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Load quantification of the wheel–rail interface of rail vehicles for the infrastructure of light rail, heavy rail, and commuter rail transit

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Abstract

The type and magnitude of loads that pass through the track superstructure have a great impact on both the design and the performance of the concrete crossties and fastening systems. To date, the majority of North American research that focus on quantifying the rail infrastructure loading conditions has been conducted on heavy-haul freight railroads. However, the results and recommendations of these studies may not be applicable to the rail transit industry due to a variety of factors. Unlike the freight railroads, which have standardized maximum gross rail loads and superstructure design practices for vehicles, the rail transit industry is home to a significant variety of vehicle and infrastructure designs. Some of the current transit infrastructure design practices, which were established decades ago, need to be updated with respect to the current loading environment, infrastructure types, and understanding of the component and system-level behavior. This study focuses on quantifying the current load environment for light rail, heavy rail, and commuter rail transit infrastructure in the United States. As an initial phase of this study, researchers at the University of Illinois at Urbana-Champaign (UIUC) have conducted a literature review of different metrics, which is used to evaluate the static, dynamic, impact, and rail seat loads for the rail transit infrastructure. UIUC will compare these methods and their computed values to determine which provide the most accurate depictions of the expected loading condition given a set of operating and infrastructure characteristics. A proper load quantification of rail transit systems, gained through an improved understanding of the load path and rail seat load, will help to establish the basis for developing recommendations for a mechanistic design process for the rail transit infrastructure components. Ultimately, the results of this research will allow transit agencies to increase the effectiveness of their capital spending and transit agencies will have the potential to improve safety, ride quality, capacity, and the life cycle of the rail transit infrastructure.

Keywords

Rail transit, load quantification, light rail, heavy rail, commuter rail

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Introduction

Understanding the type and magnitude of loads that pass through the track system at the wheel–rail interface is critical to develop a holistic understanding of the structural performance of the track superstructure. Quantifying the loading condition is also the first step in further improving the design of the rail transit infrastructure and its components. In the context of experimentation and modeling, these input loading data provide the basis to guide field and laboratory experimental efforts as well as the analytical finite element (FE) modeling of the track's structural performance. A quantitative understanding of the loading environment can lead to optimized components and system designs for the unique loading conditions encountered in various rail transit systems. Unlike the freight railroads, the rail transit industry does not have any common design standards, which specifies the loading and capacity of the rail transit vehicles. Hence, there are a great variety of transit vehicles that are currently in operation in the United States due to the

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fact that transit agencies have the flexibility to modify the design of their vehicles to accommodate their infrastructure conditions and operational demands. Prior research at the University of Illinois at Urbana-Champaign (UIUC) on the load quantification has been focused on the understanding of the heavy-haul freight railroad environment. However, the results and recommendations from these studies may not be completely applicable to the transit industry, due to the fundamental differences between the infrastructure and operational characteristics of the rail transit and heavy-haul freight railroads.

Presently, there is no widely accepted research on quantifying the loading environment for the rail transit infrastructure and its components. There are, however, some focused reports and studies that can guide this research effort. The D-5 research report used data captured by a wheel impact load detector (WILD) on VIA Rail in Canada. The report shows that the typical static wheel loads of the VIA Rail vehicles are 16 to 18 kips (71 to 80 kN) with a maximum value of 38 kips (169 kN).[1] Vuchic[2] documented the vehicle characteristics of several rail transit systems in the United States, Europe, and South America. He also studied the relationship between the average gross axle load and the gross floor area, as well as between power and tare weight.[2] The Track Design Handbook for Light Rail Transit summarized the vehicle characteristics from 26 light rail systems in the United States and Canada in 2010.[3] Another example of the rail transit infrastructure track loading research are case studies that were commissioned by the transit agencies.[4,5] However, there is no comprehensive study of the rail transit vehicle characteristics in the United States across light rail, heavy rail, and commuter rail systems. In addition, some transit vehicle and track design standards were established decades ago, and have not been changed with respect to the current loading environment. These standards are in the need of updating to reflect the changes in the current infrastructure and vehicle conditions.

Rail transit static load quantification

In order to develop an understanding of the current state of practice regarding the loading environment of the rail transit vehicles, researchers at UIUC collected information pertaining to the rail transit vehicles using several sources. The 2013 Revenue Vehicle Inventory published by National Transit Database (NTD) is used as the primary reference of the rail transit vehicles in the United States.[6] The 2013 Revenue Vehicle Inventory is a comprehensive database that contains up-to-date information of the rail transit rolling stock from more than 40 of the nation's transit agencies.[6] It provides the rail transit vehicle fleet size and characteristics, including the owner, transit mode, manufacturer, year of manufacture, model number, and seating and standing capacity. However, it fails to document the other critical vehicle characteristics, such as tare weight, number of axles, and wheel diameter.[6]

Extensive efforts were made to ensure the quality of the information used in this analysis and to obtain as much data as possible. It was not possible, however, to obtain information for every railcar. In addition, as the rail transit systems are frequently purchasing new vehicles, selling vehicles to other systems, and retiring or rehabilitating old vehicles, it is difficult to keep the rolling stock information up to date in such a dynamic environment. The results stemming from this research are valid for understanding the general differences in the rail transit loading environment in the United States for the three rail transit modes. However, those seeking research on the track structural design for the transit systems should consult the transit agencies for the most up-to-date information.

Weight categories and definitions of passenger vehicles

The rail transit industry is currently using the AW0 to AW4 design criteria to design cars that are used to transport passengers. AW0 is defined as the empty car weight without any passenger loading. AW1 is the seated load, which is defined as the empty car weight plus the weight of seated passenger loads at maximum seating capacity. AW2 is the design load of the railcar, which is defined as the sum of the AW1 load and the weight of standing passengers at the density of four passengers per square meter (3.3 passengers per yd^2). AW3 is the crush load, which is defined as the sum of the AW1 load and the weight of standing passengers at the density of six passengers per square meter (5.0 passengers per yd^2). AW4 is the structural design load, which is defined as the AW1 load and the weight of standing passengers at the density of eight passengers per square meter (6.7 passengers per yd^2). AW4 is not typically considered in the track superstructure design since it is a theoretical loading only for bridge design and virtually certain to never be experienced in service. The rail transit industry is currently using the AW3 load, the crush load, as the maximum load that track components can withstand.[3] Since commuter locomotives do not carry revenue passengers, only the AW0 load is used for calculating the load of commuter locomotives.

Given that data on standing space are not generally available for most of the rail transit vehicles in the United States, an alternative expression of the AW3 load is used in this research effort, which equals to the empty car weight plus the product of average passenger weight and the maximum passenger capacity for the vehicle.[7]

Empty car weight

Empty car weight, also known as tare weight or the AW0 load, was collected for all the passenger vehicles considered in this research effort. UIUC collected the empty car weight for the passenger vehicles and locomotives using various sources, including the vehicle design specifications and datasheets published by the vehicle manufacturers and transit agencies. Some transit authorities also directly provided their rolling stock data to UIUC. Although the empty car weight information is not available for all the transit rail vehicles, UIUC was able to locate information for 2070 out of 2070 (100%) light rail vehicles, 9781 out of 11,474 (85%) heavy rail vehicles, 4353 out of 6047 (72%) commuter railcars, and 674 out of 738 (91%) commuter locomotives.

Average passenger weight

According to the Light Rail Design Handbook and the design specifications from the rail transit agencies, the average passenger weight is specified to be 155 pounds (70 kg).[3] However, APTA research shows that 155 pounds (70 kg) is the median weight of the population in the 1970s, and the median weight of the population in the United States is currently 182 pounds (83 kg).[8] Most of the transit agencies and track component suppliers are currently using 175 pounds (79 kg) as the average passenger weight. There are also examples of the rail transit vehicle design using an average passenger weight of 165 pounds (75 kg) and 180 pounds (82 kg) for the rail transit vehicles.[7,9] None of these values of average passenger weight fully address the increase in average weight since the 1970s. APTA's research suggests the use of 199 pounds (90 kg) for seated passenger weight, and 106 lbs/ft^2 (517 kg/m^2) for standing passenger weight, taking into account 10 pounds (4.5 kg) of personal items and 7 pounds (3.2 kg) for year-round clothing.[8] Since the data of standing area are generally unavailable for most of the railcars, it is impractical to calculate the total weight using the standing area. Additionally, this research fails to consider the weight of children, which might lower the average passenger weight. Therefore, we propose to use 195 pounds (88 kg) as the average passenger weight. This value takes into account the increases in weight over the past four decades, as well as seasonal clothing and personal baggage items.

Railcar passenger capacity and number of active revenue vehicles

The 2013 Revenue Vehicle Inventory provides the passenger capacity, both seated and standing capacities, as well as the number of active revenue vehicles for each transit vehicle model in the United States.[6] With the passenger capacity and the empty weight obtained for most of the transit rail vehicles in the United States, the AW0 and AW3 loads could be calculated, and the total transit vehicle weight distribution could be analyzed.

Results and discussion regarding weight of rail vehicles

The most common unit for light rail vehicles consists of two semi-permanently coupled cars that are operational only when coupled together. A married pair is considered as one vehicle for light rail articulated cars. Diesel multiple units (DMUs) and electrical multiple units (EMUs) are two common units for heavy rail and commuter rail vehicles. They are self-propelled railcars that can operate either as single cars, or consist of two or more units. Therefore, for heavy rail and commuter rail vehicles, one vehicle could be defined as one single-unit car, half of a married pair, or one-third of a three-car unit in this research.

The individual axle loads of the majority of light rail and heavy rail transit vehicles are not typically uniformly distributed for a given vehicle. Due to the unbalanced weight distribution in the car body, the axle loads may vary. Overall, since the difference in axle loads on a given vehicle is relatively small, we assume that the weight of the car is uniformly distributed on all axles. Therefore, the axle load is calculated by dividing the gross weight of the car by the number of axles. The axle load distribution for three modes is shown in Figure 1. Additional statistical information of the axle load distribution is included in Table 1.

It is important to note that the rail transit vehicles do not always govern the design load of rail transit infrastructure. Many commuter rail systems share their infrastructure with freight railroad rolling stock, which typically generate significantly higher axle loads. Additionally, work equipment, such as ballast cars, usually have a higher axle load than the rail transit vehicles. For instance, the largest AW3 axle load of passenger railcars on the Massachusetts Bay Transportation Authority (MBTA) heavy rail system is 33.5 kips (149 kN), while the static axle load of work equipment on MBTA heavy rail system could be as high as 38 kips (169 kN).[10]

Dynamic wheel load factors

Van Dyk[11] studied the effectiveness of several methods of calculating the dynamic wheel load factors for heavy-haul freight railcars by comparing the theoretical results with field data. This paper adopts a similar methodology to analyze the effectiveness of these design factors with respect to the rail transit loading conditions. Table 2 contains general equations for the dynamic factor with the input parameters for each equation, and Table 3 provides a definition of the variables used in each dynamic factor equation.

Among the equations analyzed in Van Dyk's paper, the South African Railways equation is a variant of Talbot equation, modified for narrow gage tracks. The majority of the rail transit systems in the United States are constructed with standard gage, with the exception of Bay Area Rapid Transit

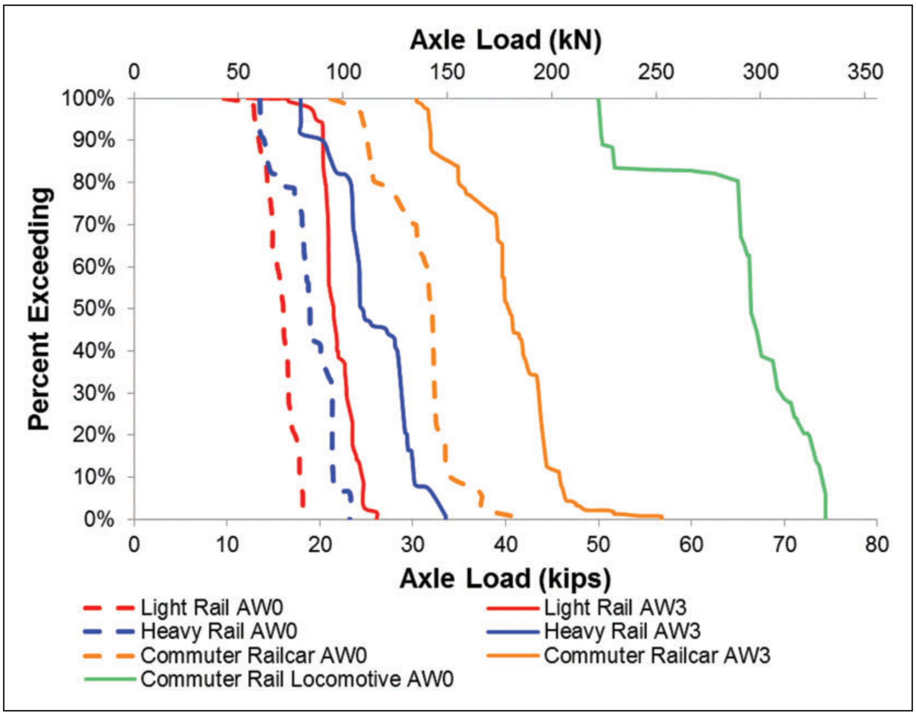

Figure 1. Light rail, heavy rail, and commuter rail axle load distribution.

Table 1. AW0 (empty load) and AW3 (crush load) axle loads for light rail, heavy rail, and commuter rail transit vehicles.

Imperial unit	AW0 axle load (kips)			AW3 axle load (kips)		
Transit mode	Minimum	Maximum	Average	Minimum	Maximum	Average
Light rail	9.6	18.2	15.7	12.2	26.1	21.8
Heavy rail	11.9	23.2	18.7	16.2	33.5	25.5
Commuter railcar	21.1	40.8	30.6	30.4	56.7	40.0
Commuter locomotive	50.0	74.4	65.4	N/A	N/A	N/A
Metric unit	AW0 axle load (kN)			AW3 axle load (kN)		
Transit mode	Minimum	Maximum	Average	Minimum	Maximum	Average
Light rail	42.7	81.0	69.9	54.3	116.1	97.0
Heavy rail	53.0	103.2	83.2	72.1	149.1	113.5
Commuter railcar	93.9	181.6	136.2	135.3	252.3	178.0
Commuter locomotive	222.5	331.1	291.0	N/A	N/A	N/A

(BART), Southeastern Pennsylvania Transportation Authority (SEPTA) Market-Frankford Line, Washington Metro, and Pittsburg Light Rail. Therefore, the South African Railways equation will not be included in this research. As the British Railways equation is designed specifically for rail joint dips and AREMA Chapter 30 (Ties) equation is to be applied as an upper bound at rail seat in combination with an impact factor, it is not appropriate to compare them with other factors.[11,12]

As the majority of the dynamic factors have vehicle speed, wheel diameter, and track modulus as parameters, measurements or assumptions must be made for the specific rail transit system under investigation. According to Urban Transit: System and Technology, the maximum speed for light rail systems is 43 mile/h (69 km/h), 75 mile/h (120 km/h) for heavy rail transit systems, and 80 mile/h (130 km/h) for commuter rail transit systems.[2] Maryland Area Regional Commuter (MARC) operates the Penn Line, the fastest commuter rail line in the United States, at speeds of up to 125 mile/h (201 km/h).[13] The upper bound of the operating speed used in this analysis is 160 mile/h (257.5 km/h) so that the results could also be applicable to Amtrak trains with higher speeds in the future. The majority of light

Table 2. Dynamic factor equations and listing of input parameters (adapted from Van Dyk[11])

		Vehicle parameters included						Track parameters included					
Dynamic factor	Expression for ϕ	Train speed	Wheel diameter	Static wheel load	Unsprung mass	Vehicle center of gravity	Locomotive maintenance Condition	Track modulus	Track stiffness at rail joint	Track joint dip angle	Cant deficiency in curves	Curve radius	Track maintenance condition
Talbot	$1+\frac{33V}{100D}$	●	●										
Indian Railways	$1+\frac{V}{3\sqrt{U}}$	●						●					
Eisenmann	$1+\delta\eta t$	●											●
ORE/Birmann	$1+\alpha+\beta+\gamma$	●				●	●				●	●	●
German Railways	$1+\frac{11.655V^2}{10^5}-\frac{6.252V^3}{10^7}$	●											
British Railways	$1+14.136(\alpha_1+\alpha_2)V\sqrt{\frac{D_jP_u}{g}}$	●		●	●				●	●			
South African Railways	$1+0.312\frac{V}{D}$	●	●										
Clarke	$1+\frac{15V}{D\sqrt{U}}$	●	●					●					
WMATA	$\left(1+0.0001V^2\right)^{\frac{2}{3}}$	●											
Sadeghi	$1.098+0.00129V+2.59\left(10^{-6}\right)V^2$	●											
AREMA C30	For $20<V<120$: $0.6+0.005V$	●											

Table 3. Dynamic factor variable definition (adapted from Van Dyk[11]).

Variable	Definition
V	Train speed (mile/h)
D	Wheel diameter (in)
U	Track modulus (psi)
δ	0.1, 0.2, 0.3, depending on track conditions
η	1 for vehicle speeds up to 37 mile/h $1+\frac{V-37}{87}$ for vehicle speeds between 37 and 125 mile/h
t	0, 1, 2, 3, depending on the chosen upper confidence limits defining probability of exceedance
α	Coefficient dependent on the level of track, vehicle suspension, and vehicle speed, estimated to be $0.167\left(\frac{V}{100}\right)^3$ in the most unfavorable case
β	Coefficient dependent on the wheel load shift in curves (0 in tangent track)
γ	Coefficient dependent on the vehicle speed, track age, possibility of hanging crossties, vehicle design, and locomotive maintenance conditions, estimated to be $0.10+0.071\left(\frac{V}{100}\right)^3$ in the most unfavorable case
$\alpha_1+\alpha_2$	Total rail joint dip angle (radians)
D_j	Track stiffness at the joints (kN/mm)
P_u	Unsprung weight at one wheel (kN)
g	Acceleration due to gravity (m/s^2)

vehicles have a wheel diameter of 26 in to 28⅜ in (660–721 mm). The wheel diameter of heavy railcars ranges from 26 in to 34½ in (660–876 mm). The wheel diameter of commuter railcars ranges from 32 in to 36 in (813–914 mm), while most commuter locomotives have a wheel diameter of 40 in (1016 mm). Therefore, the lower and upper bounds of the new wheel diameter of the transit railcars in the United States are 26 in and 36 in (660.4–914.4 mm), respectively. A track modulus of 3200 psi (22.1 N/mm^2) is used for the lower bound of track modulus, representing well-maintained timber crosstie track. A track modulus of 10,000 psi (68.9 N/mm^2) is used for the upper bound of track modulus, representing typical direct fixation (DF) track.[3] Since the Talbot, Indian Railways, and Clarke dynamic factors incorporate either or both track modulus and wheel diameter as the parameters in the formula, these three dynamic factors are calculated using both upper and lower bound of track modulus and wheel diameter. Figure 2 displays the dynamic factors increasing due to speed for the rail transit infrastructure.

Evaluation of dynamic factors

The dynamic factors discussed in the previous sections were developed using different assumptions to adjust

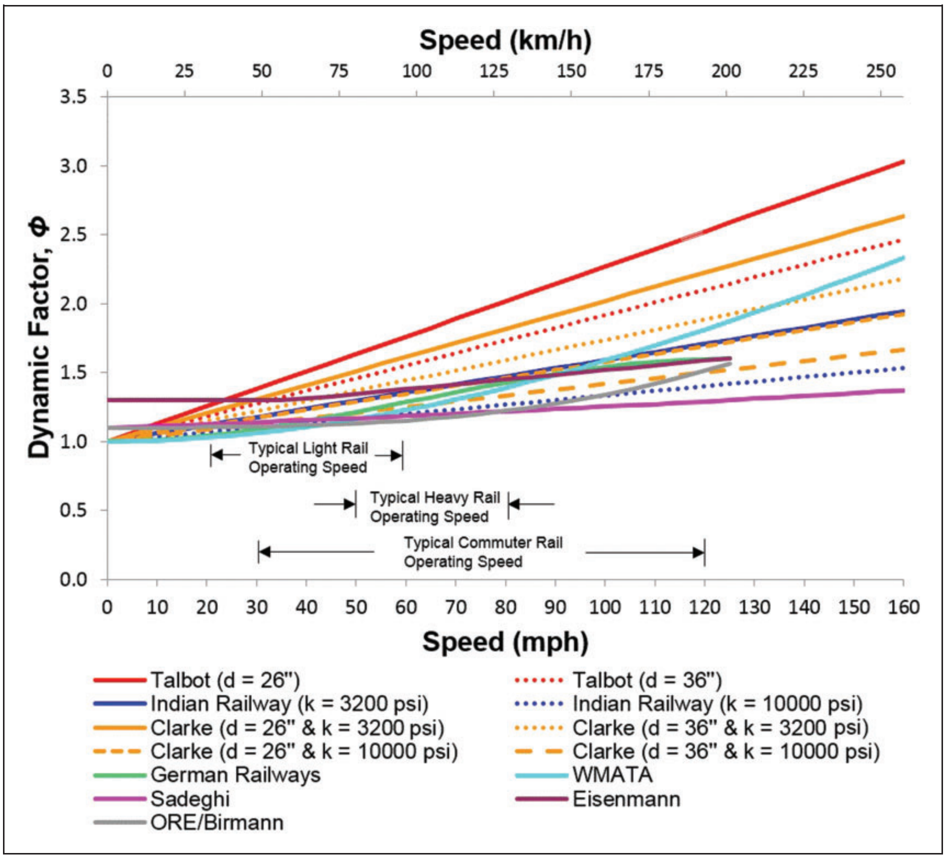

Figure 2. Summary of design dynamic factors as a function of speed.

for infrastructure and operational conditions. Some of these dynamic factors are also developed specifically for the freight railroad systems, and their applicability to the rail transit systems has not been studied. To evaluate the effectiveness of the dynamic factors, the actual field-collected wheel impact load detector (WILD) data were used to compare the field measured real-time data with the theoretical results generated from the formulas.

Due to the fact that the light rail and heavy rail transit systems rarely have WILDs installed on their infrastructure, the evaluation of the dynamic factors using WILD data will only be applicable to the commuter rail systems. The WILD data used in this research were measured on the tangent tracks in Edgewood, Maryland, Marcus Hook, PA, and Mansfield, MA, where MARC, MBTA, and SEPTA Commuter Rail operate their commuter rail trains on Amtrak's Northeast Corridor (NEC). (Note: No WILD data of SEPTA commuter rail trains were used in this analysis. The MARC trains at the Marcus Hook WILD site were operated under Amtrak during the Thanksgiving weekend for special operation.) Several parameters in the dynamic factor formulas are modified to accommodate the track and vehicle conditions at these WILD sites. A track modulus of 6000 psi (41.4 N/mm^2) is used to represent well-maintained concrete crosstie track at these WILD sites. The wheel diameters of MARC and MBTA commuter railcars are typically 36 in (914.4 mm). Track quality is assumed to be 0.1 to represent track in a very good condition. A confidence factor of 3 is used for upper confidence limit of 99.7%, applicable for rail stresses, fastenings, and crossties. The dynamic factor values predicated by the equations are plotted with the ratio of peak vertical wheel load to nominal wheel load based on the field-captured data. Figure 3 shows the commuter railcar wheel load data relative to the dynamic factors. The metrics in Table 4 are used to further evaluate the effectiveness of the dynamic factors, and the metrics are explained in detail in Van Dyk's paper.[11]

Over 60% of the wheel loads measured exceed the predicted values generated by the ORE/Birmann and Sadeghi dynamic factors. Both of these equations largely underestimate the dynamic factors with a negative signed difference and negative percentage error; therefore, they are not appropriate to calculate the dynamic factors for the rail transit vehicles. Other than the ORE/Birmann and Sadeghi formulas, all the other dynamic factors produce accurate results, with small mean signed differences, small mean percentage error, and small root mean square. Among all the dynamic factors, Talbot dynamic factors have the lowest percentage exceedance and the largest mean signed difference, which indicate that it is the most

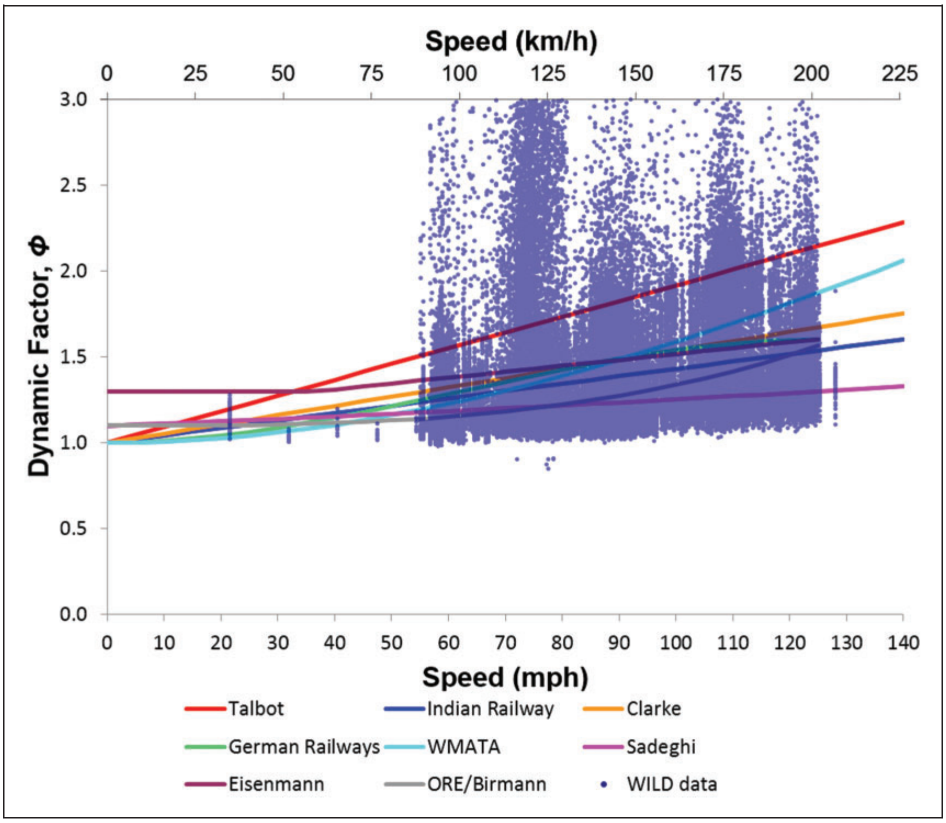

Figure 3. Peak/nominal wheel load ratios of Commuter rail rolling stock at Edgewood, MD, Marcus Hook, PA, and Mansfield, MA (WILD data from 2010 and 2011) and design dynamic factors.

Table 4. Evaluation of the dynamic factors using various metrics.

	Dynamic Factors							
Evaluation metric	Talbot	Indian Railways	Eisenmann	ORE/Birmann	German Railways	Clarke	WMATA	Sadeghi
Percent exceeding	7	35	26	68	27	26	24	79
Mean signed difference $\sum \frac{(f(x_i)-y_i)}{n}$	0.47	−0.02	0.07	−0.15	0.08	0.09	0.14	−0.19
Mean percentage error $\frac{100\ \%}{n}\sum(f(x_i)-y_i)/y_i$	35.6	1.5	7.8	−7.9	8.1	9.1	12.7	−10.8
Root-mean-square deviation $\sqrt{\sum(f(x_i)-y_i)^2/n}$	0.30	0.07	0.08	0.10	0.08	0.08	0.10	0.11
Speed-weighted signed difference $\sum(x_i f(x_i)-x_i y_i)/\sum_i^x$	0.48	−0.01	0.07	−0.16	0.08	0.10	0.16	−0.19
Load-weighted signed difference $\sum(Q_i f(x_i)-Q_i y_i)/\sum_i^Q$	0.48	0.00	0.09	−0.13	0.10	0.11	0.16	−0.17

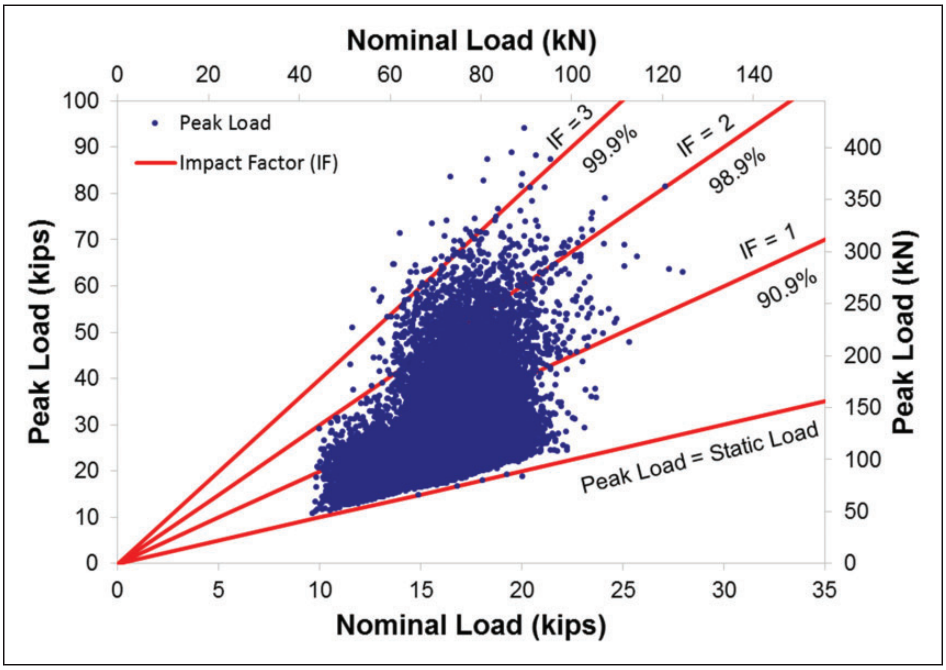

Figure 4. Relationship between peak and nominal wheel loads of commuter railcars on Amtrak Infrastructure at Edgewood, MD, Marcus Hook, PA, and Mansfield, MA (WILD data from 2010 and 2011) and design impact factors.

conservative method used to calculate the dynamic loads.

Evaluation of impact factor

The concept of impact factor has been adopted by the rail industry to calculate the increase in the wheel load due to the track and wheel irregularities and speed. The AREMA Manual on Railway Engineering (hereafter referred to as the "AREMA Manual") defines the impact factor as a percentage increase over the static vertical loads intended to estimate the dynamic effect of the wheel and rail irregularities.[14] The AREMA Manual currently specifies an impact factor of 200%, which indicates that the design load is three times the static load.[12] Since the use of impact factors in the AREMA Manual is the same for both freight railroads and rail transit systems, the WILD data show that the current impact factor may not be suitable for the rail transit loading environment. The applicability of the impact factor requires further studies with respect to today's rail transit loading environment. Due to the difference between commuter railcars and locomotives in terms of the loading characteristics, these two types of commuter rail equipment are analyzed separately. Using the WILD

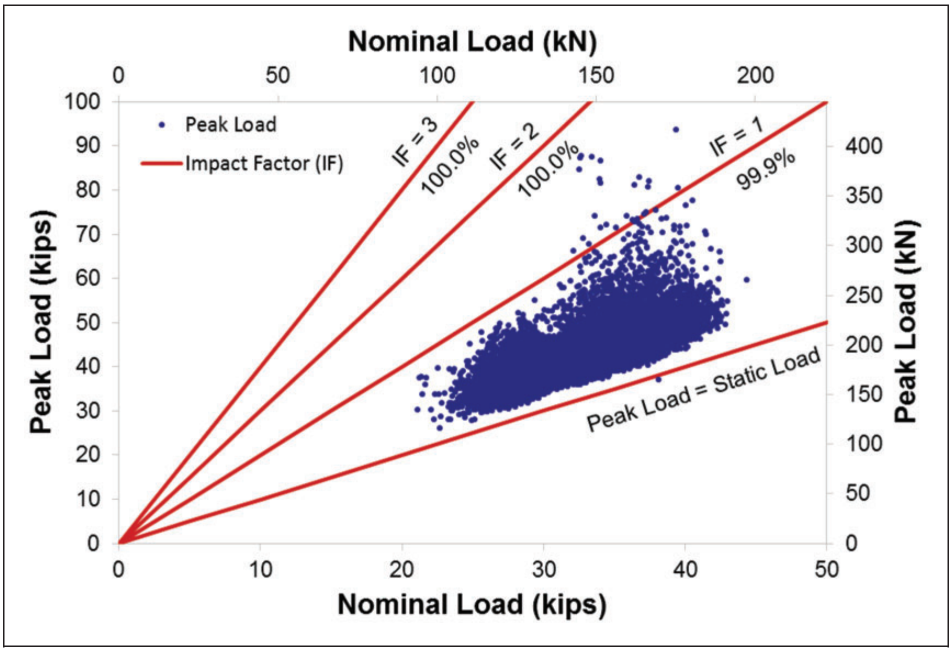

Figure 5. Relationship between peak and nominal wheel loads of commuter locomotives on Amtrak Infrastructure at Edgewood, MD, Marcus Hook, PA, and Mansfield, MA (WILD data from 2010 and 2011) and design impact factors.

data at Edgewood, MD, Marcus Hook, PA, and Mansfield, MA, the peak load is plotted against the nominal load in Figures 4 and 5 for the commuter railcars and locomotives respectively with lines representing the impact factor of various values.

Figures 4 and 5 show that the impact factor of 200% exceeds 98.9% and 100% of the commuter railcar and locomotives wheel loads, respectively. This indicates that the impact factor of 2 (200%) specified by the AREMA Manual is adequate for calculating the design load for the commuter rail vehicles. Figure 5 shows that the impact factor of 1 (100%) exceeds 99.9% of the commuter locomotives wheel loads, which indicates an impact factor of 1 is sufficient for calculating the peak wheel load for the commuter locomotives. As the nominal wheels of the commuter locomotives are significantly higher than those of the commuter railcars, an impact factor of 1 for commuter locomotives could reduce the design load for the passenger-only track. WILD sites are typically constructed on tangent track using premium track components so that the track irregularities are minimized in order to better understand the health of the rolling stock. More demanding track conditions and other track irregularities could lead to a higher impact factor.

Conclusions and future work

A comprehensive static load quantification has been conducted for the light, heavy, and commuter rail transit systems in the United States. A better understanding of the rail transit loading environment was developed using industry databases and design recommendations. The applicability of several dynamic factors to the rail transit loading environment was evaluated by comparing the predicted results with the WILD data measured on the commuter rail rolling stock. Most of the dynamic factors are able to predict the peak wheel loads for the commuter rail systems with high-level accuracy and precision. The effectiveness of the impact factor of 200% was also studied with respect to today's rail transit loading environment in the United States. It is shown that the impact factor of 2 is adequate for quantifying the effect of track and wheel irregularities on the commuter rail transit systems, and this study provides a conservative estimate of the wheel loads. Future work could incorporate WILD (or similar) data from the light rail and heavy rail transit systems to evaluate the effectiveness of the dynamic factors and impact factors on the light rail and heavy rail transit systems.

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