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Development of a parametric model for the prediction of concrete railway crosstie service bending moments

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Abstract

Concrete crosstie usage in North America continues to increase for rail transit and heavy axle load freight railroad applications. As such, it is important to design optimized crossties to save both capital and maintenance funds. Recently, a method for quantifying concrete crosstie bending moments using concrete surface strain gauges has been developed, deployed, and validated. Data from this method are used in this paper for (1) building a model to quantify sources of variability for field bending moments and the relative influence of each source, (2) generating an accurate model to predict bending moments at the two field locations surveyed, and (3) comparing the relative effects of predictor variables on rail transit and heavy axle load freight rail modes to determine their influence on service bending moments. Results show that it is possible to develop a reliable model to predict bending moments, and that several factors have a strong influence on these predictions, namely vertical load, temperature gradient, and axle location within a railcar truck. The most significant factor is the crosstie support condition, especially with respect to center moments. While the aforementioned model's primary utility is for the two sites and railroad systems surveyed, the model provides a valuable tool for determining which variables are the most critical for inclusion in the future mechanistic design of concrete crossties.

Keywords

Concrete crosstie, flexural strength, center negative bending moments, rail seat positive bending, bending moment variability, multicollinearity, parameter estimates

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Background and introduction

Ballasted track is commonly used throughout the world, and consists of the rail, fastening systems, crossties, ballast, sub-ballast, and subgrade.[1] In the United States, concrete is the second most common material used in the manufacture of crossties, but is the dominant crosstie material used in many locations internationally.[2,3] The use of prestressed concrete for crossties is beneficial due to the increased flexural strength, ductility, and resistance to cracking gained through the use of pre-tensioned steel wires.[4] Additionally, prestressed concrete crossties are commonly used due to their improved ability to maintain track gauge in the demanding railroad loading environment.[2,5,6]

The design of prestressed precast monoblock crossties includes proper materials selection and proportioning, consideration of economic impact, and meeting overall performance criteria with respect to their structural design. While the structural design of crossties should involve consideration of a variety of potential failures, the flexural design is widely considered to be the most critical design element given its linkage to the structural integrity and long-term performance of the crosstie. To date, flexural design is based largely on a static analysis of loads, with the application of estimated empirically-derived impact factors.

As such, it is important to quantify the variability in bending moments associated with load (wheel–rail interface input loads) as well as other factors that may influence bending, including crosstie support

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conditions, axle location within truck, ambient temperature, and temperature gradient between top and bottom of crosstie.[7] If data are available for these variables, a useful means of understanding the relative effect of each on bending moment is multiple linear regression and the generation of a parametric model.

Prior research aimed at understanding variability in the field performance of crosstie bending moment was conducted by Edwards et al.[8,9] Controlled laboratory experimentation in which the support conditions were varied in order to quantify their effect on bending has also been undertaken.[10,11] Additionally, the effect of variability in temperature on bending moments has previously been considered.[7,12–14] While all these efforts have provided insight into the influence of individual parameters on crosstie bending moment, none have addressed the relative importance and possible interactions among inputs, as they relate to the calculation of bending moments.

To address this, sources of bending moment variability were investigated using data from New York City Transit Authority (NYCTA) and a heavy axle load (HAL) freight railroad. Use of rail transit data enabled us to investigate variation in applied bending moments that are independent of load because of their lower wheel loads as compared to HAL freight service.[7,15] This is partly due to the distinctly different loading magnitudes, combined with the similar sectional geometries of the crossties. Additionally, the selection of HAL freight data serves to increase the range of axle loads applied to crossties, providing insight into a broader range of factors that influence crosstie bending than would be possible with a review of rail transit data alone.

By developing a model that explains how critical variables affect bending moments, one can understand how to either improve new designs or adjust current maintenance practices. For example, if temperature gradient is a reliable predictor of flexural demand, future designs and/or maintenance strategies could account for this (assuming causation can be demonstrated in addition to correlation).

Methodology

Instrumentation technology – Concrete surface strain gauges

To address the aforementioned topic areas, concrete surface strain gauge instrumentation was deployed in the field. This method was previously developed, deployed, and validated by the University of Illinois at Urbana-Champaign (UIUC) under rail transit and HAL freight[16] and rail transit applications.[13] Data from strain gauges were collected using a National Instruments (NI) compact data acquisition system (cDAQ).[15,17] cDAQ signals from the instrumentation were recorded through a NI LabVIEW virtual instrument (VI). A minimum sampling resolution of 12.7 mm (0.5 in.) and sampling rate of 2000 Hertz was selected based on the maximum authorized train speed at both of the field sites, desired data sampling resolution, prior experience, and expert recommendation.

Instrumentation deployment on crosstie

Concrete surface strain gauges were oriented longitudinally along the chamfer near the top surface of the crosstie to quantify bending strains at critical discrete locations along the length of the crosstie. Three strain gauges (labeled A, C, and E) were used on each crosstie, with one applied at each of the two rail seats and one at the center (Figure 1(a) and (b)). Additional relevant dimensions and properties for the specific designs of crossties investigated are shown in Table 1. Further information on the deployment of instrumentation as a part of prior research quantifying field bending moments was documented previously.[16] Table 1 also includes the owner-provided ''specification'' value that is required to be met or exceeded to avoid crosstie cracking. Design values are the first crack capacities associated with the unique crosstie designs that are supplied by the crosstie manufacturers.

To relate the field-measured strains to center and rail seat bending moments, calibration factors were generated through laboratory experimentation at UIUC's Research and Innovation Laboratory

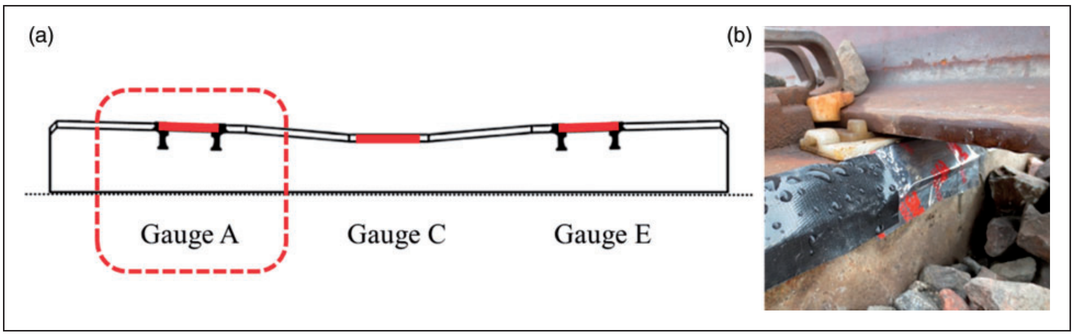

Figure 1. (a) Profile view of the instrumented crosstie showing locations of strain gauges and (b) image showing an example of the installed rail seat gauge.

Table 1. Characteristics of heavy rail transit and HAL freight railroad loading conditions and crosstie structural geometric properties for the locations considered in this study.

Crosstie/system characteristic			Heavy rail transit		HAL freight	
	Units:	SI	Imperial	SI	Imperial	
Static wheel loads	Maximum (AW3)[a]	62.9 kN	14.1 kips	35.8 kips	159 kN	
	Minimum (AW0)[a]	50.6 kN	11.4 kips	Varies	Varies	
Crosstie geometry	Length	2.59 m	8′ 6″	2.59 m	8′ 6″	
	Tie spacing	0.61 m	24″	0.61 m	24″	
Crosstie prestressing	Number of tendons	18	20			
	Jacking force	31.1 kN	7 kips	31.1 kN	7 kips	
	Precompression (Center)	13,858 kN/m^2	2.01 ksi	15,444 kN/m^2	2.24 ksi	
Theoretical crosstie cracking capacity	Center negative	Specification	19.0 kN-m	168 kip-in	26.0 kN-m	230 kip-in
		design	21.9 kN-m	194 kip-in	26.0 kN-m	230 kip-in
	Center positive	Specification	13.3 kN-m	118 kip-in	N/A	N/A
		design	14.9 kN-m	132 kip-in	21.0 kN-m	186 kip-in
	Rail seat positive	Specification	28.3 kN-m	250 kip-in	33.9 kN-m	300 kip-in
		design	32.0 kN-m	283 kip-in	43.1 kN-m	381 kip-in
	Rail seat negative	Specification	15.6 kN-m	138 kip-in	N/A	N/A
		design	20.1 kN-m	178 kip-in	24.7 kN-m	219 kip-in

HAL: heavy axle load.
[a]AW0 loads are the as-delivered, ready-to-operate static loads and AW3 loads represent the AW0 load with an additional "live load" of six passengers/square meter, a common load used for design. For HAL freight, AW3 loads are reflective of typical 286,000 lb gross rail load railcar loading.

(RAIL) in the Harry Schnabel Jr. Geotechnical Engineering Laboratory in Champaign, IL, USA. A calibrated load cell is used to monitor the applied loads to relate strain and bending moments. Laboratory calibration of surface strain gauges was conducted by applying known moments using pre-established standardized testing procedures outlined in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering[18] as documented by Edwards et al.[16] Given the nature of manufactured products and their inherent variability, the accuracy of calibrations used to map strains in the field to bending moments is adequate but not without its limitations. This variability is due to changes in concrete compressive strength and prestressing force from crosstie to crosstie. These effects are assumed to be minor based on prior sensitivity studies of replicate crossties from similar designs and vintages.[16]

Field instrumentation deployment

The experimentation discussed in this paper was conducted on ballasted track locations on heavy rail transit (HRT) operator New York City Transit Authority at Far Rockaway, NY, USA (hereafter referred to as "HRT") and a high-density mainline HAL freight railroad location in the western United States. Because of the observed variability of support conditions seen in past field experimentation[13,15,19] and knowledge of load dispersion,[1,2] data were collected and processed from multiple consecutive crossties, with a minimum of five crossties per field installation. A larger set of instrumented crossties was installed at the HAL field site to capture additional variability due to expected support conditions associated with inherently higher loads generated in the HAL freight operating environment.

Regression analysis of bending moments

A regression analysis was conducted to understand which predictor variables were most useful in explaining the variability associated with a given response variable (in this case, center or rail seat bending moment). It is important to understand the ultimate objective of a model when determining how to construct it. For this study focusing on concrete crosstie center negative and rail seat positive bending moments, we were interested in the relationships between predictor and response variables and in predicting bending moments. This meant that accurate estimates of the model parameters were of greatest importance. Thus, some multicollinearity among the predictor variables could be tolerated that would otherwise be undesirable.[20] Consequently, while investigating the effects of multicollinearity among predictor variables, we do not over-emphasize the need to mitigate their effects. Whenever possible, a smaller, more parsimonious model (i.e. one with fewer predictors) was preferred because it would facilitate simpler implementation of a future field experimentation program to collect necessary data.

There are, however, limitations to the use of regression analysis. First, correlation does not necessarily imply causation between predictor variables and the response variable. Second, it is important to understand that hidden extrapolations may exist, depending on the ranges of predictor variables that were sampled. These should be avoided to ensure that inaccurate inferences are not generated. Finally, broader generalization of these findings beyond the specific field sites surveyed should be undertaken with care for the reasons listed above. Nevertheless, the utility of regression to investigate the effects of multiple predictors on the center and rail seat flexural demands for concrete crossties has value. The results will inform development of practices to generate mechanistic methods to quantify the flexural response of crossties and ultimately optimize their design.

Model development

Four models were developed to account for bending moments at center and rail seat for both HRT and HAL freight lines. To address the question of which predictors best explain variability in bending moment data, a subset of a much larger dataset was used to build a model that predicts bending moment. The predictor variables that were considered for initial concrete crosstie bending moment model development are shown in Table 2. Different subsets of the predictor variables were used to model the rail seat or center moments, and these initial selections were made using *a priori* knowledge of which values had the ability to physically influence the response variables.

A dataset containing a random sample of approximately 5000 center and rail seat bending moment observations for each rail mode was used as training data to build the two models. An additional 5000 observations were retained as testing data for each mode and bending moment location. In total, there were approximately 9800 trains processed at NYCTA, with 1,571,000 and 2,027,520 center and rail seat bending moment observations, respectively. For the HAL freight location, approximately 30 HAL freight trains were processed with 460 axles each resulting in 142,600 and 138,000 center and rail seat bending moment observations, respectively. The datasets were sampled in a manner that minimized bias by maximizing the coverage (range of values) for each predictor variable.

Preliminary models considered squared continuous predictor variables and interactions among all continuous predictor variables. The results from the second order model and a model containing both interactions and second order terms provided negligible gains in both the coefficient of multiple determination (R^2) and adjusted coefficient of multiple determination $\left(R_a^2\right)$. This also introduced challenges with multicollinearity that limited the utility of the model. Thus, a second order model would not improve the ability to explain variability between predictors and the response variable, and parsimonious first order parametric regressions were developed.

The general form of one such model is shown in equation (1), with the specific predictor variables listed in Table 2. The predictors associated with crosstie or rail seat location are separated from

Table 2. Units and descriptions for the predictor and response variables for the development of concrete crosstie center and rail seat bending moment models.

Variables		Notation	Type	Unit	Description
Response	Center bending moment	M_C	Quantitative	kip-inches	Center bending moment measured by surface strain gauges
	Rail seat bending moment	M_{RS}	Quantitative	kip-inches	Rail seat bending moment measured by surface strain gauges
Predictor	Vertical load (one rail)	x_{i1}	Quantitative	kips	Vertical load at wheel–rail interface
	Total vertical load	x_{i2}	Quantitative	kips	Summation of both vertical loads
	Lateral load	x_{i3}	Quantitative	kips	Lateral Load at wheel–rail interface
	Speed	x_{i4}	Quantitative	miles/hour	Speed of train at time of loading or moment capture
	Ambient temperature	x_{i5}	Quantitative	°F	Temperature at field instrumentation site
	Temperature gradient	x_{i6}	Quantitative	°F	Difference between the top of bottom surface of the crosstie
	Axle location	x_{i7}	Classification	Binary	1 = Leading, 2 = Trailing axle on a given railcar's truck
	Season	x_{i8}	Classification	Binary	1 = December-March, 0 = Otherwise
	Crosstie location	C_{LOC}	Classification	Integer, 10 Total	Identifies different crossties
	Rail seat location	RS_{LOC}	Classification	Integer, 10 Total	Identifies different rail seats

the independent predictors, as these vary among the models

$$y_i = \beta_0 + \sum_{j=1}^{p}(\beta_j x_{ij}) + \sum_{k=p+1}^{p+q}(\beta_k x_{ik})00A0 + \varepsilon_i \qquad (1)$$

where

y_i = value of response variable for trial i

$x_{i1}, x_{i2}, \ldots, x_{ij}, x_{ik}, \ldots, x_{i(p+k-1)}, x_{i(p+k)}$ = values of predictor variables for trial i

p = total number of predictor variables (not reflecting crosstie or rail seat location)

k = total number of predictor variables in the model (for crosstie or rail seat location)

β_0 = regression parameter for the intercept

β_j = regression parameter associated with x_{ij}

ε_i = random error term for trial i

Using the HRT and HAL data, SAS® software was used to construct two unique models for each of the two rail transport modes – one for rail seat and another for center bending moments. Using stepwise selection, it was determined that all relevant (i.e. predictors related to the measurement under consideration) indicated in Table 2 should be included in each of the respective models. For the stepwise selection process to terminate, none of the variables omitted from the model had an F statistic significant at $\alpha = 0.10$ and all variables remaining in the model were significant at $\alpha = 0.15$, which are commonly accepted values for model development.[20] There were only negligible improvements to the respective model's R^2 values if some of the latter variables were included in the models, indicating models with fewer predictors were probably feasible.

Evaluation of parameters and multicollinearity

Of specific interest were the parameter estimates, their standard errors, and the values within the covariance matrix, the latter of which allows for detection of multicollinearity of predictor variables. The independent development of center and rail seat bending models is discussed below.

Center bending moments. Table 3 provides the parameter estimates for the full models for HRT and HAL freight center bending moment models along with their respective standard errors. Table 4 provides the same data for the reduced model. Visual inspection of the data indicates a large intercept term and relatively large and opposite sign parameter estimates for axle location. The latter result is inconsistent with prior findings demonstrating that leading axles apply greater load.[8,9,21]

The covariance matrix revealed that there was minimal multicollinearity of parameters, with the exception of the predictor for season, which was highly correlated with both ambient temperature and temperature gradient. The removal of season increased the mean square error (MSE) from 232 to 250, and R_a^2 decreased from 0.82 to 0.80 for HAL freight. A similar, minimal effect was observed for HRT. As such, season was retained in the model as a predictor variable. Additionally, there was only moderate

Table 3. Parameter estimates and standard errors for the full concrete crosstie center bending moment model.

		Heavy rail transit		HAL freight	
Variable	Units	Parameter estimate	Standard error	Parameter estimate	Standard error
Intercept	kip-inch	−76.920	1.705	−103.564	3.677
Vertical load	kips	−0.318	0.049	−0.247	0.038
Speed	mph	0.057	0.019	−0.392	0.041
Ambient temp.	Deg. F	0.290	0.009	0.565	0.031
Temp. gradient	Deg. F	0.548	0.011	0.496	0.022
Axle location	1 = Lead; 0 = Trail	−8.110	0.216	6.089	0.387
Season	Binary (1 = Winter)	2.456	0.333	26.541	1.085
Crosstie 1	1 = Crosstie; 0 = Not Crosstie	1.073	0.300	−12.659	0.848
Crosstie 2		−15.746	0.305	17.076	0.861
Crosstie 3		46.832	0.303	−43.682	0.872
Crosstie 4		12.229	0.305	−108.784	0.872
Crosstie 5		N/A	N/A	−59.585	0.874
Crosstie 6		N/A	N/A	−37.803	0.856
Crosstie 7		N/A	N/A	−17.192	0.868
Crosstie 8		N/A	N/A	−36.900	0.859
Crosstie 9		N/A	N/A	−36.057	0.851

HAL: heavy axle load.

Table 4. Parameter estimates and standard errors for the reduced concrete crosstie center bending moment model.

		Heavy rail transit		HAL freight	
Variable	Units	Parameter estimate	Standard error	Parameter estimate	Standard error
Intercept	kip-inch	−52.816	1.311	−79.980	2.180
Vertical load	kips	−0.456	0.050	−0.233	0.038
Temp. gradient	Deg. F	0.681	0.011	0.485	0.022
Axle location	1 = Lead; 0 = Trail	−8.263	0.236	6.008	0.413
Crosstie 1	1 = Crosstie; 0 = Not Crosstie	1.081	0.337	−12.367	0.904
Crosstie 2		−15.805	0.343	17.539	0.917
Crosstie 3		46.798	0.340	−43.416	0.928
Crosstie 4		12.183	0.342	−108.076	0.928
Crosstie 5		N/A	N/A	−59.212	0.930
Crosstie 6		N/A	N/A	−37.314	0.912
Crosstie 7		N/A	N/A	−16.627	0.925
Crosstie 8		N/A	N/A	−36.024	0.914
Crosstie 9		N/A	N/A	−35.760	0.906

HAL: heavy axle load.

correlation between speed and vertical load, which was unexpected based on a review of previous literature on the interaction between speed and wheel load.[8,9,21] Finally, given that the inclusion of both speed and temperature in the model did little to improve it, these predictors were removed. No other values in the variance–covariance matrix were significant ($\alpha = 0.05$).

A parsimonious model that excluded speed, ambient temperature, and season was developed (Table 4). These three predictor variables showed moderate to high levels of multicollinearity and previous research indicated that they were correlated with other variables already in the model (e.g. relationship between ambient temperature and temperature gradient). Any remaining multicollinearity was related to the classification variables and their interaction with the continuous predictors. Their variance inflation factors were low (always less than two) and thus they were not a concern.[20]

Temperature gradient parameter estimates differed by approximately 40% for HRT and HAL freight and were calculated as 0.681°F (0.378 °C) and 0.485°F (0.269 °C), respectively. Assuming equal magnitude temperature gradients for both locations (but opposite in sign) ranging from −9°F (−5 °C) to 38°F (21 °C) this results in additional center negative bending moments of up to 26 kip-in (2.9 kNm). For the rail transit crosstie, this additional thermal-induced bending moment is 13% of the center design capacity and 45% of the mean center flexural demand observed. For HAL freight, a 26 kip-in (2.9 kNm) additional moment represents 21% of the mean flexural service demand observed. Temperature gradient rather than ambient temperature was selected as a predictor given the direct relevance of gradient to the flexural response of the crosstie due to the influence of thermal expansion and crosstie curling.

Rail seat bending moments. Parameter estimates for HRT and HAL freight rail seat bending moments along with their respective standard errors were obtained. The data indicate a negative intercept term. This was not initially expected for rail seat moments because they are generally thought to be positive. Unlike the crosstie center, the parameter estimates associated with axle location were similar for both modes. This is of interest because this is where the load is first transferred into the crosstie. It indicates that the opposite effect observed at the center was either an artifact of the location where the data were collected, or indicative of a dynamic response of the crosstie that is different at the center and rail seat.

A review of the covariance matrix revealed that there was significant multicollinearity of temperature gradient and lateral load and a variety of other combinations. As such, several predictors were removed with the objective of reducing multicollinearity. As in the center bending moment model discussed in the previous section, the removal of season had a minimal effect on the quality of the model predictions. After removal of the aforementioned predictor variables, a significant correlation between lateral load and vertical load remained. Removal of lateral load improved the model, and no values in the covariance matrix were significant ($\alpha = 0.05$).

Again, applying the principle of parsimony, a model was generated that excluded speed, ambient temperature, and season (Table 5). These three predictor variables showed moderate to high levels of multicollinearity and were previously identified to be correlated with other variables already included in the model. Like the center bending moment models, the

Table 5. Parameter estimates and standard errors for the reduced rail seat bending moment model.

		Heavy rail transit		HAL freight	
Variable	Units	Parameter estimate	Standard error	Parameter estimate	Standard error
Intercept	kip-inch	−9.505	1.150	70.889	1.574
Vertical load	kips	1.235	0.086	−0.451	0.054
Temp. gradient	Deg. F	0.582	0.014	Excluded	Excluded
Axle location	1 = Lead; 0 = Trail	−13.958	0.286	−3.345	0.216
Rail seat 1/A1	1 = Rail Seat; 0 = Not Rail Seat	10.802	0.612	7.354	0.696
Rail seat 2/E1		−9.476	0.605	−5.350	0.682
Rail seat 3/A2		−0.520	0.612	−41.209	0.707
Rail seat 4/E2		−2.495	0.605	−41.234	0.692
Rail seat 5/A3		−11.928	0.612	−39.768	0.683
Rail seat 6/E3		−12.028	0.605	−27.268	0.697
Rail seat 7/A4		−4.319	0.612	1.729	0.687
Rail seat 8/E4		−13.690	0.605	−23.018	0.683
Rail seat 9/A5		10.202	0.612	−32.364	0.697

HAL: heavy axle load.

Table 6. Comparison of predictor variables for each of the fitted regression models.

			Initial model		Final model	
Variable	Notation	Unit	Center	Rail seat	Center	Rail seat
Center bending moment	M_C	kip-inches	•		•	
Rail seat bending moment	M_{RS}	kip-inches		•		•
Vertical load (one rail)	x_{i1}	kips		•		•
Total vertical load	x_{i2}	kips	•		•	
Lateral load	x_{i3}	kips		•		
Speed	x_{i4}	miles/hour	•	•		
Ambient temperature	x_{i5}	°F	•	•		
Temperature gradient	x_{i6}	°F	•	•	•	•[a]
Axle location	x_{i7}	Classification	•	•	•	•
Season	x_{i8}	Classification	•	•		
Crosstie location	C_{LOC}	Classification				
Rail seat location	RS_{LOC}	Classification		•		•

[a]Only in heavy rail transit model.

variables retained in the final rail seat bending moment model are vertical load, temperature gradient, and axle location. It is of interest that the temperature gradient has a much larger parameter estimate for HRT (0.58) compared to HAL freight (0.07). As such, temperature gradient was excluded as a predictor for HAL freight (Table 5).

A summary of the final models for both the center and rail seat moments is provided in Table 6, demonstrating which predictor variables were included in each of the four models previously introduced.

Model validation

Another 5000 data points were randomly extracted from each dataset to validate the models. The parameter estimates generated when running the final model with these new data were similar to the ones generated with the training dataset and final predictor variables (Tables 3 through 6). There was agreement between the training and validation parameter estimates and standard errors for crosstie center bending moments. Similar agreement was found for rail seat bending moment testing data but is not included for purposes of brevity (Table 7). This was expected due to the large size of the dataset used to generate the model, and its convergence on representation of the total population. Given the similarity of these values, further validation of the model was deemed unnecessary.

Model functionality and use

Given proper validation of the parsimonious models as described earlier, they can now be used to predict

Table 7. Comparison of parameter estimates and standard errors for model building and model validation data for the concrete crosstie center bending moments.

		Heavy axle transit				HAL freight			
		Training data		Validation data		Training data		Validation data	
Variable	Unit	Parameter estimate	Standard error	Parameter estimate	Standard error	Parameter estimate	Standard error	Parameter estimate	Standard error
Intercept	kip-inch	−52.816	1.311	−51.340	1.430	−79.980	2.180	−78.650	2.163
Vertical load	kips	−0.456	0.050	−0.505	0.054	−0.233	0.038	−0.260	0.038
Temp. gradient	Deg. F	0.681	0.011	0.648	0.012	0.485	0.022	0.481	0.022
Axle location	1 = Lead; 0 = Trail	−8.263	0.236	−8.499	0.250	6.008	0.413	6.479	0.414
Crosstie 1	1 = Crosstie; 0 = Not Crosstie	1.081	0.337	0.831	0.359	−12.367	0.904	−12.131	0.925
Crosstie 2		−15.805	0.343	−15.394	0.357	17.539	0.917	17.807	0.895
Crosstie 3		46.798	0.340	46.356	0.361	−43.416	0.928	−43.757	0.909
Crosstie 4		12.183	0.342	11.807	0.357	−108.076	0.928	−108.330	0.906
Crosstie 5		N/A				−59.212	0.930	−60.062	0.907
Crosstie 6						−37.314	0.912	−37.580	0.924
Crosstie 7						−16.627	0.925	−16.863	0.906
Crosstie 8						−36.024	0.914	−37.850	0.915
Crosstie 9						−35.760	0.906	−36.080	0.932

HAL: heavy axle load.

center bending moments given values for predictor variable coefficients. As discussed above, these predictions should be made with the range of data in mind. The next two sub-sections discuss the prediction of moments, absent consideration of support condition variability, in an attempt to understand the influence of non-support related variables.

Center moment prediction. Equations (2) and (3) facilitate the prediction of center bending moments for the HRT and HAL freight field sites, respectively. The prediction equations are incomplete, given that they do not include a term for support conditions. This factor will be included in the model later and is referred to as R (support **R**eaction). After estimating the regression parameters, the final fitted models are shown in equations (2) and (3) for the center moment prediction on HRT and HAL freight, respectively, where $\hat{y}_i$ is the expected value of y_i (see Table 2 for additional nomenclature of predictor variables).

$$\hat{y}_{HRTcenter} = -52.8 - 0.456x_{i2} + 0.681x_{i6} - 8.263x_{i7} + R_{HRC-} \tag{2}$$

$$\hat{y}_{HALcenter} = -79.9 - 0.233x_{i2} + 0.485x_{i6} - 6.01x_{i7} + \mathrm{R}_{HALC-} \tag{3}$$

Rail seat moment prediction. Equations (4) and (5) facilitate the prediction of rail seat bending moments for HRT and HAL freight, respectively. These equations follow the same general form as equation (2), and do not include a term for rail seat location.

$$\hat{y}_{HRTrailseat} = -9.51 - 1.23x_{i1} + 0.582x_{i6} - 14.0x_{i7} + \mathrm{R}_{\mathrm{HRRS+}} \tag{4}$$

$$\hat{y}_{HALrailseat} = -79.9 - 0.451x_{i1} - 3.34x_{i7} + R_{HALRS+} \tag{5}$$

Crosstie support effects. Crosstie or rail seat location was used as a proxy for support condition, as prior research has indicated significant variation in support among crossties.[13,15,16] To build on these findings, parameter estimates generated in the two models provide another method for quantifying variability. For HRT, parameter estimates for crossties range from −16 kip-in (1.8 kNm) to 47 kip-in (5.3 kNm) and those that are thought to have poorer support are negative (Table 5 and Figure 2). For HAL freight, parameter estimates for crossties that are thought to have poor support range from −108 kip-in (12.2 kNm) to −36 kip-in (4.1 kNm) (Table 4 and Figure 2). The disparity among crosstie location parameters signifies the differences in support conditions in the two modes and their relative contribution to center negative bending moment.

The disparity is also seen among rail seats (Figure 3). Support condition parameter estimates for negative rail seat moments range from −14 kip-in (4.6 kNm) to 11 kip-in (1.2 kNm) for HRT and −41 kip-in (4.6 kNm) to 7 kip-in (0.8 kNm) for

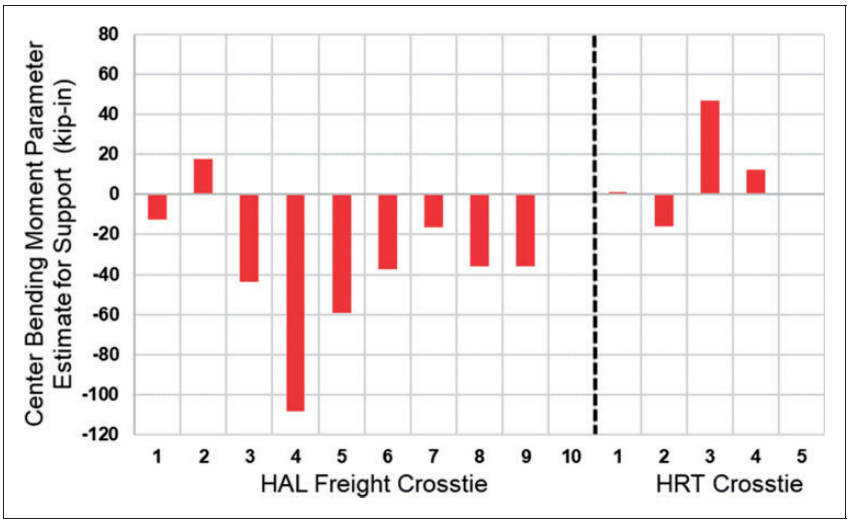

Figure 2. Comparison of parameter estimates for crosstie location for use in the prediction of crosstie center bending moments. HAL: heavy axle load; HRT: heavy rail transit.

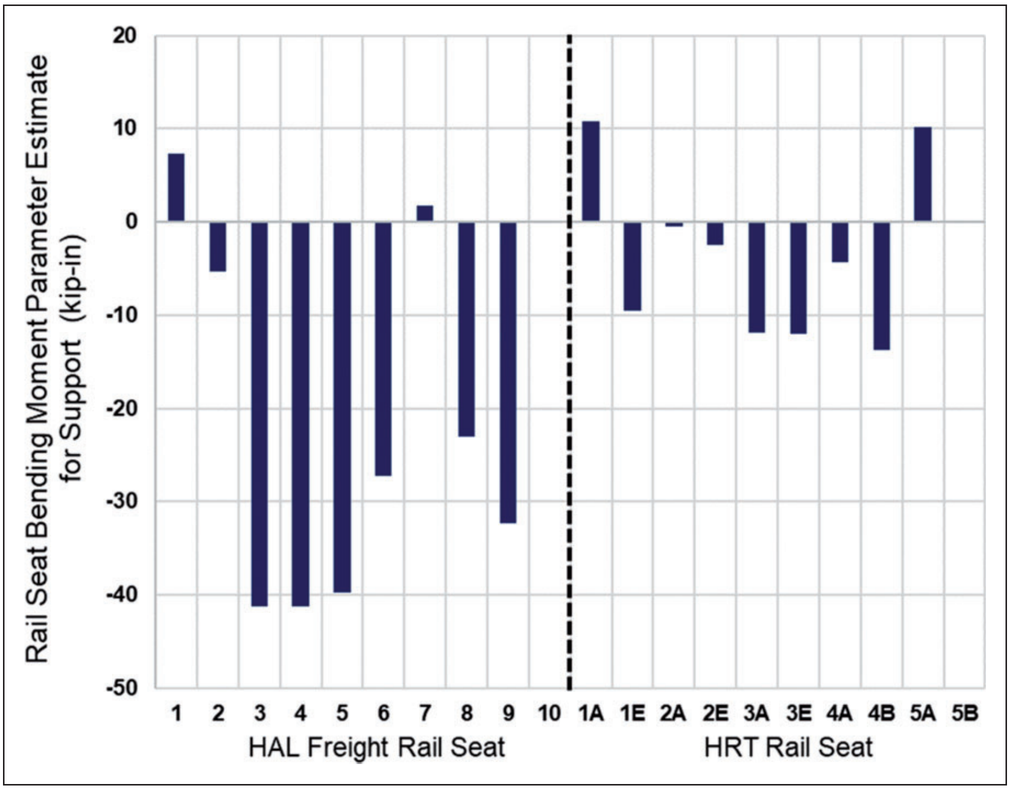

Figure 3. Comparison of parameter estimates for rail seat location for use in the prediction of crosstie center bending moments. HAL: heavy axle load; HRT: heavy rail transit.

HAL freight. These range of parameter estimates for rail seat support are lower than center support. This is due to support at the rail seat having less influence on rail seat bending than variations in support at the crosstie center. The latter drives high bending moments due to the comparatively long moment arm from the center of the crosstie to the point of load application, which is the rail seat.

Figures 2 and 3 indicate the significant influence that support condition has on crosstie bending. Focusing on the objective of the research described in the section 'Model development' and absent *a priori* knowledge of how the crosstie is supported, it is difficult to assign estimates to a parameter that relates to crosstie or rail seat location. One possibility is to assume general groupings and categories of the aforementioned predictors for crosstie location, assuming that the subset of crossties and rail seats tested are representative of the broader set of support conditions likely to be encountered. Using this

Table 8. Constants proposed for use in the prediction of rail seat and center moments to include the influence of support condition variability.

		Center negative			Rail seat positive		
Rail mode	Symbols	Low	Average	High	Low	Average	High
Heavy rail transit	RHRC−, RHRRS+	46.80	0.00	−18.81	−13.69	0.00	10.80
HAL freight	RHALC−, RHALRS+	17.54	−35.76	−108.00	−41.23	−5.35	7.35

HAL: heavy axle load.

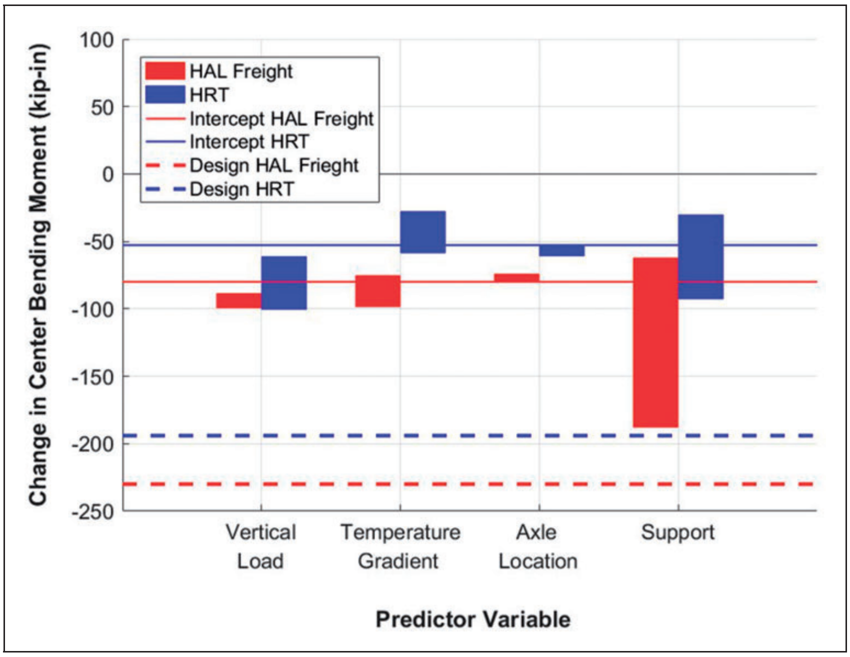

Figure 4. Sensitivity of the center bending moments to changes in predictor variables.
HAL: heavy axle load; HRT: heavy rail transit.

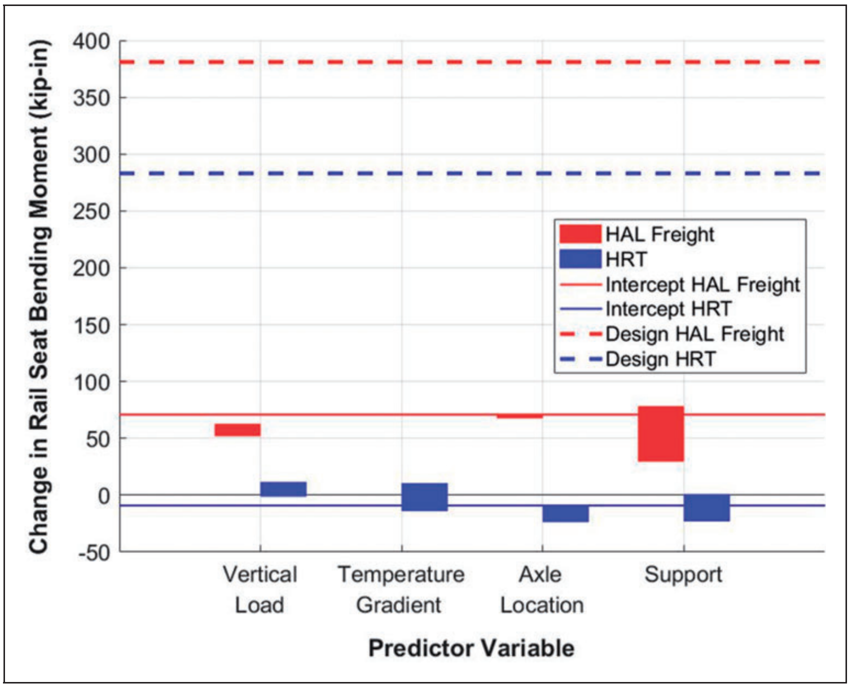

Figure 5. Sensitivity of the rail seat bending moments to changes in predictor variables.
HAL: heavy axle load; HRT: heavy rail transit.

approach, Table 8 provides low, average, and high values for the range of possible support conditions. These values can be added to equations (2) through (5) to include the effect of support condition.

Explanation of variability. To use the model to explain the variability between predictor variables and response variables, the change in bending moments was plotted for both center and rail seat locations for both field locations (Figures 4 and 5). The sensitivity of center bending moments to predictor variables representing load, temperature gradient, and axle location is quite low compared to the influence of support condition. The intercept values for both modes and moments are also plotted using solid horizontal lines, and the first crack flexural capacity for both modes is shown using a dashed horizontal line. Reviewing the results in comparison to the various capacities provides insight on the relative magnitude of each of the predictor variable's influence.

For the rail seat region, the sensitivity of bending moments to predictor variables load, temperature gradient, and axle location is similar in magnitude to the influence of support condition (Figure 5). This aligns with earlier conclusions related to the different moment arms and resulting sensitivities of support conditions at the crosstie center and rail seat regions.

Conclusions

The installation of concrete surface strain gauge instrumentation on HRT and HAL freight railroad concrete crossties was successful in measuring bending strains and resulting moments at both the center and rail seat. Data were used to generate four distinct multiple linear regression models for the prediction of moments to understand the interaction and influence of key parameters. It is important to note that results described within this paper are most relevant to the specific field sites that were investigated, and extrapolating the results to other sites or operating conditions should be done with discretion.

For the center bending moment prediction, models developed identified an opposite effect of axle location on center bending moment for HAL and HRT. The magnitude of the center bending moment variation due to axle location is likely due to the response time of the crosstie as it receives load and reacts in bending. The opposite effect for the two modes is most likely due to different support conditions present at the two sites. The effects of vertical axle load and train speed are minimal, which is unexpected based on prevailing design standards.[18] Previous work by Wolf et al.[7] on the effect of temperature was extended in this study and its effects were significant, especially at the crosstie center. The effect is similar in both rail transport modes studied, and provides a useful metric for considering the effect of temperature differentials on concrete crosstie bending moments. The effect of train speed and axle load was much less pronounced at the center than expected. This may also be due to differing railcar mechanical components and vehicle track interaction characteristics between rail transit and HAL freight.

A notable finding with respect to rail seat moment prediction is the minimal influence of support conditions, limited sensitivity to wheel–rail interface vertical load, and that temperature gradient was unnecessary for generating an accurate model of rail seat bending for HAL freight.

For both center and rail seat bending moments, the predictor that describes the most variability is crosstie or rail seat location, which is considered a proxy for support condition. This finding builds on prior research demonstrating the importance of adequate support for crossties to reduce bending moment demand.

Equations (2) through (5) in combination with Table 8 provide a means of predicting the center and rail seat field bending moments for HRT and HAL operations. Future work should aim to develop more generalized models that facilitate broader application of the findings in this study. Specifically, this research suggests the need to consider temperature gradient in the design of crossties.[14] This research also indicates the variability and influence of support conditions on the flexural response of the crosstie and its implication to maintenance practices. Finally, additional research on the effect of axle location on the crosstie center flexural demand was identified.

Author's Note

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