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Improved Concrete Crosstie and Fastening Systems for US High Speed Passenger Rail and Joint Corridors: Volume 1 – Project Summary Report

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13. ABSTRACT (Maximum 200 words)

Rail corridors often experience a wide variety of passenger and freight train loads, track geometry characteristics, and environmental conditions. These factors must be considered when developing an "optimized" concrete crosstie and fastening system capable of performing under a wide range of service conditions.

This project used basic and applied research and experimentation to address the need for an improved railway crosstie and fastening system for high speed passenger and joint passenger and freight routes in the US. The effort provided answers to a number of concrete crosstie and fastening system design and performance questions that apply to the US railroad industry. The results obtained from this effort will provide the rail industry with a better understanding of the factors that affect the performance of concrete crossties and fastening systems, an improved set of performance requirements for tie and fastener system design based on field and laboratory data, and a novel, mechanistic design approach to tie and fastener design.

Volume 1 (the *Project Summary Report*) summarizes the activities and results from this research project. A separate Volume 2 provides further detailed information regarding the major tasks completed for this project.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH** (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA** (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT** (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME** (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE** (EXACT)		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

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Executive Summary

This research project addressed a number of concrete crosstie and fastening system design and performance questions that applies to the US railroad industry, with an approach that included multi-faceted basic and applied research, and experimentation. This study was conducted between June 2011 and December 2014 by researchers at the University of Illinois at Urbana-Champaign, funded by the Federal Railroad Administration (FRA).

The goal was to better understand the various factors that affect the performance of concrete crossties and fastening systems, then use that knowledge to develop improved design requirements, quantify system behavior (including loading path and magnitude), and improve design practices for systems in use on high-speed passenger and joint passenger/freight corridors in the US.

Every high- and higher-speed rail infrastructure construction or rehabilitation project must deal with multiple operational conditions, which must be considered as part of the infrastructure components that are selected and designed. Since a rail corridor can be used for multiple services, it can experience a wide variety of passenger and freight train loads, track geometry characteristics, and environmental conditions. These factors are internal (e.g. railcar loading) and external (e.g. climatic) to the crosstie and fastening system, and they must all be considered in order to develop an "optimized" concrete crosstie system that will perform under a wide range of service conditions.

The research investigated the following areas of this summary report:

1. **Friction's Role in Crosstie and Fastening System Performance** – The team obtained data from laboratory and field experimentation, then validated the results using finite element (FE) modeling. The design of crossties and fastening systems should include a careful analysis of the effects of friction on components and the system. Designers can use friction to control the location and magnitude of component displacements that tend to damage one or more components in the system.
2. **Vertical Load Path and Variability of Rail Seat Loads** – The variability in the vertical load carried by individual rail seats is high and it can affect the design decisions for crossties. To reduce costs, designers may select a design load that is less than the maximum expected load.
3. **Lateral Load Path and Distribution of Lateral Loads** – Lateral wheel loads are distributed over approximately three ties and approximately half of the lateral load applied at the wheel-rail interface is carried by friction. As lateral wheel load increases, the lateral friction and bearing restraint forces begin to converge. The percentage of the applied lateral wheel load restrained by frictional forces starts to decrease while the percentage of the applied lateral wheel load restrained by bearing forces starts to increase. A rail seat with a higher lateral stiffness can also result in a higher percentage of the lateral load bearing on the insulator post and shoulder face.
4. **Need for System-Level Designs** – The general design process used in North America does not consider the full system. There are system-level tests used for design validation, but these tests occur very late in the overall process. This study proposes a

> method that uses assumptions for the ballast reaction and rail seat load. For rail seat positive bending, a newly tamped condition is proposed, and for center negative bending, a uniformly supported condition is proposed. These assumptions do not capture the worst-case field scenario, but they do provide a more mechanistically based analysis methodology. Using FE modeling techniques and the mechanistic design process proposed here within, designers can address system-level performance prior to prototype testing. System-level design is a required step in a mechanistic design process.

This research effort developed a vision for mechanistic design for concrete crossties and fastening systems. A mechanistic design process will provide many benefits that are not currently achieved by the American Railway Engineering and Maintenance-of-Way Association's (AREMA) iterative design process. While mechanistic design will provide more accurate predictions of the load experienced by components, a large amount of capital and time is needed in order to develop the process. In addition, even if both process types were fully developed, using the mechanistic design will take more time as the full load path will need to be determined. As concrete crosstie and fastening system finite element models become more robust, it should be possible to determine the load path and distributed forces more quickly, but currently this is a time-consuming process. Once a mechanistic design is developed, it will provide much more flexibility than the iterative design process, allowing for variable factors of safety for each failure mode, as well as allowing multiple types of fastening systems while still producing reliable predictions of performance.

1. Introduction

Every high and higher-speed rail infrastructure construction or rehabilitation project must deal with multiple operational conditions that owners must consider during the design and selection of infrastructure components. A single rail corridor can experience a wide variety of passenger and freight train loads, track geometry characteristics, and environmental conditions. These factors are internal (e.g. railcar loading) and external (e.g. climatic) to the crosstie and fastening system, and they must all be considered in order to develop an "optimized" concrete crosstie system that will perform under a wide range of service conditions.

This project's key technical impacts include:

1. **Revised Understanding of Lateral and Vertical Wheel-Rail Loads** – Through the analysis of wheel impact load detector (WILD) and truck performance detector (TPD) data, researchers determined that the wheel loads used for the design of crossties and fastening systems were frequently too conservative. Designers must consider wheel condition in combination with the trend toward higher axle loads. Researchers generated revised design tables reflective of current loading conditions.
2. **Rail Seat Load Variability** – Researchers derived a quantitative understanding of the variability in rail seat loading conditions as dictated by changing support conditions, even on well-maintained track. These loading conditions assisted concrete crosstie and fastening system manufacturers while they developed designs that achieved expected life cycles.
3. **Mapping of Rail Seat Pressure Distributions** – The large variability in rail seat pressure distributions that stemmed from variable support conditions, geometry, lateral/vertical (L/V) load ratios were quantified. Qualitative data showing rail seat pressure distribution provided useful information for fastening system design.
4. **Fastening System Lateral Load Path Quantification** – A quantitative understanding of the lateral load path was developed and the number of rail seats over which the lateral load were distributed.
5. **I-TRACK** – An analytical tool that compared the influence of key inputs on the performance of the system was developed. The team used the tool to perform parametric analyses to better understand the sensitivity of input variables with respect to critical output parameters that related to the overall performance of the fastening system.
6. **Crosstie Flexural Analysis** – A clear and concise format was developed for the analysis of the flexural capacity of concrete crossties that was more representative of the types of support conditions that were encountered in track. In 2015, this format was adopted by American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 30 (Ties) for inclusion in AREMA Chapter 30 (Ties).

This project leveraged the expertise of concrete crosstie and fastening system researchers from the University of Illinois at Urbana-Champaign (UIUC) and from around the world, taking advantage of the civil, structural, and materials expertise at UIUC. The research focus of this project was refined through extensive discussions with railroad industry experts in the field of concrete crosstie design, manufacture, quality assurance, installation, and maintenance.

Ultimately, the research findings from this project will facilitate the advancement of infrastructure component design and performance for high and higher-speed passenger rail operations in the US.

1.1 Background

The use of concrete crossties in the US began in 1960. Since then, the development of concrete crossties and fastening systems has been mostly iterative, with very few novel breakthroughs occurring over the past several decades. A lack of significant concrete crosstie research in the US freight and passenger rail environment has led to this iterative approach to design.

Recently, the industry has developed crossties and fastening systems to resist rail seat deterioration (RSD) and fastening system wear and fatigue, but additional basic and applied research is needed to ensure that systems can be designed and manufactured with the ability to support the new loading demands typical of joint passenger and freight corridors. Manufacturers and designers have noted the need for an increased understanding of the forces/pressures generated at the multiple interfaces within the tie and fastening system.

The current deficit in publicly available research data on concrete crossties and fastening systems stems from the fact that most experimental and design results are proprietary, conducted by the organizations actively engaged in the design and/or manufacturing of these systems.

Concrete crossties ensure stringent gauge restraint and other track geometry requirements that are required for high and higher-speed passenger rail and joint passenger/freight corridors in the US. Deficient concrete crosstie performance exists in both heavy-haul freight and passenger corridors in the US. Effective basic and applied research, which should culminate in performance-based design criteria, could resolve many of these deficiencies.

UIUC researchers noted concrete crosstie and fastener performance deficiencies in a failure mode and effects analysis (FMEA) conducted in 2008. This study found that the most prominent concrete crosstie and fastener problems were RSD and fastener system wear and fatigue. Additionally, UIUC found that there was a need for improved concrete crosstie designs for joint passenger and freight corridors in the US. At present, joint corridors are the most prominent type of emerging higher-speed passenger rail routes in the US; thus this research is critical to the safe and efficient operation of these new corridors.

The American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 30 (Ties), the primary industry-supported organization for developing recommended design practices for concrete crossties in the US, has noted the need for improvements to the current method of analyzing and designing concrete crossties and fastening systems. Areas of the AREMA recommended practices in need of improvement range from crosstie flexural analysis to clarification of expected lateral load behavior at the system level.

1.2 Organization of Report

Volume 1 of this report summarizes the activities and results from the research project. A separate Volume 2 accompanies this summary report and provides detailed information in the following 10 chapters regarding the major tasks completed under this project:

Chapter 1: International Survey Results

Chapter 2: Loading Quantification Document

Chapter 3: Laboratory Experimental Plan

Chapter 4: Laboratory Experimental Results

Chapter 5: Field Experimental Plan

Chapter 6: Field Experimental Results

Chapter 7: FE Modeling Methodology and Development

Chapter 8: FE Modeling Results and Conclusions

Chapter 9: Analytical Tool for Track Component Response Measurement (I-TRACK)

Chapter 10: Mechanistic Design of Concrete Crossties and Fastening Systems

1.3 Project Objectives and Goals

The objectives of this project was to understand the factors that affect the short- and long-term performance of concrete crossties, and then use this improved understanding to characterize the desired requirements for concrete crossties and fastening systems. This characterization included the quantification of component and system behavior (including loading path and magnitude), and the development of a more effective design practice for systems used on high-speed passenger and joint passenger/freight corridors in the US. These parallel and complimentary objectives define the following goals of this project, its research, and results:

- Develop an in-depth analytical understanding of the performance and design specifications for concrete crossties and fastening systems from around the world.
- Characterize (measure) the forces in the crosstie and fastening system to facilitate mechanistic designs.
- Develop a revised set of recommended practices for tie and fastener design that lead to improved safety, lower maintenance costs, and lower life cycle costs.

The project effort focused on understanding the requirements for concrete crossties and fastening systems that will lead to improved infrastructure safety, increased network reliability, and reduced life cycle costs. Outcomes of this project include research findings and an improved understanding of concrete crossties providing the following benefits:

- Centralized knowledge and document depository for the international domain of concrete ties and fastening systems—to be hosted at UIUC and made publicly available.
- Investigation of best practices (design and performance) from around the world.
- Improved safety due to improvements to the robustness of critical infrastructure components (e.g. concrete crossties, rail pads, insulators, fasteners, etc.).
- Improved understanding of crosstie and fastening system-loading path – A calibrated analytical model of how loads are transferred through the fastening systems and rail seat of a concrete crosstie.

1.4 Project Approach

UIUC's multi-faceted research program on the design and performance of concrete crossties and fastening systems was divided into three primary focal areas:

1. Field experimentation (Field Study)
2. Laboratory experimentation (Laboratory Study)
3. FE modeling (Modeling)

The three focus areas are interrelated, and information was exchanged within the project areas through shared inputs and outputs. Additionally, there was a common vision in which a series of deliverables would lead to the final deliverable that would contain improved recommended practices (Figure 1).

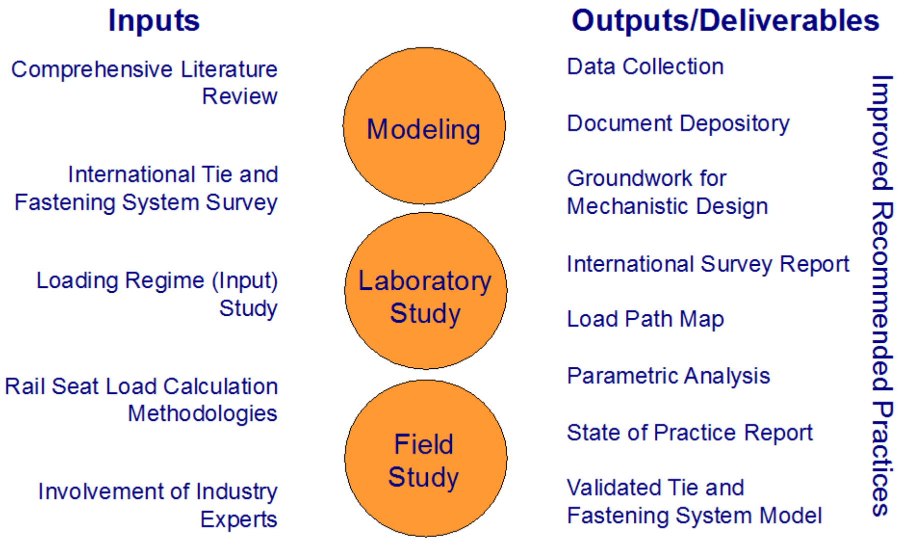


Figure 1. Three Primary Areas of Project Focus and Inputs and Outputs Relating to These Areas

The project team worked to ensure that each of the relevant inputs and outputs would guide multiple areas of the project. This was accomplished via weekly team meetings and frequent coordination between the management team and the research assistants. For example, the findings of the international crosstie survey played an important part in guiding the other research undertaken by UIUC.

1.4.1 Project Team

The project team is represented in the organizational chart shown in Figure 2. Most of the research personnel were faculty, staff, and students at the University of Illinois at Urbana-Champaign. The cost-sharing industry partners primarily fell into one of two categories:

1. **Railroads** – Provided access to the past performance of concrete crossties and fastening systems, and allowed access to infrastructure to understand the challenges that needed investigation.
2. **Suppliers** – Provided designs, interpreted current designs, and provided concrete crossties and fastening system specimens for laboratory and field investigations.

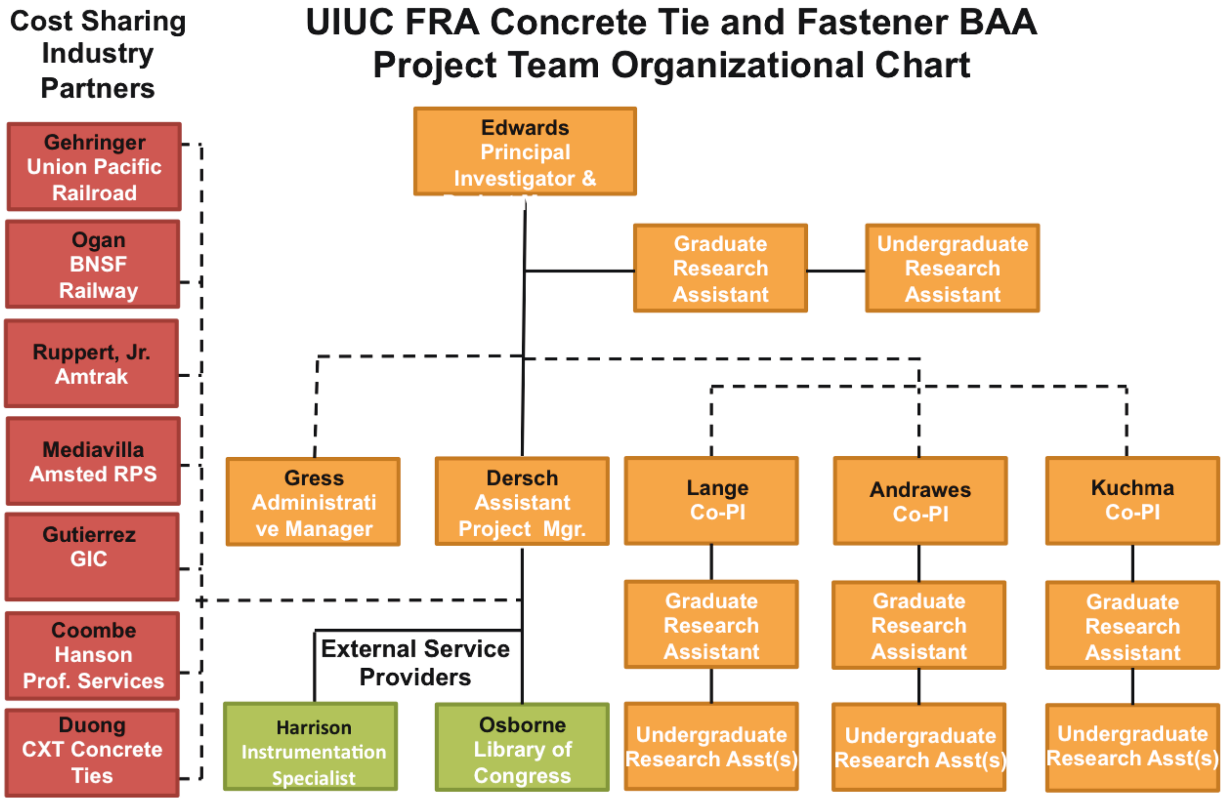
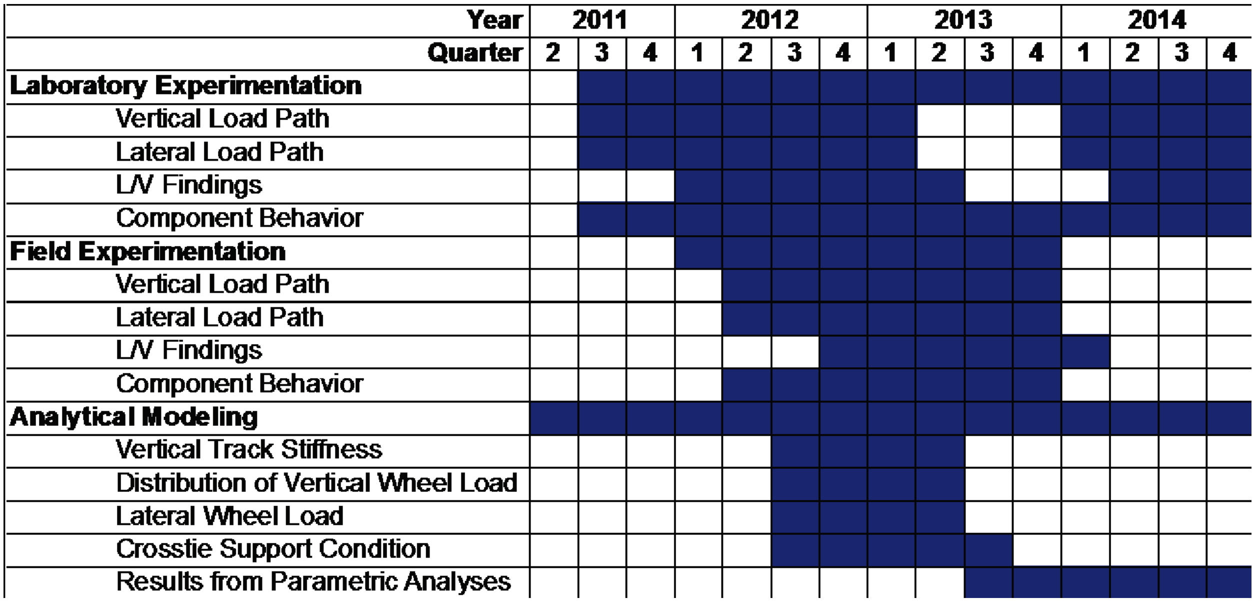


Figure 2. FRA's Crosstie and Fastening System Project Team

1.4.2 Project Schedule

The project schedule is shown in Figure 3.



Year	2011			2012				2013				2014			
Quarter	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Laboratory Experimentation		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Vertical Load Path		■	■	■	■	■	■	■				■	■	■	■
Lateral Load Path		■	■	■	■	■	■	■				■	■	■	■
L/V Findings				■	■	■	■	■	■				■	■	■
Component Behavior		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Field Experimentation				■	■	■	■	■	■	■	■				
Vertical Load Path					■	■	■	■	■	■	■				
Lateral Load Path					■	■	■	■	■	■	■				
L/V Findings							■	■	■	■	■	■			
Component Behavior					■	■	■	■	■	■	■				
Analytical Modeling	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Vertical Track Stiffness						■	■	■	■						
Distribution of Vertical Wheel Load						■	■	■	■						
Lateral Wheel Load						■	■	■	■						
Crosstie Support Condition						■	■	■	■	■					
Results from Parametric Analyses										■	■	■	■	■	■

Figure 3. FRA's Crosstie and Fastening System Project Schedule

2. Project Execution

2.1 Field Research

The project's field experiments are designed to enhance the current understanding of concrete crosstie and fastening system behavior under representative loading conditions. This experimentation was not as controlled as the laboratory experimentation, but it was better at simulating the loading environment seen in the field. However, since testing was conducted at the Transportation Technology Center (TTC), some variables were controlled, which helped to better understand the effect of these variables on the full system performance.

The field experiments facilitated a comprehensive study of the entire concrete crosstie and fastening system under realistic service conditions. The interaction between different components of the system was analyzed by applying static and dynamic loadings on both tangent and curved track. Researchers applied static loads in both the vertical and lateral direction at varying magnitudes and multiple rail seat locations. Passenger and freight consists passing at varying speeds and track geometries provided dynamic loads.

To achieve the overall purpose of gaining a deeper understanding of concrete crosstie and fastening system behavior, the primary objectives of this field experimental plan were:

- **Investigate the Dynamic Loading Effects** – Understand how dynamic and impact loads differ in magnitude, distribution, and load path from static loads.
- **Characterize the Effect of the Loading Environment on the System Load Path** – Determine the flow of forces through the rail, fastening system, and crosstie vary under different vertical and lateral loadings.
- **Collect Representative Validation Data for Analytical Model** – Provide realistic data to develop and validate the three-dimensional finite element models of the crosstie and fastening system.

2.1.1 Field Activities

Field activities consisted of the following sub-activities:

Vertical Load Path – Determine the distribution of vertical forces over adjacent rail seats and quantifying the magnitude of rail seat loads. These results aided in the calibration and validation of the analytical model.

Lateral Load Path – Developed and deployed novel devices to quantify the lateral forces entering the fastening system at the shoulder interface. These results also aided in the calibration and validation of the analytical model.

Combined Vertical and Lateral Load Path – The vertical and lateral load path results were used by UIUC to develop combined conclusions aimed at understanding the expected performance of concrete crossties and fastening systems under a variety of lateral and vertical load combinations.

Component Behavior – While no component-level tests were conducted in the field, component behavior could be estimated. Specific component behavior was investigated, including concrete crosstie strain/moments and fastening system clip strain/forces.

2.1.2 Field Test Locations

UIUC conducted field experiments at TTC in Pueblo, CO, with the support of the Transportation Technology Center, Inc (TTCI). The team conducted experiments on a section of tangent track on the Railroad Test Track (RTT) and a segment of five-degree curved track on the High Tonnage Loop (HTL) with 4 inches of super elevation, and a 33 mph (53 kph) balance (Figure 1). Both test track sections had 136RE rail, concrete crossties spaced at 24-inch center-to-center, Safelok I type fastening systems, and premium ballast.

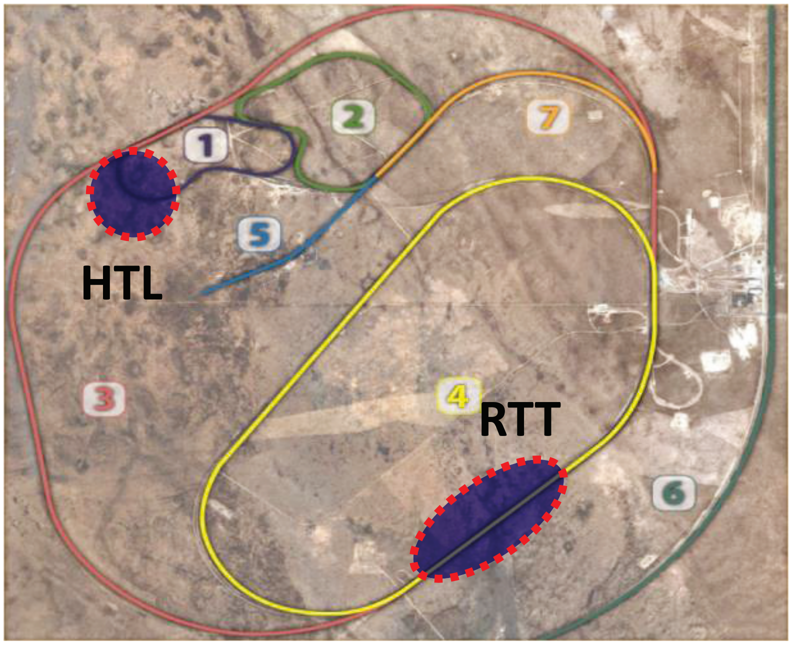


Figure 4. Testing Locations at TTC

2.2 Laboratory Research

UIUC conducted a comprehensive laboratory experimental effort at the Advanced Transportation Research Engineering Laboratory (ATREL) in Rantoul, IL, and the Newmark Structural Engineering Laboratory (NEES) and the RailTEC Research and Innovation Laboratory (RAIL) in Champaign, IL.

Laboratory experiments deepened the team's understanding of the load path through the crosstie and fastening system in two distinct ways. First, the team gained an understanding of the load going through an individual crosstie and its fastening system. Secondly, the team developed an understanding of the distribution of a given load over adjacent crossties.

As a part of the laboratory experimental phase, researchers examined the load path into each crosstie and fastening system under known loading conditions. Then they evaluated the behavior of each system component. Experiments determined the load demand and capacity of each component, the support conditions provided by the ballast, and the stability of the system due to changing load and system boundary conditions.

UIUC designed the laboratory experimental plan to achieve the following objectives:

- **System Load Path Determination** – Understand the load transfer mechanics of the crosstie and fastening system from the wheel-rail interface, through the fastening system, and into the crosstie.

- **Crosstie-Fastener Response** – Quantify the system response by analyzing the characteristic deformation and deflection of all crosstie and fastening system components.
- **Analytical Model Development** – Provide reliable data to develop and validate the three-dimensional FE model of the crosstie and fastening system.

2.2.1 Laboratory Activities

Laboratory activities for this project consisted of the following sub-activities:

<u>Vertical Load Path</u> – Determined how many rail seats the vertical load was distributed over, as well as quantifying the magnitude and distribution of rail seat loads. These results aided in the calibration and validation of the analytical model.

<u>Lateral Load Path</u> – Conducted lateral load path experiments as part of a large experimental program, and deployed novel devices to quantify the lateral forces entering the fastening system at the shoulder. These results were used in the calibration and validation of the analytical model.

<u>Combined Vertical and Lateral Load Path</u> – The vertical and lateral load path results were used to develop combined conclusions, which were aimed at understanding the expected performance of concrete crossties and fastening systems under a variety of lateral and vertical load combinations.

<u>Component Behavior</u> – Component-level tests were a primary thrust for the initial laboratory experimentation. Specific component behaviors were investigated, including rail strain, concrete crosstie strain/moments, pad compression and modulus testing, and fastening system clip strain/forces.

<u>Development and Use of Track Loading System</u> – UIUC developed the Track Loading System (TLS) to allow researchers to finely control variables related to the loading and response of the track structure in a controlled laboratory environment.

2.2.2 Laboratory Test Equipment

Uniaxial Loading Machine

Researchers used the uniaxial loading machine to test the compression and flexural behavior of concrete crossties and fastening system components (Figure 5). The uniaxial loading machine employs a hydraulically powered actuator to apply a load up to 100,000 pound-force (100 kips) in the vertical direction, perpendicular to the loaded face of the component being tested. A ball-joint cast in the upper-loading head minimized the effect of eccentric loading and the machine was adjusted to fit components with varying dimensions. A calibrated load cell was used to monitor applied load.

Figure 5. Uniaxial Loading Machine

Static Load Testing Machine

UIUC used the Static Load Testing Machine (SLTM) to apply loads to a concrete crosstie and fastening system, test the behavior of rail, and calibrate strain gauge configurations installed in various locations on the rail (Figure 6). The SLTM employs a hydraulic jack to apply vertical load supported by an overhead loading frame, and its loading head has a simplified wheel profile that applies a fixed combination of vertical and lateral load on both rails. The angle between the normal direction of the contact surface of the loading head and the vertical plane is designed to be 26.5 degrees, equating to a L/V force ratio of 0.5 applied to both rails. The loading head could be modified to apply pure vertical loads. A calibrated load cell was used to monitor applied loads.

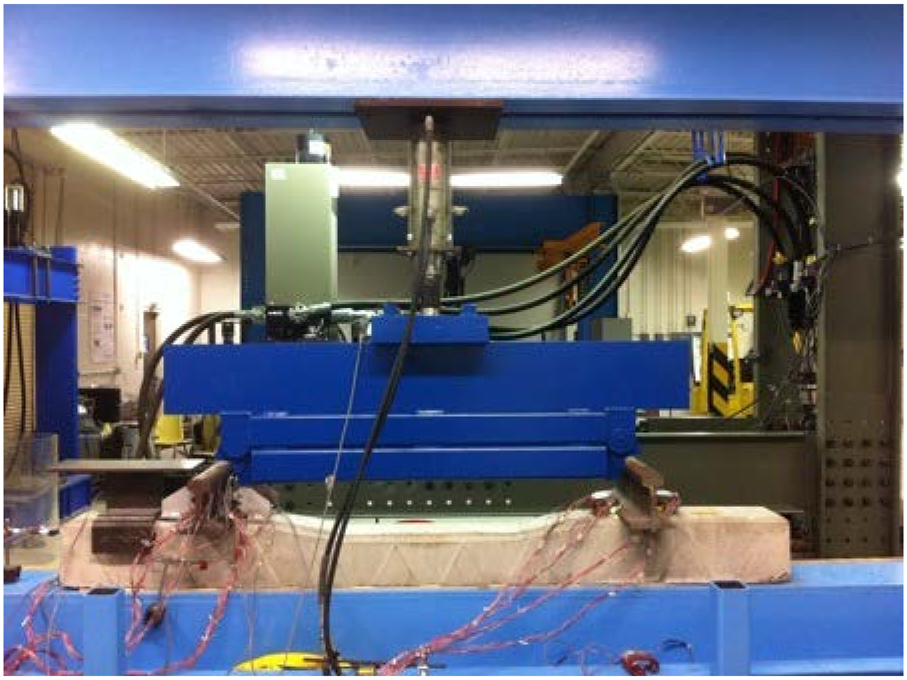


Figure 6. Static Load Testing Machine

Pulsating Load Testing Machine

The team used the Pulsating Load Testing Machine (PLTM) to apply loads to a single concrete crosstie and fastening system and test the magnitude and distribution of applied forces (Figure 7). Static or dynamic vertical and lateral loads were applied to the rail on one rail seat of a full-scale concrete crosstie, and a complete fastening system assembly was installed. Vertical and lateral loads were adjusted separately using a control system. The PLTM has three hydraulic actuators (two vertical and one lateral) mounted on a self-reacting steel frame and a loading head. The loading head is bolted to the head of a 2-foot segment of 136RE rail. The actuators were calibrated for load and displacement prior to installation.

Figure 7. Pulsating Load Testing Machine

Static Tie Tester

UIUC used the static tie tester (STT) (Figure 8) to apply loads then test the flexural and compressive behavior of concrete crossties. Rail seat compression tests, rail seat positive and negative bending tests, and crosstie center positive and negative bending tests were conducted. The STT has a hydraulic cylinder to apply loads to the rail seat or center of a crosstie up to a maximum capacity of approximately 100,000 pound-force. A calibrated pressure gauge was used to monitor applied loads.

Figure 8. Static Tie Tester

Track Loading System

UIUC designed and constructed the full-scale TLS, which applied loads to a 22-foot long section of concrete crosstie track (Figure 9). Researchers installed track components on a full depth section of track that included 11 crossties spaced at 24 inches on center. The system uses a 36-inch diameter wheel set to transfer static or dynamic loads to the track structure; vertical and lateral loads are adjusted independently using a control system. The TLS has two hydraulic actuators mounted vertically and a hydraulic cylinder mounted laterally on a self-reacting steel frame. A special assembly for each journal attached one vertically mounted actuator and the horizontally mounted hydraulic cylinder to one journal and the second vertically mounted actuator to the opposite journal. The actuators were calibrated for both load and displacement.

Figure 9. Track Loading System

2.3 Finite Element Model Development

UIUC used FE modeling to help interpret the loading demands that originate at the wheel-rail interface. The FE models improved the understanding of the vertical, lateral, and longitudinal load path. The models also served as an important analytical means to examine the behavior of complex systems under multiple loading scenarios. UIUC designed the laboratory and field instrumentation techniques to extract measurements of the critical outputs in the laboratory and field environment, and used the FE model to predict the track system responses.

After the test data was collected, the modeling predictions were compared with the experimental data to verify the assumptions and simplifications included in the model. To improve the credibility of the FE models, UIUC validated the model in a hierarchical fashion based on experiments at different levels. After the model was validated, parametric studies based on the critical inputs and outputs were completed. Using this process, UIUC evaluated the correlation between inputs and outputs, and then they developed and compared possible alternatives to the current design of concrete crosstie and fastening systems. The results of the parametric analyses serve as the basis for the proposed mechanistic design approach.

2.3.1 Modeling Activities

The following modeling sub-activities were completed as a part of the project:

Vertical Track Stiffness – Results from field and laboratory experiments were used to calibrate and validate the FE model, which was used for later parametric analyses.

Vertical Wheel Loads – Results from field and laboratory experimentation were used to calibrate and validate the FE model, which was used for later parametric analyses.

Distribution of Lateral Wheel Load – UIUC used the FE model and parametric analysis to understand the distribution of lateral forces.

Evaluation of Crosstie Support Condition – UIUC used results from field and laboratory experimentation to calibrate and validate the FE model. The FE model played a major role in understanding lateral forces by conducting parametric analyses.

Parametric Analysis – Tying the earlier sections of the project together was the execution of a widespread parametric analysis. This allowed us to gain additional granularity in our understanding of how various inputs and outputs interacted with one another.

2.4 Lessons Learned

The team's approach to the research project was effective. However, the team learned these lessons that can be applied to future efforts:

1. Ensure that all elements of experimentation answer a specific question, preferably one rooted in a hypothesis. This will ensure that the instrumentation design, construction, and use is focused towards answering the hypothesis.
2. Use FE modeling early and often in the project. FE models inform all other elements of the project and they help the team develop a more streamlined experimental plan. If UIUC had developed the FE model in advance of the experimental work, the project results would be greater.
3. Have frequent project coordination meetings. For future projects, we would consider using a software package that tracks tasks and expected deliverables. Holding weekly project meetings on instrumentation and experimentation was valuable for our team.

3. Overview of Key Findings

3.1 International Concrete Crosstie and Fastening System Survey

Prior to this research program, there has not been much effort invested in documenting the current state-of-the-art of international design and performance trends for concrete crossties and fastening systems. The primary objective of the International Concrete Crosstie and Fastening System Survey was to poll the international railway community on the use and performance of concrete crossties and elastic fastening systems.

The survey provided information that was used in many parts of the project, including FE modeling, laboratory experimentation, and field experimentation. In terms of modeling, the results of this survey helped to determine typical loading scenarios using modeling and loading methodologies from previous research. The modeling-related survey results also provided references for literature that was related to previous analyses, which allowed UIUC's team to incorporate past research efforts and findings into the project. The responses from the survey also included criteria from laboratory testing performed on concrete crossties and fastening systems around the world, allowing us to compare North American test criteria and methodologies with international standards. Finally, the survey results helped steer field experimentation efforts by identifying conditions where failures commonly occur and by allowing UIUC to develop a greater understanding of probabilistic loading conditions and failure modes.

There were several important conclusions that came from this survey. Researchers and designers should consider them when planning additional research or system designs:

1. The differences between the manufacturing process were that the North American and international respondents may be the cause of significantly different trends in requirements and performance of concrete crossties. Future research and testing may aid in determining the correlation between these trends and any resulting performance differences.
2. The most important critical failures in North America involve wear or fatigue on the rail seat, rail pad, or shoulder. International respondents state that tamping damage, cracking from dynamic loads, and shoulder wear are also concerns (Figure 10). For example, 71% of respondents indicated that concrete deterioration beneath the rail seat was a failure mechanism in their system.
3. Fastening system manufacturers indicated that component and system interactions play a large role in their design, and this fact should be considered when developing mechanistic design recommendations for concrete crossties and fastening systems.
4. The survey provided insight into the most important concrete crosstie and fastening system research needs (Figure 11). The needs were inverted when comparing North American and international responses. Domestically, RSD and fastening system wear and fatigue were at the top of the list.

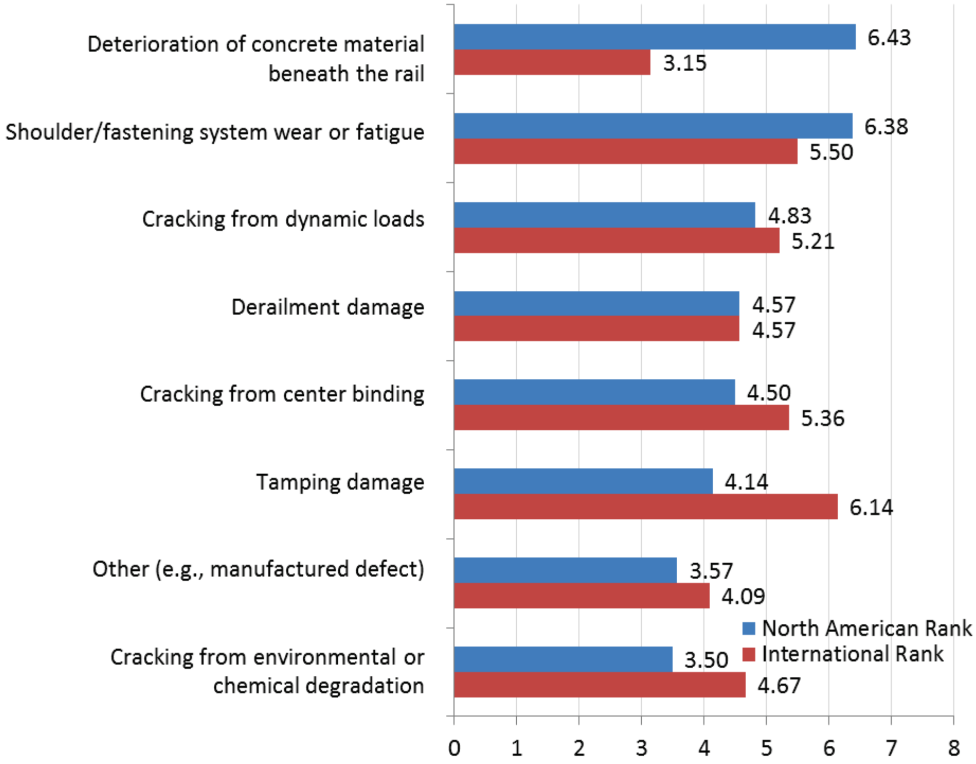


Figure 10. The Most Critical Concrete Crosstie and Fastening System Problems Ranked from 1 to 8, with 8 Being the Most Critical

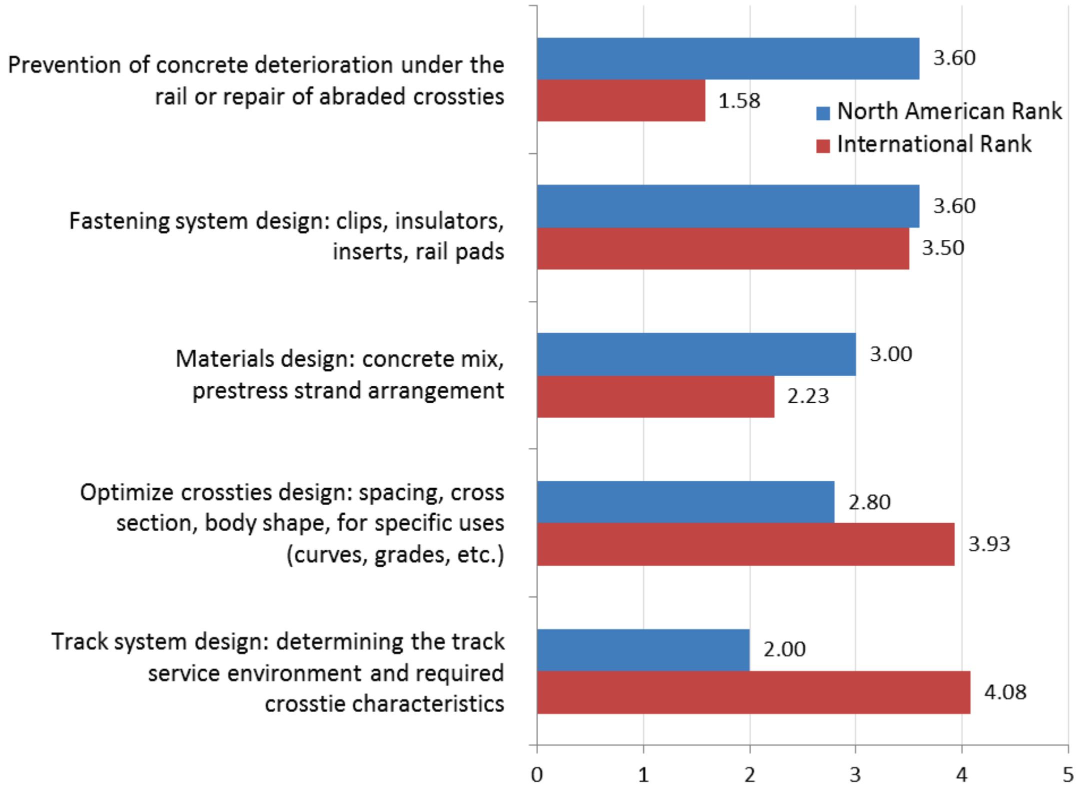


Figure 11. International Survey Results - The Most Important Concrete Crosstie and Fastening System Research Topics; Ranked from 1 to 5, with 5 Being the Most Important

3.2 Vertical and Lateral Load Characterization

To improve the design process for concrete crossties and fastening systems it is necessary to quantify the wheel loads that place demands on the system. To quantify these loads, researchers at UIUC used wayside detectors on mainline railroads to collect wheel load magnitudes. Vertical wheel loads were quantified using wheel impact load detectors (WILD), while lateral wheel loads were quantified using truck performance detectors (TPD). This data was used to compare wheel loads from different car types to predict the magnitude of a typical wheel load.

Figure 12 represents the distribution of nominal (static) vertical wheel loads categorized by car type. The magnitude of vertical wheel loads vary significantly based on the weight of the railcar. The distribution of vertical wheel loads in freight cars can have a large spread, due to the difference in weight between empty and loaded cars. Locomotives have the least variance in nominal vertical load, both for passenger and freight railcars. Table 1 provides a numerical representation of Figure 12, which were used to determine the typical static wheel loads for passenger and freight trains in the United States.

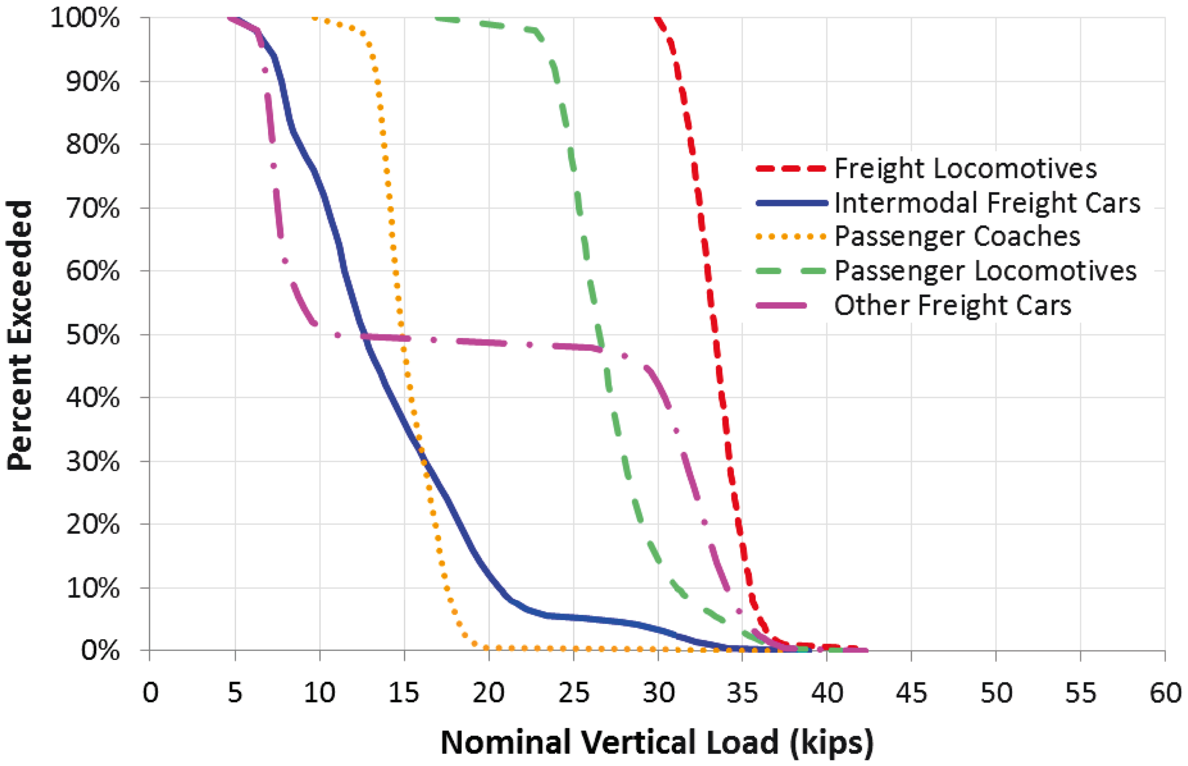


Figure 12. Percent Exceeding Particular Nominal Vertical Loads on Amtrak at Edgewood, Maryland (WILD Data from November 2010)

Table 1. Distribution of Static Vertical Wheel Loads

	Nominal Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car[1]	7	10	11	14	15
Loaded Freight Car[1]	34	40	41	42	46
Intermodal Freight Car[1]	21	36	37	40	51
Freight Locomotive[1]	34	37	38	39	44
Passenger Locomotive[2]	27	36	38	40	43
Passenger Coach[2]	15	19	19	21	46

[1] Source of data: Union Pacific Railroad; Gothenburg, Nebraska; January 2010

[2] Source of data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010

To determine the magnitude of vertical wheel loads to use for design, the peak wheel loads must be evaluated. A peak load is the highest value recorded by the WILD site during the full rotation of a wheel. A car could have a flat wheel that causes a very high magnitude vertical load, possible damaging the infrastructure. Designers can use the highest wheel loads to determine the most severe demands on the system.

Peak vertical wheel loads are highly dependent on the distribution of static vertical wheel loads. The shape of the distribution of vertical wheel loads (according to car type) is essentially the same for static and peak vertical wheel loads, as shown in Figure 13. The primary difference is how much the peak wheel load increased from the static wheel load, with both passenger and freight locomotives experiencing a higher increase in vertical wheel load when compared with other car types. However, at the very highest magnitude loads, loaded freight cars have the highest peak vertical wheel loads. Table 2 provides a numerical representation of Figure 13, which researchers and designers can use to determine the typical peak wheel loads for passenger and freight trains in the United States.

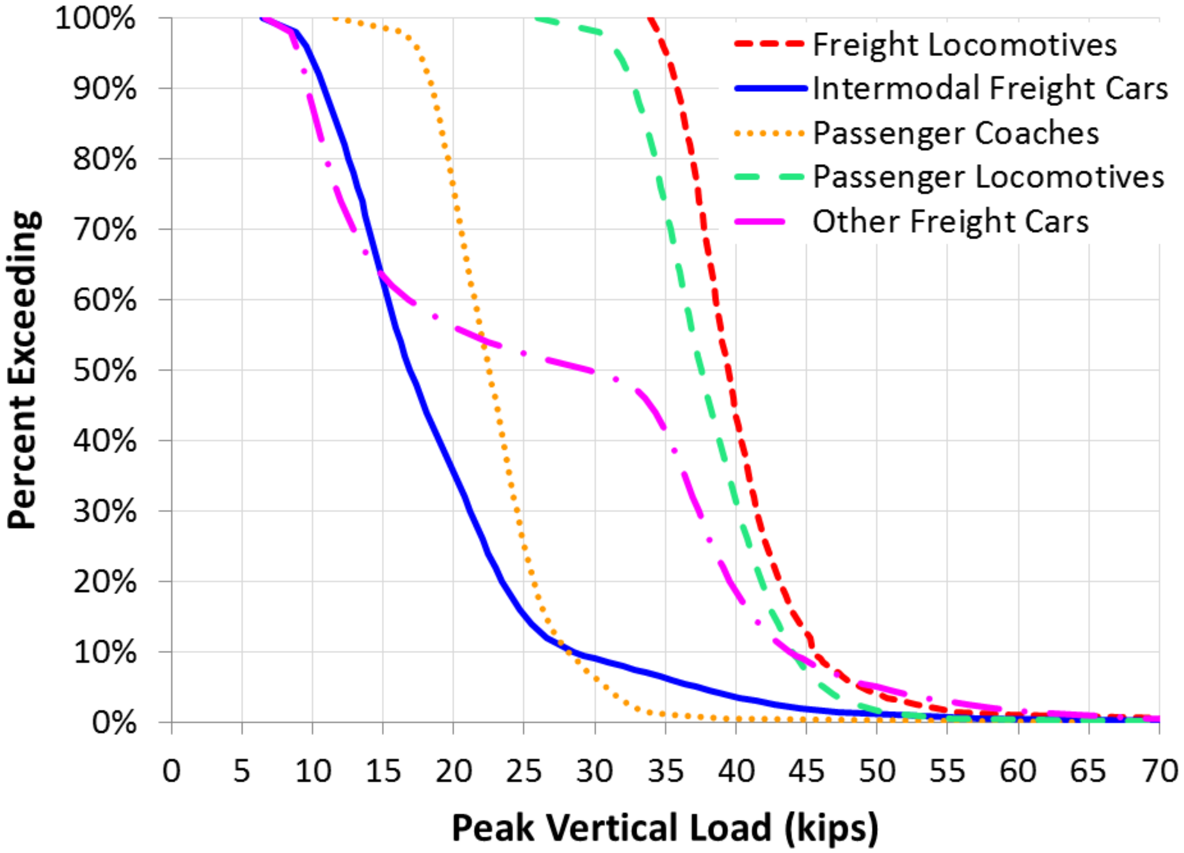


Figure 13. Percent Exceeding Particular Peak Vertical Loads on Amtrak at Edgewood, Maryland (WILD Data from November 2010)

Table 2. Distribution of Peak Vertical Wheel Loads

	Peak Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car[1]	11	21	27	40	101
Loaded Freight Car[1]	43	57	66	85	157
Intermodal Freight Car[1]	28	47	55	75	142
Freight Locomotive[1]	43	54	58	69	110
Passenger Locomotive[2]	39	50	54	64	94
Passenger Coach[2]	24	36	43	59	109

[1] Source of data: Union Pacific Railroad; Gothenburg, Nebraska; January 2010

[2] Source of data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010

The lateral wheel loads must be quantified to determine the overall demand on the crosstie and fastening system. Lateral wheel loads tend to be negligible in tangent track. However, the magnitude of lateral loads increases in curves, becoming a critical component of design. TPD sites were used to quantify lateral wheel loads in curves at locations throughout the United States.

Figure 14 illustrates the magnitude of lateral wheel loads as quantified by TPDs. Similar to vertical wheel loads, car type and weight affects the magnitude of lateral load carried by the track. Locomotives and loaded freight cars have higher average static vertical wheel loads than the other car types, thus, they tend to have higher lateral wheel loads. The shape of the distribution of lateral wheel loads is approximately the same throughout all car types, with only the magnitude of these loads varying significantly. Table 3 provides a numerical representation of Figure 14, which can be used to determine the typical lateral wheel loads for freight traffic in the United States.

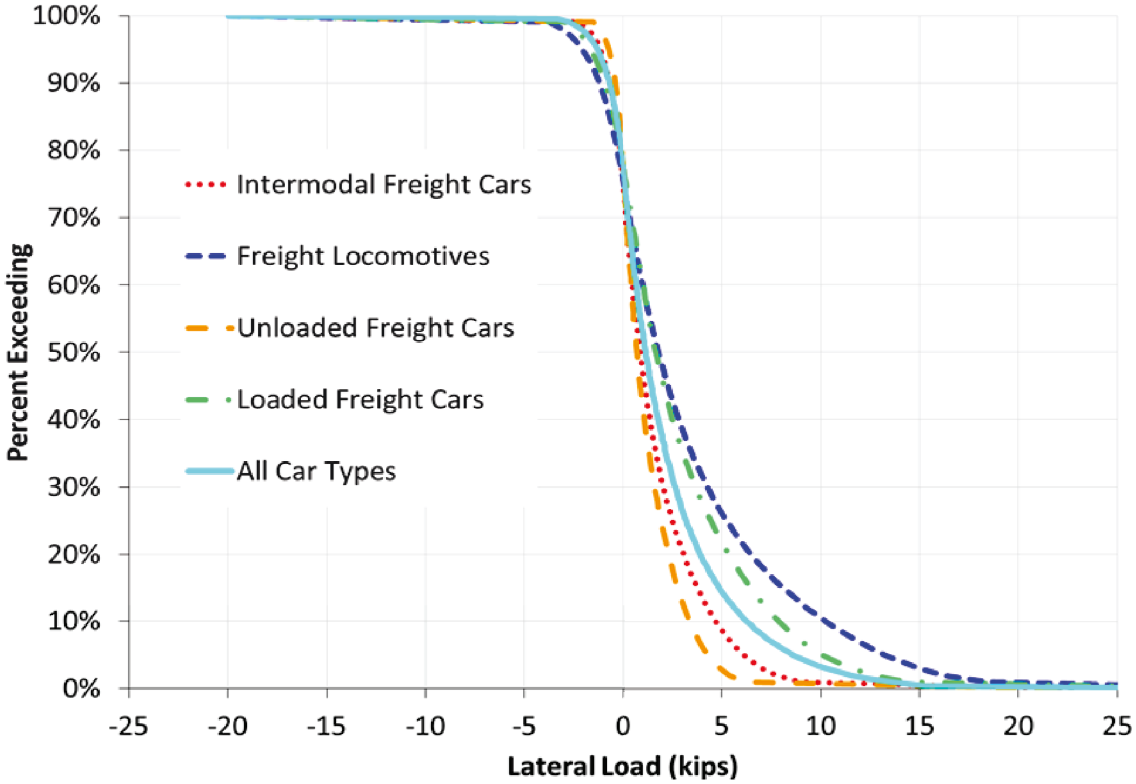


Figure 14. Lateral Load Variation with Car Type

Table 3. Distribution of Peak Lateral Loads

	Lateral Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car	1.1	4.4	5.2	6.9	22.4
Loaded Freight Car	2.7	10.1	12.1	15.9	33.5
Intermodal Freight Car	1.9	6.2	7.4	10.1	22.8
Freight Locomotive	3.9	13.3	15.6	20.5	34.4

Designers can use the loads recorded from WILD and TPD sites for the design of concrete crosstie and fastening systems. The input loads can be determined from Table 1, Table 2, and Table 3. These input loads will determine the demands on the concrete crosstie and fastening system components. Designers can determine the demands on the system components by analyzing the load path through the fastening system. This information can be used to optimize the design of the components, based on the transfer of forces and associated stresses and strains.

3.3 Laboratory and Field Experiments

Laboratory and field experiments answered critical questions about the load path and the behavior of the components in the concrete crosstie and fastening system. The results in this section are divided into four parts: vertical load path, lateral load path, combined lateral and vertical load path, and component behavior. The most critical results associated with each element of the crosstie and fastening system are described. Additional data is available in Volume 2 of this report.

3.3.1 Vertical Load Path

To design concrete crossties, the rail seat load must be estimated. The support conditions under each rail seat are characterized by the global displacement of the end of the crosstie and the strain measured on the surface of the rail. When the rail seat is properly supported, the rail seat immediately under the load supports approximately 45-60% of vertical wheel load, as measured by rail-mounted strain gauges. However, if a rail seat is poorly supported (i.e. a gap between the concrete crosstie and ballast), the rail seat will pick up only a negligible amount of load (Figure 15, RSV 8). With very poor support conditions (Figure 15, DGV 8), a higher amount of vertical crosstie global displacement is expected. Both laboratory and field results show that rail seat loads are highly variable, and the wheel-rail interface loads do not provide a strong indication of the magnitude of the rail seat load.

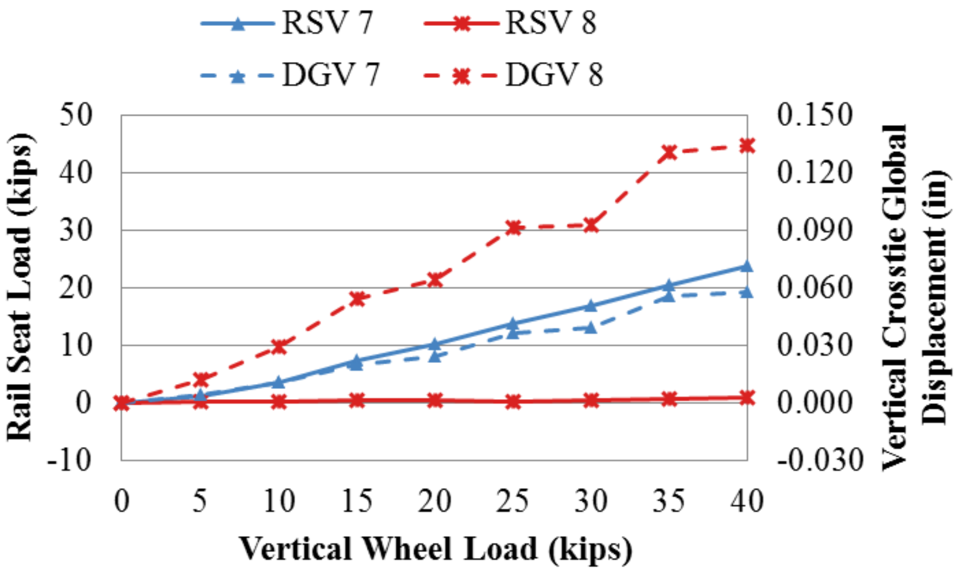


Figure 15. Vertical Rail Seat Reaction Force (RSV) and Vertical Crosstie Global Displacement (DGV) Under Various Vertical Wheel Load and No Lateral Force (Laboratory)

With newly tamped track, the static vertical load was distributed over three to five crossties (Figure 16). Each rail seat in Figure 16 is indicated by one of the bars and labels (i.e. "5V"), and the load is being applied over rail seat 5V, while all readings were captured to show the longitudinal distribution of the vertical force. Results also showed that the static load was carried over as few as three crossties, and as many as seven crossties. These results are linked to the previous conclusion about the variability in rail seat loads as a function of the support stiffness. While the 45-60% assumption provides a sensible average value, variation in support under individual rail seats cause variations in the actual load, which should be considered when designing infrastructure components.

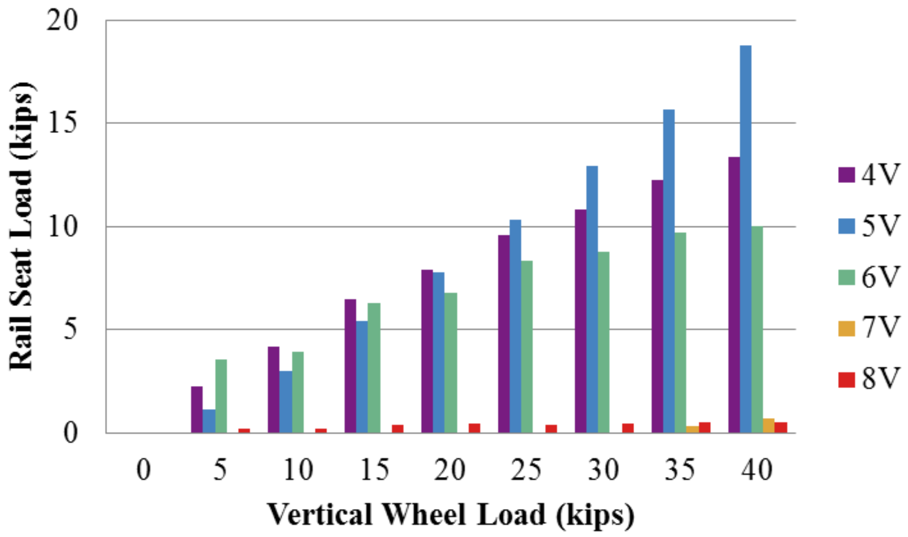


Figure 16. Distribution of Vertical Rail Seat Reaction Force Under Various Vertical Wheel Load and No Lateral Force (Laboratory, Wheel Load over Crosstie 5-16 [Rail Seat 5V])

To further investigate the assumption that between 40% and 60% of the applied vertical wheel load is transferred into the rail seat under the point of loading, additional data were collected with matrix based tactile surface sensors (MBTSS). The support condition under each rail seat is indicated by the displacement of the end of the crosstie, which allows researchers to establish an inverse relationship between crosstie displacement and maximum pressure. Poor support conditions result in higher crosstie displacements and lower rail seat loads, the latter of which should result in lower maximum pressures exerted on the rail seat.

Figure 17 illustrates the change in crosstie displacement and maximum pressure with increased vertical wheel load. The predicted correlation of higher displacements to lower maximum pressures is not reflected in the data. The highest and lowest pressures recorded correspond to displacements in the middle of the observed range, while the highest and lowest displacing rail seats yield nearly identical maximum pressures above a vertical wheel load of 25,000 lb (111 kN). It is therefore clear that the assumption of the average case, 50% load transfer, is not appropriate for examining the results from discrete rail seats.

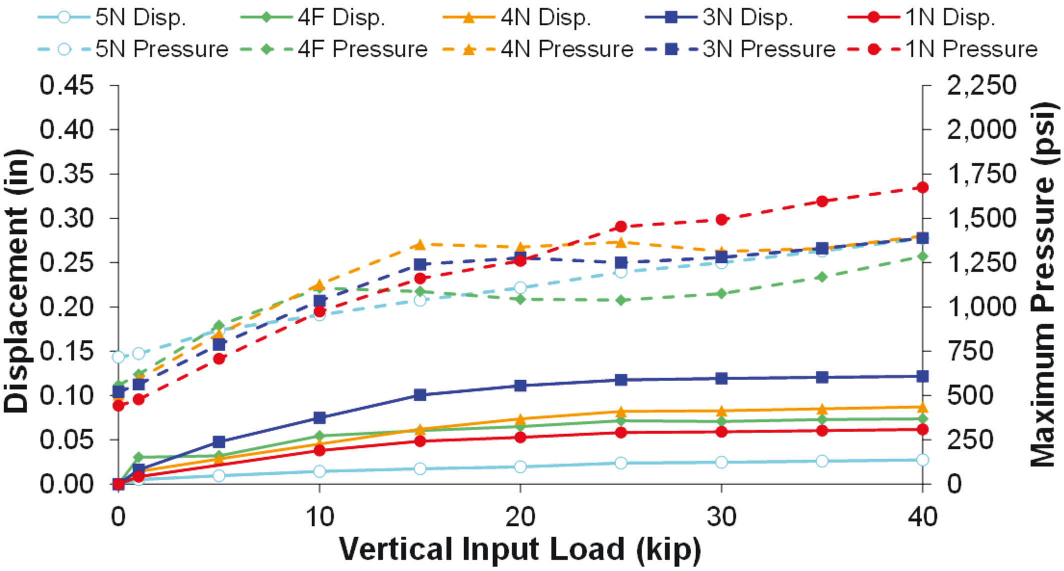


Figure 17. Comparison of Crosstie Displacement and Maximum Pressure at a Rail Seat

Total dynamic vertical wheel loads were as much as 30% higher than static wheel loads, especially at higher speeds (Figure 18). This finding has implications on the dynamic load factors that designers apply in the flexural design of concrete crossties. This variation may be due to the dynamic structural response under different speeds, which includes the interaction of car body, truck system, wheel, and track structure. Impact loads, generated by irregularities in the tread of the wheel, generated loading events well in excess of the static wheel load.

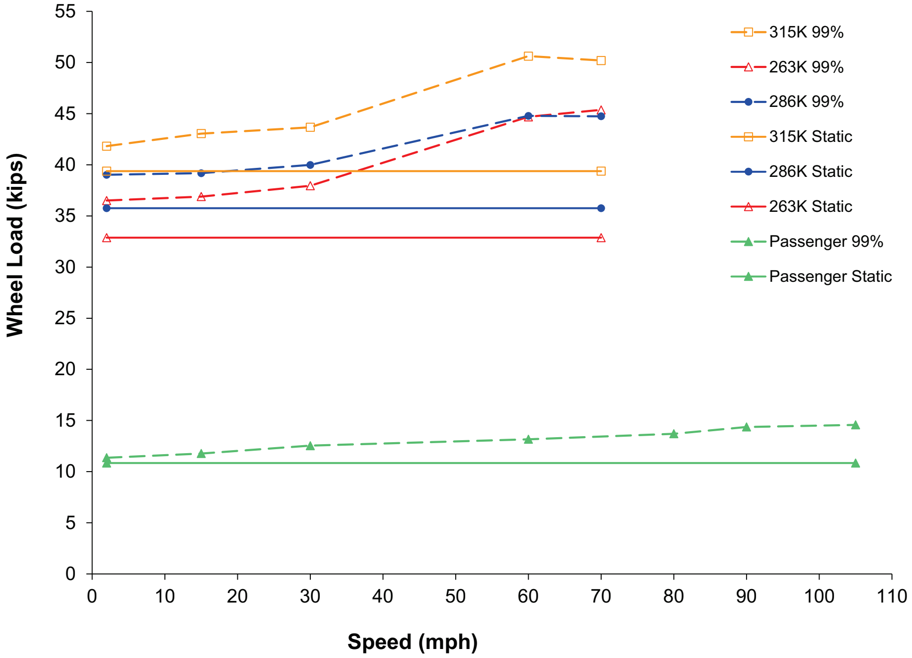


Figure 18. Vertical Wheel Loads (99% Confidence) of Freight and Passenger Cars at Various Speeds on Tangent Track (Field, Tangent Track)

For a given rail seat, when the train speed was low, vertical rail seat reaction force increased linearly in response to increasing vertical wheel loads (Figure 19). As train speed increased, so did the variability (scatter) of data (Figure 19 and Figure 20).

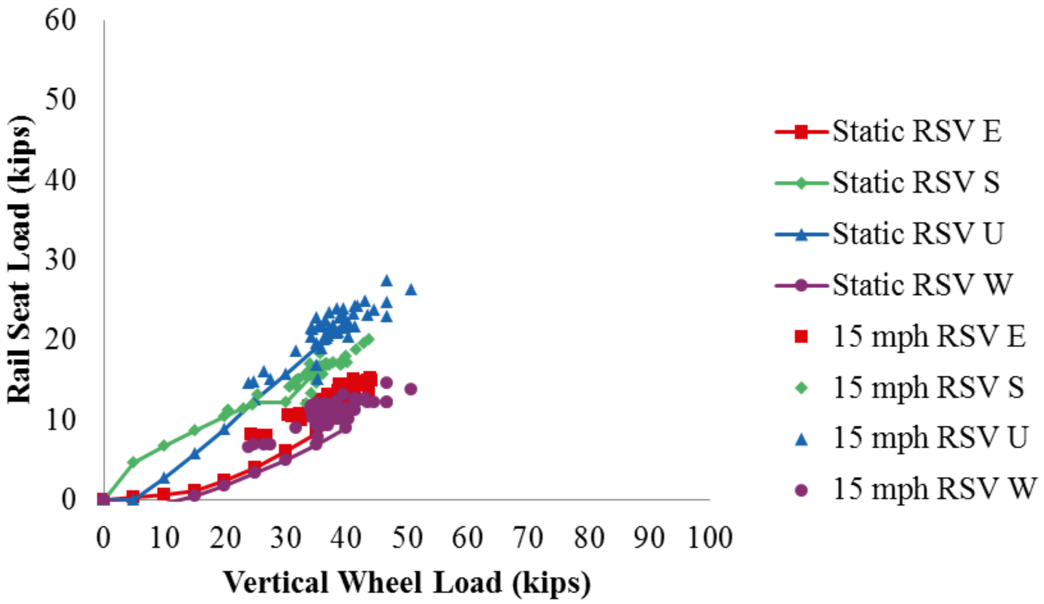


Figure 19. RSV Under Dynamic Wheel Load (Field, Speed = 15 mph)

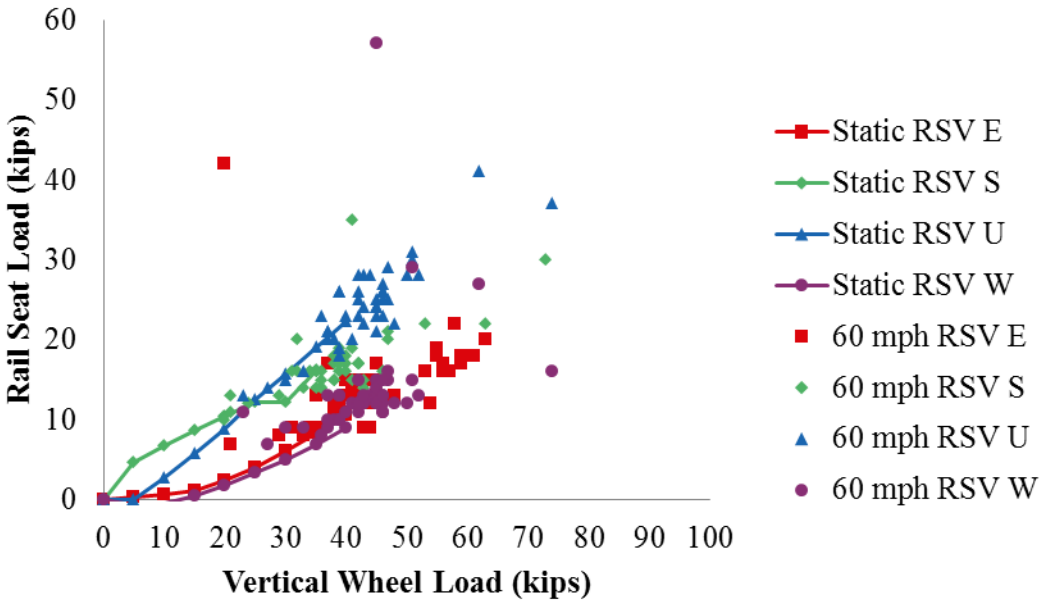


Figure 20. RSV Under Dynamic Wheel Load (Field, Speed = 60 mph)

Concrete crosstie global vertical deflection increased linearly in response to the vertical wheel loads when there was no gap between the crosstie and ballast. That is the hinge point in Figure

21 (at approximately five kips). This behavior is important to note, as it affects the magnitude of loads that are carried by individual rail seats and dictates how the load is transferred to adjacent crossties.

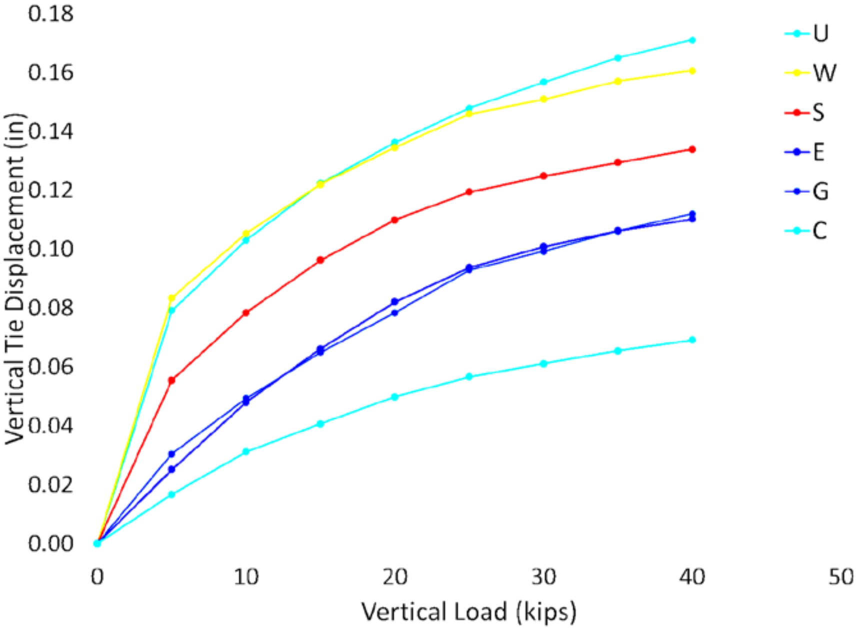


Figure 21. Vertical Crosstie Global Deflection for Individual Rail Seats Under Various Vertical Load and No Lateral Force (Field)

3.3.2 Lateral Load Path

On average, UIUC found that lateral loading demands were three to six times higher on curved track than on tangent track. There was also significant variation in lateral loads applied to the high rail and low rail on curved track, and between passenger and freight trains traversing the same curves (Figure 22).

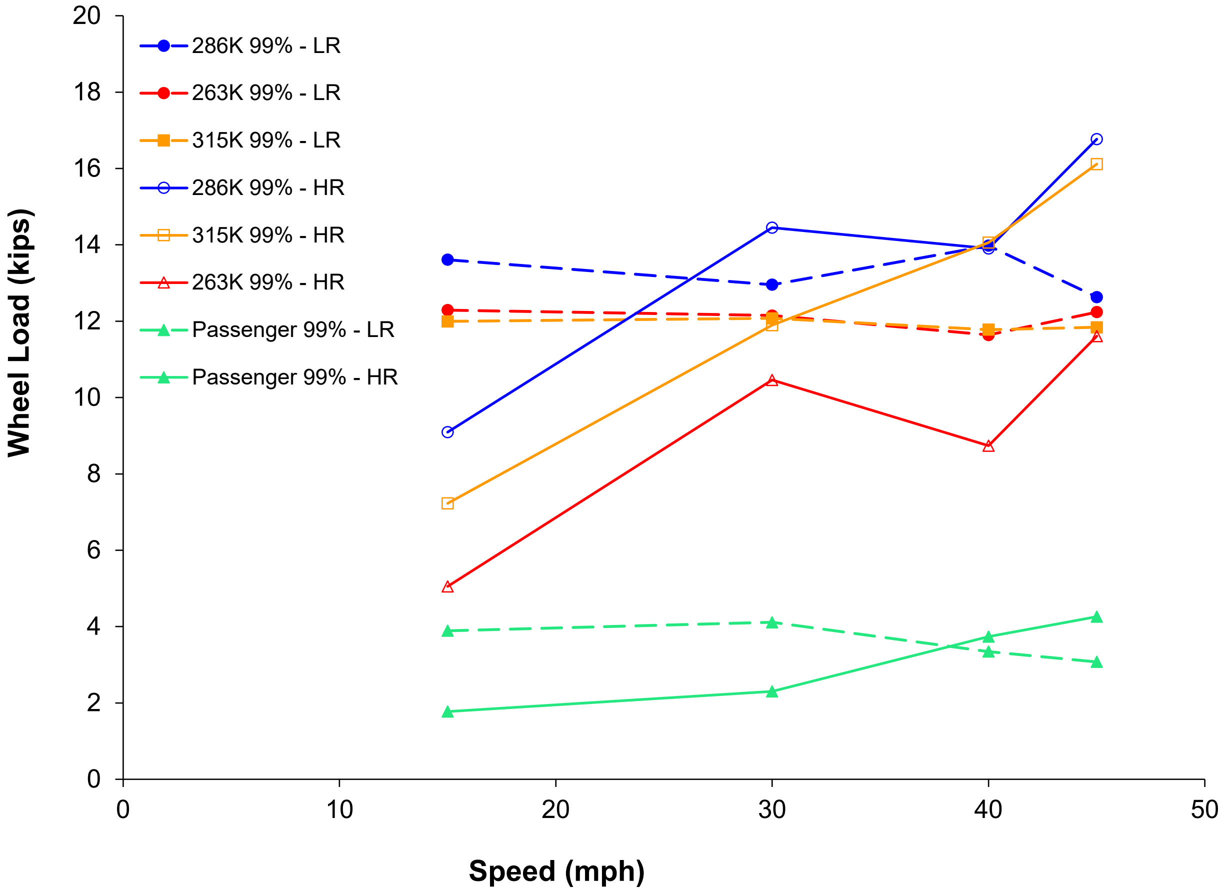


Figure 22. Lateral Wheel Loads (99% Confidence) of Freight and Passenger Cars at Various Speeds on High and Low Rails on Curved Track (Field, Curved Track, High Rail)

The data indicates that lateral loads are primarily distributed among three to five crossties under static wheel loads (Figure 23). AREMA's current design assumption is that the lateral loads are spread among the same number of crossties as the vertical loads.

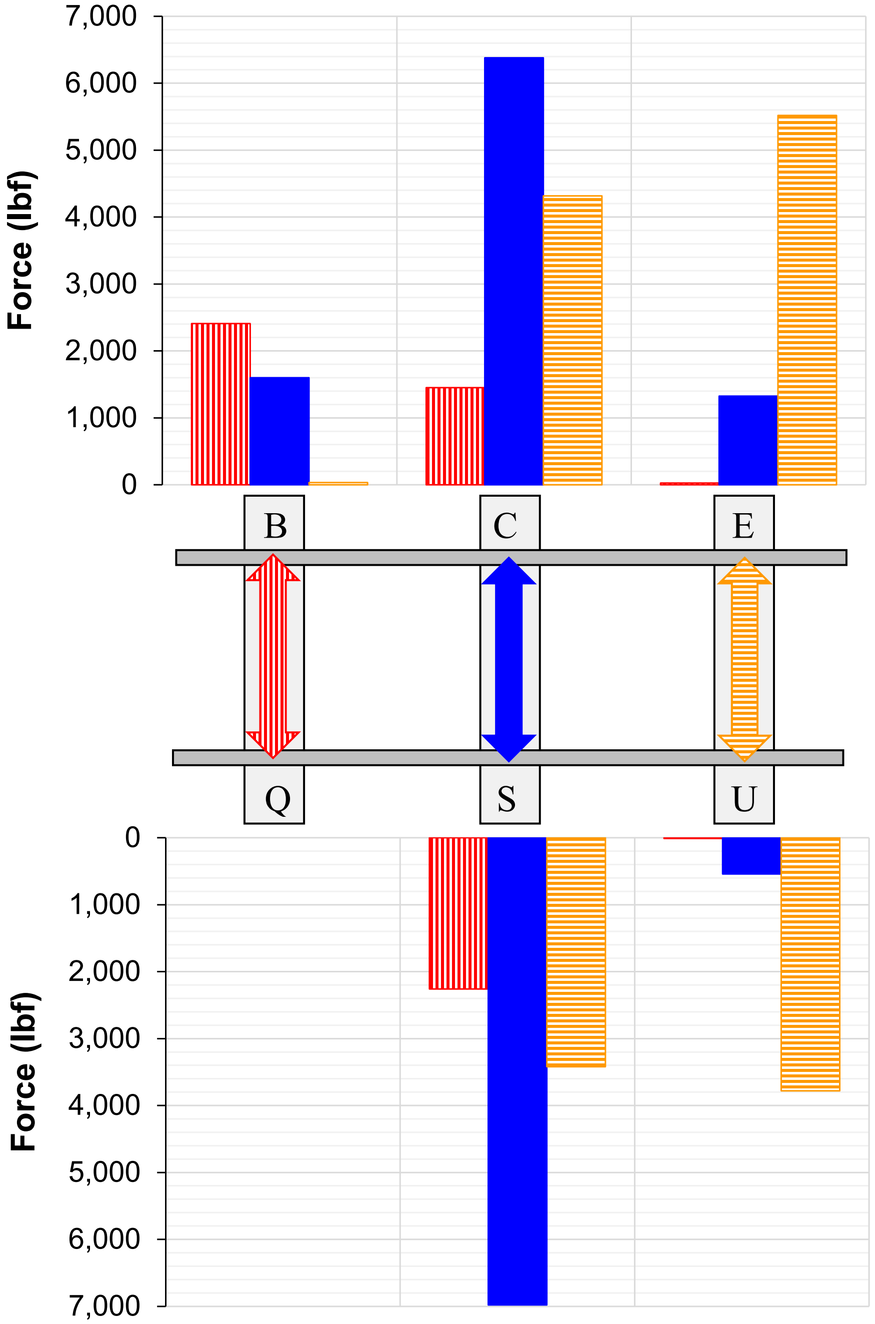


Figure 23. Lateral Load Distribution Measured at the Shoulder Under 40 kip Vertical and 20 kip Lateral Wheel Loads (Field)

Additionally, as the applied lateral wheel load increases, the ratio of frictional forces to bearing forces decreases while the percentage of the applied lateral wheel load restrained by lateral bearing restraint forces increases (Figure 24). Laboratory experiments and the FE modeling outputs support this result.

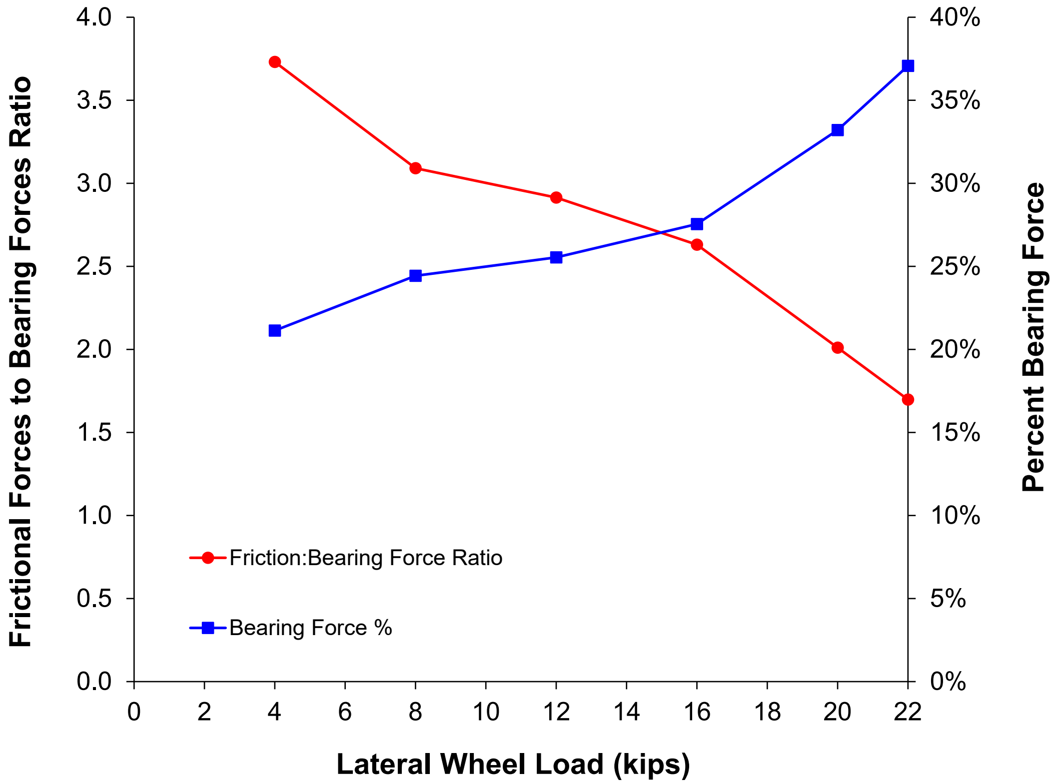


Figure 24. Change in Lateral Restraint Forces as a Function of Lateral Wheel Load (Field)

3.3.3 Combined Lateral and Vertical Load Path

The conventional concrete crosstie design methodology assumes that the distribution of loads at the rail seat is uniform, even under the application of high L/V force ratios. Data from the project's laboratory and field experiments reveal that the distribution of rail seat load are non-uniform.

Figure 25 illustrates the behavior of three rail seat load distributions under a constant 40,000-lb (178 kN) vertical wheel load:

- *Rail seat (A)* illustrates a theoretical uniform distribution and therefore, by definition, the distribution does not change with L/V force ratio.
- *Rail seat (B)* illustrates a typical rail seat with a healthy fastening system, exhibiting a concentration of load on the field side of the rail seat, but maintaining more than 99% of the initial contact area observed at 0.0 L/V.
- *Rail seat (C)* illustrates a typical rail seat with a worn fastening system, exhibiting severe concentration of the rail seat load on the field side of the rail seat due to increase rotation of the rail. Rail seat (C) also exhibits unloading of the gauge side of the rail seat from the rail rotation, resulting in a loss of 42% of the initial contact area observed at 0.0 L/V.

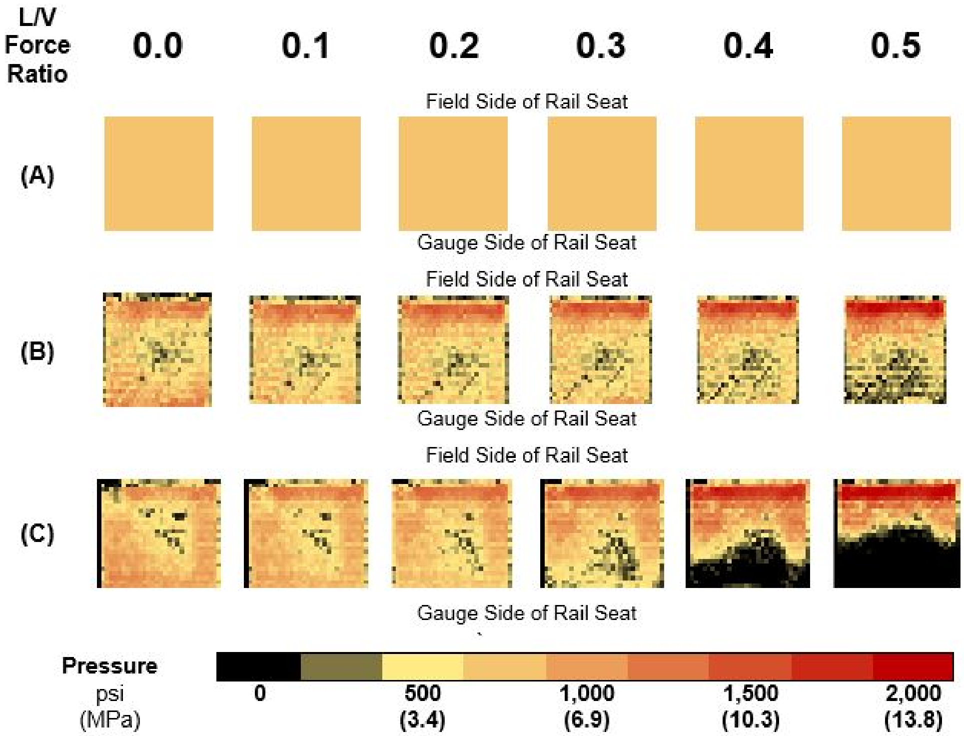


Figure 25. Change in Rail Seat Load Distribution under Increasing L/V Force Ratio (Field)

Figure 26 illustrates the effect of varying load distributions on the pressure carried by the rail seat. The figure shows two metrics of the applied pressures as compared to a theoretical uniform load distribution. The average pressure is calculated as the uniform distribution of the rail seat load across the actual area engaged in load transfer, measured by MBTSS. Below an L/V of 0.3, the average pressure is nearly equal to the uniform pressure, indicating that the entire rail seat is loaded. From 0.3 to 0.5 L/V, the average pressure increases by 47%, nearly 1.5 times the predicted uniform pressure. The maximum pressure is the highest pressure exerted on the rail seat at a given L/V force ratio, and increases quadratically with increased L/V force ratio. The maximum pressure exhibits a 70% increase from the 0.0 L/V case, yielding values 259% higher than the predicted uniform pressure at 0.5 L/V.

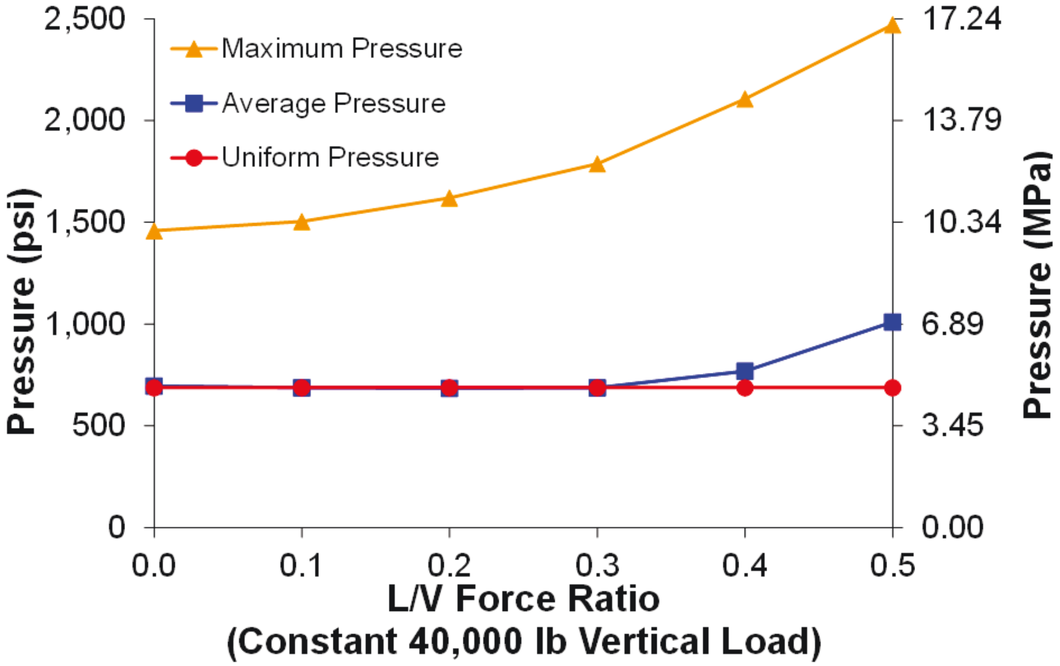


Figure 26. Change in Pressure at 40,000 lb (178 kN) Vertical Wheel Load (Field)

The results indicate that the design assumption that the rail seat load distribution is uniform does not adequately describe the loading environment at the rail seat, and that the non-uniformity of the rail seat load distribution should be considered in the design of concrete crossties and fastening systems. Additionally, the project's research highlights the need for specialized crosstie and fastening system designs that are specific to the loading environment (e.g. expected L/V ratios) that will be encountered.

3.3.4 Component Behavior

Concrete Crosstie

The concrete crosstie bending moments measured in the laboratory and field is below the calculated cracking limit of 405.6 kip-in (Figure 27).

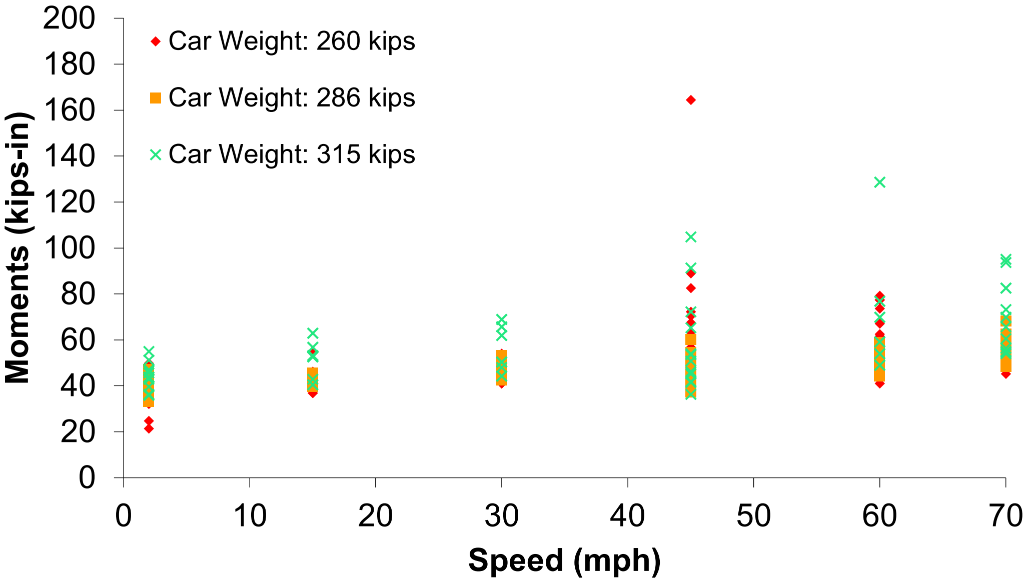


Figure 27. Measured Rail Seat Bending Moments Under Various Car Weight and Speed (Field, RTT, cracking limit is 405.6 kip-in)

Figure 28 shows the theoretical ballast reactions for Crosstie #4-15 that would be required for the crosstie to experience the measured bending moment values at the rail seat and center.

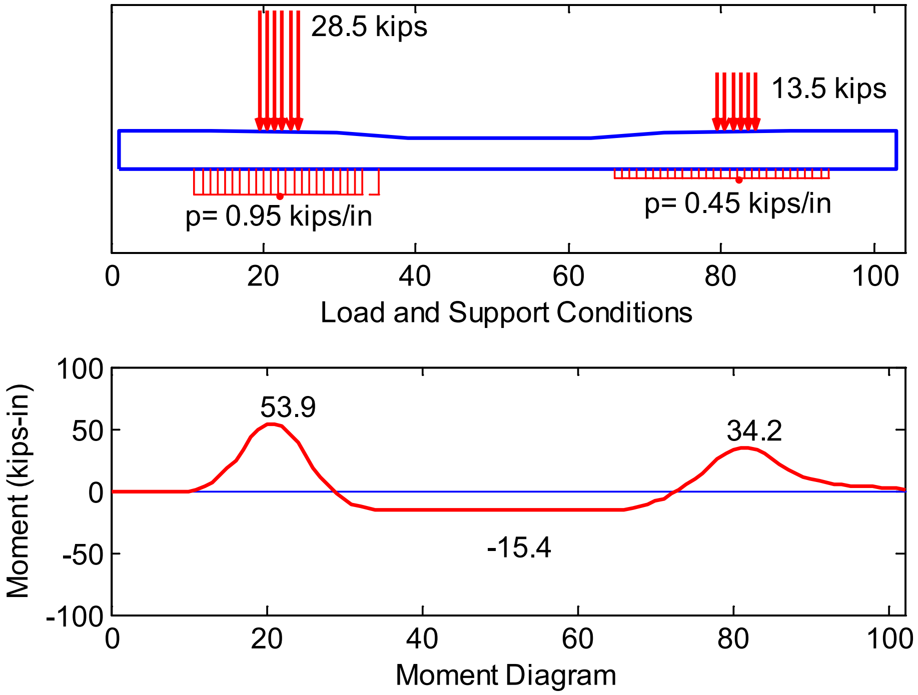


Figure 28. Loading and Support Conditions of Concrete Crosstie and Distribution of Bending Moment (Laboratory, Load at Crosstie 4-15)

Theoretical Crosstie Flexural Analysis and Behavior

Three current recommendations for the flexural analysis of pre-stressed monoblock concrete crossties (AREMA C30.4, UIC (International Union of Railways) 713R, AS (Australian Standard)1085.14) were compared under the same design inputs (axle load, crosstie length, crosstie spacing, etc.) (Table 4).

Table 4. Comparison of Flexural Analysis Methodologies*

	AREMA	UIC	AS
Design Rail Seat Load (R)	62.1 kips	66.4 kips	53.3 kips
Rail Seat Positive Moment (M_{RS+})	300 kip-in	224 kip-in	280 kip-in
Rail Seat Negative Moment (M_{RS-})	159 kip-in	112 kip-in	187 kip-in
Center Positive Moment (M_{C+})	141 kip-in	209 kip-in	112 kip-in
Center Negative Moment (M_{C-})	201 kip-in	299 kip-in	240 kip-in

*For 82 kip axle load, 8’-6” crosstie length, 60” rail center, 24” crosstie spacing

As seen in Table 4, each design recommendation provides different values for each moment design parameter. Under the given design inputs, AREMA provides the most conservative estimate for rail seat positive moment; UIC provides the most conservative estimates for design rail seat load and center positive and negative moment; and AS provides the most conservative estimate for rail seat negative bending moment. Researchers found two key differences in the assumptions used in these methods, the support conditions of the crosstie, and the area of the rail seat load.

The support conditions assumed in each analysis method varied, which affected the design bending moments greatly. AREMA C30.4 only providing bending moment values and it does not clearly state the assumed support conditions used in the analysis. As a result, the support conditions were traced back to a 1983 paper by P.J. McQueen that calculates the 300 kip-in recommendation currently found in AREMA C30.4 using a uniformly supported crosstie under an 82 kip axle load instead of the 78 kip axle load currently used in AREMA C30.4. The support condition assumptions used for center negative bending were back-calculated to find that the ballast reaction was reduced 39%. Both UIC and AS standards clearly state the support condition assumptions used in the analysis. The support condition assumptions for each of the three methods are in Figure 29.

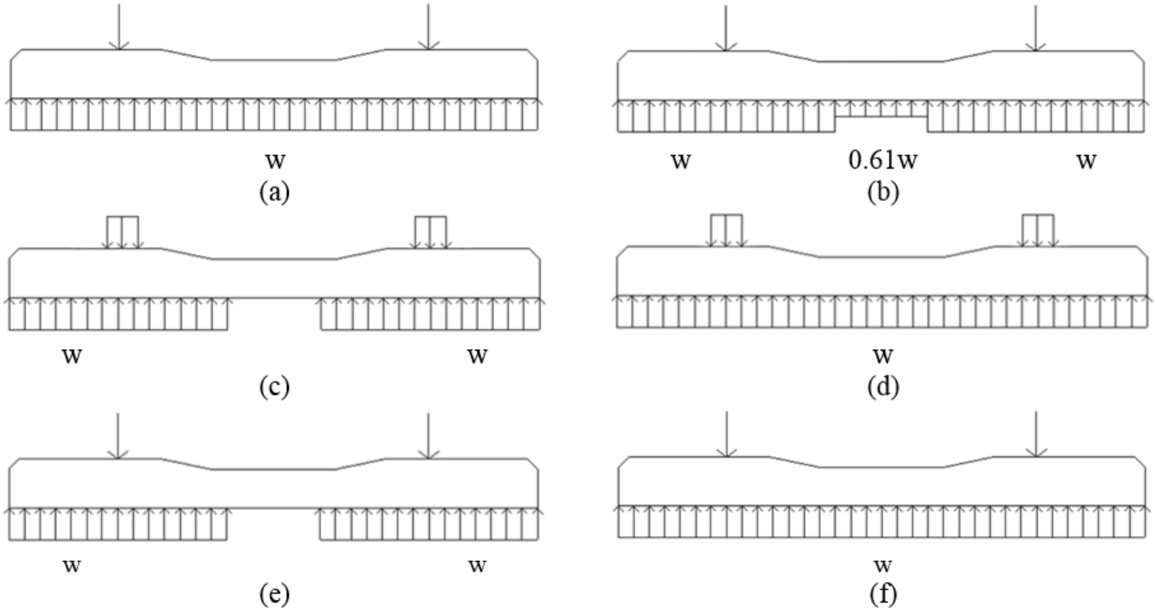


Figure 29. Support Condition Assumptions for Select Design Recommendations: (a) AREMA M_{RS+}, (b) AREMA M_{C-}, (c) UIC M_{RS+}, (d) UIC M_{C-}, (e) AS M_{RS+}, and (f) AS M_{C-}

The area of the load that was assumed to be acting on the rail seat also varied between different design recommendations. Both AREMA and AS assume that the rail seat load acts as a point load at the center of the rail seat. UIC, however, assumes the formation of a compression field acting from the ends of the rail and spreading downwards at a 45-degree angle to the crosstie's neutral axis. This compression field assumption greatly affects the rail seat positive bending moment, reducing it from 349 kip-in (under a point load) to 224 kip-in (under the compression field assumption), a 36% decrease.

UIUC developed an analytical model (Figure 30) to improve their understanding of the bending moments that are experienced by a crosstie under varying support conditions,. The model assumed that loading and support acted symmetrically about the crosstie center. The rail seat load was treated as a point load and the ballast reaction was split into nine sections or "bins" that could be modified to any percentage of the total ballast reaction.

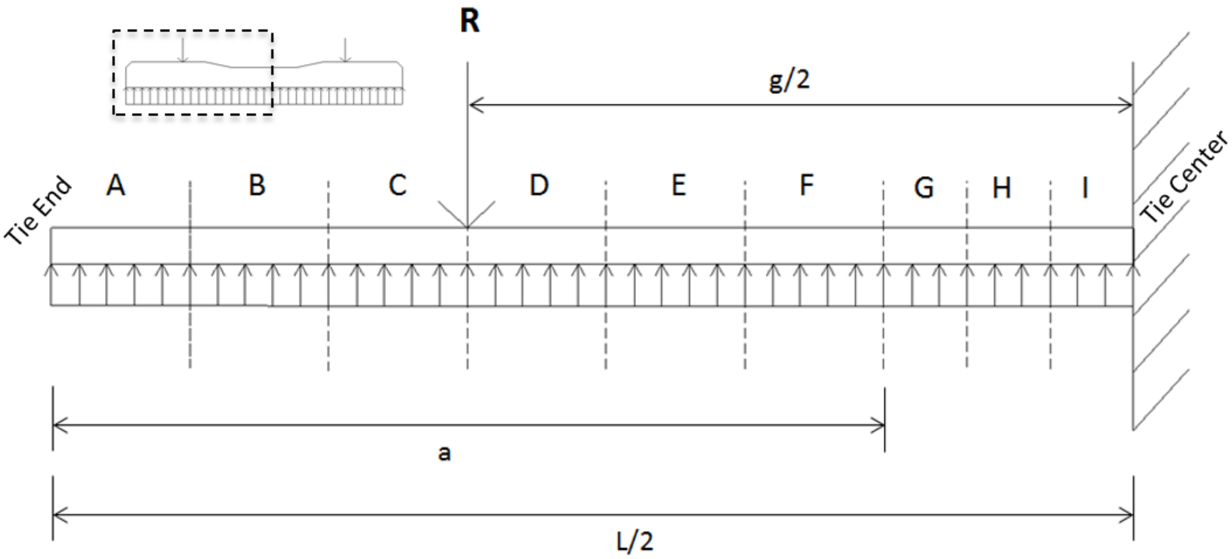


Figure 30. Illustration of Linear-Elastic Crosstie Model

For the 62.1 kip design rail seat load recommended by AREMA C30.4 (Table 4), a parametric study was performed to determine the sensitivity of the crosstie bending to changes in the ballast reaction in different bins (A-I in Figure 30). This study modified a single bin to take a certain percentage of the total ballast reaction, and the remaining reaction was shared equally between the remaining eight bins. For example, if bin A received 25% of the total ballast reaction, bins B-I received the remaining 75%. Under these support conditions, the rail seat and center moments were 375 kip-in and -101 kip-in, respectively. The full results of this study are shown in Table 5, with the values that exceed the design recommendations highlighted in grey. The only bins that can take ballast reaction percentages larger than 25% without exceeding design recommendations are bins C and D. This result emphasizes the importance of good maintenance practices and regular tamping to keep the majority of the ballast reaction near the rail seat.

Table 5. Effect of Ballast Reaction on M_{RS} and M_{C}

Bin		A	B	C	D	E	F	G	H	I
Rail Seat Moment (M_{RS}) (kip-in)	**0%**	138	207	277	311	311	311	285	285	285
	25%	375	319	262	233	233	233	214	214	214
	50%	613	430	247	156	156	156	143	143	143
	75%	850	541	232	78	78	78	71	71	71
	100%	1087	652	217	0	0	0	0	0	0
Center Moment (M_{C}) (kip-in)	**0%**	-497	-428	-358	-289	-220	-151	-210	-198	-187
	25%	-101	-158	-215	-272	-328	-385	-506	-544	-582
	50%	295	113	-70	-253	-436	-618	-804	-891	-978
	75%	691	382	74	-235	-544	-853	-1100	-1237	-1374
	100%	1087	652	217	-217	-652	-1087	-1397	-1584	-1770

To illustrate the sensitivity of the center section to high bending moments, Figure 31 shows the center bending moment as the percentage of total ballast reaction is increased in each bin. The maximum design recommendations for center positive and negative bending have been included to show the moments that, if exceeded, indicate crosstie cracking.

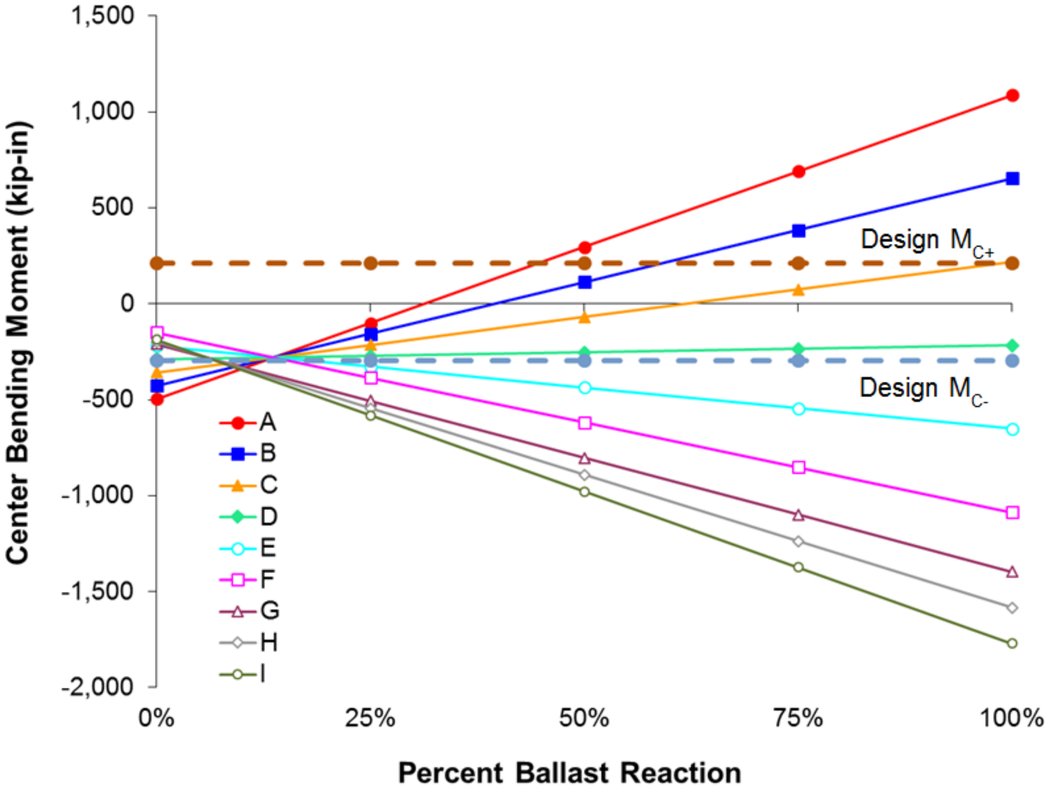


Figure 31. Center Bending Moment under Varying Support Conditions

Table 5 and Figure 31 show that even low concentrations of ballast reaction under the crosstie (i.e. areas of higher pressure) can lead to very high moments and may cause flexural cracking.

Rail Pad

To understand the effect of rail pad modulus on the rail seat load distribution, UIUC selected three rail pads for analysis. Two custom-manufactured rail pads, one made of thermoplastic vulcanizate (TPV) with a 15,000 psi (103.4 N/mm^2) flexural modulus and one made of medium-density polyethylene (MDPE) with a 120,000 psi (827.4 N/mm^2) flexural modulus, were compared to a conventional two-part rail pad assembly consisting of a thermoplastic polyurethane rail pad and a Nylon 6-6 abrasion frame. Each of the rail pads were used in conjunction with a Safelok I fastening system, and were subjected to varying L/V force ratios at a constant vertical load of 32,500 lb (144.6 kN). Figure 32 shows the rail seat distributions under the three rail pad assemblies at L/V force ratios from 0.25 to 0.6. The field side of the rail seats were on the right side of the image.

The results of the experiment indicated that an increase in pad flexural modulus yields a decrease in contact area and an increase in maximum rail seat pressure. The MDPE rail pad yielded a reduction in contact area by 81 percent compared to the two-part pad assembly, and 70 percent compared to the TPV rail pad, which resulted in maximum pressures 23 percent and 20 percent higher than those observed under the two-part pad assembly and TPV pad, respectively. This reduced contact area and increased maximum pressure may result in accelerated damage to the concrete rail seat. However, the TPV rail pad allowed for greater rail rotation and a complete unloading of the gauge side of the rail seat. This increase in rail rotation may lead to accelerated wear of fastening system components such as the clips, insulators and cast-in shoulders. The two-part pad assembly combines the positive effects of both experimental rail pads: the low-stiffness rail pad deforms under the rail base, increasing contact area, while the high-stiffness abrasion frame prevents excessive rail base rotation. These data point to the need to understand the required level of fastening system stiffness and its impact on the system-level performance of the crosstie and fastening system.

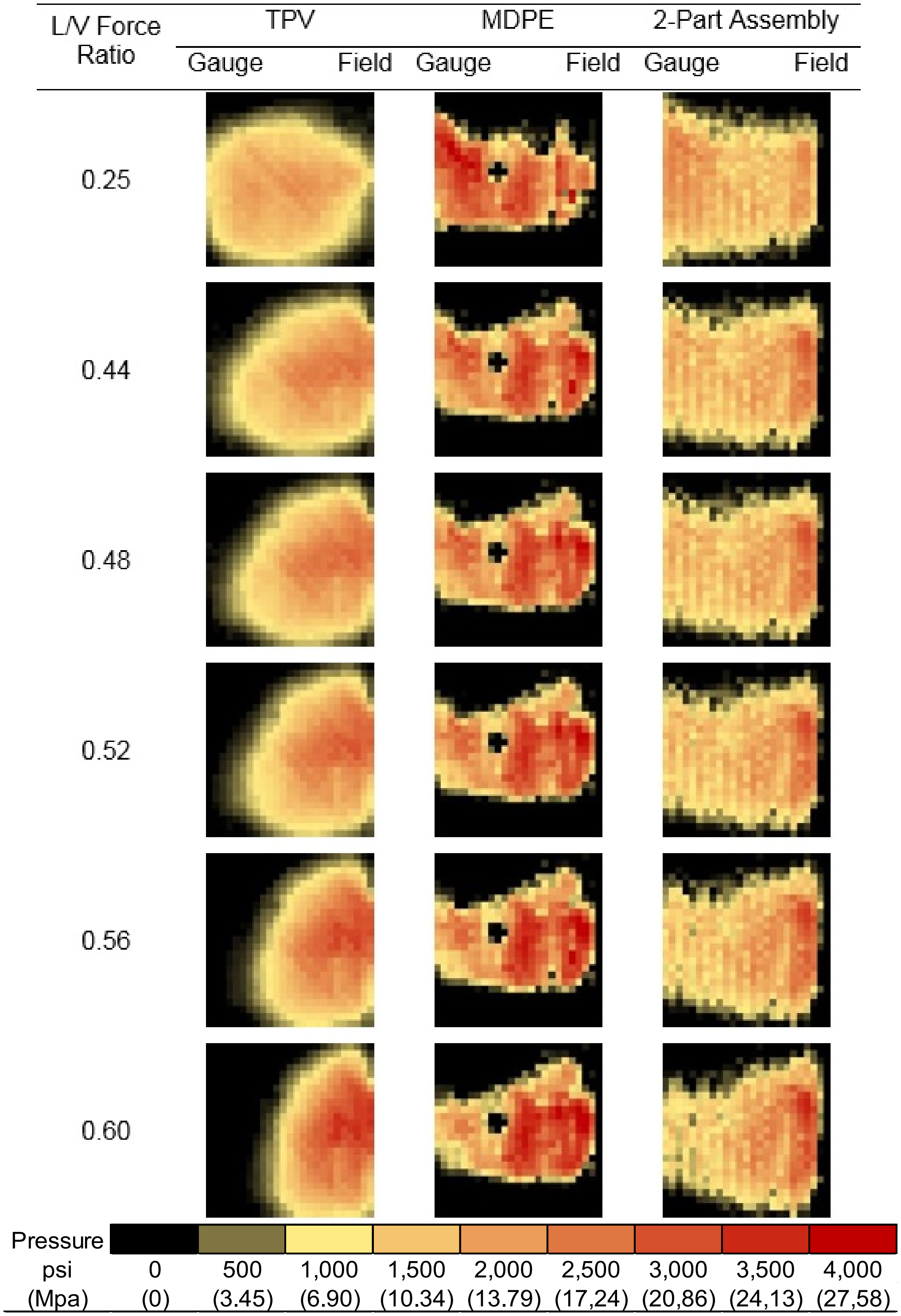


Figure 32. Effect of Rail Pad Modulus on Rail Seat Load Distribution

3.4 Finite Element Modeling

UIUC built and validated detailed FE models with data supplied by manufacturers and data obtained through laboratory and field experiments. The team used the validated FE models for parametric studies to further their investigations into the load path and design of concrete crossties and fastening systems.

Prior to developing the FE model, UIUC identified the most critical input and output parameters (Table 6 and Table 7). Researchers designed and executed a multitude of parametric analyses to address engineering questions related to some of the critical needs highlighted in the International Survey.

Table 6. Critical FE Modeling Input

Component	Input	Component	Input
Load	Vertical loading	Abrasion Frame	Young's modulus
	Lateral loading		Frame geometry
Rail	Rail geometry	Shoulder	Young's modulus
	Location of contact patch		Shoulder geometry
	Young's modulus		Yielding strength
Insulator	Insulator geometry	Reinforcement	Prestress force
	Yielding strength		Young's modulus
	Young's modulus		Strand diameter
Clip	Young's modulus		Strand distribution
	Yield strength		Number of reinforcement members
Crosstie	Compressive strength	Support	Track modulus
	Tie spacing	Rail Pad	Young's modulus
	Geometry		Geometry
	Bond-slip behavior		Poisson's ratio

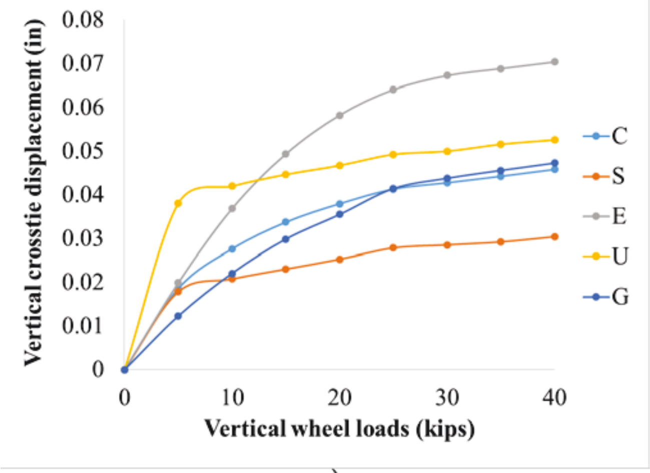
Table 7. Critical FE Modeling Output

Critical Modeling Output	
Track vertical deflection	Rail base rotation
Track lateral deflection	Shoulder bearing force
Rail-base lateral displacement	Rail pad frictional force
Abrasion frame lateral translation	Crosstie rail-seat moment
Vertical rail-seat load	Crosstie center moment
Lateral rail-seat load	Vertical rail-seat load at adjacent crossties
Gauge-side clamping force	Lateral rail-seat load at adjacent crossties
Field-side clamping force	Relative sliding between abrasion frame and rail seat
Maximum rail-seat pressure	Relative sliding between rail and rail pad

The following sections contain conclusions about vertical track stiffness, vertical load distribution, lateral wheel load, and concrete support conditions.

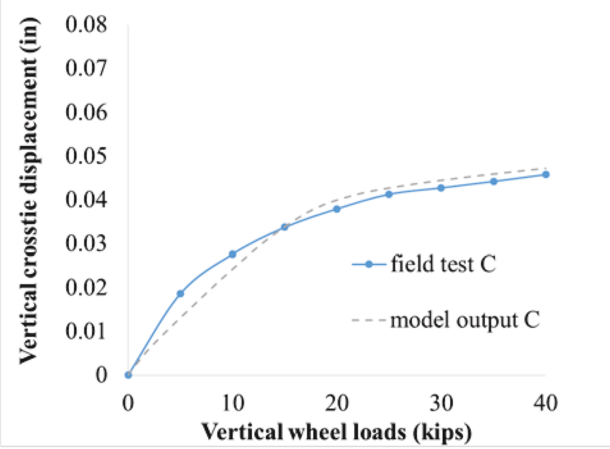
3.4.1 Vertical Track Stiffness

Based on the field measurement of crosstie vertical displacement under vertical wheel loads, the vertical track stiffness (incremental vertical wheel load divided by incremental crosstie vertical displacement) gradually increases under higher vertical wheel load (Figure 33). Track stiffness varied considerably among different crossties (Figure 34), further illustrating the variability of support conditions.



a)

Figure 33. a) Relationship between Vertical Crosstie Displacement and Vertical Wheel Load at Different Rail Seats (Field Data)



b)

Figure 34. b) Comparison between FE Model Output and Experimental Measurement of Vertical Crosstie Displacement

3.4.2 Distribution of Vertical Wheel Load

Field experimentation provided data showing that vertical wheel load is primarily distributed among three to five concrete crossties. Based on the varying support condition of different crossties, according to the FE model, 28 percent to 63 percent of the applied vertical wheel load was resisted by the loaded rail seat (Figure 35).

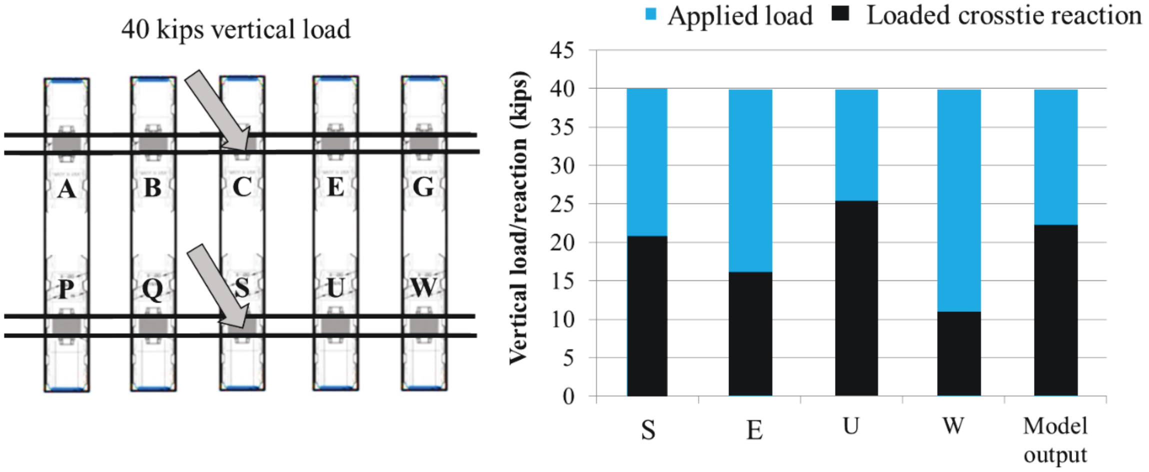


Figure 35. Rail Seat Vertical Reaction When the Wheel Load Was Applied Over Different Crossties and Rail seats

3.4.3 Lateral Wheel Load

Based on results from field experimentation, the lateral wheel load is primarily distributed among the three concrete crossties that are closest to the point of loading (Figure 36). At a specific rail seat, the lateral deflection of the rail under lateral wheel load is resisted by the frictional force at the bottom of the rail and the bearing force from the field-side shoulder.

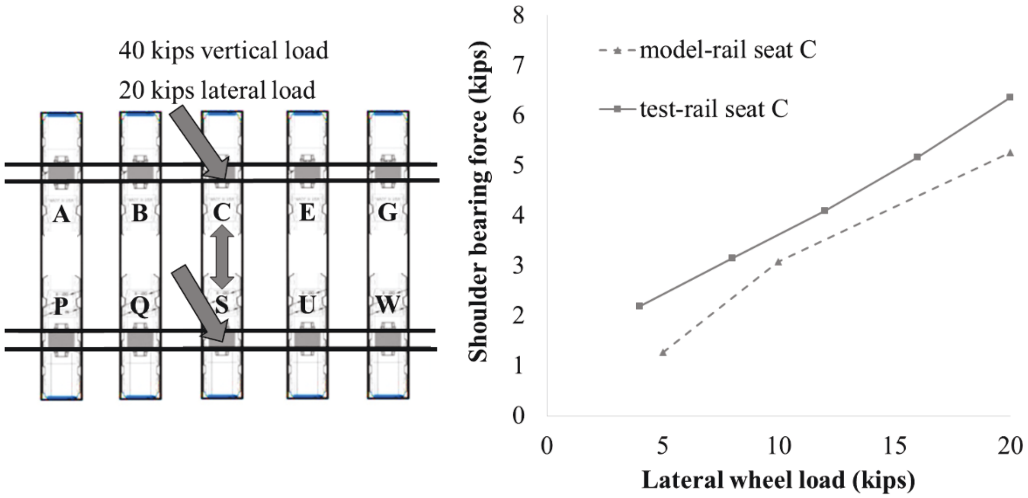


Figure 36. Comparison of FE Model vs. Experimental Data Showing Shoulder Bearing Force at Rail Seat C

3.4.4 Crosstie Support Condition

Based on the measurements obtained from concrete embedded strain gauges and surface gauges installed on concrete crossties, the ballast support is not uniform. Gaps of different sizes exist between concrete crossties and the ballast, and they close under vertical wheel loading (Figure 37).

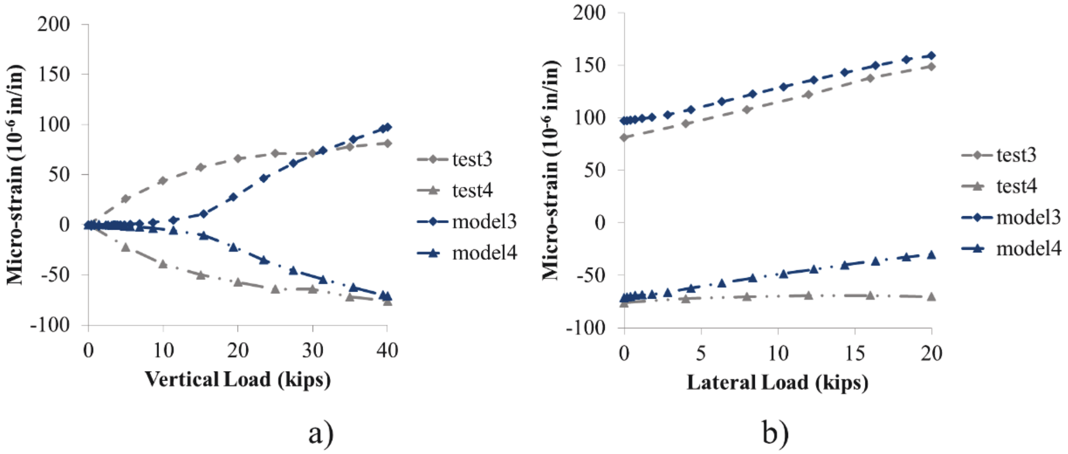


Figure 37. Comparison of FE Model and Field Data for Concrete Surface Strain at Crosstie Center under a) Increasing Vertical Wheel Load and b) Increasing Lateral Wheel Load

3.4.5 Results from Parametric Analyses

UIUC used the FE model to capture critical mechanisms, including the distribution of wheel loads and the flexure of concrete crosstie. Because the parametric studies use the laboratory and field-validated FE model, these conclusions can be drawn:

- The frictional behavior (frictional force and relative sliding) at the bottom of the rail seat is primarily governed by the interface (i.e. rail-pad interface and plate-concrete interface) with the lowest value of coefficient of friction (COF).
- Contrary to conventional wisdom and discussions with industry experts, the elastic modulus of the fastening system insulator has little effect on the lateral load path through the fastening system.
- Compared to the COF at the rail-pad and plate-concrete interfaces, and the elastic modulus of rail pad, crosstie spacing has a minimal impact on the performance of the fastening system under lateral wheel loads.
- The COF at the rail-pad and the plate-concrete interfaces, and the elastic modulus of the rail pad significantly affect the performance of the fastening system under lateral wheel load.
- Crosstie spacing significantly affects the distribution of vertical wheel load among multiple rail seats, and the relationship between crosstie spacing and the vertical rail seat load under the point of load application is approximately linear.

The project bases its conclusions on the cases generated for this parametric study, and they are only valid within the range of input parameters considered in the parametric study. However, as the range of input parameters in this study covers what is typically used for track design in North America, the conclusions provide useful insights regarding the future design and optimization of the concrete crosstie and fastening system.

3.5 I-TRACK

UIUC's I-TRACK, which is based on a statistical analyses of the FE model data, models the mechanical behavior of track components using a neural network that is capable of predicting mechanical outputs with respect to certain user-defined inputs (e.g. wheel loads, components material properties, etc.). I-TRACK has been useful in the development of mechanistic design practices focused on component performance. When fully developed, I-TRACK will allow track component manufacturers and railroad engineers to rapidly assess the loading conditions, safety, and expected performance of the track infrastructure.

UIUC developed and executed case studies using I-TRACK, and there was good correlation between the results extracted from I-TRACK and the expected behavior for these parameters. As an example, we have been able to see how input variables such as rail pad modulus (RPM) affect rail seat loads (Figure 38). These findings agreed with the results from filed and lab experiments.

Eventually, I-TRACK should be a powerful and adaptable tool that provides component manufacturers and track engineers with the capability to analyze track responses and the ability to assist them in developing improved fastening system components.

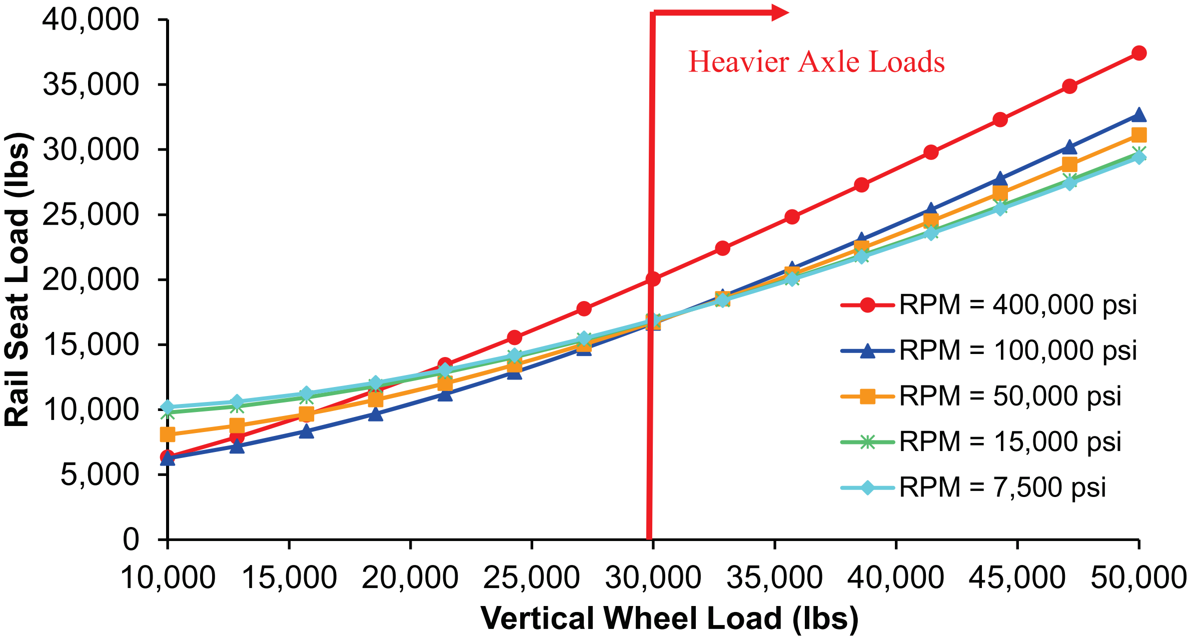


Figure 38. I-TRACK Results Showing Effects on Rail Pad Modulus on Rail Seat Loads for Increasing Vertical Wheel Loads

3.6 Mechanistic Design of Concrete Crossties and Fastening Systems

UIUC used analytical and scientific principles, with consideration of field loading conditions and other performance requirements, to derive the mechanistic design process. The process uses representative input loads and load distribution factors to determine the required component, geometric, and material properties. Measured track loads and the necessary material properties of the components used to withstand or transfer these loads forms the basis of the approach. The approach uses component responses to items such as contact pressure or relative displacement to optimize component geometry and material requirements. A mechanistic design requires a thorough understanding of the load path and distribution it allows for the development of load factors. By understanding exactly how loads transfer through the system, one can determine the failure points in the system and develop a load factor that ensures that these failures are eliminated. This load factor can change based on location and traffic composition. Mechanistic design has been used in other disciplines, including the design of rigid and flexible highway pavements using particular input values, performance analyses, and alternative evaluations.[1]

UIUC is developing a mechanistic design process that uses the existing loading environment to optimize the design of the concrete crosstie and fastening system. First, their approach defines the vertical, lateral, and longitudinal input loads and notes how these loads are passed through the system. In the next step, the load thresholds are defined, which are limits of critical properties for the materials used to build the components, the components themselves (i.e. considering their geometry in addition to material properties), and the fully assembled fastening system. After the criteria for loading thresholds are defined, users can design the components using a set of pre-defined criteria. The last step is to verify that the system as a whole is performing according to expectations, primarily by installing the system in the field and measuring critical performance properties. The overall design process, shown in Figure 39, is discussed in further detail in Volume 2 of this report.

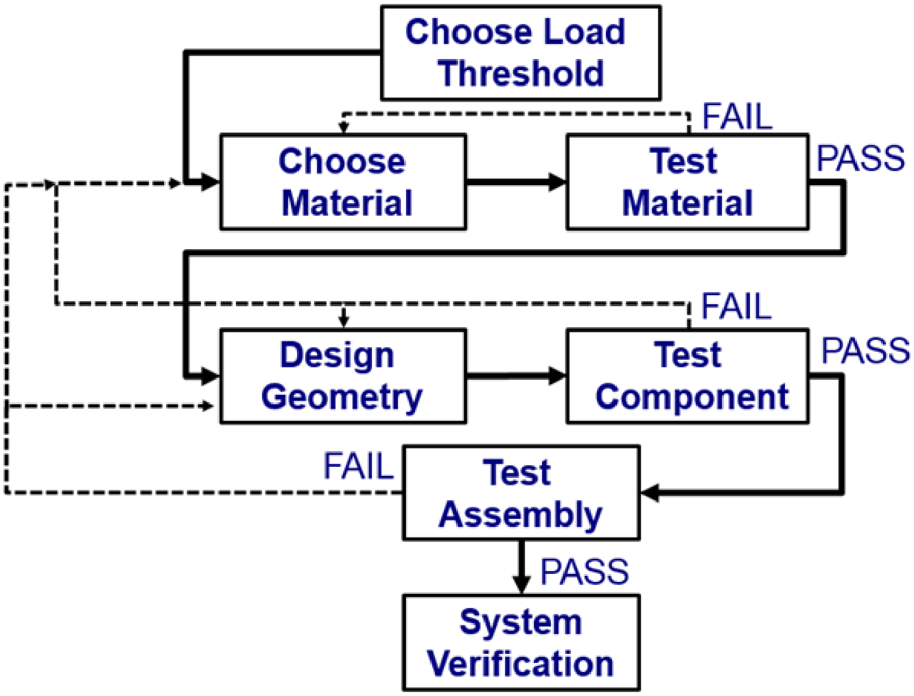


Figure 39. Mechanistic Design Process Flow Chart

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[1] ARA, Inc. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* ERES Consultants Division. Champaign, IL.

A mechanistic design process will provide many benefits that are not provided by the iterative design process that is currently defined by AREMA. Table 8 compares the two methods.

Table 8. Qualitative Comparison of Iterative and Mechanistic Design Processes

Category	Iterative Design (Current)	Mechanistic Design (Proposed)
Ease of development	Already developed	Will require large amounts of capital investment and time
Time required to run analysis	Relatively quick	Requires lengthy analysis process
Accuracy of demand estimates	Variable, could be inaccurate	Highly accurate, based on system specific analysis
Ability to account for specific failure modes	Limited, mostly focused on crosstie failure modes	Design specifically accounts for each failure mode of every component
Potential for design of new systems	Low, may not be accurate	High, very flexible for material or geometry chosen for the system
Safety factor of design	Relatively conservative	More variable according to choice of designer

Unlike iterative design processes, mechanistic designs will require a large amount of capital and time in order to develop a process, even if it provides enhanced predictions of the loads experienced by components. Even if both processes were fully developed, designing a system using a mechanistic design process will take more time as the full load path must be determined. As finite element models become more robust, it should be possible to determine the load path and distributed forces more quickly, but currently this is a time-consuming process. Once a mechanistic design is developed, it will provide much more flexibility than the iterative design process and it will allow for variable factors of safety for each failure mode, as well as allowing multiple types of fastening systems while still producing reliable predictions of performance.

3.7 Integrated Findings

Many project results were achieved by combining the focus areas. The most significant, integrated results from this project included:

- **Friction's Role in Crosstie and Fastening System Performance** – Researchers gained a better understanding of the role of friction in the crosstie and fastening system. The team obtained data from laboratory and field experiments then validated the results using FE modeling. The design of crossties and fastening systems should include a careful analysis of friction. Designers can use friction to control the location and magnitude of component displacements that are typically damaging to one or more component in the system.

- **Vertical Load Path and Variability of Rail Seat Loads** – The variability in the vertical load carried by individual rail seats is high. This variability can affect the design decisions for crossties. Designers may choose to select a design load that is less than the maximum expected load in order to reduce costs.

- **Lateral Load Path and Distribution of Lateral Loads** – Lateral loads are distributed over approximately three ties. Additionally, approximately half of the lateral load applied at the wheel rail interface is carried by friction. As lateral wheel load increases, the lateral friction and bearing restraint forces begin to converge. The percentage of the applied lateral wheel load restrained by frictional forces starts to decrease while the percentage of the applied lateral wheel load restrained by bearing forces starts to increase. A rail seat with a higher lateral stiffness can also result in a higher percentage of lateral load bearing force on the insulator post and shoulder face.

- **Need for System-Level Designs** – The general design process used in North America does not consider the full system. There are system-level tests that are used for design validation, but these tests are very late in the overall process. As part of this project, we have proposed a method that uses assumptions for the ballast reaction and rail seat load: A newly tamped condition was recommended for rail seat positive bending and a uniformly supported condition was recommended for center negative bending. These assumptions do not capture the worst-case scenario that could be experienced in the field, but they are part of a more mechanistically-based analysis methodology. Using FE modeling techniques and the mechanistic design process proposed here within, designers can address system-level performance prior to prototype testing. System-level design is a required step in a mechanistic design process.

4. Conclusion

UIUC accomplished the following objectives over the course of the project:

- Developed centralized knowledge and document depository for the international domain of concrete ties and fastening systems.
- Investigated best practices (design and performance) from around the world.
- Developed improved, and at times foundational, understanding of crosstie and fastening system loading path.
- Developed a system-level calibrated FE analytical model of how loads are transferred through the fastening systems and rail seat of a concrete crosstie.
- Developed a framework for improved safety due to improvements to the robustness of critical infrastructure components.

The project's results have been disseminated through interim reports, conference papers, journal papers, technical presentations, and this summary report. While UIUC did not finish developing the comprehensive mechanistic design method in this initial project, the team made significant progress toward addressing some of the more critical research areas. In addition, the project realized qualitative benefits relating to workforce development, education, and industry participation in crosstie and fastener research. The project results have directly led to improvements for AREMA, which is the primary industry-supported organization for developing recommended design practices for concrete crossties in the US.

4.1 Technical Outcomes

The technical outcomes of this report include:

- **Revised Understanding of Lateral and Vertical Wheel-Rail Loads** – Through the analysis of WILD and TPD data, UIUC researchers determined that the wheel loads used for the design of crossties and fastening systems are often too conservative. Designers must consider wheel condition in combination with the trend toward higher axle loads. Researchers generated revised design tables that reflect current loading conditions.
- **Rail Seat Load Variability** – Researchers derived a quantitative understanding of the variability in rail seat loading conditions as dictated by changing support conditions, even on well-maintained track. These loading conditions will assist concrete crosstie and fastening system manufacturers to develop designs that achieve expected life cycles.
- **Mapping of Rail Seat Pressure Distributions** – Researchers were able to quantify the large variability in rail seat pressure distributions that stem from variable support conditions, geometry, and L/V load ratios. Qualitative data showing rail seat pressure distribution provided useful information for fastening system design.
- **Fastening System Lateral Load Path Quantification** – The research yielded a quantitative understanding of the lateral load path and the number of rail seats over which the lateral load is distributed.
- **I-TRACK** – Researchers developed an analytical tool that compares the influence of key inputs on system performance. The team used the tool to perform parametric analyses

and better understand the sensitivity of input variables with respect to critical output parameters that relate to the overall performance of the fastening system.

- **Crosstie Flexural Analysis** – UIUC researchers developed a clear and concise format for the analysis of the flexural capacity of concrete crossties that is more representative of the types of support conditions encountered in track. In 2015, AREMA Committee 30 (Ties) adopted this format for inclusion in AREMA Chapter 30 (Ties).

4.2 Non-Technical Outcomes

The non-technical outcomes of this report include:

- **Education in Rail Transportation and Engineering** – Many students gained valuable knowledge of the fundamentals of rail transportation and engineering through this project. The project fully or partially supported 3 PhD candidates, 8 Masters in Science candidates, and 16 Bachelors of Science candidates. A number of these students graduated to careers in the rail industry.

- **Full-Scale Track Loading Frame** – When the team designed and built the full-scale TLS, it gained the ability to simulate field conditions through a laboratory setting and improve efficiency, safety, and repeatability. The TLS has drawn considerable attention from researchers and practitioners, and provides a unique set-up not replicated elsewhere in North America.

4.3 Future Research

Topics for future research include:

- **Analysis of Worn Components and Demanding Track Conditions** – As this project focused on analyzing new components and did not examine components that are worn or are not fulfilling their intended design function, research should be conducted on deteriorated components and poor support conditions that could be encountered in revenue service.
- **Prototype Concrete Crossties and Fastening Systems** – Prototype concrete crossties and fastening systems, based on mechanistic design recommendations that are in place thus far, were developed. These components can be modeled and studied experimentally in the laboratory, and their performance could be tracked with laboratory testing and field experimentation.
- **Focus on Other Types of Emerging Fastening Systems in the US** – As this project experimented with fastening systems that have a narrow shoulder to transfer lateral forces into the crosstie, conducting a thorough analysis of fastening systems that have a wide shoulder (i.e. SKL rail clip systems) would prove useful in understanding how modifying system geometry alters behavior. This is especially critical given the increased use of SKL-style fastening system in the US.

Abbreviations and Acronyms

AREMA	American Railway Engineering and Maintenance-of-Way Association
AS	Australian Standard
ATREL	Advanced Transportation Research Engineering Laboratory
COF	Coefficient of Friction
FE	Finite Element
FMEA	Failure Mode and Effects Analysis
FRA	Federal Railroad Administration
HTL	High Tonnage Loop
L/V	Lateral/Vertical
MBTSS	Matrix-Based Tactile Surface Sensors
MDPE	Medium-Density Polyethylene
NEES	Newmark Structural Engineering Laboratory
PLTM	Pulsating Load Testing Machine
RAIL	RailTEC Research and Innovation Laboratory
RTT	Railroad Test Track
RSD	Rail Seat Deterioration
RSV	Rail Seat Vertical Reaction Force
SLTM	Static Load Testing Machine
STT	Static Tie Tester
TLS	Track Loading System
TPD	Truck Performance Detector
TPV	Thermoplastic Vulcanizate
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
UIC	International Union of Railways
UIUC	University of Illinois at Urbana-Champaign
WILD	Wheel Impact Load Detector