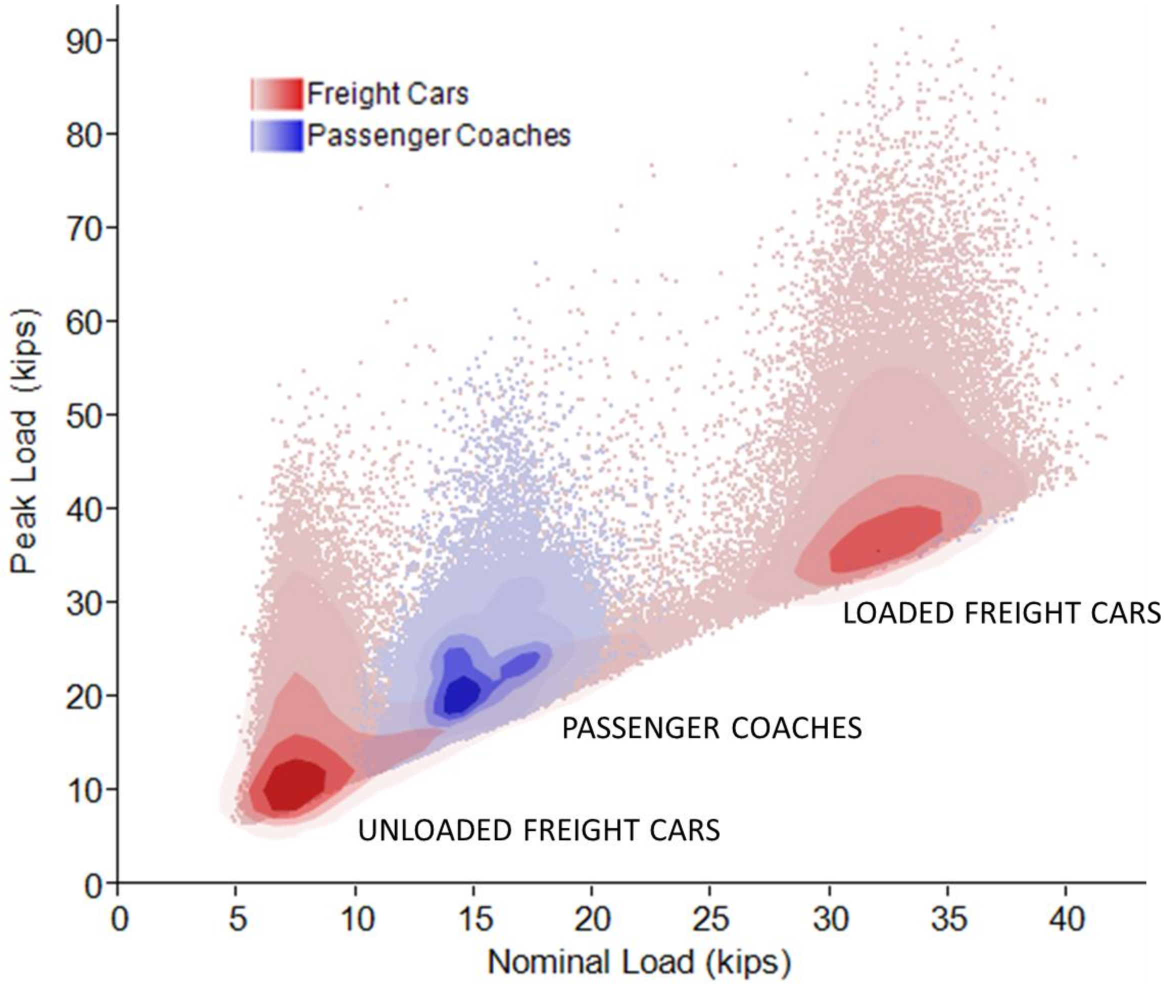
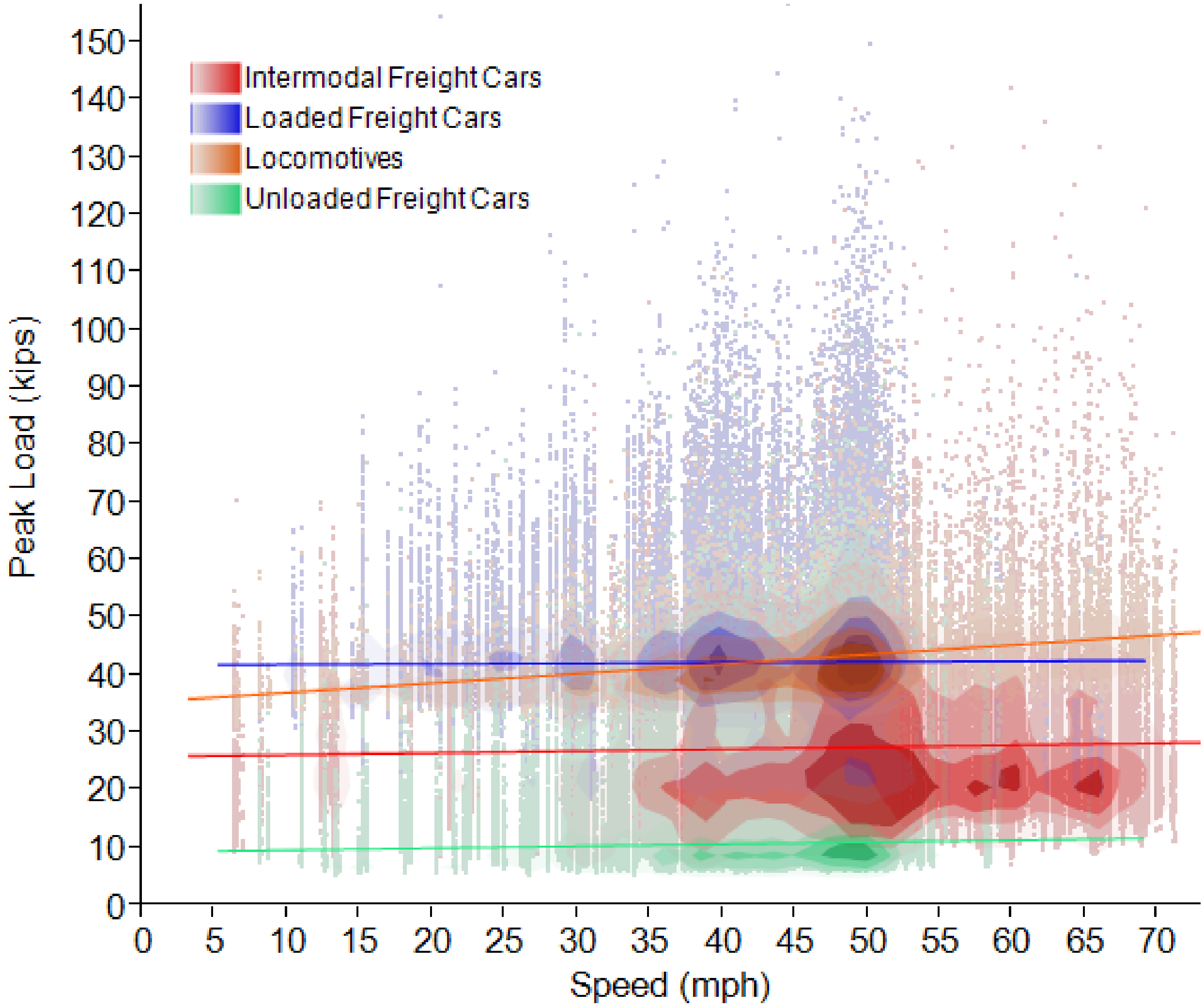


FIGURE 3 Effect of car type on peak load on Amtrak at Edgewood, Maryland (WILD data from November 2010) (1 kip = 4.45 kN).

Speed

Field observations suggest that loads at the wheel-rail interface produced by moving loads are greater than those produced by the same wheel loads at rest *(6)*. Specifically, dynamic loads can be produced by roll, slip, lurch, shock, buff, torque, load transfer, vibration, and unequal distribution of lading within the rolling stock *(7)*. Generally, dynamic and impact forces can be caused by imperfections in the moving vehicles (as listed above), track geometry irregularities, and variations in track stiffness *(6)*. However, the relationship between speed and total vertical load is not easily quantified or characterized. As shown in Figure 4, the majority of the peak vertical wheel loads exhibit minimal increases with increased speed. Figure 5 shows a similar relationship with much higher maximum speeds. This increase may simply be due to dynamic interaction between the naturally-oscillating vehicles and the track *(8)*.



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180 **FIGURE 4 Effect of speed on peak load on UPRR at Gothenburg, Nebraska**
181 **(WILD data from January 2010) (1 kip = 4.45 kN, 1 mph = 1.609 kph).**

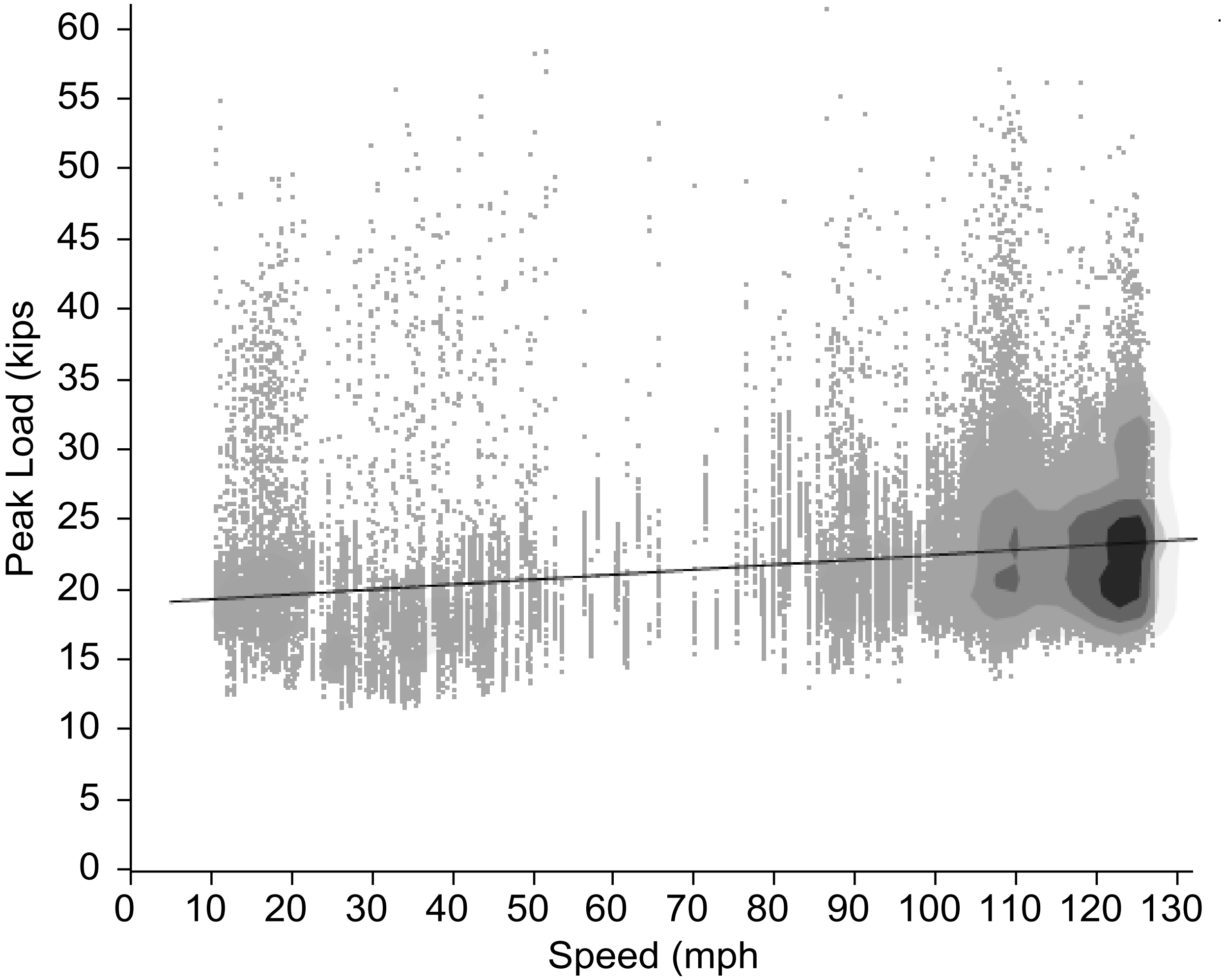

FIGURE 5 Effect of speed on peak load on Amtrak at Edgewood, Maryland (Passenger WILD data from November 2010) (1 kip = 4.45 kN, 1 mph = 1.609 kph).

WILD Site Location

The location of the WILD site provides another very significant source of variation in loads. Each site sees different distributions of car types and operating speeds. These varied traffic characteristics often produce widely varied loads at the wheel-rail interface. To illustrate this, Figure 6 compares non-intermodal freight traffic at Martin Bay, NE (where 99% of all wheels exceed 30 kips) with that at Elton, LA (where only 48% of all wheels exceed 30 kips). Figure 6 also illustrates the different load magnitudes associated with loaded and unloaded freight cars, indicated by the steepest portions of the Elton curve. It appears as if only loaded freight cars pass the Martin Bay WILD, causing significant deviation from a distribution that includes unloaded cars as well.

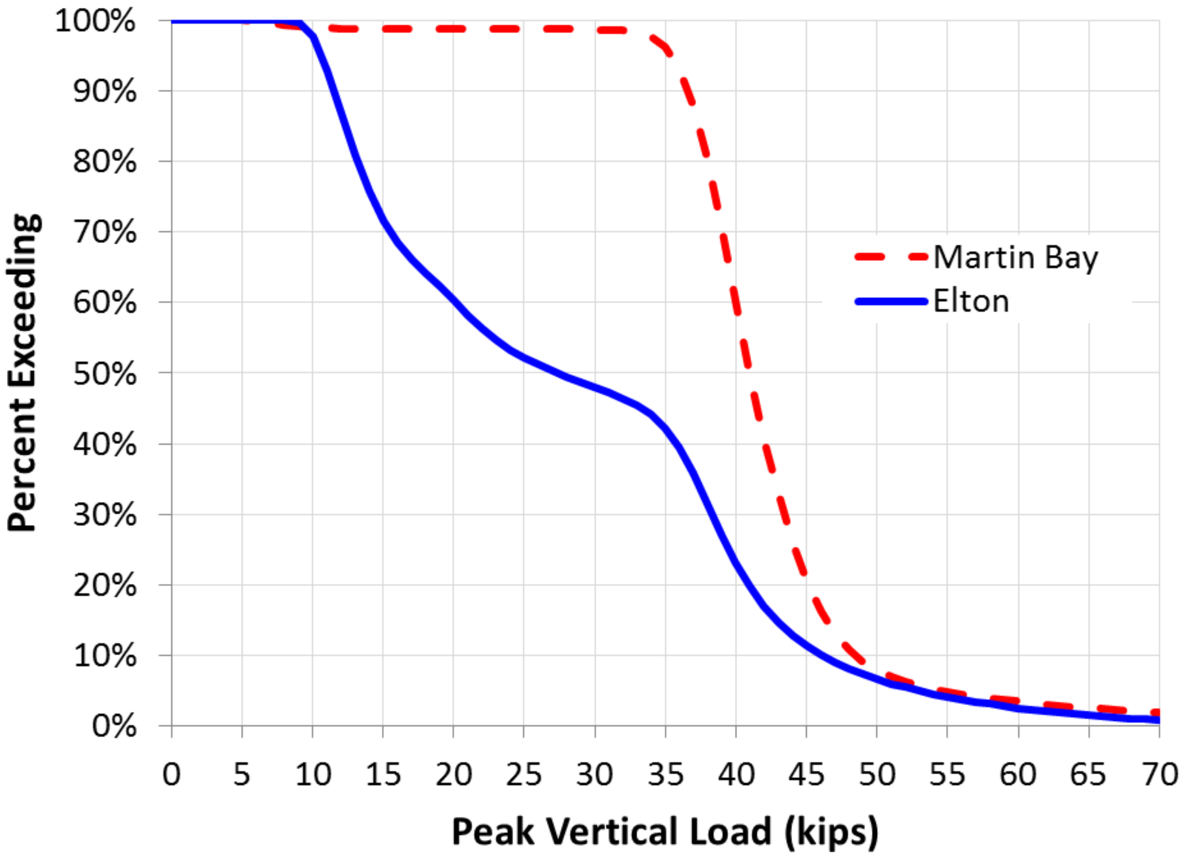

FIGURE 6 Variation of peak vertical loads between Martin Bay, Nebraska and Elton, Louisiana (non-intermodal freight car WILD data from January 2010) (1 kip = 4.45 kN).

The variation depicted in Figure 6 is to be expected, as these two WILD sites are in different regions of the country and have vastly different traffic compositions. However, WILD sites in the same region on infrastructure owned by one railroad can also exhibit significant differences in loading. Figure 7 illustrates passenger coach wheel loads from four sites along Amtrak's Northeast Corridor. While each distribution represents passenger coaches, there are multiple types of passenger coaches at each site, adding further variation within traffic type. Each site experiences commuter service (with different types of equipment) and Amtrak regional service and Mansfield (150 mph (241 kph)), Edgewood (135 mph (217 kph)), and Hook (110 mph (177 kph)) experience Acela Express service. Each of these operating services uses different types of equipment, resulting in significant variability even within a particular traffic type (i.e. passenger coaches). As shown in the figure, just 5% of the peak wheel loads captured at Hook exceed 25 kips, while almost 57% of the wheels passing over the Mansfield site produce peak loads in excess of 25 kips. The compositions of passenger traffic at these two sites are similar, yet there are evidently other sources of variability affecting the distribution of peak wheel loads.

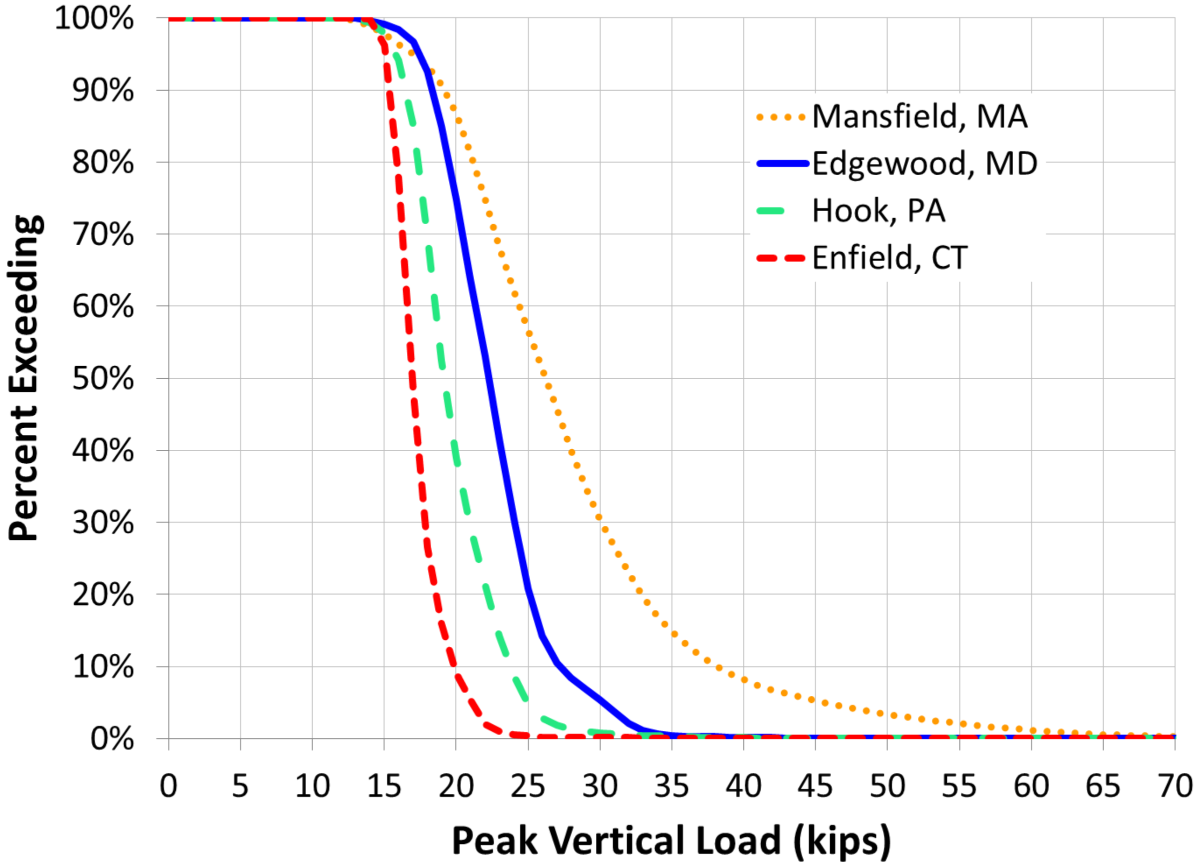

FIGURE 7 Variation of peak vertical loads along Amtrak's Northeast Corridor (passenger car WILD data from April 2011) (1 kip = 4.45 kN).

Month within the Year

While it has already been shown that there is variability across sites due to varying traffic characteristics, there also exists seasonal variability in loading at a single site. According to Kerr, when the track substructure is frozen, it becomes stiffer and causes higher loads at the wheel-rail interface *(6)*. The condition of the wheel may also deteriorate during the winter months due to a harsher braking environment. In fact, certain conditions, including frozen ballast and subgrade, can result in up to a nine-fold increase in track stiffness from freshly-tamped track *(6)*. Cold weather can also stiffen various damping components within the carbody *(9)* and perhaps the track superstructure, further increasing the wheel load. One would then expect significant variability in loads according to seasonal changes. In fact, UPRR has collected WILD data showing a clear increase in the number of severe impacts during the winter months on its network *(10)*.

Generally, month-to-month variability at a particular site is actually quite minimal. A brief review of the static loads collected during multiple months indicates that the rolling stock traveling over the WILD sites remains relatively constant regardless of the month. Compared to other sites and other years within the data provided by UPRR, Figure 8 depicts relatively large month-to-month variability in peak loads experienced at the Gothenburg, Nebraska WILD site. However, the loads do not follow the expected trend (higher wheel loads during the colder months) according to monthly temperature fluctuations at a location that sees significant seasonal temperature variation. Therefore, there doesn't appear to be enough evidence to conclude that seasonal variations affect the general shape of the wheel load distribution.

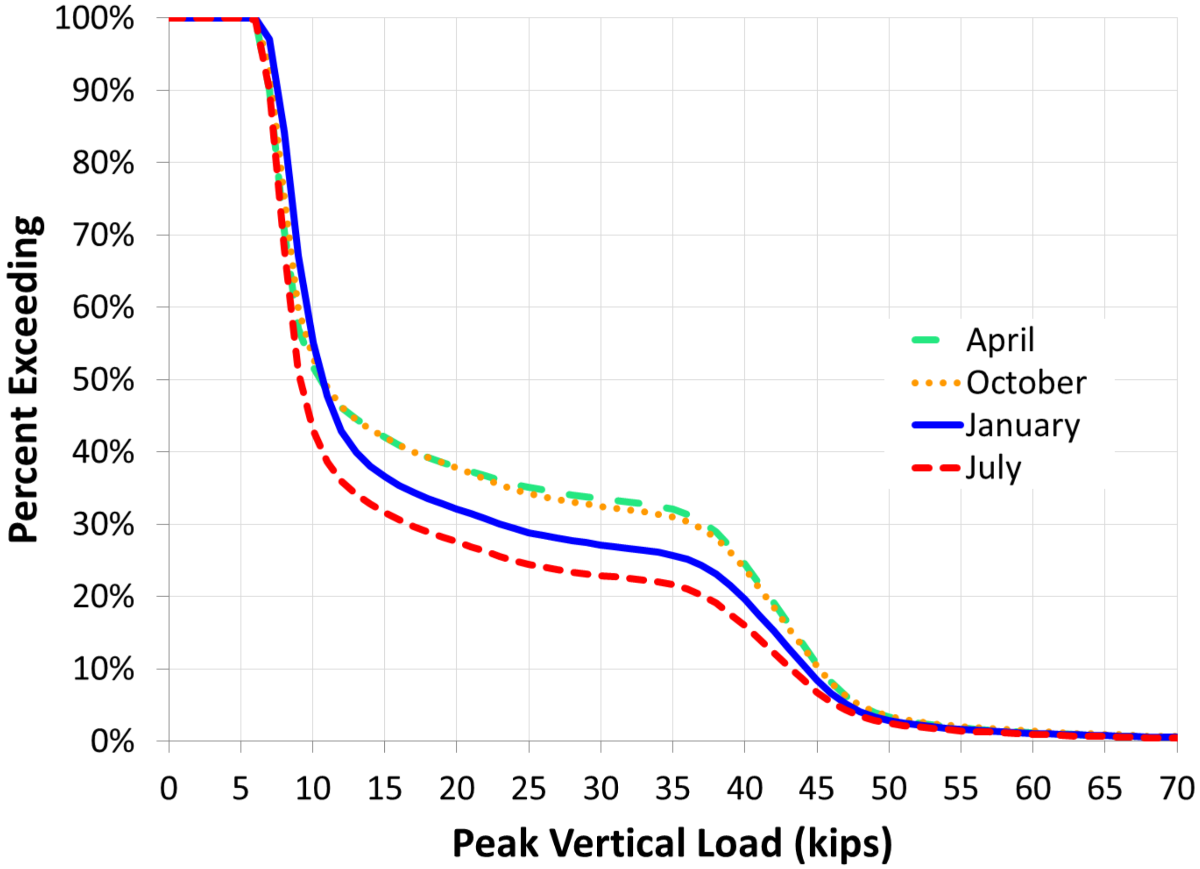

FIGURE 8 Monthly variation of peak vertical loads on UPRR at Gothenburg, Nebraska (non-intermodal freight car WILD data from 2010) (1 kip = 4.45 kN).

However, focusing on the highest loads provides some clarity regarding the most severe impacts, as shown in Figure 9. The highest 0.1% of peak vertical loads in January is higher than the most severe impact loads recorded during the warmer months. This observation is consistent across both operators (Amtrak and UPRR) and multiple WILD sites (locations where significant seasonal temperature fluctuations would occur), confirming the hypothesis that the stiffer track structure (higher track modulus) resulting from colder temperatures does not attenuate the high impact loads as well as a more flexible track structure (lower track modulus).

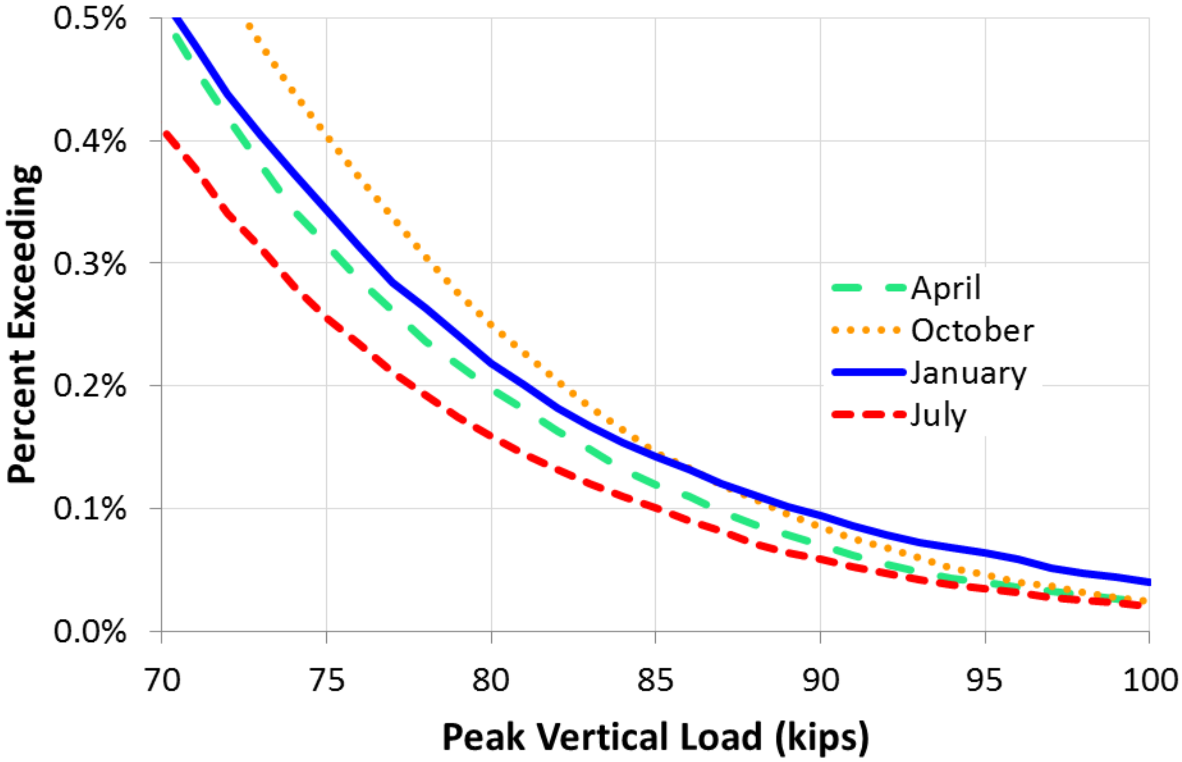

FIGURE 9 Monthly variation of highest peak vertical loads on UPRR at Gothenburg, Nebraska (non-intermodal freight car WILD data from 2010) (1 kip = 4.45 kN).

Wheel Irregularities

Perhaps the greatest contributor to increases in loads entering the track structure as detected by the WILD is the condition of the wheel. Irregularities on the wheel can result in impacts that severely damage the rail and other components of the track structure. For instance, a 100-kip impact resulting from a flat wheel can increase the contact stress in the rail by up to 200% *(10)*. Therefore, variability in the quality of wheels traveling over the infrastructure creates significant variation in the loads entering that structure. Figure 10 shows peak wheel load as a function of speed for passenger coach data on Amtrak's Northeast Corridor. The significant number of wheel loads exceeding 50 kips at roughly half the maximum speed suggests a high volume of poorly-performing wheels travelling over this WILD site. These wheels are imparting loads up to six times their static load into the track structure, increasing the potential for damage to the rail and other track components. The condition of these wheels may contribute to the site-specific diversity as shown in Figure 7.

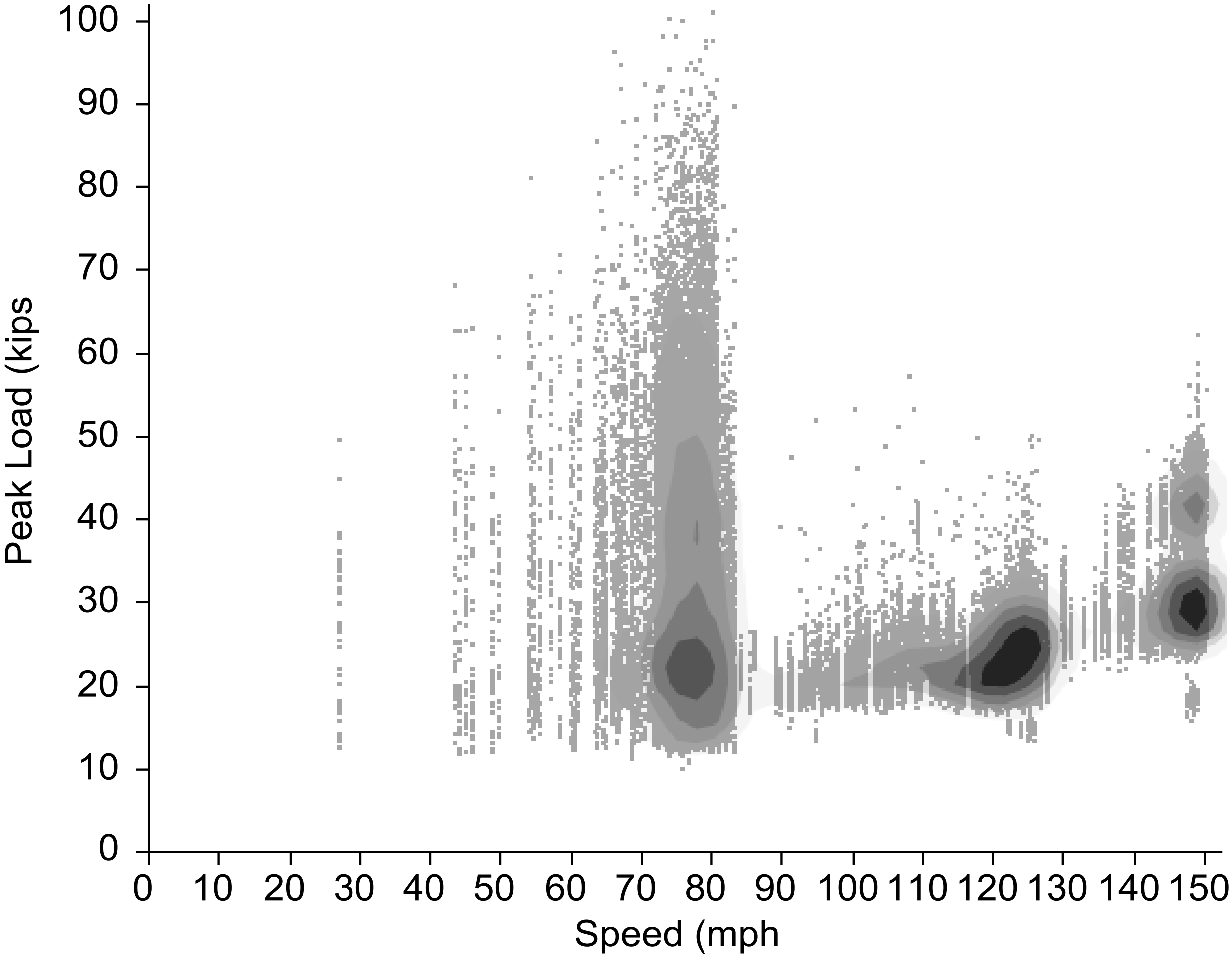

FIGURE 10 Effect of wheel condition on peak vertical load on Amtrak at Mansfield, Massachusetts (passenger WILD data from November 2010) (1 kip = 4.45 kN, 1 mph = 1.609 kph).

Other Sources of Variability

Because the WILD is installed on high-quality tangent track, the effect of wheel position within the truck, car, or train may not be fully realized. It is well understood, though, that the leading axle of any particular truck will create the highest lateral loads within a curve *(11)*. In distributed power applications with curvature and gradients, there is also significant variation along the length of the train in lateral and longitudinal wheel loads (*12*). In the future, the UIUC research team will further test this hypothesis using both WILD and IWS data to determine what effect, if any, the axle's position within the rolling stock has on the loading environment.

The effect of curvature and grade are also not clear from WILD data due to the detector's characteristics. Curvature significantly affects the lateral loads applied by the wheel and, along with gradients, can also cause variation in vertical loads (Figure 11).

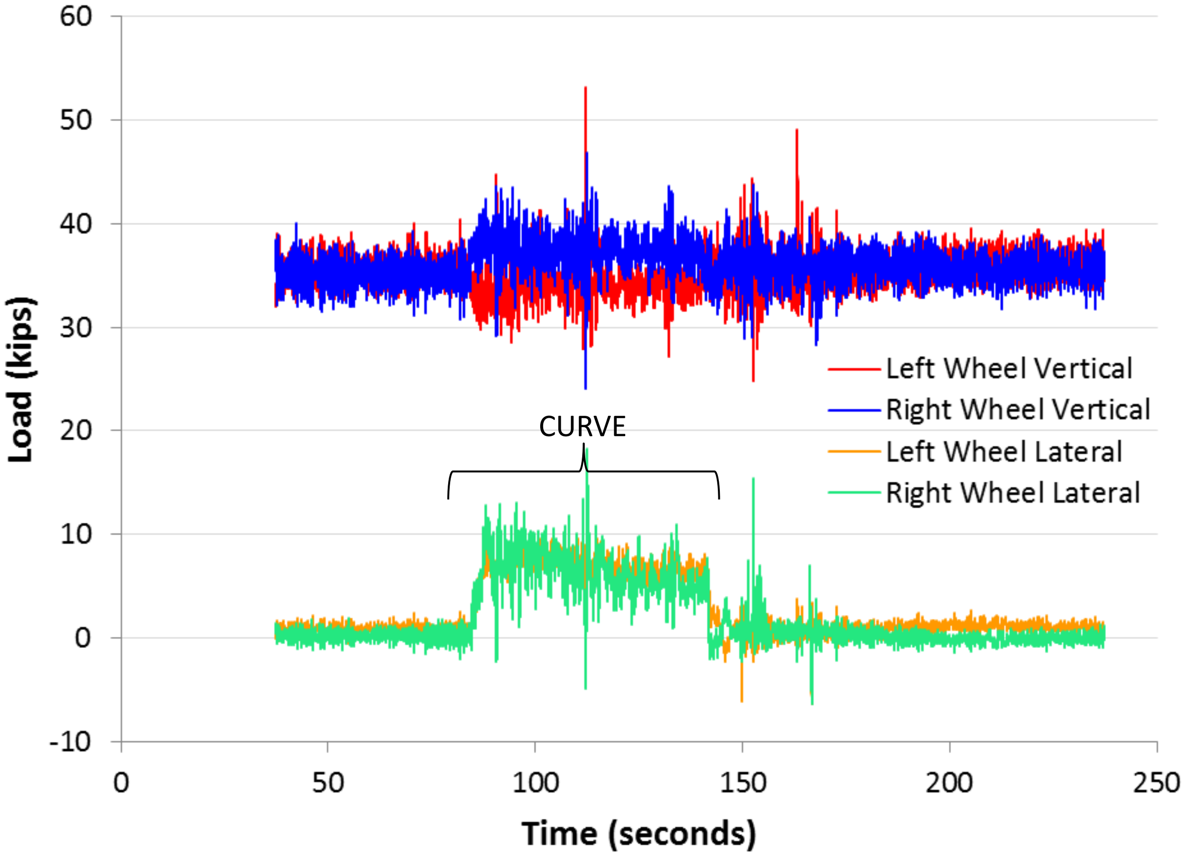

FIGURE 11 Vertical and lateral wheel loads in a left-handed curve on UPRR (IWS data from March 2006) (1 kip = 4.45 kN).

As shown in Figure 11, the vertical load created by the outside wheel increases during the curve, while the vertical load from the inside wheel decreases in the curve section. Furthermore, the lateral loads from both wheels increase significantly in the curved portion of the track when compared to the tangent sections. However, the lateral load decreases throughout the duration of the curve because the train is slowing down as it travels through the curve. To better understand the effect of speed on the lateral wheel loads in a curve, the degree of curvature and superelevation must be considered. Cant deficiency, which is the difference between equilibrium superelevation and actual superelevation in a curve (*11*), considers degree of curvature, curve superelevation, and vehicle speed and can be expressed 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 1500 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)

Relating lateral wheel load magnitudes to cant deficiency allows different curves with different balance speeds to be more effectively compared. Figure 12 shows the relationship between cant deficiency and lateral wheel loads on the same left-handed curve illustrated in Figure 11.

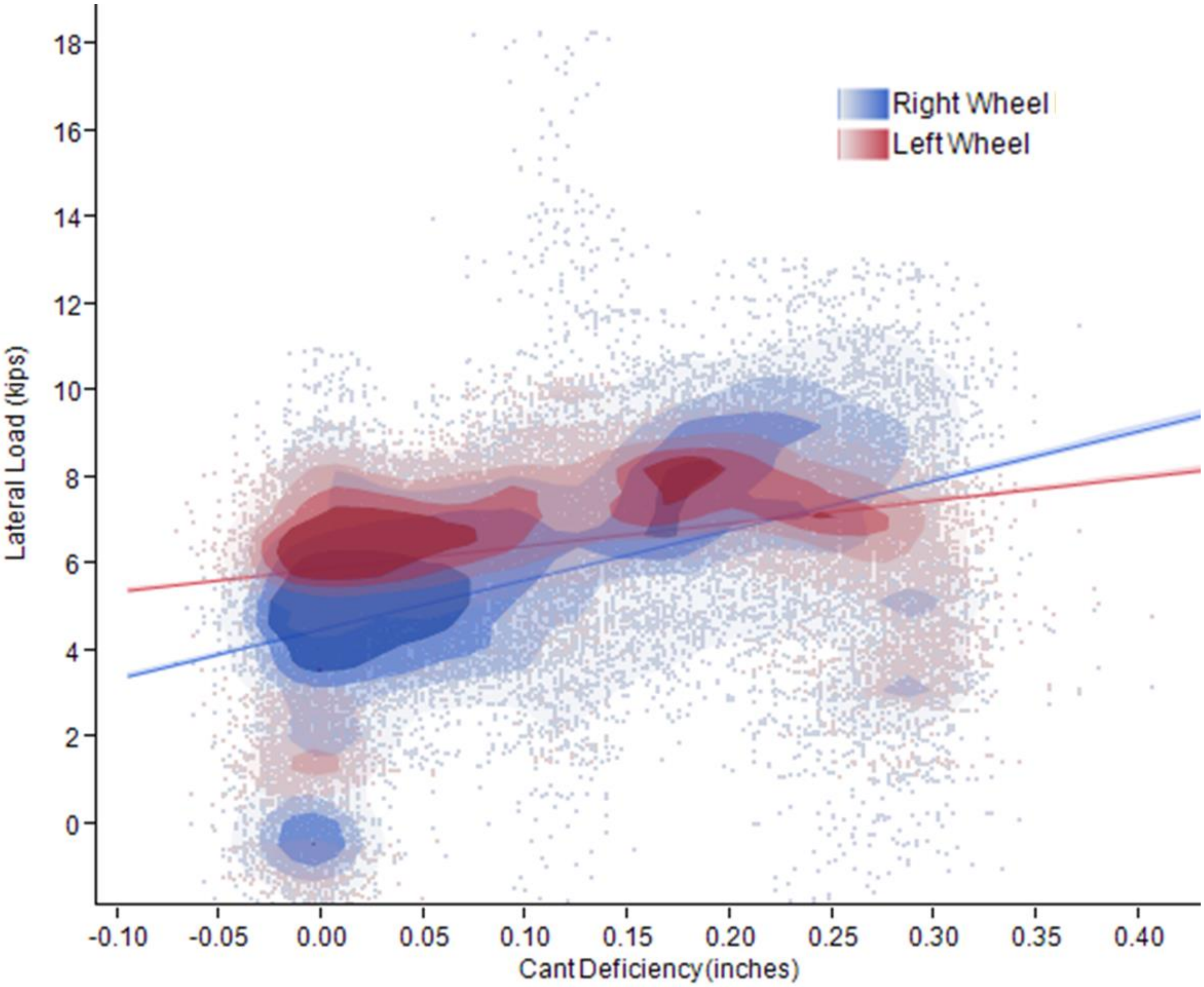

FIGURE 12 Effect of cant deficiency on lateral loads in curved track on UPRR (IWS data from March 2006) (1 in = 25.4 mm, 1 kip = 4.45 kN).

Because the instrumented wheel set is installed on a standard, relatively stiff truck, the lateral forces from both wheels increase with increased cant deficiency (a function of increased speed). The rate at which the right (outer) wheel increases is higher partially due to increased centrifugal forces at higher speeds, but mostly due to higher angle of attack (yaw angle). In the future, UIUC will utilize truck performance detector (TPD, a wayside device the utilizes strain gauges to measure vertical and lateral forces on the low and high rail at a field location that has two reverse curves to evaluate the curving performance of the truck and vehicle *(13,14)*) data to explore the relationship between angle of attack and the magnitude of lateral loads entering the rail in curved track.

CONCLUSIONS

The data collected at the Amtrak and UPRR WILD sites provide unique insight into the loading trends of the rolling stock travelling over each of these networks. Specifically, these data provide insight on primarily passenger operations, primarily freight operations, and true shared-use operations. Therefore the following conclusions can be roughly applied for each of these situations across North America:

- The WILD is a useful tool for collecting and analyzing data about loads entering the track structure

- Vehicle type and its associated static load provides a baseline for the expected total load at the wheel-rail interface
- Increasing speed minimally increases the most common wheel loads; however, severe impact loads become much more severe at higher speeds
- Traffic composition and other site-specific parameters play a significant role in the distribution of the loading environment
- Seasonal effects in load variation, while greatly contributing to the magnitude of severe impacts, minimally affect the majority of the wheel load distribution
- Wheel condition is a significant factor in determining peak loads entering the track structure
- Lateral loads on both rails increase with increased cant deficiency on curved track

Identifying the sources of wheel load variation, as well as determining relationships between parameters that incorporate multiple data collection methods, will more accurately capture the loading environment. This will lead to improvements in design and performance of critical infrastructure components and the entire track structure.

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