MULTIFACETED APPROACH FOR THE ANALYSIS OF RAIL PAD ASSEMBLIES RESPONSES

BY

THIAGO BIZARRIA DO CARMO

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2014

Urbana, Illinois

Advisers:

Research Scientist and Senior Lecturer J. Riley Edwards
Professor Bassem O. Andrawes

ABSTRACT

To achieve the performance demands due to growing heavy-haul freight operations and increased high-speed rail service worldwide, advancements in concrete crosstie fastening systems are required. A mechanistic design approach based on scientific principles and derived from extensive laboratory and field investigation combined with computational analysis has the potential to improve the current best practices in fastening system design. The understanding of failure modes and effects on each component, associated with an improved understanding of load distribution and mechanical behavior, will ultimately increase production and operational efficiency while reducing unscheduled maintenance, track outages, and unplanned additional costs. Improvements on the rail pad assemblies, the components responsible for attenuating loads and protecting the concrete crosstie rail seat, will enhance the safety and efficiency of the track infrastructure. Lateral, longitudinal, and shear forces exerted on the components of the fastening system may result in displacements and deformations of the rail pad with respect to the rail seat and rail base. The high stresses and relative movements are expected to contribute to multiple failure mechanisms and result in an increased need for costly maintenance activities. Therefore, the study rail pad's mechanical response is important for the improvement of railroad superstructure component design and performance. In this study, the lateral displacement of this component with respect to the rail base and rail seat is analyzed. Additionally, the development of an analytical tool (I-TRACK) based on UIUC's concrete crosstie and fastening system FE model is described, serving as the basis for a rail pad assembly mechanical behavior investigation. The ultimate goal of I-TRACK is to provide component manufacturers and track engineers a powerful and adaptable tool to analyze the track responses and assist the development of improved fastening system components.

to my family,

Leila, Valério and Filipe,

for allowing me to pursue my dreams,

and for blessing my life with unconditional love

"para minha família,

Leila, Valério e Filipe,

por me permitirem perseguir meus sonhos,

e por abençoarem minha vida com amor incondicional"

ACKNOLEDGEMENTS

The pages of this Thesis are not sufficient to express my sincere gratitude to all the people who contributed in this research and guided me through the challenges inherent with the graduate school experience. First of all, I would like to thank the National University Rail (NURail) Center and the Federal Railroad Administration (FRA) for providing funding for my research position and for sponsoring this research project. Additionally, I would like to extend my appreciation to Amsted RPS, specifically Jose Mediavilla, for supplying experimental resources and giving very valuable advices.

This study was possible because Riley Edwards has always believed in my potential, giving me the opportunity to be part of an outstanding research team. Riley has opened doors that I have never imagined being able to enter, helping me understand the importance of building into the lives of people around us. His example as a role model have shaped my character and encouraged me to grow as individual. There are not enough words to describe my gratitude for him and for all the blessings he allowed to happen in my life.

I will be forever thankful to Ryan Kernes, for investing an overwhelming amount of time and energy into our friendship. He has touched my life in a very special way, being a mentor and challenging me to become a better person every day. Ryan has intentionally devoted his attention to build me up as a leader, showing me the importance of fostering lasting relationships. Through his examples I will always remember that every man is capable of changing, and it is never too late for a fresh start.

I am also profoundly thankful to Francesco Bedini for introducing me to our research team and encouraging me to pursue a career in railroad engineering. His passion for trains and his kindness are some of the main reasons why I became part of the RailTEC family. Many thanks are also due to Brent Williams, for the valuable advices he has given me along the past two years, and for his friendship. His refined sense of humor will never be forgotten, as it has definitely contributed to make a better working environment.

I would like to express my gratitude to my advisor Dr. Bassem Andrawes for all the guidance and support he has given me along the way. His knowledge and critical thinking have brought a different perspective to this study, elevating the standards for this research. I greatly appreciate all the patience and time he devoted to supervise my work.

Many thanks are due to Marcus Dersch and Prof. Christopher Barkan, for their valuable opinions and advices. Additionally, I would like to thank Chris Rapp, Brandon Van Dyk, Justin Grassé, Sihang Wei, Xiang Liu, Prof. Moochul Shin, Prof. David Lange and all the people who have participated in the FRA BAA Research Project. Special thanks are due to Zhe (George) Chen and Ashish Khetan for all the help provided in the computational routines and statistical model development presented in this thesis.

Last, but most importantly, I would like to thank my family. My mom and dad, Leila and Valério, I will forever be thankful for the opportunity that you gave me to follow my dreams. Without your encouragement, emotional support, and love, I wouldn't be able to withstand the distance, loneliness, and challenges that I faced during this endeavor. To my brother Filipe, thank you for standing by my side every time I need you. You reminded me not to take my problems too seriously, and that they are nothing compared to the blessings I have in my life. Finally, I would like to thank Ana Beatriz for all the miles travelled, unconditional love, patience, kindness, and for bringing light into my life.

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CHAPTER 1: INTRODUCTION

To meet the increasingly rigorous performance demands due to growing heavy-haul freight operations and increased high-speed inter-city passenger rail development worldwide, advancements in concrete crosstie fastening system designs are imperative. In North America, a limited understanding of the complex loading environment affecting the concrete crosstie and elastic fastening system components led to an empirical design process based primarily on previous timber crossties fastening system design techniques, which fail to incorporate loading demands and loading paths of a concrete crosstie (Van Dyk 2013). This process has generated components that are unable to achieve their intended design life. While initially functional, they ultimately require more frequent maintenance or fail prematurely, causing track outages, reduced capacity, and added maintenance and capital costs (Van Dyk 2013).

The current fastening system design methodology can be improved through a design approach based on scientific principles and derived from extensive laboratory and field investigation combined with analytical modeling. This type of design technique, derived from measured and predicted track responses to load input and taking into consideration the material behavior of components is also called mechanistic design approach. The understanding of track components failure modes and its effects on the track structure, in concert with a deep understanding of load distribution and mechanical behavior of components, would lead to component designs that ultimately increase production and operational efficiency while reducing unscheduled maintenance, track outages, and replacement costs. Furthermore, the understanding of the mechanistic behavior of the fastening system will result in improved practices and standards that lay the groundwork for a refined design approach focused on the performance, efficiency, and durability of fastening system components.

One component that will benefit from such an approach is the rail pad assembly, also referred to as rail pad or pad. This is the component within the fastening system responsible for providing vertical load attenuation and protection for the concrete crosstie rail seat. This component is important to the track structure because of its capability to alter the track stiffness and load distribution. This versatile engineered product can be designed with multiple layers, a variety of materials, and different geometric characteristics.

1.1. Motivation and Objectives

Given the rail pad assembly is in contact with most components within the concrete crosstie fastening system, undesired changes on its mechanical behavior and material properties may ultimately affect the performance of all other components. The investigation of the mechanical responses of rail pads subjected to a realistic loading environment must be considered a key factor in the development of this product, since its deformation and relative displacement may be used to prevent excessive demands on the track superstructure (Rhodes 2013). Additionally, the capacity of the rail pad assembly to dissipate the high stresses generated on the track under severe operating conditions can also be used to improve the performance and increase the life cycle of the fastening system (Rhodes 2013).

This study investigates the mechanics of rail pad assemblies within the concrete crosstie fastening system, focusing on the lateral relative displacement between this component and the concrete crosstie rail seat and rail base. Initially, a Failure Mode and Effect Analysis (FMEA) was conducted to define, identify, and evaluate failures causes and effects related to rail pads (Chapter 2). This study served to guide the process of answering questions related to the component behavior and set the groundwork for future phases of research. Laboratory and field experiments were carried out at the University of Illinois at Urbana-Champaign (UIUC) and the Transportation Technology Center (TTC) in Pueblo, Colorado, where multiple realistic loading regimes were imposed to the fastening system to gain understanding of the mechanics of rail pad assemblies. Finally, a simplified analysis tool for track component response, named I-TRACK, was developed based on a 3D finite element model (Chen et al. 2013), to assist in the mechanistic design of concrete crosstie and fastening system components.

1.2. Concrete Crosstie Fastening Systems

The concrete crosstie fastening system, also known as "fasteners", is the group of components that form the structural connection between the rail and the concrete crosstie (Esveld 2001). They are responsible for holding the rail, maintaining track geometry, and distributing the loads from the rail to the concrete crosstie. The loads primarily come from the action of the vehicles on the rail, although the effects of the environment (e.g. temperature) also have a significant influence on the forces exerted on the fastening system (CEB FIP 1987). Throughout the world, a great variety of fasteners exist, and new types are added regularly in order to keep up with changes in design requirements and material supply. The requirements for each fastening system application vary, but the fasteners primary role of maintaining rail gage and transferring vertical and lateral wheel loads from the rail to the crosstie is the same for all applications (AREA Bulletin 752 1995). There are also other important requirements regarding installation, maintenance, and operating characteristics that directly affect track operating costs and the overall behavior of the structure. The following points are key performance criteria for a concrete crosstie fastening system (CEB FIP 1987, Esveld 2001):

i. The fastening system must hold the rails to the correct track gauge and inclination.
ii. The system must safely transmit the rail forces to the concrete crosstie. These include train wheel loads (vertical and lateral) and thermal forces.
iii. The system must absorb the rail forces elastically (without permanent deformations) and transfer them to the crosstie.

iv. The vertical clamping force should be sufficient in all load situations, even in case of wear.

v. The fastening system should provide the necessary longitudinal resistance to limit the longitudinal strain in constant welded rail (CWR) track, reduce the gaps in the case of rail fractures, and resist creeping forces.

vi. The fastening system should be able to withstand torsional forces exerted in the track components.

vii. The fastening must have sufficient elasticity and fatigue resistance to guarantee a long life cycle.

viii. The fastening system must be resistant to corrosion.

ix. Installation and maintenance must be considered and the fastening system should preferably be able to be installed by manual and mechanized methods.

x. The fastening system should provide electrical insulation between the rails and the crossties.

xi. The fastening system must be vandal-proof.

Although not a requirement, and at times not feasible, another desirable feature regarding the fastening system is to retain its functionality after a derailment. This capability would include low exposure to wheel damage and strength to resist impact by a derailed wheel (AREA Bulletin 752 1995). It is important to mention that not all of these performance criteria are included in the fastening system requirements for many of the world's railway recommended design practices (Van Dyk 2013, Kernes 2013). Many of them are considered to be idealistic properties that an optimal fastening system should exhibit. The American Railway Engineering and Maintenance-of-Way Association (AREMA) only references, for example, that fastening systems need to provide adequate lateral strength to maintain rail gauge, constrain the rail against rollover, control longitudinal rail movement, and withstand repeated loads without fatigue failure or excessive maintenance demands (AREMA 2012). Even though fastener designs have evolved to accommodate higher wheel loads, speeds, and the increased performance requirements (e.g. reduced life cycle costs and maintenance), further advancements must be undertaken to ensure that all of the aforementioned functions of the fastening system are well executed and the life cycle of components satisfactorily match to the concrete crosstie.

1.3. History of Concrete Crosstie Fastening Systems

After the Second World War, European countries started to adopt prestressed concrete crossties in the rehabilitation of the damaged tracks (Kerr 2003). Compared to timber crossties, concrete crossties are stiffer and more resistant to compressive forces. These particular characteristics don't allow the installation of spikes. Therefore, other mechanisms to attach the rail to the superstructure of the track were needed. In the beginning, there was an attempt to adapt the timber crossties fastening systems for the new application, which was largely unsuccessful and caused a setback in the use of concrete crossties. The West German Railways (DB) and the former USSR Railways used, for example, a modified K-Fastener (Figure 1.1) until 1960. As a result, the implementation of these redesigned fastening systems proved to be incompatible with the mechanical behavior of the stiffer concrete crosstie tracks (Kerr 2003).

The rails displaced above their horizontal unloaded position at both sides of a passing wheel. Therefore, they attempted to lift the crossties from the ballast when the fastening system was too stiff, which was true of the K-fasteners. For heavier concrete crossties, this tendency lead to large vertical forces in the fastening system, potentially causing fatigue in the bolts and connection. Moreover, the repetitive lift-off and drop of the heavier superstructure on the ballast generated an increased rate of ballast and subgrade deterioration, requiring higher maintenance expenditures (Kerr 2003).

Improvements in the fastening system design were required to solve this problem. Spring elements were incorporated in fastening systems in order to reduce the large vertical uplift forces between the rail and the concrete crosstie. Also, it was of paramount importance that the improved fastening systems were able to apply a large longitudinal and rotational resistance to eliminate longitudinal displacement and rail rotation in the track, especially after the development of CWR. These design parameters were achieved by choosing appropriate spring elements that were able to exert higher clamping forces on the rail base. The development of electrical signaling systems also demanded that the improved fastening systems provide electrical insulation between the rails and the concrete crossties, which imposed new design characteristics to prevent circuit shunting in the track (Kerr 2003).

Throughout the world, many concrete crosstie fastening system designs were developed and tested. Some were more successful in achieving the aforementioned design criteria than others, but the pursuit of an optimum design continues to date (Kerr 2003).

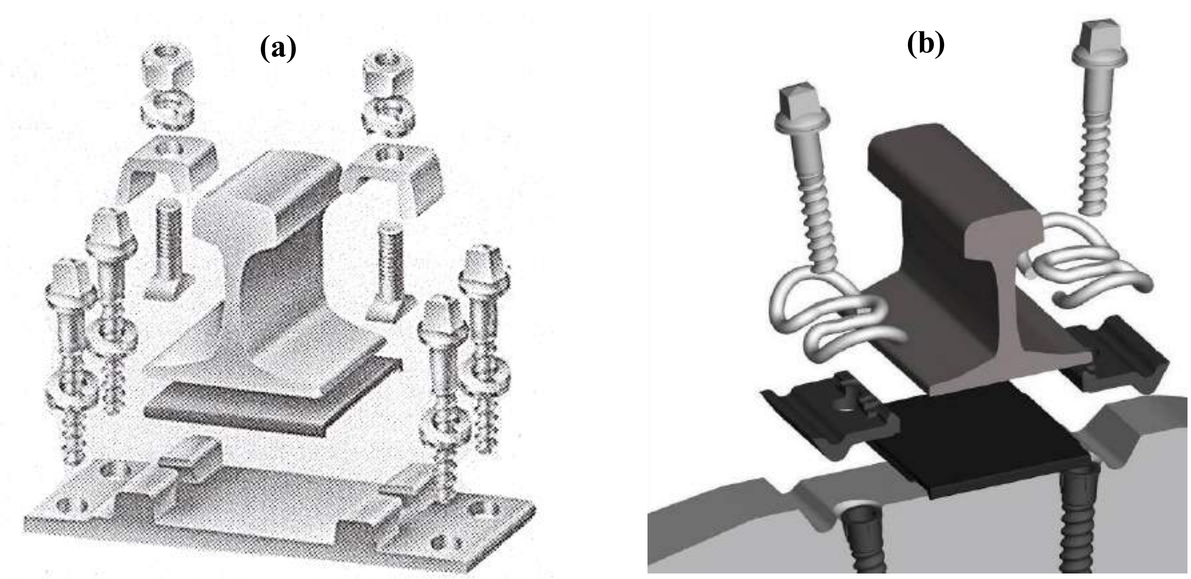

Figure 1.1 (a) Previous K-Fastener and (b) improved fastening system for concrete crossties (Adapted from Kerr 2003)

1.4. Types and Characteristics of Concrete Crossties Fastening Systems

The development and spread of CWR, combined with the increasing use of concrete crossties, required additional elasticity in the track components to overcome and protect the system against higher contact pressures caused by the increase in the superstructure movement restraints. Therefore, elastic fastening systems were introduced to allow higher deformations of components and also to provide absorption of impact forces, which are higher on concrete crosstie tracks. The design of the elastic fastening system requires the spring displacement to be large, meaning that the clamping force involves considerable elastic spring displacement. The low stiffness and higher spring displacement in elastic fasteners make the clips less susceptible to fatigue and premature deterioration during the wheel passage and these characteristics also reduce the possibility of looseness, factors that significantly contribute to decrease the amount of wear in the fastening system components (Esveld 2001). All types of elastic fasteners have some form of spring element that is built into the system according to the particular design trademarks of each manufacturer. Depending on how the spring is incorporated to the concrete crosstie and fastening system, it may be categorized in one of the following two groups: screw systems and clip systems (Fastenrath 1977, CEB FIP 1987, Esveld 2001, Kerr 2003).

1.4.1. Screw systems

Screw systems are characterized by the use of bolts and nuts pressing a clip or plate against the rail base in order to provide adequate clamping force (Figure 1.2). The advantages of this kind of elastic fastening system are the possibility of adjusting the height of the rail (in some models), and the capability of directly modify the clamping force. On the other hand, screw systems are very operator-sensitive, which means that they are susceptible to variations in clamping force depending on how the system is assembled. Moreover, they require more periodic maintenance than clip systems and demand a certain level of skill to ensure the right adjustment of the clamping force (Kerr 2003).

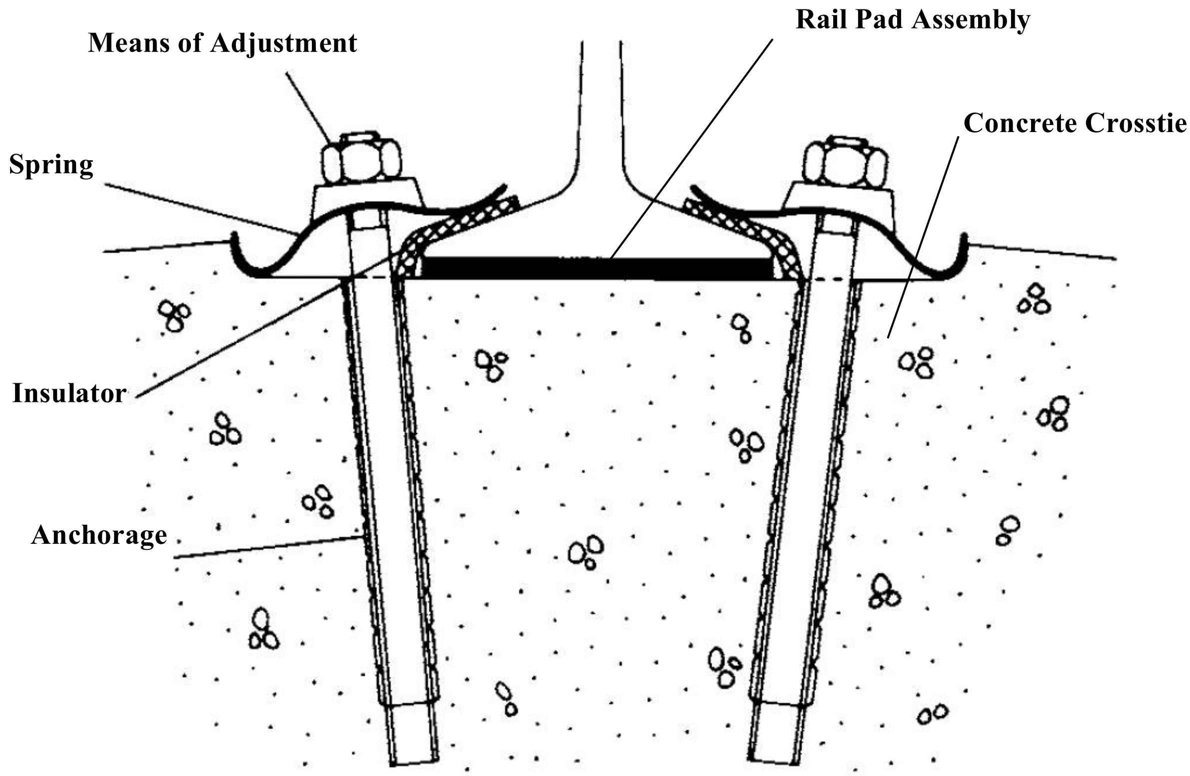

Figure 1.2 Usual components of a generic screw system (Adapted from CEB FIP 1987)

Among the most common models of screw-type elastic fastening systems are the W-Fasteners and the Nabla Systems (CEB FIP 1987) (Figure 1.3). Despite differences in design, they are based on a similar concept characterized by the use of bolts and nuts to secure the rail. The most significant difference, in this case, is the component used to clamp the rail to the crosstie. The W-Fasteners use W-shaped clips whereas the Nabla Systems rely on a steel plate attached to a plastic insulator to transfer the desired clamping force.

W-Fastener

Nabla System

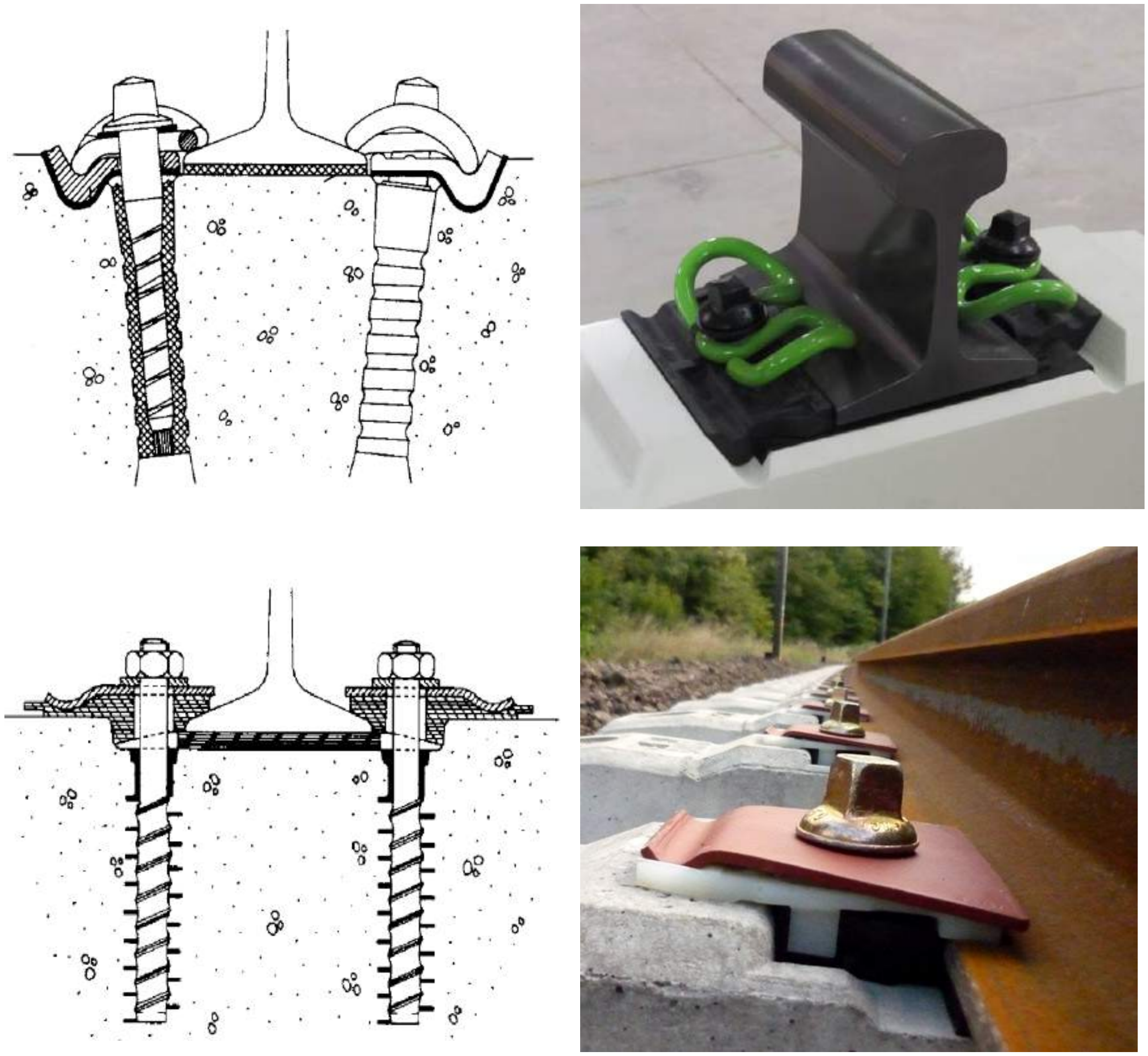

Figure 1.3 Elastic fastenings - Screw systems
(Adapted from CEB FIP 1987)

1.4.2. Clip systems

The primary design advantage of a clip system is the capability to be self-stressed. They provide elasticity using sprung clips or fastening elements such that when forced into the final position, the clips exert a prescribed clamping force on the rail base that is adequate to generate the desired longitudinal resistance (Kerr 2003).

The advantages of the clip systems rely on the ease of installation and reliability regarding the provision of correct clamping force. These systems are robust and less sensitive to operator errors as their correct installations is readily checked by visual inspection (CEB FIP 1987). The main shortcoming of this type fasteners is the lack of an adjusting mechanism to correct drops of clamping force variations due to wear in contact areas, yielding of components, or metal fatigue. Therefore, if there is a reduction in the desired clamping force, the entire clip needs to be replaced.

There are extensive varieties of clip systems that have already been adopted. Among the most common systems of this type are: the e-clip, the Safelok I and III, the Fastclip, the Linelock, the Fist BTR, and the Sidewinder. The first three models are the most common used in the United States and Canada (Kerr 2001). Each design has its own particular characteristics, they all incorporate sprung clips anchored to a cast in steel shoulder to apply the desired clamping force to the rail base (Figures 1.4 and 1.5).

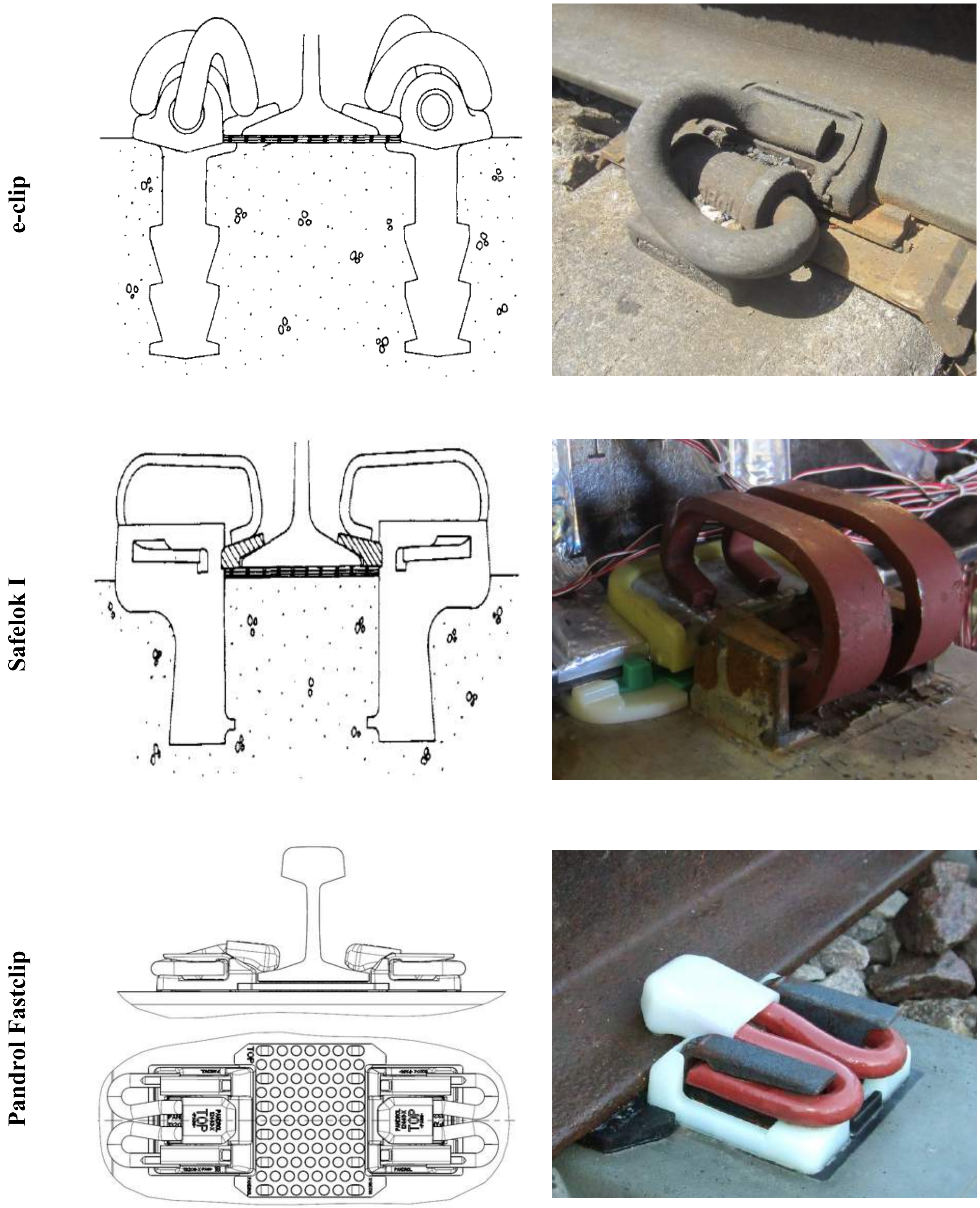

Figure 1.4 Most common clip-type fastening systems found in North America (Adapted from CEB FIP 1987 and Kerr 2003)

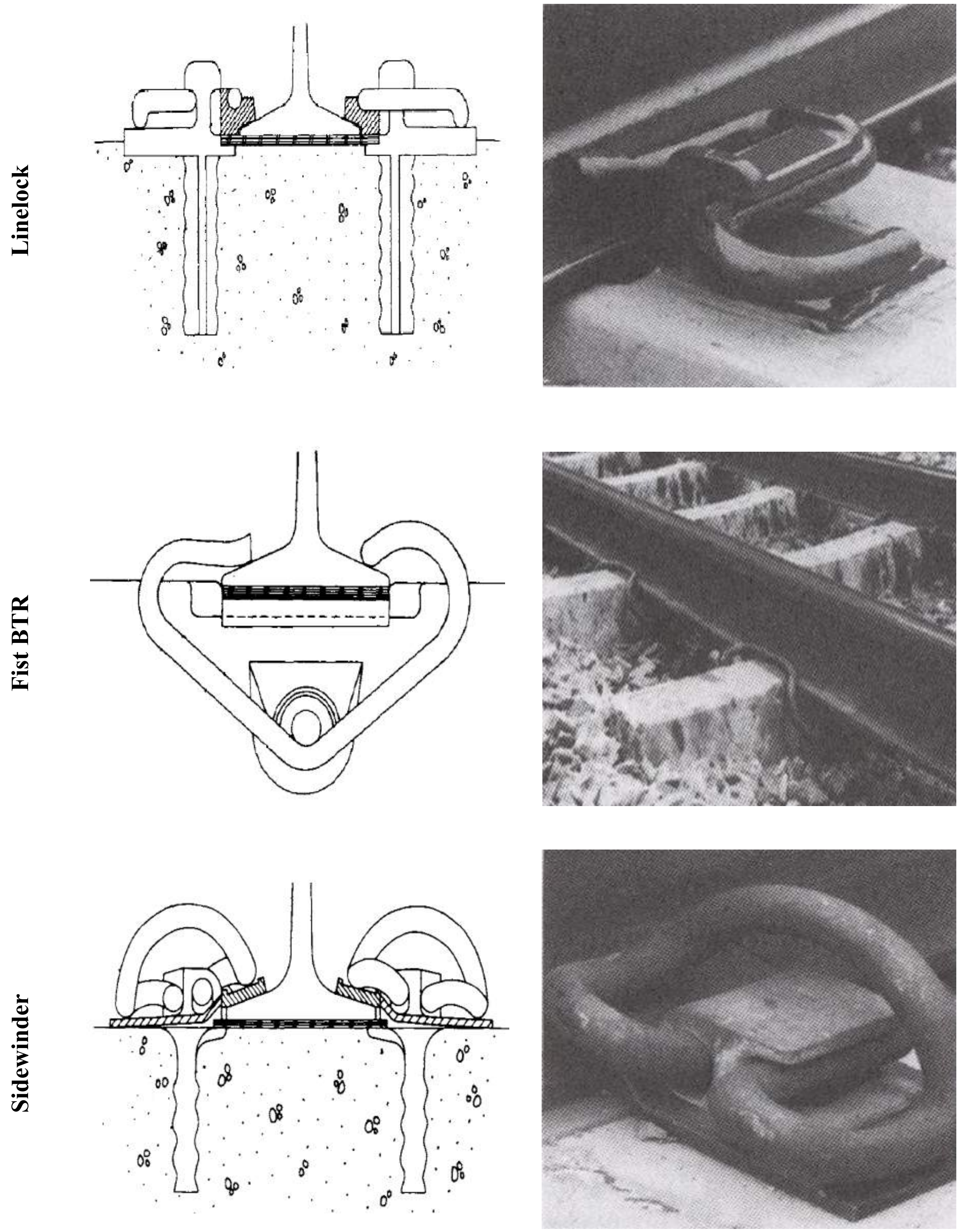

Figure 1.5 Clip-type elastic fastening systems (Adapted from CEB FIP 1987 and Kerr 2003)

1.5. Main Components of a Typical Elastic Fastening System Used in North America

Throughout the world there is an extensive number of elastic fastening systems that have been implemented on track. Each one has special characteristics and mechanical properties, but there are similarities regarding the main components and functionalities that are common to most designs. Section 1.3 introduced and described the two different categories of concrete crosstie elastic fastenings, the screw systems and the clip systems. As was discussed, the main feature that differentiates one from the other is the mechanism that holds down the rail. Although there is a high variability in materials, geometry, and manufacturers, all elastic fastening systems present common components used to adequately generate the desired clamping force and to provide electrical isolation for the rail. Figure 1.6 shows a typical Safelok I fastening system commonly used in North America and the characteristics of each component is specified in the next sections.

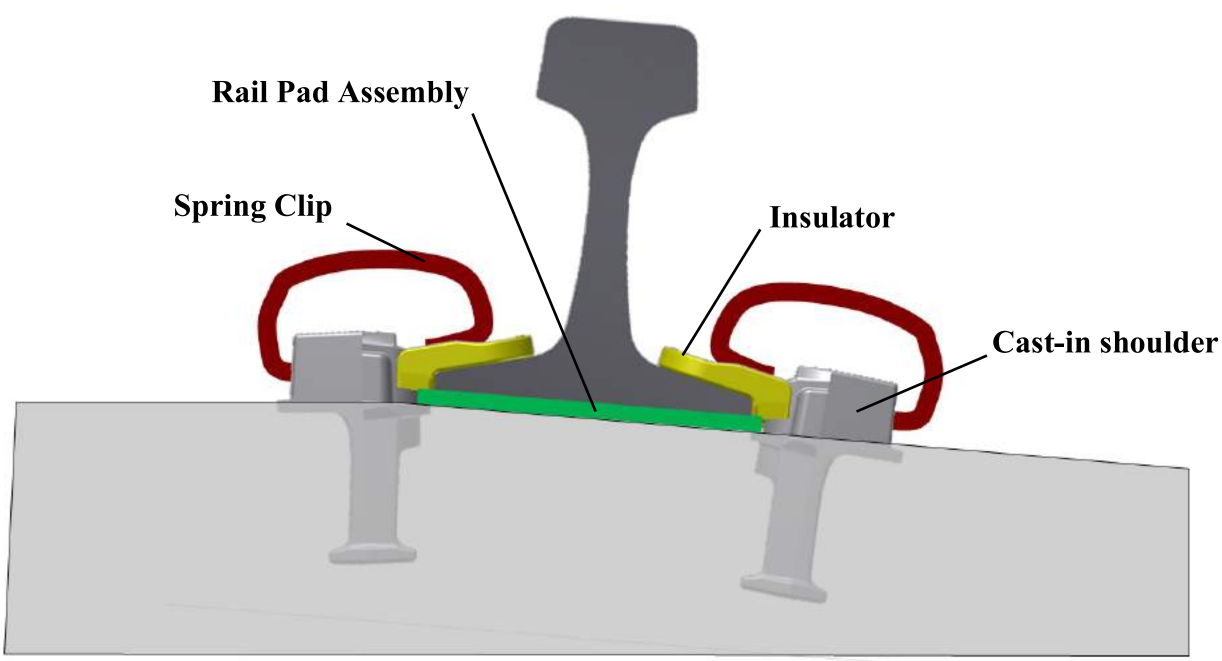

Figure 1.6 Typical fastening system used in North America

1.5.1. Cast-in shoulder

The cast-in shoulder is the connection between the spring element and the concrete crosstie. It joins two components of completely different stiffness and must be able to transfer lateral and torsional loads to the crosstie without breaking the concrete or becoming loose. Usually cast-in shoulders for clip systems, like the ones presented in Figures 1.4 and 1.5, are made out of cast iron or forged steel. Screw systems have a different design for the inserts anchorage, also known as dowels, which is often composed of either nylon or polypropylene plastic. Further details on screw systems anchorage can be found in Figures 1.1, 1.2, and 1.3.

Cast-in shoulders must have good adherence with concrete and high pull-out force resistance. These characteristics are needed to avoid loosening of the component stem and the reduction of stability. They should also present high lateral and torsional resistance to withstand the demands exerted by train passages, providing the adequate load distribution to maintain track gauge and the original geometric characteristics of the superstructure. Multiple designs of cast-in shoulders incorporate fins on the head of the component to provide torsional and side forces resistance, and also rag stems for a better grip inside the concrete crosstie.

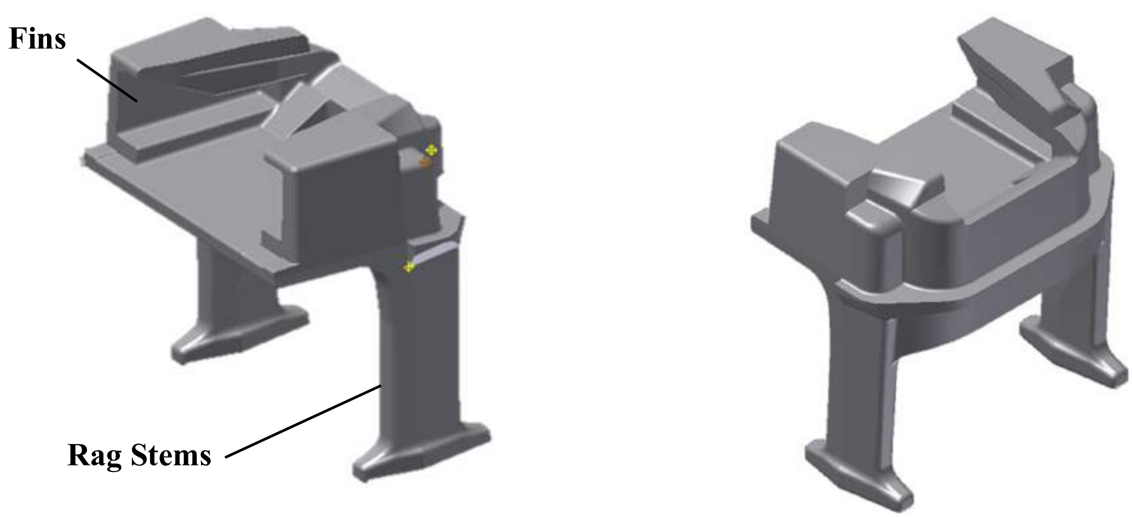

Figure 1.7 Model of a cast-in shoulder for a concrete crosstie clip fastening system

1.5.2. Insulator

The insulator is one of the key components within the fastening system responsible for providing adequate electrical isolation between the rail and the concrete crosstie. It is an extremely important element where track circuiting is used for signaling (CEB FIP 1987). Not only are insulators designed to electrically isolate the rail, but they should also act as a means of load attenuation for the forces entering the cast-in shoulder, protecting this component from early deterioration. Insulators transmit the clamping force from the clip to the rail, playing an important role on the lateral load path and also on the track gauge restraint (Williams 2013).

Given the harsh loading environment the insulator is usually subjected to, this component must be developed using materials capable of withstanding high compressive forces, high shear forces, abrasion, moisture, ultraviolet light, and chemical attack. One of the most common materials used to produce insulators is Nylon 6/6, a polyamide from the nylon class known for its high mechanical strength, good abrasion resistance, great rigidity, and stability under heat. The AREMA manual, on section 1.7.3.2 in Chapter 30, specifies a set of ASTM tests that should be performed on every plastic material intended for insulator manufacture. Figure 1.8 shows one of the most common designs of insulators currently in use.

In North America, there are over 25 million concrete crossties in service, and the great majority has insulators incorporated into their fastening system. Therefore, overcoming the failures on this component is considered to be one of the top component design and performance challenges in the railroad industry. Insulator failure effects impact track geometry since they usually result in defects on the original geometric characteristics of the track. When an insulator failure occurs, problems such as gauge widening become more prevalent. These defects can facilitate excessive rail movement and increase the wear rate on the fastening system, which will further expedite failure mechanisms on other track components (Williams 2013).

Researchers from UIUC have conducted research to quantify the lateral loads in the concrete crosstie fastening system. A new technology called the Lateral Load Evaluation Device (LLED) was developed to measure the forces at the insulator-shoulder interface. The outcomes of this study will increase knowledge related to the demands placed on insulators, allowing a mechanistic design approach on the development of this component.

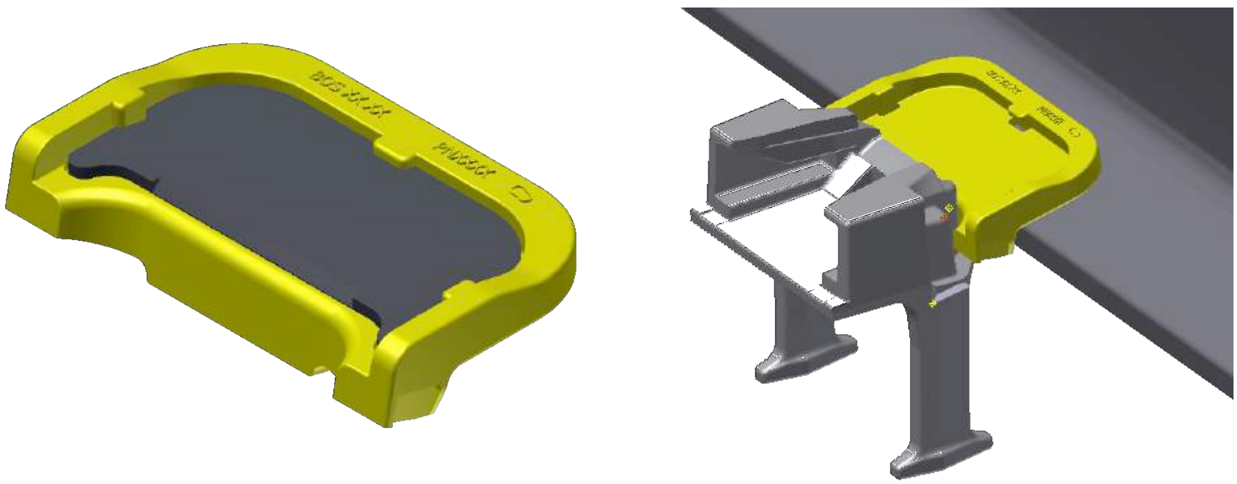

Figure 1.8 Model of an insulator commonly used in North America

1.5.3. Spring clip

The clip is the component within the fastening system responsible for applying the forces to the rail base required to maintain proper track geometry (Figure 1.9). These forces, also referred to as “clamping forces”, are generated by the clip deflection or the screw torque, depending on the type of fastening system used.

The AREMA manual specifies that spring clips shall provide adequate lateral strength to maintain track gauge, shall constrain the rail against rail rollover, and shall also control longitudinal rail movement due to thermal and tractive forces, minimizing rail gap in the event of a rail break. Moreover, the manual indicates that, when necessary, spring clips shall be covered with a coating to protect against corrosion and stress corrosion cracking. The last, and perhaps one of the most important specifications, is that spring clips should have the capability to prevent fatigue failures within the expected dynamic deflection range (AREMA 2012). A set of mechanical tests to evaluate the fastening system performance is proposed in Section 2.6 of Chapter 30 of the AREMA manual. Even though these tests are designed to output a reference criteria for the overall behavior of the fastening system, they are all highly dependent on the performance of the spring clips, since the capability of restraining rotation, lateral movements, longitudinal movements, and uplift displacements, is dictated by the effectiveness of this component.

Depending on the fastening system and customer requirements, the clamping force provided by the spring clips varies. Most systems are able to apply forces between 1.7 kips (7.5 KN) and 3.5 kips (15.5 KN) with clip deflections in the range of 0.04in (10mm) and 0.06in (15mm) (CEB FIP 1987, Gutierrez 2010). Another important characteristic regarding spring clips is the capability of withstanding a large load capacity beyond its working range to guarantee a good fatigue life. The rail clamping force requirements come from the rail size, vehicle weight, train speed, radii of track curves, and temperature of operation (CEB FIP 1987). Researchers at UIUC have conducted laboratory and field experimentation on spring clips to better understand the distribution of forces within this component and the behavior of clamping force changes according to the variation of other track parameters, such as rail vertical deflection (Wei 2013).

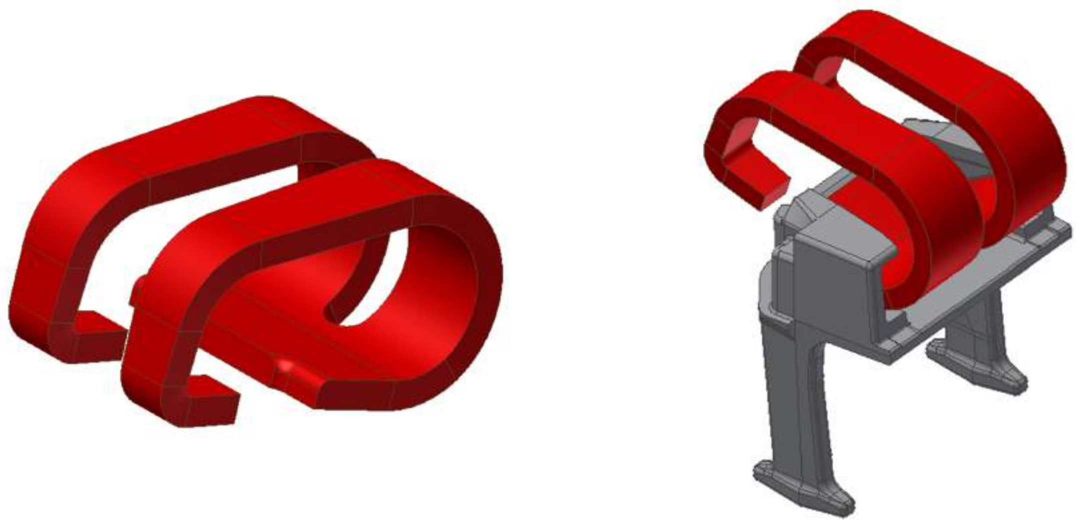

Figure 1.9 Model of spring clips used in the Safelok I System

1.5.4. Rail pad assembly

The interface between the rail and the crosstie rail seat is a key area for the distribution of forces originated from the wheel loads. In this region, components with different material properties and mechanical behaviors interact to transfer the loads throughout the track superstructure. Therefore, problems related to the deterioration of components may arise if this interface is not well protected and the loads are not adequately distributed. Timber crosstie track used steel plates, also known as tie plates, between the rail base and the crosstie rail seat for mechanical wear protection and to provide the crosstie resistance against the sawing action from longitudinal rail movements under traffic. Additionally, the steel tie plates distribute rail loads over a greater area, decreasing unit pressure and reducing crushing action on wood fibers. Tie plates on timber crossties also help to equalize spike-holding forces, contributing to the stability of the track system, and reducing the tendency of plate cutting and gage widening on the track (Hay 1982).

Concrete crossties are much stiffer structures compared to timber crossties. Therefore, in modern concrete crosstie designs, steel plates were substituted for lower elastic modulus rail pad assemblies. The assembly, usually composed of a rail pad and an abrasion frame, provide a protective layer between the concrete crosstie and rail base by reducing the dynamic loads imposed on the rail seat and distributing the forces to acceptable stress levels. In other words, rail pad assemblies evenly transfer the loads to the crosstie while filtering out higher frequency loads (Esveld 2001). Additionally, the rail pad assembly interacts with other fastening system components in order to restrain the rail movement, maintain desirable track geometry, and electrically isolating the track.

The rail pad assembly is an important component to the track structure because of its versatility as an engineered product that can be designed with multiple layers, a variety of materials, and optimized geometry. Each configuration is capable of providing different elastic characteristics to the fastening system, dictating the load distribution behavior and also the overall mechanical performance of the track structure. Modern rail pad assemblies vary considerably in appearance and material properties, depending on which type of fastening system is used and the load environment they are subjected to. Figure 1.10 shows multiple designs of rail pad assemblies commonly used in North America.

Figure 1.10 Designs of rail pad assemblies: (a) Vossloh; (b) Amsted RPS; (c) Pandrol Three-Part Assembly; (d) Pandrol Anti-Abrasion; (f) Pandrol EVA

Railway design codes and recommended practices throughout the world typically contain a section dedicated to specifications and design qualification testing for the rail pad assembly. Despite some threshold choices for performance and other testing similarities, none of them provide a mechanistic design approach to evaluate the behavior of this component. It is important to emphasize that a mechanistic design approach is the one derived from analytical and scientific principles, based on the understanding of forces and displacements on the system and considering field loading conditions to obtain performance requirements (Van Dyk 2013).

The railroad manuals, AREMA, the Australian Standards, and the European Standards, lack information regarding certain threshold choices that are key parameters in understanding the performance of the rail pad assembly, such as allowable displacements, energy dissipation, and rate of deterioration. In other cases, no criteria are specified for qualification testing, and the specifications only provide a description of the experiment to be conducted. Therefore, with the intent to overview and evaluate the current standard practices regarding the performance analysis of rail pad assemblies, the next sections summarize the requirements and testing protocols adopted by the aforementioned codes.

1.6. AREMA Standards for Rail Pad Assemblies

AREMA specifies in section 1.7.3.4 of Chapter 30, requirements related to the performance of rail pad assemblies. The most important considerations are listed in the following bullet points:

i. Rail pad assemblies should be used between the rail and the concrete crosstie to reduce impact and vibration effects on the track structure and also to minimize rail seat deterioration (RSD).

ii. For curves over three degrees, special consideration must be given to the pad selection. Multi-layered pads containing an abrasion frame and also a shape-factored thermoplastic have proven to be effective on those areas.

iii. The rail pad assembly must have minimum width equal to the base width of the rail plus 1/8 in (3mm). The thickness of the pad shall not be less than 1/5 in (5mm).

iv. Rail pad assemblies should provide protection against abrasive wear and wheel impact loads.

v. All rail pad assemblies should be marked in a permanent manner to indicate manufacturer and identification.

1.6.1. Material properties

AREMA recommends a set of ASTM tests that should be performed for the evaluation of suitable materials to be used in the manufacture of rail pad assemblies. However, it is important to note that not all of the tests are suitable for plastics, as some of them were designed specifically for rubber materials. Additionally, the tests are only recommendations, and not standards that materials should comply with before being considered applicable to be used in the manufacture of fastening system components. Further details on the specified material tests can be found on section 1.7.3.4 of Chapter 30, and they primarily cover the following properties: hardness, compression, tensile strength, ozone resistance, abrasion resistance, volume resistivity, resistance to fluids, and Vicat softening temperature.

1.6.2. AREMA evaluative tests for the rail pad assembly

Part 2 of AREMA Chapter 30 (AREMA 2012) is dedicated to qualification tests for the crosstie and fastening system. In this section, two tests are listed that are designed to evaluate performance parameters related to the rail pad assembly, the Tie Pad Test (Section 2.5.1 Test 4A) and the Rail Pad Attenuation Test (Section 2.5.2 Test 4B).

The tie pad test measures the load-deflection properties of the rail pad assembly. The experimentation consists of applying dynamic and static loads to a fastening system setup, while measuring the rail pad deflection. The test criterion is specified in section 4.9.1.15 of Chapter 30 and it requires the pad assembly to return to within 0.002 in (0.051 mm) of its original position after the load is removed. Additionally, the spring rate calculated from three different specimens should not vary more than 25%. No explanation is given regarding the choice of these thresholds or their possible effects on the track components if they are not met. Even though this test is able to provide a simple evaluation of the rail pad assembly stiffness and resilience, it fails in supporting a deeper understanding about the load distribution and behavior of the component under realistic loading scenarios, where lateral loads and shear forces are present.

The rail pad attenuation test was designed to determine the ability of the rail pad assembly to attenuate the effects of impact loads on crossties. On this test, strain gages are attached near to the bottom of the crosstie in order to measure the strain resultant from a 115 lbs weight dropped from a height of 12 inches, simulating an impact load on the head of the rail. The result is given in comparison to a measured control strain when a 5mm EVA flat pad is used on the fastening system. There are no criteria for the results obtained from this specific test.

The AREMA manual lacks explanations about the mechanistic behavior of rail pad assemblies. Even though the tests provide an initial evaluation of the stiffness, resilience, and damping capabilities of this component, they do not address important factors that contribute to the rail pad assembly performance. Previous studies have already pointed out that supporting conditions of the tie, effects of lateral and longitudinal loads, and the variation of the coefficient of friction between components are also parameters that highly contribute to the system behavior, controlling the transfer and distribution of loads (Giannakos 2007, Carrascal 2006, Rapp 2012, Kernes 2013, Van Dyk 2013). Addressing all the aforementioned issues and variability present on the system is of paramount importance when developing design recommendations for a component that will be subjected to severe loading environments during its service life.

1.7. Australian Standards (AS) for Rail Pad Assemblies

The Australian Standards (AS) specify in section 5 of part 1085:19 (AS 2003) the requirements for rail pad assemblies used in resilient fastening systems. It provides design recommendations regarding the expected functions, desired performance, and suitable materials to be used on the manufacturing process. The AS brings all these considerations in a concise manner, shifting most of the component behavior criteria under the responsibility of the manufacturer and the client. The most important specifications are as follows:

i. Rail pad assemblies should be used between the rail and the support structure to: provide load distribution from the rail to the crosstie; protection for components from abrasion and damage resulted from high localized loadings or differential movements; electrical isolation; and dynamic load attenuation.

ii. The rail pad assembly shall perform adequately under the assembly tests given in section 2 of the manual, which specify performance criteria for the entire fastening system behavior.

iii. The AS provides tests (Appendix J and Appendix G) with thresholds to characterize the types of rail pad assemblies according to the stiffness and impact attenuation capabilities of this component. However, it does not specify loading environments or situations where each type of rail pad assembly should be used.

iv. The materials used to manufacture rail pad assemblies should be resistant to natural levels of ultraviolet radiation and ozone. The manual also mentions that high-density polyethylene and elastomeric materials are often used for this purpose, giving a few tests parameters (section 5.4.2 part 1085:19, section 5.4.3 part 1085:19) these materials should comply with.

1.7.1. Australian Standards (AS) evaluative tests for the rail pad assembly

The AS contain two tests related to the determination of rail pad assemblies performance. The first is in Appendix G, called the Resilient Fastening Assembly Repeated Load Test, which consists of procedures for applying repeated load cycles representative of the displacements caused by traffic on a fastening system assembly. One of the outputs for this test is the rail pad vertical stiffness, measured indirectly by the relationship between the maximum load applied to the rail head and the maximum rail displacement, taking into considerations that the crosstie is in a fixed position in the test set up. Unlike the AREMA manual, the AS do not specify a load-deflection test specific for rail pad assemblies. The performance of this component is determined according to the results obtained from the fastening system tests, which are focused on the qualification of the entire system behavior. Therefore, the AS bring a different perspective on how fastening system components should be evaluated, focusing on the overall performance of the system rather than defining threshold parameters for each component.

The second test, described in Appendix J of the AS, is called the Impact Test for Rail Pad Attenuation. It specifies procedures for applying impact loads on the rail, simulating peak loads, and for characterizing the damping properties of rail pad assemblies. The procedures are very similar to the ones specified in the AREMA manual, where a mass is dropped onto the head of the rail fastened to a concrete crosstie using the rail pad assembly being tested. The results are also given in comparison to a reference 5 mm thick High-Density Polyethylene (HPDE) or Ethylene-Vinyl Acetate (EVA) rail pad.

1.8. European Standards (EN) for Rail Pad Assemblies

The European Standards (EN) number 13481-2:2002 (EN 2002) contain the fastening system requirements for concrete crossties. They provide design recommendations regarding the longitudinal rail restraint, the torsional resistance, the attenuation of impact loads, electrical isolation, exposure to severe environmental conditions, clamping force and the dimensions of the components. The rail pad assemblies are classified by the capability of load attenuation (EN 13146-3) and the dynamic stiffness (Annex B). The test procedures to determine these properties are very similar to what is described by AREMA and by the AS, with minimal differences related to support conditions and pre-loads.

One of the particular characteristic of the European Standards regarding the rail pad assembly is the specification of rail pads with different stiffness when running repeated loading tests. The EN determine certain lateral to vertical (L/V) force ratio and angles of load application where soft, medium, and hard rail pad assemblies shall be used when performing these repeated loading tests.

1.8.1. European Standards (EN) evaluative tests for the rail pad assembly

The EN evaluative tests are based on the fastening system performance to assess the behavior of rail pad assemblies. The only exception is the determination of the rail pad dynamic stiffness, presented in Annex B of EN 13481-2:2002.

The dynamic stiffness test is intended to provide data for the determination of rail pads mechanical behavior when subjected to cyclic loading. A repeated load is applied normally to the rail pad through an actuator at a constant frequency. The resulting maximum and minimum displacements of the pad’s surface are measured and related to strains, which are then translated into a dynamic stiffness. The rail pads are classified in soft, medium, or hard according to the results given in this test (Section 5.4 EN 13481-2:2002). Extracting a specific mechanical property of components with different geometries and materials allows the determination of the appropriate loading scenario and application for each product, which will later guarantee it meets the performance requirements and expected life cycle.

The determination of impact loads attenuation is described in Part 3 of EN 13146-3. This test is used to compare the attenuation of impact loads on concrete crossties by different rail pad assemblies, similar to what is described in AREMA and AS. It specifies procedures for applying impact loads on the rail, simulating peak loads, and for characterizing the damping properties of rail pad assemblies. One of the main differences is that it gives the possibility of testing the specimens using ballast as the support conditions or using a rubber mat on the top of a flat surface. The results are also given in comparison to a reference 5 mm thick High-Density Polyethylene (HPDE) or Ethylene-Vinyl Acetate (EVA) rail pad.

Table 1.1 contains the major differences in the standards analyzed in this Chapter, summarizing the specifications regarding the requirements and the test procedures.

Table 1.1 Specifications and evaluative tests for rail pad assemblies

		AREMA	EU	AS
Specifications/Requirements	Material	Meterials should comply with ASTM D2240, D395, D1229, D412, D573, D518, D2228, D257, D471, and D1525	Non metallic material	Polyethilene (60 - 70 Type D), Elastomeric Materials. Materials should comply with ASTM D2240 and AS 1683.23 and AS 1683.24
	Dimensions	Minimum width equal to the rail base width +1/8in (3mm)	Within the limits stipulated by the envelope shown in Figure 2 of EN 13481-2:2002	Not specified
	Attenutation	Not characterized	>15% and <30% - Medium >30% - High	<15% - Low >15% and <39% - Medium >39% - High
	Stiffness	Not characterized	k<100 MN/m - Soft 100 MN/m<k<200 MN/m - Medium >200 Mn/m - Hard	k<100 MN/m - Soft 100 MN/m<k<200 MN/m - Medium >200 Mn/m - Hard
Stiffness Test	Section	Chapter 30 - Section 2.5.1	EN 13481-2:2002 - Annex B	No specific Stiffness Test - See Appendix G
	Purpose	Determine load-deflection properties	Describe a procedure to determine the dynamic stiffness of rail pads	---
	Requirements	Pad temperature = -45°F, 70°F, and 140°F (± 5°F)	Area of the test maintened at 23°± 5°C)	---
	Installation	- Rail pad can be tested in a fastening system or as plan pad - Rail pad should be loaded vertically using a rail section	- Place rail pad on a flat, horizontal surface - Use an abrasive cloth, and steel plate to assemble the test set up	---
	Load Frequency	- Static load at a rate of 3-6 kips/min (max 50 kips) - Cyclic load from 4-30 kips at a rate of 4-6 cycles/s for 1000 cycles	- Cyclic load of 20 KN to 95 KN at 4Hz for 1000 cycles	---
	Criteria	- Rail pad should return to within 0.002 in (0.051mm) of original posistion after 10s - Spring rate variation < 25%	No criteria, just thresholds. See Specifications/Requirements	--- ---
Impact Attenuation Test	Section	Chapter 30 - Section 2.5.2	EN 13146-3:2002	AS1085.19 - Appendix J
	Purpose	Determine the ability of a rail pad to attenuate impact loads on the crosstie	Compare strains induced by a dropping mass onto a rail head with a reference rail pad assembly	Simulate impact loading caused by traffic and measure the strains induced on the bottom of the crosstie
	Requirements	- 12 inches, 136 RE rail section - 115lbs (52 Kg) dropped 12 inches	- 30cm (12in) to 100cm (40in) rail - Drop height based on 80% of crosstie cracking strain within 5 ms	- 30cm (12in) to 100cm (40in) rail - Drop height based on 80% of crosstie cracking strain
	Installation	- 4 inches strain gages installed to each side of the rail seat 0.75 in from the bottom of the tie - 3 kips pre load on the rail pad	- 2 100mm to 120mm strain gauges installed on the side of the crosstie in the center line of the rail seat - Aggregate should support the crosstie (nominal size of 5 to 15mm) - 50 KN pre load	- 2 100mm to 120mm strain gauges installed on the side of the crosstie in the center line of the rail seat - Aggregate should support the crosstie
	Reference	5mm Amtrak EVA flat rail pad Dupont Elvax 660 7500 kip/in	5mm HPDE or EVA rail pad 500 MN/m stiffness	5mm HPDE or EVA rail pad 500 MN/m stiffness
	Criteria	No criteria determined	No criteria, just thresholds. See Specifications/Requirements	No criteria, just thresholds. See Specifications/Requirements

1.9. Rail Pad Assembly Mechanics and Development of Track Analysis Tool (I-TRACK)

Uncertainties related to the causes of deterioration on the fastening system, associated with the lack of a deep understanding regarding the mechanical interaction among components, led the railroad industry to pursue design modifications to enhance the performance of the fastening system and extend the life cycle of components. Most of the design techniques applied were purely empirical, where improvements were solely based on the increase of robustness required to overcome the observed loading demands. In some cases this method may have proven to be effective, but in a world with increasing heavy-haul freight operations and larger competition for revenue, the design advancements need to be more efficient, focused on the mechanical behavior of each component to maximize its performance and reduce the capital and maintenance costs.

Given that the rail pad assembly is in contact with the concrete crosstie and most of the components within the fastening system, undesired changes on its behavior will ultimately affect the performance of other components. Understanding the mechanics is critical to improving the performance and life cycle of the entire infrastructure, which will ultimately reduce the occurrence of failure modes on each track component.

Prior research conducted at UIUC succeeded in determining that relative displacement between the rail seat and the rail pad assembly results in an abrasion process that is capable of deteriorating both the concrete and the material that composes the rail pad (Kernes 2012). Therefore, this research will be focused on understanding the displacements that the rail pad assemblies undergo when acting together with the fastening system to support wheel loads. The intent is to gain knowledge about how the rail pad assembly responds to the loads and how this response relates to the failure modes observed on the field. Additionally, this study will determine the magnitude and significance of the rail pad assembly displacements and its relationship with track stiffness and load paths.

This study is one step in developing mechanistic design practices focused on the performance of components. However, this is a complex and intricate process that demands a broad understanding of the track behavior, where material properties, loading environments, support conditions, and components interactions play different roles in the responses of the system. Researchers at UIUC have developed a detailed finite element (FE) model of a track section to improve the knowledge regarding the mechanical behavior of fastening system components, potentially leading to the recommendation of new design guidelines (Chen et al. 2012). This is a powerful tool capable of accurately representing the system behavior, but is limited by the computer effort needed to analyze each loading case and is also limited by the FE experience required by the user when developing the model. Therefore, a framework for a simplified tool, named I-TRACK, based on statistical analyses of the FE model is suggested in this thesis. The intent is to extract the model behavior and reproduce it in a tool that is efficient in assisting in the mechanistic design of concrete crossties and fastening systems. The ultimate goal is to turn the model results into output that is accessible to the general user, improving the current state-of-art of the design process of track infrastructure components. The simplified tool will be able to recreate the mechanical behavior of the rail pad assembly under a variety of load environments and different combinations of material properties, assisting the understanding of the effects of this component on the track mechanics.

CHAPTER 2: FAILURE MODE AND EFFECT ANALYSIS (FMEA) OF CONCRETE CROSSTIE RAIL PAD ASSEMBLIES

In North America, the geometry and materials used in the design and manufacture of concrete crosstie rail pad assemblies have changed significantly over the past thirty years. Single-layer components made out of synthetic rubber were superseded by higher-density polymers and eventually replaced by multi-layer components made from multiple materials. Today, the most common rail pad assemblies are comprised of polyurethane rail pads on top of nylon 6/6 abrasion frames. The design intent of layered pad assemblies is to provide both abrasion resistance and impact attenuation and to combine materials with distinct qualities and mechanical behavior to obtain improved rail pad assembly performance. These material and design characteristics have the capability to affect the vertical and lateral load path in the fastening system, as observed in previous laboratory testing at UIUC (Rapp 2013).

Even though the rail pad assembly design has improved over the past thirty years, these components can fail prior to the end of their intended life due to a variety of failure mechanisms. After a field investigation and discussion with railway industry infrastructure maintenance experts, patterns related to common failure modes were identified and analyzed to serve as base for a Failure Mode and Effect Analysis (FMEA).

2.1. Failure Mode and Effect Analysis (FMEA)

A failure mode and effect analysis is a technique developed in the mid-1960's by reliability engineers in the aerospace industry to increase the safety of products in the development or manufacturing processes. Later, the automotive industry recognized the advantage of using this tool to reduce risks related to poor quality (McDermott 2009). The FMEA is used to define, identify, evaluate, and eliminate failures before they occur. The FMEA represents a proactive process, and involves the systematic analysis of failure modes with the objective of detecting potential causes and investigating their effects on the system. From this analysis it is possible to identify actions that must be taken to reduce the probability of failure (Stamatis 1995). Additionally, the FMEA provides historical documentation for future reference to aid in the analysis of field failures and consideration of design, manufacturing, installation, and maintenance.

The general FMEA procedure (Figure 2.1) begins by determining the desired functions of the product, serving as guiding parameters for the study. Then, the different manners in which failures manifest themselves in the product (i.e. failure modes) are identified. Next, the potential consequences, usually referred to as "failure effects", are analyzed. After these steps, the causes are identified and investigated, allowing the development of preventive measures to reduce the risk of failure occurrence. This chapter will focus on the detection, causes, and effects of failure mechanisms in rail pad assemblies, since the development of preventive measures demands - in this case - a deeper understanding of the component mechanics.

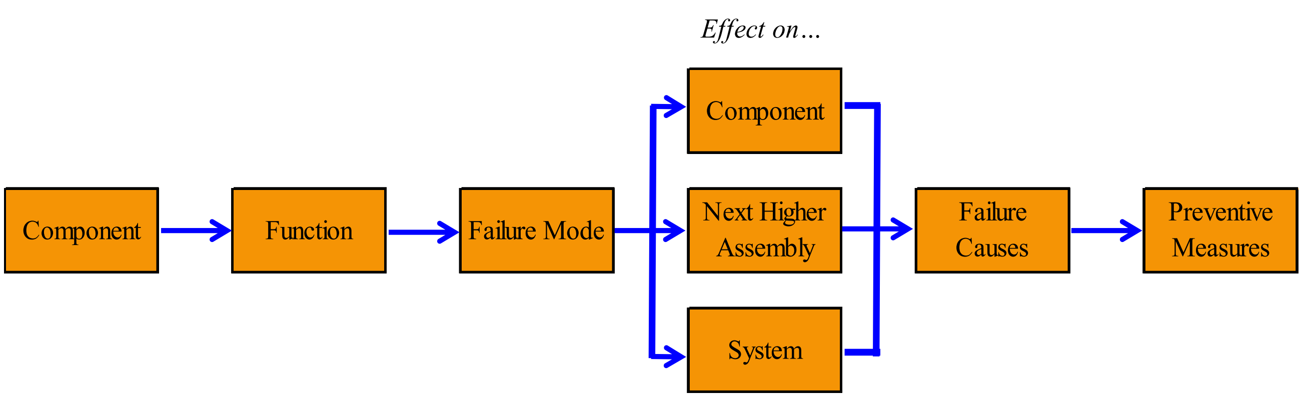

Figure 2.1 FMEA diagram characterizing the steps related to the analysis process

After combining the input from laboratory and field investigations, railroad infrastructure experts, fastening system manufactures, and railway industry technical committees, a simplified FMEA for the rail pad assembly was developed. The FMEA guided the process of answering questions related to component behavior and helped in proposing design and material properties recommendations to enhance the safety and durability of rail pad assemblies, which is the overall goal of this research.

2.2. Rail Pad Assembly Functions

The rail pad assembly is the core of the fastening system, and directly affects the transfer of vertical wheel loads through the track superstructure. It constitutes an interface for force distribution between the rail and the crosstie rail seat. Therefore, one of its main functions is to provide impact attenuation and protection for the rail seat bearing area. Furthermore, the rail pad assembly is designed to insulate the crosstie from track circuits, preventing the occurrence of circuit shunting. The preservation of desired track geometry is also another function associated with the rail pad assembly. Possible failures within this component may significantly affect the original configuration of the fastening system and ultimately result in loss of clamping force, rail seat deterioration (RSD), and gage widening for example.

2.3. Failure Modes

Failure modes result from the failure of a component to perform its designed function. In other words, it is the way in which it "functionally" fails on a component level (McDermott 2009, Stamatis 1995). In the context of rail pad assemblies, failure modes are manifested in different patterns, usually involving the degradation of component materials and loss of original geometry.

2.3.1. Tearing

Tearing is a common failure mode observed in rail pad assemblies. It is defined as shear stresses acting parallel to the plane of the crack and parallel to the crack front, breaking the interparticle bonds of the material (ISO 34-1 2004). In the fastening system context, cyclic loads exerted on the rail seat area act on the rail pads, generating stresses on the component capable of breaking the material into multiple pieces. Materials present different susceptibility to tearing and, even though some provide high resistance when they are in the original shape, after the process has initiated they become weak and compromised. The tearing process is likely to be accentuated with the material degradation, which increases the vulnerability of the component to an intensified degradation process. This failure mode has been observed in different kinds of rail pad assemblies and is not related to a unique type of design or geometry (Figure 2.2). Furthermore, torn pad assemblies are usually unable to appropriately attenuate vertical loads and maintain desired track geometry, since this failure mode often intensifies the component loss of material, changing the component's geometry.

Figure 2.2 Tearing acting as a failure mode on rail pad assemblies

2.3.2. Crushing

Crushing is a failure mode associated with the concentration of vertical and lateral forces acting in the rail pad assembly. When the loads overcome the compressive strength of the component, it is permanently deformed and loses its original configuration (Figure 2.3). This failure mode can be extremely harmful to the fastening system because it prevents the pad assembly from properly attenuating the loads imposed on the rail seat. After reaching the yield strength, which is an intrinsic material property, the accommodation of elastic deformation on the rail pad assembly is compromised. As a result, the distribution of stresses within the rail seat area is affected and the pressure demands on the crosstie are intensified, possibly contributing to accelerating rail seat deterioration (RSD). The likelihood of crushing occurring on rail pad assemblies is greater on tracks that operate freight service, since the vertical, lateral, and dynamic loads imposed on the fastening system components are much higher.


Figure 2.3 Crushed rail pad assemblies

2.3.3. Abrasion

Abrasion occurs as frictional forces act between two surfaces that move relative to one another, and a harder surface cuts or ploughs into the softer surface, resulting in the removal of some of the softer material (Bayer 2004, Williams 1997, Halling 1978, Kernes 2013). Usually, abrasion is classified as two-body abrasion or three-body abrasion. Two-body abrasion occurs when the contact points, often referred to as protuberances (asperities), on one surface are harder than the other surface. Three-body abrasion occurs when hard particles that are not part of either surface penetrate the contact interface and slide and roll between the two surfaces (Bayer 2004, Williams 1997, Kernes 2013).

In rail pad assemblies, abrasion can be caused by relative slip between fastening system components. This abrasion process is usually three body-wear, involving the concrete crosstie rail seat, the rail pad assembly, and abrasive fines. Additionally, three-body wear can also be observed on the top surface of the rail pad assembly, where relative slip occurs between this component and the rail. This phenomenon is likely associated with the accumulation of corrosion debris and abrasive particles between the sliding interfaces. Typically, this failure mode can be easily noticed, since worn dimples and groves are very distinguishable on the abraded surfaces of the rail pad assembly (Figure 2.4).

Figure 2.4 Worn dimples and grooves on rail pad assemblies

2.3.4. Rail Pad Assembly Slippage ("Pad Walk Out")

Another common failure mode related to the rail pad assembly is usually referred to as pad "walk out". In this failure mode, the rail pad assembly translates partially or completely out of the rail seat area. As a result, the rail begins to touch the rail seat without any protective layer to reduce the impact loads and distribute the stresses (Figure 2.5). The wheel loads are then directly transferred from the rail to the crosstie, which can be extremely harmful for the integrity of the track superstructure, especially the rail seat. Furthermore, the rail pad assembly slippage is a failure mode that is able to trigger other failure modes at important track components. The RSD process, for example, is much more likely to occur on a rail seat where the pad assembly has walked away rather than on a rail seat with a properly assembled fastening system. In many cases, improper installation of the rail pad assembly leads to this failure mode, which can also be intensified by the loss of the cast-in shoulders or the spring clips.

Figure 2.5 Examples of rail pad assemblies "walking out" of the rail seat

2.4. Failure Effects

To aid in understanding the consequences of a rail pad assembly failure, it is beneficial to divide the effects into three parts: the effects on the component itself, the effects on the next higher assembly (i.e. the adjacent components of the fastening system), and the effects on the track system.

The failure effect on the pad assembly itself is the loss of the original geometry, usually observed as loss of thickness, permanent deformation, and changes in material properties. The loss of thickness is often related to the abrasion process, which is defined by the removal of material particles. Additionally, permanent deformations due to high loads can also reduce the thickness of the rail pad assembly if they are capable of overcoming the yield strength of the materials that compose this component, being the pad assembly subjected to crushing in this case. Lateral and shear forces may also act on this component contributing to the intensification of the demands that degrade the pad assembly original geometry. Once the degradation process has initiated, the aforementioned failure modes have the capability to impact the component original material properties. Tearing strength, abrasion resistance, shear strength, compressive strength, water absorption, and impact attenuation are a few properties that are likely to be significantly changed as failure modes act on rail pad assemblies.

The effects on the next higher assembly, the adjacent components of the fastening system, are considered to be the change in the desired load path through each component. The rail pad assembly loss of original geometry associated with a change in material properties is likely to impact the intended behavior of the fastening system components. The reduction of thickness, for example, is able to directly impact the desired clamping force, since the vertical displacement on the spring clips is reduced. As a result of less restraint, the movements of the rail and also the other fastening system components are increased, allowing components to undergo higher relative displacements. Another interesting case of change in desired load path occurs when the pad walks out of the rail seat. When this phenomenon takes place, the vertical, lateral, and shear forces on the system are directly transferred from the rail to the crosstie rail seat without a layer that provides impact attenuation and stress distribution. The demands on the concrete significantly increases, and the concrete, which was not designed to withstand such high demands starts to wear, deteriorate, and possibly fail. Therefore, failure modes associated with rail pad assemblies are likely to trigger wear intensifications processes on the other components of the fastening system.

Regarding the track system, the effects are mostly noticed in the superstructure geometry. Gauge widening, which is the increase of the distance between rails beyond the standardized limits, is one common system effect related to rail pad assembly failures. Loss of cant, usually associated with the RSD mechanism, is also another possible system effect, which results in higher forces and moments on the rail. As a consequence, rail running can be observed in tracks with deteriorated rail pad assemblies. All of the aforementioned effects imply more periodic maintenance, reduction in the life cycle of fastening system components, loss of track geometry, and they also significantly increase the possibility of derailments.

2.5. Failure Causes

The rail pad assembly has been used as the focus of a FMEA study, which has identified four principal failure modes of this component: crushing, tearing, rail pad "walk out", and abrasion. For each of the aforementioned failure modes, there are multiple potential root causes that result in a loss of functionality. Some of these causes are listed in Table 2.1 to assist the prevention of failure modes.

Table 2.1 Potential failure causes related to rail pad assemblies failure modes

Failure Modes	Potential Failure Causes
Tearing	High localized compressive stress High localized shear stress Low tearing strength of material Rail pad assembly material deterioration
Crushing	High compressive stress Low compressive strength of material Rail pad assembly change in stiffness Concentration of stresses on a particular area of the rail seat
Abrasion	Relative slip between rail pad assembly and crosstie rail seat Relative slip between rail pad assembly and rail Intrusion of abrasive fines Intensified slip and deterioration caused by the intrusion of moisture Rail pad assembly material deterioration
Pad Assembly "Walk Out"	Damage or loss of the cast-in shoulder Damage or loss of the spring clip Rail seat deterioration Relative slip Erroneous installation

The FMEA provides a deep qualitative understanding of the degradation processes observed in the fastening system, particularly in the rail pad assembly, and also its effects on the system structure. This study sets the ground for the mechanistic investigation of the rail pad assembly behavior, which is motivated by the cause and effect relationship developed for the failure modes observed on this component.

The criticality of each failure mode is highly related to its likelihood of causing failure effects, the severity of these effects, and the difficulty to detect them when failures occur (Stamatis 1995). Prior research conducted at UIUC focused on investigating the criticality and the behavior of physical mechanisms that contribute to RSD (Zeman 2011, Kernes 2013). Abrasion was found to be one of the principal causes of this phenomenon. The abrasion process occurs when the rail pad assembly moves relative to the rail seat, in a process that wears of these components (Zeman 2011, Kernes 2011, Shurpali 2013, Kernes 2013). Therefore, quantifying the magnitude of this relative motion when the system is subjected to a variety of loading scenarios is of paramount importance to the understanding of the mechanics and life cycle of rail pad assemblies. Even though relative displacement between the rail pad assembly and rail seat has been consistently described by experts as one of the main causes of failure (Kernes 2013), there is a lack of studies quantifying relative slip between these components. The pad assembly displacements and deformations under current load environments must be analyzed for the understanding of critical failure processes affecting the fastening system.

3. CHAPTER 3: LABORATORY AND FIELD INVESTIGATION OF THE RAIL PAD ASSEMBLY MECHANICAL BEHAVIOR

The rail pad assembly is a key component in the transfer of wheel-rail forces into the track superstructure. It has also a fundamental influence in system performance parameters such as track gauge, rail seat inclination, track vertical and lateral stiffness, and electrical insulation (Rhodes 2013). The rail pad also plays an important role in the track structure because of its versatility as an engineered product that can be designed with multiple layers, a variety of materials, and unique geometry. As a result, it can be designed to achieve specific mechanical properties to improve the track structure response.

The mechanics of the rail pad assembly, specifically the displacements and deformations this component undergoes when subjected to a track loading environment, is of great interest as a research topic. This is due to the fact that one of the most common crosstie failure mechanisms in North America, rail seat deterioration (RSD), occurs on the bearing area of the rail seat. This is the interface where the rail pad displaces relative to the crosstie, driving possible RSD mechanisms (Van Dyk 2012). The rail pad assembly's movement at the rail seat surface can be understood as the combination of three distinct phenomena that ultimately dictate the displacements and deformations of this component (Kernes 2013). *Compressive motion*, also known as Poisson's effect, is the tendency of elastic materials to expand in directions orthogonal to the direction of the compressive stress. Therefore, the rail pad assembly tends to deform laterally and longitudinally as vertical loads are transferred from the rail to the crosstie. *Rigid body motion* is a simplified characterization of the component translation assuming no relative displacement between the rail pad interparticle distances. The *shear slip* of rail pad assemblies can be described as the interlayer transfer of forces and relative slip of the rail pad surfaces in relation to the concrete crosstie and rail base.

The mechanics of the rail pad assembly are more complex than the intrinsic material properties of the component and the loading regime it is subjected to, since this component is surrounded by a variety of other fastening system elements that also affect the load transfer and responses within the track structure. Therefore, a set of laboratory and field experiments is suggested in this chapter to explain the effects of different loading scenarios on the displacement and deformation of rail pad assemblies. The ultimate goal is to gain a greater understating about the mechanics of this component, which will ultimately assist the analysis and prediction of the deterioration process.

3.1. Motivation

The relative displacement between the rail pad and the crosstie rail seat has proved to be one of the feasible causes of abrasive wear (Kernes 2013). Additionally, abrasion is a mechanism that drives rail seat deterioration (RSD), the degradation of the concrete material directly beneath the rail pad on the bearing surface of the concrete crosstie (Kernes 2013). Previous research has shown that the longitudinal shear slip of rail pad assemblies is a key component in crosstie skewing (Rhodes 2013). These studies also indicate that rail pad assemblies must allow the largest possible elastic displacement of the rail pad before slip occurs, giving to the system a large capacity to accommodate more displacement in the elastic range (Rhodes 2005, Rhodes 2013). This shear elasticity is also important in the lateral direction because it may allow the fastening system to absorb the energy from the lateral loads and causes the rail pad assembly to deform instead of translating rigidly relative to the rail seat (Bizarria 2013).

Laboratory experiments conducted at UIUC used a servo-hydraulic system to produce lateral displacements in a rail pad sample relative to a concrete specimen while a static normal force was applied. This experiment was part of a novel laboratory test setup referred to as the

Large-Scale Abrasion Test (LSAT). Results showed that the imposed displacements, around $\frac{1}{8}$ inch (3.18 mm), were capable of deteriorating both the concrete and the rail pad in a pattern that resembled that of many RSD cases. This result confirmed abrasion as one of the viable mechanisms to induce RSD, proving that significant amounts of the concrete and the plastic that composes the rail seat-rail pad interface could be worn away by isolating this abrasion mechanism (Kernes 2013). However, the aforementioned experimentation did not consider the actual rail pad geometry, or the realistic confinement these components are subjected to within the fastening system, which constrains the displacements of the rail pad relative to the rail seat. When combined, the various interfaces of the fastening system produce interactions among components that may significantly impact the mechanics of abrasion and the occurrence of RSD.

After an extensive literature review and analysis of previous experiments conducted at UIUC, several hypotheses were formulated in order to systematically investigate the rail pad assembly mechanics within the crosstie fastening system. It was hypothesized that (a) rail pad assemblies are, indeed, subjected to lateral displacements relatively to the rail seat, but in a magnitude smaller than the displacements that were simulated with the LSAT [1/8 inch (3.18 mm)], (b) the increase of lateral wheel load will result in larger displacements and forces being applied to the rail pad assembly, and (c) rail pad assemblies experience shear slip under realistic loading environments.

Further experimentation focused on determining the causes of rail pad assembly slippage, and the relationship between the applied loads and the magnitude of the displacements. The rail pad assembly deformation characteristics and shear behavior were also investigated, given the direct impact on the dissipation of the energy in the system, which determines the elastic behavior of the fastening system. The ultimate goal is to gain a greater understating of the behavior of this component, which will ultimately assist in the analysis of the deterioration process that rail pads suffer when submitted to field loading demands.

3.2. Laboratory Experimental Setup

In the pursuit of data to investigate the relative displacement between rail pad and crosstie rail seat, UIUC has undertaken a comprehensive effort to formulate a realistic testing regime to simulate forces and motions generated through the fastening system. The experiments were performed at the Advanced Transportation Research and Engineering Laboratory (ATREL), on the Pulsating Load Testing Machine (PLTM). The PLTM is owned by Amsted RPS and was designed to perform the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6 (Wear and Abrasion. This equipment is consisted of one horizontal and two vertical actuators, both coupled to a steel loading head that encapsulates a 24 inch (610 mm) section of rail attached to one of the two rail seats on a concrete crosstie. The concrete crosstie rests on wooden boards placed on the top of the steel frame that forms the base of the testing fixture, simulating stiff support conditions. Loading inputs for this experiment were applied to the rail in the vertical and lateral directions, and no longitudinal load was applied due to constraints of the current test setup. UIUC researchers recognize that moving wheel loads impart longitudinal forces onto the track structure that add complexity to the analysis of loads imparted to the track components, and the effect of longitudinal forces is an area in need of further research.

A high-sensitivity potentiometer mounted on a metal bracket was attached to the gage side cast-in shoulder to capture the lateral motion of the pad assembly. The potentiometer was in direct contact with the abrasion frame (Figure 3.2b). In this case, the rail pad assembly consisted of a polyurethane rail pad and a nylon 6/6 abrasion frame manufactured by AMSTED RPS

(Table 3.1 and Figure 3.1). Details about the specific loading protocol used for laboratory testing can be found in Appendix A, where the static and dynamic loading cases are detailed.

Table 3.1 Material properties of the experimental rail pad assembly

Component	Material	Young's Modulus (psi)	Poisson's Ratio	Area (in^2)	Mass Density (lb/in^2)
Abrasion Frame	Nylon 6/6	440,000	0.350	38.250	0.049
Rail Pad	Polyurethane	7,500	0.394	36.600	0.068

Figure 3.1 Rail pad assembly used for the laboratory and field tests

(a) **(b)**

Figure 3.2 Images of (a) PLTM and (b) linear potentiometer and test set up used to measure the rail pad assembly lateral displacement

3.3. Field Instrumentation Setup

To quantify relative displacements of the rail pad assembly and rail base with respect to the rail seat, as well as many other response variables, researchers at UIUC formulated a testing regime to analyze forces distributed throughout the concrete crosstie and the fastening system (Grassé 2013). Two track sections were instrumented at the Transportation Technology Center (TTC) in Pueblo, CO. A tangent section was instrumented in the Railroad Test Track (RTT) while a section of a 2 degree curve was instrumented on the High Tonnage Loop (HTL). It is important to mention that the HTL design curvature for the body of the curve was 5 degrees, but the local value was 2 degrees due to a geometry deviation. For each location, 15 new concrete crossties and fastening systems were placed on new ballast, spaced at 24 inch centers, and machined tamped. The new crossties on the HTL were exposed to over 50 million gross tons (MGT) of freight traffic prior to testing (Grassé 2013).

Three distinct loading methodologies were employed as part of the field experimentation. First, loads were applied through the Track Loading Vehicle (TLV). The TLV is comprised of actuators with load cells that are coupled to a deployable axle that facilitates application of known loads through actual wheel-rail contact. Therefore, the TLV was used to create a static loading environment comparable to the one designed and deployed for laboratory experimentation. The other two loading scenarios consisted of a passenger train consist and a freight train consist operated at varying speeds. These two cases were implemented to capture the responses of the track components under dynamic and impact loading scenarios.

A set of strain gauges, linear potentiometers, and pressure sensors were installed on the infrastructure at strategic locations to map the responses of the track components. The lateral displacements of the rail base and rail pad assemblies were recorded using linear potentiometers mounted to the concrete crossties with metal brackets at 6 different rail seats (Figures 3.3 and

3.4). The components were the same model used for the laboratory experiments. Additionally, the lateral forces exerted on the rail were captured using strain gauges placed on a full (Wheatstone) bridge configuration. These strain gauges were installed in the cribs between rail seats C-E, E-G, S-U, and U-W.

Both track sections had the same instrumentation layout and naming convention for identifying the location of the instruments used to measure rail pad assembly lateral displacement and rail base lateral displacement (Figure 3.3). This study will only reference the instrumented crossties (BQ, CS, EU, and GW). At some locations, unique types of instrumentation do not overlap, which was intentional in the design of the instrumentation plan.

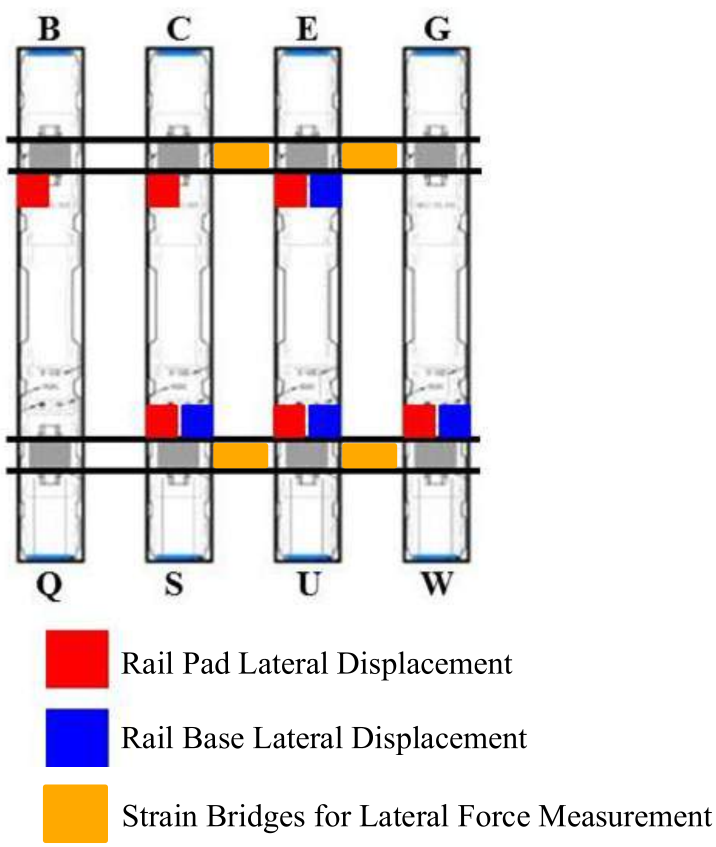

Figure 3.3 Location of instrumentation and naming convention for rail seats and cribs located at the RTT and HTL track sections

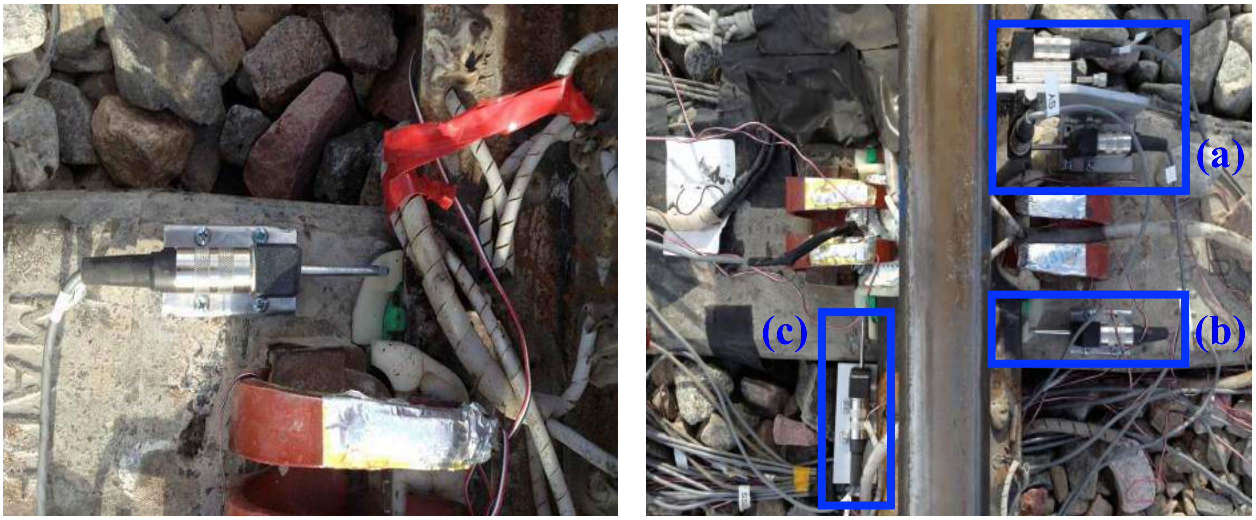

Figure 3.4 Field experimental setup showing instrumentation to measure (a) rail base translation, (b) rail pad lateral translation, and (c) rail pad longitudinal translation

3.4. Laboratory results

Lateral and vertical loads were applied to the rail during the tests carried out in TTC, with L/V force ratios varying from 0.1 to 0.5. The maximum lateral load applied was 18,000 lbf (80kN). Initially, only static loads were applied, beginning with a low L/V ratio. Next, lateral loads were increased for each constant vertical force (18 kips, 30 kips, and 32.5 kips). The dynamic test used the same loading protocol, and the loading rate was 3 Hertz (Hz). The measured maximum displacement was 0.042 in (1.05 mm) for a 0.5 L/V ratio and a 36,000 lbf (160kN) vertical load.

The displacement increased linearly with the variation of the lateral load (Figure 3.5). Even for a lateral load less than 2 kips, displacements were recorded, indicating the potential of relative slip between the rail pad assembly and the rail seat even under loading scenarios commonly associated with less demanding track geometry (low lateral forces). As expected, the magnitudes of these displacements were small compared to the dimensions of the rail seat, since there are very small gaps between the rail pad assembly and the shoulders in the rail seat area that allow the rail pad to displace (Figure 3.6). When this test was repeated with different crossties, there was a variation in the maximum displacement higher than 50% based on the geometry and manufacturing differences. Therefore, it is likely that manufacturing tolerances and the resulting fit of components have a measurable impact on displacements.

Although the magnitude of the vertical loads applied in the system have a large impact on the longitudinal elastic deformation of the rail pad assembly (Rhodes 2005, Rhodes 2013) its effects on the lateral displacement behavior are not evident when lateral loads less than 6.3 kips (28 kN) were considered. For lateral loads up to 6,300 lbf (28 kN), vertical forces ranging from 18,000 lbf (80 kN) to 32,500 lbf (145 kN) did not exhibit differences in the pad assembly lateral displacement. The results recorded for these three different vertical loading cases were similar for lateral loads up to 6,300 lbf (28 kN) despite the 14,500 lbf (65kN) difference between the minimum and maximum vertical force applied (Figure 3.6). However, given the results obtained from this experiment, it is plausible that for lower lateral loading cases, the pad assembly is capable of overcoming the static frictional forces existent at the rail pad assembly – rail seat interface. In contrast, for higher lateral loads, the vertical forces reduced the magnitude of the lateral displacement, pointing to the influence of friction on the shear behavior of the pad assembly. This is more evident when comparing the inclination of the curves, where the tests carried out using 18 kips for vertical load presented a much steeper curve compared to the other results.

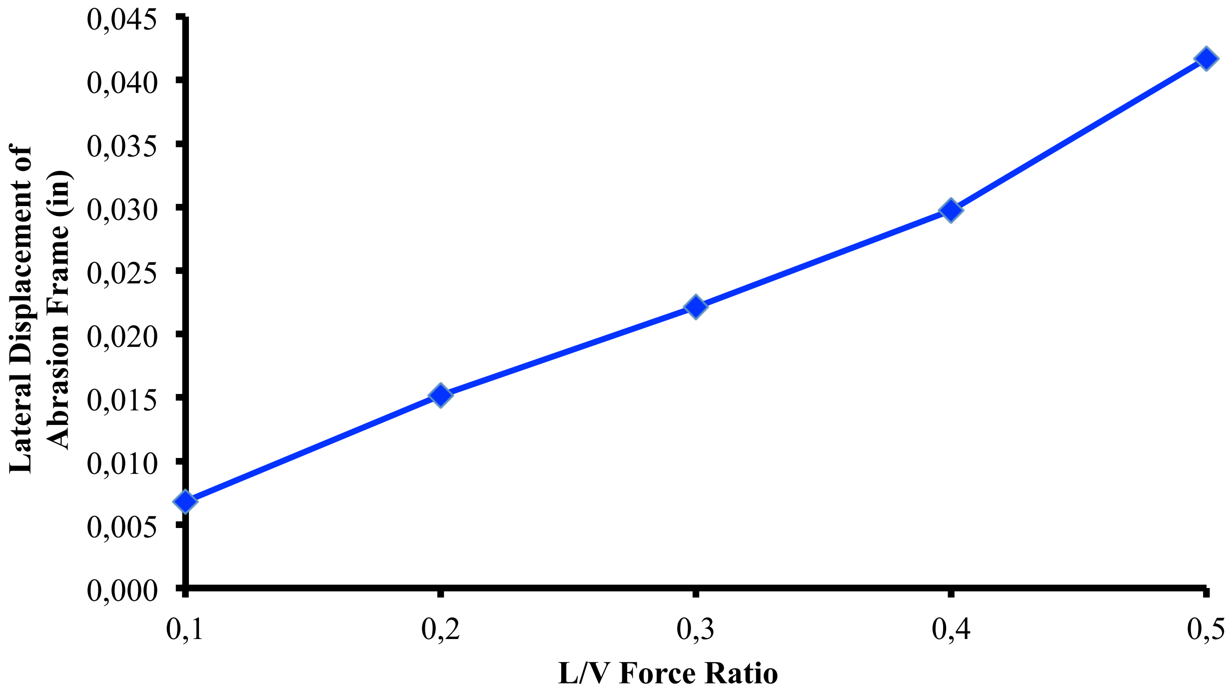

Figure 3.5 Lateral displacement of the abrasion frame with 36,000 lbf (160kN) vertical load for increasing L/V force ratio

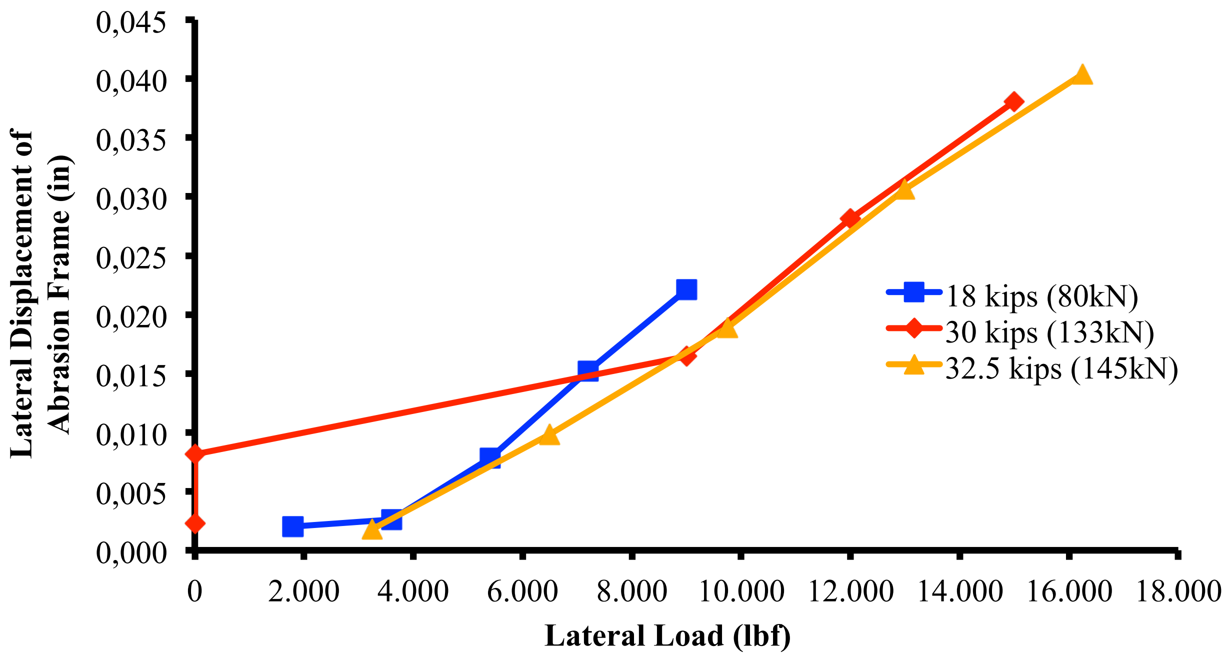

Figure 3.6 Lateral displacement of the abrasion frame for increasing lateral loads and constant vertical loads (18 kips, 30 kips, and 32.5 kips)

Under severe loading cases, where high L/V ratios and high lateral loads are encountered, the magnitude of the wheel load will likely affect the lateral displacement of the pad assembly. It is also important to notice that the lateral and longitudinal motion of the rail pad assembly is restrained by the shoulders and is highly dependent on the condition of the rail seat. Based on the results from laboratory testing, large lateral and longitudinal displacements are less likely to occur when the rail pad assembly fits tightly within the rail seat.

Comparing the displacements obtained by the laboratory experiments and the imposed displacements used to run the LSAT experiments (Kernes 2013), it is possible to conclude that relative translation between the rail pad and crosstie rail seat equal to 1/8 inch (3.175 mm) is unrealistic for new components, since the maximum displacement measured, 0.04 inches, corresponds to only 30% of the LSAT motion. It is important to emphasize that the objective of setting a large displacement in the LSAT was to simulate a deteriorated fastening system where insulators or clips were missing, providing a larger gap and less restraint to the rail pad motion.

3.5. Field results

3.5.1. Track loading vehicle (TLV)

This section presents the results obtained for the TLV and the train runs. First, the TLV static runs were analyzed to allow a comparison between laboratory and field experiments. Second, the data from the moving passenger and freight trains were investigated to allow the understanding of the track components responses under realistic dynamic loading scenarios.

During the TLV runs, static vertical loads of 20 kips (89kN) and 40 kips (178kN) were applied to the track statically, with the L/V force ratio varying from 0.1 to 0.55. These L/V ratios represent the common wide range of loads that are encountered in the field, including some of the severe loading conditions that are typically observed on high tonnage freight service. For a 40 kip (178kN) vertical load applied at crosstie CS on the RTT, the maximum lateral pad assembly displacement was approximately 0.006 in (0.15 mm) at rail seat E for a 0.55 L/V. The maximum displacement recorded for the rail base was approximately 0.04 in (1 mm) at rail seat S, at the same location of the load application. An increase in lateral load resulted in the increase of lateral displacement for both the rail base and the rail pad, which is similar to the behavior captured on the PLTM. The difference in the displacement magnitude between the two components is evident in Figure 3.7, where the rail base has experienced a lateral movement seven times higher than the rail pad assembly.

A variety of factors may have led to this difference in displacement magnitude and the position where the maximum displacements occurred. Differences in the rail seat geometry and variation in shoulder spacing are two parameters that can significantly restrain the pad assembly motion. The rail base sits on the top of the rail pad and is not in contact with the shoulders, which gives more freedom for this component to move within the rail seat area. At rail seats C and S, where the vertical load was applied, the vertical force is likely to have increased the frictional forces in the rail pad assembly interfaces, since the maximum displacement for this component was recorded at rail seat E. For vertical loads applied at different locations, similar behavior and magnitudes of displacements were captured. Differences in behavior may be caused by variations in supporting conditions at each crosstie, challenges in alignment during the lateral load application, and differences in the load required to settle and close gaps at each rail seat (seating loads).

The magnitude of the displacements observed in the field was smaller than the measurements recorded using the PLTM. This result is likely due to lateral load distribution throughout the track structure provided by the restraint of adjacent fastening systems. Additionally, the rail longitudinal rigidity appears to have contributed to the distribution of loads, by reducing the rail pad assembly and rail base movement. In the PLTM, the entire lateral force is resisted by one rail seat.

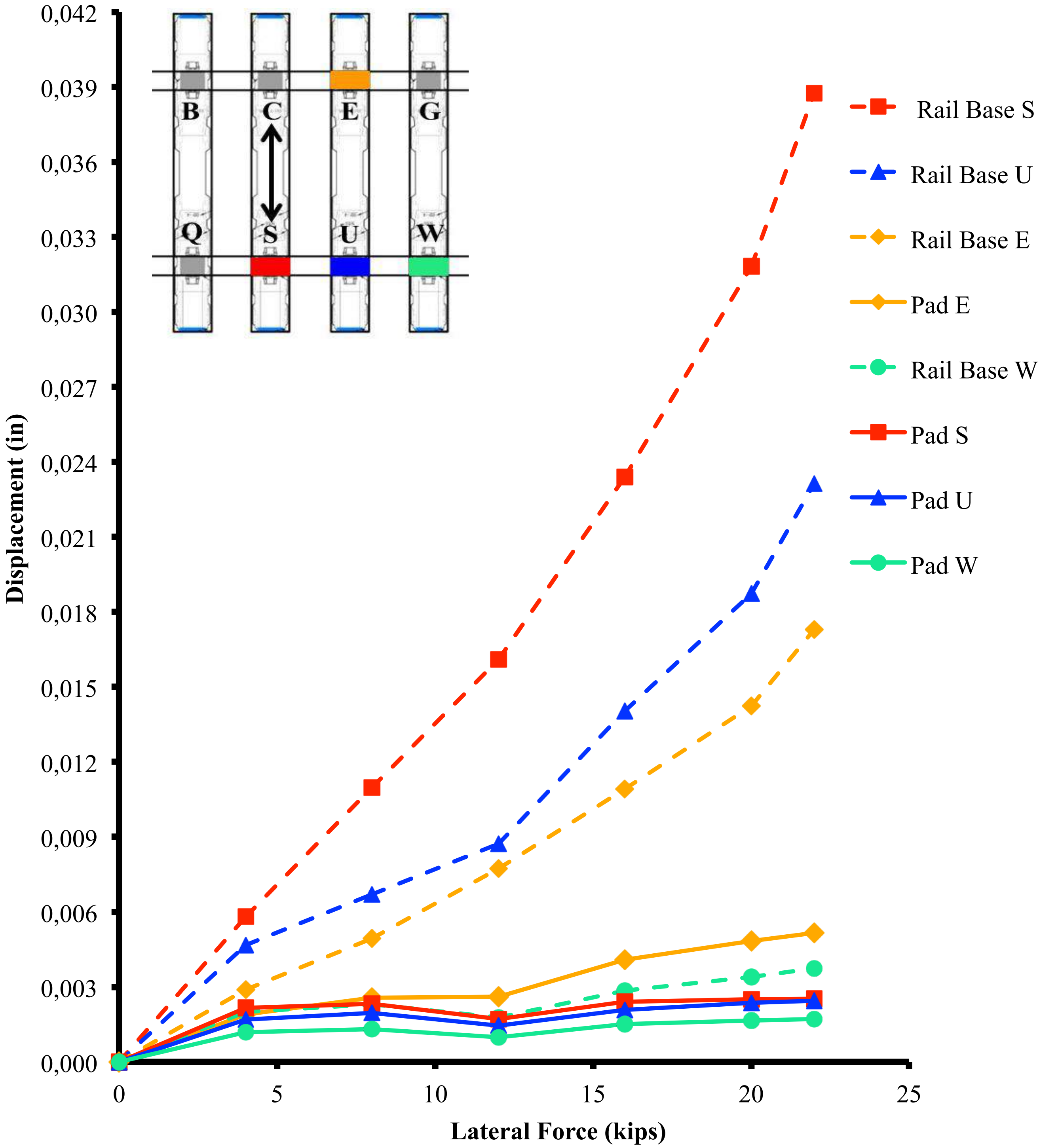

Figure 3.7 Rail base and rail pad assembly lateral displacement for increasing lateral loads with a 40 kip (178 kN) vertical load (RTT, tangent track)

Relative slip between the rail base and the pad assembly was recorded for all rail seats (Figure 3.8). The difference in relative displacement increased as the lateral force on the system increased. The relative slip between the rail base and pad assembly indicates a possible occurrence of shear at the rail pad assembly interfaces, which supports the feasibility of hypothesis “b”. Therefore, this motion should be taken into consideration in the design of rail pad assemblies.

For crosstie GW, which is located two crossties away from the load application, the rail base and the rail pad lateral displacements were significantly smaller than the displacements measured on the other crossties. This result points to lateral load path and lateral load distribution. The track is able to resist and completely transfer all the lateral loads throughout the system among three crossties (24 inches from either direction from point of load application). Only displacements and/or deformations smaller than 0.003 inches on the components were observed at distances greater than 48 inches (1220 mm) (Figure 3.8d). The rail base lateral displacement has a clear tendency to increase as the lateral load increases, but this trend is less evident for the rail pad assembly. As previously discussed in this thesis, factors related to the rail seat geometry, frictional forces, and boundary constraints at these components interfaces are likely causes of this difference in lateral displacement magnitude.

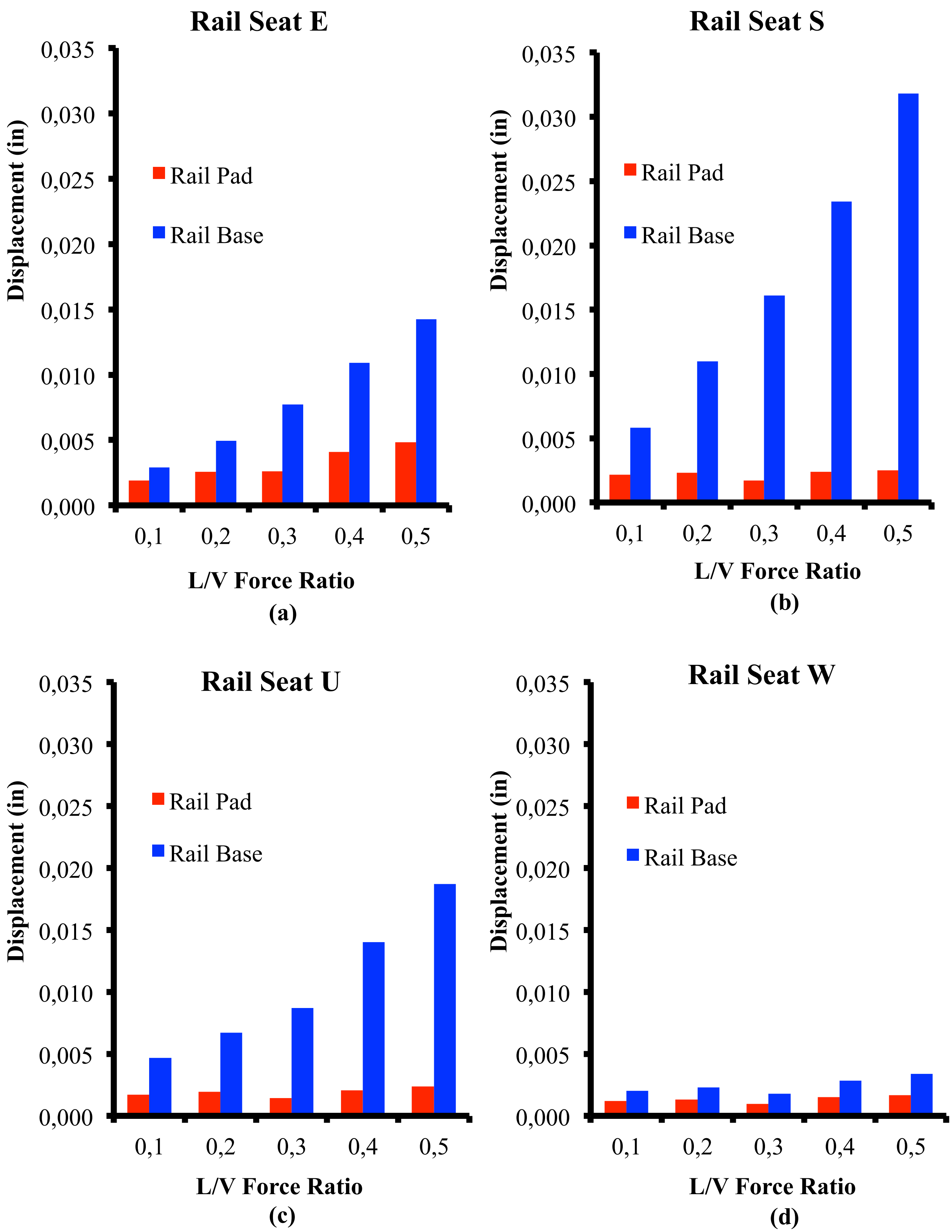

Figure 3.8 Relative lateral displacement between rail pad assembly and rail base for varying L/V force ratio at 40 kips vertical load applied at crosstie CS

3.5.2. Train runs

The freight train consist was the loading scenario expected to impose the highest demands on the track components, resulting in higher deformations and displacements. This section will focus on results from 315,000 lbs (1400 kN) rail cars with vertical wheel loads of approximately 40 kips (178 kN). Rail seats “S” and “U” on the low rail are highlighted because these two locations had the necessary overlapping instrumentation necessary to simultaneously measure the rail pad displacement, rail base lateral displacement, and the lateral wheel loads imposed on the rail.

During the freight train runs, the speed was increased from 2 mph up to 45 mph. Initially, the strain gauges captured lateral average wheel loads of 18 kips (80 kN) and 21 kips (94 kN) being applied to the rail at the rail seats “S” and “U” location respectively. These wheel loads gradually decreased with the increase of train speed, reaching a minimum value of 7.9 kips (35 kN) at rail seat “S” and 9.6 kips (43 kN) at rail seat “U” (Figure 6). The potentiometers placed on the rail pad “U” captured a maximum lateral displacement close to 0.004 inches (0.10mm), which presented an increase in magnitude for increasing lateral wheel loads. The behavior of rail pad “S” has also showed a trend to increase the magnitude with respect to the increase in wheel load. However, the displacements were smaller when compared to the adjacent rail pad assembly (Figure 3.10). The behavior of the rail base lateral displacement has also presented a direct relationship with the increase in lateral wheel load. Both potentiometers positioned at rail seats “S” and “U” have captured an increase in lateral displacement magnitude for the increase in wheel load (Figure 3.11). The maximum rail displacement was close to 0.22 inches (5.5 mm), value much higher than the displacements recorded for the rail pads. A possible explanation for the variation in displacements between these adjacent rail seats are differences in rail seat geometry and variation in shoulder spacing, which are two parameters that restrain the pad assembly motion. The difference in magnitude between rail pad and rail base lateral displacement is likely to be related to the bearing restraints. Cast-in shoulders confine the rail pad assembly while insulators confine the rail base. Shoulders are stiffer than insulators. Additionally, the pad assembly is subjected to the action of significant frictional forces at most of its surfaces, which forces all the interfaces of this component to interact within the fastening system on its top and bottom surfaces. Loads of similar magnitudes imposed different displacements to the rail pads of rail seats “U” and “S”. This variation is likely due to the inherent difference in support conditions of crossties, possible variable and distinct local stiffness of the fastening systems, and geometric variations in the rail seats that may lead to differences in gaps between rail pad and shoulders. This last parameter is a function of the manufacturing tolerances, which allows a tighter or looser fit of the rail pad depending on the shoulder-to-shoulder distance.

As a result of field experimentation, the relative displacement between rail pad and crosstie rail seat and also the relative displacement between rail base and crosstie were successfully captured during train runs, supporting the hypotheses that forecast the existence of this motion under realistic loading environments (hypothesis “a”). The final displacement observed for the rail pads were approximately 40% than the initial measurements. Compared to the static results obtained from the laboratory experiments (Figures 3.5 and 3.6), these displacements were also significantly smaller, one order of magnitude lower.

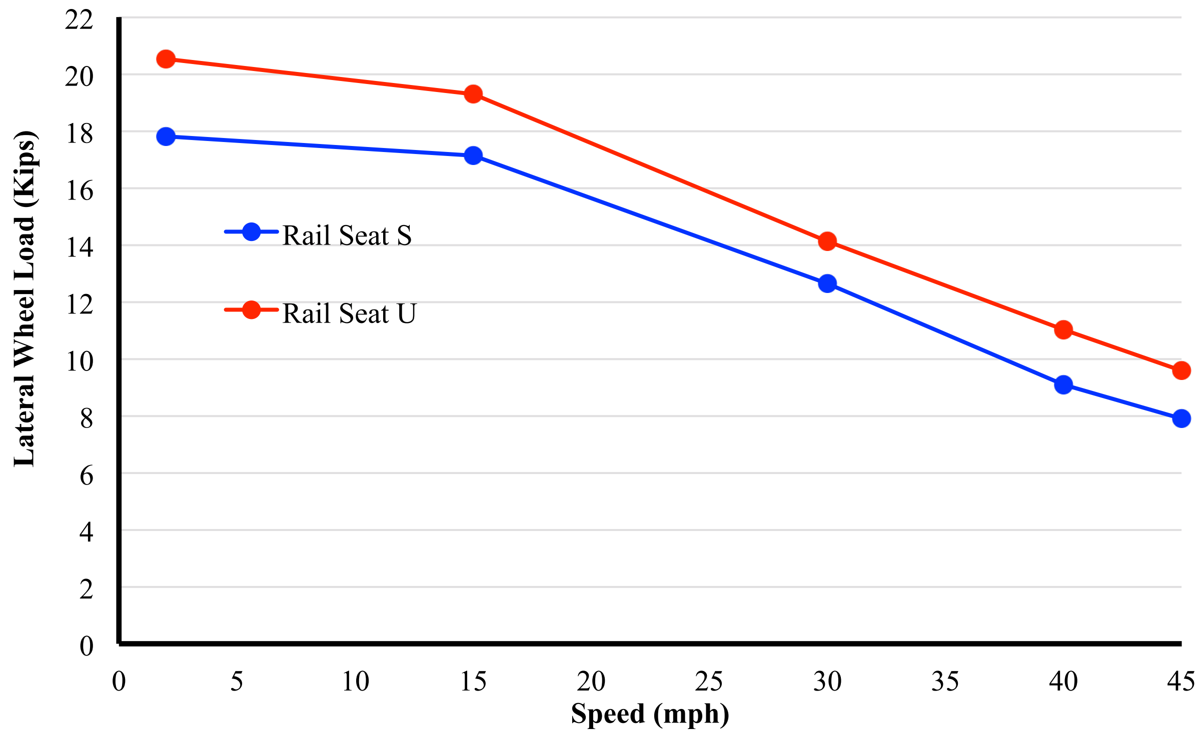

Figure 3.9 Lateral wheel load in rail seats "S" and "U" for increasing speed

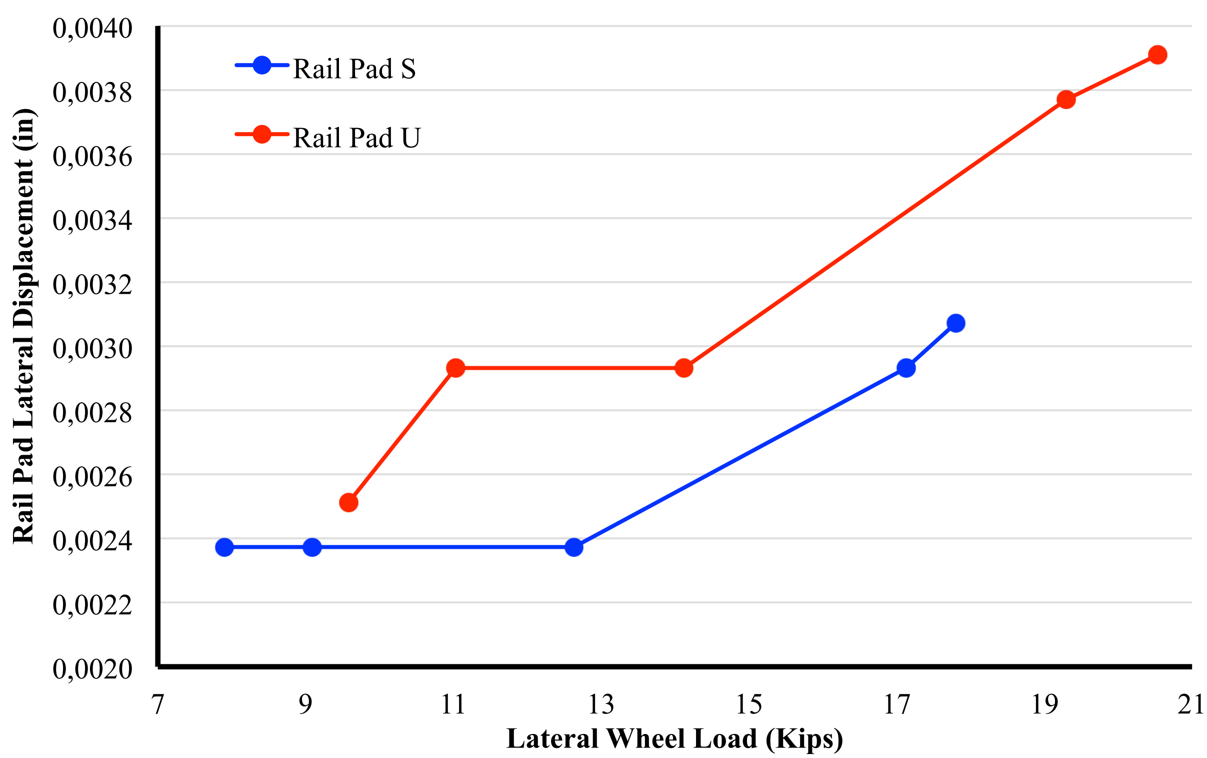

Figure 3.10 Rail pad lateral displacement for increasing lateral wheel load

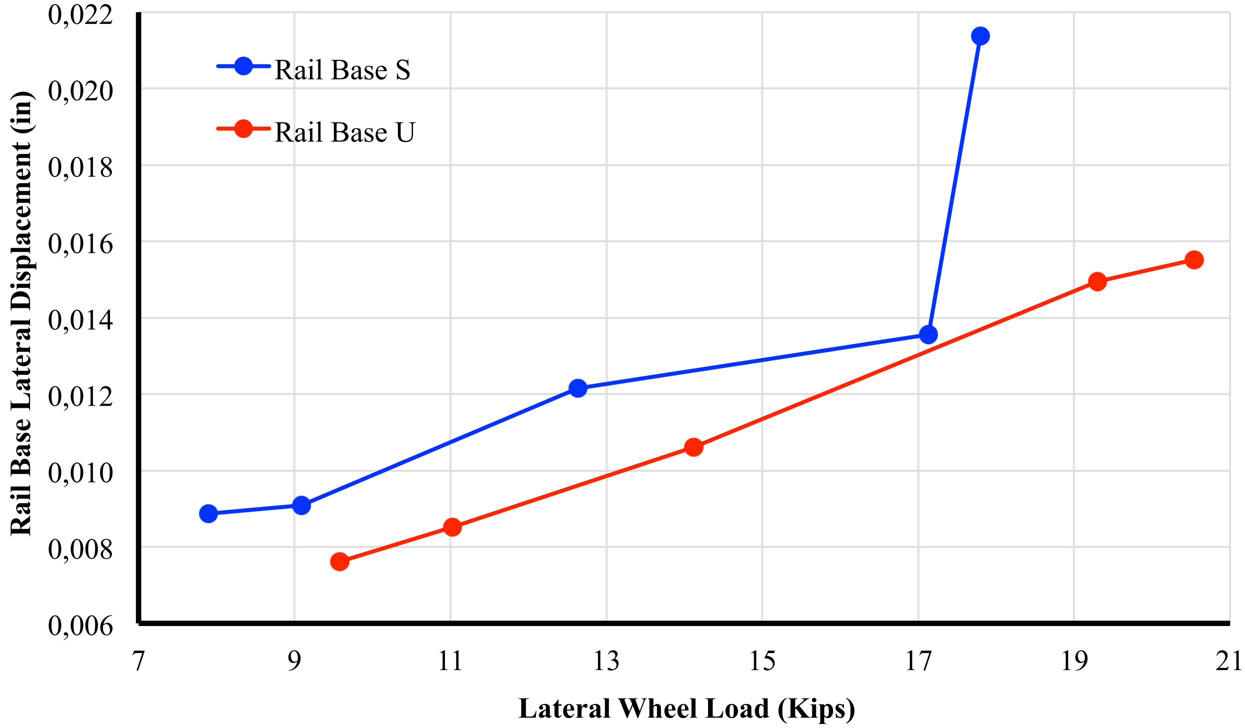

Figure 3.11 Rail base lateral displacement for increasing lateral wheel load

The impact of speed on the lateral wheel loads and forces imposed on the fastening system components resulted in an inverse relationship between these variables, with lateral forces acting on the rail pad and rail base going down with increased speed on the low rail of a curve. Another notable factor is the relative slip between rail pad assembly and rail base, and the significant difference in magnitude of slip between these two components. This relative slip indicates a possible occurrence of shear at the rail pad interfaces, which identifies the need for further investigation of the shear capacity of current materials used in the design of rail pad assemblies and how they should appropriately resist shear forces, minimizing the occurrence of component degradation.

3.6. Conclusions

Understanding the mechanistic behavior of the rail pad assembly and how it interacts within the fastening system is important in the development of improved track components. The relative displacement of the rail pad assembly is frequently associated with RSD failure mechanisms, especially the abrasion mechanism. The occurrence of relative displacement between the rail pad and rail seat was identified and successfully measured in the experiments carried out in the laboratory at UIUC and in the field at TTC. As previously hypothesized, the occurrence of these displacements was observed under train runs in the field, but with reduced magnitude when compared to the results from the laboratory experimentation. Comparing the displacements obtained in the lab and the imposed displacements used in the previous abrasion experimentations at UIUC (Kernes 2013), the maximum measured displacement, 0.04 inches (1 mm) of new fastening system components, corresponded to only 30% of the simulated LSAT motion [1/8 inch (3.18 mm)]. Despite the reduced displacement magnitude, the high frequency recurrence of the relative displacement throughout the rail pad service life may be harmful to the integrity of this component and the crosstie rail seat. Therefore, further experimentation should focus on analyzing the relationship between this measured relative displacement and the severity/rate of abrasion.

The consistent increase in the lateral wheel load directly affected the magnitude of the lateral displacement of rail pad and rail base for both lab and field investigations. This result points out the influence of lateral wheel loads on the relative displacement of these components. An improved fastening system design should consider the lateral load path and the slip between components to create mechanisms that prevent relative displacements and minimize the occurrence of abrasion. A possible solution for this problem is the design of components that allow for internal shear, dissipating the energy before relative slip takes place. Additionally, the incorporation of more strict geometric tolerances for the concrete crosstie and fastening system in the codes would prevent the occurrence of large gaps. This action would likely mitigate relative displacements between components and reduce the accumulation of moisture, dust, and chemicals that may intensify their degradation.

For increasing train speeds, the lateral wheel loads presented a decrease in magnitude on the low rail, which was reflected in smaller lateral displacements of the rail pad and rail base. The range of load distribution (in the longitudinal direction of the track) due to the application of the loads in the rail was approximately two crossties. This result supports the findings described by Williams (2013), which points out the considerably smaller range, which lateral loads are distributed within throughout the track when compared to vertical loads.

Relative lateral slip between the rail base and the rail pad assembly was identified during the field tests. Therefore, these two components were found to displace relative to each other with an increase in lateral loads, likely resulting in increased shear demands exerted on the pad assembly. If confirmed, this result indicates the need for additional investigation of the shear capacity of current materials used in the design of rail pad assemblies and how they should appropriately resist shear forces. In addition, future work should be able to determine if under cyclic loading cases, displacements of similar magnitudes to the ones found on this research are capable of triggering a wear process on the fastening system components, especially the rail pad assembly and the rail seat.

CHAPTER 4: ANALYTICAL TOOL FOR TRACK COMPONENT RESPONSE MEASUREMENT (I-TRACK)

4.1. Motivation to Develop a Track Component Response Tool

The quality and state-of-repair of the track infrastructure and its components determines the permissible wheel loads, speeds, safety, and reliability of railroad operations (Hay 1982). With the development of high and higher-speed rail corridors and increasing axle loads in North America, there is increased demand on the railroad track components. This is especially true with concrete crosstie and fastening systems, which tend to be located in some of the most demanding operating environments. Despite the fact that the mechanics of the railroad track structure has been object of extensive investigation for many years (Chen et al. 2012, Shin et al. 2013), the historically dominant design approach adopted by track component manufacturers has been largely empirical.

As part of a research program funded by the Federal Railroad Administration (FRA), researchers from UIUC have undertaken a major effort to develop a detailed 3D finite element (FE) model of the concrete crosstie and fastening system (Figure 4.1). The model, which has been validated with both laboratory and field data, has proved to be a valuable tool for theoretical comparison between realistic loading cases and experimental testing. Additionally, the FE model serves to perform parametric studies varying component material and geometric dimensions, which will assist in the development of recommended mechanistic design criteria for the concrete crosstie and fastening system (Chen 2012, Chen 2013, Shin 2013).

The FE model is a powerful tool capable of accurately representing the loading environments, support conditions, component interactions, load path, and system behavior. Nevertheless, there are accessibility and computational limitations that make its use impractical for the general user. The intensive computational effort needed to conduct each iteration of the model, combined with the level of expertise demanded from the user when programming experimental runs, motivated UIUC researchers to develop of a track component response tool (I-TRACK).

I-TRACK is a software based on statistical analyses of data from the FE model, where the mechanical behavior of track components is modeled 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.). In other words, the FE model is used to generate a broad set of outputs that are correlated with different inputs, allowing the development of a statistical model that reproduces the effects of the variation of inputs on the magnitude of outputs. I-TRACK is one tool that will play a role in improving the current design process for track components and will aid in developing mechanistic design practices focused on component performance.

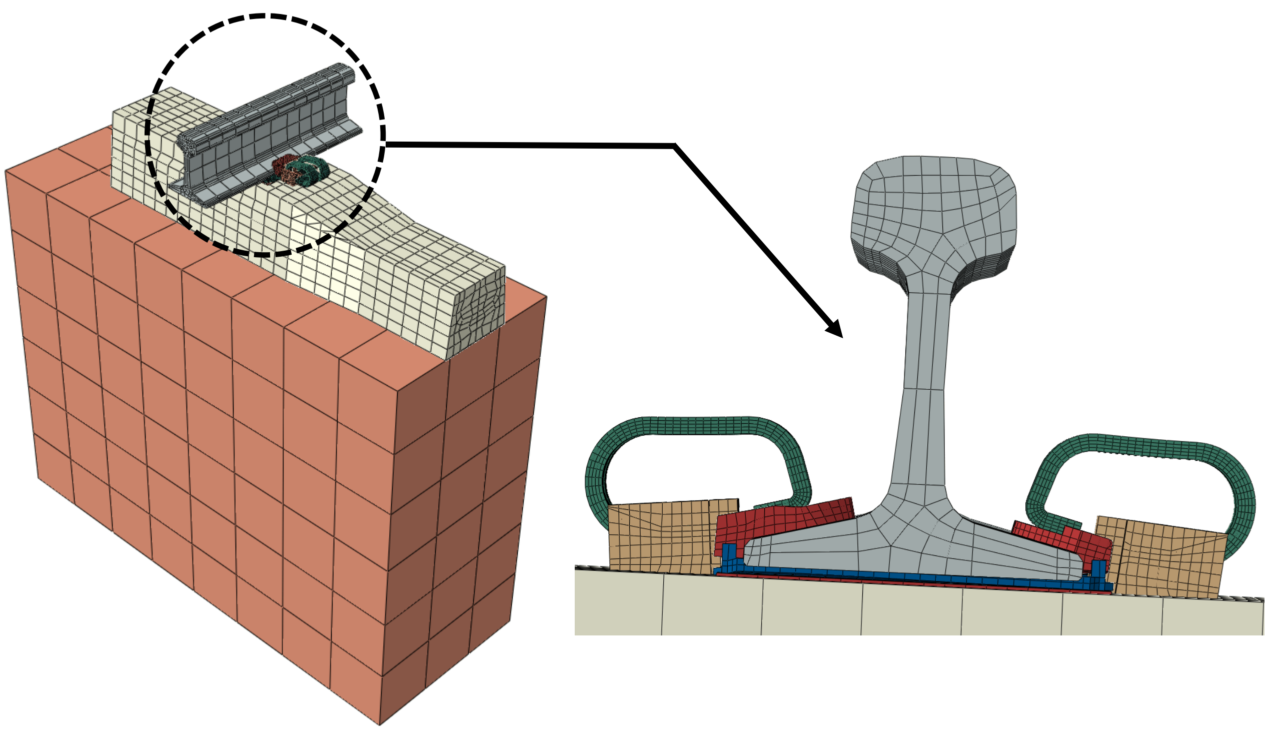

Figure 4.1 Concrete crosstie and fastening system FE model developed by UIUC

4.2. Characterization of I-TRACK - Features and Capabilities

Current concrete crosstie and fastening system design recommendations are primarily based on empirical approaches, and there is a lack of clarity behind some of the critical design limits. This is due, in part, to the fact that design load specifications related to speed and traffic at AREMA were developed empirically, with input loads and forces distribution not clearly addressed as part of the design methodology (Chen et al. 2012, Van Dyk 2013). In particular, the fastening system component design recommendations present an inconsistent level of detail, and many of the requirements do not represent the realistic loading demands and environments (Van Dyk 2013). Improvements to current design processes are difficult to implement without understanding the complex behavior of the track structure. Therefore, the development of an analytical tool to predict the mechanical behavior of the track system and its components can be a powerful asset in a mechanistic approach to track design, where the responses of these components (e.g. maximum stresses, relative displacements, deformations, etc.) are used to optimize their geometry and materials requirements (e.g. strengths, wear resistance, etc.).

I-TRACK has been designed as a practical and adaptable tool capable of quickly estimating the system and component performance based on a set of user defined input conditions. I-TRACK was designed with a degree of sophistication that doesn't demand proficiency in computer coding or knowledge in FE modeling. The primary functional objective of this tool is to provide both user accessibility and adaptability that facilitate rapid access to track component responses. When fully developed, I-TRACK can be used to assist manufacturers in improving the design of components and railroad track engineers in assessing the conditions, safety, and expected performance of the track structure.

The development of I-TRACK follows a systematic process, with its release divided into three versions, where each version adds additional capabilities and features to the tool. This phased approach expedites the development process, allows the model accuracy and functionalities to be tested on a continuous basis, and provides interim utility to users.

First, input and output parameters were prioritized for each project phase. A Design of Experiments (DoE) based on Half Fractional Factorial Design was used to reduce the number of model iterations that were required to develop I-TRACK. DoE is a strategic way of extracting the system's behavior, optimizing the quality of the information and the effects of a response variable due to one or more factors (Krishnaiah 2012). Section 1.3 of this chapter will provide a detailed description of the techniques used to define the DoE. After the experimental matrix was completed using the DoE, the experiments were coded in the FE model, which was used to generate the track outputs. The matrix of results from the FE model runs was the database used to generate the radial basis function neural network model. This technique correlates the inputs to the output parameters with no error in the training data, allowing the correlation between input variations and their effects on the outputs magnitudes with good accuracy. Other methodologies based on multivariate regression analysis were tested in the development of the statistical model. Higher order effects and the inability to predict most of the correlations between inputs and outputs led to large errors in the results. Therefore, a neural network model approach was chosen as opposed to the aforementioned technique.

The final model was embedded in Microsoft Excel, due to the fact that it is a well-known application used throughout the world. In the future, researchers intend to launch I-TRACK in different platforms, possibly as cellular phone applications and open-source software.

4.2.1. I-TRACK - Version 1.0

I-TRACK's initial development involved determining the key inputs to be analyzed in the FE model and choosing the primary outputs to be monitored. The inputs were selected based on their capability of affecting the track and fastening system component's mechanical responses. Additionally, the ease of coding them in the model has also contributed in their selection. The limitation on the number of inputs is due to the amount of experiments that must be carried out in the FE model when extracting their effects in the monitored outputs. The number of experiments that are required for I-TRACK development grow exponentially with the amount of inputs (Section 1.3) and significantly increases the total computational effort that is required.

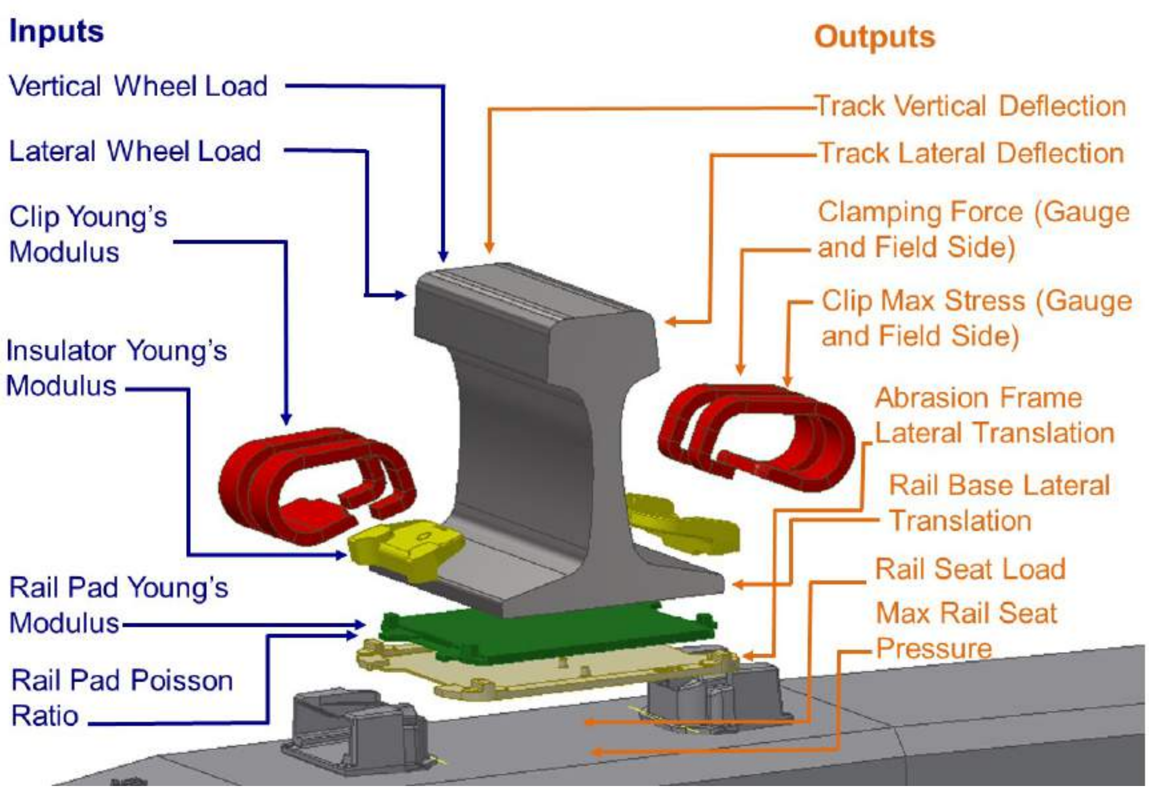

Figure 4.2 List of inputs and outputs included in I-TRACK Version 1.0

For I-TRACK Version 1.0, static wheel loads (vertical and lateral) and some of the fastening system components material properties were prioritized as inputs (Figure 4.2). The first set of outputs (Table 4.1) were selected to capture the general behavior of the track, giving the user insight about the behavior of key fastening system components. Figure 4.2 and Table 4.1 present the inputs and outputs captured for this version of the project and explain the relative location in which these outputs where measured in the FE model. It is important to note that the development of I-TRACK is a continuous process dependent on the FE model capabilities and is subject to a level of accuracy and variability that is related to the number of FE model runs. I-TRACK Versions 2.0 and 3.0 are still under development and additional details of these versions can be found in the next section of this chapter.

Table 4.1 Definition and relative position of outputs monitored in I-TRACK Version 1.0

Output	Definition and Relative Position
Track Vertical Deflection	The global vertical deflection at the top of the rail head
Track Lateral Deflection	The global lateral deflection measured at right-angles to the rail in a plane 5/8" below the top of the rail head. Positive value indicates the railhead moved to the gauge side, and negative value indicates the rail head moved to the field side
Rail Base Lateral Translation	The lateral translation measured at the middle of the rail base edge. Positive value indicates the rail base moved to the gauge side, and negative value indicates the rail base moved to the field side
Abrasion Frame Lateral Translation	The lateral translation measured at the field side edge of the abrasion frame. Positive value indicates the abrasion frame moved to the gauge side, and negative value indicates the abrasion frame moved to the field side
Rail Seat Load	The vertical component of the force resultant from the interaction between rail and rail pad on the loaded crosstie
Gauge Side Clamping Force	The vertical component of the force resultant from the interaction between the insulator and the gauge side clip
Field Side Clamping Force	The vertical component of the force resultant from the interaction between the insulator and the field side clip
Gauge Side Clip Maximum Stress	The maximum principal stress in the gauge side clip
Field Side Clip Maximum Stress	The maximum principal stress in the field side clip

4.2.2. I-TRACK - Versions 2.0 and 3.0

The second and the third versions of I-TRACK will allow the user to modify a larger number of inputs and the software will provide additional output parameters. I-TRACK Version 2.0 is designed to enable the modification of surface interactions and support conditions that will be used as inputs. Therefore, the coefficient of friction between components and the track stiffness will be added as user-defined parameters (Table 4.2). The monitored outputs will consist of a set of 39 parameters (Table 4.3), which will permit a detailed understating of the track behavior and its components. Researchers at UIUC believe these are the main values that are likely to be the most significant from a mechanistic design standpoint, since they encompass macro and micro characteristics of the track mechanical response.

Table 4.2 Input capabilities for I-TRACK Versions 2.0 and 3.0

Version	Inputs
I-TRACK 2.0	All the inputs considered in version 1.0
	Coefficient of Friction between rail seat and abrasion frame
	Coefficient of Friction between insulator and shoulder
	Coefficient of Friction between rail pad and rail
	Track Stiffness
	Concrete Compressive Strength
I-TRACK 3.0	All the inputs considered in versions 1.0 and 2.0
	Insulator Post Thickness
	Rail Pad Thickness
	Abrasion Frame Thickness
	Concrete Crosstie Dimensions
	Rail Section (Size)

Table 4.3 Outputs for I-TRACK Versions 2.0 and 3.0

Component	Outputs
Track	Track Vertical Deflection
	Track Lateral Deflection
Rail	Rail Base Lateral Deflection
	Rail Base Rotation
	Maximum Stress in the Rail
Rail Pad Assembly	Abrasion Frame Lateral Deflection
	Rail Relative Lateral Displacement (Relative to Rail Seat)
	Abrasion Frame and Rail Pad Relative Lateral Displacement (Rel. to Rail Seat)
	Rail Pad Lateral Load
Insulator	Field Side and Gauge Side Insulator-Shoulder Relative Vertical Displacement
	Field Side and Gauge Side Insulator-Clip Relative Lateral Displacement
	Gauge Side Insulator-Shoulder Relative Lateral Displacement
	Field Side Insulator and Rail Relative Vertical Displacement (Relative to Rail)
	Gauge Side Insulator and Rail Relative Vertical Displacement
Clips	Gauge Side and Field Side Clamping Force
	Gauge Side Clip Maximum Stress
	Field Side Clip Maximum Stress
Shoulder	Contact Pressure between Shoulder and Insulator
	Field Side and Gauge Side Shoulder Lateral Force
	Shoulder Lateral Load
Concrete Crosstie	Maximum Rail Seat Pressure
	Rail Seat Pressure at 0.5, 2.0, 4.0, and 5.5 inches from Shoulder
	Concrete Crosstie Maximum Compressive Stress
	Concrete Crosstie Maximum Compressive Stress at Center
	Concrete Crosstie Maximum Tensile Stress at Center
	Moment at Concrete Crosstie Rail Seat
	Moment at the Center of the Concrete Crosstie
	Rail Seat Vertical Deflection at Center
	Concrete Crosstie Vertical Deflection at Center
	Lateral Rail Seat Load at Center
	Rail Seat Load at Adj. Crosstie (Including Clamping Force) for 3 Crossties
	Rail Seat Load at Center

I-TRACK Version 3.0 will incorporate component geometry in the input capabilities. Therefore, it will allow the modification of track components, concrete crosstie, and rail dimensions. However, the variation in geometry adds a significant computational challenge when running the DoE, since the relative position between components change in every run. The current FE model uses the Safelok I fastening system, the most prevalent system on concrete crossties in North America. Even though the incorporation of different fasteners in I-TRACK would be extremely beneficial to the analyses capabilities, this is a limitation of the current FE model that will not be overcome and implemented in I-TRACK in the near term.

4.3. Radial Basis Function Network

Neural networks are computational models inspired by animals' central nervous systems (in particular the brain) that are capable of machine learning and pattern recognition. They are usually presented as systems of interconnected "neurons" that can compute values from inputs by feeding information through the network. A Radial Basis Function Network (RBFN) is an artificial neural network that uses radial basis functions as activation functions, which are the functions that define the outputs of a network node for a given set of inputs. The outputs are linear combinations of radial basis functions of the inputs and neuron parameters. RBFN typically have three layers: an input layer, a hidden layer with a non-linear radial basis activation function, and a linear output layer. The input can be modeled as a vector of real numbers $\mathbf{X} \in \mathbb{R}^n$. The output of the network is then a scalar function of the input vector $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}$, given by:

$$\varphi(\mathbf{x}) = \sum_{i=1}^{N} a_i \rho(\|\mathbf{x} - \mathbf{c}_i\|) \quad (1)$$

Where N is the number of neurons in the hidden layer, $\mathbf{c}_i$ is the center vector for neuron "i", and a_i is the weight of neuron "i" in the linear output neuron. In the basic form all inputs are connected to each hidden neuron. The norm is taken to be the Euclidean distance and the radial basis function is generally taken to be Gaussian as expressed in Equation 2.

$$\rho(\|\mathbf{x}-\mathbf{c}_i\|) = \exp[-\beta\|\mathbf{x}-\mathbf{c}_i\|^2] \quad (2)$$

The figure below depicts the configuration of a radial basis function neural network. It has three input neurons and four neurons in the hidden layer and one neuron in the output layer.

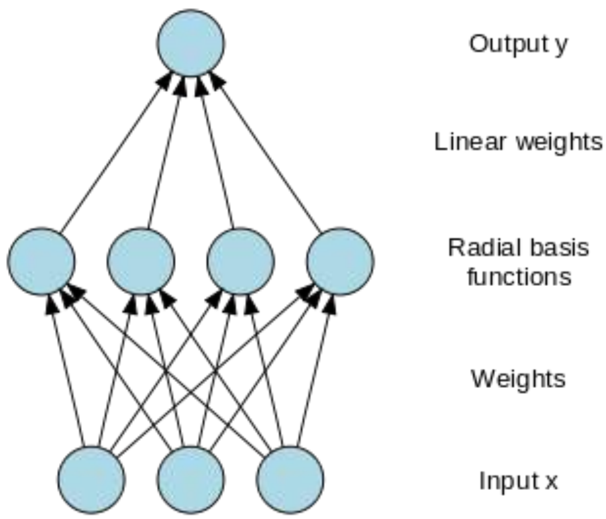

Figure 4.3 Representation of a Radial Basis Function Network (RBFN) Model

Radial basis function networks can be used to interpolate a function $y:\ \mathbb{R}^n \to \mathbb{R}$ when the values of that function are known for a finite number of points:

$$y(\mathbf{x}_i) = b_i, i = 1, \dots, N \quad (3)$$

Taking the known points $\mathbf{x}_i$ to be the centers of the radial basis functions and evaluating the magnitude of the basis functions at the same points ($g_{ij} = \rho(\|\mathbf{x}_j - \mathbf{x}_i\|)$ the weights can be solved from the equation below:

$$\begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1N} \\ g_{21} & g_{22} & \cdots & g_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ g_{N1} & g_{N2} & \cdots & g_{NN} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} \quad (4)$$

The interpolation matrix $\mathbf{G}$ is non-singular, if the points $\mathbf{x}_\mathrm{i}$ are distinct, and thus the weights $\mathbf{w}$ can be solved by simple linear algebra:

$$\mathbf{w} = \mathbf{G}^{-1}\mathbf{b} \tag{5}$$

For the development of I-TRACK, the radial basis function network was trained using the aforementioned function approximation method. All the data points in the training set (95 observations obtained from the FE model) were taken as the centers of the radial basis functions. For each new input value, its Euclidean distance from the all the training points was calculated and the output was predicted based on the weights **w**. The outputs are considered independent and a separate model is generated for each output. In other words, the parameter beta and weights $\mathbf{w}$ are evaluated for each output separately.

A total of 111 observations were obtained from the FE model. From this data matrix, 95 runs were used for training the model and 16 were used for testing it. The 95 observations used for training included 45 observations created using Design of Experiments (DoE). These output values were specifically chosen at the bounds of the input points and at central points. Inclusion of these observations in the model ensured high accuracy for the test data as the function approximation methodology requires output values at the extreme values of the input points. The model results have an average error of less than 20% for all the output values and highest error was less than 30%.

4.4. Design of Experiment (DoE)

A common method for conducting an experimental design is to set all of the input factors at two levels. These levels are called "high" and "low," or "+1" and "-1", respectively. A design with all possible high and low combinations of all input factors is called Two-Level Full Factorial Design (TLFFD). If there are k factors, each at two levels, a full factorial design has 2^k runs. When all factors have been coded so that the high value is "1" and the low value is "-1", the design matrix for any full factorial experiment has columns that are all pairwise orthogonal and all the columns sum to 0. Orthogonality is important because it eliminates correlation between the estimates of the main effects and interactions. Moreover, it guarantees that the effect estimate of one factor or interaction is clear of any influence related to any other factor or interaction. This is a very desirable property and it is the main reason why two-level factorials are precise and generate accurate results.

Even if the number of factors in a design is small, the 2^k runs specified for a two-level full factorial can quickly become very large. For example, I-TRACK Version 1.0 has six different inputs, which result in 64 runs for a TLFFD. For this design there is a need to add a number of center-point runs to capture non-linear effects, another factor that can greatly increase the required computational time and effort when running FE model iterations.

A solution to this problem is using a fraction of the runs specified by the TLFFD, resulting in a leaner matrix of experiments through the use of Half Fractional Factorial Design (HFFD). There are several strategies to ensure an appropriate number of runs are chosen, to ensure that experiments are still balanced and orthogonal. A common technique relies on starting the design using the TLFFD of a one lower order of inputs. If the HFFD for three input factors (2^3) was desired, the starting point for its development would be the TLFFD for two input factors (2^{3-1}), for example (Table 4.4). The missing column (X3) for the third input factor would be replaced by the interaction between the first and the second factors (X1*X2), multiplying the two columns.

Table 4.4 Factors combination for a Half Fractional Factorial Design with 4 runs (3 inputs)

Run	X1	X2	X1*X2 (X3)
1	-1	-1	+1
2	1	-1	-1
3	-1	+1	-1
4	+1	+1	+1

One of the drawbacks in using HFFD is the inability to obtain an estimate of the interaction effect for X1*X2 that is separate from the main effect for X3. In other words, the main effect estimate for factor X3 is confounded with the estimate of the interaction effect for X1 and X2. The whole issue of confounding factors is inherent to the construction of fractional factorial designs, but its advantages far exceed the reduction in accuracy that may arise from the use of this technique.

The DoE is developed to allow an estimate for the interactions resulting from input variation in the output behavior. The intent of this modeling technique is to obtain the local shape of the response surface that is investigated. Under some circumstances, a model only involving main effects and interactions may be appropriate to describe a response surface when the analysis of results reveals no evidence of pure quadratic curvature in the output of interest (e.g. the response at the center is approximately equal to the average of the responses at the factorial runs). In other circumstances, a complete description of the output behavior may require higher order interactions, such a cubic model for example.

If a response behaves linearly, the design matrix to quantify this behavior only needs to contain factors with two levels (high and low). This model is a basic assumption of simple two-level factorial and fractional factorial designs. If a response behaves as a quadratic function, the minimum number of levels required for a factor to quantify this behavior is three. In this case, a Central Composite Design (CCD) based on factorial or fractional factorial design facilitates estimation of the responses' curvature. I-TRACK's DoE used face centered central composite design (CCF) with an embedded HFFD to augment the experiments and capture the behavior of the track components responses. First, 32 experiments were developed based on HFFD and were analyzed in the FE model. Another 13 runs were included to capture the curvature of the outputs that presented a strong indication of nonlinear behavior. Additionally, the final DoE matrix considered extra 56 runs used to improve the accuracy of the outputs results and reduce errors. Ten of these runs were not used to train the model, and they were later applied to verify the accuracy of the results. Appendix B of this thesis contains the matrix of experiments and results obtained for each run.

4.5. Functionality

The primary objective behind the development of I-TRACK is to give users the capability of analyzing track mechanics and behavior using an accessible and accurate tool that runs on a commonly supported platform. For this reason, a series of functions were developed to intuitively guide users through the analysis process, including tutorials and a graphing tool that relates inputs to outputs. These features allow I-TRACK to provide reasonable approximations of the actual response (e.g. stresses, displacements, forces) of track components under different loading conditions.

4.5.1. User interface

I-TRACK relies on a Visual Basic for Application (VBA) code embedded in Microsoft Excel (Figure 4.4). "Macro" functions were added to the interface of I-TRACK to guide the analysis and automate the calculations involved in the process. When possible, figures were introduced to assist users in visualizing the track components and loading application points.

Once the I-TRACK spreadsheet is opened, users can access a tutorial that explains how to use the tool or to tabs where the necessary inputs are added. The outputs are accessed in a similar manner, which takes place after the user initiates the calculations. Additionally, there is the option to generate a Microsoft Word document summary report, containing the magnitude of the values of all outputs available in a particular version (i.e. run) of I-TRACK.

To prevent unintended changes to the configuration of the spreadsheet, all cells in the I-TRACK spreadsheet are blocked except the ones where inputs are entered. However, users have the option to unblock these cells, thereby accessing the code and making modifications. Since the code can be easily accessed, modifications in the program can be made to adapt its interface and features to the specific needs of users.

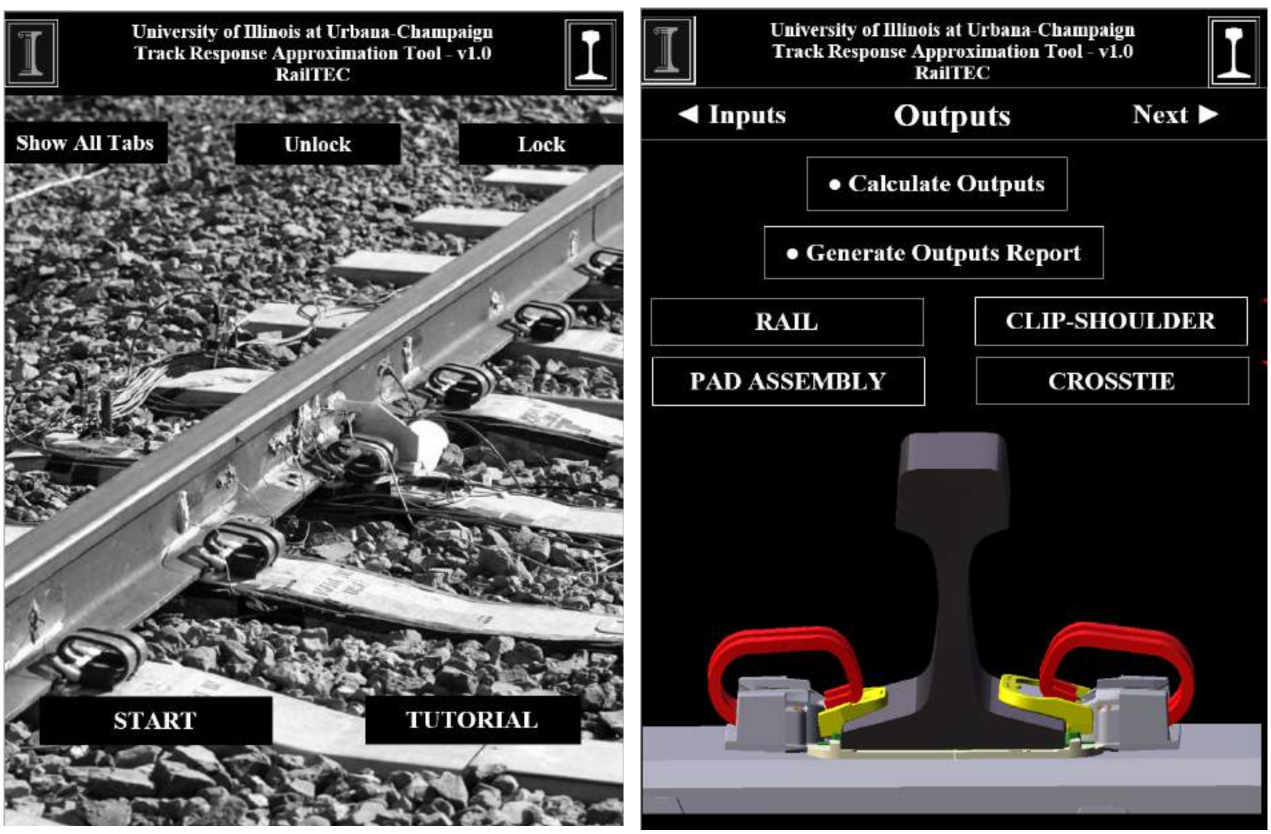

Figure 4.4 I-TRACK Version 1.0 interface - Main Page and Outputs Page

4.5.2. Tutorial

I-TRACK includes a tutorial tab explaining how to use the software. This tutorial also contains output specifications detailing the meaning of positive and negative values, direction of axes, and the specific location in the FE model where the outputs were extracted. Additionally, an example analysis routine is provided.

4.5.3. Selection of baselines

During the analysis process, users have the option to choose from several baseline scenarios for comparing the outputs that are calculated for each combination of inputs. This feature allows users to understand how the set of inputs they choose affects the behavior of the track and its components as compared to baseline values for these inputs. Table 4.5 shows results extracted from I-TRACK Version 1.0 where baseline values are compared to the results given for a specific set of inputs.

Table 4.5 Use of defined baseline values for results comparison

	Baseline	**User's Inputs**	**Variation (%)**
Inputs			
Vertical Load (lb)	37,500	40,000	6%
Lateral Load (lb)	12,500	20,000	38%
Insulator Young’s Modulus (psi)	400,000	1,000,000	60%
Rail Pad Modulus (psi)	202,000	20,000	-910%
Rail Pad Poisson Ratio	0.380	0.490	22%
Clip Young's Modulus (psi)	25,000,000	23,000,000	-9%
Outputs			
Track Vertical Deflection (in)	0.052	0.055	6%
Track Lateral Deflection (in)	-0.010	-0.043	312%
Rail Base Lateral Translation (in)	-0.010	-0.029	198%
Clamping Force Gauge Side (lb)	2,682	2,616	-2%
Clamping Force Field Side (lb)	2,919	2,748	-6%
Clip Maximum Stress Gauge Side (psi)	188,830	197,974	5%
Clip Maximum Stress Field Side (psi)	189,690	187,880	-1%
Rail Seat Load (lb)	28,819	25,845	-10%
Abrasion Frame Lateral Translation (in)	-0.006	-0.010	73%

4.5.4. Inputs

The inputs are defined as all of the parameters that a user must define when conducting an analysis using I-TRACK. They are the set of forces, material properties, and component interactions that will dictate the mechanical behavior of the track and its components. I-TRACK Version 1.0 gives users the capability to vary six different inputs that include forces and track properties. The forces are the vertical and lateral wheel loads going into the system and the track parameters are the component material properties that users may define. As explained in Section 1.2, subsequent versions of I-TRACK will allow the modification of a larger set of parameters, increasing the number of potential input combinations and improving the software's analytical capabilities.

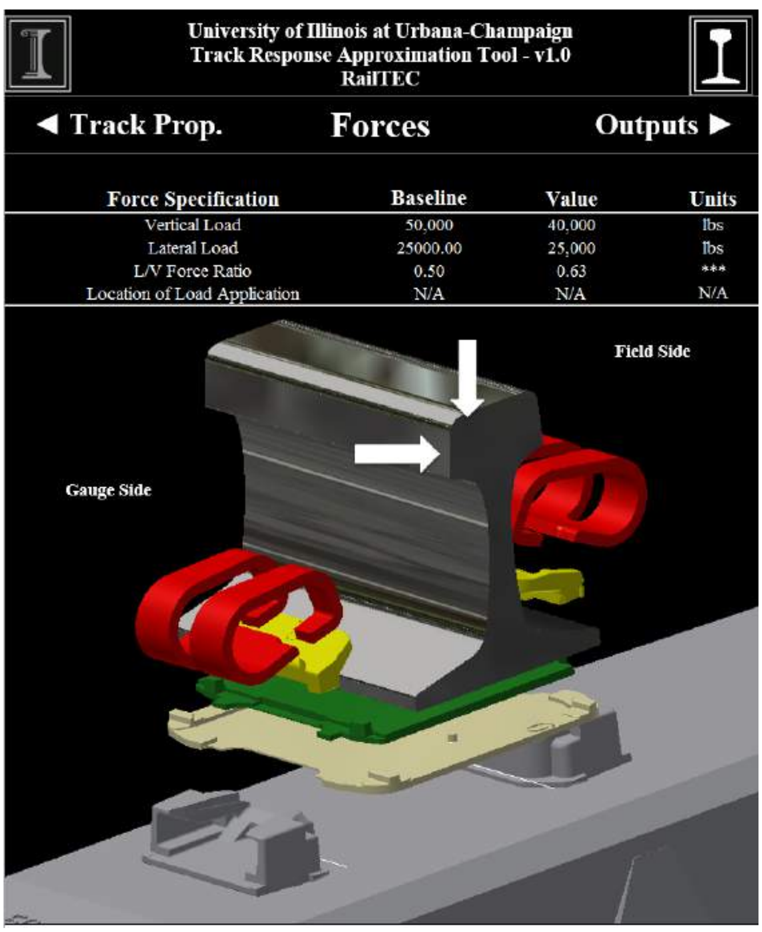

Figure 4.5 Force Page showing input loads for I-TRACK Version 1.0

4.5.5. Outputs

The outputs are the component and system level track responses that are generated by I-TRACK. They are the parameters used to assess the mechanical behavior of the track and understand how loads, material properties, and surface interactions affect the forces distribution throughout the crosstie and fastening system. I-TRACK Version 1.0 provides nine different outputs, categorized by the fastening system component. A specific tab redirecting users to the results of each individual component was created to facilitate the easy access to the outputs. Subsequent versions of I-TRACK will include a total of 49 outputs, covering the majority of parameters track component manufacturers, railroad personnel, and researchers may use to improve current design methodologies and predict the behavior of components under different loading environments and track conditions.

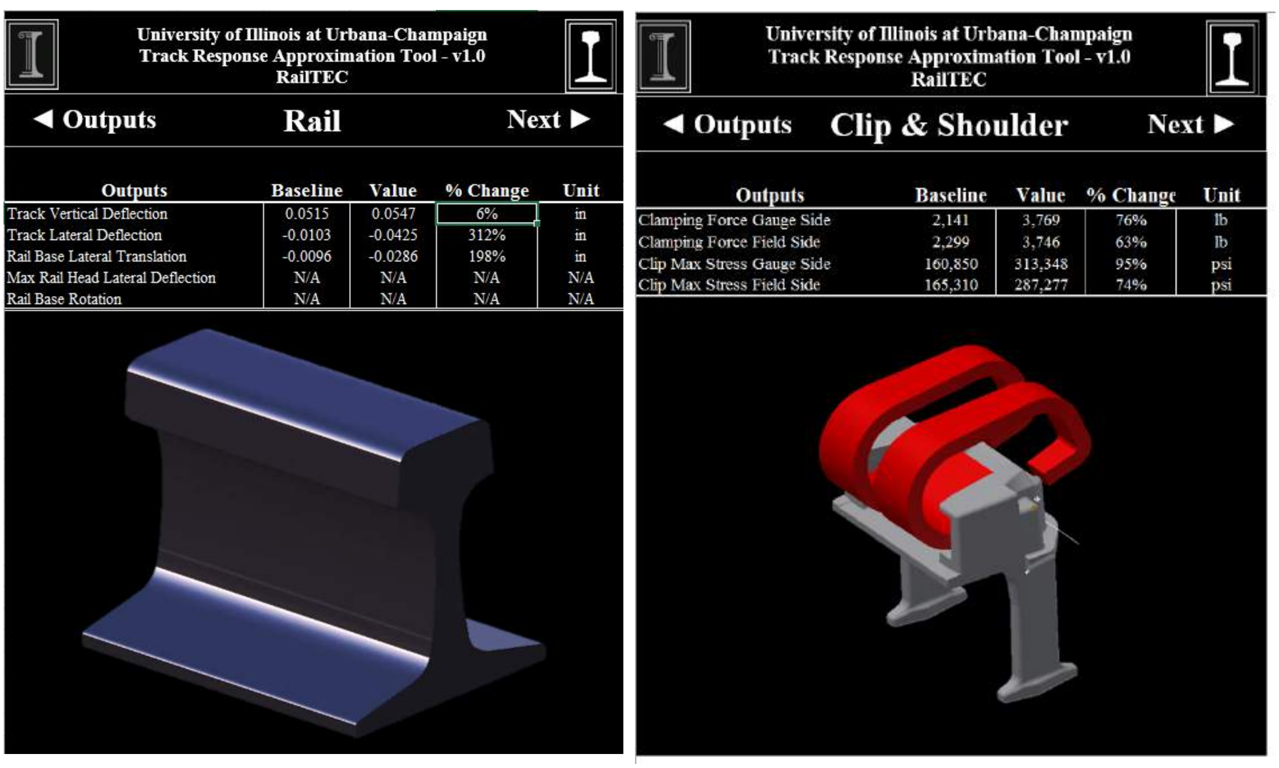

Figure 4.6 Rail Page and Clip & Shoulder Page as outputs for I-TRACK Version 1.0

4.5.6. Automated generation of Inputs vs Outputs graphs

I-TRACK includes a "macro" that automatically generates Input vs Output graphs. After defining a set of base values, which are the inputs that will be used to generate these graphs, users may choose specific input and output combination to be plotted. If a certain input is chosen, all the other inputs of the analysis will assume the base values.

This tool assists in the visualization of the outputs behavior when one specific input is varied and all the others are kept constant. Using these graphs, the user can determine how sensitive individual outputs are with respect to the variation of each input. Therefore, an analysis process may determine how track vertical deflection is affected by rail pad stiffness, for example, providing valuable information in a future mechanistic design process of this component.

Figure 4.7 shows an analysis routine where baseline values were chosen according to the inputs used by Chen (2012) and a graph plotting vertical load with respect to track vertical deflection was selected. Any graph can be plotted using the combination of the available inputs. However, the shape of the curves is not always intuitive due to a variety of reasons, including secondary effects from other inputs and the inherent mechanical complexity existent in some of the components interactions.

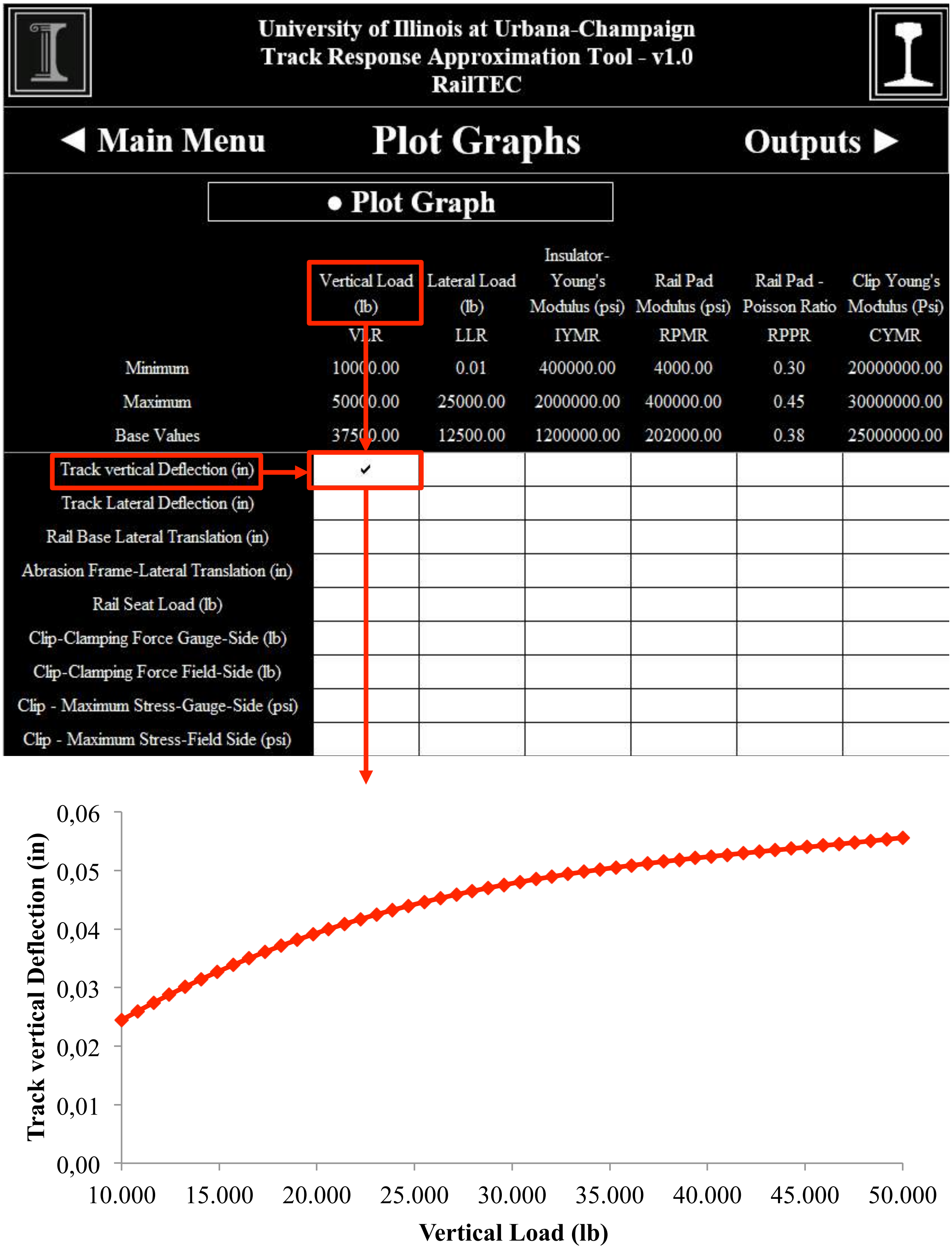

Figure 4.7 Automated generation of graphs relating user defined inputs and outputs

4.5.7. Analysis report

At the end of the analysis process, users have the option to generate a Microsoft Word document report containing the results for the calculated parameters. Once generated, this file is automatically saved in the same folder where the software is located. This is a useful tool for comparing multiple results from I-TRACK, and documenting results for future use.

4.6. Case Study for a Rail Pad Mechanical Behavior Investigation Using I-TRACK

This section is focused on the validation of I-TRACK results when compared to the FE model outputs. Additionally, I will provide a simplified framework for rail pad assembly mechanical behavior study using the software. The main intent is to test the accuracy of I-TRACK's outputs and demonstrate how this tool can be used when developing improved design methodologies for fastening system components. The standard wheel loads and components properties used for the analyses are specified in Table 4.6. They are the same properties used for the FE model parametric study described by Chen (2013).

Table 4.6 Wheel loads and components properties used to conduct the case studies

Input	Magnitude
Vertical Load (lbs)	30,000
Lateral Load (lbs)	7,500
Insulator Young's Modulus (psi)	440,000
Rail Pad Young's Modulus (psi)	7,500
Rail Pad Poisson Ratio	0.49
Clip Young's Modulus (psi)	23,000,000

4.6.1. I-TRACK results accuracy

The accuracy of the statistical model embedded in I-TRACK was compared to the FE model results to ensure its credibility and accuracy. Using the material properties from Table 4.8 and vertical load equal to 40 kips, the lateral displacement of the track and the rail base was plotted for increasing lateral wheel loads. Good agreement is found between the results, with the magnitude of displacements close to each other. Error is present for all the simulated data points, but this factor is due to the amount of variables in the system and the reduced number of experiments used to develop the statistical model. Overall, I-TRACK was successfully able to capture the FE model behavior, providing results with satisfactory accuracy with R^2 value of around 0.98 for both outputs. However, the high level of adaptability of the tool brings inherent constraints of a statistical model representation of the FE model output. For the purposes for which I-TRACK was developed, the results provide reasonable correlation with the FE model.

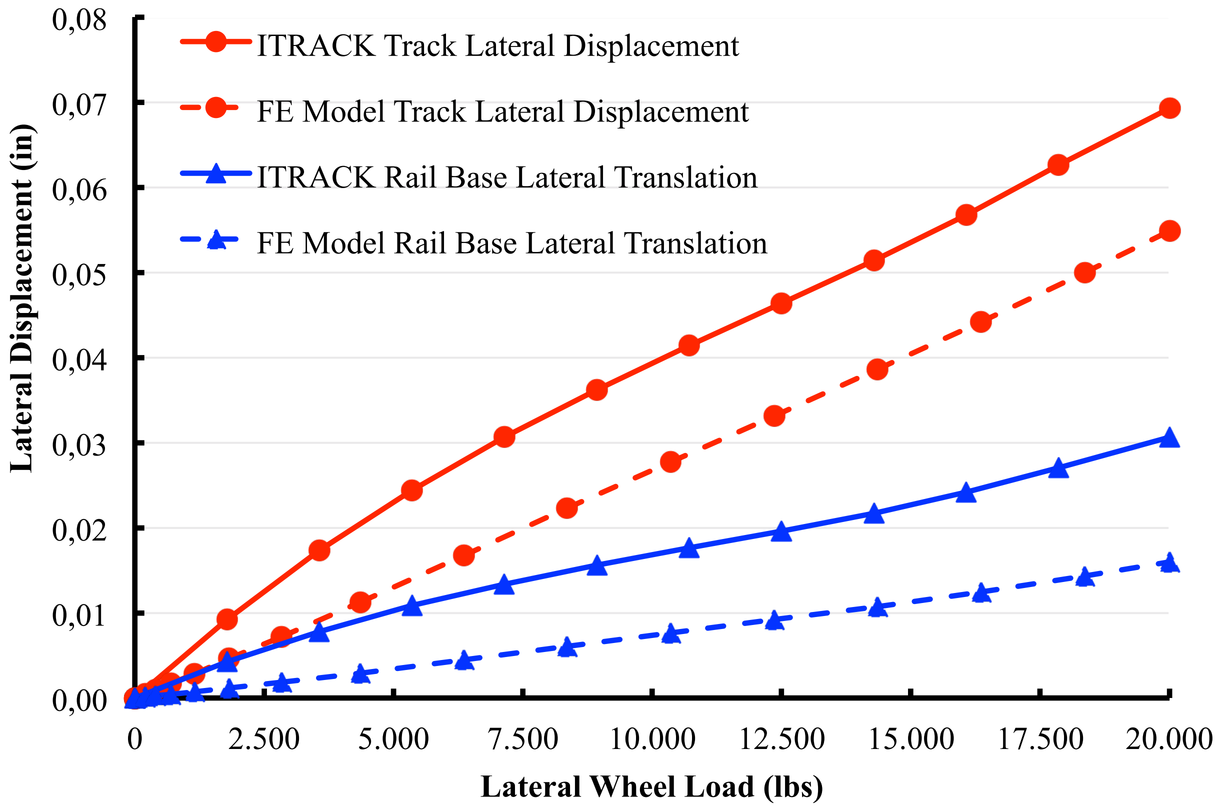

Figure 4.8 Comparison between track and rail base lateral displacement for increasing lateral wheel load

4.6.2. Rail pad assembly mechanical behavior investigation using I-TRACK

There are two system parameters that can be assessed using I-TRACK Version 1.0. The first is track vertical deflection, a global measurement of the of the rail head displacement when wheel loads are applied. This output is important to predict the general condition of the track structure, since large displacements must be prevented in order to maintain proper track geometry and adequate service levels. AREMA (2012) states that track vertical deflection is related to track performance and a poor performance equates to excessive maintenance and slow orders. The recommended maximum desirable range for track vertical deflection to ensure a proper balance between flexibility and stiffness is between 0.125 in (3.18 mm) and 0.25 in (6.35 mm) (AREMA 2012). Deflections smaller than the ones specified in this range may be desired to maintain adequate track geometry but may cause larger loading demands on the fastening system components due to increased stiffness.

Analyzing I-TRACK's outputs, I have shown that rail pad assembly Young's modulus (RPM) is capable of also affecting the total track vertical deflection (TVD) to a limited extent (Figure 4.8). An increase in the RPM from 7,500 psi to 400,000 psi was able to reduce up to 0.01 in (0.25 mm) of the total TVD, which corresponds to 4% of the maximum deflection allowed in AREMA 2012. Even though it may seem to be a small difference in a system parameter, this change in rail pad modulus can affect component responses, especially the load distribution in the crosstie rail seat area (Rapp 2013). Strains at the bottom of the concrete crosstie and the vertical load path are also other parameters that are directly affected by the rail pad assembly elastic modulus.

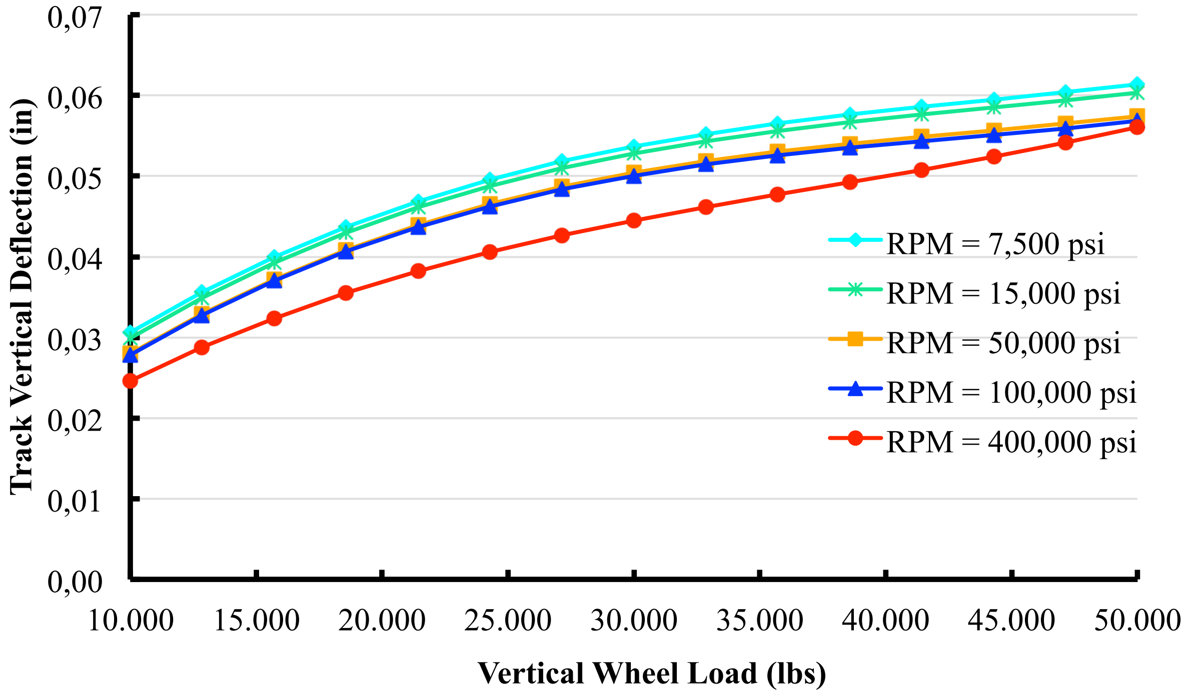

Figure 4.9 Relationship between track vertical deflection and vertical wheel load for increased rail pad Young's modulus

The other system parameter that can be analyzed through I-TRACK is the track lateral deflection (TLD), a global measurement of the rail head lateral displacement when wheel loads are applied to the rail. This parameter is not currently used in track design, even though researchers have indicated the significant influence of lateral load distribution and fastening system lateral stiffness in track components responses (Bizarria 2013, Williams 2013). This output can also be used to assess the overall performance of the track structure, since large displacements may indicate the occurrence of insufficient frictional forces in the system and relative slip between components.

I-TRACK analyses have shown that increased lateral wheel loads cause larger track lateral deflections (Figure 4.9). The increase of vertical wheel loads (VL) affected the magnitude of this output, leading to smaller displacements. A 40 kip increase in the VL was capable of reducing 40% the TLD, indicating the significant difference in track behavior when the system is subjected to heavier axle loads. Higher vertical loads significantly change frictional forces in the fastening system interfaces, reducing the component's lateral displacements (Kernes 2013, Bizarria 2013). The development of shared passenger and freight train corridors imposes design challenges in the track infrastructure that must be overcome in order to guarantee adequate track geometry and desired service levels. Therefore, the current railroad trend to increase axle loads and combine passenger and heavy haul operations in the same infrastructure must take into consideration the impact of such loading environment in the infrastructure responses. I-TRACK can be a useful tool to predict components behavior and provide insightful data to answer questions related to the structural design of shared corridors.

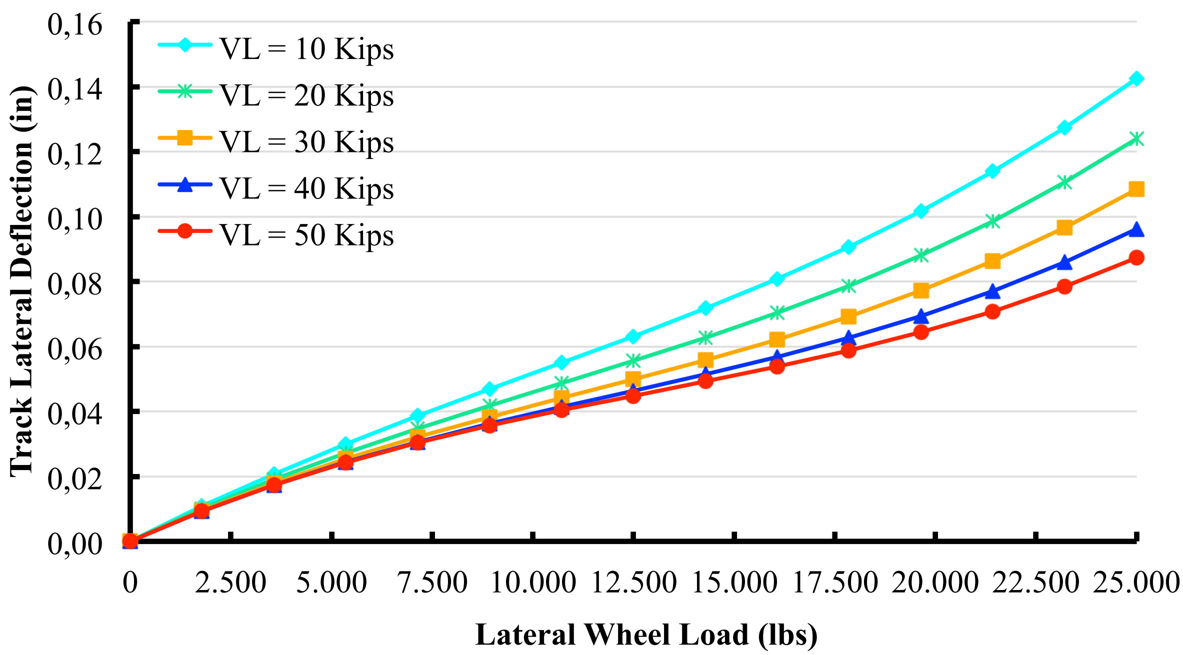

Figure 4.10 Track lateral deflection for increasing lateral wheel loads considering different vertical wheel loads

As observed in the outputs provided by I-TRACK, the rail pad modulus is another parameter affecting TLD. An 5200% increase in the RPM, from 7,500 psi to 400,000 psi, reduced the initial TLD by 15%. This result is likely due to the fact that softer pads allow more rail head rotation, which is the point where TLD was measured. Additionally, softer rail pads are able to undergo higher shear deformation, which also contributes to an increased magnitude of this output. Both system parameters analyzed in I-TRACK indicate that RPM may be used as a guiding parameter for track geometry. Even though its effects on TVD and TLD are limited, this is a component that can be altered to modify and achieve desired track performance parameters.

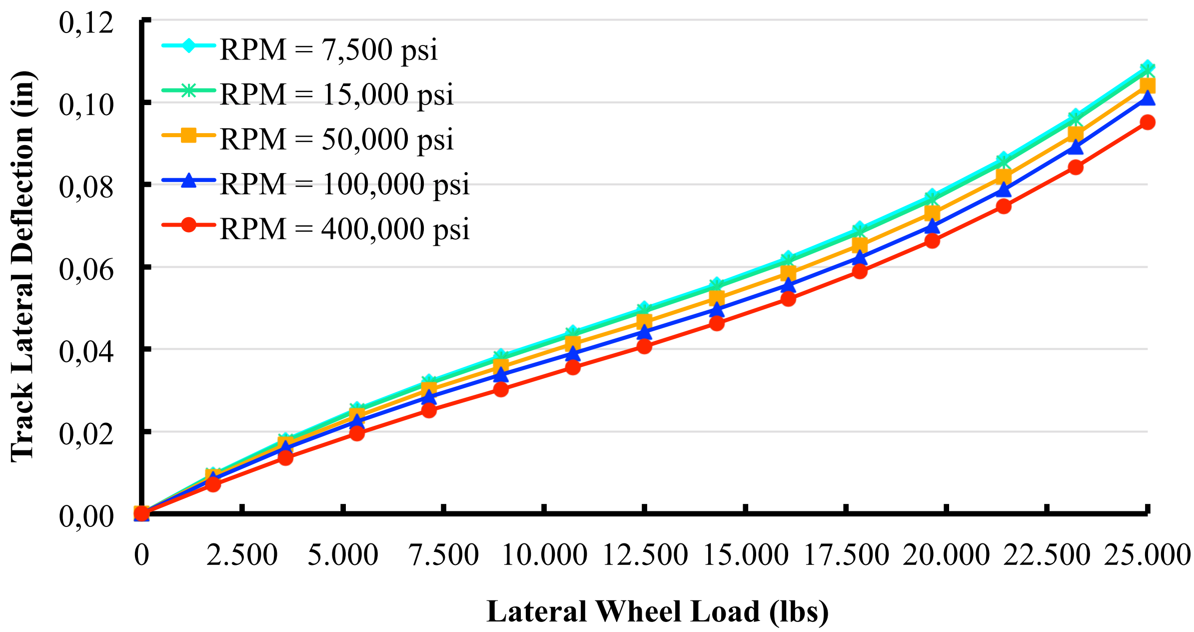

Figure 4.11 Influence of rail pad modulus in track lateral deflection for increasing lateral wheel loads

Another important capability of I-TRACK is related to the analysis of the wheel load path throughout the system, allowing the identification of key inputs that influence the stresses distribution throughout the system. The rail seat load has been the objective of several studies, especially after deterioration of the concrete surface on this interface was identified and related to crushing mechanisms (Marquis 2011, Rapp 2012, FRA 2012).

Using I-TRACK, it is possible to predict the rail seat load for increasing vertical wheel loads when different rail pad moduli are considered. For vertical wheel loads higher than 30 kips, which corresponds to heavy axle loads, the approximate 5200% increase in RPM resulted in a 20% increase of loads being transferred to the rail seat. These results support the studies conducted by Rapp (2012) in which the author indicates that higher modulus rail pads distribute rail seat loads in more highly concentrated areas, possibly leading to localized crushing of the concrete surface under extreme loading events. For vertical wheel loads lower than 30 kips a trend in rail seat load with respect to RPM cannot be identified. Even though results indicate that lower rail pad modulus induce higher rail seat loads, this behavior is not clear. For lower vertical wheel loads the system possibly settles before forces start to be distributed from the rail through the rail pad assembly to the crosstie rail seat. Higher RPM may settle first and start distributing loads earlier, leading to the behavior presented in Figure 4.11.

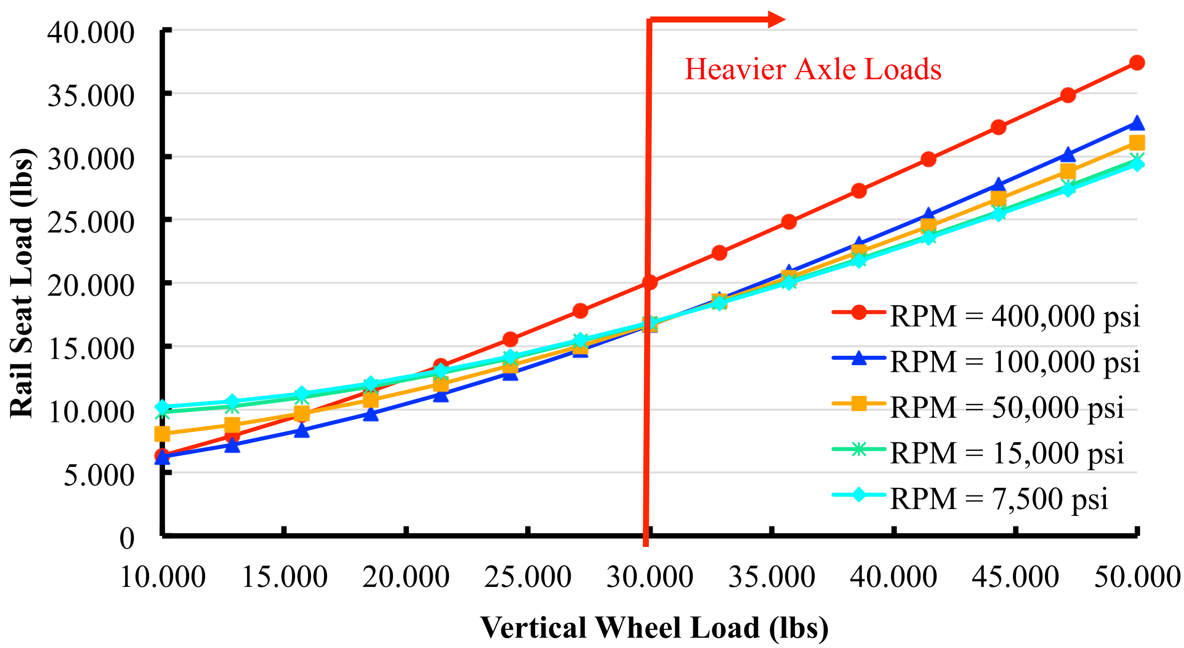

Figure 4.12 Effects on rail pad modulus on rail seat loads for increasing vertical wheel loads

Chapter 3 presented a discussion related to the rail pad assembly mechanical behavior and attempted to investigate the causes of relative slip between this component and the crosstie rail seat. During the field experimentation, the rail base lateral translation (RBLT) at several rail seats was measured and compared to the rail pad assembly lateral displacement (RPLD). This comparison was important to verify the possible occurrence of shear slip in this interface. It was also capable of pointing out new areas in which future studies could be focused when investigating the mechanical behavior of rail pad assemblies.

The rail base lateral translation is a good proxy to measure fastening system lateral stiffness, a property that has been proved to significantly affect the track lateral load distribution (Williams 2013). Taking advantage of I-TRACK's capabilities, it is possible to observe the influence of vertical loads in RBLT. A 400% increase in the vertical wheel load decreased the magnitude of this output by almost 50% (Figure 4.12). For all the cases considered, the increase in lateral wheel loads was directly correlated to the increase in RBLT. This result also points out the difference in stiffness the fastening system may demonstrate when subjected to different magnitudes of vertical wheel loads. Improved design methodologies for the fastening system should take this difference in responses into account in order to provide adequate track geometry and maintain desired service levels throughout the life cycle of components.

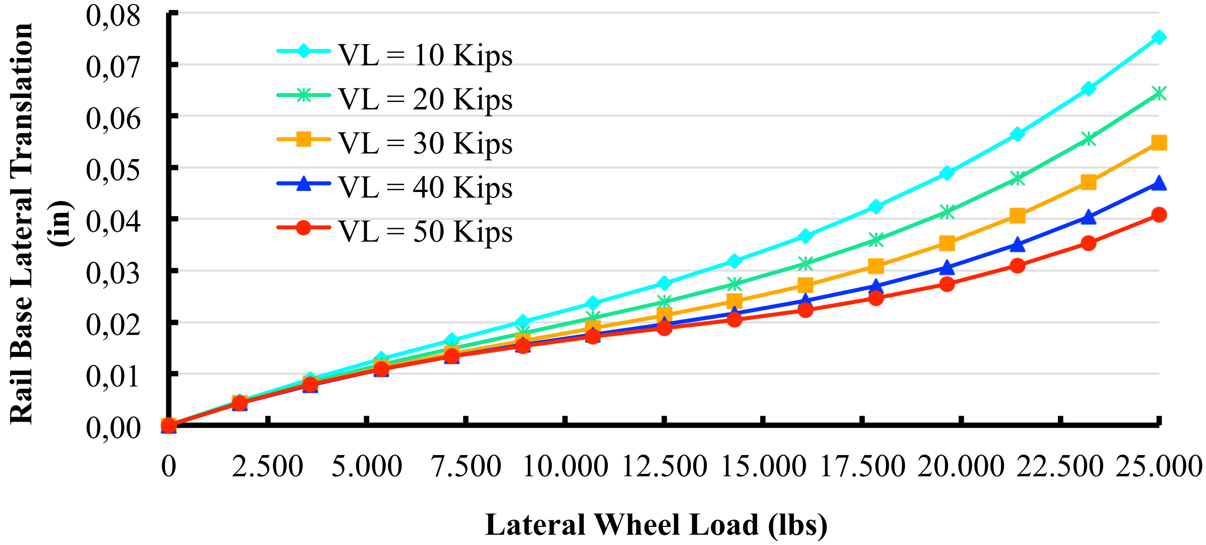

Figure 4.13 Rail base translation for increasing lateral wheel loads considering different vertical wheel loads

An important step in validating the reliability and usefulness of I-TRACK is the comparison between the software output results and field measurements (Figure 4.14). By analyzing the data related to rail base lateral translation presented in Chapter 3 and simulating these results in I-TRACK using the same components properties, it is possible to observe a good correlation. The trend of the output to increase with the increase of lateral wheel load was successfully captured by the model. The magnitudes of the output were also close to the field measurements, even though an error close to 100% was observed for higher lateral wheel loads. It is important to note that a variety of factors are related to the difference in translation magnitudes measured in the field and the ones extracted from I-TRACK. The model is based on a static analysis of the track behavior, whereas the field results presented in Figure 4.14 are related to maximum track responses generated from dynamic freight train passes. The dynamic response of the track has already been shown to present a smaller magnitude of displacements when compared to static loading cases (Grassé 2013). A possible explanation for this phenomenon is the transient characteristic of the loads, and the fact that they don't allow enough time for the components to fully respond to the demands. Additionally, variability in rail seat geometry, cast-in shoulder spacing, and clamping force are also other factors that may have contributed to the differences observed between the field experimentation results for RBLT and the results provided by I-TRACK.

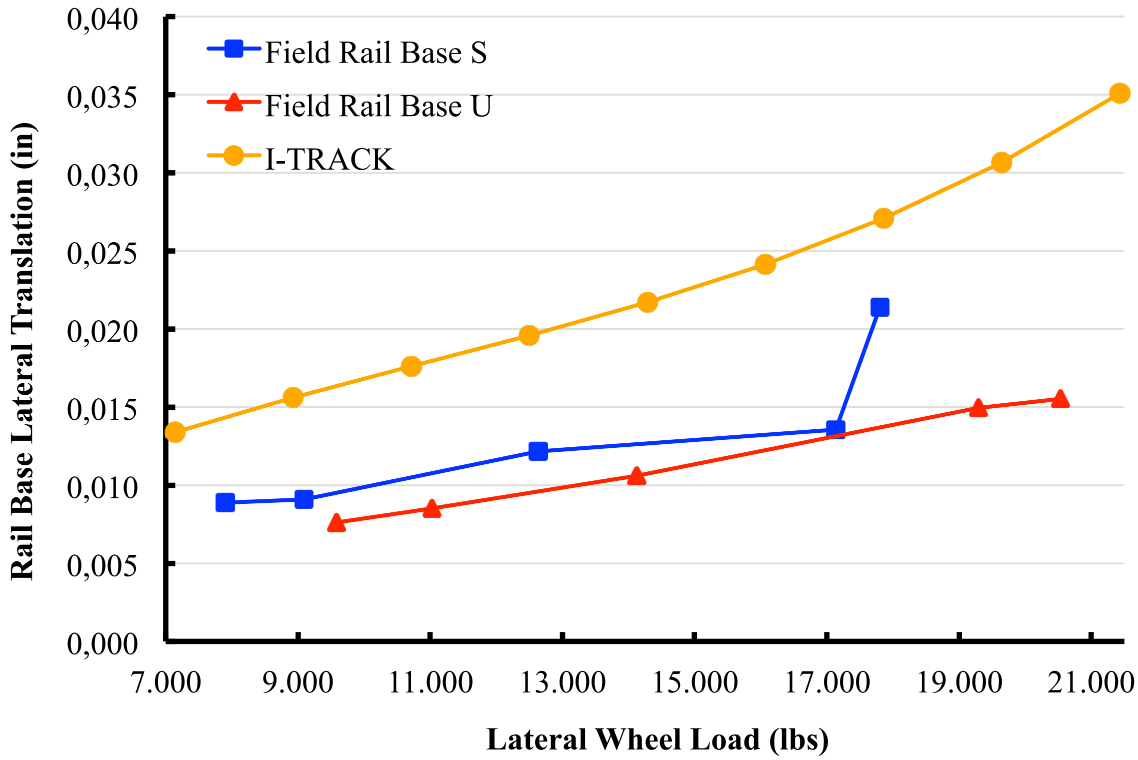

Figure 4.14 Comparison between rail base translations from I-TRACK and field experimentation results considering a 40 kips vertical wheel load

4.7. Conclusions and Future Vision for I-TRACK

The development of I-TRACK is still in its early stages, but I-TRACK has already proven to be a useful tool in assisting with the development of mechanistic design practices focused on component performance. The ease of use, coupled with the capability to analyze a broad set of outputs considering multiple loading cases and different components properties, is one of the greatest advantages of this software. After it is fully developed, I-TRACK will allow track component manufacturers and railroad engineers to rapidly assess the conditions, safety, and expected performance of the track infrastructure.

The case studies presented in this chapter demonstrated good correlation between the results extracted from I-TRACK and the expected behavior for these parameters. The radial basis function network (RBFN) that was developed to capture the FE model results has successfully demonstrated to be efficient when used for this purpose. Even though the analyses were mostly focused on the rail pad assembly mechanical behavior, it is possible to see how a systematic investigation of the track responses can be carried out using this tool. The field experimental data for rail base lateral translation has also shown good correlation with the results provided by I-TRACK, which is a strong indication of the accuracy of both I-TRACK and the FE model. It is important to mention that I-TRACK provides estimates for the realistic behavior of the track and its components, but user should be aware that analyses are based on static loading cases. When comparing to the dynamic loading environment, errors should be expected due to variability in the manner by which wheel loads are applied in the field, the differences in each individual fastening system configurations, and external factors such as magnitude of clamping force and presence of fines and moisture between components.

Researchers at UIUC will continue to develop and refine I-TRACK's features, and the second and third versions of the software will contain additional inputs and outputs to further improve the current analysis capabilities. The ultimate goal of I-TRACK is to provide component manufacturers and track engineers with a powerful and adaptable tool to analyze the track responses and assist the development of improved fastening system components.

CHAPTER 5: CONCLUSIONS

5.1. Summary

Lateral relative displacement between rail pad assemblies and the crosstie rail seat has been successfully identified and measured in laboratory and field tests. The results indicate that the relative displacement is highly dependent on the magnitude of the lateral wheel load applied to the system. Higher displacements were captured for increasing lateral forces. Laboratory and field experiments have shown that vertical wheel loads appear to affect relative displacements, probably caused by the increase in frictional forces in the bearing area of the rail seat. The geometry of the rail seat and the dimensions of the rail pad (e.g. rail seat area, cast-in shoulders face to face distance, etc.) were also factors that seemed to play a role in the magnitude of relative displacement between rail pad assembly and crosstie rail seat, indicating the importance of more strict geometric design tolerances to ensure a tighter fit of components. Additionally, differences in lateral displacement of the rail base and the rail pad were captured, pointing to the possible occurrence of shear slip at this interface.

The development of a simplified track component response tool based on a FE model statistical analysis (I-TRACK) has also been presented during this study. Good correlation between I-TRACK results and the FE model outputs were found when conducting case studies, providing satisfactory accuracy for simulations carried out by this tool. Results have also demonstrated good agreement between I-TRACK outputs and data captured during the field tests, which is a strong indication of the reliability this tool has when used to conduct realistic case studies. A simplified framework for the analysis of rail pad properties and vertical wheel loads on the track responses has been developed to demonstrate the usefulness and capabilities of the tool. When fully developed, I-TRACK is expected to be an important tool in the development of improved design recommendations for concrete crossties and fastening system components.

5.2. Rail Pad Assembly Relative Displacement as a Driving RSD Mechanism

The relative displacement of the rail pad assembly with respect to the crosstie rail seat is frequently associated with RSD failure mechanisms, especially abrasion. Laboratory and field experiments were successfully able to identify the occurrence of relative displacements and measure their magnitude. Even though these displacements were small when compared to the rail seat dimensions, their correlation with the wear severity is still unknown. Further investigation should be conducted to correlate the displacement and wear severity with the number of loading cycles required to induce a failure mode through an abrasion mechanism. Static loading tests induced displacements one order of magnitude higher when compared to the displacements captured for the dynamic train runs. This result is a strong indication that load distribution and components responses are a function of the load application duration, which is a finding consistent to previous field experimentation results obtained by UIUC researchers. This is also a result that highlights the significant challenges encountered when designing fastening system components for shared corridors, due to the high variability in train speed and axle loads in service.

The increase of lateral wheel loads directly affected the magnitude of the lateral displacement of rail pad and rail base for both lab and field investigations. A reduction of displacements was obtained for increased vertical wheel loads, probably caused by the increase in frictional forces between components. Observations also indicated that cast-in shoulder face to face distance is another key factor that plays a major role in relative displacement, since they are a physical barrier to confine components movements. Therefore, more strict geometric tolerances should be considered in design codes to reduce the occurrence of relative displacements and prevent it from triggering an abrasion process at the rail pad-rail seat interface.

Results have also presented a translation up to ten times higher for the rail base when compared to the rail pad values. This difference may be related to bearing restraints and variation in frictional forces, but it is also a good indication of shear slip occurrence. If confirmed, fastening system manufactures may use this material property to control the lateral load path in the system, reducing the stress demands on components at critical interfaces (e.g. insulator). If rail pads were designed to deform and present shear slip, part of the energy usually transferred to the insulator post interface could be dissipated, reducing the demands on the other fastening system components. Additional investigation of the shear deformation of current materials used in the design of rail pad assemblies should be conducted to determine how they may appropriately resist and absorb the lateral forces in the system.

5.3. I-TRACK as a Tool to Develop Improved Track Components Design Practices

The development of a simplified track component response tool gives component manufactures and track engineers the capability of assessing the impact of a variety of input factors (e.g. wheel loads, material properties, interfaces interaction) on the system and component level behavior. This is a powerful asset when developing improved track components design because it allows the choice of optimized parameters (e.g. stiffness, Poisson ration, coefficient of friction) used to define design characteristics these components must have to overcome the predicted loading demands and achieve the desired life cycle.

Chapter 4 presented a framework for the investigation of rail pad assemblies' mechanical behavior using I-TRACK. The practicality and adaptability of the statistical model was capable of quickly estimating response parameters based on the defined inputs. Even though I-TRACK still has a limited amount of analysis capabilities, the tool proved to be effective when estimating the effects of rail pad modulus variation on the behavior of certain track responses, such as track vertical deflection, track lateral deflection, and rail seat load. The impact of increased vertical wheel loads on the system was also predicted and analyzed during the study, providing valuable insight on the effects this input has on the track and fastening system components behavior. The case studies at the end of the chapter were an attempt to demonstrate how this tool can play a significant role improving the current state-of-art design process of track components and developing mechanistic design practices focused on component performance. Nevertheless, results indicated good correlation between FE model outputs and I-TRACK results, a strong indication of the reliability and accuracy of this tool. When fully developed, I-TRACK can be used to assist manufacturers improving the design of components and railroad track engineers in assessing the conditions, safety, and expected performance of the track structure.

5.4. Recommendations for a Mechanistic Design of Rail Pad Assemblies

Uncertainties related to the fastening system deterioration causes associated with a lack of understanding regarding the mechanical interactions among components, led the railroad industry to pursue design modifications. Attempts to enhance the life cycle and performance of components were developed based on empirical design approaches, usually relying on the increase of robustness and stiffness to overcome the loading demands and withstand wear rates. An improved design methodology for rail pad assemblies should be based on a mechanistic approach, where material properties, relative displacements, stress distribution, and component deformation are taken into consideration when optimizing its geometry and performance. The following topics present suggestions for modifications in current design recommended practices that would contribute to the development of improved rail pad assemblies.

5.4.1. Materials choice

The materials choice should be based on stress capacity (compressive and shear), abrasion resistance, and damping properties. FE model analyses and field experimentation are capable of determining peak loads and stresses distribution for a variety of loading cases. I-TRACK simulations can also assist components manufacturers to choose the appropriate rail pad assembly compressive and shear strength according to the intended service level and loading demands.

The material abrasion resistance should be able to withstand usual wear rates measured for the intended type of application. For this reason, it is of paramount importance that railroad companies start mapping rail pad assembly wear rate. A correlation between this factor and track service conditions such as tonnage, degree of curvature, and grade would be extremely beneficial when determining appropriate abrasion resistance each rail pad should have when applied into specific locations or areas.

The desired damping properties can be assessed using dynamic tests of energy dissipation for example, which would determine the materials that are more efficient in absorbing and distributing cyclic vertical and lateral wheel loads.

5.4.2. Design specifications

Rail pad designs should minimize relative displacements of this component with respect to the rail seat surface and rail base, preventing abrasion to take place. Studies conducted at UIUC indicate that this measure would reduce the risk of abrasive wear and premature deterioration of materials. The incorporation of more strict geometric tolerances for the manufacture of track components (e.g. concrete crosstie dimensions, shoulder spacing) would guarantee a tighter fit of the components assembly, preventing the occurrence of gaps and displacements in the fastening system. Excessive moisture, dust, and chemicals accumulation may take place in such gaps, what would likely contribute to initiate a deterioration process of components.

The shear deformation of rail pad assemblies should also be further investigated as a viable way of dissipating the energy that goes into the system without resulting in relative displacements between components. If future studies indicate the benefits of having rail pad shear deformation, this property must be part of the design. Additionally, new recommended practices should then be created in order to address the desired characteristics for this component behavior, optimizing its performance and life cycle.

5.4.3. Improved evaluative tests

Improved evaluative tests would greatly contribute to assess rail pad assembly performance and prevent possible failure modes from occurring under service conditions. The recommended practices should contain tests with additional details and specifications on rail pad stiffness, impact load attenuation, and rail seat pressure distribution. The rail pad assembly stiffness test can be improved with the inclusion of stiffness thresholds, to classify the components according to their load-deflection properties (soft, medium, hard). This specific action would allow a proper choice of design used in different service applications and would also provide valuable information related to the material resilience. The load magnitude and frequency should represent the usual demands encountered for each specific application (e.g. heavy haul, passenger rail), with cycles representing the repetitive axial loads acting on the rail head for a standardized train passage.

The impact attenuation test can also be modified in order to consider more realistic support conditions, using ballast to guarantee an adequate representation of bearing forces. The Australian and European Standards (AS, EN) give the option of using aggregate to support the crosstie. This action should also be extended to AREMA and specified as an enforced test characteristic. More realistic support conditions would provide a better sense of the strains generated at the bottom of the crosstie when impact loads are imposed on the rail. Additional recommendations should also be made on the loads applied to the rail head. These loads need to be more representative of the impact factors observed in the field, for both vertical and lateral directions. WILD detectors data analysis is a good source to extract realistic impact loads for an improved impact attenuation test.

The rail seat load distribution should be assessed in a standardized test, which could make the use of pressure sensors to determine how effective the rail pad is in distributing the forces in the rail seat area. Researchers at UIUC have proposed a novel index for this measurement, which could be an innovative parameter to evaluate the effectiveness of rail pad designs in distributing the wheel loads (Greve 2014).

5.5. Future Work

The study of rail pad assemblies' mechanical behavior present several challenges when relating the component responses to the failure modes observed in the field. Usually described as one of the driving mechanisms of RSD, abrasion has been correlated to the occurrence of relative motion at the rail seat, specifically rail pad relative displacements. Even though this study was able to successfully identify and measure the magnitude of such displacements, further investigation must be conducted to establish their relationship to wear rates generated at the concrete crosstie rail seat. Laboratory tests similar to the improved AREMA test 6 proposed by Kernes (2013) could be a starting point to determine how wear intensity is related to rail pad assembly relative displacement magnitude and loading cycles.

Chapter 3 presented field results with a strong indication of shear slip taking place at the rail pad, since significant differences in translation magnitude were observed for this component when compared to the rail base displacements. It has been hypothesized that increased rail pad assembly shear slip may induce reduced forces being transferred to the insulator and cast-in shoulder in the lateral direction, since the deformation of the rail pad could absorb part of the energy that would be otherwise transferred to other fastening system components. Future work could make the use of the Lateral Load Evaluation Device (LLED) developed by Williams

(2013) to determine if rail pad assemblies with different elastic moduli present variation in the lateral loads being transferred to the cast-in shoulder. If confirmed, this property could be used as a design parameter, taking the shear modulus and strength of materials into consideration during the development of improved rail pad assemblies.

The continued development of I-TRACK will also demand further computational analyzes and improvements to the neural network. Additional design of experiments must be created and analyzed in the FE model to provide a broader matrix of results to be used in the statistical model. For I-TRACK versions 2.0 and 3.0 interfaces interactions and support conditions must be added as input capabilities and an extra set of outputs must be included in the software to provide users the capability to investigate additional system and components responses. When fully developed, I-TRACK can be launched in different platforms, with the potential to become a phone and tablet application in the future.

Researchers at UIUC will continue their effort to improve the state-of-art design practices in railroad engineering. The aforementioned research topics are an attempt to address some of the challenges associated with the development of improved fastening system components, especially the rail pad assembly. Additional research topics involve the rail seat load distribution, insulator mechanical behavior, characterization of the wheel load path, and the continuous development of current UIUC FE model.

6. REFERENCES CITED

American Railway Engineering and Maintenance-of-Way Association (AREMA). 2012. *AREMA Manual for Railway Engineering*, American Railway Engineering and Maintenance-of-Way Association, Landover, Maryland, Chapter 30.

BASF Polyurethanes GmbH. 2012. *CAMPUS datasheet Elastollan 1195 A*. Available at: http://www.campusplastics.com/campus/en/datasheet/Elastollan%C2%AE+1195+A/BASF+Polyurethanes+GmbH/59/b5a54956. [Accessed 31 January 2012].

Edwards, J.R., M.S. Dersch and R.G. Kernes. 2013. *UIUC FRA Concrete Tie and Fastener BAA International Survey,* Federal Railroad Administration. Washington, DC.

Gutierrez, M.J., J.R. Edwards, D.A. Lange and C.P.L. Barkan. 2011. Design and Performance of Elastic Fastening System Assemblies and Measurement of Rail Seat Pressure Distribution for Concrete Sleepers for Heavy-Haul Service. In: *Proceedings of the 9th World Congress on Railway Research*, Lille, France, May 2011.

Kernes, R.G., J.R. Edwards, M.S. Dersch, D.A. Lange and C.P.L. Barkan. 2011. Investigation of the Impact of Abrasion as a Concrete Crosstie Rail Seat Deterioration (RSD) Mechanism. In: *Proceedings: American Railway Engineering and Maintenance-of-Way Association Annual Conference*, Minneapolis, MN, September 2011.

Kernes, R.G., J.R. Edwards, M.S. Dersch, D.A. Lange and C.P.L. Barkan. 2012. Investigation of the Dynamic Frictional Properties of a Concrete Crosstie Rail Seat and Pad and Its Effect on Rail Seat Deterioration (RSD). In: *Proceedings of the Transportation Research Board 91st Annual Meeting*, Washington, DC, January 2012.

Kerr, A.D. 2003. *Fundamentals of Railway Track Engineering*, Simmons-Boardman Books, Omaha, NE.

Rapp, C.T. M.S. Dersch, J.R. Edwards, D.A. Lange and C.P.L. Barkan. 2013. Field instrumentation of concrete crossties for investigating rail seat pressure distribution. *Accepted, Transportation Research Record - Journal of the Transportation Research Board.*

Rhodes, D. and S.J. Cox. 2013. Rail Fastenings for Heavy Haul and Extreme Longitudinal Forces. In: *Proccedings: 10th International Heavy Haul Association Conference*, New Delhi, India, February 2013, pp. 122-126.

Rhodes, D. 1988. How resilient pads protect concrete sleepers. *Railway Gazette International*, February. pp. 85-87.

Shin, M.W., S.S. Kim and H. Jang. 2011. Friction and wear of polyamide 66 with different weigth average molar mass. *Tribology Letters* 44: 151-158.

Shurpali, A. A. R.G. Kernes, J.R. Edwards, M.S. Dersch, D.A. and C. P. L. Barkan. 2013. Investigation of the Mechanics of Rail Seat Deterioration (RSD) and Methods to Improve Rail Seat Abrasion Resistance in Concrete Sleepers. In: *Proccedings: 10th International Heavy Haul Association Conference*, New Delhi, Indai, February 2013, pp. 127-133.

Zeman, J.C., J.R. Edwards, D.A. Lange and C.P.L. Barkan. 2010a, Investigation of Potential Concrete Tie Rail Seat Deterioration Mechanisms: Cavitation Erosion and Hydraulic Pressure Cracking. In: *Proceedings of the Transportation Research Board 89th Annual Meeting*, Washington, DC, January 2010.

Zeman, J.C. 2010b. *Hydraulic mechanisms of concrete-tie rail seat deterioration*, MS Thesis. University of Illinois at Urbana-Champaign.

Zeman, J.C., J.R. Edwards, D.A. Lange and C.P.L. Barkan. 2010c. Sealing Characteristics of Tie Pads on Concrete Crossties. In: *Proceedings: American Railway Engineering and Maintenance-of-Way Association Annual Conference*, Orlando, FL, August 2010.