UNDERSTANDING THE VERTICAL LOAD PATH UNDER STATIC AND DYNAMIC LOADS IN CONCRETE CROSSTIE AND FASTENING SYSTEMS

BY

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THESIS

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Abstract

An understanding of the load path is necessary for developing a mechanistic design approach for the crossties and fastening systems. It is important to follow the flow of forces through the system to understand the demands on each individual component. In spite of extensive research focusing on the vertical load path a lack of clear understanding of the loads on the components exists. A number of failure mechanisms of ties, pads, insulators and fasteners still exist. This study focuses on understanding how the stiffness of the components in the system affects the flow of forces in the vertical direction. It has been identified that the stiffness of the support (ballast) underneath the crossties is crucial in determining the flow of forces.

An extensive field testing program was undertaken at Transportation Technology Center (TTC) in Pueblo, CO by researchers from the University of Illinois at Urbana-Champaign (UIUC) in May 2013. Meticulous measurement of various parameters like loads, strains, rail seat pressure and displacements for the rail, pads, shoulders, ties were collected. Two sections of a track comprising of fifteen crossties each were chosen as test sections, one tangent section and one curved section. A TLV (Track Loading Vehicle) was used to apply static loads on the system. Freight and passenger trains were also deployed to study the response of the system under dynamic loading. A comparison between the static demands and the dynamic demands, as a result of the trains passing over the test section at different speeds, has been made which yields an important design factor. These understandings provide better insight into the loading demands on the system. An attempt has also been made to understand the response of the system under impact loads, a result of irregularities in the rail and wheel interface.
Acknowledgement

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1. Introduction

1.1. Thesis Organization

Chapter 1 of this report outlines the previous works in the field of concrete crossties and fastening systems. It references the historical understanding of the system and the gaps in the research. It brings into perspective the objectives to be achieved as a part of this project.

Chapter 2 of the thesis explains the objectives of the instrumentation plan adapted for this project. It explains in detail the instrumentation technologies used, methodologies adopted and the chosen test matrix. This chapter only explains in detail the instrumentation used to understand the vertical load path. It must be kept in mind that their existed other instrumentation as well which were used to study other aspects of the track system.

Chapter 3 of the thesis explains in detail the results obtain from the field testing. It progress along the vertical load path involving the results of each component in it. While following the flow of forces an attempt has been made to quantify the forces experienced by each component of the system. As a part of this chapter, an attempt was also made to identify the factors that affect the vertical load path the most. Also, the influence of lateral load on the vertical load path was studied.

Chapter 4 outlines the current recommended design practices across various standards. Certain topics which need to be revisited have been proposed with recommended suggestions. This chapter lays the foundation and ground work for the development of a mechanistic design framework for concrete crossties and fastening systems which is underway by researchers at the University of Illinois.
1.2. Literature Review

With the ever increasing axle loads and traffic on the freight transit, the use of concrete crossties is on the rise as it becomes a competitive alternative to the historical wood ties. Concrete crossties provide superior durability and capacity, which allow them to outlast standard timber crossties in tracks which have high degrees of curvature and are exposed to extreme weather conditions. [1] Concrete crossties also have the distinct advantage of improved track geometry retention, especially important in sustaining high speed rail and heavy freight lines. [2]

In the current scenarios multiple failure mechanisms in the crosstie and fastening system arise which need to be repaired or replaced increasing the maintenance costs of the service lines. Loss of clamping force in the clips, abrasion and sliding out of the pads, center and rail seat cracking and rail seat abrasion of concrete crossties, loss of support among other failure mechanisms have become an increasing concern. [3] [4] It has become critical to have an improved understanding of the flow of forces in the system for developing a mechanistic design of the entire system contrary to the current individual component design methodology.

In order to understand the mechanisms of the crosstie-fastener system, component behavior and system demands must be investigated. This includes an understanding of load transfer among each component. There is also a need for the magnitude of these input loads with respect to the train speed, car weight, track curvature, grade, and various fastening systems.

In order to understand dynamic loads in a system, numerous lab results, field results and numerical models have been published in the past which contributed to the development of the dynamic factor used in most of the design standards and recommendations used in North America. A summary of many dynamic wheel load factors was provided by Doyle [5]. A dynamic factor, based on speed, was prepared for the Washington Metropolitan Area Transit
Authority (WMATA) in 1968 and used in subsequent recommended standards for transit track work [6]. More recently, another speed-dependent dynamic factor was developed in Iran [7]. The speed factor has also been proposed in Chapter 30 of the AREMA Manual (AREMA C30 [8]). The Chapter 30 Speed Factor was developed in the early 1980s by the AREMA Committee. It is used as part of the flexural design of concrete crossties after a distribution factor.

The dynamic factors developed by many researchers do incorporate additional parameters beyond train speed. The Talbot dynamic factor incorporates wheel diameter and is still used in modern North American track analysis [8]. The South African Railways formula is similar to the Talbot formula, but is calculated for narrow gauge track. The Indian Railways dynamic factor incorporates track modulus as an indicator of track condition [9]. A more detail literature review of the same topic can be found in Van Dyk’s thesis [10].

These dynamic factors do not make the distinction between the two different factors proposed by Van Dyk - dynamic and impact, as discussed in his thesis [10]. The current proposed dynamic factor encompasses both into one single factor. This report intends to point out this distinction based on the data collected in TTCI. It has been observed in our study that impact loads are more a case of rail and wheel irregularities like flat spots on wheel, rail grinding etc. and dynamic loads are a result of the various degrees of freedom in the system including, but not limited to, speed, temperature, location, position within the train, vehicle characteristics, track geometry, curvature, and grade. The Impact loads are much higher (about 300%) compared to static loads and can be restricted / avoided by good maintenance practices while dynamic loads are only slightly higher (about 120%) than static load and are an inherent property and cannot be avoided.
Researchers at the University of Illinois at Urbana-Champaign (UIUC) conducted a research to lay the groundwork for an improved and thorough understanding of the loading environment entering the track structure in North America. As a part of this effort WILD (wheel impact load detector) data from multiple sites across the United States was collected from multiple industry partners. The data collected included sites which run both freight and passenger traffic. The data collected also reflected seasonal changes to understand the effect of temperature. Extensive data analysis regarding the same produced many important conclusions.

Apart from understanding the input loads a considerable effort was also placed to understand the mechanisms behind the flow of forces in the system to better understand failure mechanisms. In North America, the most common failure mode in concrete ties is rail seat deterioration (RSD): the wearing out of the concrete within the rail seat, often due to abrasion. [4] In fact, North American Railroads, ranked RSD as the most critical problem facing concrete crosstie track. [10] This abrasion is accelerated in the presence of water and in complex track geometry such as steep track grades and high degree curves. Concrete crossties are also susceptible to flexural cracking, which often propagates from the tie center with diminished ballast support. [11] Other components of the fastening system are also at risk of failure. Fatigue and abrasion of the fastening clips, shoulders, and insulators can allow for additional movement in the system and subsequent deterioration of other components.

In order to understand the mechanisms of the crosstie-fastener system, component behavior and system demands must be investigated. This includes an understanding of load transfer among each component. There is also a need for the magnitude of these input loads with respect to the train speed, car weight, track curvature, grade, and various fastening systems. Obtaining these measurements synchronously will provide insight into the more complex
interactions and allow for a more purposeful, mechanistic design of the system, and the field results to help create more practical design recommendations.
2. **Instrumentation and Test Plan**

2.1. **Instrumentation objective**

The research executed significant field experimentation aimed at both filling voids in our current understanding of concrete crossties and fastening systems and aiding future designers by obtaining quantifiable data regarding the expected loading environment for these components. The overall objective of the field experimentation was to quantify the loading demands placed on the individual crosstie and fastening system components as well as the system as a whole under a variety of operational conditions. This data will aid in providing answers to critical questions about the design and performance of concrete crossties and fastening systems. This data will also aid in development of a mechanistic design framework.

The field experimentation accomplished three primary goals stemming from the overall objective listed above: quantification of crosstie and fastening system response, determination of system mechanics and development of an analytical model.

Instrumentation of the system under known applied loads led to quantification of individual component characteristic deformations, strains and displacements. An understanding of the demands on each individual component is important in the optimization their design. The instrumentation used also helped understand the behavior of the all the components in unison as a system. This analysis helped understand the interaction among components revealing the system mechanics. The data obtained from the field experimentation was used in the calibration and validation of a three dimensional (3D) finite element model (FEM) of the concrete crosstie and fastening system which was used as a tool for conducting parametric analyses to aid in the design of concrete crossties and fastening systems.
2.2 Instrumentation Technologies and Loading Systems

2.2.1 Strain Gauges
Four types of strain gauges were used in this project based on the application. Standard 120-ohm foil type shear strain gauges were used for quarter bridge circuits used on the rail. Shear strain gauges in a chevron pattern with two 120-ohm gauges oriented 90° to each other were used for full bridge circuits on the rail. 120-ohm concrete internal strain gauges and 120-ohm concrete surface strain gauges were also used. The strains could be resolved to one microstrain.

2.2.2 Potentiometers
Displacement transducers called linear potentiometers were used to measure relative displacement between components. The transducers used had a maximum stroke length of 1.1 inch. Displacements could be measured accurately resolved to thousandth of an inch.

2.2.3 compact Data Acquisition
All strain gauges and potentiometers were plugged into a compact Data Acquisition system (cDAQ) using the relevant modules needed. This system was connected to the laptop and run in conjunction with a Labview program to record all the data. Data was recorded at 2000Hz for all loading scenarios.
Figure 1: cDAQ and other accessories

2.2.4 Matrix Based Tactile Surface Sensor (MBTSS)
MBTSS have the ability to record pressure distribution on a surface. In this experimentation, MBTSS were used to capture the pressure distribution at the rail seat. Data from MBTSS was recorded at 100Hz for static loading and dynamic loading.

2.2.5 Track loading Vehicle
The track loading vehicle (TLV) can be defined as a loading frame for railway track systems. It is more of less a locomotive with a deployable axle at the center. The two trucks of the locomotive are separated by a distance longer than usual to stay out of the influence region of this deployable axle. The TLV, in Figure 2, was used to apply known static and dynamic loads on the test section with its deployable axle. The TLV had the capability to apply vertical and lateral loads up to 40Kips and 22kips respectively accurately on each rail. The TLV had split-axles that allowed applying forces individually on each rail.
Figure 2: Track Loading Vehicle (TLV) in operation

2.2.6 Freight and Passenger consists
Freight and passenger consists were used to apply dynamic loads representative of the freight and transit revenue service lines. The weights of the locomotives, freight and passenger consists were known. The static weight of each passenger car, freight car and the locomotives were provided by TTCI. The freight cars were loaded to the typically permitted 286k lbs and 315k lbs. The passenger cars used were used empty and weighed around 86k lbs.

2.3 Test Sections
Two test sections were selected at Transportation Technology Center (TTC) in Pueblo, CO for the purpose of this research. The two sections were a tangent track and a curved track section, as shown in Figure 3 below. The tangent test section helped understand the loading demands as experienced by most of the track in service. Trains were run at speeds up to 105mph simulating the loading condition in revenue service. The curved test section had a 30° curve and helped understand the varied demands of all components of the system in a curved section. Freight and passenger consists were run up to slightly above balance speeds in this section.

Figure 4 is the location map of the all the instrumentation that was used as a part of this research exercise. The location map is identical for both the tangent and curved sections. This
report will not discuss all the instrumentation used and its applications but will limit itself to the once needed to understand the vertical load path.

Figure 3: Tangent and Curved Section at TTCI, Pueblo

Figure 4: Locations of all instrumentation technologies used during May 2013
Table 1 compiles the location of each of the instrumentation used for the purpose of this testing.

**Table 1: Location of each instrumentation used**

<table>
<thead>
<tr>
<th>Test Methodology</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Wheel Loads</td>
<td>D, F, T, V</td>
</tr>
<tr>
<td>Vertical Rail Seat Loads</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Lateral Wheel Loads</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Longitudinal Rail Loads</td>
<td>F, V</td>
</tr>
<tr>
<td>Vertical Rail Base Displacements</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Lateral Rail Displacements</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Vertical Crosstie Displacements</td>
<td>Ties C/S, E/U, G/W</td>
</tr>
<tr>
<td>Lateral Crosstie Displacements*</td>
<td>C, E, G</td>
</tr>
<tr>
<td>Internal Crosstie Strains</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>External Crosstie Strains</td>
<td>Ties C/S, E/U, G/W</td>
</tr>
<tr>
<td>Rail Seat Pressure Distributions</td>
<td>I, 5, 6, 7, 8, 13, 14, 15</td>
</tr>
<tr>
<td>Rail Base Bending Stresses</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Insulator Post Stresses</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Fastening Clip Stresses</td>
<td>E, S, U, W</td>
</tr>
<tr>
<td>Vertical Rail Strains</td>
<td>ALL</td>
</tr>
<tr>
<td>Lateral Force in Shoulder</td>
<td>B, C, E, Q, S, U</td>
</tr>
<tr>
<td>Pad Lateral Displacement</td>
<td>B, C, E, S, U, W</td>
</tr>
<tr>
<td>Pad Longitudinal Displacement</td>
<td>E, S, U, W</td>
</tr>
</tbody>
</table>

**2.4 Instrumentation Methodology**

This section discusses in detail the instrumentation methodologies used to accomplish the objectives stated above. Some measurements used were well-established instrumentation methodologies while some novel approaches were used to capture some data not captured reliably to data. The section will describe in detail how the data is captured and the intended use of the instrumentation. This section lists and discusses only those instrumentation methodologies that will be discussed in this report. It must be kept in mind that there were other instrumentation technologies as well which were used as a part of this research exercise which has not been discussed here.
2.4.1 **Vertical Wheel Loads**

Vertical wheel loads were determined using an arrangement of strain gauges in the crib of the rail (Figure 5). Weldable strain gauges were assembled in a Wheatstone bridge as shown in Figure 5 and Figure 6. Four gauges were placed, at two sections, in a chevron pattern just above and below the neutral axis oriented at $45^0$. A mirror of these four gauges was also made on the gauge side. The two sections chosen were 10” apart in the middle of the crib of the rail. The choice of 10” was made to accommodate the vertical and rail seat load bridges in a 24 in. (tie spacing in the test section) span. These eight gauges were wired to form a full Wheatstone bridge as shown in Figure 7. This has served as a commonly used methodology for determining accurate measurements of vertical wheel loads, well established within the railroad industry since its development in the 1970’s. [12]
Figure 6: Applied load and strain gauge location

Figure 7: Wheatstone bridge connections

This methodology is a well-established and trusted method which has been used for decades in the rail road industry. The vertical load, $P_Z$, which the system experiences when a train passes over the section, can be determined by:

$$P_Z = V_{ZL} - V_{ZR}$$  \hspace{1cm} (1)

The shear forces at each face ($V_{ZL}$ and $V_{ZR}$) can be calculated as follows:

$$V_{ZL} = \frac{EI}{(1+\nu)Q} \varepsilon_1$$  \hspace{1cm} (2)

$$V_{ZR} = \frac{EI}{(1+\nu)Q} \varepsilon_2$$  \hspace{1cm} (3)
where \( E \) is the steel modulus of elasticity, \( I \) is the moment of inertia of the rail cross-section, \( \nu \) is the Poisson’s ratio, \( Q \) is static moment of area, and the principal strains \((\varepsilon_1 \text{ and } \varepsilon_2)\) are comprised of the strains shown in Figure 6:

\[
\varepsilon_1 = \varepsilon_a - \varepsilon_b + \varepsilon_{a'} - \varepsilon_{b'} \tag{4} 
\]

\[
\varepsilon_2 = \varepsilon_c - \varepsilon_d + \varepsilon_{c'} - \varepsilon_{d'} \tag{5} 
\]

Thus, the load \( P_z \) could be rewritten as:

\[
P_z = \frac{EI}{(1+\nu)Q}(\varepsilon_1 - \varepsilon_2) \tag{6} 
\]

The strains \( \varepsilon_1 \) and \( \varepsilon_2 \) can be obtained by using a Wheatstone bridge (Figure 7). Strain \( \varepsilon_1 \) can be measured separately by using the Wheatstone bridge connection shown on the left of Figure 7, and strain \( \varepsilon_2 \) can be found similarly. The strain difference \((\varepsilon_1 - \varepsilon_2)\) can then be measured directly by including each strain gage into the Wheatstone bridge connection shown on the right of Figure 7. This configuration to directly yield the value \((\varepsilon_1 - \varepsilon_2)\) was used in our test setup.

This setup of strain gauges was calibrated using the TLV. The deployable axle was positioned right above the center of the crib of the rail. Vertical forces were applied in increments of 5 kips until a total load of 40Kips was reached. The forces recorded were used as inputs into the system which would result in stresses in most of the components within the system. The strain resulted due to the forces applied was recorded at each load step. As a result a gain factor was established for these vertical load bridges. Theoretically, if all the bridges were installed identically without any human error and the rail being perfectly uniform, all the gain factors would be the same. However, to take into account human error and external factors, this procedure was repeated at all locations of these vertical load bridges. Now with the gain factor
known, whenever train consists ran over the section, the response of the bridge could be interpreted as a load value.

2.4.2 Vertical Rail Seat Loads

Vertical rail seat loads were also strain gauges assembled in the same pattern as the vertical wheel loads, but the strain gauges on the rail web were directly above the rail seat area (Figure 5) as compared to being in the crib. An attempt was made to make the Wheatstone bridge in the crib as identical to the vertical load bridges as possible. This was done so that an average of all the gain factors of the vertical load bridges could be used as a gain factor for these bridges.

This was done because the reaction force from the tie (\( T_z \), Figure 8) cannot be eliminated to calibrate these bridges purely based on the response of the rail (\( V_{ZL} \) and \( V_{ZR} \)). Thus, these bridges were used to indirectly determine the rail seat load experienced at a rail seat under the influence of a known load (\( P_z \)) right above the rail seat. When the load applied on the rail (\( P_z \)) is right above the rail seat the response of the bridge is obviously influenced by the reaction force from the rail seat (\( T_z \), equal and opposite to the rail seat load \( R_z \)). This reaction force (\( T_z \)) is the only difference compared to when the rail is loaded in the crib. Thus, the difference in the response of the bridges in the crib and on the rail seat, under similar loads, gives us (\( T_z \), which is equal to \( R_z \)) the rail seat load experienced by the tie. This method These forces were used as inputs imparted into the pad assembly and crosstie rail seat.
2.4.3 Lateral Wheel Loads
Lateral wheel loads were determined using an arrangement of strain gages in the crib of the rail (Figure 5). Instead of measuring shear in the y-direction, these shear strains were rotated about x-axis and positioned on the rail base in order to measure shear in the direction of the lateral loads. Weldable strain gages were assembled in a Wheatstone bridge, similar to the left diagram in Figure 7, and calibrated with the TLV.

2.4.4 Longitudinal Rail Loads
Longitudinal rail loads were determined using an arrangement of strain gauges in the crib of the rail (Figure 1). Weldable strain gauges were assembled in a Wheatstone bridge and the strains resolved into forces. These forces were measured to understand how the train braking and acceleration influence the components in the longitudinal direction.

2.4.5 Vertical Rail Base Displacements
Vertical rail base displacements were measured on the rail base, 1.5 inches from the edge of the gauge-side rail base. These measurements were acquired with linear potentiometers, mounted to the crosstie to provide relative rail uplift to the crosstie. These measurements were used to further define the vertical stiffness at this interface and, when coupled with other
measurements, quantify rail rotation. Figure 9 below shows the instrumentation on the gauge side of the rail. The image shows three potentiometers mounted on one bracket to measure three different displacements of the rail, two in the lateral direction and one vertical.

![Figure 9: Gauge side instrumentation](image)

### 2.4.6 Lateral Rail Displacements
Lateral rail displacements were measured at the rail base and at the neutral axis of the rail relative to the crosstie using linear potentiometers, see Figure 9. These measurements, in conjunction with lateral force measurements, were used to define the lateral stiffness of the system at this interface. These two measurements also helped quantify the extent of bending of the rail due to the lateral forces.

### 2.4.7 Global Vertical Crosstie Displacements
Global vertical crosstie displacements were measured at each end of the crosstie relative to the ground using linear potentiometers affixed to steel rods driven to refusal. The displacements were measured at the end of the tie with the tip of the potentiometers touching the top face of the tie. These measurements, when coupled with other measurements, were used to
determine the support stiffness of each rail seat. These displacement values were also used as critical input parameters to validate the UIUC finite element model.

2.4.8 Global Lateral Crosstie Displacements
Global lateral crosstie displacements were measured at the end of the crosstie relative to the ground using linear potentiometers affixed to a rod driven to refusal. These potentiometers were also mounted on steel rods such that their tip touches the side face of the tie. These measurements, when coupled with other measurements, were used to determine the lateral support stiffness of each crosstie. These measurements were only captured on the curved section of the track where we would expect significant lateral loads. These measurements were not captured on the tangent section of the track.

2.4.9 Crossties Strains (Measured Internally)
Internal crosstie strains were measured using embedment strain gauges. Internal crosstie strain gauges were measured 1.5” below the surface of the rail seat using embedment gages (Figure 10). Embedment gages were installed during crosstie manufacturing in a 2x2 pattern (centered and spaced 3” apart). These strains were used to calculate the rail seat force imparted onto the crosstie rail seat. These measurements complemented the other methodology of rail seat load measurement as described in 2.4.2. These measurements were also used to determine the compressive forces and pressure distribution at the rail seat. This report will only highlight the findings from this instrumentation, more results and detailed analysis will be represented by Sihang Wei, a PhD. student at UIUC [13].
2.4.10 Crossties Strains (Measured Externally)

External crosstie strains were determined by concrete surface strain gages positioned longitudinally to the crosstie below the rail seats and tie center (Figure 10). Knowing the distance between these strains provided a measurement of curvature and, provided the cross-sectional properties of the crosstie, bending moments at three integral sections. These values help understand the bending behavior of the ties. Back calculating the moments in these sections also helps us understand the support conditions underneath the rail seats. Similar to the embedment gages, the data analysis of these strains is presented briefly and details of which are ongoing with the work of Sihang Wei (UIUC).

2.4.11 Rail Seat Pressure Distribution

Once the load going into the rail seat was known an attempt was also made to understand the distribution of pressure on the rail seat areas using matrix based tactile surface sensors (MBTSS). These sensors were able to map the distribution of loads onto a single rail seat surface, however, the sensors were first calibrated by applying known loads with a vertical loading frame and using input loads calculated through the strain gage data. MBTSS was installed on five consecutive crossties, with the purpose of measuring the distribution of the load longitudinally and data was collected during successive train operation. The MBTSS were installed on crossties which were away from the center of the test section, which had most of the

![Figure 10: Crosstie strain gage locations](image-url)
instrumentation. This was done deliberately to avoid the influence of MBTSS on the flow of forces, especially in the lateral direction. The installation of MBTSS reduced the friction between the rail and pad interface significantly influencing the lateral load path as was identified by Christopher Rapp [14].

Installing the sensors involved removing the fastening clips of the crossties to be instrumented, as well as approximately five crossties on either side to raise the rail to a height adequate for accurately placing a sensor. The rail was then lowered and all the clips reapplied. Removal of the sensors required the same process. Figure 11 shows a profile view of the fully instrumented crosstie with all components of the MBTSS installation. shows a plan view of the MBTSS as it was installed on the rail seats.

There has been a significant amount of research that has been done using MBTSS. This report will not discuss those results in detail but will only refer to data from this source to supplement other results being discussed here. Rapp et al [14] discusses more about data collected from these devices and gives a better understanding of the rail seat pressure distribution.

![Figure 11: Profile view of MBTSS installation on crosstie](image-url)
2.4.12 Rail Base Bending Stresses
Rail base bending stresses were measured transverse to the field side of the rail using weldable strain gauges located 1 inch from the edge of the rail base. These gauges measured the bending of the rail base. These measurements were used to help establish two objectives, to determine the bending behavior of the rail base if any and to determine the longitudinal distribution of the applied loads. Justin Grasse’s thesis [15], UIUC, discusses results from this data which establishes the rigid behavior of the rail base. It establishes the fact that the rail base acts as a rigid body for all practical rail road applications.

2.4.13 Vertical Rail Strains
Vertical rail strains were measured near the base of the web (Figure 4) using three vertical strain gauges applied two inches apart on each side of the rail, centered over the rail seat. Using these measurements across seven crossties, the strain values assessed the load distribution of the applied load longitudinally along the track. These strain values were also used to validate the UIUC finite element model. The purpose of using three gauges on each side per rail seat was to identify the distribution of load over the rail seat longitudinally. For the purpose of this testing only the center gauge was used to collect data as it was established that the distribution of load longitudinally on the rail seat did not vary significantly as identified by these gauges in previous testing [15].

2.4.14 Fastening Clip Stresses
Fastening clip stresses were measured on the field and gauge side of the rail using strain gauges located on the surface of the fastening clips; the strains were then be used to calculate the change in the normal and tangential components of clamping force applied to the base of the rail. These measurements were used to further define the load transfer path within the fastening system and determine the demands placed on the clips. These strain values were also used to
validate the UIUC finite element model. Data collected from this component has not been discussed in this report. Sihang Wei, a PhD. student at UIUC has made significant strides in understanding the behavior of this component and will document this in detail in his future reports and dissertation.

2.5 Overview of Field Test

A number of loading scenarios were used to troubleshoot instrumentation, seating loads for components, loads to calibrate instrumentation, static loads to define and understand component and system behavior and dynamic loads to understand component and system dynamics, system inertia etc.

A rigorous and well planned test matrix was used to accomplish the above tasks effectively. The TLV was used very effective for calibration of most of the instrumentation. The TLV was also used to apply static loads over the test sections. Passenger and freight consists of known car and locomotive weights were used to apply dynamic loads to system. The choice of speeds, acceleration and braking responses of the train were made to simulate loads as seen in revenue service. Table 2 below is a compilation of the tests run on the curved section of the track in TTC. A similar set of tests was run on the tangent section of the track as well. Table 3 below is a compilation of the same.

Table 2: Test matrix for the curved track section

<table>
<thead>
<tr>
<th>Filename</th>
<th>Train Type</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>130520_HTL_259</td>
<td>Passenger</td>
<td>HTL</td>
<td>Train Backing up</td>
</tr>
<tr>
<td>130520_HTL_260</td>
<td>Passenger</td>
<td>HTL</td>
<td>Dry run</td>
</tr>
<tr>
<td>130520_HTL_261</td>
<td>Passenger</td>
<td>HTL</td>
<td>2mph</td>
</tr>
<tr>
<td>130520_HTL_262</td>
<td>Passenger</td>
<td>HTL</td>
<td>Backing up and dynamic braking</td>
</tr>
<tr>
<td>130520_HTL_263</td>
<td>Passenger</td>
<td>HTL</td>
<td>2mph</td>
</tr>
<tr>
<td>Time</td>
<td>Type</td>
<td>Speed</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>15mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>Accelerating back up</td>
</tr>
<tr>
<td>15mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>10 pound reduction</td>
</tr>
<tr>
<td>15mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>Accelerating back up</td>
</tr>
<tr>
<td>30mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>15mph</td>
</tr>
<tr>
<td>30mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>15mph, 10 pound reduction</td>
</tr>
<tr>
<td>30mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>Backing up at 30mph and braking</td>
</tr>
<tr>
<td>40mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>Backing up at 30mph and braking</td>
</tr>
<tr>
<td>40mph</td>
<td>Passenger</td>
<td>HTL</td>
<td>15mph</td>
</tr>
<tr>
<td>40mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Dry run, before Freight passes</td>
</tr>
<tr>
<td>2mph</td>
<td>Freight</td>
<td>HTL</td>
<td>2mph reverse, dynamic stop over section</td>
</tr>
<tr>
<td>2mph</td>
<td>Freight</td>
<td>HTL</td>
<td>2mph</td>
</tr>
<tr>
<td>15mph with 10lb set</td>
<td>Freight</td>
<td>HTL</td>
<td>15mph with 10lb set</td>
</tr>
<tr>
<td>15mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Accelerating while backing up to 17mph</td>
</tr>
<tr>
<td>15mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Accelerating while backing up to 17mph</td>
</tr>
<tr>
<td>15mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Braking in reverse at 10mph</td>
</tr>
<tr>
<td>30mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Full service reduction braking to stop from 20mph</td>
</tr>
<tr>
<td>30mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Acceleration from previous stop</td>
</tr>
<tr>
<td>30mph</td>
<td>Freight</td>
<td>HTL</td>
<td>Backing up slowly, then max acceleration to 17mph</td>
</tr>
<tr>
<td>40mph</td>
<td>Freight</td>
<td>HTL</td>
<td>40mph</td>
</tr>
<tr>
<td>40mph</td>
<td>Freight</td>
<td>HTL</td>
<td>40mph</td>
</tr>
<tr>
<td>45mph</td>
<td>Freight</td>
<td>HTL</td>
<td>45mph</td>
</tr>
<tr>
<td>Dry Run</td>
<td>Freight</td>
<td>HTL</td>
<td>Dry Run</td>
</tr>
</tbody>
</table>
### Table 3: Test matrix for the tangent track section

<table>
<thead>
<tr>
<th>Filename</th>
<th>Train Type</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>130523_RTT_303</td>
<td>Passenger</td>
<td>RTT</td>
<td>2mph</td>
</tr>
<tr>
<td>130523_RTT_304</td>
<td>Passenger</td>
<td>RTT</td>
<td>Backing up, upto 13mph and dynamic braking</td>
</tr>
<tr>
<td>130523_RTT_305</td>
<td>Passenger</td>
<td>RTT</td>
<td>15mph</td>
</tr>
<tr>
<td>130523_RTT_306</td>
<td>Passenger</td>
<td>RTT</td>
<td>Backing up, 15mph, 10 pound shovel</td>
</tr>
<tr>
<td>130523_RTT_307</td>
<td>Passenger</td>
<td>RTT</td>
<td>15mph</td>
</tr>
<tr>
<td>130523_RTT_308</td>
<td>Passenger</td>
<td>RTT</td>
<td>Backing up, Accelerating upto 31mph</td>
</tr>
<tr>
<td>130523_RTT_309</td>
<td>Passenger</td>
<td>RTT</td>
<td>30mph</td>
</tr>
<tr>
<td>130523_RTT_310</td>
<td>Passenger</td>
<td>RTT</td>
<td>Backing up, Accelerating upto 8mph</td>
</tr>
<tr>
<td>130523_RTT_311</td>
<td>Passenger</td>
<td>RTT</td>
<td>30mph</td>
</tr>
<tr>
<td>130523_RTT_312</td>
<td>Passenger</td>
<td>RTT</td>
<td>Backing up, Accelerating upto 8mph</td>
</tr>
<tr>
<td>130523_RTT_313</td>
<td>Passenger</td>
<td>RTT</td>
<td>30mph</td>
</tr>
<tr>
<td>130523_RTT_314</td>
<td>Passenger</td>
<td>RTT</td>
<td>60mph</td>
</tr>
<tr>
<td>130523_RTT_315</td>
<td>Passenger</td>
<td>RTT</td>
<td>60mph</td>
</tr>
<tr>
<td>130523_RTT_316</td>
<td>Passenger</td>
<td>RTT</td>
<td>80mph</td>
</tr>
<tr>
<td>130523_RTT_317</td>
<td>Passenger</td>
<td>RTT</td>
<td>80mph</td>
</tr>
<tr>
<td>130523_RTT_318</td>
<td>Passenger</td>
<td>RTT</td>
<td>90mph</td>
</tr>
<tr>
<td>130523_RTT_319</td>
<td>Passenger</td>
<td>RTT</td>
<td>90mph</td>
</tr>
<tr>
<td>130523_RTT_320</td>
<td>Passenger</td>
<td>RTT</td>
<td>105mph</td>
</tr>
<tr>
<td>130523_RTT_321</td>
<td>Passenger</td>
<td>RTT</td>
<td>105mph</td>
</tr>
<tr>
<td>130523_RTT_322</td>
<td>Freight</td>
<td>RTT</td>
<td>Dry Run</td>
</tr>
<tr>
<td>130523_RTT_323</td>
<td>Freight</td>
<td>RTT</td>
<td>2mph</td>
</tr>
<tr>
<td>130523_RTT_324</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up, minimum set (6-8 pounds) 5mph</td>
</tr>
<tr>
<td>130523_RTT_325</td>
<td>Freight</td>
<td>RTT</td>
<td>2mph</td>
</tr>
<tr>
<td>130523_RTT_326</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up, Accelerating up to 11mph</td>
</tr>
<tr>
<td>130523_RTT_327</td>
<td>Freight</td>
<td>RTT</td>
<td>15mph</td>
</tr>
<tr>
<td>130523_RTT_328</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up, Accelerating upto 13mph</td>
</tr>
<tr>
<td>130523_RTT_329</td>
<td>Freight</td>
<td>RTT</td>
<td>15mph</td>
</tr>
<tr>
<td>130523_RTT_330</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up, Accelerating upto 8mph</td>
</tr>
<tr>
<td>130523_RTT_331</td>
<td>Freight</td>
<td>RTT</td>
<td>30mph</td>
</tr>
<tr>
<td>130523_RTT_332</td>
<td>Freight</td>
<td>RTT</td>
<td>22mph reverse</td>
</tr>
<tr>
<td>130523_RTT_333</td>
<td>Freight</td>
<td>RTT</td>
<td>30mph</td>
</tr>
<tr>
<td>130523_RTT_334</td>
<td>Freight</td>
<td>RTT</td>
<td>Acceleration from stop</td>
</tr>
<tr>
<td>130523_RTT_335</td>
<td>Freight</td>
<td>RTT</td>
<td>60mph</td>
</tr>
</tbody>
</table>
As can be seen in the tables above, most of the choices of speeds were those used in revenue service. A speed of 105mph for the passenger train was attained on the tangent track to simulate loading criteria of a high speed rail. Speeds of up to 45mph in a freight car were reached on the curved section as well which simulated high L/V ratios. A conscious effort was made to collect replicates in every case to gather a significant sample size.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>130523_RTT_336</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up 30mph</td>
</tr>
<tr>
<td>130523_RTT_337</td>
<td>Freight</td>
<td>RTT</td>
<td>60mph</td>
</tr>
<tr>
<td>130523_RTT_338</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up, minimum set (6-8 pounds) 16mph</td>
</tr>
<tr>
<td>130523_RTT_339</td>
<td>Freight</td>
<td>RTT</td>
<td>70mph</td>
</tr>
<tr>
<td>130523_RTT_340</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up 30mph</td>
</tr>
<tr>
<td>130523_RTT_341</td>
<td>Freight</td>
<td>RTT</td>
<td>70mph</td>
</tr>
<tr>
<td>130523_RTT_342</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up 30mph</td>
</tr>
<tr>
<td>130523_RTT_343</td>
<td>Freight</td>
<td>RTT</td>
<td>45mph</td>
</tr>
<tr>
<td>130523_RTT_344</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up 30mph</td>
</tr>
<tr>
<td>130523_RTT_345</td>
<td>Freight</td>
<td>RTT</td>
<td>45mph</td>
</tr>
<tr>
<td>130523_RTT_346</td>
<td>Freight</td>
<td>RTT</td>
<td>Backing up</td>
</tr>
</tbody>
</table>
3. **Vertical Load Path**

3.1 **Definition**

There exist several components in the system that affects its vertical load path. The loads, component geometry, dimensions, material properties, tolerances, component interactions etc. defines how the forces are transferred from wheel to the subgrade. The vertical load path as defined for the purpose of this project is pictured in Figure 12 and Figure 13.

![Figure 12: Vertical Load Path (Wheel to Rail Seat)](image)

The load of the car comes into the system through the wheel- rail interface at the head of the rail. It must be noted that in spite of the loads from the car being purely vertical, the loads going into the rail are not. There exists an eccentricity of the loading on the rail head which introduces a component of lateral load. In this report we will only discuss the component of vertical load. This load flows through the web of the rail into the base. The vertical load that acts
on the rail distributes itself longitudinally. Only a fraction of this vertical load will act on the components directly underneath it. The fraction of the load that is transferred to the components underneath is determined by a multitude of factors, some of which have been discussed in this report.

This fraction of load that acts on the pad assembly underneath the rail, compresses the pads. Further, the force flows underneath into the rail seat. The load is distributed more or less uniformly on the rail seat when a pure vertical load is acting. This distribution of load on the rail seat varies when lateral loads act. This load on the rail seat now translates into force on the ballast underneath it, compressing the ballast and displacing the tie vertically. The load in the ballast now distributes into the sub-ballast, sub-base and the subgrade underneath. In this research exercise an effort was made to understand the flow of forces only in the superstructure of the system, i.e. until the ballast.

![Figure 13: Vertical load path (Wheel to Ballast)](image)

**3.2 Input loads to the system**

Ever increasing freight traffic accompanied with an increased interest in high speed passenger rail and shared infrastructure is placing an increasing demand on railway infrastructure. In North America, AREMA design guidelines and recommendations use wheel
loads that are not representative of the loads in these rail networks. Furthermore, these recommendations are not representative because they are based on tonnages accumulated calculated based on static axle loads. The static axle loads are not what the rail system experiences when this static wheel rolls over a section of the track at a certain speed.

The limited understanding of the system under dynamic conditions has resulted in design recommendations that in some cases are overly conservative. In spite of these conservative recommendations a number of failure mechanisms have been observed which result in increased spending for track maintenance. For instance, the ties that are currently designed, as used in this project, are overly conservative in their bending moment capacity. But the same system at times cracks under impact loads not because the tie lacks the capacity but the lack of damping of these forces. It has thus become a critical area of the infrastructure to further research the concrete sleeper and elastic fastening system. A clear understanding of the nature and magnitude of these wheel-rail loads has become increasingly important to adequately evaluate the track components in order to make design improvements.

In this report several loads are used to define various loading conditions: static, dynamic, and impact loads. The static load is simply the weight of the rail vehicle at rest. The dynamic load is the additional load (above static load) due to high-frequency effects of wheel/rail load interaction, considering track component response and involving inertia, damping, stiffness, and mass. The impact load, which often creates the highest loads in the track structure, is created by track and vehicle irregularities. These impacts create high-frequency, short-duration loads that travel through the infrastructure and can lead to significant damage.

A number of parameters contribute to the loads imparted to the track structure. The motion between various components of the axle and wheel, the wheel-rail interface, friction,
stiffness of the fastening system etc. greatly complicating the problem. In addition to the rail, vehicle itself, the track and roadbed comprise a dynamic system which must be included in any dynamic analysis if accurate results are to be obtained. Understanding the influence of these factors is beyond the scope of the field instrumentation in this project. Some of these degrees of freedom of the system can be understood using the FEM model. It is important to understand all these factors to best design the concrete crosstie and fastening system.

In this section of the report the quantification of these dynamic loads on our section of the track is discussed. This intends to highlight the difference between a static load of an axle compared to the loads exerted by the axle under dynamic conditions, with the rail and wheels in well maintained condition. In this section an attempt has been made to make a distinction between dynamic loads and impact loads observed in our data. This distinction between dynamic and impact loads has also been collected from WILD detectors. This has been discussed in section 3.2.1, 3.2.2 and has also been documented in detail in the Masters’ thesis work of Brandon Van Dyk, a graduate student at UIUC [10].

Using the testing procedure described in the previous chapters an attempt was made to understand the difference in magnitude between static loads and dynamic loads. In this set of tests a deliberate attempt was made to eliminate certain factors like rail scrapping and wheel irregularities. These factors were successfully eliminated as the sections chosen for testing were well maintained sections of track. Also, the wheels chosen for both the passenger and freight trains were regularly inspected for defects and corrected if any.

The static weight of each passenger car, freight car and the locomotives were provided by TTCI. The freight cars were loaded to the typically permitted 286k lbs and 315k lbs. The passenger cars used were used empty and weighed around 86k lbs. The static weight of each car
was used to estimate the static wheel load of each wheel. This was done assuming that the load was distributed and carried equally by each of the eight wheels of the car.

In order to collect dynamic data the vertical wheel load strain gauges attached to rail as described in 2.4.1 were used. The dynamic loading data was collected by running freight and passenger trains over the test section. Both the passenger and freight cars were run at multiple speeds to understand the influence of speed on the behavior of the system. The experimental test matrix of different speeds used at the RTT (tangent track) and HTL (curved track) is summarized in Table 2 and Table 3. The speeds for the passenger train were varied from 2mph to 105mph and for the freight train from 2mph to 70mph on the RTT. The top speeds for these trains on the HTL were lower than the RTT for obvious reasons. The top speeds chosen were based on track geometry and permitted TTCI guidelines.

3.2.1 Static and dynamic loads
A comparison between the dynamic loads at different speeds and the static loads was made. This comparison was made for data collected both at the RTT and HTL, for the freight and passenger trains. This section also discusses the magnitude of contribution of load due to the dynamic effects of the system in comparison to the static loads. Most of the results in this section have also been summarized as a part of the Joint Rail Conference proceedings [16].

Figure 14 indicates the dynamic loads, recorded by the instrumentation under the influence of a passenger train at different speeds, in comparison to the static axle load (blue) of the same car. The data points of the dynamic loads (brown) presented in Figure 14 are mean values of six consecutive axles, with the same static axle load, run twice over the test section (tangent track). Thus, each point is the mean of 12 data points. The graph also includes error bars indicating the maximum and minimum values among the 12 data points. This graph additionally includes upper (red) and lower (blue) quartiles encompassing 25 and 75 percentile occurrences.
of the values respectively. These error bars and quartiles indicate the statistical significance of these average values.

**Figure 14: Dynamic wheel loads of a passenger car at different speeds, Tangent track**

It can be observed that the dynamic loads experienced by the track section are higher by about 10-20% compared to their static loads. It should also be noted that the speed of the train does not have a significant influence on the loads observed on a tangent track, in this data set.

Figure 15 represents the data collected on the same section of the track under the influence of a loaded freight train. The data presented in Figure 15 is also a mean value of six consecutive axles, with the same static axle loads, run twice over the test section (tangent track). A similar trend as compared to the passenger train can be seen even in the case of a freight train where the dynamic loads differ by about 10% compared to the static loads.
The above two graphs give us an indication that the increase in load due the dynamic effects of the system is approximately 20\% of the static wheel load. This suggests a factor of about 1.2 to estimate the dynamic wheel load from static wheel load for tangent tracks. It should be noted here that this test was conducted in May (summer) when the temperatures are relatively high compared to the rest of the year. The same track section under similar loading conditions could produce slightly higher dynamic loads in winter.

In the analysis of WILD data as part of Van Dyk’s thesis [10] to estimate the effect of speed, a linear estimate of wheel load data was developed restricting the data to a particular car type. In an example for linear estimate for dynamic factor on UPRR at Gothenburg, Nebraska (loaded freight car WILD data from January 2010, Figure 16) an estimate of $1.197 +0.00177[\text{speed(mph)}]$ was made. This factor is similar to the estimate provide by data collected in this project, 1.2. This indicates that the loading environment simulated in this project is representative of the environment observed in service lines.
However, on the curved section of the track the results were slightly different. The load experienced by the system was influenced by the speed of the train, as depicted in the case of a freight train in Figure 17. It was observed that beyond a certain speed (balance speed of the curve), as the speed of the train increased the load experienced by the system on the high rail increased. Similarly, it was also observed (not shown here) that the loads experienced on the low rail decreased. This can be explained by the fact that a centripetal force acts on the train on the curved section. The centripetal force experienced by the train is a function of the velocity and thus the dynamic load experienced changes with speed. It is to be noted that the increase in load was significant and up to 60% at 45mph on a 3° curve.
The above data suggests a dynamic factor of about 1.6 at 45mph on a 3° curve section. The dynamic factor for a curved section of the track would be significantly influenced by two major factors – geometry of the curve and speed (if above balance speed). The data collected in this case is limited to a 3° curve and thus the dynamic factor cannot be exhaustively provided. As WILD sites are not constructed on tangent tracks no data exists to validate the conformance of these results to field results.

Comparing the dynamic factors derived from the data collected all the data observed does fall within the 92 percentile of the load observed on WILD sites. The other loads experienced by the system as an effect of irregularities in the wheel and rail will be studied in more detail in the following section of this report.

### 3.2.2 Impact loads

The impact load, which often creates the highest loads in the track structure, is created by track and vehicle irregularities. These impacts create high-frequency, short-duration loads that travel through the infrastructure and can lead to significant damage.

As a part of data collection for this project, impact loads were applied by introducing irregularities to a wheel in both the freight and passenger consists. A flat spot of about an inch
(Figure 18) was present on the wheel. The loads by this flat spot exerted on the test section of track were captured to understand the nature and magnitude of these forces.

![Image](image.png)

**Figure 18: Flat spot on the wheel of freight consist**

The AREMA Manual defines the impact factor as a percentage increase over static vertical loads intended to estimate the dynamic effect of wheel and rail irregularities [8]. An impact factor of 50% was first used many years ago, and has incrementally increased to today’s 200% level [11]. A 200% increase above static load indicates that the design load is three times the static load. Because the impact factor described in this portion of the recommended practices is specifically related to the flexural performance of the crosstie, it may not be representative of the loads experienced at the wheel-rail interface. It must also be remembered that the AREMA manual does not refer to any other dynamic factor as discussed above. This impact factor of three is the sole factor above static loads used in the design. As will be discussed in the further section, this factor of three helps secure the ties over and above for the moment capacity but does not secure the other components effectively.

Since only one of the wheels used in both the freight and passenger cars had a flat spot, the sample size collected for impact loads was very small to make a generalization. But an
attempt has been made to understand the nature and magnitude of these forces. It was observed that in the case of passenger cars, these flat spots might not be as damaging as it might be in the case of freight cars.

![Figure 19: Flat spot impact, Passenger train](image)

Figure 19 above, shows the data recorded when from the vertical load bridges in the test section when a passenger car passes over it. The plot shows the strain recorded against time as the train passes over. A clear outlier can be seen in the case of the 22\textsuperscript{nd} axle. It can be seen that the strain recorded in this case is about 2.5 times that has been recorded when compared to the other axle in the same truck. The wheel on the 22\textsuperscript{nd} axle was known to have a flat spot as shown in Figure 18. The first few axles that showed similar magnitudes of strain were due to the higher axle loads of the locomotive as compared to empty passenger cars.

Figure 20 below is the plot of the strain recorded from a vertical load bridge when a freight car passes over the section. In this case all the axle loads recorded were comparable to
that of the locomotive or more. A clear outlier can be spotted in this case as well with the 39th axle. It can be noted that in case the impact load from the flat spot was about 4 times (300% higher) the load exerted by the other axle in the same truck.

Figure 20: Flat spot impact, Freight train

The sample of data collected is not large enough to comment on the magnitude of the impact loads as the flat spot did not hit the test section in every run. Thus, it is will not be statistically significant to provide an impact factor based on this data. A range of about 2 – 4.3 has been observed. The more interesting point to note though is the nature of these forces. Figure 21 is a zoomed in picture of Figure 20 at the point the system experienced the impact load. It can be seen here that the impact force experienced by the system was short-lived. The impact force experienced by the system was of a high magnitude and high frequency. It can be observed that the peak in the case of the impact force is about a fourth of the time of the other axles.
3.3 Vertical rail strain

Vertical rail strains as discussed in 2.4.13 were used to capture the distribution of vertical load in the longitudinal direction. Figure 22 shows the distribution of vertical web strains centered over adjacent rail seats on the low rail of a curve. This plot shows the response to a 40kip vertical load applied to the center crosstie by the TLV. Figure 23 shows the distribution of vertical web strains centered over adjacent rail seats on the high rail of a curve (Note: positive strains represent tension).
These distributions give us an insight into the extent of longitudinal distribution of the vertical load. It can be seen that the vertical load is distributed over a span of five ties in our case. This five tie distribution of the vertical load has been referred to by many researchers in the past. It must be kept in mind that this distribution of vertical force longitudinally is influenced by many factors such as support stiffness, tie spacing, etc.

![Figure 22: Strains in low rail in adjacent rail seats from 40kips vertical load.](image)

![Figure 23: Strains in high rail in adjacent rail seats from 40kips vertical load](image)
Figure 24 and Figure 25 show the distribution of vertical web strains centered over adjacent rail seats on the low rail and high rail of a curve respectively. This plot shows the response to a 40kip vertical load and 20kip lateral load applied to the center crosstie by the TLV. (Note: positive strains represent tension).

![Graph showing strains in low rail](image1.png)

**Figure 24: Strains in low rail in adjacent rail seats from 40kips vertical and 20kips lateral load**

![Graph showing strains in high rail](image2.png)

**Figure 25: Strains in high rail in adjacent rail seats from 40kips vertical and 20kips lateral load**

Based on the figures above, it can be clearly noticed that there is shift in flow of forces when a lateral load is introduced into the system. The field side gauges which initially do not
respond significantly under the influence of a purely vertical force experience a significant amount of compression when a lateral force is added. This clearly indicates that the there is a change of path in the flow of forces. This will be discussed again in 3.8 and 3.9.

3.4 Compression of Pad Assembly

As we move down the load path, the load from the rail base is exerted on the pad assembly below. The pad assembly which is sandwiched between the rail base and rail seat below it, experiences a compressive force. This compressive force leads to a reduction in dimension of the pad assembly in the vertical direction. Due to the Poisson’s ratio of the material it expands in the lateral direction up to some extent which is not the focus of discussion, in this section. The compression of the pad with increasing load at the four rail seats captured is presented in Figure 26. These measurements were collected on the gauge side as described in 2.4.5.

It must be noted that the compression of the pad is about 0.01 under a 40kip vertical load. This is significant amount of compression compared to its dimension. In spite of that we believe that the pad does not fail under a compressive load. It is believed to fail under shear when lateral loads act on the system and friction between the rail-pad and pad-tie plays a significant role in this failure mechanism [17].

The more important point of focus though is the observed deflection on the gauge side rail base under the influence of lateral load. The data shown in Figure 27 is that of vertical displacement of the gauge side rail base with varying lateral load and a fixed 40kip vertical load. It can be inferred that the rail base on the gauge side actually begins to loose contact with the pad assembly as signified by the negative values of displacement at higher lateral loads in Figure 27. Even before it loses contact, the compression of the rail pad decreases on the gauge side in spite
of the same vertical load in the system. Thus, transferring most of the vertical load in the system to the field side of the rail seat.

Figure 26: Pad compression with increasing vertical load

Figure 27: Gauge side vertical rail displacement with varying lateral load and 40kip vertical load
3.5 Rail seat loads and Pressure distribution

The compression of the pad assembly as a reaction to the load from the rail base results in a force acting on the rail seat. This force is commonly referred to as rail seat load. As has been discussed in the above sections, only a fraction of the vertical load acting right above a tie enters the tie underneath the load as it is longitudinally distributed among multiple ties. Rail seat load is an important input parameter in the design of concrete crossties and fastener systems. Estimating this value is critical to the efficiency of the design. As described in section 2.4.2, the rail seat loads were estimated using strain gauges on the rail in a whetstone bridge configuration above the rail seat area.

In this section, a comparison has been made between the observed rail seat loads and the loads applied to the system at the wheel rail interface. Figure 28 is a plot comparing the recorded rail seat loads at rail seats E and U (as in Figure 4) against the loads acting at the wheel-rail interface. It should be noted that these are two rail seats on the same crosstie in the center of our section.

![Figure 28: Observed rail seat loads on Tie EU](image)

Vertical loads up to 40Kips were applied on Tie EU in increments of 5Kips and the observed rail seat loads recorded. A significant difference was observed in the rail seat loads, under the same applied load at the wheel-rail interface, at the two rail seats though they are on
the same tie. Rail seat loads were observed to be 30-80% of the applied loads at the wheel-rail interface.

A number of factors determine what fraction of the vertical load translates as the rail seat load. Support stiffness, tie spacing, tolerances, etc. all contribute to this factor. Though one factor could be more important than the other. One of these factors has been discussed in greater detail later in this report. The significant degree of variability in rail seat loads on the same tie was a surprise but certain factors discussed in chapter 4 explain the reasoning reasonably.

The rail seat load acting on the tie would ideally be expected to be uniformly distributed considering that the bottom face of the pad assembly is a smooth flat surface. Uniform application of load on the tie should result in uniform degradation. But, it has commonly been observed that rail seat deterioration is more common on the field side [18]. In order to investigate this further, MBTSS was used, as described in 2.2.4 and 2.4.11.

![Figure 29: Rail seat pressure distribution under 40kips vertical load and varying lateral load (0, 4, 8, 12, 16 and 20kips)](image-url)
Figure 29 is a collection of rail seat pressure distributions of rail seat 11 under a 40kip vertical load and varying lateral load. The first image indicates the pressure distribution under the influence of purely vertical load. It can be observed that the distribution of load is mostly uniform. The following images are those of pressure distribution on the same rail seat with the same vertical load and increasing lateral load. Lateral loads of 4kips, 8kips, 12 kips, 16 kips and 20 kips were applied and the pressure distribution captured.

A clear shift in the distribution of pressure can be observed with increasing lateral load. It can be observed that a significant portion of the rail seat is completely unloaded with increasing lateral load. A concentration of forces on the field side was observed while the gauge side of the rail seat was completely unloaded. Only 58% of the rail seat area is loaded when compared to the case of a purely vertical load [19]. This is another indication of the influence of lateral load.

3.6 Crosstie strains

The rail seat load acting on the tie causes strains in tie. The region of tie underneath the rail seat disperses the load in the tie. Concrete embedment strain gauges, as in 2.4.9, were cast below rail seat to create a “load cell” to measure the rail seat vertical load. Laboratory instrumentation efforts were done to calibrate this vertical “load cell”. The compressive strain distribution in concrete below the rail seat is related with the loading eccentricity and support conditions [13]. The rail seat load as recorded by these gauges when 40kips of vertical load was applied at the rail seat U and when 20kip of lateral load was added to the existing vertical load is depicted in Figure 30. It can be observed that there is no significant change in the magnitude of rail seat load experienced under the influence of lateral load. The magnitude of these results is also good in correspondence with the rail seat loads measured using strain gauge patterns in the
rail. There exists a change in the rail seat load distribution which is not evident through this instrumentation.

Concrete cross-tie bending behavior was also investigated through the use of strain gauges applied in the longitudinal axis of the crossties in both laboratory and field experiments. It was inferred that the maximum bending strains generated are well within design limits of the concrete crosstie [13].

### 3.7 Vertical Tie Deflections

The rail seat load acting on the crossties is balanced by the reaction from the ballast. The forces acting on the ballast compress it, thus causing a vertical settlement of the tie. The vertical crosstie displacements were measured at each end of the crosstie relative to the ground using linear potentiometers affixed to a rod driven to refusal in the ballast adjacent to the ties (Figure 31). These measurements, when coupled with other measurements, were used to determine the support stiffness under each rail seat.
As described earlier and depicted in Figure 13, the loads at the wheel-rail interface translates into deflection of the crossties. Figure 32 is a plot of the observed deflections of the multiple rail seats (labelled in Figure 4) under static loads of a TLV on the curved track.

![Figure 31: Vertical crosstie displacement](image)

**Figure 31: Vertical crosstie displacement**

**Figure 32: Vertical tie deflections**
It was observed that there is a significant difference in the displacement values of different rail seats under the same applied load. Different rail seats on the same tie also showed different levels of compaction. Figure 33 is a plot of the vertical tie deflections of the same rail seats with a 10kip preload. It was observed that the under the influence of pre-load all the rail seats behaved in a similar manner, exhibiting very similar tie deflections. Thus, the significant difference seen in Figure 32 was attributed to the difference in the existing compaction level of the ballast across the length of the track. It was also observed that two rail seats on the same crosstie (eg: E and U) also exhibit different deflections indicating uneven compaction levels even under the length of the crosstie. It must be noted that this is the case in spite of it being a well maintained section of the track in a research facility and that a similar or worse conditions could be expected in the field where the maintenance activities are not as frequent. Li et at. [20] in their study state that the variability in vertical stiffness along a track section is more common on softer or weaker track section compared to a stiffer section.

![Vertical crosstie deflections with 10kip preload](image)

**Figure 33: Vertical crosstie deflections with 10kip preload**
Several methods to determine track stiffness have been used [21]. Figure 33 is a plot of the crosstie deflections after a pre-load of 10 kips was applied. This method is used by some to estimate the vertical stiffness of the track [22]. As can be seen in the plot, the deflections of the rail seats with a 10 kip preload are much more consistent with each other than before indicating that the different rail seats behave similarly once the initial voids in the ballast are closed. But this initial variation in deflection significantly affects the flow of forces in the system as will be discussed in section 3.8.

### 3.8 Tie deflections and Rail seat loads

A number of components of the vertical load path have been discussed so far in Chapter 3. The factor that influences the design of most of the components in the system is the rail seat load. An accurate estimation of this factor is critical to optimize the design of the concrete crosstie and fastening system. As have been listed earlier, a number of factors contribute to determine what fraction of the vertical load translates as rail seat load. Crosstie spacing, support stiffness, fastening system etc. play a significant role. In this project the tie spacing was chosen to be a constant 24” and fastlock-1 fastening system was used on a ballast track.

Thus keeping the above variables constant, Figure 34 depicts plots of rail seat load and vertical tie deflections of two rail seats (E and U on the same tie).
Under similar conditions of loading it was observed that higher deflections (rail seat E) resulted in lower rail seat load at the particular rail seat, indicating a greater distribution factor over to the adjacent ties. Similarly lower deflections (rail seat U) resulted in higher rail seat loads were recorded indicating lower distribution factors over to the adjacent ties. The same pattern was observed for the other rail seats recorded as well. This suggests that the deflections of the crosstie play a significant role in the fraction of the load transferred to the rail seat.

Viewing this phenomenon from a geotechnical perspective raises an apparent contradiction. Geotechnically, higher deflections should result from higher loads. But this would be the case if we assume a uniform support underneath. It must be noted that the rail seats that experienced higher deflections with the same vertical load was due to the presence of a higher voids in the ballast underneath it. Figure 33 shows that the ballast underneath all the rail seats had a similar stiffness once all the voids were closed. Indicating that the higher deflections under some rail seats was not due to the ballast having lower stiffness, but due to higher voids.

**Figure 34: Comparing rail seat loads and crosstie deflections**
3.9 Influence of Lateral load on Vertical load path

Multiple aspects of this section have been discussed throughout Chapter 3. This section provides a compilation of these findings.

In revenue service, even on a tangent track, the vertical load can never act on its own. There always exists a component of load that acts laterally on the system. Thus, in an attempt to understand the vertical load path it is necessary to understand the influence of lateral load.

Section 3.3 brings to the fore front the influence of lateral load on the strains in the rail. When a lateral load acts compressive strains due to bending, in addition to the vertical compressive load, begins to act on the field side of the rail. A comparison of the same can be seen in Figure 22 through Figure 25. At the same time as discussed in section 3.4, the rail base on the gauge side begins to lift and loose contact with the pad assembly as pictured by the negative values in Figure 27.

This conclusion, of the rail base loosing contact with the pad assembly on the gauge side, is well supported by the findings from MBTSS. It was observed, as in Figure 29, that only 58% of the rail seat area was loaded when a lateral load of 20kips was acting on the system. But, even in this case, it was observed that the rail seat load acting on the system was equivalent to the case when no lateral load was applied. This was supported by both the strain gauges on the rail and the embedment gauges in the tie (Figure 28).

Thus, when a lateral load acts on the system the same magnitude of rail seat load is carried by a smaller portion of the rail seat on the field side. This resulted in a concentration of strains on the field side, causing higher strains when compared to the case with no lateral load, also shown in Figure 29.
In summary, lateral load does not alter the magnitude of vertical load passing into each component in the vertical load path but it affects the distribution of forces, concentrating the loads on the field side.
4. Mechanistic Design

This chapter compares and contrasts specific aspects of design standards (mostly AREMA, EN and Australian) that exist across the industry and across countries. While making these comparisons, attention has been drawn to the limitations that exist in current design standards. Recommendations developed in previous chapters are reiterated here to suggest how design standards can be improved. It must be kept in mind that these suggestions are being made based on a data set that is limited to concrete crossties and testing that was done at a well maintained research facility.

4.1 Wheel load and Impact factors

Table 30-1-1 of AREMA chapter 30 defines the load environment expected to be encountered in North American Freight, High Speed Passenger and Transit Railroad segments of the industry. Table 30-1-1 presents the available data in terms of vertical, horizontal and longitudinal loads that can be expected at the wheel/rail interface. These suggested values are used as design inputs for components. Similarly, the Australian design standard suggests that most design static axle loads are 25 tonnes and the components should be designed according.

In addition to the load acting on the system the standards also propose an impact factor. AREMA suggests that an impact factor of three, i.e. 200% higher than the static load, should be used. The EN standard specifies that the impact factor is proportional to the stiffness in the system and should be provided by the designer. The Australian standard also makes a suggestion similar to that of EN and says the impact factor should be provided by the designer. But it also suggests a minimum impact of 2.5. A number of researchers have also suggested many ways to evaluate this dynamic factor. [5] [6] [7]
Based on the results observed in the project, also discussed earlier, it is necessary to have two distinct factors: dynamic and impact. Dynamic factor accounts for the loads above the static load that are a result of wheel/rail load interaction, considering track component response and involving inertia, damping, stiffness, and mass. Impact factor accounts for the loads that create the highest loads in the track structure. These are created by track and vehicle irregularities. These impacts create high-frequency, short-duration loads that travel through the infrastructure and can lead to significant damage.

From the limited data set for impact load, it was observed that this factor can at time be as high as four (300% higher than static). But it is very important to note than these forces are high-frequency short duration forces and the system need not be designed to be four times stiffer to withstand these loads. It is important to damped these forces rather than to design ties that can withstand bending moments that are 300% higher.

4.2 Rail seat load and Load distribution

The rail seat load is a critical design parameter for many component designs. It is important to estimate it accurately. The longitudinal distribution of the vertical load is dependent upon tie and axle spacing, ballast and subgrade reaction, and rail rigidity.

The percentage of wheel-to-rail load carried by an individual tie varies from location to location. AREMA suggests a conservative estimate of the distribution in Figure 30-4-1, which is based on tie spacing for the purpose of simplification. While rail stiffness does influence these percentages, its effect is small compared to other factors. The values chosen are intended to offset variations resulting from other influences. The Australian design methodology of load distribution also suggests a chart as reference based on tie spacing. It also suggests an equation
based on track modulus, rail E, rail I, sleeper spacing and static wheel load for the calculation of rail seat loads.

Most of the standards, including AREMA and Australian standard, calculate rail seat load (RSL) for moment calculations of ties as RSL = j(Q)(DF), where j, Q and DF are impact factor, static wheel load and distribution factor. The limitation being that in AREMA a standard value of 39kips is considered for Q, which over designs the tie in some cases.

Also, the distribution factor chart that is suggested is based purely in terms of tie spacing. The track stiffness, however, is an important characteristic that also contributes to this distribution. It is important to include it in the design. A detailed parametric study for the same is necessary and researchers at UIUC have begun to take steps in this direction. Based on the data collected, thus far it has been seen that the tolerances that exist in the system play a significant role in this distribution. It has been observed that the rail seat load experienced by the tie underneath the load could vary from as low as 30% to as high as 80% in cases with the same support stiffness but different tolerances.

4.3 Rail Seat Abrasion

Several preventive measures are adopted across the industry to try and eliminate this failure mechanism. AREMA suggests the use of special pads or modifying the concrete rail seat. EN believes in dealing with this problem from the concrete tie manufactures side and suggests that great care should be exercised in the selection of materials to ensure the long term durability of the concrete, consideration should also be given to the requirements for freeze-thaw resistance, porosity and abrasion resistance. The Australian standard suggests the use of abrasion-resistant pads or abrasion-vibration and impact-reducing pads between the rail and
concrete sleepers to minimize the possibility of abrasive action in the rail-bearing area of the sleepers.

Based on the findings of this project, one significant cause of RSD is the concentration of vertical load on the field side of the rail seat under the influence of a lateral load, especially on a curved section of track. This concentration causes the peak pressure on the rail seat to be much higher when compared to an even distribution of load. Also, the study of flow of forces in the lateral direction has brought into picture the shear forces acting on the pads which are significant in magnitude. To date, the railroad industry has not designed pads on the basis of performance under shear, even though this study suggests shear may be the most prominent failure mechanism under consideration. High shear stress acting in the pads would contribute towards abrasion mechanisms on the rail seat.

**4.4 Bending moments**

Wheel loads generate positive bending moments under the rail seat. Negative bending moments under the rail seat can arise from vertical movement of the track, harmonic motion from rail corrugation and curving forces of the sleeper under dynamic loading and handling during track works. Negative bending moments at the center part can arise from ballast support close to the center.

For the theoretical calculation of design bending moments, AREMA suggests equation in Chapter 30 and similarly, EN suggests referring to the UIC Report 713 R. Each standard suggest a maximum bending moments at the rail seat and the center of the tie in specific tables.

In was observed in this project that the bending moments that the ties are designed for is over conservative even while considering extreme loading scenarios. These considerations are due to the fact the design methodologies include an impact factor of 3 or more which makes the
ties very stiff. The inclusion of this design factor for the design of cross ties should be reconsidered. [13]

4.5 Track modulus

The determination of track modulus is integral to the design of a track system. The choice of support condition could alter the design of the super structure greatly. A number of researchers have suggested many a ways to determine track modulus both classically and empirically [20] [21]. Neither AREMA nor EN addresses the issue of suggested track modulus. The Australian standard suggests track modulus greater than 20MPa (2900 psi) per rail.

It was determined in this project, that for the calculation of support stiffness it is necessary to apply a pre-load (eg: 10kips) to the track structure before data points with higher loads are recorded. This is necessary to eliminate the gaps in the ballast underneath the tie. It was observed that most of the ties behaved similarly beyond a pre-load of 10kips though there response to the initial lower loads was considerably different.

4.6 Lateral load

Retention of track geometry and prevention of gage widening under the influence of lateral loads is an important design criterion. AREMA design standard assumes the lateral load distribution to be identical to the vertical load distribution. The Australian standard does not consider any lateral loads from curvature effects. The flow of forces in the lateral direction is not well understood and many assumptions have been made.

One of the major goals of this research project, though not discussed in detail in this report, was to understand the flow of forces in the lateral direction [23]. This report did discuss the effect of lateral load on the vertical load path, highlighting the fact that lateral loads force the concentration of forces on the field side of the rail seat.
5. Conclusions

The extensive test plan and instrumentation implemented effectively helped analyze a variety of topics that are not well understood. A number of conclusions drawn in this report have been summarized here. Alongside the conclusions, suggested corrections and possible future work have also been mentioned.

The choice of instrumentation technologies and test methods were effective in capturing most of the intended data. A small change in the wiring pattern of the rail seat loads to capture the rail seat loads at adjacent ties should be made to enrich the data set. The three gauges in the web of the rail used to identify the load distribution can be limited to a single gauge as this methodology did not prove to be very effective. Effective protection of the concrete surface strain gauges is essential to prevent any damages in the field.

A dynamic factor of 1.2 for tangent track and 1.6 for curved tracks was determined for this data set. It is important to incorporate this to the design of the crosstie and fastening system. In addition to the dynamic factor, an impact factor of three was also determined. It was recognized that the nature of these impact loads, caused due to wheel and rail irregularities, is different from conventional dynamic loads. The impact loads are high-frequency short-lived forces. The system should be designed differently for these forces. Making the system three times stiffer does not solve the problem as more importantly these forces need to be dampened. A deeper study to understand the nature of these forces and designing a fastening system that dampens these forces effectively would be an interesting project.

The vertical rail strains confirmed the well-established five tie vertical load distribution. The influence of the lateral load on the vertical load path was suggested by these strain values. When coupled with the displacements observed in the rail and the pressure distribution from the
MBTSS, it was concluded that the magnitude of the vertical loads is not affected by the lateral load but the concentration of pressure shifts to the field side.

The rail seat load is significantly influenced by tie spacing, support stiffness among other factors. In this project, though these factors were kept constant, the rail seat loads were observed to be varying between 30-80% of the vertical wheel load in the system. The rail seat loads observed on two rail seats on the same tie was also observed to vary significantly in some cases. It was concluded that this difference in rail seat load across the track with similar conditions was due to variable support conditions underneath each tie. The ties were also seen to behave similarly after a pre-load was introduced into the system. The difference in extent of pre-load required for each tie, before the entire track behaves uniformly, introduces this variability in rail seat loads.
References


Appendix – Miscellaneous photos from tests at TTC in Pueblo, CO in May 2013.