TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Article

Transportation Research Record
2018, Vol. 2672(10) 136–145

DOI: 10.1177/0361198118793500
journals.sagepub.com/home/trr
SAGE

Quantification of Loading Environment and Flexural Demand of Prestressed Concrete Crossties under Shared Corridor Operating Conditions

Ricardo J. Quirós-Orozco[1], J. Riley Edwards[1], Yu Qian[2], and Marcus S. Dersch[1]

Abstract

Optimization of the design of railway infrastructure and its components requires a comprehensive understanding of the loading demands that are expected. Currently, many design guidelines for track components use historical wheel loads and calculate bending moments based on broad assumptions. However, tools are available to accurately quantify and characterize the variability each load has on a particular component. This is particularly important in shared use rail corridors where higher speed passenger services operate on the same infrastructure as heavy axle load (HAL) freight trains. Each traffic type generates unique demand variabilities, and these should be incorporated into a holistic approach to optimized track design. Therefore, researchers at the University of Illinois at Urbana-Champaign (UIUC) are conducting field research aimed at the characterization of field conditions on Amtrak's Northeast Corridor through the use of wheel impact load detector (WILD) data and concrete crosstie surface strain gauges. Results from this experimentation show high variability of loads resulting from varied types of train operations and significant differences in impact load ratios. Finally, laboratory measured flexural capacity for the concrete crossties showed a conservative design with a potential margin of improvement in reduction of residual capacity (i.e., factor of safety).

Amtrak's Northeast Corridor (NEC) is the most densely traveled rail corridor in the United States, with almost 11.7 million annual passengers traveling on Amtrak services and another 250 million annual commuter rail passengers distributed among eight operators (*1*). In addition, the corridor is traversed by approximately 50 freight trains per day from two Class I freight railroads. As such, the corridor's infrastructure experiences a variety of loading conditions ranging from heavy axle load (HAL) freight operations to high-speed passenger train services. Historically, the track structure and components such as crossties have been designed through a process based to a large extent on practical experience (*2*) or have assumed simplistic static loading cases. Optimization of track components for highly variable loads and speed requires an in-depth understanding of the effect of each service.

Before this study, research efforts had been undertaken to better understand the loading environment and improve design methodologies on HAL freight and intercity passenger rail corridors (*3, 4*). These efforts were accomplished, in part, through the analysis of data from wayside systems used for monitoring the performance of rolling stock such as the wheel impact load detector (WILD) (*5*). On a component level, surface strain gauge instrumentation has been used successfully in the quantification of flexural demands on concrete crossties (*2, 6*). In the case of Amtrak's NEC, field instrumentation dates back to 1983 when one of the first WILD sites was deployed to address the causes of transverse rail seat cracks in concrete crossties (*7*). The use of both WILD sites and instrumented crossties allows for a comprehensive characterization of the demand to which the track and its components are subjected. These data, when

[1]Rail Transportation and Engineering Center (RailTEC), Department of Civil and Environmental Engineering (CEE), University of Illinois at Urbana-Champaign (UIUC), Urbana, IL
[2]Department of Civil and Environmental Engineering, The University of South Carolina, Columbia, SC

Corresponding Author:
Address correspondence to Ricardo J. Quirós-Orozco: rjq2@illinois.edu

evaluated in conjunction with supporting laboratory experimental data facilitate the evaluation of the efficiency of a design to support the actual field loading demands. This analysis was performed as part of a project devoted to improvement of concrete crosstie specifications for Amtrak's NEC.

Overview of Field Instrumentation

WILD

A WILD is an electronic data collection device designed to measure and isolate vertical and lateral wheel forces with the use of either rail mounted strain gauges or accelerometers (*8, 9*). Although its primary objective is to evaluate the performance of the rolling stock and measure the impact forces caused by out-of-round or otherwise damaged wheels (*9, 10*), it has also proven to be a practical mechanism for producing reliable wheel load data that can serve rail infrastructure researchers and practitioners (*2*).

A common strain gauge–based WILD site is over 15 m (50 ft) in length, with a series of strain gauges microwelded to the neutral axis of the rail's web. They quantify the wheel load by a direct mathematical or a calibrated relationship between strain and force (*9*). Instrumentation is divided into several ballast cribs at various intervals to capture a single wheel's rotation up to five times, recording peak impact and average forces at a data collection rate of up to 30 kHz (*7, 11*). Electronic signal processors housed in a wayside enclosure analyze the data using an algorithm which isolates wheel tread irregularities and computes both nominal and peak load values (*12*). Rail infrastructure owners commonly define loading thresholds according to their operational procedures which facilitate the delivery of alerts when limits are exceeded (*8*). A WILD located adjacent to the surface strain–gauged crossties on Amtrak's NEC can provide information related to nominal load, dynamic load, peak load as well of peak ratios lateral load, car type, lateral load, hunting index, and speed. Further processing of WILD data was used to create a loading input database on which the present analysis is based.

Concrete Crosstie Surface Strain Gauges

Researchers in the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) have previously used surface mounted strain gauges to measure bending moments experienced by concrete crossties under revenue service HAL freight trains (*13*) and in rail transit applications (*14*). In the case of Amtrak's NEC, temporary instrumentation of concrete crossties was performed in 1983 to identify causes of premature cracks (*7*) and again in 2014 to investigate a later generation of crosstie design and performance questions (*15*).

Field experimentation for this project was conducted in Edgewood, Maryland. Researchers instrumented a total of seven crossties on Track 2 (which handles primarily northbound traffic) near an operative WILD that provided wheel loads for the project. The sensors deployed allowed for the quantification of bending strains at discrete locations along the length of the crosstie caused by train loading (Figure 1). Surface strain gauges were oriented longitudinally along the chamfer near the top surface of the crosstie. Four crossties were instrumented with three gauges: under the two rail seats and one in the center of the crosstie. A fifth crosstie was instrumented with two additional gauges located halfway between each rail seat and center. Finally, two external crossties were instrumented with a single center strain

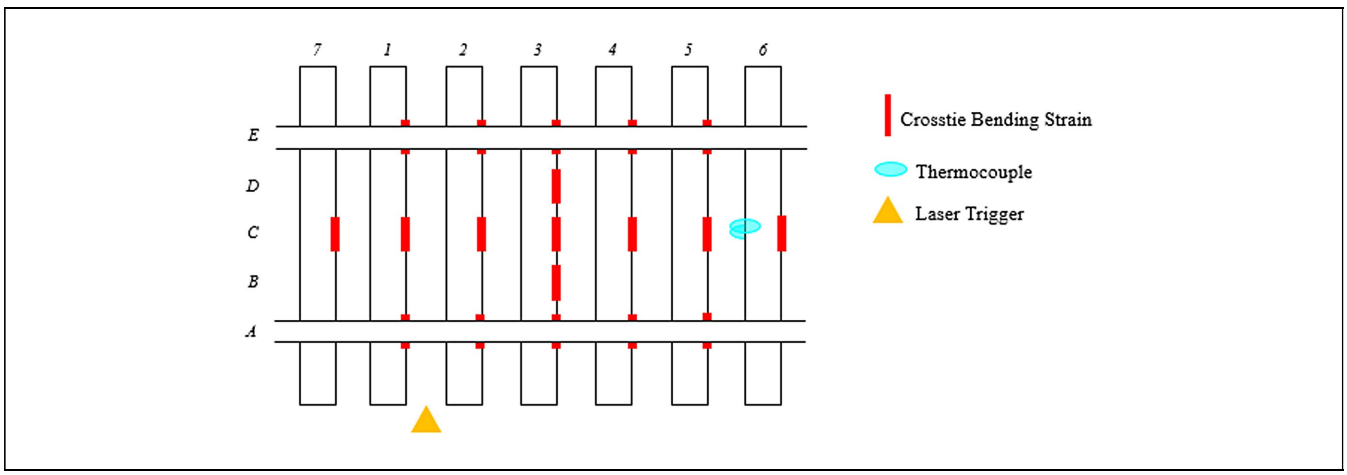

Figure 1. Plan view of instrumented crosstie section on Amtrak's NEC in Edgewood, Maryland.

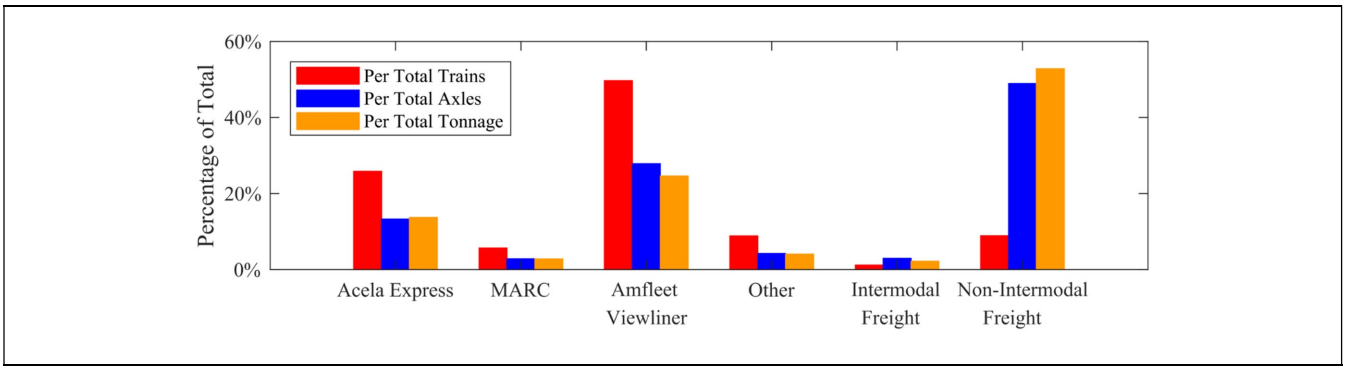

Figure 2. Distribution of services on the Amtrak NEC Edgewood, MD field site by total number of trains, axles, and gross tonnage.

gauge to capture additional bending data at the crosstie center given its critical nature as a design region. Independently of strain gauge instrumentation, thermocouples were deployed to capture ambient, top, and bottom of crosstie temperature. Collection of data using the aforementioned forms of instrumentation was automatically initiated through the use of a laser monitoring the track. Autonomous operation of the site allowed for uninterrupted data collection for weeks at a time.

Concrete crosstie calibration factors were determined through laboratory experimentation to relate the measured strains to a known bending moment, through a process that was detailed by Edwards et al. (*6*). In summary, these parameters were found by instrumenting several crossties of the same design and vintage as those installed in track using the same strain gauge layout as was used in the field. A calibrated load was applied to each crosstie at its rail seats in a configuration adapted from the design validation tests presented in Chapter 30, Section 4.9 of the American Railway Engineering and Maintenance-of-way Association (AREMA) *Manual for Railway Engineering* (*16*).

Wheel Load Analysis

Nominal and Peak Loading (using WILD Data)

Data were collected and processed from the Amtrak NEC WILD site located in Edgewood, Maryland from 1 January to 30 June 2017. These data are an aggregate of the information available for the two tracks at the WILD site. As such, an average of 100 trains per day were recorded for a total of 18,117 trains, 1,127,422 axles and 19.28 million gross tons (MGT) during the analysis period. Passenger train services at this location vary widely and include Amtrak's Acela Express and multiple intercity and regional rail services using Viewliner and Amfleet rolling stock. Commuter rail service is operated by the Maryland Area Regional Commuter (MARC) Agency with a mixture of different passenger coaches and locomotives.

In terms of total number of trains, traffic is dominated by Amtrak's intercity services, followed by Acela Express and MARC commuter trains (Figure 2). Freight transport is the dominant traffic type when measured by both total axles and tonnage. The "Other" category relates to maintenance or inspection equipment and trains in which the automatic equipment identification (AEI) tag was not properly read as the vehicle passed by the WILD site.

Descriptive statistical analysis of the wheel load data allows for the comparison of the variability of the rolling stock currently in use along this section of Amtrak's NEC. Results for nominal loads are presented in Figure 3 as percentage exceeding curves for each train type classification. On further analysis of both tracks, it was found that the distribution of passenger services is quite similar, whereas loaded freight traffic mostly used Track 3 and empty freight trains typically operated on Track 2.

For passenger trains, the variation between the weight of cars and their respective power units can be seen from the bimodal nature of the data (i.e., sharp change of slope of the data) around the 20 kips (89 kN). The commuter rail service operated by MARC also shows the presence of two types of locomotives with a significant disparity in their static wheel loads, as evidenced by the gradual slope of the curve. For freight services, the disparity is particularly noticeable between empty and loaded freight cars within the non-intermodal category. Meanwhile, for the intermodal cars, one can observe a higher variability in loads because of the varied nature of their payloads.

Figure 4 shows the same data once dynamic and impact factor effects are considered. The dynamic load is the highest load that is captured by the WILD for a given wheel as it passes through the series of instrumented cribs (i.e., the maximum reading from all of the strain-gauged cribs). As expected, there is an increase in the magnitude of loads in all train type categories. Although the differences between passenger coaches and power units are still visible, the change is more gradual, indicating a relationship of the impact factor with the nominal load of each wheel. This effect is particularly

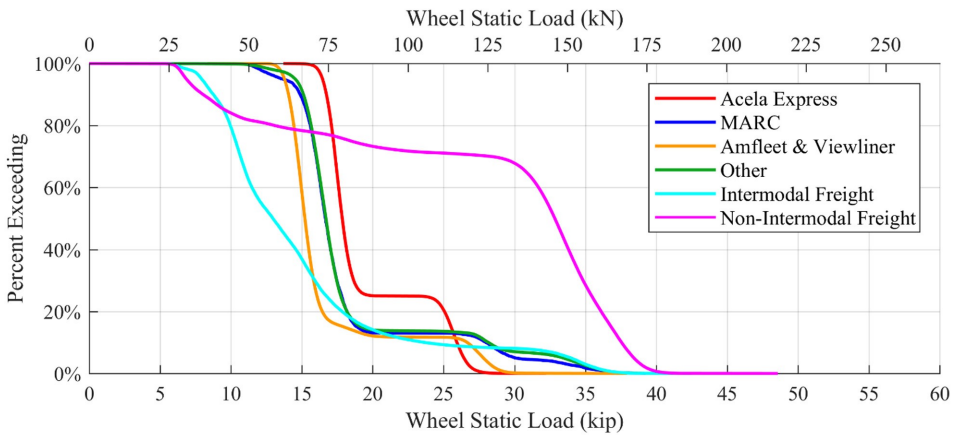

Figure 3. Nominal wheel load distribution on the Edgewood, MD field site by car type.

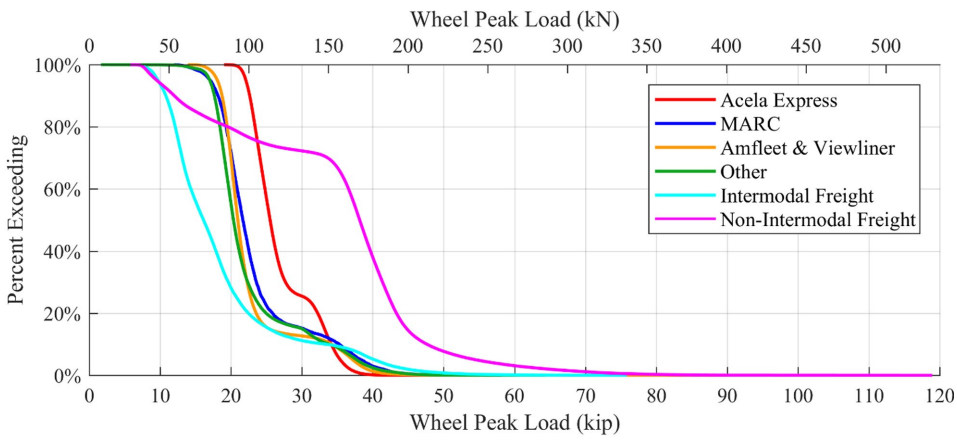

Figure 4. Peak wheel load distribution on the Edgewood, MD field site by car type.

noticeable for the HAL freight traffic, a possible indication that the impact factors for the empty cars are considerably higher than the loaded vehicles. Amfleet and Viewliner coaches also seem to have a higher average impact factor than MARC trainsets as the relationship between nominal and dynamic loads between both categories is reversed.

Impact Factory Variability

The relationship between nominal and dynamic loads for each wheel's passage is shown in Figure 5, in which black lines represent specific impact factor values. Most of the data (98.3% of all wheel loads) are located under the line representing an impact factor of 3 (200% over the nominal load), which is the design value proposed by AREMA for concrete crosstie design (*16*). Out of the 1.7% of wheels exceeding this threshold, the majority of wheels are from unloaded freight cars, with an average peak load of 27.9 kips (124 kN). This finding reinforces the assumption that 1) empty freight vehicles typically experience higher impact factors than loaded cars and 2) the total magnitude of these loads is unlikely to be damaging to the infrastructure, even with a high impact factor.

Flexural Bending Moments on Concrete Crossties

Flexural Bending Moments Results

Concrete crosstie bending moment data represent a subset of the total traffic passing Edgewood, MD on Track 2 during several multiweek time periods during the late

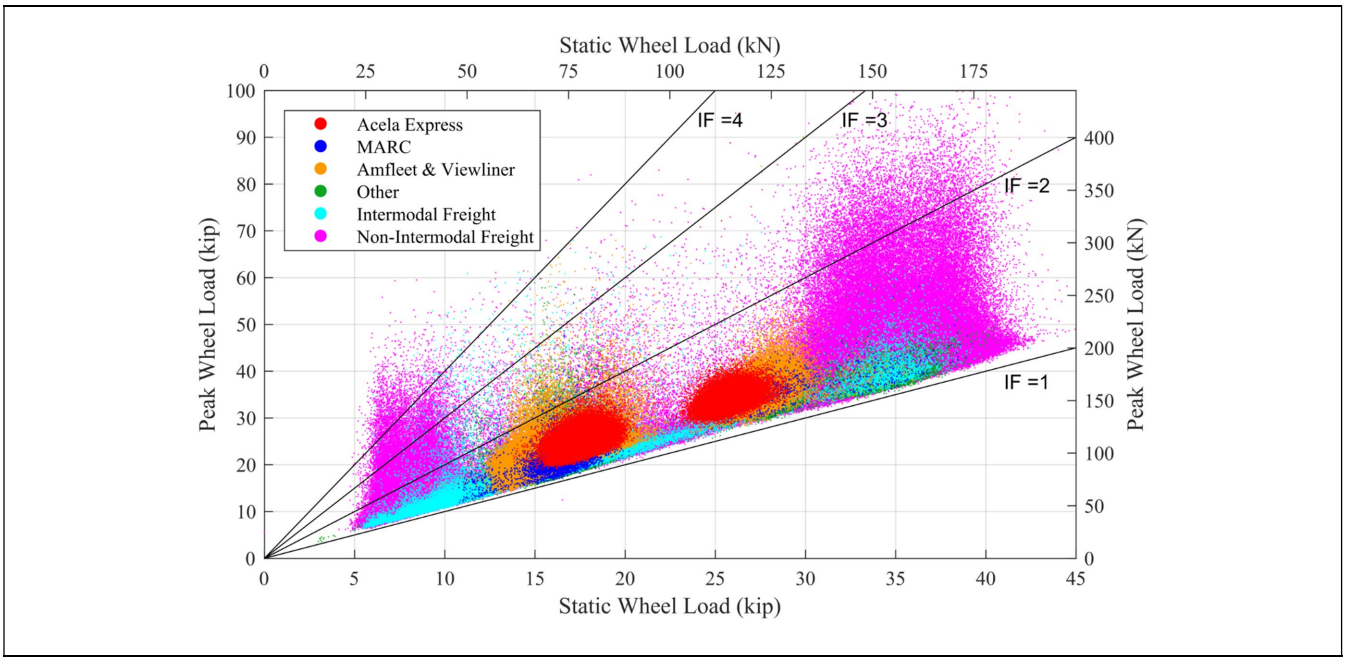

Figure 5. Relationship between static and peak wheel loads by vehicle classification.

part of 2016 and early 2017. In total, 4,612 trains were processed from 13 December 2016 to 17 May 2017. This dataset includes 4.5 out of the 7.6 MGT of traffic previously discussed with respect to WILD data.

Data processing techniques were required to identify peak data accurately. The most common noise encountered in strain gauges is related to typical alternate current (AC) interference at a frequency of 60 Hz (*17*). However, because of the presence of the electrified catenary on the NEC operating at 12 kV 25 Hz (*18*), interference in the strain gauge signal was identified at 25 Hz through visual analysis of the frequency spectrum. Filtering techniques based on the Chebyshev Type II band stop filter were used to remove the interference at the 25 Hz frequency and its harmonics.

Each dataset was compared with its respective WILD site data to obtain a classification of the rolling stock, quantify the number of axles and speed, and refine the processing algorithms. Descriptive statistics were prepared for bending moments the crossties were subjected to, based on the type of train traffic. Figures 6 and 7 show the results for the center and rail seat section, respectively.

As was expected, higher bending moments were recorded for loaded non-intermodal trains, reaching a maximum of 149 and 275 kips·in. [16.8 and 31.1 kN·m] for center negative and rail seat positive regions, respectively. It is important to note that these values have not reached the specified capacity of the crossties which are defined as 208 and 306 kips·in. [23.5 and 34.6 kN·m] for center negative and rail seat positive regions, respectively. Furthermore, laboratory quantified performance of the current crosstie design revealed actual first crack capacities of 347 and 487 kips·in. [39.2 and 55.0 kN·m] for center negative and rail seat positive regions, respectively. Center positive bending moments are likely to be related to temperature curling effects and associated changes in the support condition as well as relatively low magnitude vertical loads (*19*).

A comparison of the field bending moment data with the WILD site loads was performed to qualitatively assess the relationship between the variables. In general, there was a steady increase of bending moments as wheel load increased, as expected. However, it was also noted that center bending moments are not as sensitive to wheel load increases as rail seat moments are. This behavior was previously mapped to crossties with sufficient support under their rail seats (*20*), and good support under the rail seats is a plausible scenario considering the traffic characteristics at this location. A more detailed analysis of the support conditions for the site is presented in subsequent sections.

Detailed analysis of the top 10% of bending moments is presented in Table 1 as they reflect potential design level values. It is interesting to note the significant jump in the values from the two sources of data from the 99.5% to 100% percentiles in both flexural bending moment data and wheel peak loads.

Crosstie Support Condition Evaluation

Evaluation of ballast existing support conditions was performed through the use of a numerical back calculator

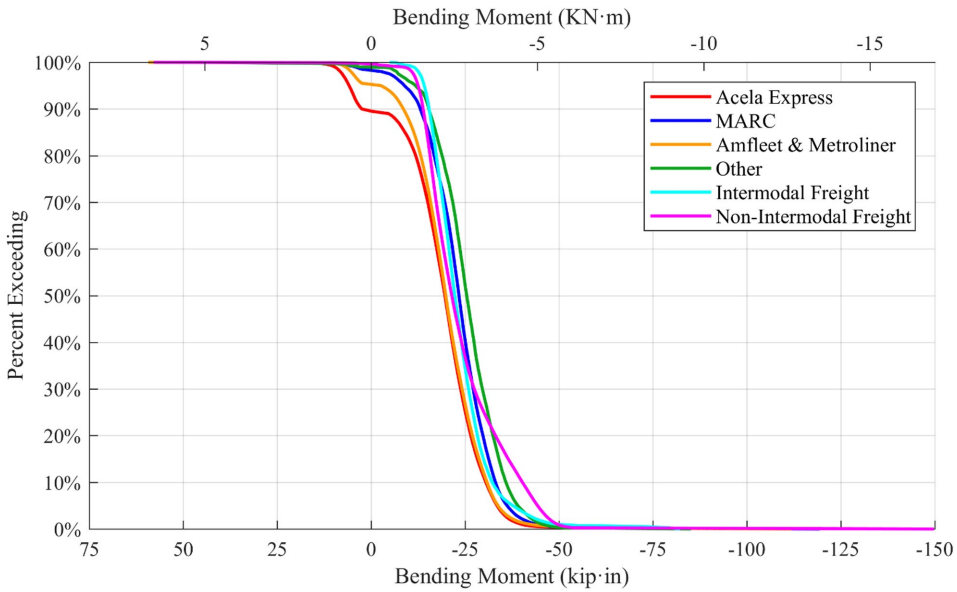

Figure 6. Flexural bending moments of prestressed concrete ties on the center region by train type.

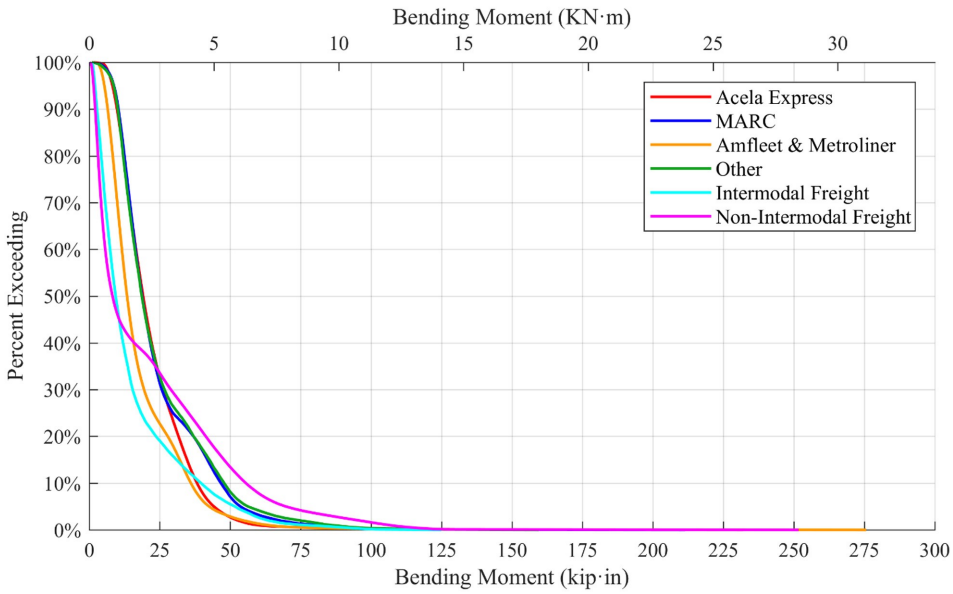

Figure 7. Flexural bending moments of prestressed concrete ties on rail seat region by train type.

developed by Gao et al. (*21*). This calculator uses bending moment profiles from instrumented concrete crossties and approximated rail seat loads using WILD data as inputs (*21*). Understanding the existing support condition on an instrumented site is a fundamental element in the analysis of data and prestressed concrete crossties as the bending moment is highly sensitive to variations of the support condition (*20*). The computational algorithm divides the crosstie into six bins and optimizes the percentage of total ballast reaction in each bin required to re-create the bending moment collected with the use of surface strain gauges in the field.

Table 1. Top Ten Percentiles of Peak Wheel Load and Bending Moment Data per Car Classification for the Edgewood, MD Field Site

Classification	Measured data	90%	95%	98%	99%	99.5%	100%
Acela	Wheel load (kips)[a]	33.9	35.2	36.2	37.5	38.6	50.5
	C- moments (kips·in.)[b]	2 31	2 34	2 36	2 40	2 44	2 111
	RS + moments (kips·in.)[b]	38	44	51	60	80	232
MARC	Wheel load (kips)[a]	31.9	38.5	41.1	43.3	44.9	57.4
	C- moments (kips·in.)[b]	2 33	2 36	2 39	2 44	2 48	2 119
	RS + moments (kips·in.)[b]	47	54	64	80	90	211
Amfleet and Viewliner	Wheel load (kips)[a]	35.4	39.2	41.3	43.4	45.2	68.8
	C- moments (kips·in.)[b]	2 31	2 34	2 37	2 42	2 50	2 112
	RS + moments (kips·in.)[b]	36	43	52	64	75	276
Other	Wheel load (kips)[a]	32.5	37.2	40.3	43.8	46.8	65.3
	C- moments (kips·in.)[b]	2 36	2 39	2 42	2 46	2 48	2 85
	RS + moments (kips·in.)[b]	48	56	70	86	95	160
Intermodal freight	Wheel load (kips)[a]	31.8	40.9	44.2	47.9	50.5	73.2
	C- moments (kips·in.)[b]	2 32	2 38	2 43	2 50	2 73	2 82
	RS + moments (kips·in.)[b]	40	52	61	77	90	125
Non-intermodal freight	Wheel load (kips)[a]	43.1	47.2	52.7	62.6	69.2	119.5
	C- moments (kip·in.)[b]	2 40	2 44	2 47	2 50	2 52	2 150
	RS + moments (kip·in.)[b]	56	70	91	107	115	252

[a]1 kip=4.45 kN.
[b]1 kip·in.=0.113 kN·m.

A subset of data from the aforementioned bending moment dataset was used in the analysis back calculator. Particular focus was placed on selecting train passes of similar load levels and negative temperature differentials to capture worst-case conditions for center negative bending moments. Upward curl in concrete crossties has the potential for inducing high ballast reaction in the center of the element and therefore maximizing the effect of load on the center negative bending moment (*13*). For that reason, the analysis was limited to selected non-intermodal freight locomotives on the night of 23 April 2017. Negative temperature differentials recorded on site ranged from 2 4.4°F to 2 5.4°F (2 2.5°C to 2 3°C). Locomotive wheels showed both the highest loads and the least variation and therefore represent a stable condition on which to perform the analysis. Figure 8 presents the results of the ballast pressure distribution of six locomotives passing the Edgewood, MD field site. Each line represents the average of the conditions calculated for each of the six axles of the individual locomotives. Even with the effect of upward temperature curling, there is a high concentration of support under the rail seats. It is possible to conclude that the dominant support condition at the site is one of a recently tamped track, with adequate support of rail seats. This aligns with the expected results as presented in previous sections.

Although existing support conditions at the field site align with those expected for well-maintained track, certain sections of the NEC might experience different support conditions because of differences in maintenance frequencies or because of track irregularities such as transition zones (e.g., bridge approaches). Using the same computational algorithm developed by the support condition back calculator (*21*), fixed hypothetical support conditions adapted from Bastos (*20*), and the aforementioned wheel load data, it is possible to generate simulations of expected bending moments for different support scenarios.

Results from this analysis are presented in Figure 9 for the center region of the crosstie. Also included in Figure 9 are the aggregated field measured data from Figure 6, specified and laboratory measured first crack flexural capacity of the current crosstie design. Depending on the support case, simulated values exceed current design first crack and even ultimate capacity, especially those related to localized support under the center of the crosstie (i.e., moderate center binding). Although the analytical model does not consider potential dynamic changes in the support condition caused by the interaction between the tie deformed shape and ballast, the data presented show bending moments that are feasible based on current NEC wheel loading conditions. If the track is maintained to the current level that was observed in the field, it is not expected that bending moments should exceed current specification values, which is probably a strong indicator of favorable long-term crosstie performance.

Results for the rail seat region are presented in Figure 10 and provide a different outlook. The existing support conditions generate the highest potential bending moment. In contrast with the center region, it is not expected that changes in the support condition will

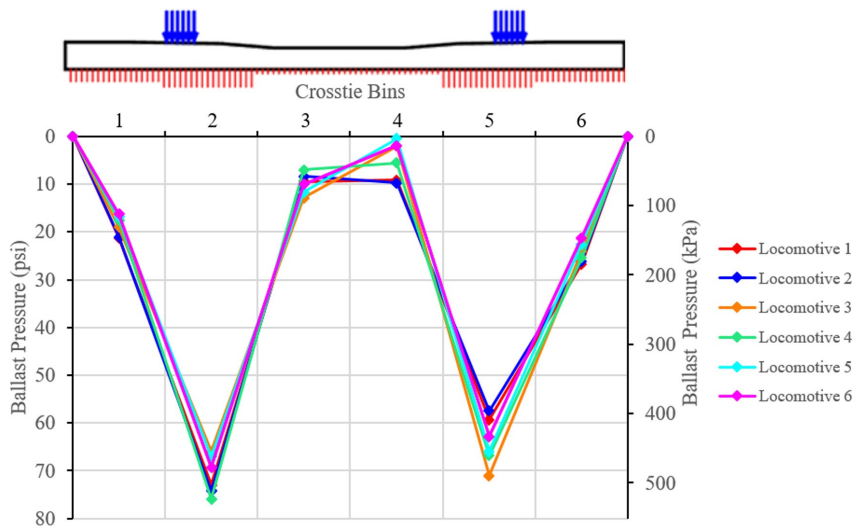

Figure 8. Average ballast pressure distributions for six separate freight locomotives on April 23, 2017.

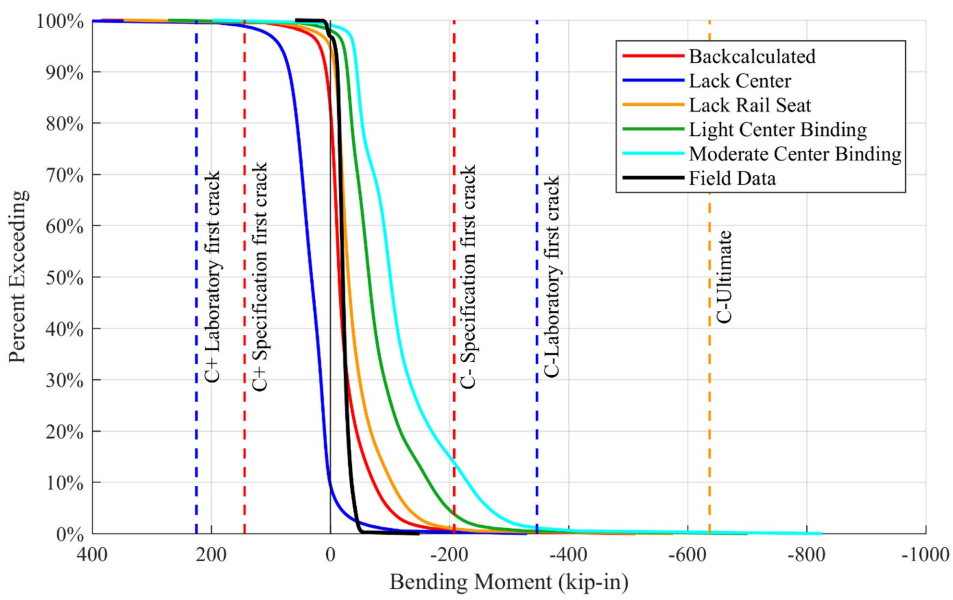

Figure 9. Extrapolated bending flexural bending moments of prestressed concrete ties on the center region associated with different support conditions based on field loading data.

generate higher flexural values at the rail seat. Considering that the current specification value of 306 kips·in. (34.6 kN·m) is surpassed neither by field measured data nor by analytical scenarios, it can be concluded that the current design provides a strong rail seat section that can be further optimized by potentially reducing the specification value of the rail seat section.

Conclusion

Optimization of the track structure and its components requires a comprehensive understanding of the effect and variability of loads. Field instrumentation such as WILD sites and instrumented crossties proved to be a valuable resource for addressing these questions through loading and bending moment quantification. From the field

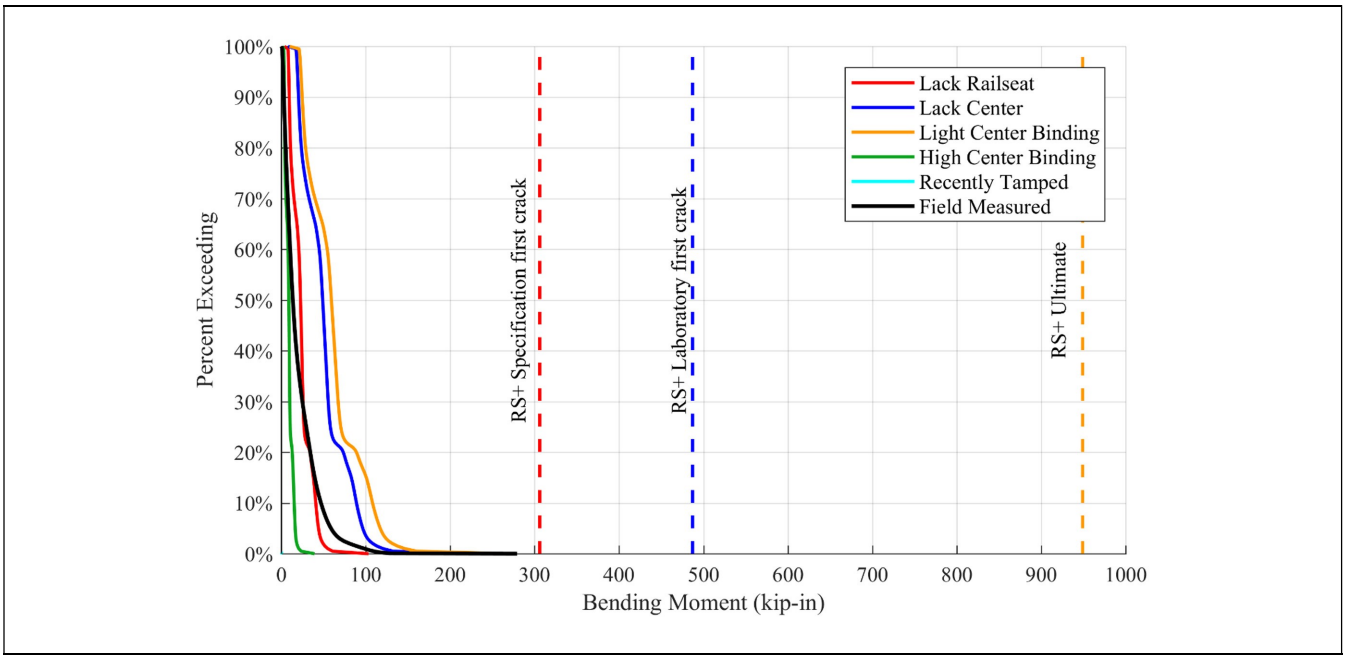

Figure 10. Extrapolated bending flexural bending moments of prestressed concrete ties on the rail seat region associated with different support conditions based on field loading data.

experimentation conducted on Amtrak's NEC at Edgewood, MD, and supporting laboratory experimentation several conclusions can be drawn:

- The loading environment of the NEC shows high variability of load levels between equipment types and operators.
- The top 1% of peak wheel loads show extreme values, which was also observed in the distribution of bending moments.
- Crosstie center bending moments are less sensitive to load increases than rail seat bending moments, implying adequate support conditions under the rail seats at this field location.
- Considering measured field values, neither specification nor laboratory flexural capacities of the current crossties are exceeded by current operations.
- Back calculation of existing support conditions of the Edgewood, MD site confirmed the previous observations and showed sufficient support under the rail seats even when the crosstie is subjected to negative temperature differentials (upward curl).
- There is potential for high flexural demands in the center region of the crosstie which exceed current specification values and actual measured capacity in localized parts of the NEC.
- Infrastructure owner experience with the performance of the current design on those more demanding sections of the NEC will govern the necessity of increasing the center negative specification value to align with potential flexural demands.
- For the rail seat region of the crosstie, there is no expected scenario in which flexural specification value can be surpassed; this indicates room for design optimization to levels of either the actual field demand or currently capacity specified by the owner.
- Maintaining track condition to the level quantified in the field will ensure bending moments, not in exceedance of current specification values, which will probably be a strong indicator of good long-term performance.
- In the near term, future research for the project should focus on the incremental optimization of the crosstie, based on the existing design to align recorded demand to actual element capacity.
- Longer term research objectives should focus on the development of a new crosstie design considering recent and innovative trends in the industry that could optimize the use of resources and provide flexural capacities in alignment with the actual flexural demand in the field.

Use of these data for track structure and component performance could influence future designs that are better suited to the operational characteristics of Amtrak's NEC. Additionally, they provide a basis for the future implementation of a reliability-based design approach, in alignment with the vision for the mechanistic design of track systems.

Acknowledgments

This research effort is funded by The National Railroad Passenger Corporation (Amtrak). Additional support was provided by National University Rail (NURail) Center, a U.S. DOT-OST Tier 1 University Transportation Center. The authors would like to thank Mike Hudson of LB Foster Inc., Salient Systems for his assistance. J. Riley Edwards has been supported in part by grants to RailTEC from CN and Hanson Professional Services, Inc.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: J. Riley Edwards, Marcus S. Dersch, Yu Qian, Ricardo J. Quirós-Orozco; data collection: Marcus S. Dersch, Yu Qian, Ricardo J. Quirós-Orozco; analysis and interpretation of results: Ricardo J. Quirós-Orozco, J. Riley Edwards, Yu Qian; draft manuscript preparation: Ricardo J. Quirós-Orozco J. Riley Edwards. All authors reviewed the results and approved the final version of the manuscript.

References

1. Amtrak. *The Amtrak Vision for the Northeast Corridor 2012 Update Report*. Amtrak, Washington, D.C., 2012, p. 42.
2. Van Dyk, B. *Characterization of the Loading Environment for Shared-Use Railway Superstructure in North America*. MS thesis. University of Illinois at Urbana-Champaign, Champaign, IL, 2015.
3. Van Dyk, B. J., C. T. Rapp, M. S. Dersch, J. R. Edwards, C. J. Ruppert, Jr., and C. P. L. Barkan. Evaluation of Existing Loading Environment in North America for Improved Concrete Sleepers and Fastening Systems. Presented at the 2013 World Congress of Railway Research, Sydney, Australia, 2013.
4. Edwards, J. R., M. S. Dersch, and R. G. Kernes. *Improved Concrete Crosstie and Fastening Systems for US High Speed Passenger Rail and Joint Corridors*. RailTEC, University of Illinois at Urbana-Champaign, Champaign, IL, 2017.
5. Remennikov, A., M. Murray, and S. Kaewunruen. Dynamic Design Guidelines for Prestressed Concrete Sleepers. *Proc., 20th Australasian Conference on the Mechanics of Structures and Materials*, Queensland, Australia, 2008, pp. 743–748.
6. Edwards, J. R., Z. Gao, H. E. Wolf, M. S. Dersch, and Y. Qian. Quantification of Concrete Railway Sleeper Bending Moments Using Surface Strain Gauges. *Measurement*, Vol. 111, No. Supplement C, 2017, pp. 197–207. https://doi.org/10.1016/j.measurement.2017.07.029.
7. Harrison, H. D., and J. M. Tuten. Wheel Load Measurement. WO1986003582, 1984.
8. LB Foster Salient Systems. *Wheel Impact Load Detector Product Sheet*. http://www.lbfoster-salientsystems.com/pdf/LBF_Wild_Product_sheet_LOWRES.pdf. Accessed July 10, 2017.
9. Barke, D., and W. K. Chiu. Structural Health Monitoring in the Railway Industry: A Review. *Structural Health Monitoring*, Vol. 4, No. 1, 2005, pp. 81–93. https://doi.org/10.1177/1475921705049764.
10. Harrison, H. D., L. R. Cheng, and W. GeMeiner. Tracking the Performance of Heavy Axle Load Vehicles in Revenue Service. Presented at the ASME 2006 International Mechanical Engineering Congress and Exposition, Chicago, IL, 2006.
11. Canadian National. *Wheel Impact Load Detectors: The Early History on CN*. St. Louis, MO, 2011.
12. Stratman, B., Y. Liu, and S. Mahadevan. Structural Health Monitoring of Railroad Wheels Using Wheel Impact Load Detectors. *Journal of Failure Analysis and Prevention*, Vol. 7, No. 3, 2007, pp. 218–225. https://doi.org/10.1007/s11668-007-9043-3.
13. Wolf, H. E. *Flexural Behavior of Prestressed Concrete Monoblock Crossties*. Master's thesis. University of Illinois at Urbana-Champaign, Champaign, IL, 2015.
14. Edwards, J. R., A. Cook, M. Dersch, and Y. Qian. Quantifying Rail Transit Concrete Monoblock Sleeper Field Bending Moments. *Journal of Transportation Engineering: Part A (Systems)*, 2017.
15. Mayville, R. A., L. Jian, and M. Sherman. *Performance Evaluation of Concrete Railroad Ties on the Northeast Corridor*. Publication DOT/FRA/RPD-14/03. Federal Railroad Administration, Waltham, MA, 2014, p. 171.
16. American Railway Engineering and Maintenance-of-Way Association. Chapter 30, Ties. In *Manual for Railway Engineering*. The American Railway Engineering and Maintenance of Way Association, Landover, MD, 2017.
17. National Instruments. *Making Accurate Strain Measurements*. http://www.ni.com/white-paper/6186/en/. Accessed July 11, 2017.
18. Fisher, R. B. Introduction of Static Frequency Converters on SEPTA's 25 Hz Commuter Rail System. *Proc., ASME/IEEE Joint Conference on Railroads,* Chicago, Ill., IEEE, New York, NY, 1990.
19. Wolf, H. E., Y. Qian, J. R. Edwards, M. S. Dersch, and D. A. Lange. Temperature-Induced Curl Behavior of Prestressed Concrete and Its Effect on Railroad Crossties. *Construction and Building Materials*, Vol. 115, 2016, pp. 319–326. https://doi.org/10.1016/j.conbuildmat.2016.04.039.
20. César Bastos, J. *Analysis of the Performance and Failure of Railroad Concrete Crossties with Various Track Support Conditions*. Master's thesis. University of Illinois at Urbana-Champaign, Champaign, IL, 2016.
21. Gao, Z., H. E. Wolf, M. S. Dersch, Y. Qian, and J. R. Edwards. Non-Destructive Estimation of Concrete Crosstie Support Conditions Using Field Bending Moments. Presented at 96th Annual Meeting of the Transportation Research Board, Washington, D.C., 2017.

The Standing Committee on Rail Transit Infrastructure (AR055) peer-reviewed this paper (18-02775).

The material in this paper represents the position of the authors and not necessarily that of Amtrak.