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Evaluation of dynamic and impact wheel load factors and their application in design processes

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Abstract

A sustained increase in heavy axle loads and cumulative freight tonnages, coupled with increased development of high-speed passenger rail, is placing an increasing demand on railway infrastructures. Some of the most-critical areas of the infrastructure in need of further research are track components used in high-speed passenger, heavy haul and shared infrastructure applications. In North America, many design guidelines for these systems use historical wheel loads and design factors that may not necessarily be representative of the loading currently experienced on rail networks. Without a clear understanding of the nature of these loads and how design processes reflect them, it is impossible to adequately evaluate the superstructure in order to make design improvements. Therefore, researchers at the University of Illinois at Urbana-Champaign are conducting research to lay the groundwork for an improved and thorough understanding of the loading environment imparted into the track structure using wheel loads captured by wheel impact load detectors. This paper identifies several design factors that have been developed internationally, and evaluates their effectiveness based on wheel loads using several existing and new evaluative metrics. New design factors are also developed to represent the wheel-loading environment in a different manner. An evaluative approach to historical and innovative design methodologies will provide improvements to designs, based on actual loading experienced on today's rail networks.

Keywords

Rail seat load, dynamic wheel load factor, impact factor, peak tonnage, concrete sleeper

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Introduction

In North America, many design guidelines for track components in shared-use railway infrastructure use historical wheel loads and several evaluation factors. To evaluate the components found in the superstructure and make design improvements, the nature of these loads and how the design process reflects them must be thoroughly understood. There are many parameters that contribute to the actual load imparted into the track structure from the car body. Some of these parameters are considered in designs by using a dynamic factor or impact factor for more-accurate load estimation. Both of these factors will be defined and evaluated using actual wheel-loading data in this paper.

There are several types of loads that can be used to design the track structure: static, quasi-static, dynamic, and impact loads. The static load is simply the weight of the rail vehicle at rest. The quasi-static load can be considered to be the combined static load and the effect of the static load at speed, independent of time.[1] The quasi-static load is perhaps best illustrated in curved track, where the vehicle imparts loads onto the rail due to centripetal force and curving.[2] The dynamic load is the additional load (above static load) due to high-frequency effects of wheel/rail load interactions, considering time-dependent track component responses and involving highly variable inertia, damping, stiffness, and mass effects. The impact load, which often creates the highest loads in the track structure, is created by track and vehicle irregularities, producing potentially damaging high-frequency short-duration forces.

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Identification and evaluation of dynamic wheel load factors

It is well-understood that loads at the wheel/rail interface produced by moving loads are greater than those produced by the same wheel loads at rest.[3] Typically, therefore, the design wheel load is higher than the static wheel load to account for this increase due to speed, that is

$$P_d = \phi P_s$$

where P_d is the dynamic wheel load, ϕ is the dynamic wheel load factor, and P_s is the static wheel load.

The dynamic wheel load factor is typically developed empirically using field data and is expressed in terms of train speed. The number of elements considered in its development can depend on the sophistication of the track instrumentation implemented and the applied assumptions.[4] Historically, there have been many efforts undertaken to quantify the increase of load expected at the wheel/rail interface due to speed.

Previous dynamic factors

Doyle[4] provided a summary of many dynamic wheel load factors. Several factors were calculated using only train speed. Beginning in 1943, the Deutsche Bahn (Germany Railways) began using an equation that is only valid for speeds up to 200 km/h (125 mile/h).[5] In 1968, a dynamic factor was prepared for the Washington Metropolitan Area Transit Authority (WMATA) and used in subsequent recommended standards for transit trackwork.[6] More recently, another speed-dependent dynamic factor was developed in Iran.[7] The final factor that is dependent only on train speed, although not applied at the wheel/rail interface, is included because of its importance in the design of the track structure. The speed factor found in chapter 30 of the AREMA manual[8] is used as part of the flexural design of concrete crossties with a distribution factor and impact factor. The chapter 30 speed factor, developed in the early-1980 s by the American Railway Engineering Association (AREA) Committee, is constant below 20 mile/h (32 km/h) and above 120 mile/h (193 km/h).[9]

Most of the dynamic factors, however, have been developed to incorporate additional parameters beyond train speed. Talbot provided a factor to the AREA based on tests his committee conducted in the 1910 s.[10] The Talbot dynamic factor incorporates the wheel diameter and is still used in modern North American track analysis.[8] The South African Railways formula is similar to the Talbot formula, but is calculated for narrow gauge track. The dynamic factor proposed by Indian Railways incorporates track modulus as an indicator of track condition,[11] whereas the Clarke formula algebraically combines the Talbot and Indian Railways dynamic factors.[4]

Three additional dynamic factors have been developed that incorporate many other parameters. The Eisenmann dynamic factor incorporates the condition of the track and uses a statistical approach where the rail bending stresses and deflections are normally distributed and calculated using Zimmermann's longitudinal beam model.[12] The British Railways dynamic factor is used for discrete irregularities, such as a dipped rail joint, and was developed in the 1970 s using specific track infrastructure, incorporating the vehicle's unsprung mass, track stiffness at the irregularity and speed. The most-comprehensive dynamic factor was developed by the Office of Research and Experiments (ORE) of the International Union of Railways, particularly Birmann.[13] This factor, valid for speeds up to 200 km/h (125 mile/h), incorporates the track geometry, vehicle suspension, vehicle speed, vehicle center of gravity, age of track, curve radius, super-elevation, and cant deficiency. Due to the lack of experimental data related to each of these parameters, Doyle[4] made some reasonable assumptions and accordingly simplified parts of the factor.

A comparison of vehicle and track parameters included in each of the dynamic factors is shown in Tables 1 and 2, while Figure 1 displays the design dynamic factors increasing with speed. Previous research has shown that the rate of load increase due to speed is much higher when wheel geometrical quality is poor.[14]

Evaluation of Dynamic Factors

Many of the dynamic factors discussed in the previous section can only be used to predict the load amplification due to speed in specific operating applications. As they have been developed over many years in different regions of the world, they may not accurately reflect the operating conditions found in North America. To determine the applicability of these formulas to the North American operating environment, wheel impact load detector (WILD) data was used to compare actual loading data to predicted speed-induced gains. WILD sites are typically constructed on well-maintained tangent track with concrete crossties, premium ballast, and well-compacted subgrade to reduce sources of load variation within the track structure. Although loads experienced elsewhere on the network will vary and may have a higher magnitude due to track geometry deviations, these data still provide insight to the varied loading landscape at representative sites throughout North America. Specific loading properties, such as peak vertical load, peak lateral load, impact factor, and speed are analyzed by creating various distributions of these properties and determining relationships between them. Figure 2 shows an example of locomotive, freight car, and passenger coach wheel load data to be compared with the plotted dynamic factors. Table 3 displays the distribution of static wheel loads for

Table 1. Summary of dynamic factors (adapted from Doyle[4]).

		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 (Hay[10])	$1+\frac{33V}{100D}$	•	•										
Indian Railways (Srinivasen[11])	$1+\frac{V}{3\sqrt{U}}$	•						•					
Eisenmann (Esveld[12])	$1+\delta\eta t$	•											•
ORE/Birmann (Birmann[13])	$1+\alpha+\beta+\gamma$	•				•	•				•	•	•
German Railways (Schramm[5])	$1+\frac{11.655V^2}{10^5}-\frac{6.252V^3}{10^7}$	•											
British Railways (Doyle[4])	$1+14.136(\alpha_1+\alpha_2)V\sqrt{\frac{D_jP_u}{g}}$	•		•	•				•	•			
South African Railways (Doyle[4])	$1+0.312\frac{V}{D}$	•	•										
Clarke (Doyle[4])	$1+\frac{15V}{D\sqrt{U}}$	•	•					•					
WMATA (Prause et al.[6])	$(1+0.0001V^2)^{\frac{2}{3}}$	•											
Sadeghi (Sadeghi and Barati[7])	$1.098+0.00129V+2.59(10^{-6})V^2$	•											
AREMA C30	For $20<V<120: 0.6+0.005V$	•											

Table 2. Variable definitions for Table 1.

Variable	Definition
V	Train speed (mile/h)
D	Wheel diameter (inches)
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 chosen upper confidence limits defining probability of exceedance
α	Coefficient dependent on level of track, vehicle suspension and vehicle speed, estimated to be $0.167(V/100)^3$ in most unfavorable case
β	Coefficient dependent on wheel load shift in curves (zero in tangent track)
γ	Coefficient dependent on vehicle speed, track age, possibility of hanging crossties, vehicle design, and locomotive maintenance conditions, estimated to be $0.10+0.071(V/100)^3$ in 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)

different types of rolling stock shown in Figure 2. To adequately assess the effectiveness of each of the previously developed dynamic factors, several evaluative metrics are considered for each factor (Table 4). The speed-weighted signed difference and load-weighted signed difference were developed to provide a different perspective by weighting train speed and static load, respectively.

WILD data may underestimate the actual loading conditions, due to the sites being built with premium components to remove the variation in load resulting from irregularities in the track geometry and support conditions. However, these data still provide loading information representative of the rail network as a whole, and are sufficient for the comparison of the effectiveness of dynamic factors.[14]

As shown in Table 1, many of the dynamic factors incorporate other parameters. Therefore, several parameters must be held constant to maintain effective comparisons with respect to speed (Table 5). Two factors have been omitted from the analysis. As the dynamic factor developed for British Railways is appropriate only at rail joint dips, it is not appropriate to evaluate its effectiveness using WILD data. Also, as the AREMA speed factor is used in combination with an impact factor and is applied as an upper bound at the rail seat, it is not necessarily appropriate to compare it with other factors that should be used to predict wheel loads.

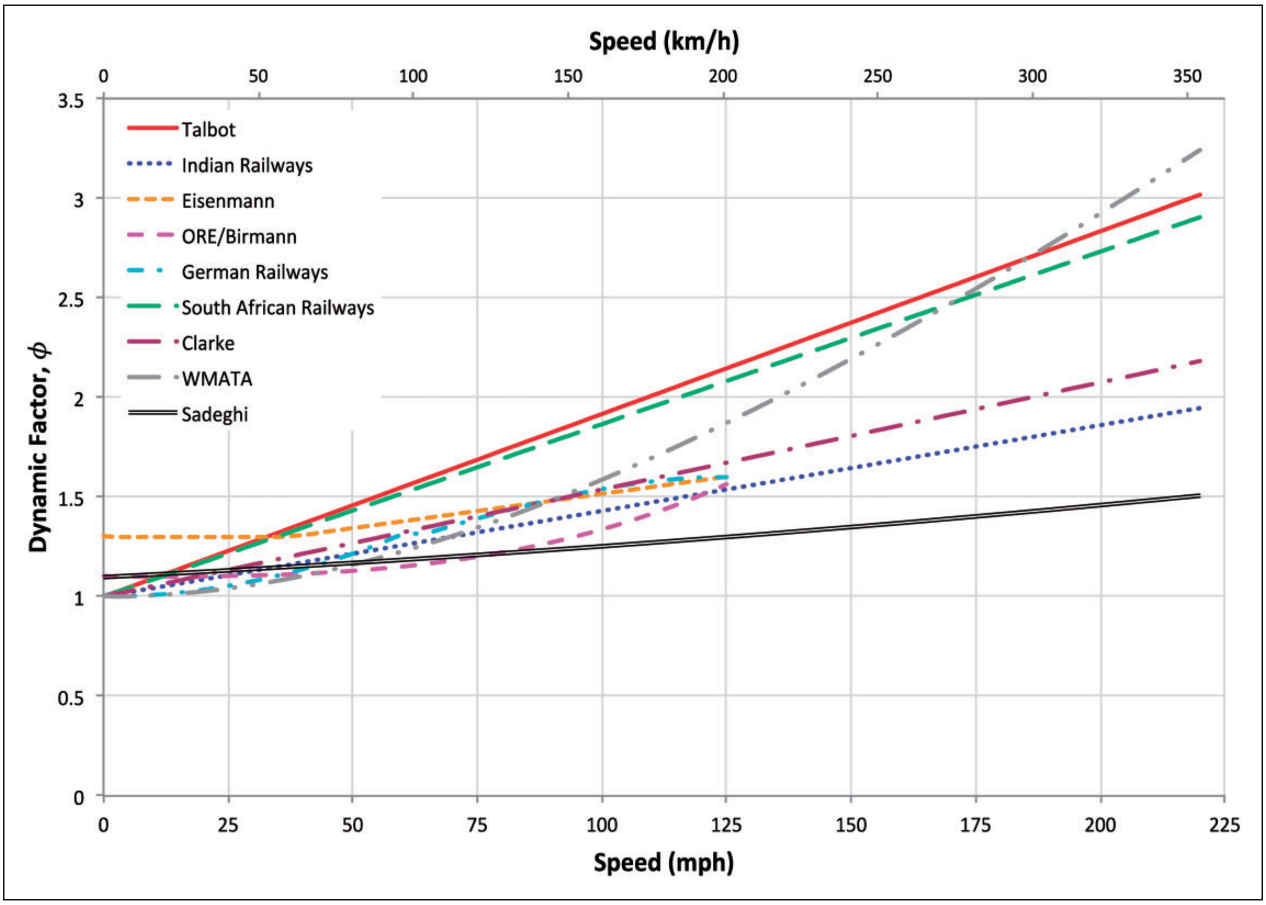

Figure 1. Design dynamic factors increasing due to speed (1 mile/h = 1.609 km/h).

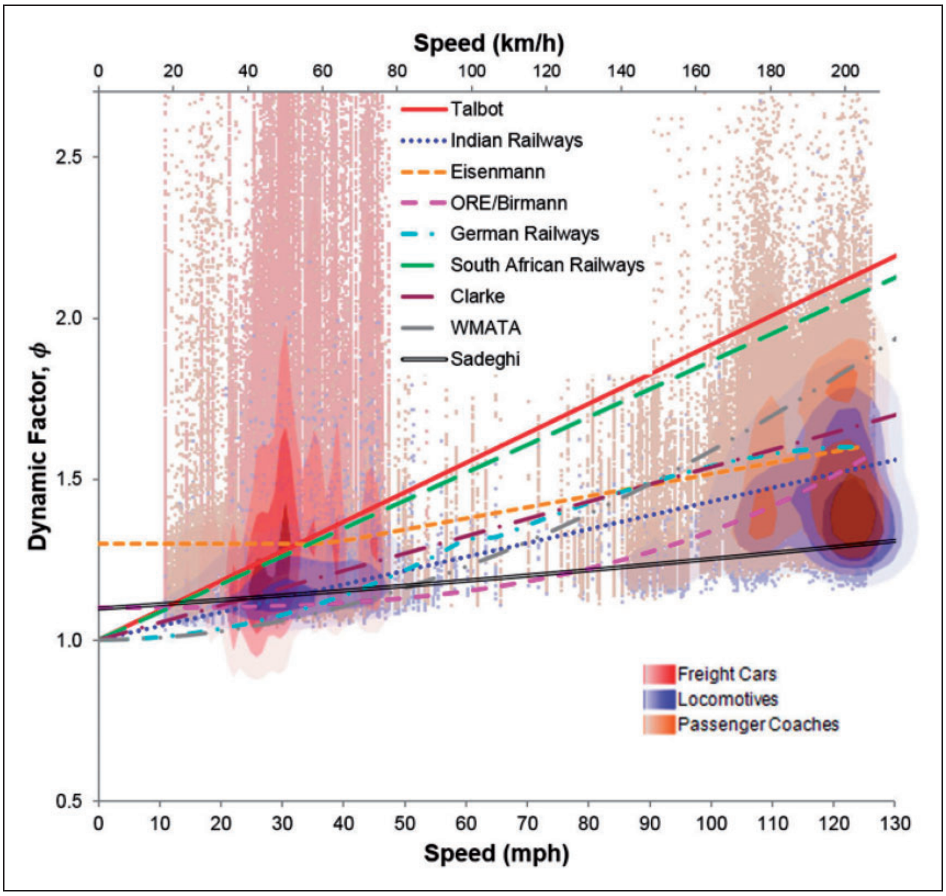

Figure 2. Peak/nominal wheel load ratios on Amtrak at Edgewood, Maryland (WILD data from November 2010) and design dynamic factors (1 mile/h = 1.609 km/h).

Table 3. Distribution of static wheel loads.

Car type	Nominal load (kips), by percentile								
	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

Note: Freight data: UPRR – Gothenburg, NE, January 2010. Passenger data: Amtrak – Edgewood, MD; Hook, PA; and Mansfield, MA, November 2010. 1 kip = 4.45 kN.

Table 4. Definitions of dynamic factor evaluative metrics.

Percent exceeding: percentage of wheels exceeding predicted dynamic factor

Mean signed difference: summarizes how well an estimator matches the quantity that it is supposed to estimate:

$$\sum_{i=1}^{n} \frac{f(x_i) - y_i}{n}$$

x_i is the speed of a single wheel
y_i is the ratio of the peak vertical load to the nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Mean percentage error: computed average of percentage errors by which predictions of a model differ from actual values of the quantity being predicted:

$$\frac{100\ \%}{n} \sum_{i=1}^{n} \frac{f(x_i) - y_i}{y_i}$$

x_i is the speed of a single wheel
y_i is the ratio of the peak vertical load to the nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Root mean square deviation: measures differences between values predicted by the estimator and the actual recorded values (absolute value):

$$\sqrt{\frac{\sum_{i=1}^{n} (f(x_i) - y_i)^2}{n}}$$

x_i is the speed of a single wheel
y_i is the ratio of the peak vertical load to the nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Speed-weighted signed difference: signed difference, with weight given for the speed of the wheel:

$$\frac{\sum_{i=1}^{n} (x_i f(x_i) - x_i y_i)}{\sum_i^x}$$

x_i is the speed of a single wheel
y_i is the ratio of the peak vertical load to the nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Load-weighted signed difference: signed difference, with weight given for the nominal wheel load:

$$\frac{\sum_{i=1}^{n} (Q_i f(x_i) - Q_i y_i)}{\sum_i^Q}$$

Q_i is the nominal load of a single wheel
x_i is the speed of a single wheel
y_i is the ratio of the peak vertical load to the nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

The evaluation was performed using data from three WILD sites (Mansfield, Massachusetts; Hook, Pennsylvania; and Edgewood, Maryland) on Amtrak's Northeast Corridor that experience both higher-speed intercity passenger service as well as freight service. After removing the wheels recorded in error (e.g. no nominal load) all remaining wheels that traveled over those sites for a month (November 2010) were tabulated and a value for each dynamic factor was calculated based on the speed of the particular wheel and the parameters as found in Table 5. Due to some of the dynamic factors having ranges in train speed where they are applicable, those values were calculated using only speeds for which that particular dynamic factor is appropriate. The calculated, or expected, dynamic factor was then compared with

Table 5. Parameters held constant for dynamic factor evaluation (1 in = 25.4 mm, 1 psi = 0.006895 MPa).

Parameter	Constant Value	Justification
Wheel diameter, *D*	36 in (914 mm)	Typical value for many freight and passenger vehicles in North America
Track modulus, *U*	6000 psi (41 MPa)	Representative of well-maintained concrete-tie track (as found at WILD site)
Track quality, δ	0.1	Representative of track in very good condition (as found at WILD site)
Confidence factor, *t*	3	Upper confidence limit of 99.7%, applicable for rail stresses, fastenings, and ties

Table 6. Evaluation of dynamic factors.

	Dynamic factors								
Evaluation metric	Talbot	Indian Railways	Eisenmann	ORE/Birmann	German Railways	South African Railways	Clarke	WMATA	Sadeghi
Percent exceeding	0.23	0.61	0.37	0.75	0.56	0.25	0.45	0.48	0.89
Mean signed difference $\sum^{\frac{(f(x_i)-y_i)}{n}}$	0.20	-0.19	-0.081	-0.25	-0.16	0.16	-0.10	-0.074	-0.31
Mean percentage error $\frac{100\ \%}{n}\sum^{(} f\,(x_i) - y_i)/y_i$	18	-7.6	0.23	-12	-5.9	16	-1.9	-0.38	-16
Root mean square deviation $\sqrt{\sum^{(f(x_i)-y_i)} 2/n}$	0.61	0.53	0.51	0.57	0.56	0.59	0.52	0.57	0.57
Speed-weighted signed difference $\sum^{(} x_i f(x_i) - x_i y_i)/\sum_i^x$	0.37	-0.12	-0.031	-0.18	-0.058	0.38	-0.009	0.079	-0.29
Load-weighted signed difference $\sum^{(} Q_i f(x_i) - Q_i y_i)/\sum_i^Q$	0.24	-0.13	-0.018	-0.19	-0.11	0.20	-0.051	-0.027	-0.25

the ratio of peak vertical wheel load to nominal wheel load using the metrics found in Table 4. The results of this comparison are shown in Table 6 and, in part, graphically in Figures 3 to 5.

As is shown in Figure 3, there are significant differences between many of the dynamic factors. Positive signed differences, positive mean percentage error, and a low percentage exceedance indicate that the Talbot and South African Railways dynamic factors are fairly conservative when compared with actual loading data. The WMATA speed factor can also be considered conservative by the speed-weighted signed difference metric (likely due to the magnitude of this factor at high speeds, as shown in Figure 1). The other dynamic factors are not overly conservative by any of the metrics; however, this does not indicate that they are necessarily poor dynamic factors.

To better estimate the effect of speed, a linear estimate of wheel load data was developed using WILD data. To isolate the effect of speed, locomotive wheel loads are initially examined for this analysis. In the authors' opinion, these wheels are more likely to be more consistently maintained and impart fairly reliable static loads. Therefore, the effect of wheel condition and nominal load can be minimized. The change in dynamic factor due to speed can be expressed as following and is illustrated in Figure 4.

$$\frac{Peak}{Nominal} = 1.099 + 0.00386(Speed\,(\text{mile/h}))$$

Although many of the wheel loads do exceed the predicted dynamic factor, it is likely not due to speed. There are factors that affect the magnitude of wheel load other than speed.[14] These factors can be more appropriately incorporated into an impact factor.

Definition and evaluation of impact factor

As shown in Figure 2, many wheels create loads much higher than those expected due solely to speed. As the dynamic factor does not adequately represent actual loading conditions in terms of impact loads, an additional factor should be utilized. The impact factor is

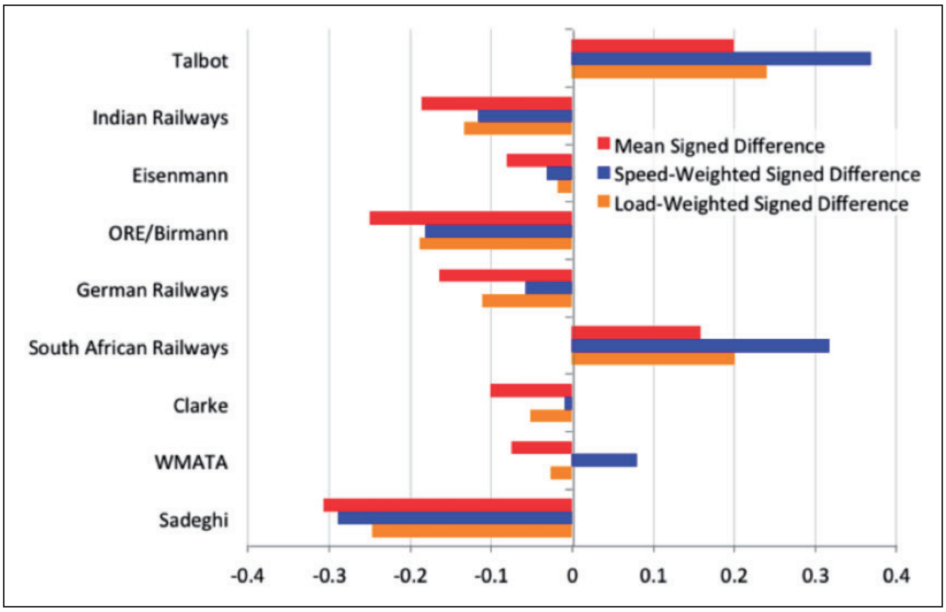

Figure 3. Mean signed difference, speed-weighted signed difference and load-weighted signed difference between predicted dynamic factor and peak/nominal ratios.

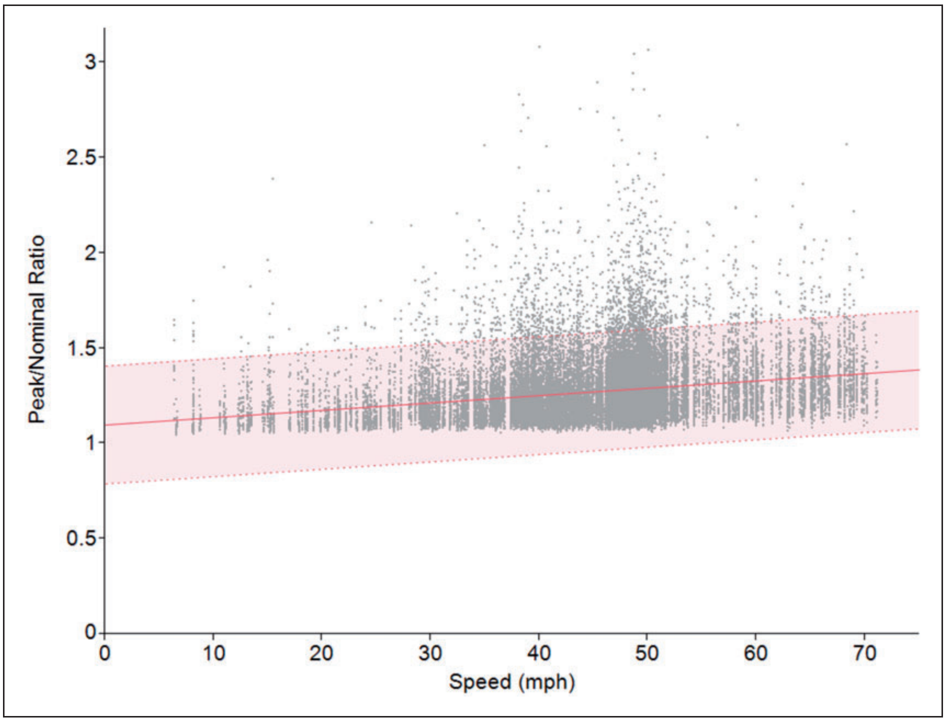

Figure 4. Linear estimate for the dynamic factor on the Union Pacific Rail Road at Gothenburg, Nebraska (locomotive WILD data from January 2010) (1 mile/h = 1.609 km/h).

extensively used in bridge design and has been a part of concrete crosstie design since the inception of AREA's design recommendations.[9]

The AREMA manual defines the impact factor as a percentage increase over static vertical loads intended to estimate the dynamic effect of wheel and rail irregularities.[8] An impact factor of 50% was first used, and has incrementally increased to today's 200% level.[9] A 200% increase above static load indicates that the design load is three times the static load, hereafter referred to as an impact factor of three. The impact factor of three specified by the AREMA manual is designed to calculate the maximum design load carried by the track components, and it takes into account the dynamic effect of wheel and rail irregularities, as well as other factors that place increased stress on the railroad infrastructure.

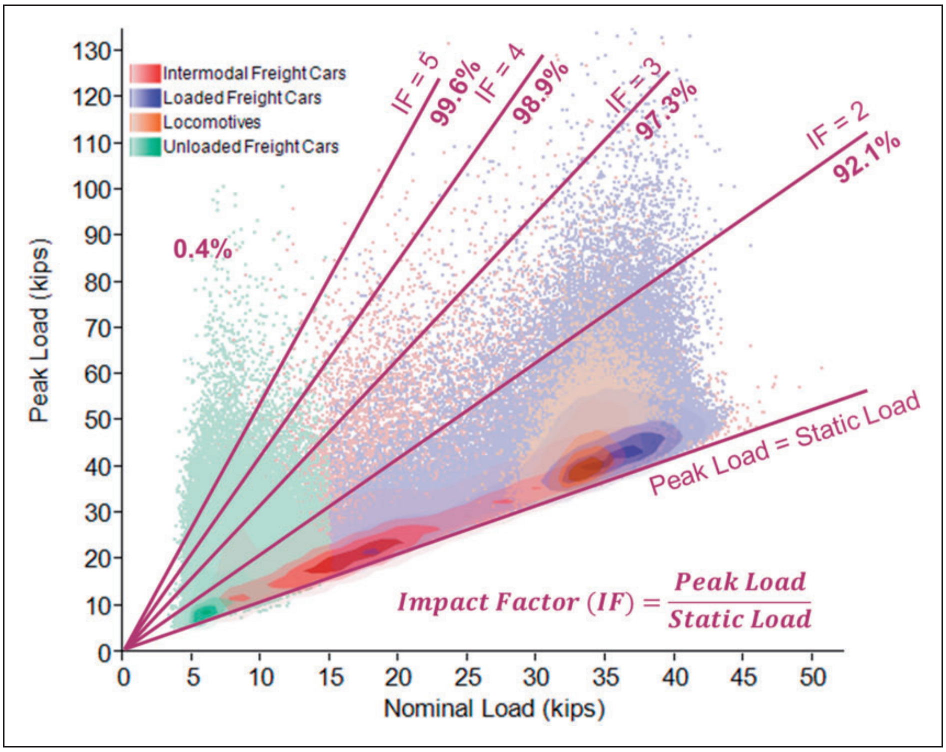

Figure 5. Relationship between peak and nominal wheel loads on UPRR at Gothenburg, Nebraska (WILD data from January 2010) and design impact factors (1 kip = 4.45 kN).

Due to the impact factor described in this portion of the recommended practices being specifically related to the flexural performance of the crosstie, it may not be representative of the loads experienced at the wheel/rail interface. Therefore, additional impact factors that may better represent wheel-loading conditions are now explored.

WILD data is again used to evaluate the effectiveness of the AREMA chapter 30 impact factor[8] and other theoretical impact factors. Figure 5 shows actual wheel loading at Union Pacific Rail Road's (UPRR's) Gothenburg, Nebraska WILD site compared with predicted loads based on various impact factors. These data include locomotive, intermodal freight car, non-intermodal loaded freight car, and non-intermodal unloaded freight car wheel loads. For the purpose of this figure, "unloaded freight cars" include any non-intermodal freight car whose nominal wheel load is less than 15 kips. Other freight WILD sites yielded similar results, whereas passenger coach wheels on Amtrak's network exceeded the design impact factors more frequently.

As shown in Figure 5, the impact factor of three as found in AREMA chapter 30 exceeds the majority of the locomotive and loaded freight car loads. As lighter rolling stock (i.e. passenger coaches and unloaded freight cars) have lower static loads, a higher impact factor can be attained with peak loads similar to those seen with other equipment. Therefore, for these types of vehicles, either a greater impact factor or a different design tool that more effectively represents the complete loading spectrum may need to be used.

Alternative design parameter: Peak tonnage

Although dynamic and impact factors have been used in design studies for close to a century, it is clearly difficult to design based solely on these factors. There is too much variability to be able to cover entire rail networks or even one line with a simple factor. It is, therefore, worthwhile to pursue alternative design parameters to supplement the factors already in use.

Infrastructure owners are typically well aware of the tonnage that traverses each segment of their network. However, this value is calculated by summing the static load of each vehicle, which is not always the best estimate for the actual load entering the track structure.[14] Therefore, the tonnage that is typically reported, or the "static tonnage" may not necessarily represent true field conditions. By accumulating the peak load of each wheel that passes a WILD site, the "peak tonnage" of a line can be calculated.

Tables 7 and 8 represent the total tonnage at UPRR's Gothenburg, Nebraska WILD site. The trends are fairly consistent between years, as shown by the peak-to-nominal wheel load difference per wheel. Table 9 shows similar information at UPRR's Sunset, California WILD site, which sees more intermodal traffic.

Similar measures can be tabulated on mixed-use lines utilizing data from Amtrak's Northeast Corridor (Tables 10 and 11). Due to the traffic composition and maintenance of rolling stock differing

Table 7. Tonnage totals on the UPRR at Gothenburg, Nebraska (WILD data from 2010) (1 ton = 0.907185 tonnes).

Car type	Number of wheels	Nominal tonnage (tons)	Peak tonnage (tons)	Difference (tons)	Difference per wheel (tons)
Locomotives	965,718	16,291,645	20,293,696	4,002,051	4.14
Intermodal freight cars	3,001,656	28,778,161	38,562,442	9,784,281	3.26
Other freight cars	20,204,202	144,556,403	197,330,434	52,774,031	2.61
Total	24,171,576	189,626,209	256,186,572	66,560,363	2.75

Note: 1 ton = 0.91 tonnes.

Table 8. Tonnage totals on the UPRR at Gothenburg, Nebraska (WILD data from 2011) (1 ton = 0.907185 tonnes).

Car type	Number of wheels	Nominal tonnage (tons)	Peak tonnage (tons)	Difference (tons)	Difference per wheel (tons)
Locomotives	959,858	16,237,983	20,170,318	3,932,335	4.09
Intermodal freight cars	2,651,116	25,353,219	33,885,533	8,532,314	3.22
Other freight cars	20,571,408	140,831,724	194,917,926	54,086,202	2.63
Total	24,182,382	182,422,926	248,973,777	66,550,851	2.75

Note:1 ton = 0.91 tonnes.

Table 9. Tonnage totals on the UPRR at Sunset, California (WILD data from 2011) (1 ton = 0.907185 tonnes).

Car type	Number of wheels	Nominal tonnage (tons)	Peak tonnage (tons)	Difference (tons)	Difference per wheel (tons)
Locomotives	165,896	2,793,015	3,437,503	644,488	3.88
Intermodal freight cars	749,760	6,133,002	9,017,303	2,884,301	3.85
Other freight cars	1,001,596	9,785,716	14,065,909	4,280,193	4.27
Total	1,917,252	18,711,733	26,520,715	7,808,982	4.07

Note:1 ton = 0.91 tonnes.

Table 10. Tonnage totals on Amtrak at Hook, Pennsylvania (WILD data from 2011) (1 ton = 0.907185 tonnes).

Car type	Number of wheels	Nominal tonnage (tons)	Peak tonnage (tons)	Difference (tons)	Difference per wheel (tons)
Passenger locomotives	234,950	2,986,719	3,922,364	935,645	3.98
Freight locomotives	11,523	186,060	209,773	23,713	2.06
Passenger coaches	1,529,770	26,040,498	35,181,894	9,141,396	5.98
Intermodal freight cars	12,135	119,534	138,446	18,912	1.56
Other freight cars	77,746	778,616	938,637	160,021	2.06
Total	1,866,124	30,111,427	40,391,114	10,279,687	5.51

Note: 1 ton = 0.91 tonnes.

greatly along the corridor, the measurements vary to a significant extent between sites.

Design processes that involve tonnage may be able to take advantage of existing peak tonnage values and apply them to other segments with a similar traffic composition. Those that are more axle-load-oriented may be able to use the appropriate "difference per wheel" value in addition to the expected static loads on a particular line. This measurement helps to provide an accurate increase of load; however, it does not address the particular reasons for an increase.

It should be noted that the peak tonnage measurement is not a completely accurate representation of the actual tonnage. As the values are obtained using "peak" loads over a discrete length of track

Table 11. Tonnage totals on Amtrak at Mansfield, Massachusetts (WILD data from 2011) (1 ton = 0.907185 tonnes).

Car type	Number of wheels	Nominal tonnage (tons)	Peak tonnage (tons)	Difference (tons)	Difference per wheel (tons)
Passenger locomotives	161,161	2,346,728	3,394,357	1,047,629	6.50
Freight locomotives	14,304	249,835	303,458	53,623	3.75
Passenger coaches	831,735	11,856,667	21,325,896	9,469,229	11.38
Intermodal freight cars	4276	34,771	53,171	18,400	4.30
Other Freight cars	139,953	1,308,788	1,865,539	556,751	3.98
Total	1,151,429	15,796,789	26,942,421	11,145,632	9.68

NOTE: 1 ton = 0.91 tonnes

(16 crosstie cribs[15]), the majority of the track structure may not experience loads at such a high magnitude. However, the quantities are also measured at well-maintained WILD sites, eliminating any track-related increase in loads. Therefore, the peak tonnage may provide an adequate estimation of actual tonnage.

Conclusions

There have been many efforts to quantify the effect of speed and irregularities in the form of dynamic and impact factors, respectively. As shown in this paper, some represent today's loading environment in North America better than others. Depending on the metric used to evaluate each factor, the factors vary in their conservatism. The appropriate level of design should be selected by the infrastructure owner, and more than one factor may be necessary in determining the design wheel load for the track infrastructure. Higher-degree estimates and dynamic factors that include other parameters may be developed and evaluated in the future to better represent the dynamic wheel-loading environment. Rigorous statistical methods may be used to effectively model the effect of speed and many other factors.

An additional design parameter methodology has been proposed, providing additional information that was not necessarily evident with the dynamic and impact factors. Multiple factors may be needed to adequately represent the existing wheel loads on the North American rail network and improve the design of the critical components that constitute the track structure.

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References

1. Standards Australia International. *Part 14: Prestressed Concrete Sleepers*. Australian Standard, Railway Track Material, Sydney, Australia, 2003.
2. Andersson E, Berg M and Stichel S. *Rail vehicle dynamics*. Report no., 2013. Stockholm, Sweden: KTH, Royal Institute of Technology.
3. Kerr AD. *Fundamentals of railway track engineering*. Omaha, NE: Simmons-Boardman Books, 2003.
4. Doyle NF. *Railway track design: a review of current practice*. Report no., 1980. Melbourne, Australia: BHP.
5. Schramm G. *Permanent way technique and permanent way economy*. Darmstadt, Germany: Otto Elsner Verlagsgesellschaft, 1961.
6. Prause RH, Meacham HC, Harrison HD, et al. *Assessment of design tools and criteria for urban rail track structures*. Washington, DC: Urban Mass Transportation Administration, Report no., 1974. Department of Transportation.
7. Sadeghi J and Barati P. Evaluation of conventional methods in analysis and design of railway track system. *Int J Civil Engng* 2010; 8: 44–56.

8. American Railway Engineering and Maintenance-of-Way Association. *AREMA manual for railway engineering*. Lanham, MD: American Railway Engineering and Maintenance-of-Way Association, 2012.
9. McQueen PJ. *Flexural performance requirements for prestressed concrete ties by factoring*. Report no., 2010. San Rafael, CA: Philip J. McQueen Corporation.
10. Hay WW. *Railroad engineering*. New York, NY: John Wiley & Sons, 1953.
11. Srinivasan M. *Modern permanent way*. Mumbai, India: Somaiya Publications, 1969.
12. Esveld C. *Modern railway track*. Zaltbommel, The Netherlands: MRT Productions, 2001.
13. Birmann F. Track parameters, static and dynamic. *Proc IMechE, Conf Proc* 1965; 180: 77–79.
14. Van Dyk BJ, Dersch MS, Edwards JR, et al. Quantifying shared corridor wheel loading variation using wheel impact load detectors. In: *The 2013 joint rail conference,* Knoxville, TN, 2013.
15. GeMeiner W. Workshop 139 - Leveraging of WILD vertical force data at Union Pacific. In: *The Transportation Research Board Annual Meeting*, Washington, DC: TRB, 9–13 January 2005.