

**Evaluation of Existing Loading Environment in North America for
Improved Concrete Sleepers and Fastening Systems**

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**2013 World Congress on Railway Research
25-28 November 2013
Sydney, Australia**

ABSTRACT

A sustained increase in heavy axle loads and cumulative freight tonnages, as well as increased interest in high speed passenger rail development, is placing an increasing demand on railway infrastructure. One of the most critical areas of the infrastructure in need of further research is the concrete sleeper and elastic fastening system used in high speed passenger, heavy haul, and shared infrastructure applications. In North America, many recommended practices and design guidelines for these systems use wheel loads that may not necessarily be representative of those seen on rail networks today. Without a clear understanding of the nature of these loads, it becomes increasingly difficult to adequately evaluate the track components in order to make design improvements. The international railway community may provide some valuable insight in terms of typical loading conditions and their resulting failure mechanisms, but there are unique challenges associated with comparing railway networks across the world. Therefore, researchers at the University of Illinois at Urbana-Champaign (UIUC) are conducting research to lay the groundwork for an improved and thorough understanding of the loading environment entering the track structure in North America. Once the load spectrum in North America is better defined, there exists tremendous opportunity for comparisons to be made within the United States and around the world to better identify and reduce potential failure mechanisms associated with specific loading characteristics. This paper will discuss the current trends in wheel loads across the North American rail network while investigating the effects of speed on dynamic and impact loads, ultimately leading to useful distinctions of loads for improved track component design methodologies.

1. Introduction

The performance of concrete sleepers and fastening systems is largely dependent on the type and magnitude of loads travelling through the track superstructure. While a qualitative understanding of these loads is useful in interpreting fastening system component interaction and resulting failure modes, quantifying these loads is critical to determining the demands each component must withstand. There have been many efforts to quantify wheel loads and limited research investigating how these loads transfer to the underlying infrastructure. However, there is not a clear understanding of how the load is distributed after passing from the wheel-rail interface through the rail and into the fastening system and rail seat. A better understanding of the load path can be obtained, as well as its distribution to the rail seat, and ultimately its path through the ballast to the subgrade. To better evaluate current designs of the track structure and move forward with offering recommendations for improvements to those designs based on mechanistic practices, University of Illinois at Urbana Champaign (UIUC) researchers are conducting research and a review of available literature to quantify loads travelling through each component as they pass through each interface of the concrete sleeper and fastening system.

2. Previous Research on Concrete Sleeper and Fastening System Load Quantification

Numerous modeling and laboratory and field experimentation efforts have been undertaken to quantify loads in the domestic and international railway communities. These efforts have been undertaken to investigate and understand specific failures or conduct and validate mathematical modeling. Some of this research on load quantification and analysis is summarized in this paper.

2.1 *Laboratory Experimentation and Mathematical Modeling*

In the 1970s, concurrent to the experimental efforts being performed by the Battelle Columbus Laboratories and partner organizations, a multilayer model was developed to better understand the support conditions of the track superstructure (Kennedy 1978). This model is more sophisticated than the “beam on an elastic foundation” model, yet simpler and less computationally intensive than finite element methods. The effects of rail bending, rail fastener stiffness, sleeper bending, variable ballast and subgrade material type, sleeper spacing, and ballast depth are included in the model and compare favorably with the experimental results described in the following section. Some recorded stresses, deflections, and track modulus values were also compared with predicted values from the computer model GEOTRACK (Stewart 1984).

In the early 2000s, researchers in India developed a mathematical finite element model (FEM) incorporating vehicle-track interaction characteristics and rail imperfections (Kumaran 2002). Additionally, Greek researchers developed a mathematical model to determine the true load acting on the superstructure, considering static, dynamic, and elastic parameters, to represent specific cracking failures experienced in the field (Giannakos 2010).

Researchers from the Volpe National Transportation Systems Center performed a theoretical study to better understand the effect of wheel and rail loads on concrete sleeper stresses, as well as the potential for rail rollover under excessive lateral forces (Marquis 2011). This research was performed largely in response to the deterioration of material on concrete sleeper rail seats, which is known as rail seat deterioration (RSD). RSD has been observed in various levels of severity, with at least one derailment that has been attributed to severe RSD. The wear pattern in these cases was triangular, with more deterioration noted on the field side of the rail seats, Volpe researchers believe that the magnitude of the pressures being applied to the concrete surface in this area on the field side of the rail seat is higher than the compressive strength of the concrete. It was also determined that an increasing lateral component of the resultant wheel load causes eccentric loading on the rail seat, and when the resultant force falls beyond the edge of the base of the rail, an unrestrained rail will roll. It is possible that a concrete rail seat having enough RSD that the elastic fastening clips are no longer functional can result in an unrestrained rail condition (Marquis 2011).

Researchers at UIUC performed a study that supports the concept of high field-side pressure values on the field side of concrete sleeper rail seats under increasing lateral loads. Matrix-Based Tactile Surface Sensors (MBTSS) were used to measure the distribution of loads onto the rail seats of concrete sleepers. Various L/V force ratios were tested in a full-scale laboratory test and it was found that increasing the lateral component of the resultant force increases the loading that is concentrated on the field side of the rail seat. The maximum pressure value recorded in this experimentation was just above 28 MPa (4,000 psi), occurring at an L/V force ratio of 0.60 (145 kN (32.5 kips) vertical, 87 kN (19.5 kips) lateral). This pressure is still much lower than the 48 MPa (7,000 psi) specified by the American Railroad Engineering and Maintenance-of-way Association (AREMA), a value confirmed by the Volpe study as potentially resulting in degradation of concrete materials (Marquis 2011). It is possible, however, that loads in the field could exceed those chosen for the laboratory study with MBTSS, leaving the potential for peak pressure values higher than 28 MPa (4,000 psi) to occur (Rapp 2012).

Based on this and other previous research, UIUC is also developing a comprehensive FEM of the concrete crosstie and fastening system that is discussed in Section 5 of this paper.

2.2 *Field Experimentation*

In 1971, concrete sleeper test sections were installed on Santa Fe Railway in Illinois. The exterior of the sleepers were outfitted with strain gauges to measure compliance with the American Railroad Engineering Association (AREA) recommended practices for bending moments at the rail seat and midsection. The sleepers were installed in groups with varying fastening systems (including different types of clips and pads) and concrete design strengths to determine which combinations of these design parameters performed well in accordance with the AREA recommended practices. The thorough visual inspections and strain gauge data indicated that these test sections performed very well under high axle loads up to 127 kilometers per hour (79 miles per hour) and after 27 million gross

tonnes (30 million gross tons (MGT)) of accumulated traffic (Weber 1976). While this testing was performed over forty years ago and the infrastructure components used for the testing are no longer in production, the testing methods are still relevant and represent some of the first load quantification efforts.

During the 1970s and 1980s, a very significant laboratory and field testing program was undertaken by a partnership of organizations including Battelle Columbus Laboratories, the University of Massachusetts, the Association of American Railroads (AAR), the Railway Progress Institute, and the Federal Railroad Administration (FRA). Much of the motivation for these tests involved comparing the Facility for Accelerated Service Testing (FAST) to various field locations (on Amtrak's Northeast Corridor and the Florida East Coast Railroad) to determine the degree to which the facility represents the conditions found in revenue service (Harrison 1984). However, the significant testing performed provided great insight into the loading environment from the wheel-rail interface through the concrete sleeper and fastening system and into the ballast. Forces, stresses, strains, deflections, and other measurements were measured using a variety of instrumentation techniques to investigate particular failure mechanisms and their causes. Some of the important parameters measured included track settlement, rail deflection, clip strain, pad deflection, wheel load, rail seat load, sleeper bending moment, sleeper-ballast pressure, sleeper cracking behavior, and rail seat deterioration. An important contribution of these efforts was the development of the Wheel Impact Load Detector (WILD) to identify impact load-producing wheel sets (Ahlbeck 1986). This development provided railroads across the country the ability to better manage their rolling stock to effectively protect their infrastructure.

An experiment was performed at the Transportation Technology Center (TTC) in Pueblo, Colorado on concrete sleepers and fasteners whose results were presented in a 1990 "Workshop on Heavy Axle Loads" at the same location (Read 1990). In this experiment, concrete sleepers and fasteners of various manufacturers were installed in a 5-degree section of track and a section of tangent track on the FAST as part of the Heavy Axle Load (HAL) Program. Both 30-tonne (33-ton) and 35-tonne (39-ton) axle load programs were performed to compare the performance of the concrete sleepers and fasteners under various loading conditions. Data were collected from a combination of strain gauging of the rails and sleepers, and instrumented wheel sets. Axial strains were measured by strain gauges installed on the top surfaces of some of the sleepers, showing negative bending behavior between the rail seats. After 386 million gross tonnes (425 MGT) of testing, limited flexural cracking had occurred, none appearing to significantly affect the performance of the sleepers in track.

The fasteners were also observed during testing for signs of failure. Modes of failure that were observed included fall-out from loss of the initial toe load and fracture of the fastener. In summary, the failure of fasteners was very low during this experiment; after 145 million gross tonnes (160 MGT) only 5.3% of the worst-performing type of fasteners failed, most commonly due to loss of toe load.

In Australia, significant field instrumentation and data collection efforts were undertaken to understand the vertical forces exerted on the track structure by various traffic types, contributing to a new limit states approach for the design of concrete sleepers (Leong 2008).

Following a number of derailments on mainline curves involving rail rollover (Wu 2006), the Norfolk Southern Railway developed a field experimentation regime in 2011 and 2012 to measure lateral wheel forces. The study concluded that very high lateral forces (resulting in near rail-rollover conditions) can be reduced by the use of certain wheel-rail interface management techniques and elastic fasteners (Kerchof 2012).

Researchers at UIUC are aware of field experimentation that was conducted by the BNSF Railway that was aimed at quantifying the loads that are passed through the cast-in shoulder. The results from this work were inconclusive, and UIUC researchers are attempting to utilize different technologies to answer questions about lateral load transfer through the shoulder.

Taking these and other field experiments into consideration, UIUC has developed and executed a series of experiments that aim to track the load path through the concrete crosstie and fastening system under loading conditions that are representative of shared passenger and freight corridors in North America. These experiments are further discussed in Section 5.

3. Wheel Load Quantification

To better understand the current loading distribution applied to North American infrastructure, UIUC has acquired significant data from WILD sites throughout the US from both Amtrak and Union Pacific Railroad (UPRR). These data provide insight to the varied loading distributions at representative sites throughout North America. Specific loading properties such as peak vertical load, peak lateral load, and speed are captured through the use of strain gauge instrumentation, and these data are graphed and analyzed by creating various distributions and determining relationships between them. The following conclusions have been made thus far (Van Dyk 2013):

- The WILD is a useful tool for collecting and analyzing loading data entering the track structure
- Vehicle type and its associated static load provides a baseline for the expected total load at the wheel-rail interface
- Increasing speed minimally increases the most common wheel loads; however, severe impact loads become much more severe at higher speeds
- Traffic composition and other site-specific parameters play a significant role in the distribution of the loading environment
- Seasonal effects in load variation, while greatly contributing to the magnitude of severe impacts, minimally affect the majority of the wheel load distribution
- Wheel condition, especially as it relates to wheel irregularities, is a significant factor in determining expected loads entering the track structure

The WILD data also provide information regarding lateral loads, but because the site is constructed on tangent track, the lateral loads do not frequently exceed 22 kN (5 kips) toward the gauge or field side of the rail. To monitor more significant lateral loads in curved section of track, instrumented wheel sets (IWS) and truck performance detectors (TPDs) can be utilized. IWS measurements, for example, on U.S. coal routes have produced lateral loads up to 138 kN (31 kips) (Koch 2007) toward the field side of track. However, it may be possible for even higher lateral loads to occur in areas with non-optimal rail profiles, friction management techniques, track condition, or wheel condition (Kerchof 2012).

Longitudinal forces in the track must also be considered. They most often occur because of thermal expansion or contraction of the rail and locomotive tractive effort or braking. Thermal forces in the rail can cause failures resulting in very serious consequences. The use of concrete sleepers (providing necessary longitudinal and lateral resistance due to rail expansion) with resilient fastening systems and signaling (for detection of rail contraction resulting in breaks) has eliminated many of these failures and their potential consequences. Significant longitudinal forces can also be generated due to wheel-rail contact. In fact, with proper support conditions, four head-end freight locomotives and a loaded train can generate longitudinal forces in excess of 1000 kN (225 kips) (Rhodes 2013).

4. Rail Seat Load Calculation Methodologies

An important part of railway track structural analysis is understanding the path of the load as it travels through the railcar suspension system, into the rail and fastening systems, onto the sleepers, and down into the supporting track substructure. It is widely accepted that a wheel load being applied to the rail is distributed over several sleepers both in front of and behind the location of the wheel, even when it is located directly above a single sleeper (AREMA 2012). An exception to this distribution might be in the case of a hanging sleeper, where there is little to no support beneath the sleeper, and the entire wheel load is supported by adjacent sleepers. Using specially designed field instrumentation, axle loads can be measured as they pass over a given section of track, thus capturing the overall input load into the track structure. The difficulty lies in understanding the distribution of these axle loads on to individual sleepers at the interface of the rail pad and the concrete rail seat area.

In order to gain a better understanding of the load path from the wheel and into the rail as it is applied to the sleeper, an investigation of various rail seat load calculation methodologies was undertaken. The methods discussed are some of what currently exist to estimate the loading conditions present at the rail seat of a concrete sleeper. The four methods presented are means of calculating the magnitude of a rail seat load in terms of the total force applied to the rail seat area, and do not relay any information on the pressure or distribution of this load. They consist of methods used by the

American Railway Engineering and Maintenance-of-way Association (AREMA 2012) and equations developed and/or used by Arnold Kerr (Kerr 2003), Josef Eisenmann (Esveld 2001), and Arthur Newell Talbot (Chambers 1980). Using simplifying assumptions and consistent values for speed and other parameters, these rail seat load calculation methodologies can be evaluated and compared (Figure 1).

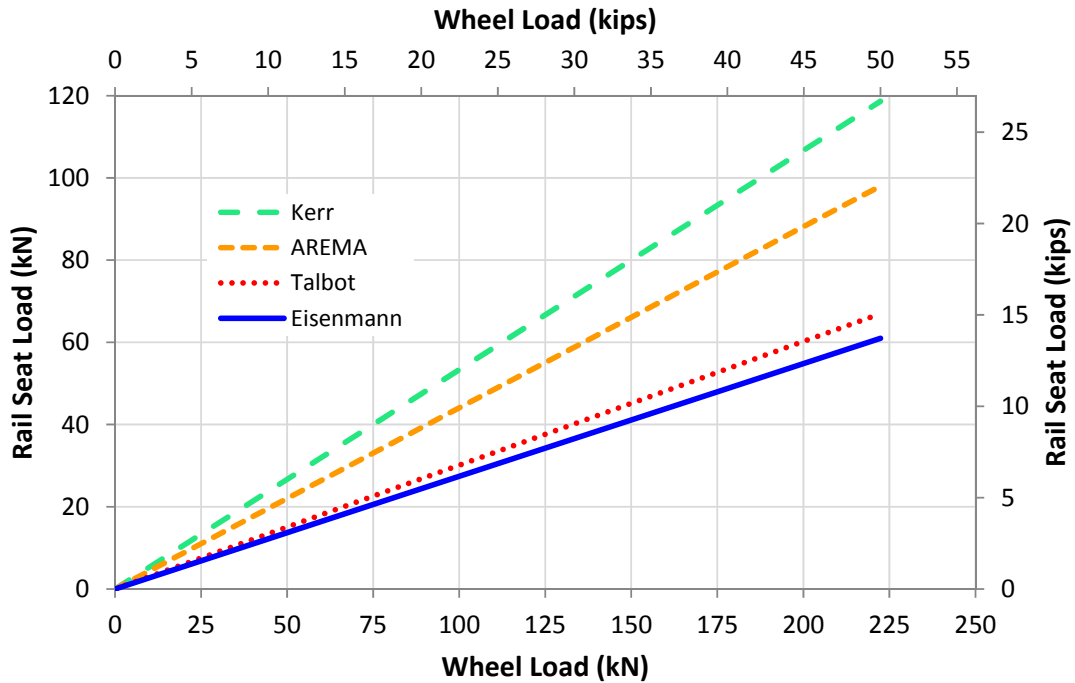


Figure 1. Comparison of rail seat load calculation methodologies

5. Load Path Mapping and Quantification

To better determine the demands on each component, an analysis of the static load path was conducted at UIUC. This static analysis of interface loads and component deflections was executed with increasingly detailed assumptions. An example of this effort for one specific fastening system and loading scenario is shown in Figure 2.

Given a particular input loading condition and appropriate simplifying assumptions, the magnitude of forces at each interface can be estimated. The effect of accelerating wheel loads and clamping force on longitudinal forces must also be considered in a comprehensive exploration. To evaluate the loads within the system more accurately, lab and field instrumentation and more sophisticated analyses, such as finite element analysis techniques, must be employed.

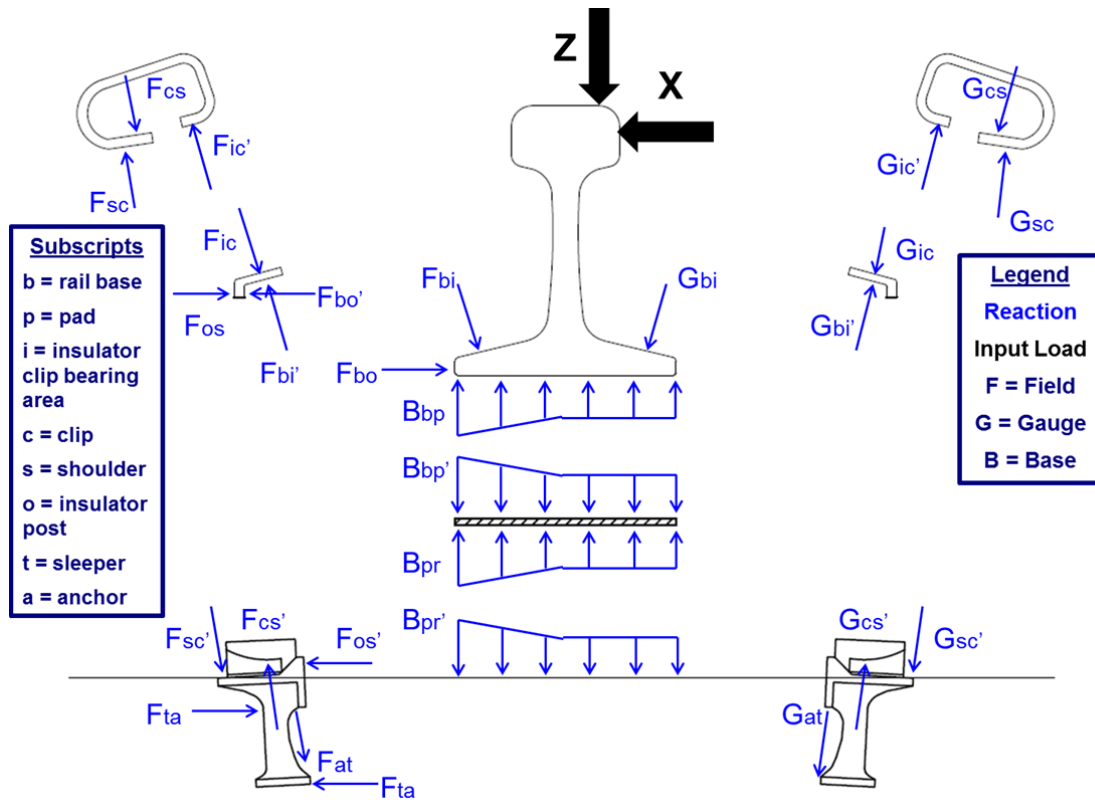


Figure 2. Concrete sleeper fastening system load path map and component free body diagram

Both laboratory and field instrumentation provide quantitative information regarding the load path through the concrete sleeper and fastening system. Using known input loads from full-scale testing in the laboratory and revenue service testing in the field, UIUC has developed a method for determining loads applied to the components within the system and their associated deflections (Grasse 2013). To correlate the interfacial loads with wheel loads applied at the wheel/rail interface, significant instrumentation is used on the rail as well. The following measurements in the vertical, lateral, and longitudinal directions were made in the laboratory and field settings: wheel loads; rail stresses, strains, and displacements; pad assembly displacements, deformations, and temperatures; sleeper strains and displacements; rail seat loads and pressure distributions; lateral force entering the shoulder; and fastening clip stress (Grasse 2013). The values obtained through these measurements provide significantly improved the understanding of the behavior of the concrete sleeper and fastening system as a whole.

In addition to the instrumentation performed on the physical system, significant three-dimensional analytical methods are also employed. Using the qualitative free body diagrams (Figure 2) as a framework and basic static principles, a fundamental analysis is performed to determine estimated loads and deflections of the components. Simplified two-dimensional finite element models are created to confirm the basic analysis and provide further guidance to the forces present within the system (Chen 2013). In parallel with both the instrumentation and basic analysis, a comprehensive finite element model is created incorporating the geometry and materials of each component and its interaction with those surrounding it (Chen 2013). This tool can model different loading scenarios, including dynamic loads, and provide valuable insight into the component response and interdependencies. Parametric analyses are performed guiding the understanding of component properties and how they relate to the performance within the expected loading regime.

6. Conclusion

While there is a relatively clear understanding of the existing static loads produced by train sets throughout the world, additional information is required for adequate design of track components and

the entire track system. It is generally understood that the complete track loading spectrum must include forces produced from various train operating speeds, as well as forces produced at various locations within the track superstructure.

This paper provides a framework for quantifying loads experienced at the wheel/rail interface. However the loading spectrum at this interface is not sufficient for the design of concrete sleepers and fastening systems because wheel loads are not the loads experienced by these infrastructure components. Various rail seat load quantification methodologies have been investigated and compared. Many factors are already considered, and there may be some additional parameters that also affect this transfer of forces. The load transfer experienced within the fastening system is of critical importance for the design of the fastening components. The efforts at UIUC will continue to improve the understanding of the demands on each of these components, leading to improved design and performance.

Acknowledgements

Funding for this research has been provided by the United States Department of Transportation (US DOT) Federal Railroad Administration (FRA). The published material in this report represents the position of the authors and not necessarily that of DOT. Industry partnership and support has been provided by Union Pacific Railroad; BNSF Railway; National Railway Passenger Corporation (Amtrak); Amsted RPS / Amsted Rail, Inc.; GIC Ingeniería y Construcción; Hanson Professional Services, Inc.; and CXT Concrete Ties, Inc., an LB Foster Company. For providing direction, advice, and resources, the authors would like to thank Mike Tomas from Amtrak, William GeMeiner from Union Pacific Railroad; and Winfried Boesterling from Vossloh. Additionally, the authors thank the members of AREMA Committee 30, Subcommittee 4 (Concrete Crosstie Technology) for their continued support and guidance in UIUC's concrete sleeper research. The authors' gratitude is also expressed to Andrew Stirk and Anusha Suryanarayanan from UIUC, who have provided invaluable service in data processing and analyzing. The authors would also like to thank Bassem Andrawes, Zhe Chen, Justin Grassé, Ryan Kernes, Daniel Kuchma, David Lange, Moochul Shin, Amogh Shurpali, and Sihang Wei from UIUC for their involvement in this research effort and Xiang Liu for review of the draft manuscript. J. Riley Edwards has been supported in part by grants to the UIUC RailTEC from CN, CSX, Hanson Professional Services, Norfolk Southern, and the George Krambles Transportation Scholarship Fund.

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