Proceedings of the 2014 Joint Rail Conference
JRC2014
April 2-4, 2014, Colorado Springs, CO, USA

JRC2014-3832

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

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Abstract

An improved understanding of the vertical load path is necessary for improving the design methodology for concrete crossties and fastening systems. This study focuses on how the stiffness, geometry, and interface characteristics of system components affect the flow of forces in the vertical direction. An extensive field test program was undertaken to measure various forces, strains, displacements and rail seat pressures. A Track Loading Vehicle (TLV) was used to apply well-calibrated static loads. The TLV at slow speeds and moving freight and passenger consists at higher speeds were used to apply dynamic loads. Part of the analysis includes comparison of the static loads and the observed dynamic loads as a result of the trains passing over the test section at different speeds. This comparison helps define a dynamic loading factor that is needed for guiding design of the system. This study also focuses on understanding how the stiffness of the components in the system affects the flow of forces in the vertical direction. The study identifies that the stiffness of the support (ballast) underneath the crossties is crucial in determining the flow of forces. The advances made by this study provide insight into the loading demands on each component in the system, and will lead to improvements in design.

Introduction

With the ever increasing axle loads and traffic on the freight transit, the use of concrete crossties is on the rise as it becomes an competitive alternative to the historical wood ties. In the current scenarios multiple failure mechanisms in the crosstie and fastening system arise which need to be repaired or replaced increasing the maintenance costs of the service lines. Loss of clamping force in the clips, abrasion and sliding out of the pads, center and rail seat cracking and rail seat abrasion of concrete crossties, loss of support among other failure mechanisms have become an increasing concern. [1] [2] It has become critical to have an improved understanding of the flow of forces in the system for developing a mechanistic design of the entire system contrary to the current individual component design methodology.

Research Objective and Scope

The objective of the field instrumentation was to quantify the concrete crosstie and fastening system response, determination of system mechanics and development of an analytical model.

In order to better design the concrete crosstie and fastening system it is imperative to understand the flow of forces in this system. It is necessary to be able to estimate the forces acting on each component. Thus, in this research an extensive field testing program was undertaken at Transportation Technology Center (TTC) in Pueblo, CO to measure various loads, strains, displacements and rail seat pressure on tangent and curved tracks (2^0 curve) under various loading scenarios. A Track Loading Vehicle (TLV) was used to apply known loads on the test section under static (zero speed) condition. The TLV was also used to calibrate some of the instrumentation as the loads applied were known and very precise. Passenger and freight cars of known weights were also used to apply dynamic loads on the test section.

This led to a comprehensive understanding of the characteristic deformations and displacements of these components and thus a comprehensive understanding of the load transfer mechanics from the wheel-rail interface, through the fastening system, and into the concrete crosstie. In this project SAFELOK 1 fastening system was used.

The data obtained from the field experimentation was also used in the validation of a three dimensional (3D) finite element model (FEM) of the concrete crosstie and fastening system which was used as a tool for conducting parametric analyses to aid in the design of concrete crossties and fastening systems.

The forces acting in the system, for the sake of understanding the system better, was be divided into two components – Vertical and Lateral. It is important to remember that these forces are not independent of each other and always act as a pair and this classification is only for the sake of convenience. The lateral force magnitude and as a result the strains and displacements in the system will be influenced by the magnitude of the vertical force and vice versa. In this paper an emphasis has been laid to understand the flow of forces in the vertical direction though that the scope of research of this project does not end here.

Instrumentation Plan

Many measurements were acquired to accomplish the objectives described above. These measurements were captured during a large-scale field experimental program conducted at the Transportation Technology Center (TTC). Some measurements were collected using well-established instrumentation methodologies, while novel approaches were used to collect data that have not been reliably captured to date.

Two section of track, consisting of 15 consecutive crossties, were selected at TTC. One on a tangent section and the other on curved section. Figure 1 provides a map of the location of all the instrumentation used in the test program at both the locations. A total of about 120 channels were used to collect data simultaneously. All data was collected using an NI CompactDAQ at 2000 Hz. It must be noted that not all the instrumentation used was used to understand the vertical load path. A description of the instrumentation relevant to the vertical load path analysis is as follows:

Vertical Wheel Loads: Vertical wheel loads were determined using an arrangement of strain gauges in the crib of the rail. Weldable strain gauges were assembled in a Wheatstone bridge pattern to measure shear in the rail and the response of the bridges were calibrated, using the TLV and applying known loads, to measure vertical wheel loads.

Gauges were placed in the chevron pattern (Figure 2) about the neutral axis of the rail section, oriented at 45° to the neutral axis. Four gauges were mirrored on each side of the rail. The centers of the two groups of gauges were measured at 5” from each side of the center of the crib.

Vertical Rail Seat Loads: A similar configuration of strain gauges, as that used for vertical wheel load, was installed directly above the rail seat area to capture the resultant shear force acting on the rail as a result of the wheel load and the reaction force from the tie. Having captured the vertical wheel load and the resultant shear force, a simple free body diagram analysis gives the vertical rail seat load (= vertical wheel load – resultant shear force).

Vertical Rail Displacement: Potentiometers were used to measure the displacement of the rail base relative to the crosstie (Figure 3). Under the influence of a vertical load the less stiff component of the vertical load path, i.e. the pad assembly, was excepted to compress. The potentiometers were mounted on the ties and touching the top face of the rail base flange 1.5” from the edge to capture this compression of the pad. It was safe enough to assume in this case that the rail base does not compress comparable to the pad assembly.

Vertical Web Strains: Strain gauges were placed nearly at the base of the web of the rail on both field and gage side above the rail seat area. Using these measurements across seven crossties, the strain values assessed the load distribution of the applied vertical load longitudinally along the track. These gauges captured the vertical strain in the rail under the influence of pure vertical loads and were also used to capture the bending of the rail when lateral loads acted on the system. The two gauges on either side together helped estimate the extent of bending in the rail.

Vertical Tie Displacement: Vertical crosstie displacements were measured at each end of the crosstie relative to the ground using linear potentiometers affixed to a rod driven to refusal in the ballast adjacent to the ties (Figure 4). These measurements, when coupled with other measurements, were used to determine the support stiffness under each rail seat.

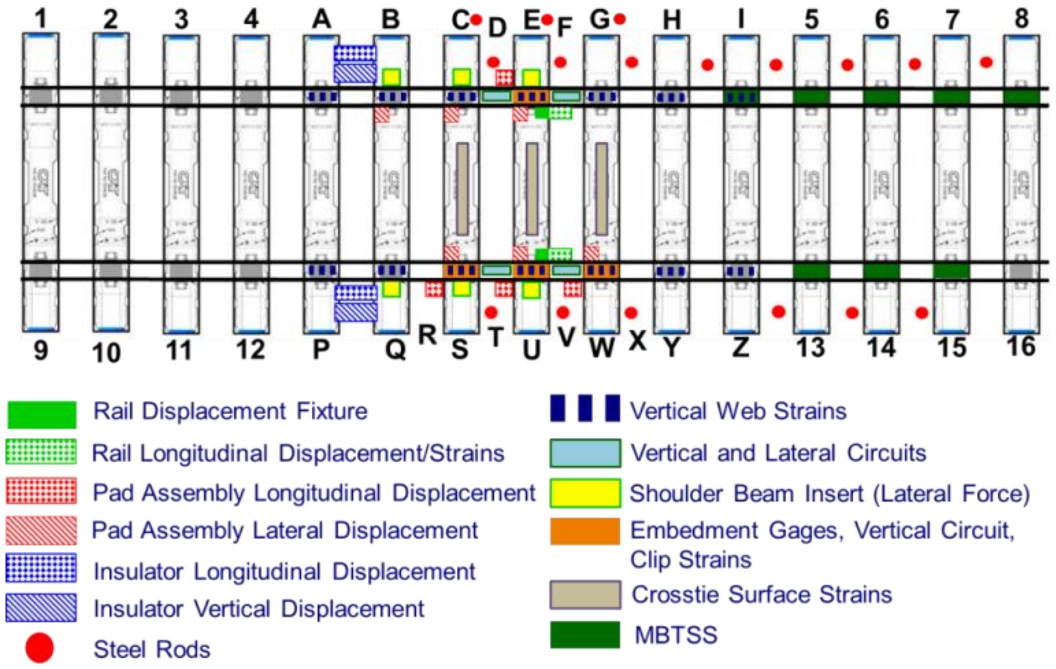


Figure 1 : Location of all instrumentation across the 15 crosstie test section

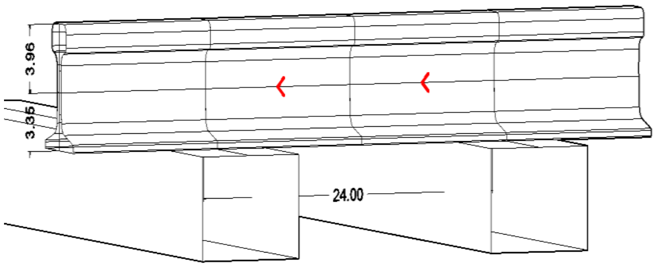


Figure 2: Arrangement of gauges to capture vertical wheel loads

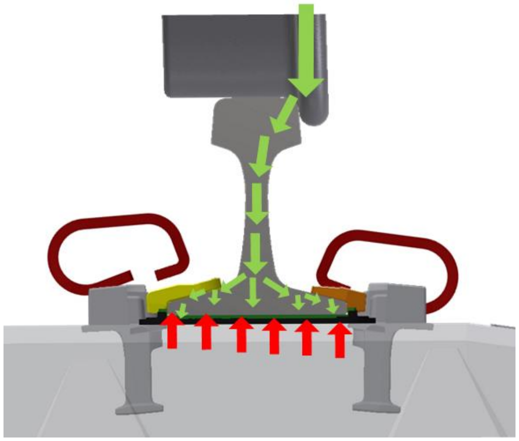
Figure 4 : Vertical crosstie displacement

Defining the vertical load path

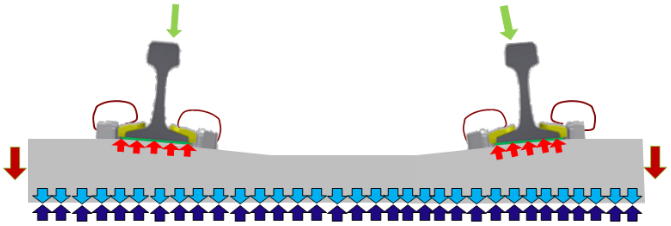
The vertical load path can be defined as the flow of forces from the wheel-rail interface through the rail, fastening system, crossties and into the ballast.

Figure 3 : Vertical rail displacement fixture

The vertical load from the wheel cars acting at the wheel-rail interface flows through the head of the rail through the web to the base flange of the rail which rests on the pad assembly below it. The pad assembly is compressed between the rail base and the reaction from the tie. The reaction of the tie translates in to a load on to the ballast underneath it. This load on the ballast compresses it and in the deflection of the tie. The stiffness of the ballast determines the extent of this deflection. It was observed that the extent of this deflection was critical to the distribution of forces as will be discussed later. Figure 5 depicts the flow of forces as described above.



5a. Flow of vertical forces until the rail seat



5b. Flow of vertical forces up to the ballast

Figure 5: Flow of vertical forces in the system

Vertical Crosstie Deflections

As described earlier and depicted in Figure 5 the loads at the wheel-rail interface translates into deflection of the crossties. Figure 6 is a plot of the observed deflections of the multiple rail seats (labelled in Figure 1) under static loading under a TLV on tangent track.

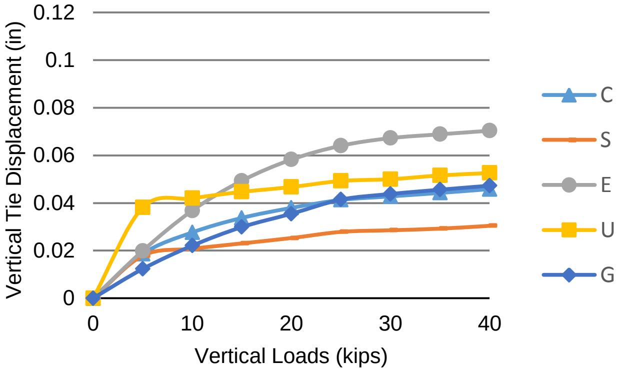


Figure 6 : Crosstie deflections under various rail seats

It was observed that there is a significant difference in the displacement values of different rail seats under the same applied load. This difference was attributed to the difference in the existing compaction level of the ballast across the length of the track. It was also observed that two rail seats on the same crosstie (eg: E and U) also exhibit different deflections indicating uneven compaction levels even under the length of the crosstie. It must be noted that this is the case in spite of it being a well maintained section of the track in a research facility and that a similar or worse conditions could be expected in the field where the maintenance activities are not as frequent. Li et at. [3] in their study state that the variability in vertical stiffness along a track section is more common on softer or weaker track section compared to a stiffer section.

Several methods to determine track stiffness have been used. [4]Figure 7 is a plot of the crosstie deflections after a pre-load of 10 kips was applied. This method is used by some to estimate the vertical stiffness of the track. [5] As can be seen in the plot, the deflections of the rail seats with a 10 kip preload are much more consistent with each other than before indicating that the different rail seats behave similarly once the initial voids in the ballast are closed. But this initial variation in deflection significantly affects the flow of forces in the system as will be discussed later.

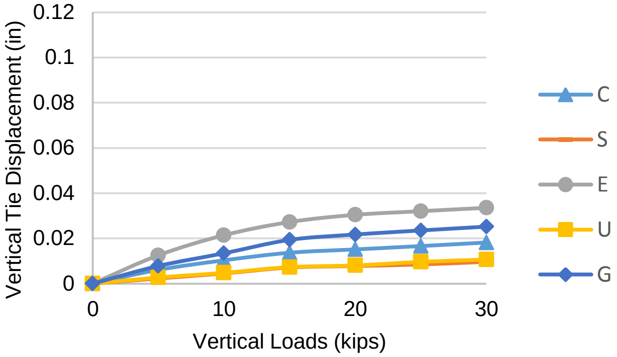


Figure 7 : Crosstie deflections with 10 kips pre-load

Rail Seat Loads

Rail seat load is an important input parameter in the design of concrete crossties and fastener systems. Estimating this value is critical to the efficiency of the design.

As described in the previous section the rail seat loads were estimated using strain gauges on the rail in a whetstone bridge configuration above the rail seat area. In this section comparison has been made between the observed rail seat loads against the loads acting at the wheel rail interface. Figure 8 is a plot comparing the recorded rail seat loads at rail seats E and U (as in Figure 1). It should be noted that these are two rail seats on the same crosstie in the center of our section.

A significant difference was observed in the rail seat loads, under the same applied load at the wheel-rail interface, at the two rail seats though they are on the same tie. Rail seat loads were observed to be 30-80% of the applied loads at the wheel-rail interface.

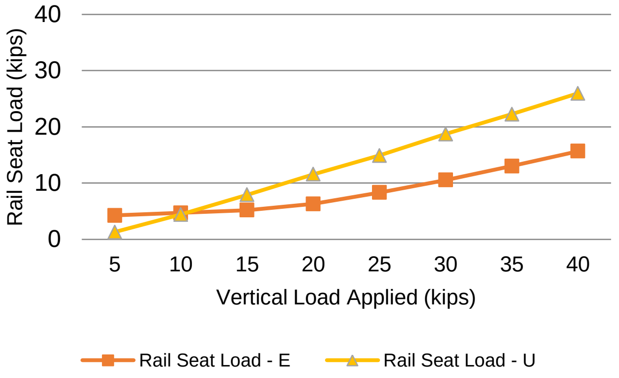


Figure 8 : Observed Rail Loads

A number of factors could contribute to this difference. But as discussed earlier and by referencing Figure 9 a relation can observed. Figure 9 is a plot comparing the rail seat loads against the vertical crosstie deflection of two rail seats E and U on the same tie.

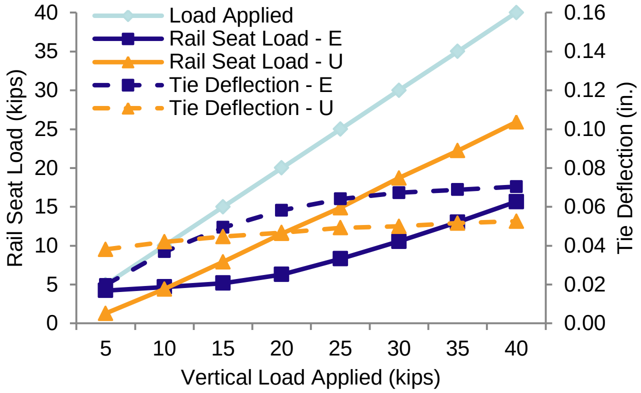


Figure 9 : Comparing rail seat loads and crosstie deflections

Under exactly similar conditions of loading it was observed that with higher deflections (rail seat E) lower the rail seat load at the particular rail seat, indicating a greater distribution factor over to the adjacent ties. Similarly with lower deflections (rail seat U) higher rail seat loads were recorded indicating lower distribution factors over to the adjacent ties. The same pattern was observed for the other rail seats recorded as well.

This concludes that the support stiffness underneath the crossties resulting in deflections of the crosstie of the plays a significant role in the fraction of the load transferred to the rail seat. .

It is the rail seat load and not the load at the wheel-rail interface that acts on the ties and the fastening system thus accurately estimating the fraction of the load transferred to the rail seat and controlling it to the extent possible is critical to the design of the components.

Dynamic Loading Conditions

All the data presented and discussions thus far were based on static loads applied on the system. Study of the system under static condition helps us understand the system better with fewer variables. But this is the case only at loading/unloading stations, maintenance yards etc. Most of the time it is dynamic forces that act on the track and thus it is critical to understand the systems response under dynamic loading conditions in comparison to the static case.

In this study, as stated earlier, dynamic loading data was collected by running freight and passenger trains over the test section. Some of the freight cars were loaded to the typically prescribed 286k lbs and upto 315k lbs. The passenger cars used were used empty and weighed around 86k lbs. Both the passenger and freight cars were run at multiple speeds to understand the influence of speed on the behavior of the system.

An attempt was also made to capture data simulating imperfections in wheels like flat spots by intentionally including an wheel with a flat spot. But due to the limitation of the length of the instrumented track section the flat spot did not always make contact with our instrumented section thus limiting the amount of data collected. The data collected was not significant enough to draw conclusions and thus has not been reported.

Dynamic loads

A comparison of the input loads into the system as a result of the dynamic effect of the freight and passenger car at different speeds was made. Figure 10 indicates the dynamic loads, recorded by the instrumentation under the influence of a passenger train at different speeds, in comparison to the static axle load of the same car. The data presented in Figure 10 is a mean value of six consecutive axles, with the same static axle load, run twice over the test section (tangent track). The graph also includes error bars indicating the maximum and minimum recorded values and quartiles encompassing 25 and 75 percentile occurrences of the values.

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

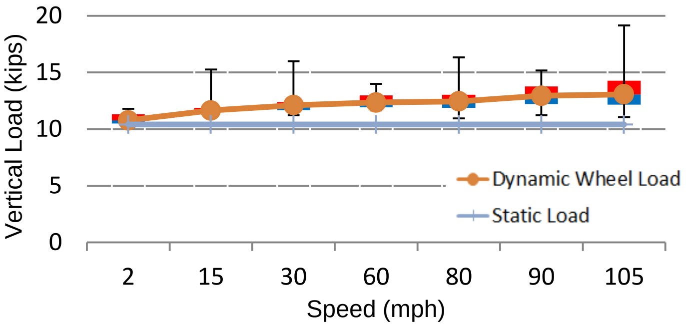


Figure 10 : Dynamic wheel loads of a passenger car at different speeds, Tangent track

Figure 11 represents the data collected on the same section of the track under the influence of a loaded freight train. The data presented in Figure 11 is also a mean value of six consecutive axles, with the same static axle loads, run twice over the test section (tangent track).

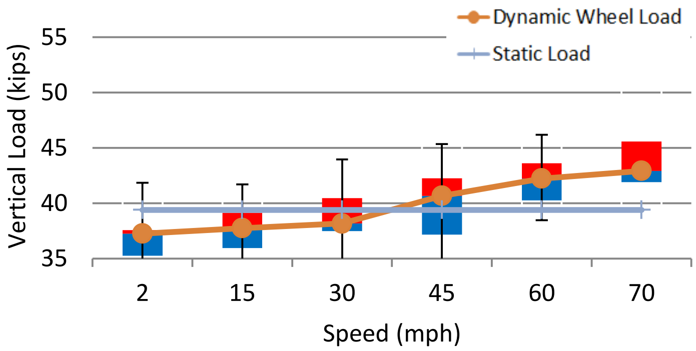


Figure 11: Dynamic wheel loads of a freight car at different speeds, Tangent track

A similar trend as compared to the passenger train can be seen even in the case of a freight train where the dynamic loads differ by about 10% compared to the static loads, suggesting a dynamic factor of about 1.2 for this data set.

On the curved section of the track the results were different. The load experienced by the system was influenced by the speed of the train, as depicted in the case of a freight train in Figure 12.

It was observed that as the speed of the train increased the load experienced by the system on the high rail increased. It was also observed (not shown here) that the loads experienced on the low rail decreased. This can be explained by the fact that a centripetal force acts on the moving train on the curved section. The loads increase on the high rail with speed indicated that the dynamic factor is a function of speed on curved tracks. It is to be noted that the increase in load was significant (upto 60%), suggesting a dynamic factor of about 1.6 at 45mph on a 2^0 curve section.

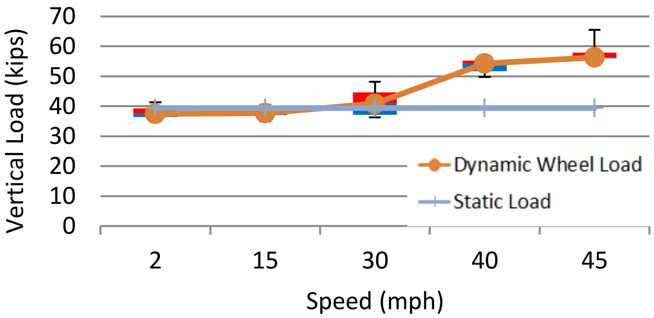


Figure 12 : Dynamic wheel loads of a freight car at different speeds, High rail - Curved track

The magnitude of impact loads due to wheel irregularities as captured in our limited data set were in the range of 200-300% of the static load. But, it must be remembered that though these irregularities resultedin significantly high loads they acted for a relatively very short duration on the system limiting their impact.

The AREMA manual, 2012, in Chapter 30 [6] suggests the use of an impact factor of 200% over the expected loads for the design of track components to account for the irregularities in the wheels and rail. But, the manual does not make a distinction between dynamic and impact factors. Dynamic factors of about 1.2 on tangent section and up to 1.6 on the curved section were observed. These values are significant and cannot be neglected, especially on the curved sections

On a track which is well maintained the effect of the irregularities could be minimized but the dynamic factor due to the motion of the train will continue to exist. It is thus important to make a distinction between dynamic and impact factors and incorporate both in the design of components.

Conclusions

The observed loads over the test sections were similar to revenue service loads, minus the impact loads as the section was on a well maintained track.

The vertical deflections of different rail seats under the influence of the same load varied significantly between adjacent ties and even between the two rail seats on the same tie, indicating high variability in ballast stiffness along the track.

The rail seat load observed varied between 30-80% of the vertical wheel load . It was observed that the rail seat load was significantly influenced by the vertical tie deflection and thus the high degree of variability in the fraction transferred as the tie deflections varied significantly. Lower rail seat loads were observed at ties with higher vertical deflection and vice versa.

The observed dynamic load factors for tangent and curved section of the tracks in this case were about 1.2 and 1.6 respectively. The dynamic factor is a function of speed on the curved track. These factors are significant and it is necessary that a distinction be made between these dynamic and impact factors for design considerations, especially on curved sections.

The impact loads were not captured effectively but in the limited data set the magnitude of these loads was in the range of 200-300% of the static load of that axle.

References

[1] J. Zeeman, "Hydraulic mechanisms ofconcrete-tie rail seat deterioration," 2010.

[2] J. White, "Concrete tie track system," *Transportation Research Record,* v 953 pg 5-11, 1984.

[3] D. Li, R. Thompson and S. Kalay, "Update of TTCI'S research in track condition testing and inspection," 2004.

[4] A. D. Kerr, "The determination of track modulus k," *International Journal of Solids and Structures,* Vols. 37, n 32, pp. 4335-4351, 2000.

[5] R. Thompson, "Track strength testing using TTCI's rack loading vehicle," *Railway track and Structures,* Vols. 97, n 12, pp. 15-17, 2001.

[6] "American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering," v 1, ch. 30,, 2012.