NON-INVASIVE MONITORING OF TRACK SYSTEM GAPS

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ABSTRACT
A reoccurring maintenance issue for railroads in the United States is differential movement at bridge transitions and a common cause of this movement is the existence of gaps and load redistribution within the track system. These gaps can increase the applied loads in the track system with two examples being gaps between the rail and tie fastening system and between the bottom of the tie and top of the ballast. Non-invasive instrumentation, e.g., miniature accelerometers and high-speed video cameras, are being used to monitor track system behavior at bridge transitions to identify poorly supported rails and ties. This paper presents data from two case studies that illustrate the non-invasive techniques and well and poorly supported track. The first site compares tie acceleration behavior of well and poorly supported concrete ties in the time and frequency domains, which includes showing the first four vibration modes of a poorly supported concrete tie. The second site illustrates the displacement behavior of a track system with rail-tie and tie-ballast gaps.

INTRODUCTION
Railway bridge transition zones often experience reoccurring track geometry issues due to differential transient and permanent displacements between the bridge and transition zone (Li and Davis, 2005; Plotkin and Davis, 2008; Coelho et al., 2011; Stark and Wilk, 2014; Wilk et al., 2015). This often requires frequent maintenance so addressing this problem is important for freight and passenger corridors. Previous research on a high-speed passenger line in the United States showed a relationship between poor tie support, e.g., gaps between the bottom of the tie and top of the ballast, and permanent vertical displacements in the substructure (Wilk et al., 2015). These gaps within the track system, e.g., rail-tie or tie-ballast gaps, can further deteriorate the track by increasing the loads applied to the substructure via load redistribution between adjacent ties (Stark et al., 2015a).

This paper introduces two types of non-invasive instrumentation, i.e., accelerometers and high-speed video cameras, to monitor track performance and illustrates how they can be used to identify gaps within the track structure. This identification method can be used to monitor both open and transition zone track to evaluate performance. This is important when implementing new or traditional transition zone remedial measures and/or design techniques to quickly and non-invasively evaluate their effectiveness.

TRACK SYSTEM GAPS

The existence of gaps or voids within the railroad track system has been incorporated for decades when estimating track modulus (Hay, 1982) but is gaining new attention for its effect on track system performance. Instrumented track transition zones in both the United States and Europe have related the existence of poorly supported ties, e.g., ties with tie-ballast gaps, with greater permanent vertical displacements of the substructure and track (Coelho et al., 2011; Varandas et al., 2011; Stark and Wilk, 2014; Wilk et al., 2015). This relationship has been verified using accelerometers and dynamic numerical modeling and is attributed to an increase of applied loads due to impact forces and load redistribution among adjacent ties created by a tie-ballast gap.

The increase in applied load due to impact forces is explained by the force amplification from a moving unsupported tie contacting the ballast via Newton’s Second Law: i.e., $F = m*a$. This can be indirectly measured with accelerometers on both well and poorly supported ties by comparing peak tie accelerations. Poorly supported ties measure peak accelerations between 15 and 80g while well supported ties consistently measure peak accelerations at or below 5g (Stark et al., 2015b, Rose et al., 2015). The variation in peak acceleration for poorly supported ties depends on the height of the tie-ballast gap at the instrumented and surrounding ties, train type, and train speed. Additionally, numerical modeling of tie-ballast gaps in open track shows a redistribution of wheel load from poorly supported ties to surrounding well supported ties (Lundqvist and Dahlberg, 2005; Stark et al., 2015a). Increases of tie-ballast load within the transition zone have also been simulated (Varandas et al., 2013; Stark et al., 2015a).

The creation of a tie-ballast gap is closely related to rail profile deviation, e.g., dips or bumps in the rail, because tie-ballast gaps develop from the uneven settlement of the underlying track substructure. This occurs from many factors including uneven ballast density or stiffness, abrupt changes in subgrade material, and/or ballast fouling (Dahlberg, 2010). If the substructure settles more at one region of the track than a surrounding region, the high rail bending stiffness causes the rail to pull the ties located over the more settled regions upward, producing a gap underneath the tie. This leaves the tie “hanging” or “cantilevering” from the better supported ties or less settled regions of track. This “hanging” also results in a rail profile deviation and is especially prevalent at railway bridge transition zones where the bridge abutment settles significantly less than the approaching track. A diagram showing a railway bridge transition zone with tie-ballast gaps is illustrated in Figure 1. The gaps below Ties 1 through 4 exist because the rail is supported from the bridge, i.e., Ties A and B, and open track Ties 5 through 7.

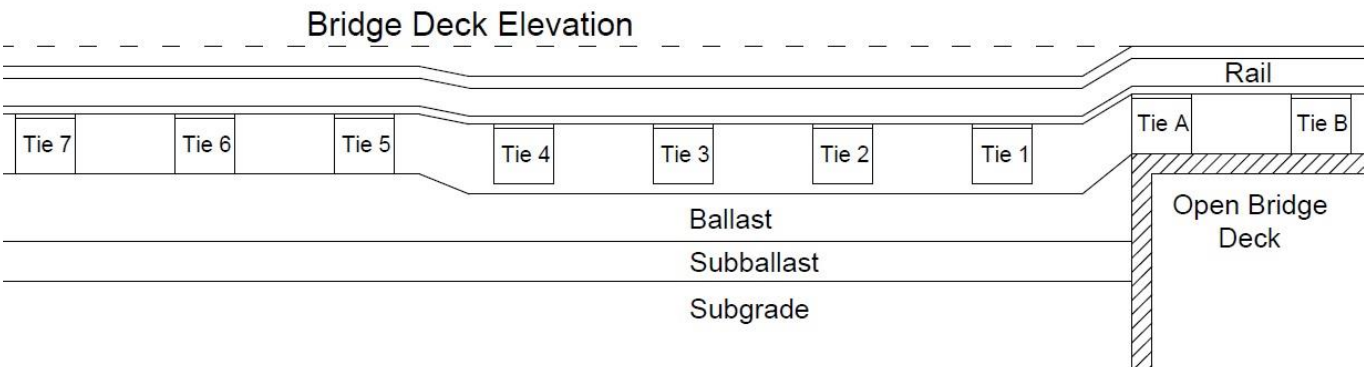

Figure 1: Example of railway bridge transition zone with tie-ballast gaps, substructure settlement, and rail profile deviation.

While the primary focus has been gaps between the tie and underlying ballast, gaps can also exist between the rail and tie plate and even the tie plate and tie. This depends largely on the type of tie and fastener with concrete ties displaying mainly tie-ballast gaps because of the good contact between the rail, tie pad, and tie while timber ties often display both rail-tie plate and tie-ballast gaps because the rail spikes holding the rail to the tie can pull out.

INSTRUMENTATION

Due to the poor track performance and geometry associated with track system gaps, a non-invasive monitoring system using accelerometers and high-speed video cameras was developed to detect track system gaps and evaluate overall track performance. This monitoring system can be used to compare various types of track transition design and remedial measures. The accelerometers and high-speed video cameras were selected because they are non-invasive, easy and quick to setup (<20 minutes), reasonably priced, and able to measure transient time histories of acceleration and vertical displacement at select locations. This paper shows how these two systems can be used to identify track system gaps and evaluate track performance.

Accelerometers

Usually eight (8) accelerometers are installed to non-invasively monitor track performance over a certain track length. Being only 13 mm long (one half inch), weighing less than 3 grams (0.1 ounces), and requiring only a drop of superglue to bond to the tie, these accelerometers result in a quick and non-invasive monitoring system that does not interfere with train operations (see Figure 2). This makes accelerometers suitable for short-term monitoring, i.e., a single train pass or day, as well as long-term monitoring during wet and inclement weather conditions because weather resistant accelerometers are available.

Acceleration time histories are beneficial because they can be used to evaluate track performance along with the increased tie-ballast loading, especially if a tie-ballast gap is present. Tie accelerations greater than 5g usually indicate poor track support, including both rail-tie gaps and tie-ballast gaps, while well supported track usually exhibits tie accelerations less than 5g (Stark et al., 2015b). If a tie is poorly supported, higher tie accelerations result in higher impact forces on the bottom of the tie and top of the ballast because Newton's Second Law states applied force (F) equals the mass (m) times acceleration (a). The acceleration time history can be converted to the frequency domain to determine the dominant frequencies of the tie deflection-vibration responses, which also provides an insight to tie support conditions that can influence different vibration modes (Harrison et al., 1984; Remennikov and Kaewunruen, 2006; Taherinezhad et al., 2013). To estimate tie displacement, the acceleration time histories can be double integrated to obtain displacement time histories. While support conditions and double integration were the initial motivation for using accelerometers, tie accelerations are now being used to investigate the impact of damaged ties, fouled ballast, moisture conditions, rail and wheel defects, and substructure support on track performance.

High-Speed Video Cameras

Transient time histories of the rail and tie also are important for estimating the rail-tie and tie-ballast gaps and can be non-invasively measured using high-speed video cameras, see Figure 3. High-speed video cameras were selected because of the mobility of the video cameras, the only required contact with the track system is the placing removable markers on the rail and tie, and the recorded video provides a visual account of track movement. The cameras typically record at a frequency of 240 frames per second and are capable up to 1000 frames per second which is enough to capture and quantify the track movement even for high-speed passenger trains.

Figure 2: Photograph of a minature accelerometer installed on a concrete tie

Figure 3: Photograph of the high-speed video camera

SITE #1: ISOLATED UNSUPPORTED TIE

The first instrumented site compares the behavior of a well and poorly supported tie in both the time and frequency domain to investigate tie movement and vibration frequencies. This information can be used to identify characteristics of poorly supported ties and help understand behavior that can affect track performance and longevity.

The instrumented site involves the east end of a railway bridge transition in the United States. The track is considered Class 3 for operations and traffic consists of both loaded and unloaded freight trains moving at about 40 km/hr (25 mph). Since construction in 1998, the track has been performing well with no required maintenance (Rose, 2013). This lack of maintenance is attributed to the combination of: (1) a ballasted bridge deck, (2) a parallel concrete wing wall that extends 9 ties (17 ft.) on the south side of the track (not included on the north side), and (3) an HMA layer underneath the ballast. These three design techniques are shown in Figure 4 and help reduce the differential transient and permanent vertical displacements between the bridge and transition zone as illustrated by the recorded acceleration time histories. This lack of differential movement helps prevent the development of significant tie-ballast gaps and substructure settlement in the transition zone, which can result in high applied loads within the track system.

Figure 4: Photograph of the east end bridge transition zone at Site #1.

Instrumentation occurred on 28 July 2014 and involved the installation of eight accelerometers with six of the accelerometers installed on the opposite ends of three concrete ties. The first concrete tie was located on the bridge, the second tie located 1.5 m (5 ft.) from the bridge abutment in the transition zone, and the third tie located 6 m (20 ft.) from the bridge abutment near the open track. The transition zone tie location (1.5 m/5 ft.) was selected because despite the overall good behavior of the transition zone, a single poorly supported tie was identified 1.5 m from the bridge abutment. The open track tie 6 m (20 ft.) from the bridge abutment was selected because it was well supported and could be used for comparison purposes. Due to space constraints, only the results of the accelerometers installed on the south end of the concrete ties at 1.5 m (5 ft.) and 6 m (20 ft.) from the bridge abutment are presented herein. These locations will be referred to a Site #1 (5 ft.) and Site #1 (20 ft.), respectively.

Figure 5 compares the tie acceleration behavior from a passing freight train at: (a) 5 ft. (Site #1, 5 ft.) and (b) 20 ft. (Site #1, 20 ft.) while Figure 6 displays the same time histories in the frequency domain. The peak tie acceleration magnitudes from the time histories of the two sites are similar (~3 to 5g), which verifies that tie accelerations at or below 5g correspond to good track geometry and performance. The large increases or spikes in acceleration above the 5g to 10g range are probably caused by wheel flats and other wheel defects which can produce wheel-rail impact forces that transmit through the rail to the ties. These impact forces are important but not considered when monitoring track performance because they represent a vehicle maintenance issue not a track performance issue. The other accelerometers displayed similar behavior in the time domain with no significant differences.

Despite the similar acceleration magnitudes in the time domain, Figure 6 illustrates substantially different behavior of these two sites (Site #1, 5 ft. and 20 ft) in the frequency domain. The well supported tie (Site #1, 20 ft.) shows only a single dominant frequency of vibration of about 110 Hz, which is the first vibration mode of a concrete tie (Harrison et al., 1984; Remennikov and Kaewunruen, 2006; Taherinezhad et al., 2013). The poorly supported tie (Site #1, 5 ft.) shows four dominant frequencies of vibration at 110 Hz, 300 Hz, 585 Hz, and 900 Hz, which corresponds to the first four vibration modes of concrete ties (Harrison et al., 1984; Remennikov and Kaewunruen, 2006; Taherinezhad et al., 2013). The additional vibration modes of the poorly supported tie are explained by the lack of damping and confinement from the ballast, which allows the concrete tie to freely "ring" during every wheel loading. The accelerometers on the opposite ends of Site #1 (5 ft.) and Site #1 (20 ft.) also displayed similar behavior.

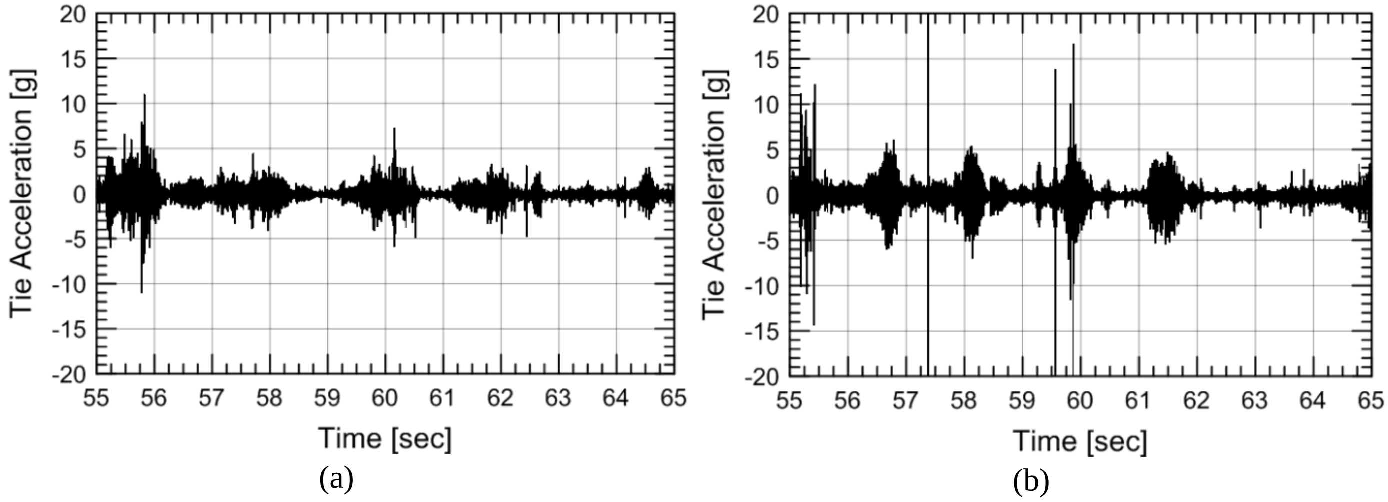

Figure 5: Measured Tie Acceleration Time Histories at: (a) Site #1 (5 ft.) and (b) Site #1 (20 ft.) for a Passing Freight Train on 28 July 2014.

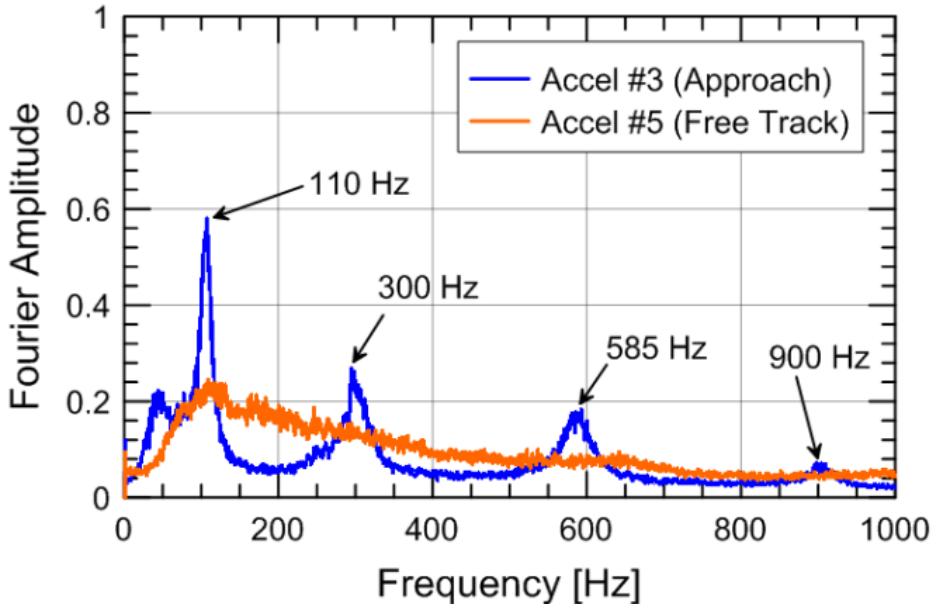

Figure 6: Measured Tie Accelerations in Figure 5 converted to Frequency Domain at: (a) Site #1 (5 ft.) and (b) Site #1 (20 ft.) for a Passing Freight Train on 28 July 2014.

The results from this site show that accelerometers can detect differences between well and poorly supported concrete ties using the time or frequency domain to analyze the data especially if a poorly supported tie is present. The second important result is a single poorly supported tie does not always mean the track transition will experience poor track geometry but it could lead to a progressive reduction in tie support. Good track geometry has been maintained at this site so far because the load redistribution from the single poorly supported tie to the adjacent well supported ties is low enough to avoid damaging or developing a significant gap underneath the surrounding well supported ties. However, if a group of ties become poorly supported instead of a single tie, the load redistribution causes a greater tie-ballast load on the surrounding well supported ties (Lundqvist and Dahlberg, 2005). This can damage or develop gaps underneath the surrounding ties and progressively spread the problem to surrounding regions. This is in agreement with most sites displaying tie-ballast gaps and reoccurring track geometry problems because they involve a number of poorly supported ties and not a single poorly supported tie.

SITE #2: POORLY SUPPORTED TRACK

The second instrumented site used both high-speed video cameras and accelerometers to evaluate track movement at a bridge transition zone site that has been experiencing reoccurring track geometry problems and developed noticeable rail-tie and tie-ballast gaps. This site is used to compare tie behavior and measured vertical displacements from the video cameras and accelerometers and also verify that both rail-tie and tie-ballast gaps can be non-invasively measured.

The instrumented site involves the south end of railway transition zone located within the United States. The traffic is considered Class 4 for track operations and consists of loaded and unloaded freight, loaded coal, and intermodal trains passing from 50 km/hr to 95 km/hr (30 to 60 mph). The bridge is a 10 m (30 ft.) steel open deck bridge constructed in 1923 with no bridge or transition zone design features, see Figure 4 for examples, to minimize differential displacements (see Figure 7). Nearly every tie in the southern transition zone contains either a rail-tie and/or tie-ballast gap and fouling is prevalent in and around all of the ties. The rail-tie gaps are found within 5 m (16 ft.) of the bridge abutment and tie-ballast gaps are mainly observed 5 m (16 ft.) or more from the abutment. Additionally, an asphalt road crossing is present 20 m (67 ft.) south of the bridge abutment, which results in two transitions in the instrumented region, i.e., a transition from an asphalt crossing to open-track and to a steel open deck bridge. This means that both north and southbound trains experience "galloping" or "bouncing" when passing over the nearby transition zones because of the multiple abrupt changes in track displacements, modulus, and geometry.

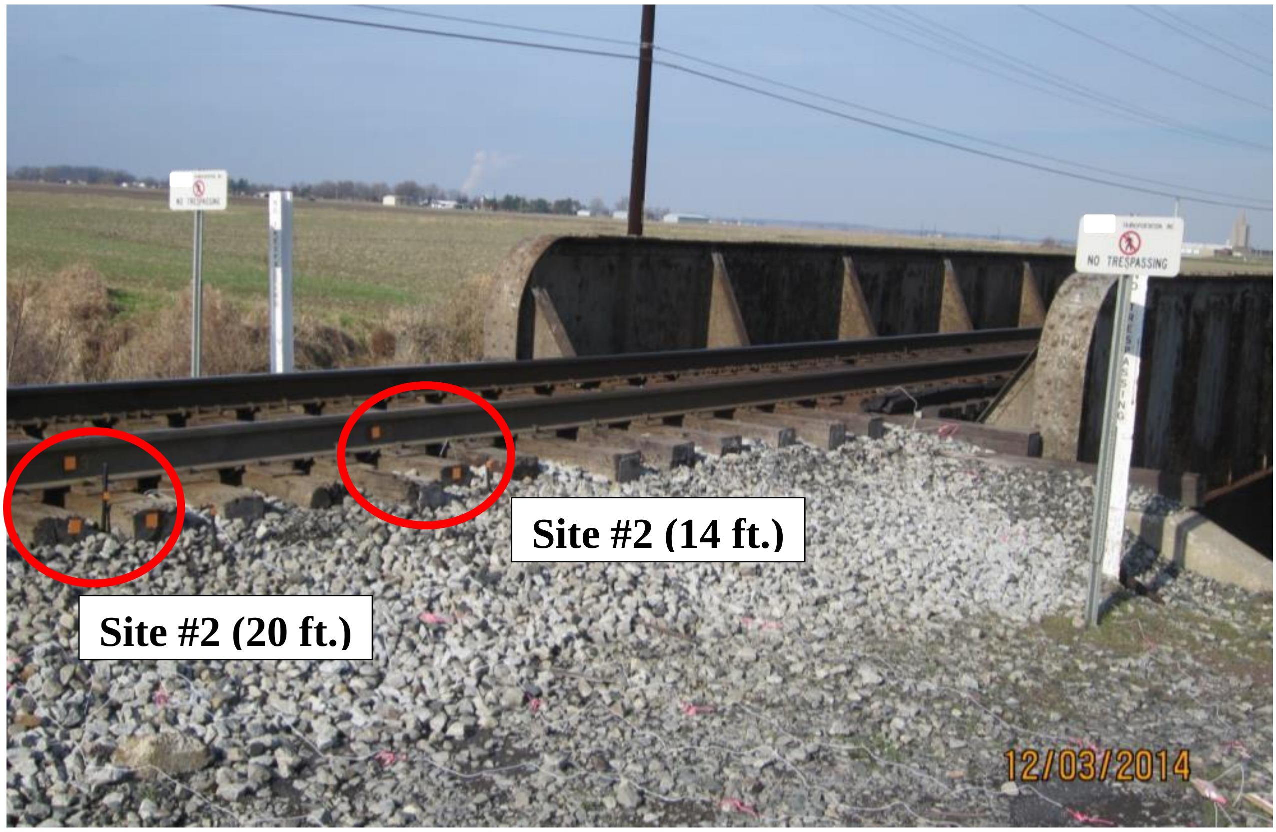

Figure 7: Photograph of the south end bridge transition zone at Site #2.

This site was instrumented on 21 October 2014 with two high-speed video cameras that measured the rail and tie displacements of two different tie locations and eight accelerometers installed on the timber ties. For this paper, the results of only two accelerometer locations are presented to compare the behavior of ties experiencing rail-tie and tie-ballast gaps. The first accelerometer discussed is located on the east end of the tie 4.3 m (14 ft.) from the bridge abutment and referred to as Site #2 (14 ft.) in Figure 7. This location displays a rail-tie gap and a high-speed video camera also measures the rail and tie displacements of the east end of the same tie. The second accelerometer discussed is located on the east end of the tie 6 m (20 ft.) from the bridge abutment and is referred to as Site #2 (20 ft.) in Figure 7. This location displays a tie-ballast gap and the high-speed video camera also measures the rail and tie displacements of the east end of the same tie. This instrumentation set up allows the comparison of displacements measured with high-speed video cameras and accelerometers after the acceleration time histories are doubled integrated to obtain tie displacements.

Figure 8 compares the rail and tie displacements measured with high-speed video cameras for: (a) Site #2 (14 ft.) and (b) Site #2 (20 ft.). Only two seconds of the time histories are shown to better illustrate the differences in track behavior. The rail-tie gap location (Site #2, 14 ft.) only shows significant displacement of the rail (~10 mm/0.4 in) while the displacement of the tie is insignificant (~1.25 mm/0.05 in). This is expected because the rail-tie gap limits the amount of loading that the rail can apply to the tie. The tie-ballast gap location (Site #2, 20 ft.) shows displacement of both the rail (~5 mm/0.2 in) and tie (~6.4 mm/0.25 in). It is typically expected that the rail displaces more than the tie but due to a suspected centerbound tie condition at this location, the end of the tie bends when loaded resulting in greater displacement at the end of the ties. Additionally, the rail-tie gap location (Site #2, 14 ft.) experiences more rail displacement than the tie-ballast gap location (Site #2, 20 ft.), which is expected because the rail-tie gap location is closer to the bridge abutment and likely experienced greater substructure settlements.

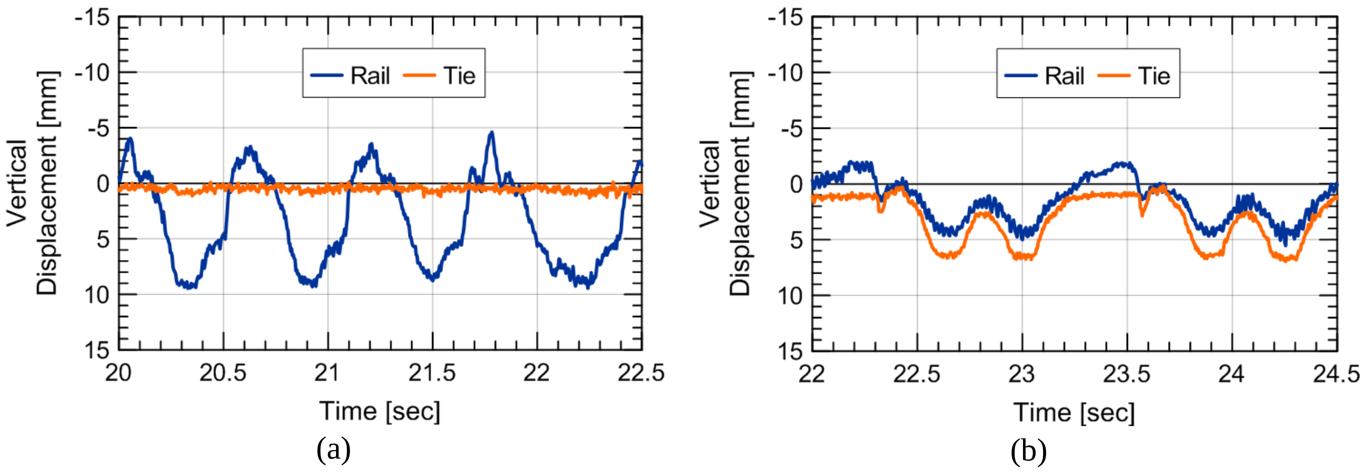

Figure 8: Video Camera Measured Rail and Tie Displacements at: (a) Site #2 (14 ft.) and (b) Site #2 (20 ft.) for a Passing Freight Train on 21 October 2014.

The installed accelerometers are used to evaluate track performance and corroborate the tie displacements estimated from the high-speed video cameras. The resulting acceleration time histories are displayed in Figure 9. While some variations exist, the tie with the rail-tie gap (Site #2, 14 ft.) experiences peak accelerations of about 10g while the tie with the tie-ballast gap (Site #2, 20 ft.) shows peak accelerations of about 20g because the rail is applying a greater load to the tie because of a smaller rail-tie gap. Previous instrumentation typically shows peak acceleration of 5g or less to be representative of good track support (Stark et al., 2015b), which puts both of these sites in the category of poor track support. With both ties measuring peak tie accelerations above 5g, accelerometers can detect both the slapping of the rail as it hits the tie or tie plate and the movement of a tie due to the presence of a tie-ballast gap and the impact forces associated with the tie contacting the ballast. The high accelerations at about 70 seconds are likely from wheel flats or some sort of wheel defect that creates an impact force on the rail that travels through rail to the tie. The conversion of the acceleration time histories to the frequency domain are not shown because timber ties do not display similar vibrations modes as concrete ties do.

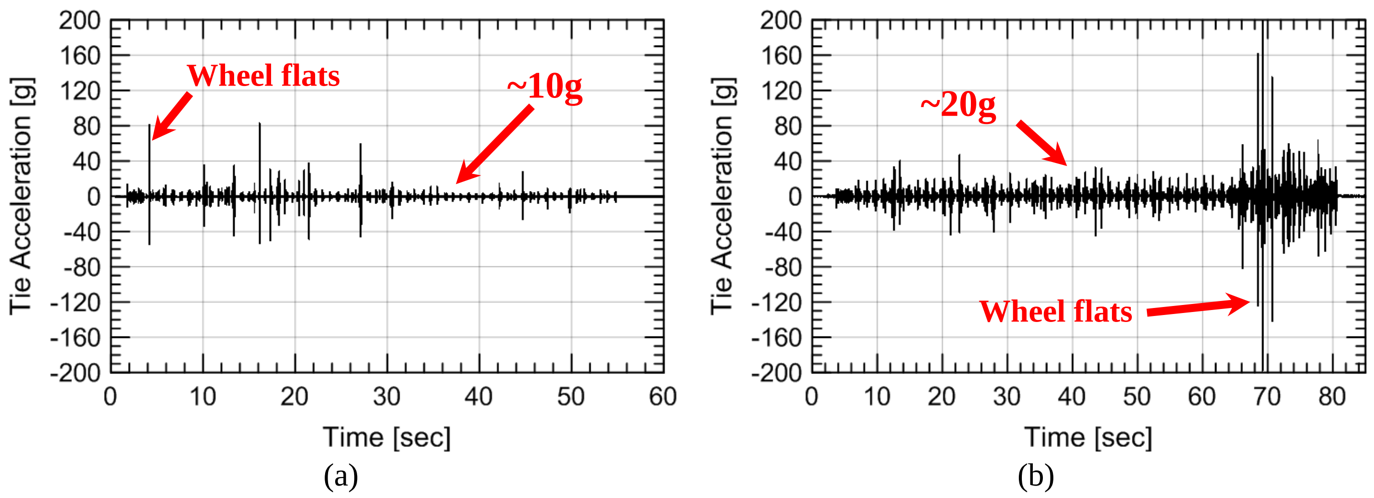

Figure 9: Measured Tie Accelerations at: (a) Site #2 (14 ft.) and (b) Site #2 (20 ft.) for a Passing Freight Train on 21 October 2014.

Lastly, acceleration time histories can be double integrated to estimate peak tie displacements. Because accelerometers accurately measure accelerations within a certain range of frequencies, filtering methods are used to eliminate background noise and other measurements that do not reflect track behavior before integration (Cui et al., 2014). This filtering affects the configuration of the time history so exact matches between the acceleration and video camera displacement time histories are not possible but the peak to peak displacements can be compared.

The double integrated displacements are displayed in Figure 10 which shows peak to peak tie displacements of 1.25 mm (~0.05 in) and 6.4 mm (~0.25 in), which are in general agreement with the peak vertical displacements measured with the high-speed video cameras shown in Figure 8. This illustrates that double integration of acceleration time histories can provide reasonable estimates peak tie displacements.

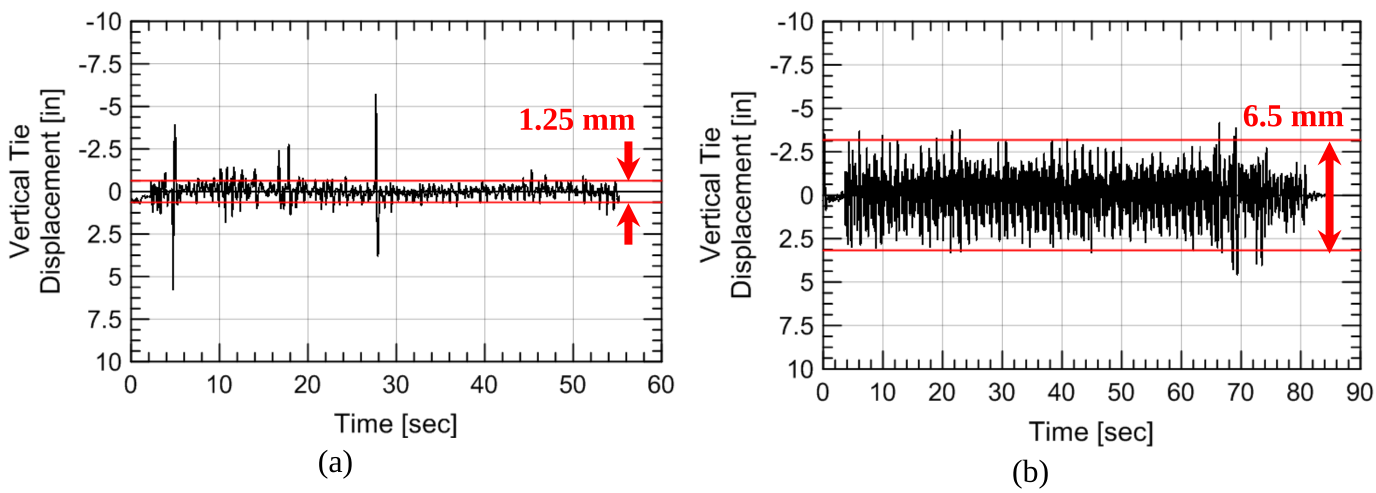

Figure 10: Double Integrated Measured Tie Accelerations at: (a) Site #2 (14 ft.) and (b) Site #2 (20 ft.) for a Passing Freight Train on 21 October 2014.

SUMMARY

This paper describes a non-invasive track monitoring system consisting of accelerometers and high-speed video cameras used to identify track system gaps that have been connected to reoccurring track geometry issues. This system can measure and diagnose track performance in a few hours or over a period of time to evaluate the effects of environmental and climate changes on track performance. Accelerometers and video cameras are also being used to evaluate the effectiveness of open track and transition zone designs and remedial measures. A summary of the main findings presented in this paper are:

- Converting measured acceleration time histories to the frequency domain provides a quick and visual means for evaluating tie support, especially for concrete ties because the first four vibration modes can be discerned for unsupported ties. For the concrete tie site described in this paper, the first four vibration modes are: 110 Hz, 300 Hz, 585 Hz, and 900 Hz. The vibration modes appear because of a lack of damping and constraint from the ballast to the unsupported concrete tie.

- High-speed video cameras can be used to non-invasively detect both rail and tie movements and provide an estimate of both the rail-tie and tie-ballast gap heights for track evaluation and remediation purposes.

- Double integrating acceleration time histories can produce similar peak tie displacements as those measured using the high-speed video cameras.

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