National University Rail Center - NURail
US DOT OST-R Tier 1 University Transportation Center

NURail Project ID: NURail 2016-UKY-R12e

Comparisons of Railway In-Track Tie/Ballast Interfacial Impact Pressure Measurements with Wheel/Rail Surface Impact Load Detector (WILD) Readings

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23-April-2018

Grant Number: DTRT13-G-UTC52

DISCLAIMER

Funding for this research was provided by the NURail Center, University of Illinois at Urbana - Champaign under Grant No. DTRT13-G-UTC52 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research & Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

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TECHNICAL SUMMARY

Title

Comparisons of Railway In-Track Tie/Ballast Interfacial Impact Pressure Measurements with Wheel/Rail Surface Impact Load Detector (WILD) Readings

Introduction

This report is based on a research study having the primary objective to compare wheel/rail surface impact loadings obtained from wheel impact load detectors (WILDs) with correspondingly transmitted trackbed tie/ballast impact pressures for revenue train operations. Particular attention was given to analyzing the effect of measured wheel/rail impact forces on transmitted tie/ballast interfacial pressures.

Approach and Methodology

A recently perfected procedure was used for measuring average pressures transmitted from the wheel to the track, directly under the rail contact patch, at the tie/ballast interface. The specially designed Geokon granular material cells were precisely positioned to measure the interfacial pressures along six consecutive ties, encompassing a complete wheel revolution. Data was obtained for a variety of freight trains over a period of several months during 2017. The test site is located at Mascot; just east of Knoxville, TN on a major east-west Norfolk Southern mainline.

A WILD is strategically located on each of the two mainlines diverging west of Knoxville. Pressure data was obtained on the combined line east of Knoxville for the eastbound trains that had recently traversed the WILD at either Flat Rock or Ebenezer, and for westbound trains that would soon traverse one of the WILDs.

Data obtained from the Mascot in-track tie/ballast interfacial pressure measurements, and data from the wheel/rail nominal and peak dynamic loadings obtained from the appropriate WILD installation for the corresponding freight trains, were compared to establish relationships and evaluate the effects of WILD impact loadings on transmitted trackbed tie/ballast interfacxial pressures for identical wheels.

Findings

This report describes the development of a method to measure average railroad track tie/ballast interfacial pressures using pressure cells specially designed for granular materials. The validity of the test method was initially verified with a series of laboratory tests using controlled loading magnitudes on prototype sections of trackbed with specially designed resilient frames/boxes for simulating typical in-track loading conditions. The selected procedure provided excellent correlation between controlled applied laboratory machine pressures and simultaneously measured cell pressures. The cells were recessed within the bottom of the ties for both the laboratory verification tests and subsequent in-track revenue train tests.

For the in-track tests, a series of cells were positioned under the rail at successive tie/ballast interfaces. Trackbed pressure measurements were conducted for numerous revenue freight trains during several months. After raising and surfacing the track, following installation of the instrumented ties, the track (mainly ballast) was permitted to further consolidate under normal accruing train traffic to insure that the ballast was tightly and uniformly compacted under the ties to effect transmission of equalized pressures from each of the ties to the ballast.

Measured pressures, directly below the rail/tie primary influence area at the tie/ballast interface, are considerably lower than trackbed pressures previously assumed for locomotives and loaded freight cars. These measured pressures range from 20 to 30 psi (140 to 210 kPa) for smooth wheels producing negligible impacts.

WILD wheel loading magnitudes obtained from nearby WILD wayside detectors were compared to trackbed pressure data for the same trains traversing the trackbed pressure cell test site. Various measured WILD parameters were compared to recorded trackbed pressures for loaded freight cars. The results indicate that increases in Peak wheel load values relate favorably to increases in recorded trackbed pressures. As an example, based on the regression relationship, as the Peak loadings increase -- the tie/ballast interfacial pressures increase by a factor of 2.25. Similar results were obtained comparing increased Nominal wheel loadings and increased tie/ballast interfacial pressures; pressures increased by a factor of 2.79.

The positive relationship between WILD loadings and corresponding tie/ballast interfacial pressure levels was further substantiated by comparing WILD Peak force and Nominal force relationships to measured tie/ballast pressures for an intermodal train. A R-squared value in the range of 0.8 was obtained for a variety of wheel loads.

The relationship between WILD Nominal wheel loading and tie/ballast pressure measurements is quite good for the higher magnitudes of wheel loadings. An R-squared value of 0.92 was obtained for a group of trains, excluding the light (empty car) wheel loads, and only considering the loaded car and locomotive wheel loads.

Conclusions

Measured pressures, directly below the rail/tie primary influence area at the tie/ballast interface, are considerably lower than trackbed pressures previously assumed for locomotives and loaded freight cars having smooth wheels producing negligible impacts.

Higher wheel load magnitudes and increased dynamic impacts due to imperfections in wheel-tread surfaces increases the magnitude of the pressures correspondingly transmitted to the trackbed support as indicated by increased in-track pressures measured at the tie/ballast interface. The added increase in tie/ballast pressure, due to the impact of imperfect wheel surfaces, basically serves in a similar manner as increasing the nominal permitted wheel loads. The resulting increased dynamic impact forces can contribute to higher degradation rates for the track component materials and more rapid degradation rates of the track geometry.

Recommendations

Based on the findings and conclusions for this study, following are several recommendations that should be implemented for further studies of this subject.

The stability and tightness of the ballast support influences the magnitudes and consistencies of the recorded ballast pressures. Considerable effort will be required to provide consistent ballast support conditions for the instrumented ties and adjacent undisturbed transition ties. Railroad maintenance crews must surface and tamp through the test section and adjacent approach ties. This effort along with normal accruing train traffic will subsequently result in reasonably consistent support pressure measurements throughout the test section.

Imbedding the cells within the ties and securing the cells to the ties negates the cells from settling in the ballast over time to develop gaps and “bridging”, however the ballast must be adequately and uniformly tamped to realize this advantage.

The ballast in the vicinity of the instrumented and approach ties should be uniformly consolidated/tamped to achieve equal vertical support for the ties assuring an equalized track modulus throughout the test area.

It is desirable for the test area to accumulate several months of normal train traffic and tonnage to further homogenize the trackbed support prior to drawing specific conclusions relative to the results of a testing program.

Publications

Watts, T.J., Rose, J.G., and E.J. Russell. “Relationships between Wheel/Rail Surface Impact Loadings and Correspondingly Transmitted Tie/Ballast Impact Pressures for Revenue Train Operations”. Proceedings of the 2018 Joint Rail Conference, Paper JRC 2018-6184, April, 2018, 10 pages.

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SECTION 1: INTRODUCTION

The undesirable effects of wheel/rail impact loadings on the track and supporting structure have been considered and evaluated for many years. A primary reason for the virtual demise of jointed rail track for mainline trackage was to eliminate the need of incorporating joints every 39 ft (11.9 m). The impact forces that ensued from the wheels having to cascade across the open section of the rail at the joint resulted in impact forces on the track and support structure with attendant settlement of the track in the vicinity of the joint. The individual rails became misaligned vertically across the joint and the wheels added additional impact forces and accelerated wear at the rail ends. This also increased impact forces and settlement of the track and support structure. Railroad track maintenance forces routinely raised and surfaced the track in the joint areas to reduce impact forces at the joints. This was particularly the prevailing situation when marginal quality trackbed support layers were often the norm, and when coupled with inadequate drainage, the trackbed provided less than desirable structural support.

Technological advances beginning in the mid-1900s to produce continuously welded rail (CWR) resulted in the advancement of installing rail without joints which was subsequently widely adopted as a standard for mainline track. A smoother and much improved ride quality ensued with greatly decreased impact forces at the wheel/rail interface. This in turn reduced track maintenance efforts and costs, which extended the life of the rail and track components.

Although the adoption of CWR for mainline, high-tonnage rail lines eliminated the primary source of wheel-rail impact forces, it alone did not completely eliminate impact forces. An additional source of impact forces was due to imperfections in the wheel tread contact surface as it rolled along the rail. These were typically flat spots, but also included imperfections in the steel, resulting in “rough” spots on the tread surface. The impact forces resulted in higher stresses in the wheel and the rail that could result in damage to the rail cars and lading and damage to the track and support structure.

The technology for continuously measuring contact forces, including normal and added impact forces due to wheel imperfections, was developed in 1983. Salient Systems (recently became a wholly owned subsidiary of LB Foster Company) was involved with the early development and applications of this technology. The incorporation of wayside wheel impact load detectors (WILDs) began in 1984 and by 1995 more than sixty systems had been installed in North America and Europe by Salient Systems.

The incorporation of WILDs is considered a standard practice for major railroads. These are strategically placed at selected locations throughout the system in order to routinely measure and evaluate the presence and severity of wheels producing high impact forces at the wheel/rail interface. Wheels having imperfections exceeding specified limits are detected, inspected, tracked, removed based on specified criteria, and replaced with new wheels based on industry standards.

SECTION 2: OBJECTIVES AND RESEARCH PLAN

The primary objective of this research was to compare wheel/rail surface impact loadings obtained from WILD defect detectors with correspondingly transmitted tie/ballast impact pressures for revenue train operations. Particular attention was given to analyzing the effect of measured wheel/rail impact forces on transmitted tie/ballast interfacial pressures.

A recently perfected procedure was used for measuring average pressures transmitted from the wheel to the track, directly under the rail contact patch, at the tie/ballast interface (1,2). The specially designed Geokon granular material cells were precisely positioned to measure the interfacial pressures along six consecutive ties, encompassing a complete wheel revolution. Data was obtained for a variety of freight trains over a period of several months during 2017. The test site is located at Mascot; just east of Knoxville, TN on a major east-west Norfolk Southern mainline.

A WILD is strategically located on each of the two mainlines diverging west of Knoxville. Pressure data was obtained on the combined line east of Knoxville for the eastbound trains that had recently traversed the WILD at either Flat Rock or Ebenezer, and for westbound trains that would soon traverse one of the WILDs. A view of the NS track layout in the area, with the test sites identified, is shown in Figure 2.

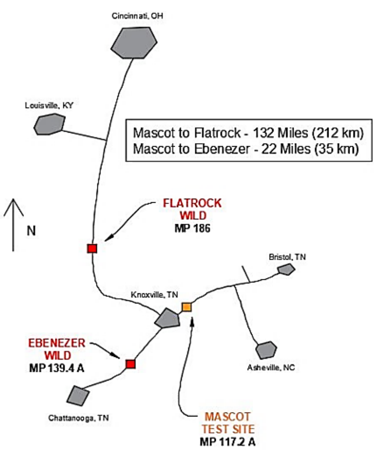

Figure 2. Track test site at Mascot and the locations of the Mascot test site and the two WILD test sites west of Knoxville for the main NS rail lines through Knoxville.

Data obtained from the Mascot in-track tie/ballast interfacial pressure measurements, and data from the wheel/rail nominal and peak dynamic loadings obtained from the appropriate WILD installation for the corresponding freight trains, were compared to establish relationships and evaluate the effects of WILD impact loadings on transmitted trackbed pressures for identical wheels.

SECTION 3: PRESSURE TESTING PROCEDURE

It has been desirable for years to develop a reasonably simple, accurate, and reliable method to directly measure average vertical pressure magnitudes and distributions at the tie/ballast interface in railroad trackbeds. Quantifying the magnitudes and relative distributions of pressures at the tie/ballast interface are important inputs for trackbed engineering design and analysis aspects. The pressures produced by millions of load applications ultimately affect the long-term performance of the track by reducing the service lives of the component materials and layers.

Ideally the interstitial pressure intensities at the tie/ballast interface can be reduced by distributing pressures uniformly over large contact areas, thereby reducing abrasion, wear, and crushing of the bottom of the tie and the surface layer of the ballast. This also reduces the proportion of the loadings having to be supported by the ties and rail, lengthening the service life of the track.

SECTION 4: PREVIOUS LABORATORY CONFIRMATION OF PRESSURE TESTING PROCEDURE

Recent research has shown that a specially designed Geokon Model 3515 granular material pressure cell is accurate and repeatable for measuring tie/ballast interfacial pressure for controlled loading conditions in the laboratory using simulated in-track loading conditions. (1).

A cell consists of two circular 8 in. (200 mm) diameter stainless steel plates welded together around the periphery, separated by a small gap (void) filled with hydraulic fluid. The pressure cells have an active area of 50.3 in2 (324 cm2). Applied pressure squeezes the two plates together, creating fluid pressure in the cell. The two plates are sufficiently thick so they do not deflect locally under the point loads from surrounding large aggregate particles.

A pressure transducer installed in the steel cell housing transforms the fluid pressure to a current signal. The measured pressure is the average pressure on the active area. The pressure range of the pressure transducer is 0 to 360 psi (0 to 2.5 MPa).

A National Instruments (NI) Model 9203 C Series Current Input Module was used for data acquisition. The 12Vdc module has eight analog -20 mA to 20 mA current input channels with a maximum 200 kHz sample rate. Figure 2 shows a pressure cell and the data logger module.

A user-friendly program for data collection was developed using LabVIEW. The program can change units from mA to MPa and psi synchronously and show the pressure magnitude trace in real time during a test. The experiment sampling rate was 2000 samples/s (Hz).

The tests showed that positioning the cell within a recessed (routed) portion of a wood tie flush with the bottom of the tie (Figure 4) did not affect the pressure distribution when compared to placing the cell below a solid tie. Recessing the cell is necessary for in-track measurements so that the cell, transducer housing, and instrument cable can be contained in the recess and be protected from track equipment routinely used to raise, surface, and tamp the ballast while adjusting the track geometry.

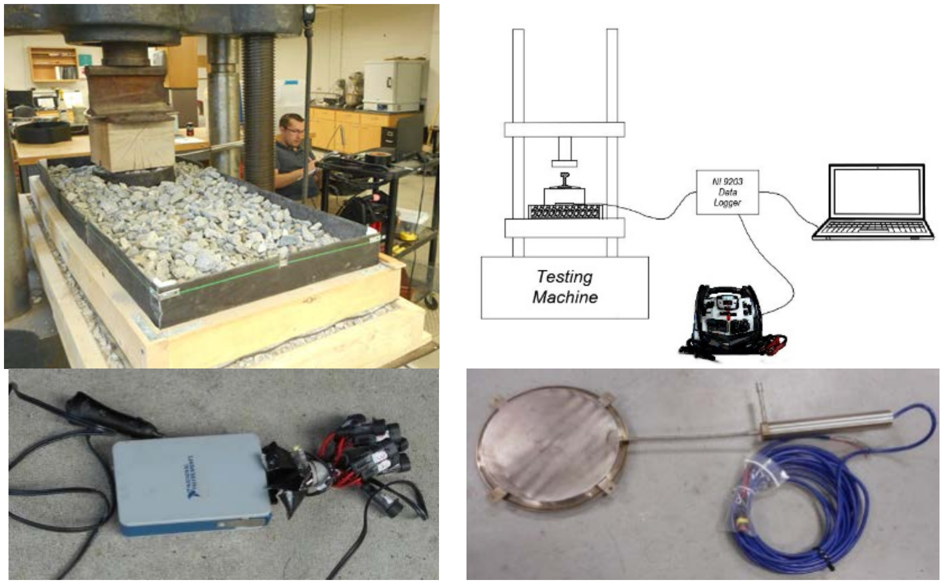

Figure 4. Laboratory trackbed support and loading system for simulated in-track loading conditions (top); pressure cell and data logger (bottom).

Furthermore, attaching the cell to the tie (necessary for in-track measurements) did not affect the transmitted pressures compared to just loosely inserting the cell. It is necessary for in-track measurements to attach the cell within the tie to prevent the cell from migrating downward in the ballast such that the tie actually "bridges over" the cell resulting in lower measured pressures than typical pressures (3).

SECTION 5: PREVIOUS IN-TRACK PRESSURE TESTING

The laboratory calibration and developed testing procedure confirmed that the Geokon Model 3515 granular materials pressure cell would be applicable for subsequent in-track tie/ballast pressure measurements provided the cell was imbedded within a recess in the bottom of the wood tie so that the active surface of the cell was even with the bottom surface of the tie. Furthermore, it was determined that if the cell had to be firmly attached to the tie.

In-track tie/ballast pressure testing has been underway at the Mascot test site for the past 18 months (2). Ten pressure cells were placed in the 1 in. (25 mm) routed portions of wood ties. NS maintenance crews removed the existing ties and installed the instrumented ties with minimum disturbance to the trackbed ballast, as shown in Figure 5a. Six of the cells are positioned under the rail for six consecutive ties on the north side of the track; test results for these six cells are used for the WILD data comparisons. Additional cells are positioned under the rail for two companion ties on the south side of the track. Also, cells are positioned under two ties in the center of the track to obtain comparative data. Schematics of the cell locations in the track at Mascot and the locations of the cell within the ties are shown in Figure 5b.

The Mascot test site is located on a mainline track with 136 RE continuous welded rail secured with cut spike fasteners to wood ties. Ties are positioned on 20 in. (500 mm) centers and each tie is box anchored. The track support consists of standard NS mainline granite ballast on a well-

Figure 5a. NS crews inserting instrumented ties in the trackbed at Mascot. The bottom view is an instrumented tie prior to installing in the track. The recessed cell will be on the bottom of the tie, level with the surface of the ballast.

seasoned roadbed. There are no indications of mud or fouling. NS personnel report that the area has a long record of stable roadbed/trackbed requiring minimal trackbed and roadbed maintenance. The test area was timbered and surfaced in November 2015. The quality of the ties in the test area is considered satisfactory for FRA Class 4 track.

The site is on a horizontal tangent with a 0.25 percent vertical grade eastbound ascending. The FRA Class 4 track annually carries 37 million gross tons (33.6 million gross tonnes) of traffic, with a maximum train speed of 45 mph (72 km/h).

All east-west bound trains passing through Knoxville traverse the test section. A wayside automatic equipment identification (ADI) reader adjacent to the test site documents passing train consists. In addition, through trains pass over a WILD site west of Knoxville, either at Ebenezer, TN or Flatrock, KY. Data from these installations permits subsequent comparisons of the tie/ballast pressures versus wheel loads at the Mascot test site.

Initial testing revealed that the properties of the track and pressure distribution within the support are highly dependent on the relative consolidation/denseness of the ballast (2). Initial pressure measurements were considered marginally representative of typical pressure distributions for a well-consolidated, ballast supported trackbed. It is highly desirable to tamp existing (undisturbed) ties on the approaches in addition to tamping instrumented ties to homogenize the compaction of the ballast in the vicinity of the ties.

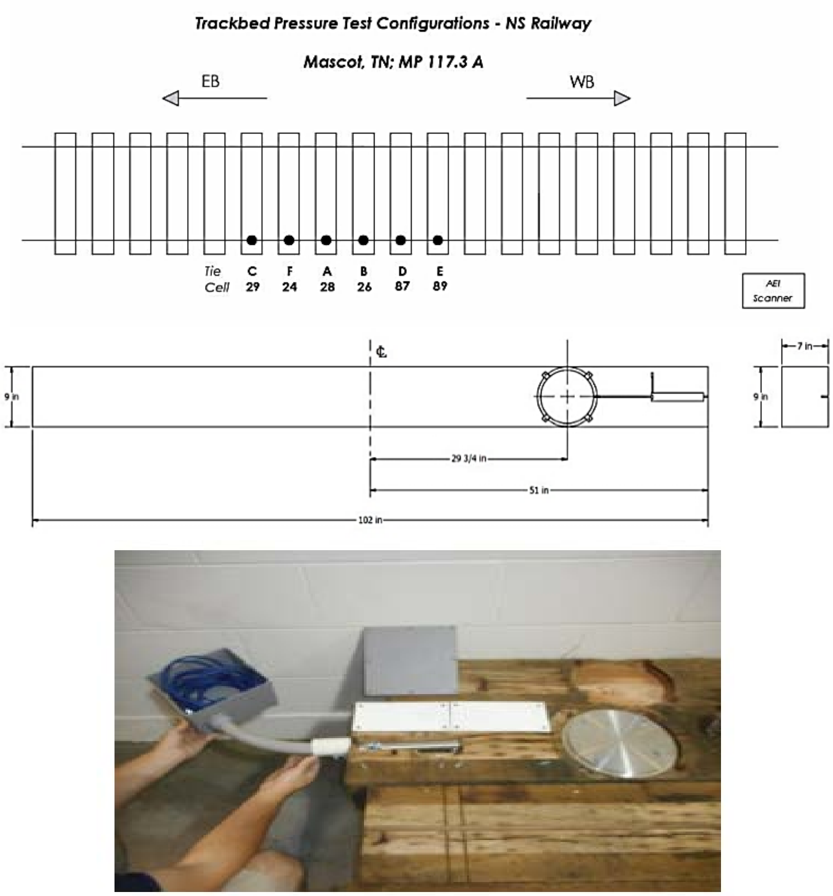

Figure 5b. Locations for the cells at the Mascot test site and locations of cells within the ties. The active portion of the recessed cell is even with the bottom surface of the tie and the remainder of the cell is protected from the ballast pressure and abrasion.

Subsequently a track raise was performed with additional tamping to insure that the level of compaction of the ballast was uniform for the approach ties and instrumented ties. This insures equalized vertical support for the ties so that an equalized track modulus will exist throughout the test area. Figure 5c contains views of raising, surfacing, and tamping the track and testing procedure for measuring tie/ballast interfacial pressures.

Cursory evaluations of the initial trackbed pressure data and comparable WILD data indicated that a relationship existed. This implied that wheels providing higher than nominal loading forces, thus impact, when traversing the WILD produced noticeable increases in tie/ballast pressures. However, several months of traffic provided sufficient compactive effort for the ballast to consolidate uniformly under the instrumented ties. Therefore, the data presented in the following sections was obtained for trains passing over the Mascot test site several months after the ballast was last manipulated.

Typical tie/ballast pressures for locomotives and loaded freight cars ranges from 20 to 30 psi (140 to 210 kPa) for smooth wheels producing negligible impacts. These measured pressures are considerably lower than typically assumed for a high-tonnage ballasted wood tie track (2).

However, the effect of increased wheel/rail impacts and peak loadings on the correspondingly transmitted pressures at the tie/ballast interface is significant, with increased pressures of several orders of magnitudes. This aspect will be discussed in detail in the following section.

Figure 5c. Experimental test equipment for obtaining pressure data (left) and raising, surfacing, and tamping process to uniformly consolidate the ballast throughout the test area and the experimental test equipment for obtaining pressure data (right).

SECTION 6: WILD TESTING PROCEDURE

A wheel impact load detector (WILD) consists of a series of individual strain gauges mounted on the neutral axis of web of the rail for a consecutive series of cribs for measuring vertical rail strain in order to calculate wheel loads. WILD sites are located on tangent track where lateral to vertical load ratios are typically less than 0.1. The track and support consists of premium size rail on concrete ties overlying a typical thickness of premium ballast supported by a well compacted thickness of subballast, typically hot-mix asphalt, and a well-compacted subgrade. This will reduce sources of variations within the track structure due to geometry and support conditions irregularities.

A WILD site normally involves about 200 to 250 ft (61 to 76 m) long section of track. This contains the track measurement zone, that is typically 50.5 ft (15.4m) long, and transitions on each ed. The rail is instrumented at various intervals to capture each single wheel's rotation at least two times. Peak loadings, which include impact, as well as nominal or average loadings are collected at 25 kHz frequency. The static wheel load is estimated by filtering the average or nominal forces from the peak forces by using an algorithm that analyzes variability along the site.

The PEAK wheel load is simply the highest recorded measurement from the strain gauge closest to the impact. It is the maximum impact force and is used for analyzing impacts for loaded cars and locomotives at a constant speed. For a given defect, the PEAK will tend to increase with vehicle weight and/or speed. The Association of American Railroads issues industry standards (criteria for repairs) for WILD alarms. The minimum alert threshold is 65 kips (290 kN).

The DYNAMIC Impact is the difference between the PEAK Load and the NOMINAL Load. This term is useful for analyzing intermediately loaded vehicles, but there are no industry threshold standards based on Dynamic Impact.

The PEAK Load divided by the NOMINAL Load is the RATIO or Impact Factor. It is useful for analyzing empty or lightly loaded vehicles. Although there is no alert threshold for Ratio, it is observed that once the ratio becomes higher than 3, it is likely that the vehicle will exceed the established Peak threshold when heavily loaded. These relationships are shown in Figure 6a.

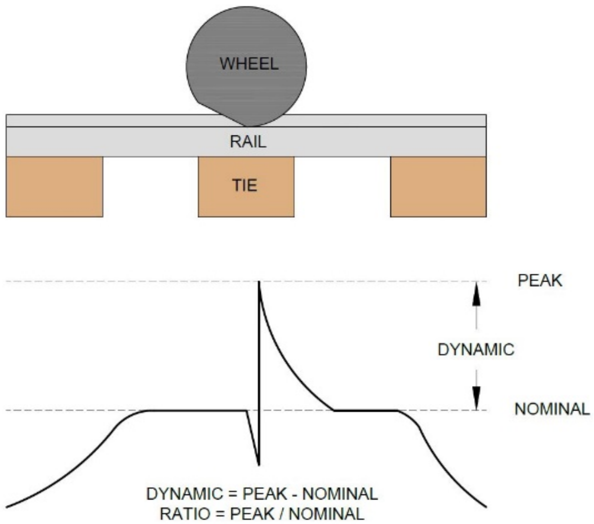

Figure 6a. WILD Measurements and Relationships for Peak Force, Nominal Force, Dynamic Impact, and Impact Ratio.

The Salient WILD design, being the initial type developed in the 1980s, is the most widely used system in the world today, with more than 200 installed worldwide to date. Over 90% of the WILD systems in the U.S. are Salient products. These evaluate millions of wheels per day throughout the international railway systems that detect and alarm when excessive wheel vertical impacts occur, so that the defective wheels are identified for inspection, tracking, treatment, and subsequent removal as standards dictate. A view of a Salient Mk-III WILD used to gather data for this study is shown in Figure 6b. This represents one of NS's fifteen WILDs designed and installed by Salient Systems.

Figure 6b. Typical Salient Mk-III WILD Installation.

The instrumented zone for the measurement of vertical forces exerted by each wheel of a passing train consists of a series of strain gage load circuits, micro-welded directly to the neutral axis of the rail.   Signal processors, housed in a nearby enclosure, analyze the data to isolate wheel tread irregularities. If any wheel generates a force that exceeds a customer-configured alarming threshold, a report identifies that wheel for subsequent action. Depending on operating procedures, multiple alarm thresholds can be configured. The reports are distributed in real-time to interested parties such as rail traffic control centers and vehicle repair shops.

WILDs are considered a strategic device for the protection of rail infrastructure. High impacting wheels can dissipate on the order of 25 horsepower each, degrading track, ballast and bridge structures, while reducing bearing and other vehicle component lives. Over time, the repetitive load cycles of defective wheels may result in rail fractures.

Particular attention was given in this research to determining the relationship of the relative increase in ballast pressures at the identified imperfect wheel traversed at close by WILD site that measured the magnitude of the increased vertical dynamic force.

SECTION 7: DATA PROCESSING

In its standard form, WILD data is produced in an axle domain with loads in its corresponding range. Being in this form allows for maintenance crews to directly identify wheel defects, which can be addressed downstream from the sensor. Although this a helpful format for maintenance purposes, the pressure measurements recorded at the tie/ballast interface in the track are in a frequency domain, which makes comparisons between the two somewhat difficult. Additionally, these WILD reports are based on a format that describes cars in an A or B-end category, and re-orients them for the convenience of engineering and maintenance crews. As additional processing for this study, individuals from Norfolk Southern Railway and LB Foster (Salient Systems) assisted in re-formatting the WILD data into a “victim’s” perceptive, which permitted matching wheel-for-wheel on the correct side of the test track.

In order to show the relationship between tie/ballast interface pressures and WILD force measurements, the pressure data recorded also had to be processed into an axle domain rather than a real-time/frequency domain in its raw existence. This was initially performed using a waveform peak operation in a software package called DIAdem, produced by National Instruments. Each peak, at least in a smooth wheel condition, is the corresponding force exerted from each axle. Although the operation is simple to use, the output file still identifies several irregular spikes and wave signatures that must be addressed for quality control. After manually checking each representative axle pressure, most irregularities are taken care of by taking an average over the irregular wave signature. After the data is processed, giving a pressure reading for each corresponding axle, several relationships can be plotted and analyzed with finer detail.

Using data provided by LB Foster, serval parameters can be analyzed to identify a tie/ballast interface pressure response relationship on several trains measured from June to November of 2017. Those parameters are Nominal Axle Loads (KIPS), Axle Load Peaks (KIPS), Dynamic Impacts (Peak - Nominal), and Impact Factor Ratios (Peak/Nominal). A schematic of the relationship between all of these parameters was depicted in Figure 6a.

Figure 8a contains plots in real time domain of trackbed pressures recorded by six cells, positioned directly under the rail at the tie/ballast interface, during the passage of a mixed freight train containing both empty and loaded freight cars. The forward half of the train, including locomotives, is exhibited.

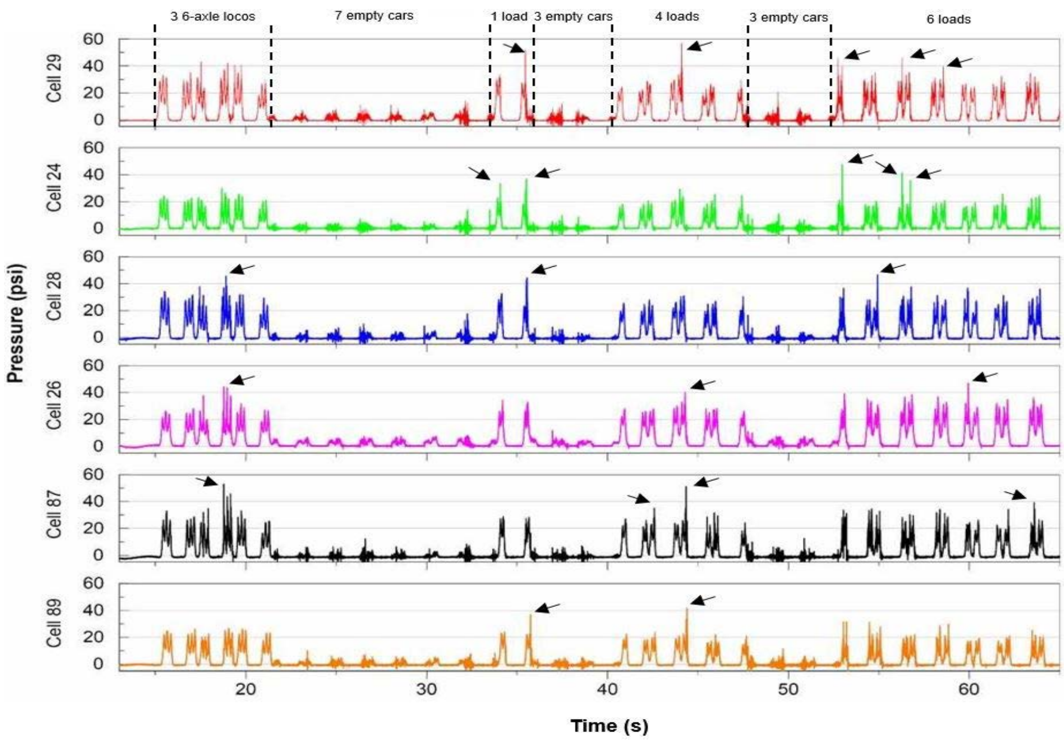

Figure 8a. Pressure traces for the forward portion of a typical mixed freight train passing over pressure cells positioned under six consecutive ties at the tie/ballast interface. The top legend notes the types of vehicles. The locomotives are on the left side; train is traveling from right to left.

The six cells were positioned under six consecutive ties under a single rail. As noted in the legend at the top of the figure, the pressures for the three 6-axle locomotives are shown on the left side of the plots for the six cells as six pressure peaks, each consisting of three sub-peaks. Following the locomotives are seven empty cars having substantially lower pressure peaks for the fourteen wheels. The empty cars are followed by a single loaded car having pressure peaks similar to the locomotives, as expected, since the individual wheel loads are similar in magnitude. Additional empty and loaded cars are follow for a total of twenty-four freight cars.

For a given wheel loading, individual cells record slightly different pressures, primarily due to the effect of variable compaction or density of the underlying ballast under individual ties, which also affects the support conditions. The greater the ballast is compacted under a given tie, the higher will be the pressure transferred by that tie to the ballast due to the increased support (2). These differences in pressure readings remain remarkably similar over a period of time. If the track is disturbed during a surfacing or tamping process, the relative distribution of pressures under individual ties will change slightly, but the average pressure will be similar to the average pressure before the track support was altered due to adjustments in the ballast compaction.

Note that the typical tie/ballast pressures under the locomotives range from 20 to 30 psi (140 to 210 kPa) and is consistent for a given locomotive. Locomotive wheel loads are typically 36,000 lbf (161.4 kN). Similar pressure values are measured for heavily loaded freight cars having typical wheel loads of 36,000 lbf (161.4 kN). Empty freight cars have typical wheel loads of 6,000 lbf (26.9 kN) producing pressure values about 6 psi (41 kN). These values are similar to those reported in previous documented findings (2).

The arrows point to wheels producing excessive pressure values, in excess of nominal pressures recorded for assumedly smooth wheels. These increased dynamic loadings can produce tie/ballast pressures twice or more of the values for the pressures exerted by smooth wheels.

Figure 8b contains enlarged views of the pressure versus time plots highlighting pressures recorded by Cell 87 for the three locomotives and groups of four empty cars, and four loaded cars. The pressures increase as the wheel approaches a given tie. The pressure peak is a maximum the instant the wheel is directly above the particular tie. A portion of the wheel load is carried by adjacent ties. Note the abnormally high peaks above the nominal pressures for smooth wheels. These are indicative of high-impact wheels.

Figure 8c contains similar plots for the initial portion of an intermodal train. The particular train consists of three 6-axle locomotives followed by loaded, primarily articulated, intermodal cars, most consisting of either 8 or 12 axles supporting the various connections and portions of the cars. The individual wheel loads vary depending on the spacing of the trucks and sharing of loadings by adjacent cars. As noted on the expanded plot below for a typical articulated car, typical tie/ballast pressures range from 8 psi (55 kPa) for lightly loaded wheels, to 20 psi (140 kPa) for intermediately loaded axles, to 35 psi (240 kPa) for heavily loaded axles.

SECTION 9: WILD WHEEL PARAMETERS AND TRACKBED PRESSURE RELATIONSHIPS

WILD wheel loading data obtained from either the Ebenezer or Flatrock detectors was compared to trackbed pressure data for the same trains traversing the Mascot trackbed pressure cell test site. Various measured WILD parameters were compared to recorded trackbed pressures. These were direct wheel-to-wheel comparisons. Cursory reviews of the digitized WILD and pressure data revealed likely relationships as the recorded WILD wheel loading magnitudes increased, the recorded trackbed pressures at the tie/ballast interface also increased.

The top trace in Figure 9a shows the relationship for the 46 loaded cars of a freight train containing predominately loaded freight cars. The train traversed the WILD at 32 mph (52 km/h) and the pressure test site at 20 mph (32 km/h). The WILD parameter of Peak load is considered the best measure for identifying the presence of high-impact wheels (see Figure 6 and associated discussion). The pressure values represent the average for the six cells

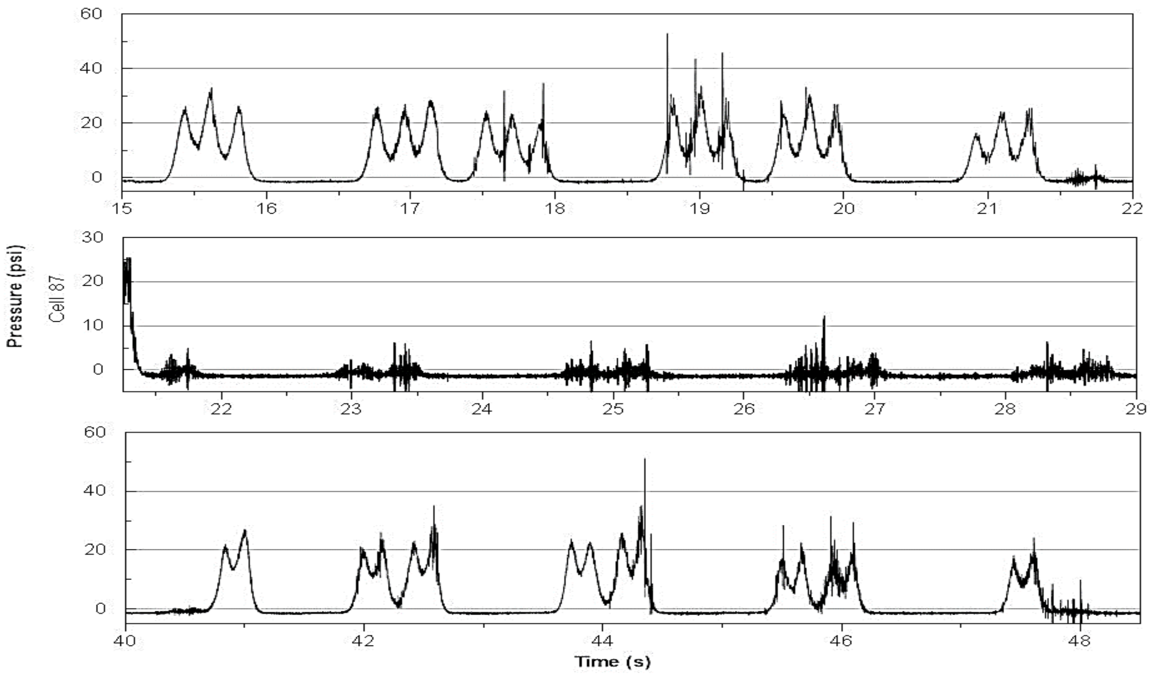

Figure 8b. Expanded view of pressure traces: top is the three 6-axle locomotives, middle is four empty freight cars, and bottom is four loaded freight cars. The abnormally high pressure peaks, above nominal pressures, are indicative of high impact wheels.

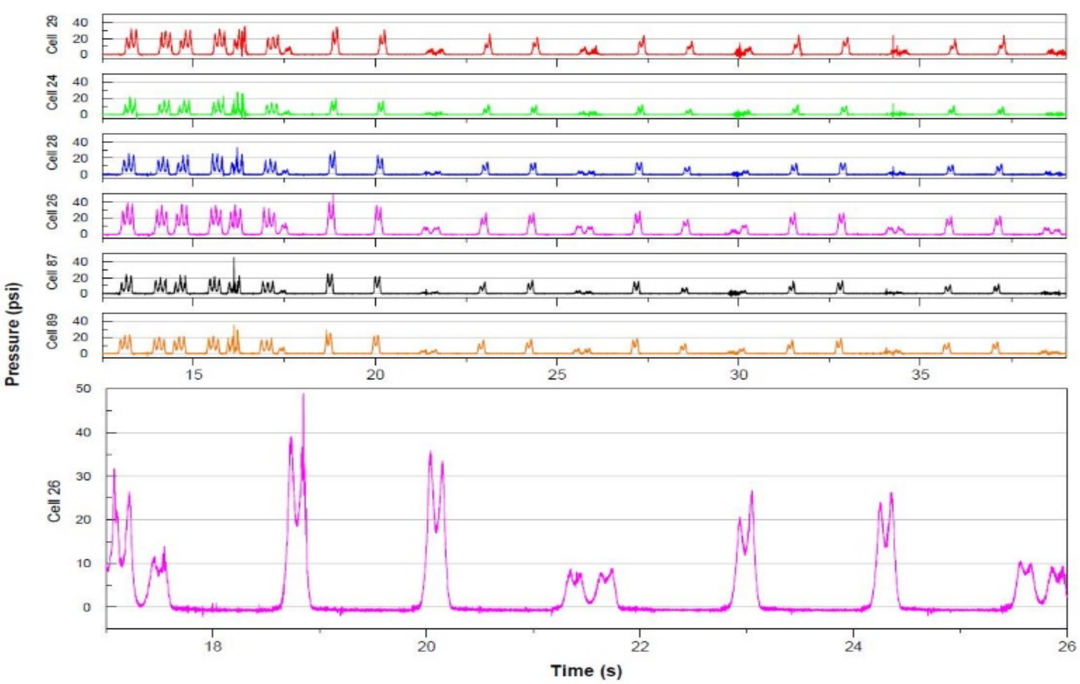

Figure 8c. Top view is forward portion of an intermodal train showing the pressures applied to the ballast as the train traverses the six cells. The three 6-axle locomotives are shown on the left with a portion of the intermodal cars following. The bottom view is an expanded pressure trace for several wheels of the intermodal cars.

As indicated, the increases in Peak values relate favorably to increases in recorded trackbed pressure. The relationship has a R-squared of 0.68. Based on the regression relationship, an increase of 36% in Peak loading results in an 81% increase in ballast pressure.

The bottom trace in Figure 9a shows the relationship between the WILD Nominal values and trackbed pressures. The R-squared was slightly higher with a value of 0.81. An increase of 29% in Nominal loading results in an 81% increase in ballast pressure.

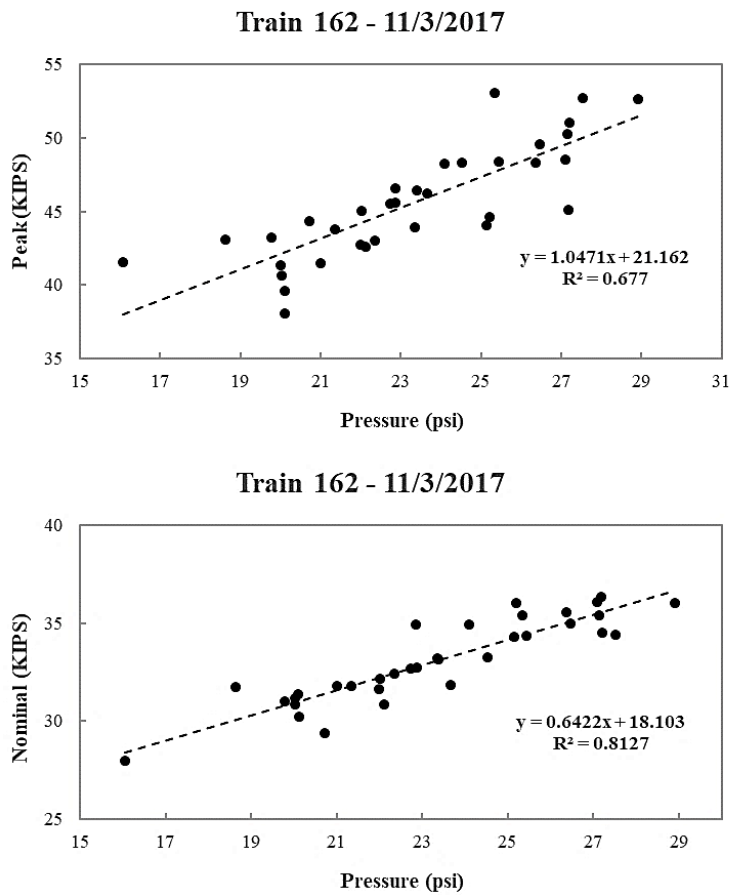

Figure 9a. Relationships between WILD Peak and Nominal wheel loadings and tie/ballast pressures for loaded freight cars.

Attempts to relate WILD parameters to trackbed pressures for empty cars were only marginally successful. The pressure differentials from wheel-to-wheel vary slightly in magnitude and the maximum pressure peaks are difficult to precisely identify. The pressure variability for a given wheel can be observed in Figure 8b, middle trace. Note the jagged variable shape of the empty car pressure peaks. This can be compared with the reasonably smooth shape of the pressure peaks for the locomotives (top) and loaded cars (bottom).

Figure 9b shows the WILD Peak force and Nominal force relationships to the measured ballast pressures for an intermodal train traveling at 35 to 40 mph (56 to 64 km/h), the same speed as when traversing the pressure test site. The wheel loads varied significantly, with average loadings less in magnitude than heavily loaded freight cars. Normally these types of trains are considered to have fewer high-impact wheels than the heavier-loaded mixed and unit freight trains. The R-squared was 0.75 for the Peak/pressure relationship and 0.83 for the Nominal/pressure relationship. This further substantiates the positive relationship between WILD loadings and companion tie/ballast interfacial pressures levels.

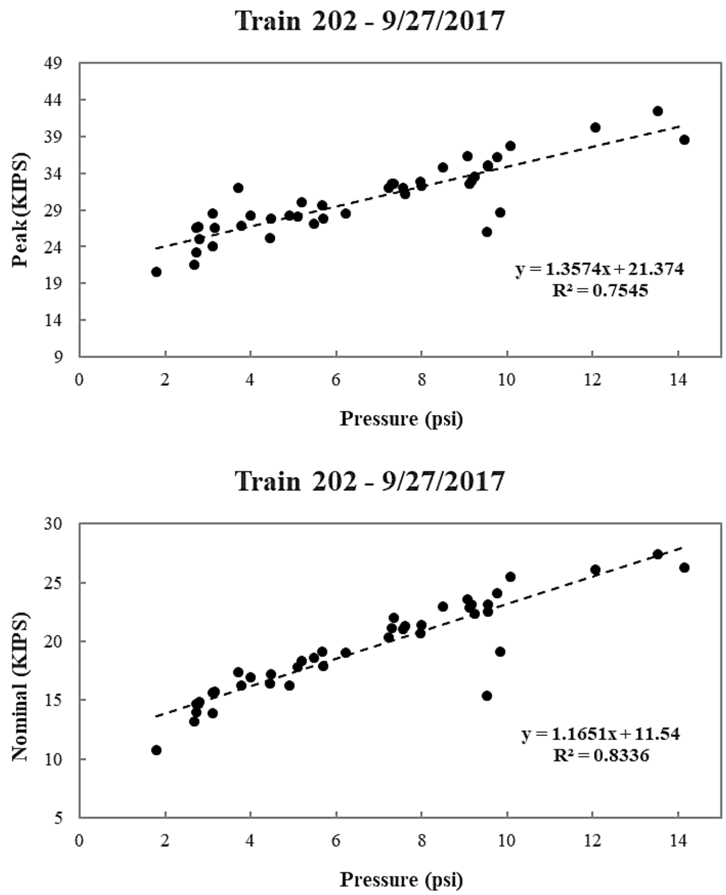

Figure 9b. Relationship between WILD Peak and Nominal wheel loadings and tie/ballast pressures for intermodal cars.

Further evaluation of the relationship between Nominal Force WILD measurements and corresponding tie/ballast interfacial pressures is shown in Figure 9c. Data for a combination of six trains – one empty unit coal, one intermodal, and four mixed freights consisting of empty and loaded cars -- is included. Data for the locomotives is also included. The data points represent the values for each wheel, rather than the averages per car as shown for the trains in Figures 11 and 12. The relationship indicates an R-squared of 0.87. The predominance of nominal wheel loads is in the 30 to 37 kip (133 to 164 kN) range, typical for loaded high capacity freights cars and locomotives.

For wheel loads below about 9 kips (40 kN), tie/ballast pressures, although low, vary significantly, as shown in Figure 9c. The primary reason the pressures vary as a given when passes over a cell is that the pressure trace is very jagged and it is difficult to determine an accurate average pressure at these low pressure levels. A typical trace for an empty car is shown in the middle trace of Figure 9. These pressures vary over a range from 1 to 9 psi (7 to 62 kPa); levels primarily produced by empty cars. The higher values in this range represent high impact empty car wheel loads.

Figure 9d contains the same data as Figure 9c except data for nominal loads less than 9 kips (40 kN) was excluded from the analysis. The remaining data represents loaded cars and locomotives with the bulk being nominal wheel loads between 30 to 40 kips (133 to 178 kN). The relationship indicates an R-squared of 0.92. The measured tie/ballast pressures for loaded cars and locomotives are better delineated than that for empty cars. This explains the slightly higher relationship between WILD Nominal loadings and corresponding tie/ballast pressures considering only the heavy wheel loads.

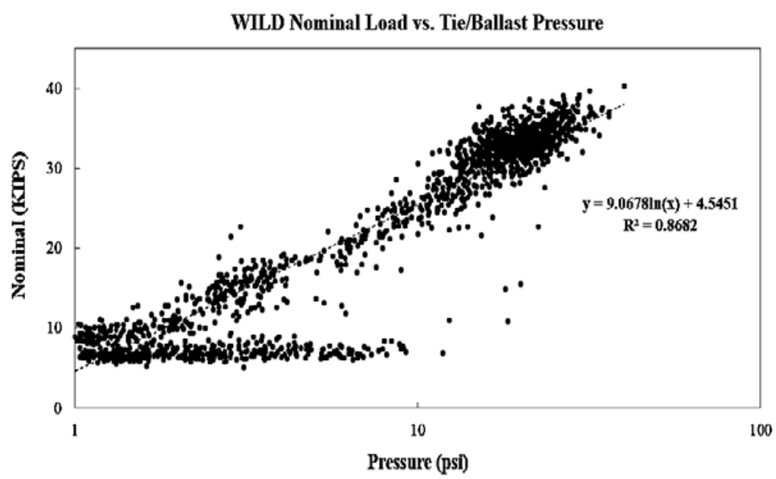

Figure 9c. Relationship between WILD Nominal wheel loadings and corresponding tie/ballast pressures.

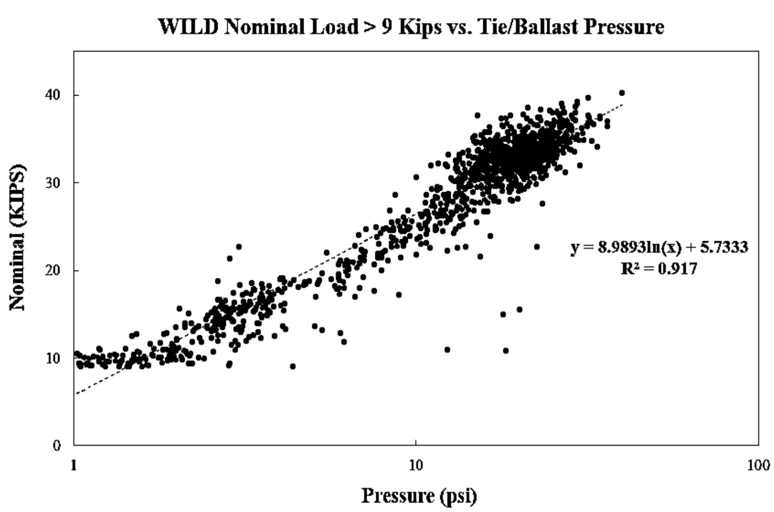

Figure 9d. Relationship between WILD Nominal wheel loadings (greater than 9 Kips) and corresponding tie/ballast pressures.

SECTION 10: RESULTS AND DISCUSSION

This report described the development of a method to measure average railroad track tie/ballast interfacial pressures using pressure cells specially designed for granular materials. The validity of the test method was verified with a series of laboratory tests using controlled loading magnitudes on prototype sections of trackbed with specially designed resilient frames/boxes for simulating typical in-track loading conditions. The selected procedure provided excellent correlation between controlled applied laboratory machine pressures and simultaneously measured cell pressures. The cells were recessed within the bottom of the ties for both the laboratory verification tests and subsequent in-track revenue train tests.

For the in-track tests, a series of cells were positioned under the rail at successive tie/ballast interfaces. Trackbed pressure measurements were conducted for numerous revenue freight trains during several months. After raising and surfacing the track, following installation of the instrumented ties, the track (mainly ballast) was permitted to further consolidate under normal accruing train traffic to insure that the ballast was tightly and uniformly compacted under the ties to effect transmission of equalized pressures from each of the ties to the ballast.

Measured pressures, directly below the rail/tie primary influence area at the tie/ballast interface, are considerably lower than trackbed pressures previously assumed for locomotives and loaded freight cars. These measured pressures range from 20 to 30 psi (140 to 210 kPa) for smooth wheels producing negligible impacts.

WILD wheel loading magnitudes obtained from nearby WILD wayside detectors were compared to trackbed pressure data for the same trains traversing the trackbed pressure cell test site. Various measured WILD parameters were compared to recorded trackbed pressures for loaded freight cars. The results indicate that increases in Peak wheel load values relate favorably to increases in recorded trackbed pressures. As an example, based on the regression relationship, as the Peak loadings increase -- the tie/ballast interfacial pressures increase by a factor of 2.25. Similar results were obtained comparing increased Nominal wheel loadings and increased tie/ballast interfacial pressures; pressures increased by a factor of 2.79.

The positive relationship between WILD loadings and corresponding tie/ballast interfacial pressure levels was further substantiated by comparing WILD Peak force and Nominal force relationships to measured tie/ballast pressures for an intermodal train. A R-squared value in the range of 0.8 was obtained for a variety of wheel loads.

The relationship between WILD Nominal wheel loading and tie/ballast pressure measurements is quite good for the higher magnitudes of wheel loadings. An R-squared value of 0.92 was obtained for a group of trains, excluding the light (empty car) wheel loads, and only considering the loaded car and locomotive wheel loads.

Higher wheel load magnitudes and increased dynamic impacts due to imperfections in wheel-tread surfaces increases the magnitude of the pressures correspondingly transmitted to the trackbed support as indicated by increased in-track pressures measured at the tie/ballast interface. The added increase in tie/ballast pressure, due to the impact of imperfect wheel surfaces, basically serves in a similar manner as increasing the nominal permitted wheel loads. The resulting increased dynamic impact forces can contribute to higher degradation rates for the track component materials and more rapid degradation rates of the track geometry.

SECTION 11: ACKNOWLEGEMENTS

This research was primarily funded by the National University Rail Center (NURail), a U.S. DOT OST Tier 1 University Transportation Center. Graduate Assistant Macy L. Purcell and Visiting Professor Qinglie Liu assisted significantly during the early phases of the research. Also appreciated are the financial assistance, cooperation, and significant contributions of Norfolk Southern Railway Company with the track site installations activities and continued monitoring and logistical aspects of evaluating the WILD data. Special appreciation is extended to LB Foster (Salient Systems) Company for their technical expertise, exportation of data, and review of the data processing.

SECTION 12: REFERENCES

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2. Rose, J.G. Clarke, D.B. Liu, Q. and T.J. Watts. “Application of Granular Material Pressure Cells to Measure Railroad Track Tie/Ballast Interfacial Pressures”. Transportation Research Record: Journal of the Transportation Research Board, 2018. 2671: In Press.

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