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Development of a Parametric Model for 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 (HAL) 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 article 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 HAL 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 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, Multicolinearity, Parameter Estimates

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 *(3,5,6)*.

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. 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 the crosstie support conditions, axle location within truck, ambient temperature, and temperature gradient between top and bottom of crosstie *(7)*. Provided that adequate data are available relating to the aforementioned variables, one of the primary means of understanding the relative contribution of each of these inputs to the bending moment experienced by the crosstie is through the use of multiple linear regression and the generation of a parametric model.

Prior work aimed at understanding field variability among crossties was conducted *(8,9)* and controlled laboratory experimentation varying support conditions and quantifying their impact on bending has also been undertaken *(10,11)*. Additionally, research has also shown that variability in temperature can impact bending moments in the field *(7,12)*. While these research efforts have provided valuable insight into the influence of individual parameters on crosstie bending moment, none were able to capture the totality of bending moment variation associated with the aforementioned inputs (e.g. thermal, loading, axle location, etc.). Instead, prior studies have been conducted with the objective of relating a single predictor variable to a response variable (most commonly, center negative bending moments).

These aforementioned sources of potential variability will be explored using data from both a heavy rail transit property and a Class I heavy axle load (HAL) freight railroad. The selection of rail transit data for addressing questions about what factors influence bending moments is intentional due to the fact that many sources of variation that are independent of load may be more critical in rail transit applications than what was observed in HAL freight service *(7,13)*. This is due in part to the distinctly different loading magnitudes yet similar sectional moduli of the crossties, providing for an interesting comparison between the concrete crosstie designs and their expected loading conditions. Additionally, the selection of HAL freight data serves to increase the breadth of axle loads that are applied to crossties, providing insight on a broader range of factors that influence crosstie bending than a review of rail transit flexural 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 recommendations. For example, if temperature gradient is a critical and reliable predictor of flexural demand, future designs and/or maintenance strategies could account for this (assuming causation can be proven 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 heavy axle load (HAL) freight *(14)* and rail transit applications *(12)*. Data from strain gauges were collected using a National Instruments (NI) compact data acquisition system (cDAQ) *(13,15)*. cDAQ signals from the instrumentation were recorded through a NI

LabVIEW virtual instrument (VI). A minimum sampling resolution of 12.7 mm (0.5 inches) and sampling rate of 2,000 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). Additional relevant dimensions and properties for the specific designs of crossties investigated are shown in Table 1. Further information on the deployment of instrumentation was documented previously *(14)*. 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.

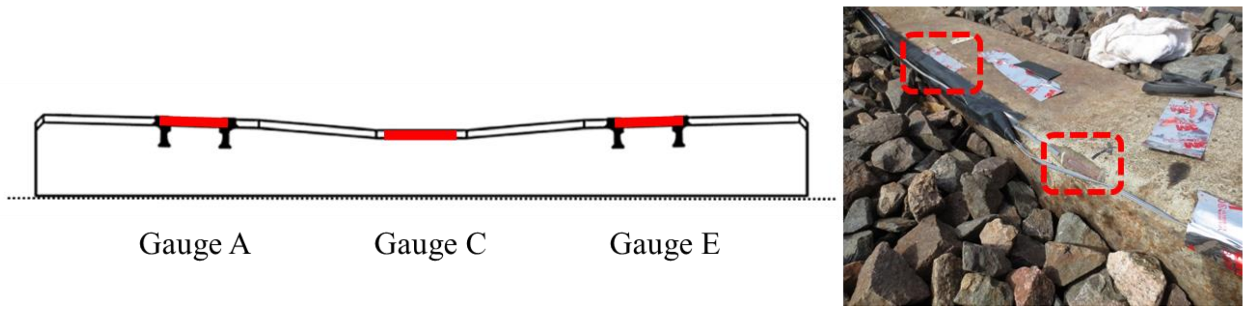

FIGURE 1 Profile view of instrumented crosstie showing locations of strain gauges and image showing example of gauges installed (foreground) and protected (background).

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)*		62.9 kN	14.1 kips	35.8 kips	159 kN
	Minimum (AW0)*		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
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

*AW0 loads are the as-delivered, ready to operate static loads and AW3 loads represent the AW0 load with an additional "live load" of 6 passengers / square meter, a common load used for design.

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 (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 *(16)* as documented by *(14)*.

Field Instrumentation Deployment

Experimentation discussed in this manuscript was conducted on ballasted track locations on heavy rail transit operator New York City Transit Authority at Far Rockaway, NY, USA (hereafter referred to as "NYCTA") 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 *(12,13,17)*, and knowledge of load dispersion *(1,3)*, 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

Regression analysis is a powerful tool to aid in understanding which predictor variables are most useful in explaining variability for a given response variable (in this case, center or rail seat bending moment). It is important to understand the ultimate objective of the model when determining the manner in which the model is to be built. For our purpose focusing on concrete crosstie center negative and rail seat positive bending moments, we are interested in both understanding the relationships between predictor and response variables and making predictions (e.g. predicting bending moments). This would dictate that we are in need of accurate estimates of the model parameters but, to favor good predictions, may be able to tolerate a level of multicolinearity among the predictor variables that would otherwise not be desired *(18)*. As such, while we will investigate the effects of multicolinearity among predictor variables, we will not over-emphasize the need to mitigate their effects. Whenever possible, a smaller, parsimonious model (i.e. one with fewer predictors) will be recommended given that it would facilitate easier implementation of a future field experimentation program to collect necessary data.

There are, however, limitations to the use of regression analysis that must be understood. Firstly, correlation does not imply causation between predictor variables and the response variable. Secondly, it is important to understand that hidden extrapolations may exist, depending on the ranges of predictor variables that were sampled. Hidden extrapolations must be avoided to ensure that improper inferences are not generated. Finally, broader generalization of these findings beyond the specific field sites surveyed should be undertaken with care, for the aforementioned reasons. With these limitations in mind, the usefulness of regression in exploring the effects of multiple predictors on the center and rail seat flexural demands for concrete crossties is still of great value and facilitates the further development of practices to generate mechanistic methods by which the flexural response of crossties can be quantified and ultimately their design can be undertaken.

Model Development

A total of four models were developed to account for bending moments at center and rail seat for both heavy rail transit and HAL operations. To address the question of what predictors can explain variability in bending moment data, a subset of a much larger dataset was used build a model that predicts the 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 with a priori knowledge of which values had the ability to physically influence the response variables.

TABLE 2 Units and descriptions for predictor and response variables for 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 guages
	Rail Seat Bending Moment	M_{RS}	Quantitative	kip-inches	Rail seat bending moment measured by surface strain guages
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=Decceber-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

A dataset containing a random sampling of approximately 5,000 center and rail seat bending moment observations for each rail mode were used as training data to build each of the two models. An additional 5,000 observations were retained as testing data for each mode and bending moment location. In total there were approximately 9,800 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. All data were sampled in a manner that minimized bias by maximizing the coverage (range of values) for the predictor variables.

Preliminary models considered squared continuous predictor variables and interactions among all continuous predictor variables. The results from the second order model, a model with interaction terms, and a model containing both interactions and second order terms provided almost negligible gains in both the coefficient of multiple determination (R^2) and adjusted coefficient of multiple determination (R_a^2) and introduced challenges with multicolinearity that limited the usefulness of the model. Thus, a second order model would not improve our ability to explain variability between predictors and the response variable.

Given these findings, the aforementioned discussion will focus on the development of a parsimonious first order parametric regression. The general form of this model is shown in Equation 1, with the specific predictor variables listed in Table 1. The predictors associated with crosstie or rail seat location are separated from the independent predictors, as these vary among the models.

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

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 in the model for trial i

p = total number of predictor variables in the model (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 aforementioned data sets, SAS® software was used to construct two unique models for each of the two rail 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 outside the model has an F statistic significant at the 0.10 level and all variables remaining in the model are significant at a level of 0.15, commonly accepted values for model development. There were only negligible improvements to the respective model's R^2 values as some of the latter variables were included in the models, indicating that models with fewer predictors may be feasible.

Evaluation of Parameters and Multicolinearity

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 multicolinearity of predictor variables. The development of center and rail seat bending moment models will be discussed below, separately.

Center Bending Moments

Table 3A provides parameter estimates for the heavy rail transit and HAL freight center bending moment models, along with their respective standard errors. Visual inspection of the data indicates a high intercept term, which is to be expected, and relatively large and opposite (in sign) parameter estimates for axle location, which does not align with conventional wisdom.

TABLE 3 Parameter estimates and standard errors for center bending moment models.

Variable	Units	Heavy Rail Transit		HAL Freight	
		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

A) Full concrete crosstie center bending moment model.

Variable	Units	Heavy Rail Transit		HAL Freight	
		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

B) Reduced concrete crosstie center bending moment model.

A review of the covariance matrix revealed that there was very little multicolinarity 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 increases the mean square error (MSE) from 232 to 250, and R_a^2 decreases from 0.82 to 0.80 for HAL freight and a similar, minimal effect, was observed for heavy rail transit. As such, season is left in the model as a predictor variable. Additionally, there is only moderate correlation between speed and vertical load, which is surprising based on the review of other literature that relates to the presence of an interaction between speed and wheel load *(19,20)*. Finally, given the inclusion of both speed and temperature in the model does little to improve the model, these predictors were removed. No other values in the variance-covariance matrix were significant with an alpha value of 0.05.

Applying the principal of parsimony, a model that excluded speed, ambient temperature, and season was created, as shown in Table 3B. These three predictor variables showed moderate to high levels of multicolinarity and were identified through previous research to be correlated to other variables already in the model (e.g. relationship between ambient temperature and temperature gradient). Any remaining multicolinarity related to the classification variables and their interaction with continuous predictors. Their Variance Inflation Factors (VIFs) were very low, and always less than two, thus they were not concerning.

Of specific interest is the fact that the temperature gradient has a similar parameter estimate for both heavy rail transit and HAL freight, 0.681 and 0.485 Deg. F, respectively. Given measured temperature gradients that range from -9 to 38°F (similar ranges at both locations, but opposite in sign), this results in additional center negative bending moments of up to 26 kip-in. For the rail transit crosstie, this additional bending moment is 13% of the center design capacity and 45% of the mean center flexural demands observed. For HAL freight, a 26 kip-in additional moment represents 21% of the mean flexural service demand observed. Temperature gradient was selected as a predictor, as opposed to ambient temperature which is more easily measured, given gradient's direct relevance to the flexural response of the crosstie due to the influence of thermal expansion and crosstie curling.

Rail Seat Bending Moments

Parameter estimates for heavy rail transit and HAL freight rail seat bending moment models were generated, along with their respective standard errors. The data indicate a negative intercept term, which is not to be expected for rail seat moments that are mostly considered to be positive. Unlike the crosstie center, the parameter estimates associated with axle location are quite similar for both modes, which is of interest given this is the first location that the load is transferred into the crosstie. This would indicate that the opposite effect that was 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 multicolinarity of temperature gradient and lateral load and a variety of other combinations. As such, several predictors were removed with the objective of reducing multicolinearity. Like the center bending moment model discussed in the previous section, the removal of season has a minimal effect on the quality of the model. After removal of the aforementioned predictor variables, significant correlation between lateral load and vertical load remains. Removal of lateral load from the model improves the model, and no values in the covariance matrix were significant at an alpha of 0.05.

Again applying the principal of parsimony, a model was generated that excluded speed, ambient temperature, and season (Table 4). These three predictor variables showed moderate to high levels of multicolinarity and were identified through previous research to be correlated to other variables already in the model. Like the center bending moment models, the variables retained in the final rail seat bending moment model are vertical load, temperature gradient, and axle location. Of interest is the fact that the temperature gradient has a much larger parameter estimate for heavy rail transit (0.58) as opposed to HAL freight (0.07). As such, temperature gradient was excluded as a predictor for HAL freight (Table 4).

TABLE 4 Parameter estimates and standard errors for reduced rail seat bending moment model.

Variable	Units	Heavy Rail Transit		HAL Freight	
		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		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	1=Rail Seat; 0=Not Rail Seat	-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

A summary of the final models for both center and rail seat moments is provided in Table 5, demonstrating which predictor variables were included in each of the four models previously introduced.

TABLE 5 Comparison of predictor variables for each of the fitted regression models.

	Notation	Unit	Initial Model		Final Model	
			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	●	●	●	●*
Axle Location	x_{i7}	Classification	●	●	●	●
Season	x_{i8}	Classification	●	●		
Crosstie Location	C_{LOC}	Classification				
Rail Seat Location	RS_{LOC}	Classification		●		●

*Only Required in Heavy Rail Transit Model

MODEL VALIDATION

Another 5,000 data points were extracted from each data set at random for use in validating each of the models. The parameter estimates generated when running the final model with these new data were very similar to the ones generated with the training data set and final predictor variables (Tables 3 and 4). Table 6 demonstrates the agreement between training and validation parameter estimates and standard errors for crosstie center bending moments, and similar agreement was found for rail seat bending moment testing data but is not presented for purposes of brevity. This is expected due to the size of the data used to generate the model, and its convergence on representation of the population. Given the similarity of these values, further validation of the model was deemed unnecessary.

TABLE 6 Comparison of parameter estimates and standard errors for model building and model validation data for concrete crosstie center bending moments.

Variable	Unit	Heavy Axle Transit				HAL Freight			
		Training Data		Validation Data		Training Data		Validation Data	
		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

MODEL FUNCTIONAILITY AND USE

Given proper validation of the parsimonious models as described earlier, they can now be used to predict center bending moments given values for predictor variable coefficients. As discussed earlier, these predictions should be made understanding the range of data that were collected, and that causation should not be implied, only correlation. The next two sub-sections will 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 below facilitate the prediction of center bending moments for the heavy rail transit and HAL freight field sites, respectively. The prediction equations are incomplete, given they do not include a term for support conditions (proxy for support conditions), presently referred to as a factor R (support **R**eaction). After estimating the regression parameters, the final fitted models are shown in Equations 2 and 3 for center moment prediction on heavy rail transit and HAL freight, respectively, where $\hat{y}_i$ is the expected value of y_i (see Table 2 for additional nomenclature of predictor variables).

$$\hat{y}_{HeavyRailCenter} = -52.8 - 0.456x_{i2} + 0.681x_{i6} - 8.263x_{i7} + \mathrm{R} \qquad (2)$$

$$\hat{y}_{HALCenter} = -79.9 - 0.233x_{i2} + 0.485x_{i6} - 6.01x_{i7} + \mathrm{R} \qquad (3)$$

Rail Seat Moment Prediction

Equations 4 and 5 below facilitate the prediction of rail seat bending moments for heavy rail transit and Class I freight, respectively. These equations also follow the same general form as Equation 2, and do not include a term for rail seat location.

$$\hat{y}_{HeavyRailRailSeat} = -9.51 - 1.23x_{i1} + 0.582x_{i6} - 14.0x_{i7} + \mathrm{R} \quad (4)$$

$$\hat{y}_{HALRailSeat} = -79.9 - 0.451x_{i1} - 3.34x_{i7} + \mathrm{R} \quad (5)$$

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 *(13,14,12)*. To further these findings, the parameter estimates generated in the two models provide another method for quantifying variability. For heavy rail transit, parameter estimates for crossties range from -16 to 47 kip-in and those that are thought to have poorer support are negative (Table 3 and Figure 2). For HAL freight, parameter estimates for crossties that are thought to have poor support range from -108 to -36 kip-in (Table 3 and Figure 2). The disparity among crosstie location variable parameters signifies the differences in support conditions on the two modes and their relative contribution to a prediction of center negative bending moment.

FIGURE 2 Comparison of parameter estimates for crosstie location classification variables (prediction of crosstie center bending moments).

The disparity is also noted among rail seats, as shown in Figure 3. Support condition parameter estimates for negative rail seat moments range from -14 to 11 kip-in for heavy rail transit and -41 to 7 kip-in for HAL freight. These range of parameter estimates for rail seat support are lower than center support. This is due to the fact that support at the rail seat has 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 – the rail seat.

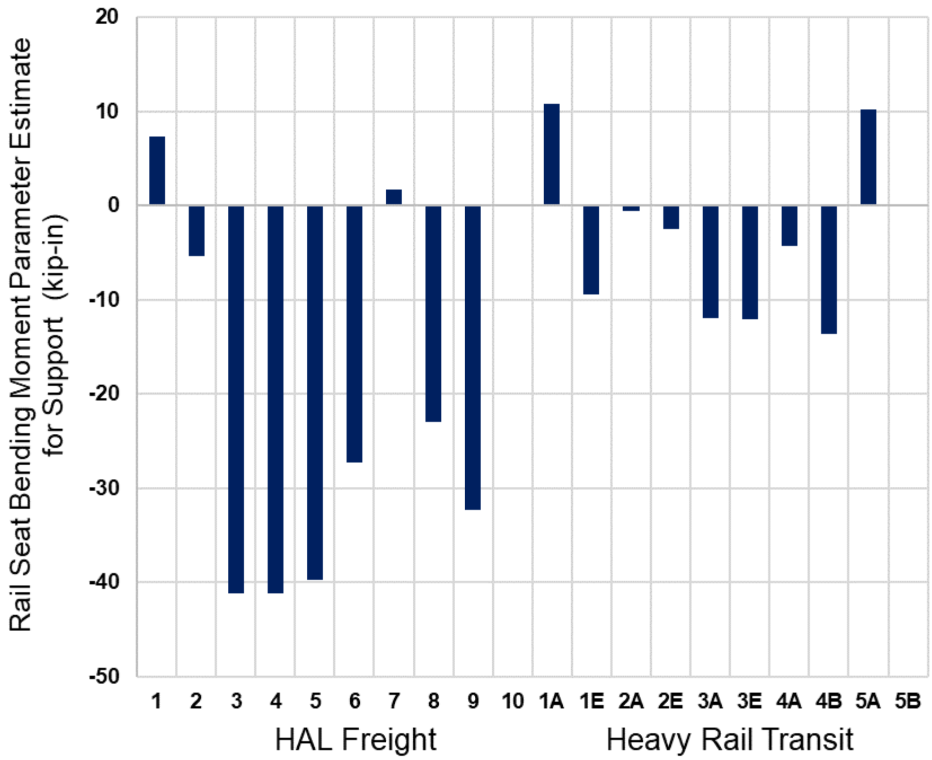

FIGURE 3 Comparison of parameter estimates for rail seat location classification variables.

Taken as a whole, Figures 2 and 3 indicate the significant influence that support condition has on crosstie bending. Focusing on the objective of the research detailed in this manuscript – the development of models – 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 approach, Table 7 provides low, average, and high values for the types of support that could be encountered, and these values are to be added to Equations 2 through 5.

TABLE 7 Constants proposed for use in the prediction of rail seat and center moments to include the influence of support condition variability.

Rail Mode	Symbols	Center Negative			Rail Seat Positive		
		Low	Average	High	Low	Average	High
Heavy Rail Transit	R_{HRC-}, R_{HRRS+}	46.80	0.00	-18.81	-13.69	0.00	10.80
HAL Freight	R_{HALC-}, R_{HALRS+}	17.54	-35.76	-108.00	-41.23	-5.35	7.35

Explanation of Variability

To use the model to explain the variability between predictor variables and response variables, the change in bending moments were plotted for both center and rail seat locations for both locations surveyed. Results for center moment sensitivities are shown in Figure 4 and rail seat moment sensitivities are shown in Figure 5. The sensitivity of center bending moments to predictor variables load, temperature gradient, and axle location is quite low as 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.

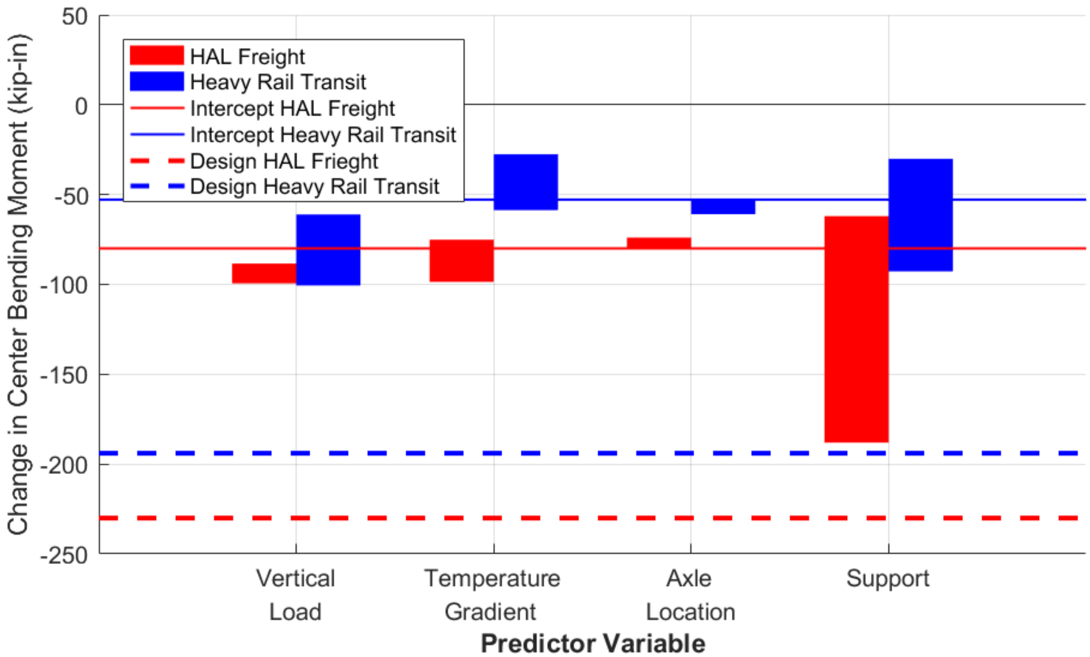

FIGURE 4 Sensitivity of center bending moments.

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 is in agreement with earlier conclusions related to the comparatively different moment arms and resulting sensitivities of support conditions at the crosstie center and rail seat regions.

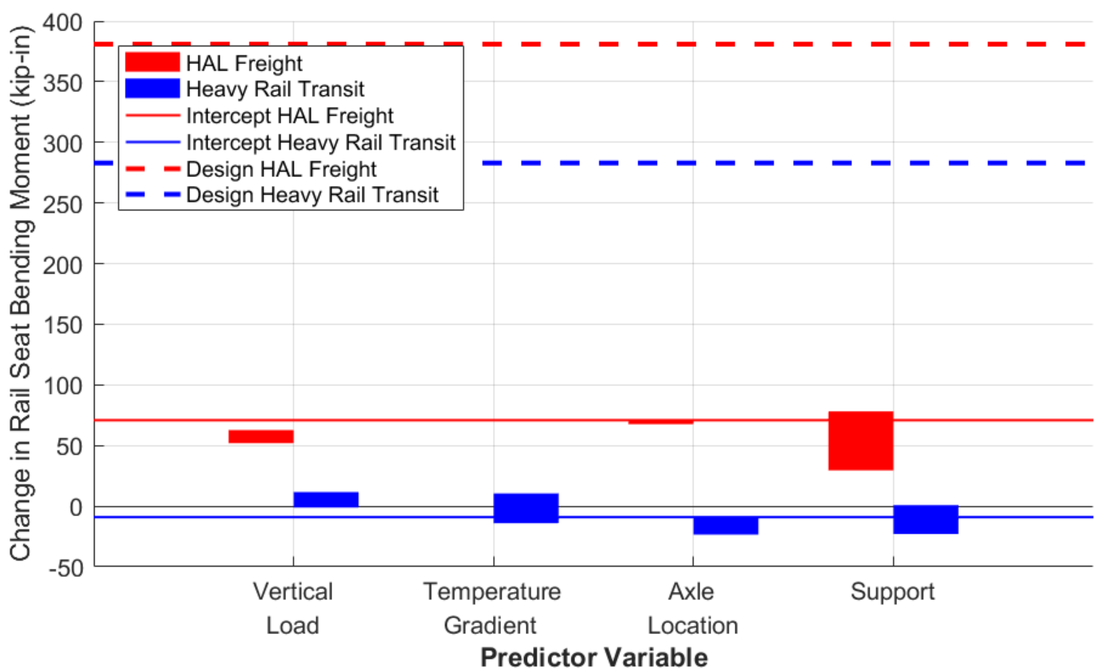

FIGURE 5 Sensitivity of rail seat bending moments.

CONCLUSIONS

Concrete surface strain gauge instrumentation on light rail transit and heavy haul freight was successful in measuring bending strains and resulting moments at both the center and rail seat. These data were used to generate multiple linear regression models for prediction of moments and understanding the interaction and influence of key parameters.

For center bending moment prediction, one of the more surprising findings was the pronounced and opposite effect of axle location on center bending moment for HAL and heavy rail transit. 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 each mode is most likely driven by the different support conditions that are present at the two sites. The effects of vertical axle load and train speed are minimal, which is not what would be expected when reviewing prevailing design standards *(16)*. The effect of temperature was further investigated in this study, building on earlier work *(7)*, and its effects are indeed significant especially at the crosstie center. The effects are similar in both rail transport modes, and provides a useful metric for considering the effect of temperature differentials on concrete crosstie bending moments. Finally, the effect of train speed and axle load is far less pronounced at the center than was expected.

A notable finding with respect to rail seat moment prediction is the comparatively small influence of support conditions, limited sensitivity to wheel-rail interface vertical load, and the fact that temperature gradient was not needed to generate an accurate model of rail seat bending for HAL freight.

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

Equations 2 through 5 in combination with Table 9 provide a means of predicting center and rail seat field bending moments for heavy haul freight and heavy rail transit operations. Challenges and future work relate to developing more generalized models that facilitate broader application of the findings associated with the two field sites in this study. Specifically, this research points to the need to consider temperature gradient in the design of crossties, the variability and influence of support conditions on the bending response of the crosstie and its implication to maintenance practices, and the need to focus additional research on the effect of axle location on crosstie center flexural demand.

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