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A Study of Environmental and Track Factors that Contribute to Abrasion Damage of Concrete Ties

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13. ABSTRACT (Maximum 200 words) Kansas State University (KSU), the University of Florida, and Infrastructure Research, LLC inspected 36 railroad track sites with suspected concrete bottom tie abrasion to determine track and environmental factors that contribute to tie abrasion. This research was conducted between April 2016 and August 2017. Field investigations revealed that abrasion occurs in diverse geographic locations around the U.S. and is a source of continued maintenance concern for railroads. Water appeared to be a significant factor involved in concrete bottom tie abrasion. Ballast fouling, center-binding cracking, rail surface profile variations, and large track movement during loading was seen in locations with concrete bottom tie abrasion. Bumps or track stiffness changes were often found at locations of abrasion damage. Specifically, some locations with known stiff track conditions exhibited significant abrasion damage.			
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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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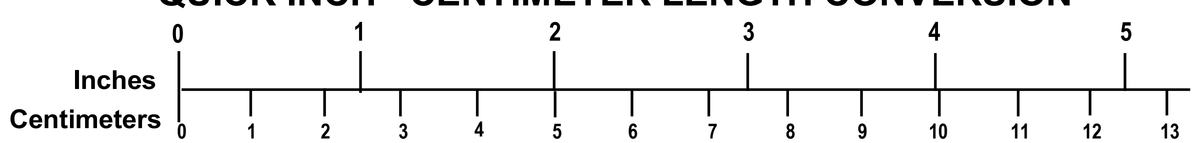
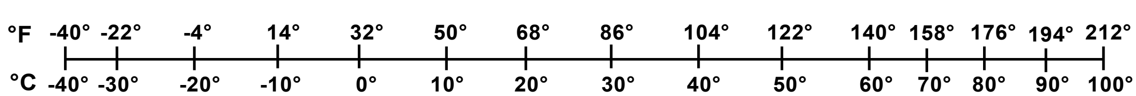
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Kansas State University, the University of Florida, and Infrastructure Research, LLC inspected 36 railroad track sites with suspected concrete bottom tie abrasion to determine track and environmental factors that contribute to tie abrasion. This research was conducted between April 2016 and August 2017 and funded by the Federal Railroad Administration (FRA). The research team also inspected concrete ties at storage yards, also known as boneyards, to determine the prevalence of concrete tie abrasion. Track availability and project objectives led the team to focus the research on rapid, qualitative visual inspections of many sites rather than in-depth quantitative measurements of only a few sites. High-definition video and accelerometers were used when possible to record tie movement during train loading of locations visited. Researchers gathered samples of ballast from each site to establish the presence of concrete fines in the granular material.

Concrete tie abrasion is not the most common form of concrete tie deterioration, but this field investigation revealed that it occurs in diverse geographic locations around the U.S. and is a significant maintenance concern for railroads. Water in track is a significant contributing factor in concrete tie abrasion. Ballast fouling, center-binding cracking, rail surface profile variations, and large track movement during loading were observed in locations with concrete tie abrasion. Bumps and/or track stiffness changes also found at these locations. Some locations with known stiff track conditions had significant tie abrasion damage. Overly stiff structures should be avoided.

The severity of tie abrasion can increase with time if railroads do not take corrective maintenance action. Tamping, localized ballast removal, or individual tie replacement can help temporarily mitigate the problem, but these methods did not adequately stop abrasion damage from progressing or recurring. Ballast undercutting was a more effective method for delaying or slowing down concrete tie abrasion but may not address the root causes of the problem.

1. Introduction

Kansas State University, the University of Florida, and Infrastructure Research, LLC inspected 36 railroad track sites with suspected concrete bottom tie abrasion to determine track and environmental factors that contribute to tie abrasion. This research was conducted between May 2016 and August 2017. The research team also inspected concrete ties at storage yards, also known as boneyards, to determine the prevalence of concrete tie abrasion. Track availability and project objectives led the team to focus the research on rapid, qualitative visual inspections of many sites rather than in-depth quantitative measurements of only a few sites.

1.1 Background

Railroad crossties are used to maintain the track gage and distribute loads to the ballast and subgrade. Concrete ties are used in heavy-haul rail lines and high-speed rail lines because of their ability to carry higher loads than wood ties. Concrete ties can last 50 years or longer when fabricated properly and the track is properly designed, built, and maintained. To achieve this lifespan, prestressed concrete ties are designed to carry significant positive and negative bending moments. These design criteria are meant to prevent excessive deflection and gage widening during train loading and to prevent tie breakage. If the tie section properties change during use, there is a potential for a loss in moment capacity, gage widening, tie breakage, and ultimately derailment. Abrasion loss on the concrete tie sides and bottom could provide such a moment capacity reduction.

On July 18, 2013, 10 cars of a northbound train containing municipal solid waste derailed, causing $827,700 in damage. At the location of derailment, the ballast was severely fouled with gray mud. The gray mud was mostly from ground-up concrete fines from concrete ties that had lost material on the bottom surface due to abrasion. The ties also had center-binding cracking from high negative moments in the tie center that occurred, or were worsened, due to the loss of ballast support near the ends and reduced tie section thickness. The investigation faulted the combination of ballast fouling, concrete tie side and bottom abrasion, center-binding cracking, rail seat abrasion, and rail surface profile issues for loss of gage and causing the accident (National Transportation Safety Board, 2014).

Concrete tie section loss on the tie bottom or sides from abrasion is a newly identified track failure risk. Concrete railroad tie section loss could result from one mechanism or a combination of mechanisms. Mechanisms that could be responsible for this section loss include classic concrete abrasion, hydro-abrasive action, ice abrasion, concrete crushing, cavitation erosion, and freeze-thaw cycling (Van Dam, E., 2014) (Kryzanowski, A., Mikos, M., Sustersic, J., & Planinc, I., 2009) (Jacobsen, S., 2014) (ACI 201.2, 2008). Classic concrete abrasion-damage action is caused by frictional rubbing of the concrete surface with another hard surface, similar in action to sandpaper wearing away a wood surface. Water and fine particles can create rubbing between the grit and the concrete, increasing mass loss of the tie and ballast particles. Hydro-abrasive action can occur when solid particles suspended in water flow past concrete, and impact and damage the concrete surface. Ice abrasion of concrete is known to occur when concrete is in contact with ice under load. This is a common problem with oil platforms in arctic climates. Ice abrasion can occur both where the concrete slides against the ice and where there is crushing; however, sliding is more severe (Jacobsen, S., 2014). When ballast is only in contact with part of the tie, concentrated loads can result in crushing of either aggregate particles or part of the concrete tie (Zeman, J. C., Edwards, J. R., Barkan, C. P., & Lange, D. A., 2014). Cavitation erosion can occur when the water pressure near the concrete surface is changed quickly, reducing below the pressure required for vapor to form. When the pressure is increased, the vapor bubble rapidly and violently collapses, causing damage to the concrete (ACI 201.2, 2008). Freeze-thaw damage can occur in concrete railroad ties and can result in micro-cracking at the concrete. No studies were found to identify the extent of this tie abrasion risk in track, or the relative contribution and importance of potential section-loss mechanisms.

1.2 Objectives

The research goals of this project were to estimate the extent of concrete tie abrasion in U.S. railroads and gather information about the abrasion site that may help characterize the service load and environmental conditions wear that contribute to tie abrasion. To accomplish these goals, the following research objectives were developed:

1. To determine the prevalence of concrete bottom tie abrasion in tie boneyards.
2. To determine tie and track design, materials, and conditions present in locations where concrete bottom tie abrasion is known to occur and nearby track locations that do not show concrete bottom tie abrasion.
3. To determine relevant geological and environmental conditions, including the presence of moisture, at locations where concrete bottom tie abrasion is known to occur and at nearby track locations that do not show concrete bottom tie abrasion.
4. To compare the track and environmental conditions present at sites visited to determine commonalities between sites known to have concrete bottom tie abrasion and nearby locations that do not show concrete bottom tie abrasion.

1.3 Overall Approach

To accomplish the project objectives, field visits were made to concrete tie storage areas, also known as boneyards, and track locations with known mud spots. The research team worked with the Federal Railroad Administration (FRA), Class I and II railroads, and concrete railroad tie producers to identify track locations to visit that could have bottom tie abrasion damage. Track sites with concrete railroad ties in muddy track sections, locations that require constant maintenance, and areas with known occurrences of tie wear were targeted for field site visits. Used concrete tie boneyards were visited to document the frequency of tie abrasion wear and wear patterns on the bottom and sides of ties. Table 1-1 summarizes the types and distributions of track and boneyard sites visited. Some sites exhibited characteristics common to several categories, such as a railroad crossing in tangent track or a crossing immediately after a switch. A total of 36 track sites were visited in 8 different U.S. States to ensure the investigation recognized diverse geographic and climatic conditions.

Table 1-1: Summary of Sites Visited

Site Type	# Sites Visited
Bridges	3
Bridge and Tunnel Approaches	4
Switches and Signals	4
Railroad Crossings	9
Curves	5
Tangent Track	11
Concrete Tie Storage Areas or Boneyards	6

Track access limitations and constrained project objectives led the team to focus the research approach on rapid, qualitative visual inspections for data collection. The research team documented the extent of ballast fouling present on the ballast surface, track drainage and moisture availability, weather conditions, tie deterioration or defects, and rail condition. Ballast samples were taken when possible to determine the source of ballast fouling and ballast condition. Discussions with local railroad personnel provided valuable information about track deterioration timelines and the potential root causes of damage. Digital image correlation from video can be used to measure track deflections during service (Murray, C. A., Take, A. W., & Hoult, N. A, 2015). When possible, videos of train passes were recorded to document track movement and support conditions. Accelerometer readings of tie movement during train passes were taken to gauge support conditions (Wilk, S. T., Stark, T. D., & Rose, J. G., 2015) to inform future laboratory studies focused on determining the mechanism of abrasion.

1.4 Project Scope

The results of this project are expected to increase industry knowledge of concrete railroad tie abrasion in track and associated contributing factors. The collected data will inform potential future studies to determine the mechanism of concrete abrasion damage and mitigation measures. Implementation of maintenance practices and track design features identified in this and future projects could prevent concrete wear, extend the life of track, and improve track safety. Specific outcomes include:

1. Determination of the prevalence of concrete railroad tie abrasion in track. This will help FRA determine how much attention to give this potential track safety issue.
2. Determination of track and environmental conditions that contribute to concrete section loss. This will help FRA determine where to focus attention in dealing with any concerns from this potential track safety issue.

1.5 Organization of the Report

This report provides a summary of concrete crosstie bottom and side abrasion prevalence, and environmental and track features identified as contributing factors. Detailed site visit information is organized by track features and is provided in Appendix A through F. Some sites contained characteristics of multiple site categories. In those cases, they were categorized by the most prevalent feature on site that was associated with the tie bottom abrasion. Appendix F contains a summary of visits to concrete boneyards. The sections of this report cover the following:

Section 2: Methodology

Section 3: Findings

Section 4: Conclusion

Appendix A: Bridges and Tunnels

Appendix B: Switches and Signals

Appendix C: Railroad Crossings

Appendix D: Curves

Appendix E: Tangent Track

Appendix F: Concrete Tie Boneyards

2. Methodology

Two environmental factors were identified as potentially contributing to concrete railroad tie abrasion wear: poor drainage and freezing conditions. Thirty-six track locations were selected to give a wide range of geographical and climatic conditions to determine the importance of water and freezing conditions on concrete abrasion damage. Figure 2-1 shows a map of States with track and boneyard locations visited in this project. Sites were selected with climatic conditions ranging from humid subtropical, with no snowfall, to subarctic conditions with an average low temperature in January of -8 °F to test whether the presence of ice was required to cause abrasion damage. Additionally, sites were selected with different rainfall patterns. Sites precipitation ranged from 9.25 in. of rainfall and 7 in. of snowfall to 106.7 in. of rainfall and 50 in. of snow.

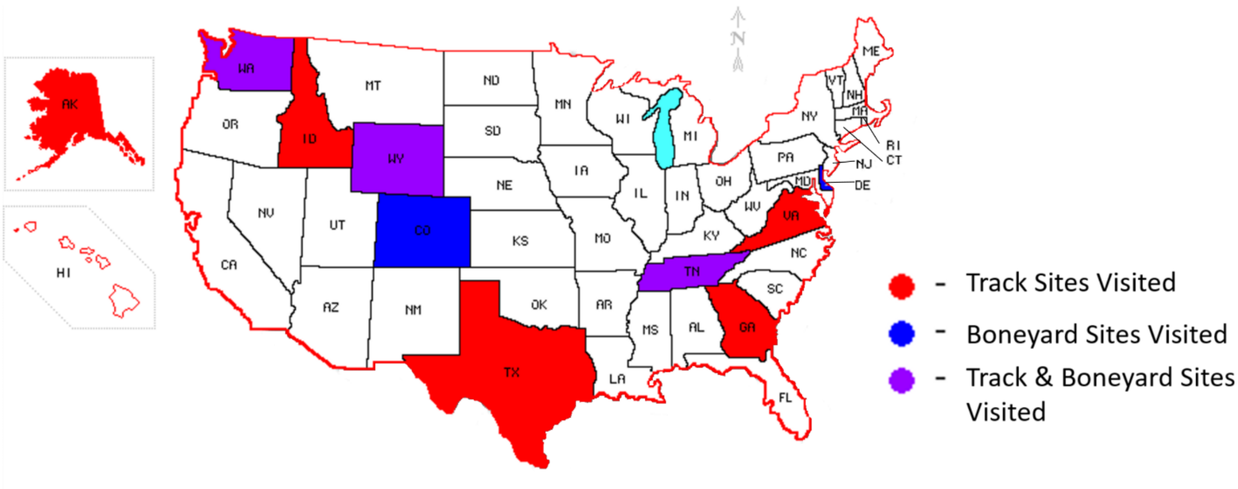

Figure 2-1: Map of States with track and boneyard sites

2.1 Visual Observations of Track Condition

Visual observations of track were the primary means of determining track condition and possible contributing factors. The research team prioritized qualitative visual observations of many sites rather than in-depth quantitative measurements of track conditions of only a few sites.

Track geometrical features, tie spacing, and track age were noted. Any track features such as signals, insulated joints, crossings, bridges, etc. were documented. Photographs were taken of the track condition, drainage, surrounding vegetation, discarded ties or rail on the side of the road, maintenance performed recently, and special track features.

Researchers noted the presence of moisture and mud pumping. In railroad track, mud pumping from track loading of fouled, wet ballast can cause material to impact the ties. Both potential causes of concrete abrasion damage involve tie movement in track.

2.2 Tie Measurements

Schmidt hammer readings were taken on the top of the ties as an index of the concrete surface hardness. The Schmidt hammer test is described in American Society for Testing and Materials (ASTM) C805 (ASTM C805, 2013). In this test, a spring hammer is released to impact perpendicular to the surface of the concrete with a constant amount of energy. The rebound of the hammer after impact is a function of the concrete elastic properties, mainly the concrete surface hardness. Concrete surface hardness is a function of the concrete strength and aggregate hardness. The higher the strength and aggregate hardness, the higher the rebound value. There is a high variability in the rebound value. Local material differences such as location of aggregates near the impact location, local variability in material properties, and surface roughness can affect the measured value. To help account for this variability, 10 Schmidt hammer measurements were averaged for each measured tie.

Ultrasonic pulse velocity (UPV) measurements were taken on the concrete ties to determine the presence of any internal damage. In UPV measurements, an ultrasonic (high frequency) pulse is imposed on the concrete. The arrival of the wave is measured by another transducer at a known distance from the pulse source. The speed of the wave arrival is calculated from the time measured for the wave arrival and the distance from the source and sensing transducer. The wave speed is a function of the concrete strength and any internal defects such as micro- or macro-cracks, with low wave speeds indicative of poor condition. Concrete ties in this study were measured using UPV by placing the pulse transducer on the tie shoulder top. Measurements were then taken by placing the sensing transducer on top of the concrete on the same shoulder as the pulse transducer, tie center, and opposite tie shoulder. This was done to determine if there was any internal damage in the concrete tie at either tie and where along the length of the tie.

2.3 Ballast Samples

Ballast samples were taken from track and placed into plastic bags for later analysis. These samples were used to determine the mineralogy of ballast and the presence of concrete in the fines. The mineralogical determination was performed by microscopic examination of the particles and was supervised by the team geologist. The presence of concrete in the fouling material in the ballast was determined by a simple drip test. A few drops of hydrochloric acid (HCl) are added to the sample, and if carbonaceous material is present, foaming results. Figure 2-2 shows a picture of a ballast sample that did not contain concrete fines after the addition of a few drops of hydrochloric acid, while Figure 2-3 shows an example of a ballast sample that did contain concrete fines after the addition of a few drops of hydrochloric acid. This could prove to be a simple test for maintenance personnel to use to determine if concrete bottom abrasion has occurred.

Figure 2-2: Ballast fines sample that was not carbonaceous and did not react with the addition of hydrochloric acid

Figure 2-3: Ballast fines sample that was carbonaceous and reacted with the addition of hydrochloric acid

2.4 Deflection Measurements

When possible, tie deflections were measured during train passes using high-definition video cameras. Video cameras were placed on tripods to minimize any camera movement. To calibrate the image pixels on the video files to the track movement, a ruler was printed onto a label and attached to the rail, as shown schematically in Figure 2-4. The track deflections were then measured by tracking pixel location changes on the printed ruler. Ten frames per second were analyzed to minimize sampling errors. Any vibrations that impacted the video were minimal compared to the large track deflections.

Figure 2-4: Schematic of rail with attached sticker to measure the deflection as the train passes

2.5 Acceleration Measurements

Concrete tie accelerations were measured when conditions were safe to do so. Acceleration data were recorded in three directions: longitudinal (X-direction), lateral (y-direction) and vertical (Z-direction), with a 20-kHz sample rate. Figure 2-5 shows the setting of the accelerometer and data acquisition equipment. The accelerometer was rigidly attached to the tie in the field using hot glue as shown in Figure 2-6. Data was analyzed to record the acceleration envelope of the tie movement.

Figure 2-5: Accelerometer and data acquisition equipment as a train passes

Figure 2-6: Accelerometer attached to the end of a tie before a train pass

2.6 Automated Track Inspection Program Geometry Car Data

FRA supplied the most recent track geometry data for each site from the Automated Track Inspection Program (ATIP) geometry car system. The ATIP geometry car measurements were taken several months-to-years before the site visits. It is possible that track maintenance activities or further deterioration changed the track conditions between the times of the geometry car visit and the research team visit. The research team looked for large variations in gauge and surface profile in the ATIP data. The track cross level and curvature information was also examined.

2.7 Interviews

Interviews with the track road master, maintenance and other railroad personnel were made when possible. They were questioned before the site visits to select the sites to visit that were most likely to contain ties with bottom-tie abrasion. Interviews were critical in obtaining details about the current state of the track, past maintenance activities, damage from derailments or other track events, slow orders, and causes of track deterioration.

3. Findings

Common environmental and track conditions were identified on locations that experienced concrete railroad tie bottom and side abrasion damage. This chapter contains a discussion of trends and contributing factors found. For more details of individual track or boneyard site visits, see Appendix A through F.

3.1 Environment

Environmental factors examined include drainage and freezing conditions. Abrasion damage at locations with a wide distribution of rain, snow, and track drainage conditions was compared to determine the significance of each for abrasion damage in track.

3.1.1 Drainage

The presence of water or poor drainage was an issue at sites with significant abrasion damage. Poor drainage was seen in 95 percent of the sites that had tie abrasion damage greater than 0.5 inches. The cause of the poor drainage was in many cases inadequate grading. Figure 3-1 shows an example of a location with drainage issues at a signal (Signal #2, Appendix B, Section B.3). In other cases, poor drainage could have been caused by ballast breakdown. Sites with center-binding tie cracking but without significant abrasion were in locations with excellent drainage and often in arid climates. In a tunnel location, water was seen in the ditches on both sides of the road, as shown in Figure 3-2. After the water in the ditch traveled a few dozen yards from the tunnel entrance, it turned and went through the track structure to empty out into the ditch on the other side of the track. Concrete ties near the location where the water went under the track were recently replaced in part because of abrasion damage.

Figure 3-1: Location with concrete tie abrasion damage had grading issues at signal controls

Figure 3-2: Water emanating from tunnel portal

Bridge decks were especially vulnerable to drainage issues. Bridges have built-in weep holes, drainage pipes, and other drainage features, however these can quickly become clogged by ground-up ballast, coal, dust, or concrete fines. Figure 3-3 shows Bridge #3 with standing water in track (Bridge #3, Appendix A, Section A.3). In this case, concrete ties with significant abrasion were removed from track and replaced with wooden ties. Figure 3-4 shows one of those ties after removal from track. Since the ballast was not cleaned and replaced, the concrete fines remained in track to block drainage. All three bridges with abrasion damage had drainage issues.

Figure 3-3: Bridge #3 section repaired with wooden ties

Figure 3-4: Tie from Bridge #3 after removal from track

Mud pumping was seen in sites with and without severe abrasion damage but was seen in 89 percent of the sites with measured abrasion damage greater than 0.5 in. The sites that did not have evidence of pumping had maintenance performed recently, making it inconclusive whether pumping was a factor or not. Ponding was also seen in track locations with pumping and abrasion damage, as shown in Figure 3-5. Pumping occurs when ties are loaded and apply pressure on the ballast below. When this occurs, water in the pores is pressurized. High pressure causes the water to move to areas of lower pressure, forcing water around the tie. When the loading is removed from the tie, the water pressure in the ballast pores decreases, sucking the water back in to the ballast (Huang, H., Tutumluer, E., & Dombrow, W., 2009). Hydro-abrasion damage from the mud pumping can contribute to tie bottom rounding.

Pumping was seen in four locations with low amounts of abrasion damage, such as described in appendices Sections C.4, D.1, E.4, and E.7. These sites did not contain gray mud and had shallow ballast layers, giving much different support conditions. This indicates that pumping by itself is not sufficient to cause bottom tie abrasion.

Figure 3-5: Water ponding in track, contributing to mud pumping

3.1.2 Freezing

Freezing was hypothesized to be a contributing factor to tie abrasion. Sites with snowfall ranging from 75.5 in. per year to no snowfall were examined to test whether ice formation in track is a prerequisite for concrete bottom tie abrasion. Abrasion damage of concrete railroad ties was seen in geographic locations with and without freezing conditions. This indicates that ice abrasion is not the primary mechanism causing concrete tie bottom abrasion. It is possible that ice formation in track could stiffen the track and slightly speed up the rate of deterioration, but it is not a primary factor required for damage.

3.2 Track Conditions

Track conditions that correlate with abrasion damage were identified. These factors include train dynamic effects, concrete tie materials, track stiffness, track maintenance, and center-binding cracking. Additional factors that could potentially contribute to tie bottom abrasion damage are discussed.

3.2.1 Train Dynamic Effects

Sudden changes in track stiffness, or discontinuities in rail or support conditions, cause vertical movement of railcars. This phenomenon is well known in the highway industry. Bumps at bridge approaches can cause vertical vehicle movement and increase impact loads on the bridge. Bumps can cause an increase in train wheel loads during the downward motion of the train. Once the train experiences significant vertical acceleration from the bump, the train can experience harmonics that may create a few locations of increased wheel loads after the original bump before the train vertical acceleration is damped and returns to normal conditions. The repeated increased wheel loads could cause increased ballast stress and breakdown. This can exacerbate drainage issues, cause mud pumping, and contribute to concrete tie wear. Common locations where these dynamics occur include: bridge abutments and transition areas, insulated joints, transitions from wood-to-concrete ties, and railroad crossings. Figure 3-6 is a close-up view of a mud spot at an asphalt crossing. Asphalt fines were found mixed in with ground concrete and ballast. The sticky nature of the asphalt particles could help agglomerate fines and limit drainage, accelerating the rate of deterioration. Sites with multiple mud spots near each other in track were found in 13 of the 36 sites visited. It is likely that most of these sites will have multiple mud spots as conditions deteriorate over time. Figure 3-7 shows examples of this phenomenon in track. The road master on this site indicated that the number of locations with mud pumping adjacent to each other grew with time. The size of each spot with gray mud also grew with time as damage accumulated. He also indicated that the damage spread wider under the ballast surface. Fouling under the surface causes additional ballast and tie breakdown, causing mud spots to grow along the track.

Figure 3-6: Mud spot at an asphalt crossing

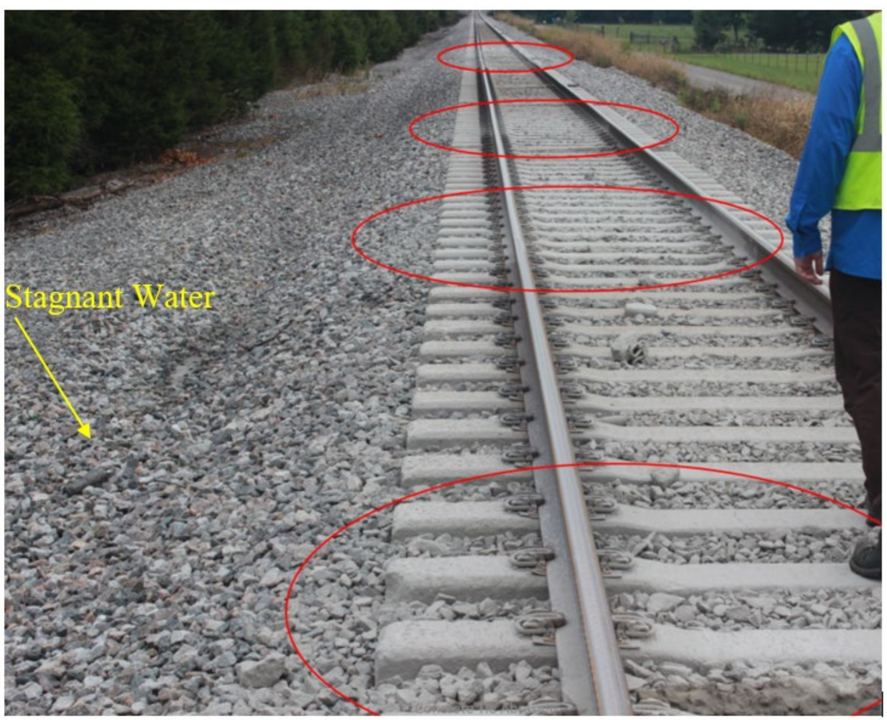

Figure 3-7: Adjacent mud spots seen near Crossing #3 (Appendix C, Section C.3)

Bumps or track stiffness changes were not a requirement for abrasion to occur but were found on 9 out of 19 sites or 47 percent of sites with more than 0.5 in of measured concrete tie loss. Abrasion damage was found at some locations in curves and tangent track without these features. Track bumps could increase train impact loads and ballast stresses. They could act as a trigger for ballast breakdown and changes in track conditions that could cause abrasion damage.

Where permitted, a three-dimensional accelerometer was fixed to the top surface of the concrete tie to measure the tie movement during a train pass. Tie movement is necessary to cause frictional rubbing and grinding according to classical abrasion mechanisms (ACI 201.2, 2008). Significant tie acceleration under train loading was measured in the vertical, rail, and tie directions in locations with abrasion damage. Figure 3-8 shows the acceleration measured for a tie located at signal #2, and described in Appendix B, Section B.2, in the longitudinal, lateral, and vertical directions. Over 10 g of acceleration was measured in the lateral direction, and over 40 g in the vertical direction during a train pass. In this case, the pumping created a gap under the tie, giving low amounts of lateral tie restraint. This resulted in some track misalignment after a single train pass, as seen in the before and after pictures in Figure 3-9 and Figure 3-10. Analysis of high-definition video of the track taken during the train pass confirms the vertical acceleration measurements recorded, as shown in Figure 3-11. Figure 3-12 and Figure 3-13 show screen shots of the video used to obtain Figure 3-11. Maintenance crews replaced ties from this location the next day. Tie bottom wear measurements after removal are shown in Figure 3-14.

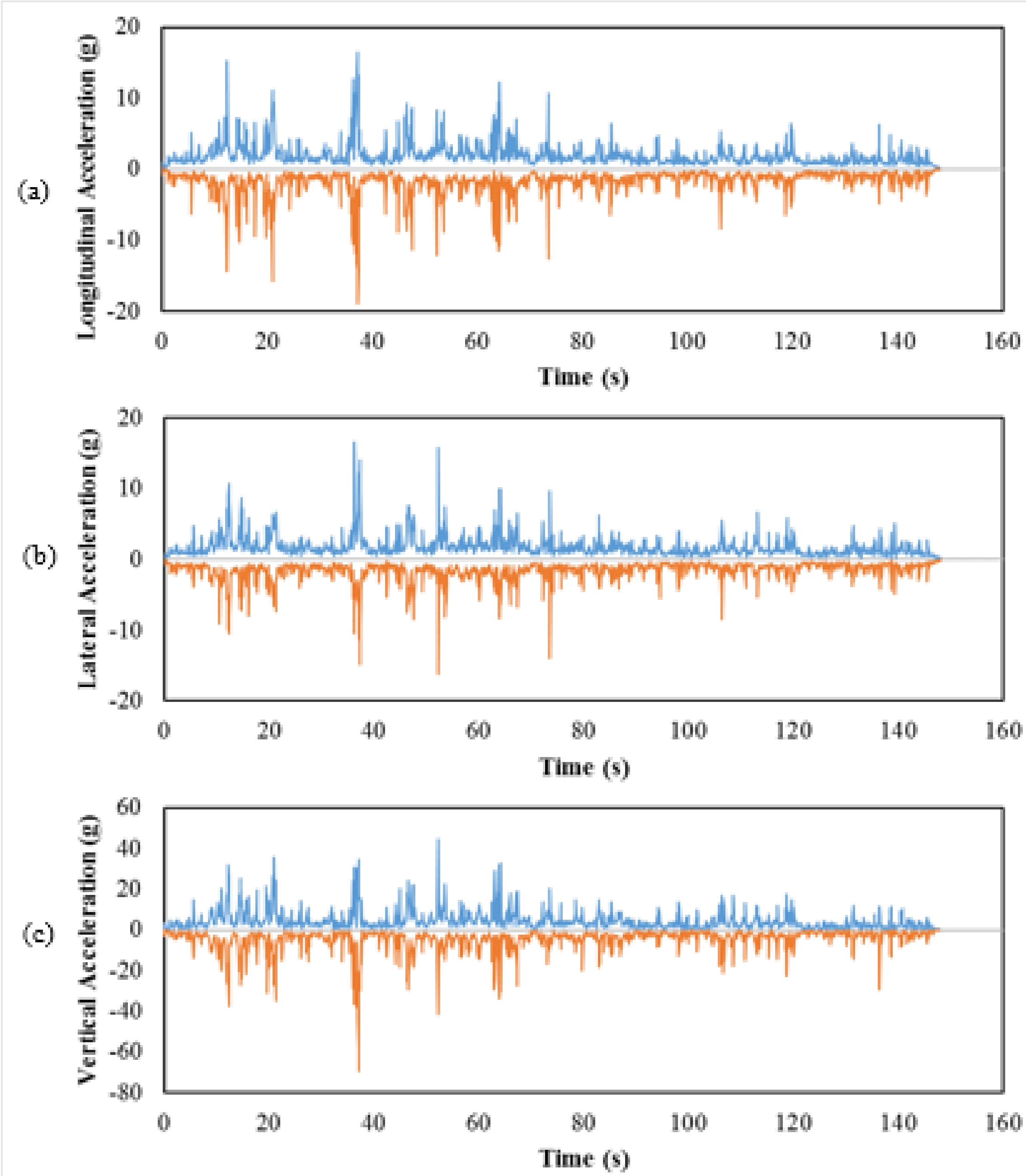

Figure 3-8: Acceleration measured with accelerometer in three dimensions: (a) vertical acceleration, (b) lateral acceleration (direction of tie), and (c) longitudinal acceleration (direction of rail).

Figure 3-9: Picture of track before the train pass

Figure 3-10: Picture of track after the train pass

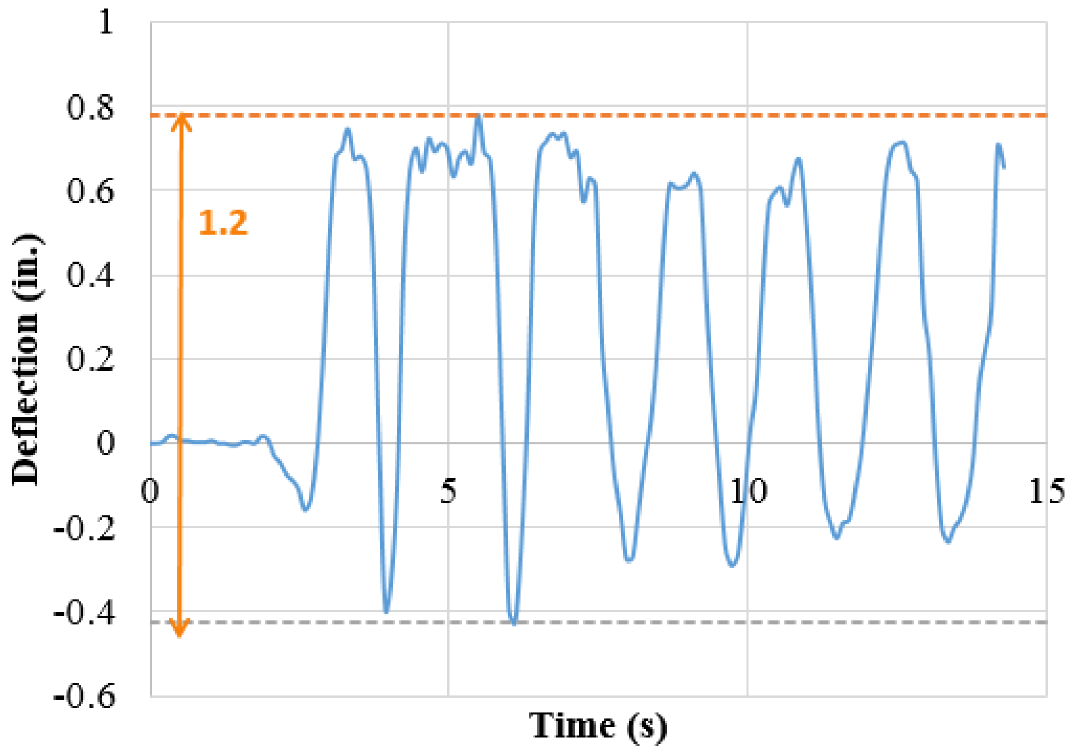

Figure 3-11: Tie deflection measured from video during train pass

Figure 3-12: Screen shot of video taken between wheel passes over the tie

Figure 3-13: Screen shot of video taken when wheel was over the tie

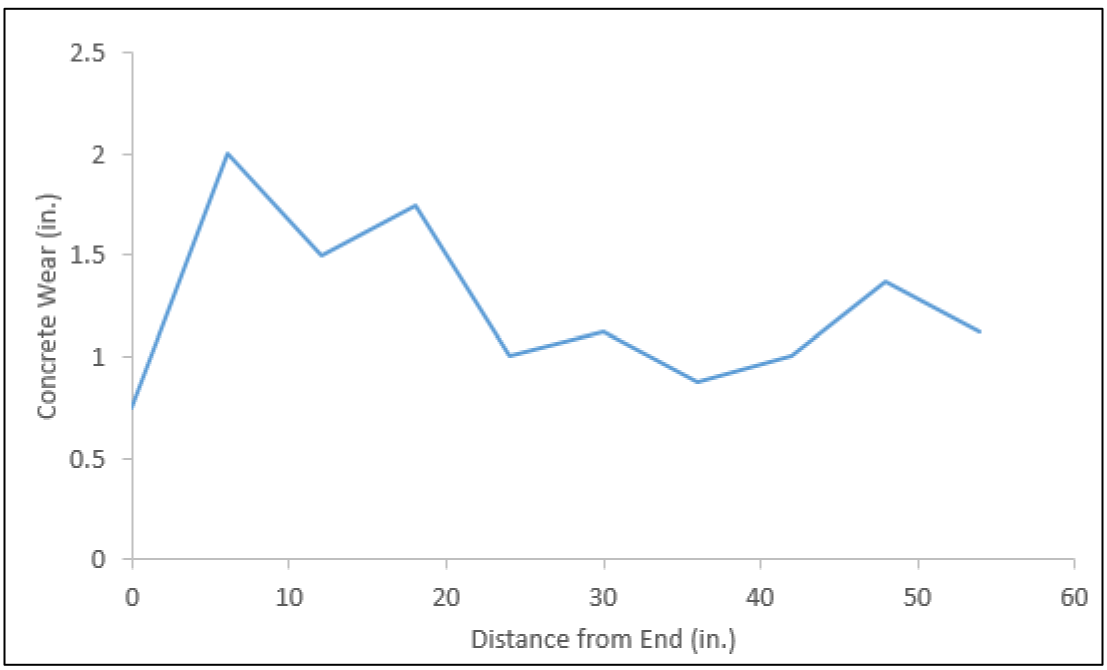

Figure 3-14: Concrete wear of tie removed from track

There was a gap between the tie and ballast underneath many ties that showed abrasion damage. Accelerations in the rail or tie can create frictional rubbing and cause significant abrasion given sufficiently high tie normal forces. Gaps between the ties and ballast were also seen in video footage. The vibrating motion of abrasive material on a surface is known to cause wear. Besides translational motion, ties are known to roll slightly as the train load is applied and removed. This rolling could also create frictional forces. The role of acceleration in the rail or tie directions in causing abrasion damage warrants further examination.

3.2.2 Concrete Material

This investigation examined ties from at least five different concrete tie plants. Each plant uses a different concrete mixture design with different, locally-available, aggregates. Concrete abrasion damage was seen in ties made from four plants. Concrete mixture proportioning and material selection cannot alone prevent abrasion damage. Due to environmental, service loading, and maintenance differences, definitive conclusions about the abrasion resistance of the different materials used in these ties cannot be made based on track inspections alone. Some conclusions about wear patterns can nonetheless be drawn based on visual observations.

Siliceous gravel and limestone aggregates are known to be harder than limestone aggregates. Limestone and dolomitic limestones typically have a Mohs hardness under 4. Gravel and granite aggregates have a Mohs hardness above 6. Softer aggregates are known to abrade at faster rates than harder aggregates. Aggregate hardness was measured with Schmidt hammer readings. The average Schmidt hammer readings of ties made with limestone aggregates was 4.8 lower than that of the ties made with siliceous gravel or granite. Ties made with limestone aggregates showed more even wear across the tie bottom and sides, with tie bottom corner rounding more pronounced as shown in Figure 3-15 and Figure 3-16. Compared to siliceous gravel, the hardness of limestone aggregates is more similar to that of cement paste, giving a more even wear. Abrasion on concrete ties with siliceous aggregates showed to be much more varied, with the cement paste wearing at a much faster rate than the aggregates. These ties have a jagged wear pattern. The more even wear seen on ties with limestone aggregates is indicative of faster abrasion rate.

Figure 3-15: Bottom of a tie made with limestone coarse aggregates found with abrasion damage on the side of the road

Figure 3-16: Tie made from hard siliceous aggregates in boneyard with significant abrasion damage

3.2.3 Rail Surface Profile and Alignment

Rail surface profile variations were seen at track locations with concrete abrasion damage. Profile variations change continuously through track use, deterioration, and maintenance activities. Rail surface-profile variations are not a cause of concrete tie wear, but they are a symptom. The observed variations are likely due to ballast fouling and mud pumping, resulting in permanent, localized settlement.

Investigators measured large amounts of tie deflection at Signal #2 as shown in Figure 3-11, and for Crossing #5 and Tangent Track #6. A large rail surface profile variation was seen at a mud spot location with abraded ties, Figure 3-17. High levels of rail and tie deflections during loading can fatigue the rail and contribute to rail breaks. Rail welds were commonly found at locations with abrasion damage.

Figure 3-17: Rail surface profile variation for track built on an old concrete highway. Red lines show the more than 1.3 in. of surface profile variation measured by the ATIP geometry car approximately 2 years before the picture was taken

Concrete tie abrasion may contribute to track alignment instability as shown in Curve #4, described in Appendix D.4, and shown in Figure 3-18. The ties in this location were scheduled for replacement because the ties were having difficulty keeping the curve radius constant during rail temperature changes. Ties in Curve #4 were made without scallops and had minor abrasion damage that may have reduce the lateral stability of the curve. Scallops may help prevent track misalignment.

Figure 3-18: Curve #4

3.2.4 Track Stiffness

Track stiffness appears to be an important contributing factor to concrete abrasion damage. Locations with known high stiffness had significant numbers of abraded ties. These locations included the three bridges described in Appendix A, Sections A.1 through A.4, and the track built an old concrete highway described in Appendix A, Section A.5, and shown in Figure 3-17 and Figure 3-19.

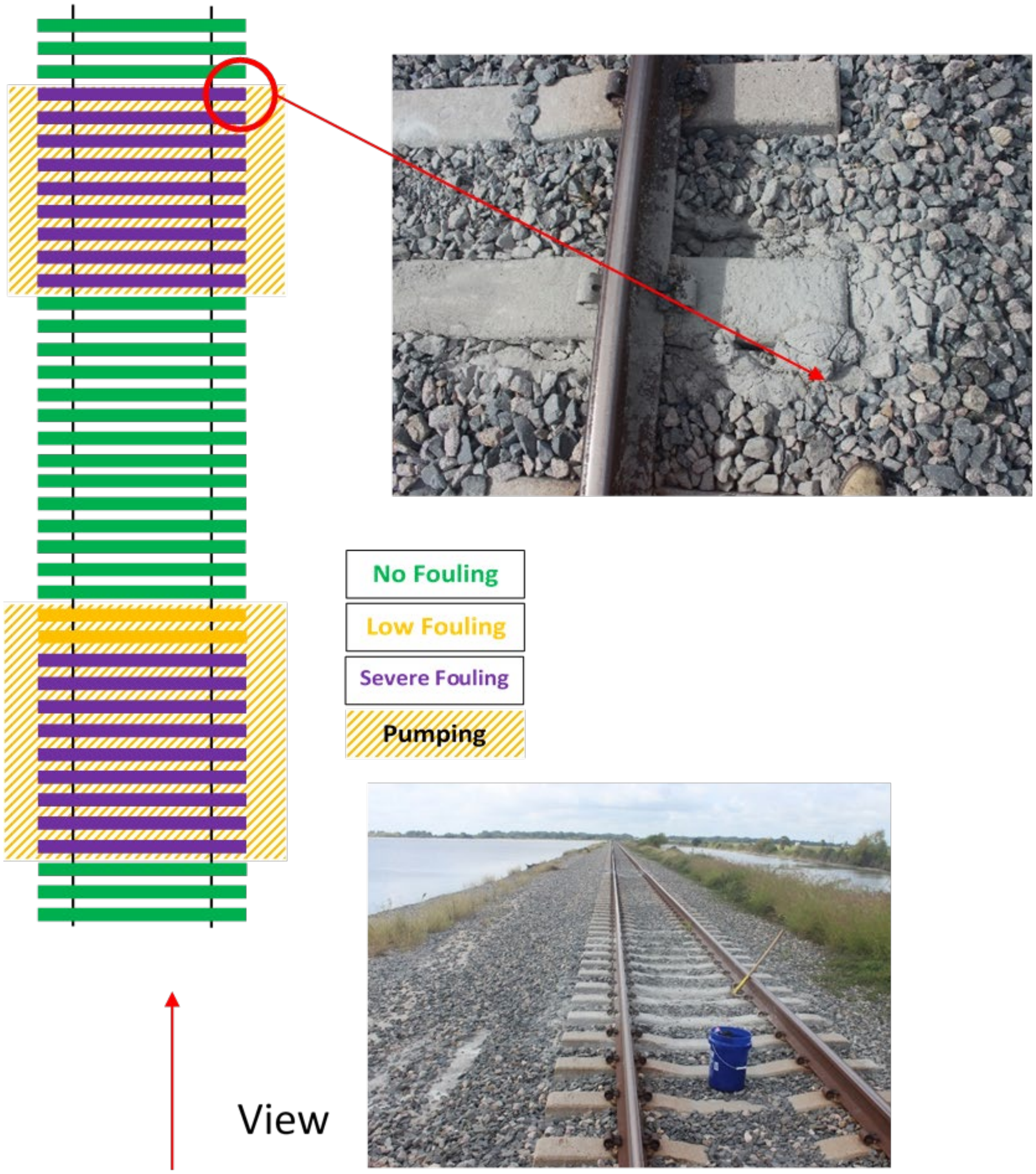

Figure 3-19: Abrasion damage at Bridge Approach #2

Figure 3-20 shows locations with tie abrasion damage in relation to a bridge (Bridge Approach #2, Appendix A, Section A.5). For the track section built over the old concrete highway, fines in track could not have come from mud or sub-ballast because of the presence of the highway in the track structure. In these locations, the ballast fouling was clearly caused by ballast and concrete tie breakdown. The fines were comprised of crushed ballast and ground concrete. Additionally, these locations have a thinner ballast layer. The thinner ballast yields higher ballast stress levels and consequently more ballast breakdown.

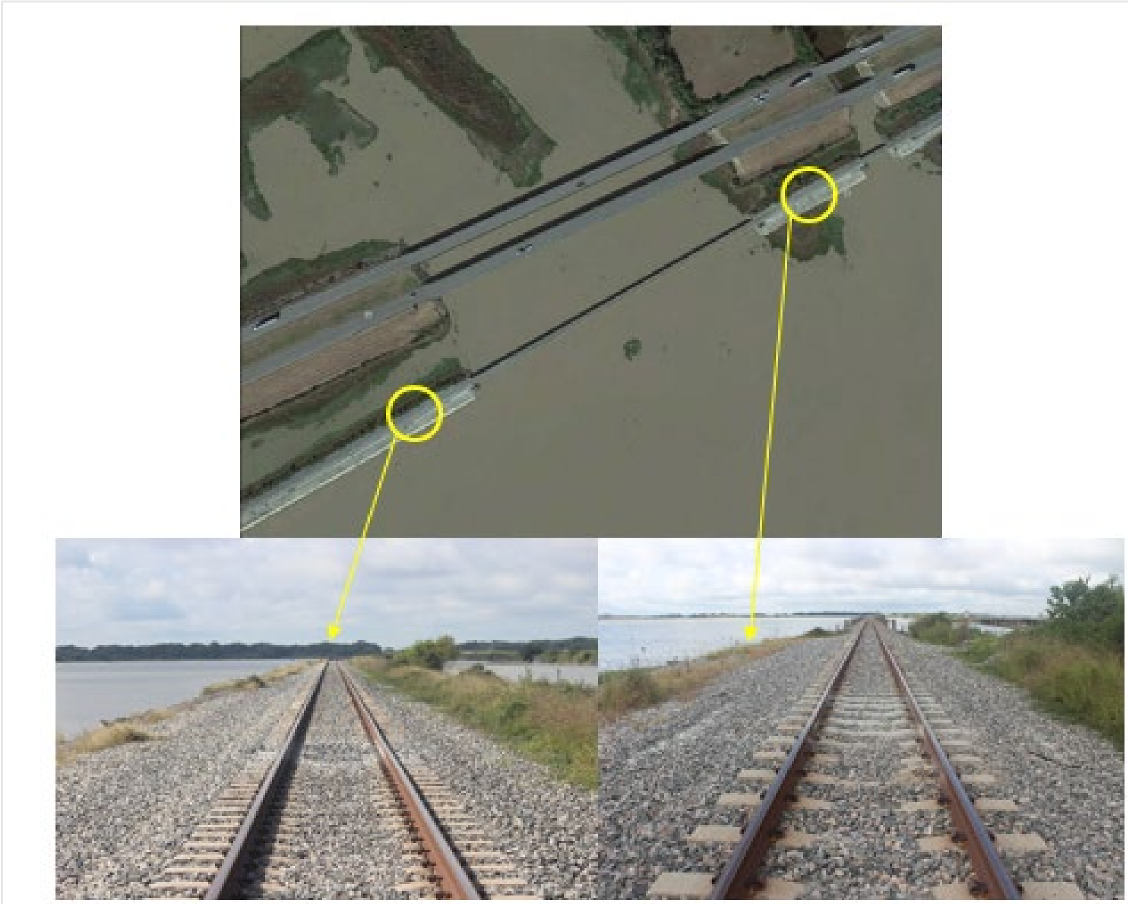

Figure 3-20: Bridge Approach #2, built over old concrete highway

Another location that was especially illustrative of the effects of increased track stiffness was Curve #3 (Appendix D, Section D.3). Two ties were found with severe abrasion on the sides facing towards each other. Part of an old tie was left between the two ties with severe side abrasion damage, as shown in Figure 3-21. This situation creates a very stiff track condition between the ties, leading to fouled ballast and retained water.

The longitudinal and lateral forces that ties can experience, Figure 3-8, can create large contact stresses between the side of the tie and ballast. In the case of the ties shown in Figure 3-21 and Figure 3-22, these high stresses cause significant mass loss. Other locations with fines and insufficient ballast underneath ties showed mud pumping, but only minor amounts of abrasion damage. Track with fouled ballast is known to have varying stiffness depending on the track moisture content. During dry conditions, the fines greatly increase the track stiffness, while during wet conditions they greatly decrease the track stiffness.

Figure 3-21: Abrasion found on sides of ties with an old tie in between, Curve #3

Figure 3-22: Close-up view of tie with side abrasion, Curve #3

3.2.5 Track Maintenance

Some locations had minimal amounts of gray mud and abrasion damage. The presence of a fine gray mud was a good sign of concrete abrasion wear. The gray color is indicative of concrete fines instead of ballast or other material. Track maintenance was emphasized at these locations, as shown in Figure 3-18 and described in Appendix D, Section D.4. The locations were well graded, ballast was undercut periodically, and ballast tamping was regularly performed. These actions ensure good drainage.

Ballast tamping was performed regularly at many locations with concrete abrasion wear. This was done to restore track profile and improve track support conditions. Tamping, however, does nothing to address the underlying conditions that contribute to tie abrasion. Tamping does not remove fouling, significantly improve drainage, or change track stiffness. Mud pumping and variable track support conditions return after tamping.

Local cribbing out of ballast did not appear to be a successful long-term strategy. This strategy was attempted at Bridge #2 (Appendix A, Section A.2). In this case drainage remained a problem and mud returned to the site. Mud spots can spread along the track. It is also difficult to remove all the fouled ballast since it is often present in a larger area under the surface. Track undercutting is more helpful but does not change underlying stiffness issues in track. Track performance after undercutting is better than after tamping alone, although pumping can eventually return.

A road master interviewed during one of the site visits provided some anecdotal evidence of a potential remedy to track sites with gray mud and concrete abrasion. The road master stated that they had tried many different remedial actions to improve the track, including pumping grout under the ballast to stiffen and stabilize the track structure. This method appeared to be counter-productive. It is possible that the grout reduced the load distribution across the ties and increased ballast stresses. He reported that the only remediation method that improved the situation was placing sheets of plywood between the ballast and sub-ballast. In theory, this method should reduce upward fine migration, better distribute forces across the sub-ballast, reduce track stiffness, and may help improve drainage. While the use of plywood in track may not be a long-term solution, it could point towards the use of under-tie pads (UTP) or under-ballast mats (UBM) as a solution to reduce track stiffness. More research is needed however to determine whether this is a viable mitigation method.

3.2.6 Center Binding Cracks

Center-binding cracks were regularly found at track locations with mud pumping and abrasion damage, as shown in Figure 3-23 for Crossing #3 (Appendix C, Section C.3). The presence of center-binding cracks did not directly correlate with abrasion damage. However, sections of track with center-binding cracking without fouling or drainage issues, but with low ballast support on the shoulders did show problems with abrasion damage. Figure 3-24 shows Tangent Track #1 (Appendix E, Section E.1) as an example of track with severe center-binding cracks, sometimes with shattered tie tops but without significant abrasion damage. In this case, the center-binding cracking was a recent phenomenon. Inadequate tamping after shoulder cleaning that had occurred the year prior to the research team visits appeared to reduce support at the rail-seat area. This led to center-bound ties and cracking within a month, without any evidence of abrasion damage.

Figure 3-23: Shattered ties at mud pumping location

Figure 3-24: Ties with center-binding cracks in an area with good drainage, maintenance, and support conditions and very low measured bottom wear

4. Conclusion

Thirty-six track sites with known occurrences of mud pumping or other track concerns were investigated by Kansas State University, the University of Florida, and Infrastructure Research, LLC, to determine the prevalence of concrete bottom tie abrasion and environmental and track conditions that could contribute to its occurrence. Field investigations showed that concrete bottom tie abrasion, while not the largest source of concrete tie safety issues present in track, does occur in diverse geographic locations around the U.S. and is a source of continued maintenance concern for railroads. Concrete bottom tie abrasion occurs in discrete locations, but its occurrence is not unusual.

Water appeared to be a significant factor involved in concrete bottom tie abrasion. Visual evidence of grading or drainage issues were found in 95 percent of the sites with significant abrasion damage. Freezing conditions were not required for bottom tie abrasion to occur.

Significant tie acceleration and displacement during train loading, rail surface profile variations, and center-binding cracking were often seen at locations with abrasion damage. These features were likely symptoms of track condition issues rather than causes of the concrete wear. Bumps or track stiffness changes were often found at locations of abrasion damage, but not always. Track stiffness appeared to be a contributing factor to concrete tie bottom abrasion. Although the research team was not able to measure in-situ track stiffness in this study, significant abrasion damage was observed at locations with known stiff track.

The severity of tie abrasion can increase with time if railroads do not take corrective maintenance action. Tamping, localized ballast removal, or individual tie replacement can help temporarily mitigate the problem, but these methods did not adequately stop abrasion damage from progressing or recurring. Ballast undercutting was a more effective method for delaying or slowing down concrete tie abrasion but may not address the root causes of the problem.

Based on the field study performed, the following are potential mechanisms involved in concrete tie abrasion wear:

- Track transition locations and bumps create dynamic loads and change how track forces are distributed. This contributes to increased ballast stress, breakdown, and tie deflections during loading.
- Track stiffness appeared to be a major contributing factor. Although higher track stiffness is desirable for distributing tie forces over a greater subgrade area and thereby minimizing rail deflection, locations with stiff track experience higher ballast stresses below the tie, which leads to ballast breakdown. Ballast breakdown in turn contributes to increased track stiffness during dry periods and increases the forces acting on the tie.
- Gaps that emerge between the tie and the ballast from ballast breakdown and settlement create rubbing between the tie and the ballast during train loading. Impacts between the tie and ballast after the tie deflects creates impact damage.
- Lateral movement in track can cause rubbing and wear. Ballast movement adjacent to ties seen during loading contributes to frictional forces and rubbing.
- Poor water drainage leads to mud pumping and ballast fine/mud slurry development that results in hydro-abrasive damage of the concrete ties.

4.1 Recommendations

Identification of environmental and track conditions present at track locations that experience concrete bottom tie abrasion has led to the development of several potential hypotheses of the wear mechanisms. Further understanding of these mechanisms would allow for improvements in recommended track design criteria and the type and frequency of maintenance that should be performed. It is recommended to investigate the following mechanisms in a laboratory environment to isolate the most significant concrete tie abrasion mechanisms and to begin development of maintenance and mitigation methods.

- The effect of track stiffness and water content on concrete tie wear should be investigated.
- Mitigation provided by UTP or UBM
- The effect of gaps between the tie and ballast.
- The influence of tie lateral movement and rolling during loading.
- Effects of hydro-abrasive forces on concrete wear.

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Appendix A.
Bridges and Tunnels

The research team visited seven bridges, bridge approach, and tunnel sites. Bridges were visited in several different U.S. regions to examine the unique track design and conditions found on bridges. Damage was found in many locations.

A.1 Bridge #1: Steel Bridge in U.S. Pacific Northwest

Researchers inspected a bridge on a 5.5-degree curve in the U.S. Pacific Northwest that in June 2016. The local climate is Dfb climate (warm summer continental climate) per the Köppen climate classification system. The bridge location has an average annual rainfall of 16.5 in., average annual snowfall of 45 in., an average high temperature of 83 °F in July and average low temperature of 25 °F in January. The concrete ties used were manufactured in 1990. The track was designed to have 12–14 in. of ballast between the top of the deck and the bottom of the ties. Ties had a center-to-center spacing of 24 in. The track speed has only one-way traffic with a maximum speed of 60 mph. Figure A-1 shows a satellite view of the inspected bridge and track-level pictures. The pumping was so extended that it was visible through Google Earth. The bridge is a three-span steel-girder bridge with steel truss supports, as shown in Figure A-2.

Figure A-1: Gray mud in track is visible in a) satellite image from Google Earth, b) track-level view, and c) up-close view of a concrete tie, Bridge #1

Figure A-2: Bridge superstructure and truss supports, Bridge #1

A.1.1 Track Visual Observations

The road master reported that the railroad began replacing the ballast on the bridge 10 years prior, but was forced to stop half-way through the project by local authorities. Half of the bridge showed large amounts of gray mud and pumping, while the other half that had been undercut did not have gray mud at the surface. Figure A-3 shows fines present at the bottom of ties. Gray mud spots were seen in periodic intervals on the bridge, with heavier fouling seen in ballast sections directly over the bridge piers. Bridge piers prevent vertical movement of the bridge deck and create localized increases in track stiffness. The higher local track stiffness likely caused high ballast stresses, particle breakdown, and concrete wear. Center-binding cracking was seen at fouled ballast locations, as shown in Figure A-4.

Figure A-3: Fine particles available due to tie abrasion, Bridge #1

Figure A-4: Moderate binding cracking on ties, Bridge #1

The road master reported that bridge drainage is a problem. The fines from ballast fouling regularly plug weep holes on the bridge. The lack of drainage, and the presence of high-absorption fines trapped water during precipitation events, traps water in the structure. Moisture was seen in the ballast at the bottom of the ties after removing ballast around the tie.

A.1.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 51. The thickness of the same tie was measured at three locations. Ballast surrounding the tie was removed to reach the bottom of the tie at both ends and in the center to measure the tie thickness. Table A-1, shows the tie thickness measured on the tie in track.

Table A-1: Tie thickness measurements, Bridge #1

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.1875	6.0625	2.125
Center	6.25	5.4375	0.8125
Tie End	8.1875	7.625	0.5625

A.1.3 Track Geometry Measurements

The ATIP geometry car measured track conditions approximately one year before the research team visited the site. Profile deviations at this location were approximately -1 in. of variation on the left profile and approximately -1.25 in. of variation on the right profile. Deviations in the alignment also increased at the same location. The maximum gage seen on-site was 58.146 in., with a large section of track with a gage above 57 inches.

A.1.4 Ballast Analysis

A ballast sample was collected on the site at the depth of the bottom of the tie. Table A-2 shows the ballast analysis. The ballast type used in this section of track was a vesicular basalt. Since the ballast sample was taken on the bridge, the only possible source of the fines could be broken-down ballast, concrete fines from the ties or bridge deck, or coal from passing trains. The ballast analysis showed that a large amount of the fines was carbonate-based, indicating that they were from the concrete ties. It is estimated that the ties lost three-quarters of a cubic foot of concrete from abrasion. Combined with ballast breakdown, ballast porosity was significantly reduced in track, significantly reducing drainage. The ballast analysis confirmed the large amounts of concrete fines present in the ballast.

Table A-2: Ballast and subgrade analysis results, Bridge #1

Sample type	Material types present:	Sample description
Ballast	Fines	Carbonate/concrete fines (strong HCl reaction); large chunks are igneous rock and also pieces of fines that are stuck together

A.2 Bridge #2: Concrete Bridge in U.S. South-Central

Researchers visited a small concrete bridge in the south-central region of the U.S. in October 2017. The bridge crosses a small stream, as shown in Figure A-5. The ties were fabricated in 2006 or 2007 and had a center-to-center spacing of 24 inches. The maximum track speed was 49 mph. The local climate is humid subtropical, a Köppen climate classification of Cfa. The track location has an average annual rainfall of 42 in., no annual snowfall, an average high temperature of 93 °F in July and an average low of 42 °F in January. A satellite view of the concrete bridge taken from Google Earth is shown in Figure A-6. A track-level view of the site is shown in Figure A-7.

Figure A-5: Stagnant water under Bridge #2

Figure A-6: Satellite view of Bridge #2 from Google Earth

Figure A-7: Bridge #2 viewed at track level

A.2.1 Track Visual Observations

A section of the ballast near the bridge abutment was cribbed out to remove fouled ballast about 8 months before the research team visited the site (Figure A-8). A water ditch, Figure A-9, was created at the same time the ballast was replaced to improve drainage. Drainage holes at the location of the ballast fouling were plugged, whereas at the other locations on the bridge they were not clogged. Eight ties at the location where the ballast maintenance was performed showed moderate-to-severe center-binding cracking, as shown in Figure A-10.

Figure A-8: Bridge #2 abutment where ballast was replaced 8 months prior to the site visit by the research team

Figure A-9: Ditch in ballast to improve drainage on Bridge #2

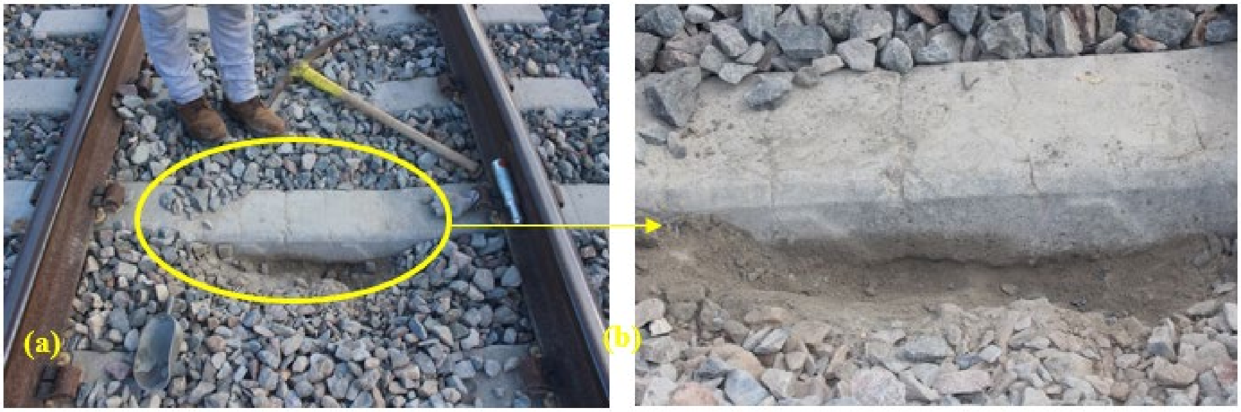

Figure A-10: Ties with moderate-to-severe center-binding cracking, Bridge #2

A.2.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 52. Ballast was removed from the sides of a tie where ballast had been replaced eight months prior and in the center of the bridge where no drainage or ballast fouling issues were seen. Table A-3 shows the tie thickness of the ties at these locations measured on the site. The tie measured near the bridge abutment showed significant abrasion wear, while the tie in the center of the bridge showed little abrasion problems. Bridge abutments are locations known to have changes in track stiffness. This can cause train dynamics and can increase the wheel loads on the stiffer portions of the track.

Table A-3: Tie thickness measurements, Bridge #2

Tie Location in Track	Measurement Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Near Abutment	7 in. from tie end	9	7.5	1.5
Near Abutment	50 in. from tie end	7	5.5	1.5
Center of Bridge	Tie End	9	8.5	0.5

A.2.3 Track Geometry Measurements

The ATIP geometry car tested this track 2 years before the research team visit. Profile variations were -1.111 in. on the left rail, and -0.903 in. on the right rail. ATIP measured 0.75 in. of crosslevel and a maximum gage of 56.591 inches.

A.2.4 Ballast Analysis

A ballast sample was taken at the depth of bottom of the concrete railroad tie from the location shown in Figure A-11. The ballast analysis is shown in Table A-4. Concrete fines were present in significant amounts, confirming that the ties lost a significant amount of material thickness. The analysis also showed that the ballast was complrised of granite and gneiss aggregates that are known for being hard and durable.

Figure A-11: Ballast sample collection location, Bridge #2

Table A-4: Ballast and subgrade analysis results, Bridge #2

Sample type	Material types present:	Sample description
Ballast	Fines, Rock	Ballast was made up of granite and gneiss. The fines reacted with the HCl acid, indicating the presence of carbonaceous material. There were also shell or fossil particles in the sample.

A.3 Bridge #3: Concrete Bridge in U.S. Southeast

Researchers visited a six-span bridge in the U.S. Southeast in December 2016. The concrete ties were inspected for signs of abrasion damage on the sides and bottoms. The ties were manufactured in 1998 and spaces 24 in. on center. The track maximum speed was 60 mph. The local climate is humid subtropical. The bridge location has an average annual rainfall of 50 in., no snowfall, an average high temperature of 93 °F in July and average low temperature of 36 °F in January. A satellite view taken from Google Earth of the bridge site is shown in Figure A-12.

Figure A-13 shows the concrete bridge site during the inspection. The bridge had 6 inches of ballast between the bottom of the concrete ties and the top of the bridge deck.

Figure A-12: Satellite View of Bridge #3 with high abrasion and pumping (Google Earth)

Figure A-13: Bridge #3

A.3.1 Track Visual Observations

The track visual inspection showed that six ties were removed from track and replaced with wooden ties, (Figure 3-3). The concrete ties that were removed from track were found on the side of the track, as shown in Figure 3-4 and Figure A-14. These were rounded on the bottom and had signficant abrasion loss, exposing prestressing steel. The section of track where the concrete ties were removed had drainage problems. Figure A-15 shows a picture of the clogging seen on the bridge ends. Figure A-16 shows a diagram of the bridge drainage system in the bridge. Ties in this track section showed significant pumping, a likely contributing factor to the abrasion damage. Moderate center binding cracking was seen on some the ties as shown in Figure A-17. Figure A-18 shows ties at the approach with center-binding cracking.

Figure A-14: Discarded tie with high abrasion, Bridge #3

Figure A-15: Drainage issues on Bridge #3

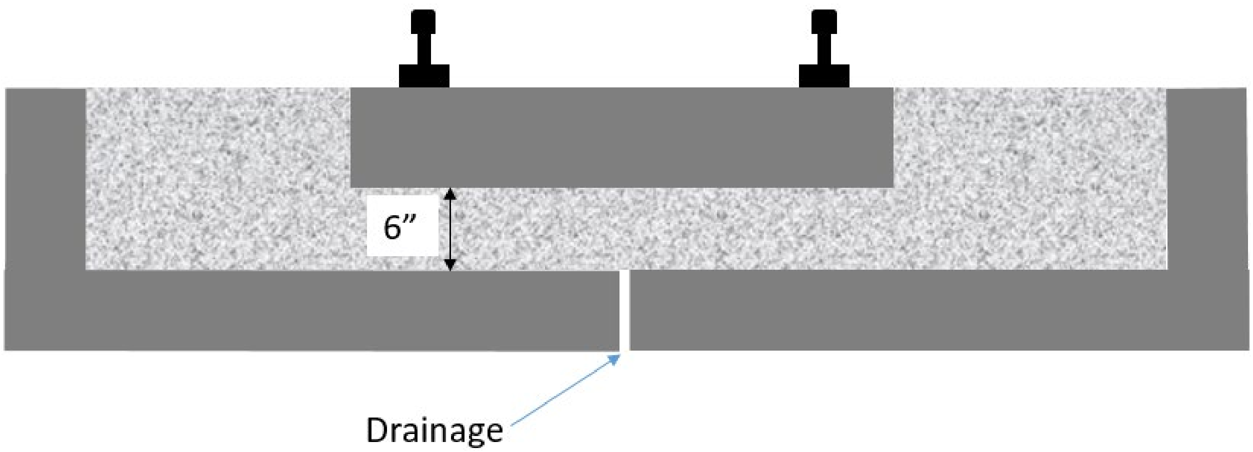

Figure A-16: Cross-section schematic of Bridge#3

Figure A-17: Moderate center binding cracking, Bridge #3

Figure A-18: Damaged and cracked ties in Bridge#3 approach

A.3.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 45.

Researchers measured thickness of a tie removed from track. The tie design dimensions, measured thickness, and estimated wear for different points along the length of the tie are shown in Table A-5.

Table A-5: Tie thickness measurements, Bridge #3

Distance from end (in.)	Design thickness (in.)	Measured thickness (in.)	Estimated wear
0	8.25	6.75	1. 5
6	8.25	7	1.25
12	8.25	7	1.25
20	8.25	7	1.25
28	8.25	7.625	0.625
36	7	6	1
48	7	7	0
60	7	6.5	0.5
66	7	7	0
75	8.25	7.5	0.75
80	8.25	7.25	1.0
92	8.25	7.625	0.625
102	8.25	7.25	1.0

A.3.3 Track Geometry Measurements

The ATIP geometry car measured the track approximately two months after the research team visited the site. The geometry car measured a maximum variation of 0.693 in. in the left rail profile and 0.890 in. in the right rail profile. The maximum crosslevel measured was 0.04 inches. The maximum gage was 57.28 inches.

A.3.4 Ballast Analysis

A ballast sample was taken from the bridge at the depth of a tie. The ballast analysis showed the sample fines were carbonate, or concrete-based, as shown in Table A-6. When the old concrete ties were removed from track and replaced with wood ties, a significant amount of concrete-based fouling was left in track and continued to block drainage.

Table A-6: Ballast analysis, Bridge #3

Sample type	Material types present:	Sample description
Ballast	Fines, Rock	Rock consists of gneiss, granite, and basalt. Strong HCl reaction with fines. Fines are carbonate (concrete).

A.4 Bridge Approach #1: U.S. South-Central

The research team visited the approach area to a concrete bridge located in the south-central zone of the U.S. in October 2017. Track and ties were inspected for evidence of concrete tie bottom and side abrasion damage, as well as ballast fouling. The ties were fabricated in 2007 and were installed on 24 in. centers. The concrete, multi-span bridge is located over a riverbed that is dry for part of the year. The track speed was 49 mph, but speed was restricted to 25 mph for 2 years prior to the site visit. The local climate is humid subtropical. The track location has an average annual rainfall of 45 in., no snowfall, an average high temperature of 95 °F in August and an average low of 42 °F in January. A satellite view of the bridge approach from Google Earth is shown in Figure A-19. Figure A-20 shows a picture of the bridge approach taken on track facing the bridge.

Figure A-19: Bridge Approach #1 with excessive pumping from Google Earth

Figure A-20: Track-level view of Bridge Approach #1

A.4.1 Track Visual Observations

The bridge approach appeared to be in good condition. The track had surfacing issues in the past, probably because of the steep side slope. The railroad had installed rip-rap and wood posts to reinforce the track bed, as shown in Figure A-21. Track maintenance personal said that before this change, the track experienced water ponding because of fouling. Little wear was seen in the bottom of the ties in track. Ties taken from track and stored with the rip-rap still have side scallops and finishing roller marks, as shown in Figure A-22, indicating little abrasion damage. The recent track maintenance activities seem to be effective. Little abrasion damage was seen in track.

(a) (b) (c)

Figure A-21: Use of piles to stabilize the slope, Bridge Approach #1

Figure A-22: Removed ties stored on the sides of the track, Bridge Approach #1

A.4.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 47. Table A-7 shows the tie thickness measured in track.

Table A-7: Tie thickness measurement, Bridge Approach #1

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	9	8.75	0.25
Center	7	6.5	0.5

A.4.3 Track Geometry Measurements

The ATIP geometry car measured the track properties two years before the research team visited the site. At that time, there was a profile variation of -1.300 in. in the left rail and -1.199 in. in the right rail. There was very little crosslevel in the track, and less than 0.09° curvature. The maximum gage was 56.611 inches.

A.4.4 Ballast analysis

A ballast and sub-ballast sample were taken from the track. There was little fouling on site, probably because of maintenance activities. The fines that did exist were reactive to acid. Material taken from sub-ballast away from the track showed that the fines also reacted with the acid, indicating a carbonaceous material is present naturally. The relatively low quantity of fines matched the low amount of abrasion seen. Concrete fines are not present in significant quantities at this site. Table A-8 presents the ballast and sub-ballast sample analysis.

Table A-8: Ballast analysis, Bridge Approach #1

Sample type	Material Types Present:	Sample description
Ballast	Fines, Rock	Diorite and Granite. Very few fines. Fines react strongly with HCl acid.
Sub-ballast	Rock	Granite, Basalt, Diorite, Fine powdered samples reacted with acid

A.5 Bridge Approach #2: Lake Crossing in U.S. South-Central Region

Researchers visited two sections of railroad track separated by a bridge in 2017. The railroad track was built on top of an old concrete highway, giving the track very stable but stiff support conditions. The concrete ties used in track were fabricated in 2007. The track maximum speed was 49 mph. The local climate is humid subtropical. The track location has an average annual rainfall of 42 in., no snowfall, an average high temperature of 93 °F in July and an average low of 42 °F in January. A satellite view of the site taken from Google Earth along with track level pictures of the site is shown in Figure 3-20.

A.5.1 Track Visual Observations

According to the maintenance crew, this site has constant maintenance issues. Figure 3-19 shows an example of the type of maintenance issues experienced on-site. The site was undercut two years before the research team visit. Gray mud was observed during the visit. The ballast appeared to be less than 12 in. at the mud spots. Low ballast levels in these locations may have contributed to high stresses in ballast and ties, causing breakdown and fouling. Some center-binding cracking and surfacing issues were seen at the site. Figure A-23 shows the round shaped tie on the site with fines under it that looks like they are more from concrete because of the color. Fines on the side of the track are shown in Figure A-24.

Figure A-23: Rounding of tie bottom, Bridge Approach #2

Surfacing issues were seen by the research team at the locations of the gray mud. Figure 3-17 shows a picture of the track at a mud spot on the western end of the bridge. Red lines are drawn in the figure to enhance the view of the vertical profile dip in track. Gray mud is shown on the rail sides at the location of the surfacing issue, highlighting the cause of the surfacing issue.

Figure A-24: Fines on the side of track, Bridge Approach #2

A.5.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 49. Table A-9 shows the tie thickness of ties measured on the site.

Table A-9: Tie thickness, Bridge Approach #2

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie #1 end	9	6	3
Tie #1 center	7	6	1
Tie #1 end	9	8.125	0.875
Tie #2 end	9	8.5	0.5
Tie #2 center	7	6	1

A.5.3 Track Geometry Measurements

The ATIP geometry car visited the track site approximately two years before the research team. 1.328 in. of maximum variation was measured in the left rail profile and 1.346 in. was measured in the right rail. Measurements showed a maximum gage of 56.563 inches.

A.5.4 Ballast Analysis

A ballast sample was taken from the track at the depth of the bottom of the tie. The ballast analysis is shown in Table A-10. The ballast was a gneiss aggregate. Gneiss are known to be hard and are often a good choice for ballast material. The fines contained a high percentage of carbonaceous material with a gray color, indicating concrete fines.

Table A-10: Ballast analysis, Bridge Approach #2

Sample type	Material Types Present:	Sample description
Ballast	Fines, Rock	Rocks are gneiss in total. There is a feldspar/quartz layer on one of the gneisses. The fines react with HCl. The fines are also all a powdered gray likely from concrete.

A.6 Bridge Approach #3: Bridge Approach in Subarctic Climate

Researchers visited track near a bridge in the U.S. Pacific Northwest in August 2016. The local climate is continental subarctic with cool summers. The location has an average annual rainfall of 16.6 in. and snowfall of 75.5 in., an average high temperature of 65 °F in July and average low temperature of 8 °F in January. The concrete ties were manufactured in 2004. Ties had a center-to-center spacing of 24 inches. The track speed was 60 mph for passenger and freight trains. Figure A-25 shows (a) a satellite view of the bridge from Google Earth, (b) a view of the bridge, and (c) a view of the site and ties. This track has a low annual tonnage. It carries principally gravel cars and passenger cars.

Figure A-25: Bridge Approach #3 a) from satellite from Google Earth, b) bridge next to site, and c) location with gray mud

A.6.1 Track Visual Observations

Figure A-26 shows a graphical representation of the general tie conditions along this track. The transition from wood ties to concrete ties is shown in Figure A-27. Longer wooden ties were used to give similar track stiffness as the concrete ties. The bridge appeared to be a few inches higher in elevation than the approach track. It is possible the change in elevation and a bump from the wood tie-to-concrete tie transition increased track dynamic loads and caused center-binding cracking in the concrete ties. The ties with center binding cracking had only minor cracks present, as shown in Figure A-28. Train vertical movement harmonics could result in higher loads where the fouling exists.

Figure A-29 shows the concrete ties with fouling and pumping present. Figure A-30 shows the gray colored fines on the site. Drainage appeared to be less than ideal in the location with ballast fouling. There was only limited drainage to the side of the track shared with another track. The area around the track showed evidence of water-loving vegetation, indicating that moisture is present much of the year. Utilities in track restrict maintenance to ballast tamping.

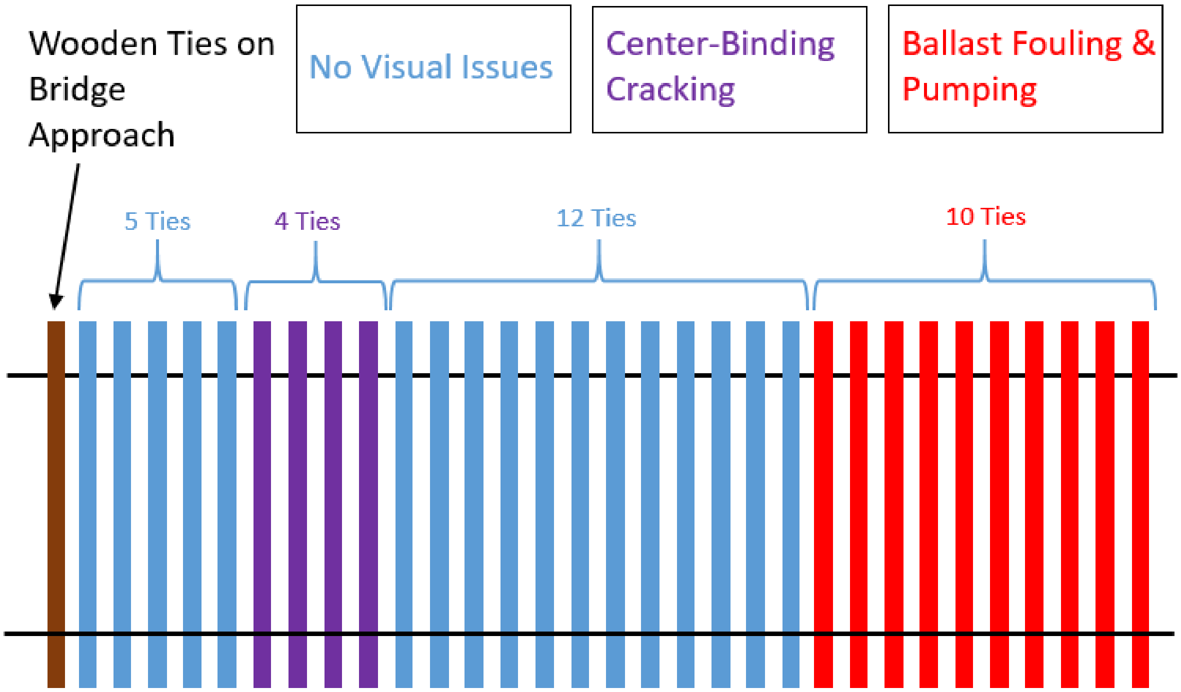

Figure A-26: Concrete tie condition, Bridge Approach #3

Figure A-27: Transition zone from concrete to wood ties, Bridge Approach #3

Figure A-28: Tie center cracking, Bridge Approach #3

Figure A-29: Area with mud pumping, Bridge Approach #3

Figure A-30: Gray mud, Bridge Approach #3

A.6.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 43. The thickness of the tie used to for the Schmidt hammer readings was measured. Ballast surrounding the tie was removed by hand to reach the bottom of the tie at the end and the center to measure the tie thickness. Table A-11 shows the tie thickness measured on the tie in track.

Table A-11: Tie thickness measurements, Bridge Approach #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7.5	0.75
Center	7	5.625	1.375

A.6.3 Track Dynamic Measurements

Researchers recorded tie acceleration during a train pass, Figure A-31. Video was taken of the train pass to document mud pumping and tie movement. The video shows a few ballast particles adjacent to the tie moving. Ballast movement during train passes could contribute to rubbing and wear. Figure A-32 shows the acceleration measured on the tie during train loading. The tie experienced significant vertical acceleration, indicating that there is a gap between the tie and ballast support. Tie lateral movement was higher than expected.

Figure A-31: Accelerometer attached to the side of the tie, Bridge Approach #3

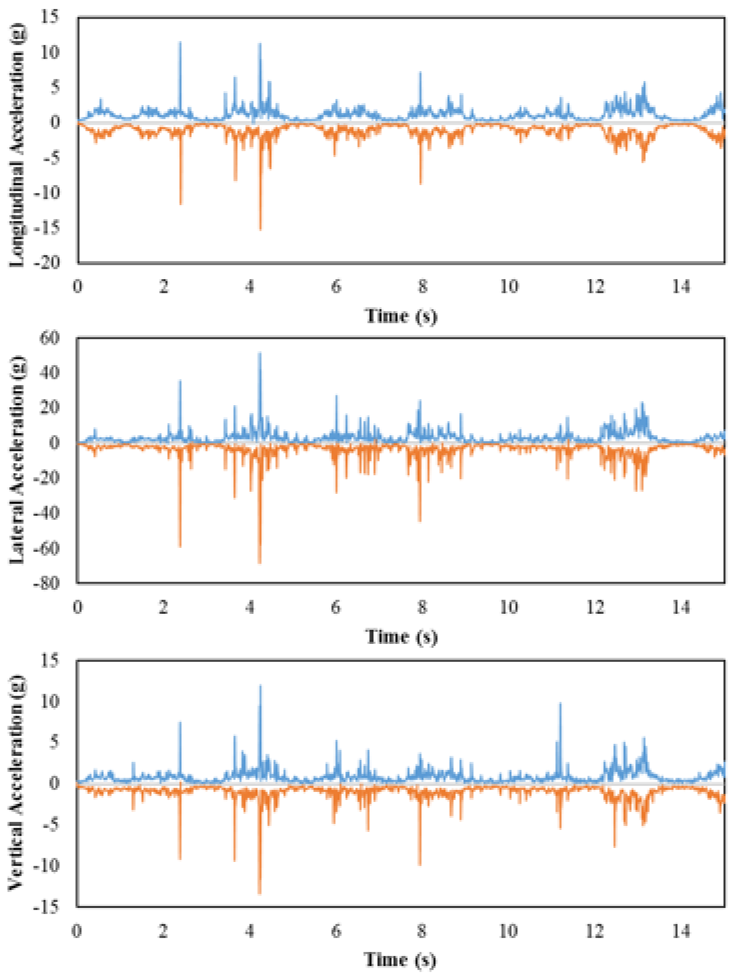

Figure A-32: Tie Acceleration data, Bridge Approach #3

A.7 Tunnel Approach

The research team visited a site in the U.S. Pacific Northwest adjacent to a tunnel in June 2016. The track near the maintenance yard is classified as Mediterranean, however the track weather conditions in the mountainous terrain can be highly variable. The maintenance yard location has an average annual rainfall of 106.7 in., average annual snowfall of 50 in., an average high temperature of 76 °F in July and average low temperature in January of 32 °F. Ties had a center-to-center spacing of 24 inches. Figure A-33 shows a satellite view of the site from Google Earth.

Figure A-33: Satellite view of tunnel approach from Google Earth

A.7.1 Track Visual Observations

The railroad claims this site needs constant maintenance. The ties were replaced 2 years prior due to wear and deterioration. There were a few ties with center-binding cracking, and a few with longitudinal splitting cracks. The remainder of the ties near the tunnel entrance appeared to be in good shape, Figure A-34. Some ballast fouling was observed as shown in Figure A-35. The team was not allowed to access the track because of safety concerns from the short sight distance at the track tunnel. This precluded the team from taking ballast samples or measuring the tie thickness in track. Track drainage was not very good. Water was seen coming from the tunnel onto ditches on both sides of the track as shown in Figure A-36. The water on south side of tunnel was seen to go through the track to the ditch in the north side of the track. It is likely that the water movement through the track contributed to the track maintenance issues.

Figure A-34: Ties at tunnel approach

Figure A-35: Ballast fouling in track, tunnel approach

Figure A-36: Water from tunnel in ditch, tunnel approach

The tunnel east portal appeared to be in good shape except for the transition between wood and concrete ties. There was no standing water in ditches or signs of water in track, but the research team did not have access to the track to document moisture conditions with depth in the ballast. Given the high amounts of precipitation and lush vegetation in the area, it is very possible that moisture was present in the track structure. Ballast churn was evident from the gray fines present on the top of the ballast shown in Figure A-37.

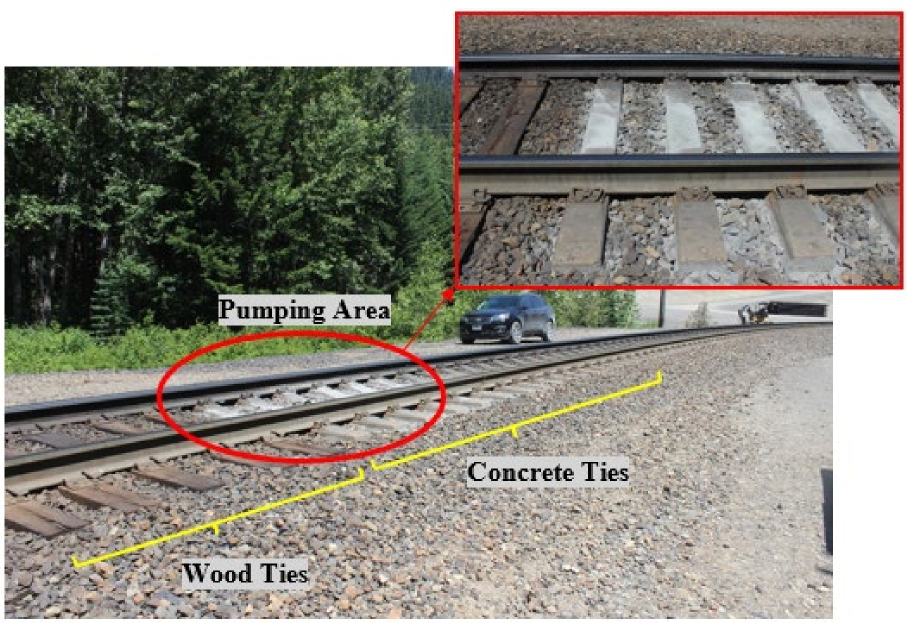

Figure A-37: Ballast churn and center-binding cracking seen at wood-concrete tie transition area, tunnel approach

A.7.2 Track measurements

The ATIP geometry car visited the tunnel approach approximately 8 months before the research team. A small variation in profile was seen before the tunnel entrance, as shown in Figure A-38. The track profile variation was likely small because the ties were only 2 years old. Based on the track condition and the presence of a wood-to-concrete tie transition, the profile will likely grow with time.

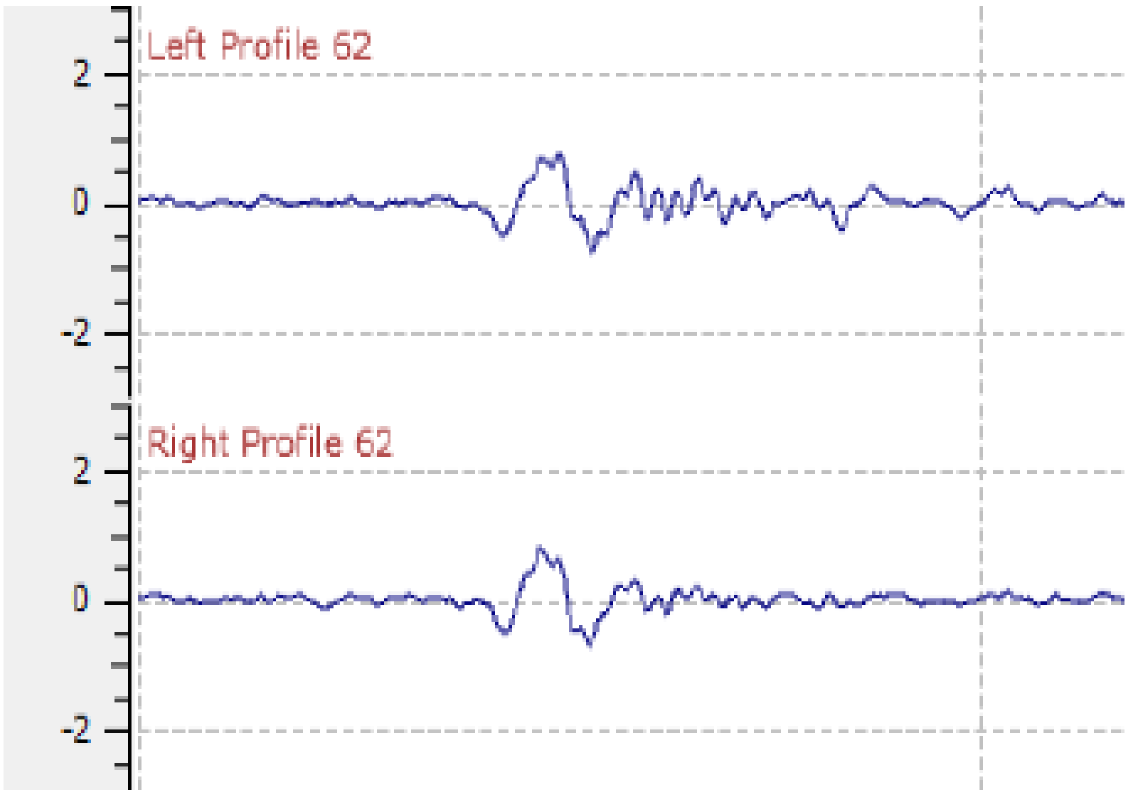

Figure A-38: ATIP track profile measurements, tunnel approach

Appendix B.
Switches and Signals

The research team visited track locations with switches and signals because these locations often have different drainage conditions than surrounding track. Additionally, switches and signals can cause changes in track stiffness and bumps in the road that can cause dynamic train loads.

B.1 Switch #1: Switch Located Under Bridge in U.S. Pacific Northwest

The research team visited a site adjacent to a switch and curve in the U.S. Pacific Northwest in June 2016. The local climate is a warm summer continental climate. The switch location has an average annual rainfall of 16.5 in., average annual snowfall of 45 in., an average high temperature of 83 °F in July and average low temperature of 25 °F in January. The concrete ties used were manufactured in 1990. Ties had a center-to-center spacing of 24 inches. The track maximum speed was 55 mph. Figure B-1 shows a satellite view from Google Earth of the inspected site, with gray mud present and visible in satellite images.

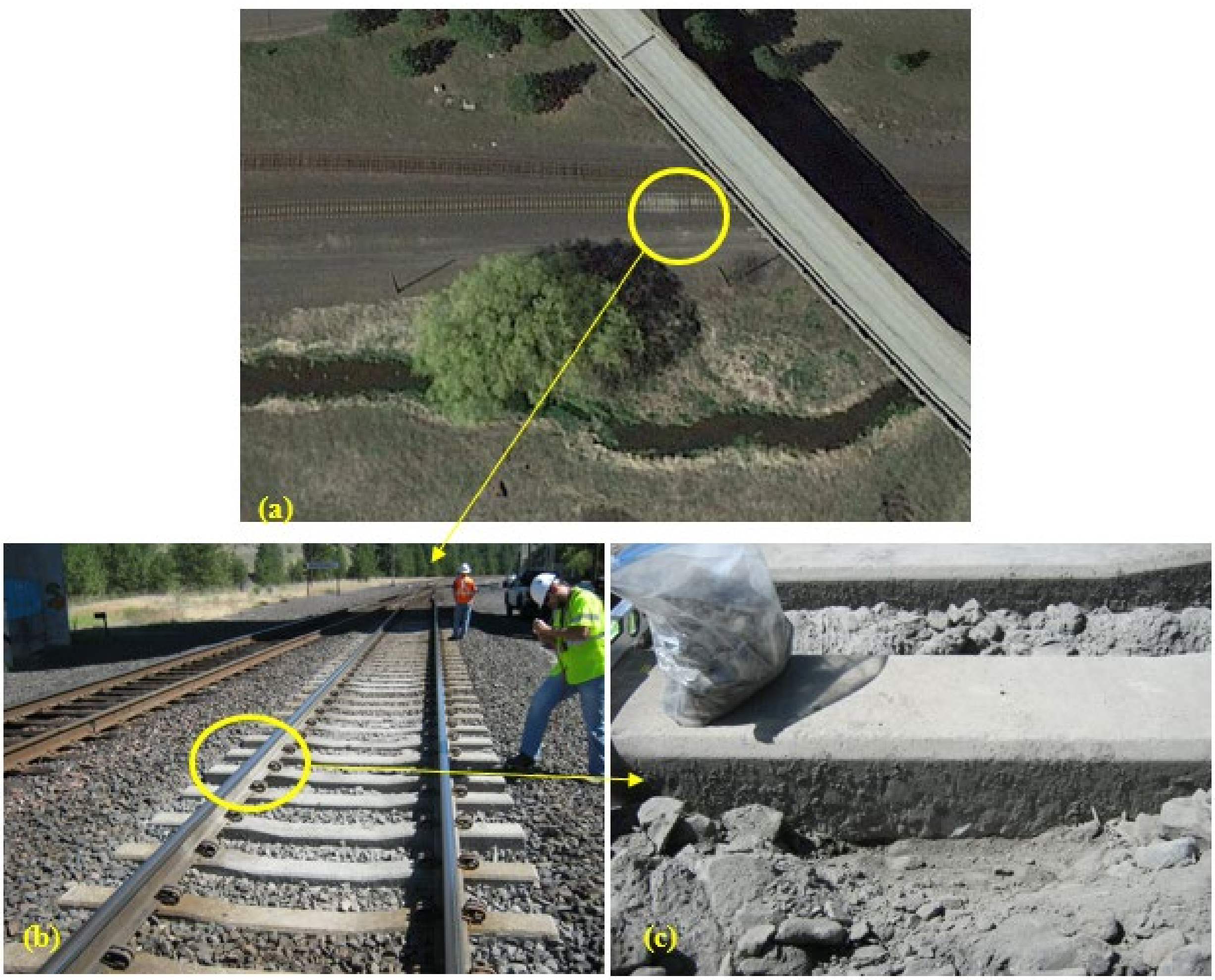

Figure B-1: Pumping area after a wood tie-to-concrete tie transition, Switch #1

B.1.1 Track Visual Observations

A section of track right after the transition from wood ties showed evidence of fouled ballast and center-binding cracking, as shown in Figure B-2. Center-binding cracking was seen in seven ties after the transition. This is indicative of variations in track stiffness and support conditions often present at transitions. Figure B-2 also shows the shadow from the bridge. It is likely that water flowing off the bridge causes an increase in water availability in track. Some moisture was seen in ballast at the tie bottom. Water loving grass and plants were seen next to track as shown in Figure B-3, indicating that water is more present in this location than in the general environment.

Figure B-2: Fouled ballast immediately after wood-to-concrete tie transition, Switch #1

Figure B-3: Water-loving plants next to track, Switch #1

A second gray-mud section of track was seen a short distance away from the switch, as shown in Figure B-4. It is possible that the change in track stiffness seen at the transition caused train vertical movement that caused large vertical forces on the track at the second fouled ballast location.

Figure B-4: Gray mud in track, Switch #1

B.1.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 49. The thickness of two ties was measured, one in fouled ballast and one without fouling present at the surface. Ballast surrounding the tie was removed to reach the bottom of the tie in order to measure the tie thickness. Table B-1 shows the ties thickness measured in track.

Table B-1: Tie thickness measurements, Switch #1

Location	Ballast Fouling Present	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	Yes	8.1875	6.9375	1.25
Tie Center	Yes	6.25	5.875	0.375
Tie Center	No	6.25	6.0625	0.1875

B.1.3 Track Geometry Measurements

The ATIP geometry car measured track conditions about a month before the research team visited the site. The measurements showed a left profile variation of approximately 0.7 in. and a right profile variation of 0.88 inches. The maximum gage measured was 58.107 inches.

B.1.4 Ballast Analysis

Two ballast samples were collected on the site, one from the ballast at the bottom of the tie where the tie thickness was measured (sample 1), and one 20 ties away in an area without ballast fouling present (sample 2). Figure B-5 shows the location where the ballast sample was taken. Table B-2 shows the ballast analysis. The ballast taken from the area with fouling had a large amount of carbonate-based fines present. Because the ballast sample taken away from the fouling did not have any carbonate fractions present, and the subbase does not have carbonate-based material, it is concluded that the fines contained a high percentage of abraded concrete fines.

Figure B-5: Sample collection from ballast at depth of tie bottom, Switch #1

Table B-2: Ballast and subgrade analysis results, Switch #1

Sample No.	Sample type	Material types present:	Sample description
1	Ballast	Fines	Fines are carbonate (concrete- strong HCl reaction) with slightly coarser silicate fragments.
2	Ballast	Rock	Basalt

B.2 Signal #1: Insulated Joint in U.S. Pacific Northwest

The research team visited a curved-track section in the U.S. Pacific Northwest in June 2016. The local climate is a warm summer continental climate. The location has an average annual precipitation of 19.2 in., average annual snowfall of 50 in., an average high temperature of 83 °F in July and average low temperature in January of 22 °F. The concrete ties were manufactured in 1990. Ties had a center-to-center spacing of 24 inches. The track maximum speed was 55 mph. Figure B-6 shows a satellite view of the site from Google Earth.

Figure B-6: Satellite view of Signal #1 from Google Earth

B.2.1 Track Visual Observations

There was an insulated joint in track, Figure B-7. Center-binding cracking and rail-seat abrasion repairs were present. The ballast at the bottom of the tie showed very little fouling and no moisture. The low rail side of the track showed slight fouling, but overall the ballast was in good condition. The railroad stated that the ballast was recently maintained which could contribute to the lack of fouling found in track. There is a creek next to the track, but no water was running in the creek when the research team visited. There was grass growing in the ballast as shown in Figure B-8, indicating that water was present in at least part of the year in the track structure. While the research team was on-site, a train passed over the track. The ties visibly moved during the train pass.

Figure B-7: Insulated joint and signal shed, Signal #1

Figure B-8: Green grass growing on the edge the track, Signal #1

B.2.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the tie surface hardness. The average of the Schmidt hammer readings was 50. Table B-3 details the tie thickness.

Table B-3: Tie thickness measurements, Signal #1

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.1875	7.8125	0.375
Center	6.25	6	0.25

B.2.3 Track Geometry Measurements

The ATIP geometry car measured this track within two months of the research team visit. Surface profile data showed a maximum negative deviation of 1.324 in. on the left rail and 0.959 in. on the right rail.

B.2.4 Ballast Analysis

A ballast sample was collected on site. The ballast sample was taken at the depth of the bottom of the tie measured for thickness, Figure B-9. Table B-4 shows the ballast analysis. Ballast analysis indicated that the ballast did not contain concrete fines, correlating with the low wear measurements. Track movement likely occurred because of soft subgrade support. It is likely that a combination of good maintenance practices and a reasonable compliant track structure combined to yield relatively good tie performance.

Figure B-9: Ballast samples collected from the middle of the track, Signal #1

Table B-4: Ballast and subgrade analysis results, Signal #1

Sample type	Material Types Present:	Sample description
Ballast	Rock	Basalt, Granite, and fines do not react with HCl

B.3 Signal #2: U.S. Southeast

The research team visited a location near a recently moved signal in the U.S. Southeast. The local climate is humid subtropical. The average annual rainfall for this site is 52.4 in. and the average annual snowfall is 2 in. The site location has an average low temperature of 25 °F in January and average high temperature of 90 °F in July. The concrete ties were fabricated in 2001 and had a center-to-center spacing of 24 in. The track speed was 60 mph, but was under a 25-mph slow order. Satellite view of this tangent track section from Google Earth is shown in Figure B-10.

Figure B-10: Satellite View of Signal #2 from Google Earth

The track contained an old insulated joint used to control a signal that was removed the previous year and moved a short distance down the track to meet Positive Train Control (PTC) requirements. Figure B-11 shows the section of track where the new PTC shed and signal was placed.

Figure B-11: New signal and PTC shed, Signal #2

B.3.1 Track Visual Observations

The railroad made repairs at this site. Six wooden ties replaced concrete ties due to fouling damage. Once mud is present in the site, the mud spot spreads quickly. The mud spot had already returned to the track when the research team visited the site. Most of the ties at the location had center binding cracking as shown in Figure B-12.

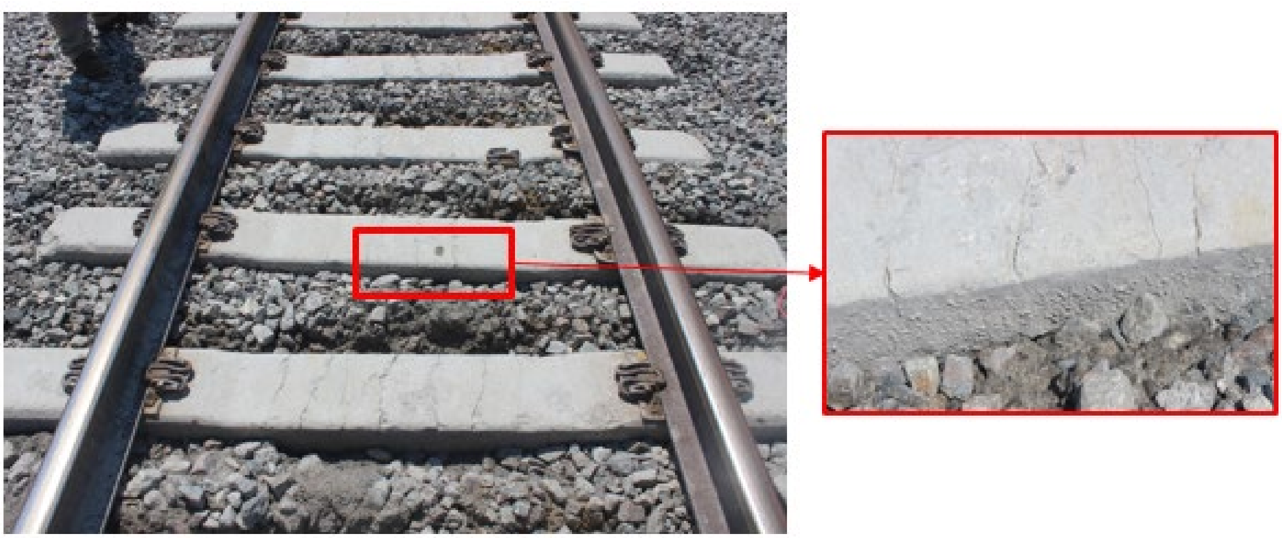

Figure B-12: Center binding cracking in the ties, Signal #2

Track grading and drainage was poor. The railroad reported that signal wires in the track would occasionally need maintenance, requiring them to be dug out of track, undermining the subgrade and ballast. In addition, the insulated joints may have contributed to additional movement and train dynamic forces on track. An engineer from the railroad indicated that it is common to see mud holes at insulated joints as well as at locations with bad rail welds.

Several ties were replaced the week before the site visit and were still on the side of the road. These ties had large amounts of abrasion damage on the bottom and sides, see Figure B-13.

Figure B-13: Removed ties with abrasion damage, Signal #2

Visually, the track displayed alignment and vertical profile deviations. A train passed over the site during the team's visit. Pictures taken before and after the train pass show the effect of this single train pass on the track, see Figure 3-9 and Figure 3-10. The track displaced laterally by approximately 1 inch.

Figure B-14 show evidence of mud pumping and lateral tie movement. Fines migrating to the sides of the track provide evidence of ballast fouling and poor drainage, see Figure B-15.

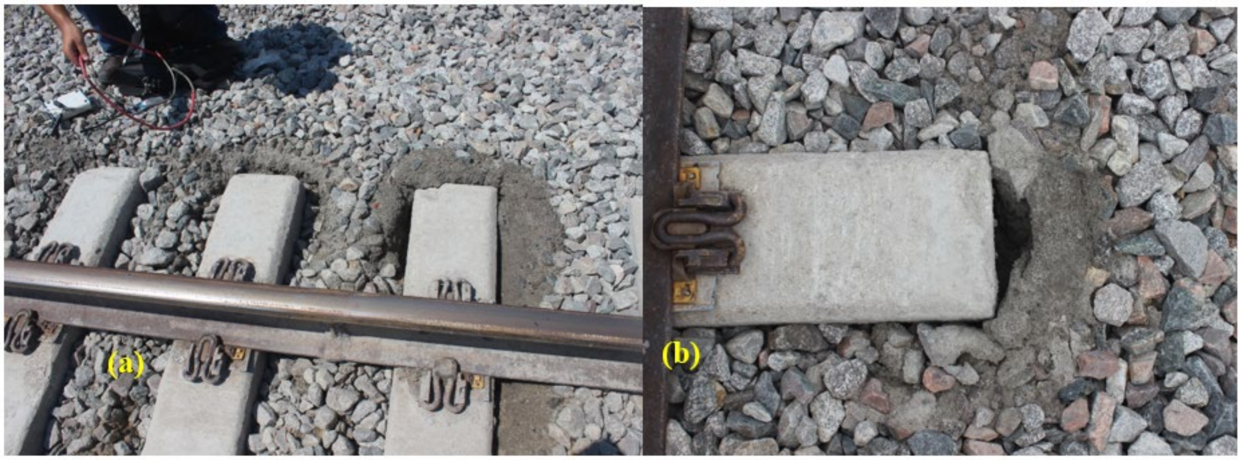

Figure B-14: Pumping and lateral movement on the end of the ties, Signal #2

Figure B-15: Mud pumping in adjacent ballast, Signal #2

The track was in a location that showed evidence of high water availability. Water-loving plants were seen in the ditch on the side of the track. Some moisture was also seen in the ballast at the bottom of the ties.

B.3.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 44. The ballast was removed from the end of a tie in track to measure the abrasion wear. One tie end had 1 in. of abrasion wear, see Figure B-16. A second tie was taken from track the following day and measured by the research team. The tie thickness for the second tie is shown in Table B-5.

Figure B-16: One-inch tie abrasion, Signal #2

Table B-5: Tie thickness measurements, Signal #2

Tie # Measured	Location from tie end (in.)	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
1	Tie End	8.25	7.5	0.75
1	Tie Center	7	6.75	0.25
2	6	8.25	6.25	2
2	12	8.25	6.75	1.5
2	18	8.25	6.5	1.75
2	24	8.25	7.25	1.0
2	30	8.25	7.125	1.125
2	36	7	6.125	0.875
2	42	7	6	1.0
2	48	7	5.625	1.375
2	54	7	5.875	1.125

Ultrasonic pulse velocity (UPV) measurements taken from the Schmidt hammer tie measured. All readings were taken with the ultrasonic pulse source on the tie shoulder. Readings were taken with the receiver on the same shoulder as the source as shown in Figure B-17, on the top of the tie in the center, and on the top of the opposite tie shoulder from the source. Table B-6 shows the measured UPV readings. UPV measurements show that the UPV readings for center-to-shoulder and shoulder-to-shoulder measurements were lower than the one for the same shoulder because the center-binding cracks reduced the wave propagation speed through the concrete tie. The rail slope and tie superelevation was measured with a digital level. Figure B-18 shows the measured rail and tie levels.

Table B-6: UPV readings, Signal #2

	Distance (in)	UPV Reading (ft/s)
Same shoulder	5	5,125
Shoulder to center	53	4,282
Shoulder to shoulder	89	1,732

Figure B-17: UPV readings from the same shoulder

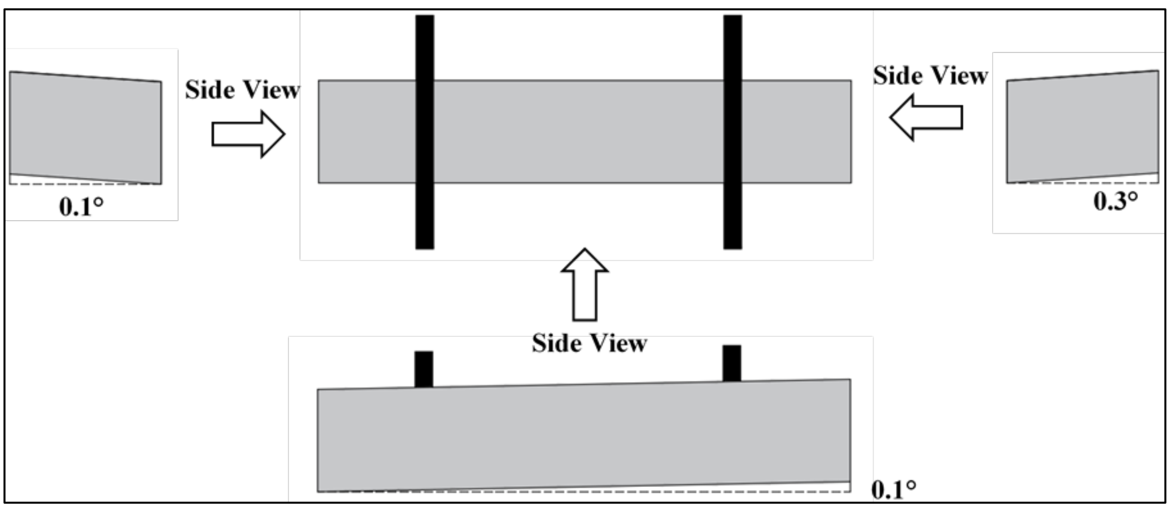

Figure B-18: Superelevation of the concrete tie and rail slope using digital level, Signal #2

B.3.3 Track Measurements

Researchers measured tie accelerations in three directions in fouled ballast area. Acceleration readings were taken at 20 kHz. Figure B-19 shows the attached sensor to the tie for acceleration measurement. Figure 3-8 shows the acceleration in three dimensions. The lateral acceleration was more than 18 g, resulting in lateral tie movement. Analysis of the recorded video showed that the tie moved vertically 1.2 in., as shown in Figure 3-11.

Figure B-19: Accelerometer placed on tie to measure acceleration in three directions, Signal #2

Track measurements were taken by the ATIP geometry car in May 2017, 10 months after the research team visited the site. While the track conditions in the 9 months between the site visit and the geometry car measurements likely changed, the profile measurements still provide an indication of the track surface condition. The profile measurements in the fouled ballast spots visited showed large anomalies, as shown in Figure B-20. The measurements showed a maximum negative profile of 1.694 in. with the left rail and 1.571 in. with the right rail, confirming the track issues seen on site. The maximum gage onsite was approximately 56.9 inches.

Figure B-20: Rail profile measurements taken by ATIP geometry car, Signal #2

B.3.4 Ballast Analysis

Researchers collected four ballast and subgrade samples from the site, as shown in Figure B-21. Ballast samples were taken in the ballast at the depth of the bottom of the tie. Table B-7 shows the ballast analysis. The results showed that concrete material in the ballast was smaller than 10 mm, indicating that the concrete material was abraded away instead of being taken off by impact.

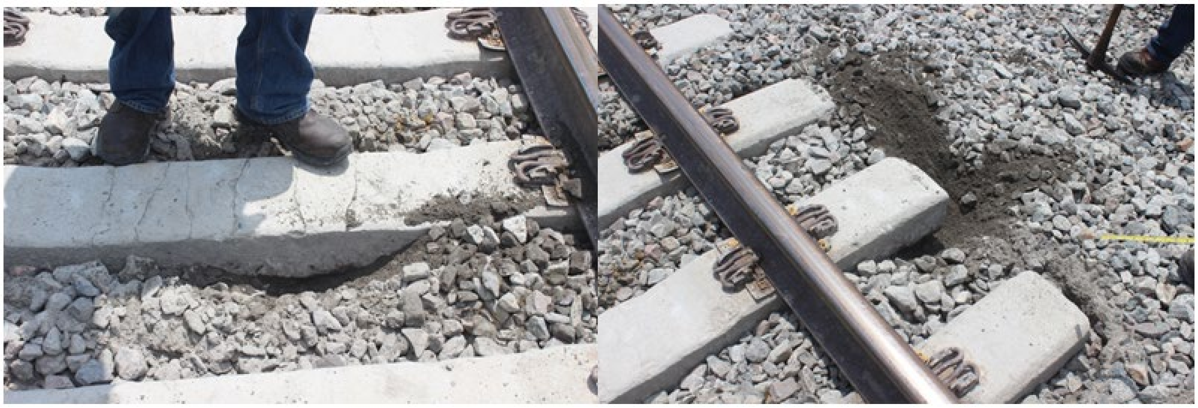

Figure B-21: Samples collected from ballast, Signal #2

Table B-7: Ballast and subgrade analysis results, Signal #2

Sample No.	Sample type	Material Types Present:	Sample description
1	Ballast, from a section without abrasion damage	Rock	Limestone, schist, granite
2	Ballast, from a section with abrasion damage	Sand, fines, rock	Silicate sand-silt clasts in a carbonate (concrete) matrix (strong HCl reaction of matrix). Particles >10 mm clasts are igneous/metamorphic (granitoid/gniess)
3	Ballast	Sand, clay	Basalt, granite, rhyolite, diorite
4	Subgrade	Mud, rock	Granite

B.4 Signal #3: Insulated Joint Adjacent to Switch in U.S. Southeast

The research team visited a site with mud pumping located at an insulated joint situated adjacent to a switch and a wood-to-concrete tie transition in the U.S. Southeast in August 2016. The local climate is humid subtropical climate. The site location has an average annual rainfall of 41.62 in., average annual snowfall of 15 in., an average high temperature of 87 °F in July and average low temperature in January of 25 °F. The concrete ties used were installed in 1993. Ties had a center-to-center spacing of 24 inches. The track had a maximum speed of 35 mph. Figure B-22 shows the satellite view of the site from Google Earth.

Figure B-22: Satellite view Signal #3 from Google Earth

B.4.1 Track Visual Observations

Train dynamics are influenced by the switch, the transition from wood-to-concrete ties, and an insulated joint at this location. Gray mud was fouling the ballast, Figure B-23. Significant mud pumping can be seen in Figure B-24. Fouling was present around nine ties in the primary mud pumping location. A second spot with minor amounts of fouling can also be seen in Figure B-24. A train that experiences vertical acceleration as it passes over an insulated joint would be expected to experience harmonics that increase wheel loads along the track. Vegetation was seen in the ballast-area of track as shown in Figure B-25. This is indicative of persistent water in the track structure, indicating poor drainage.

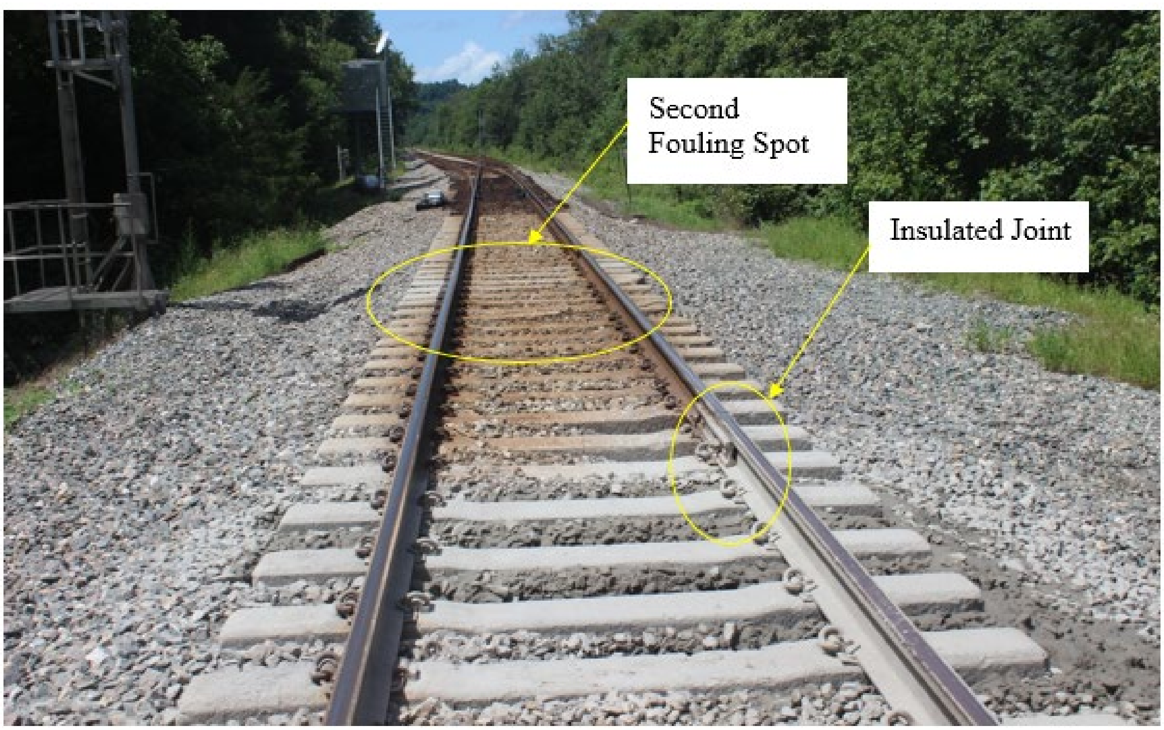

Figure B-23: Pumping next to the switch, Signal #3

Figure B-24: Mud pumping, Signal #3

Figure B-25: Vegetation near track, Signal #3

B.4.2 Tie Measurements

Two ties were measured for thickness. One was measured at the end and center, and the other in the center only, Table B-8.

Table B-8: Tie thickness measurements, Signal #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	7	6.25	0.75
End	8.25	7	1.25
Center	7	5.625	1.375

B.4.3 Track Geometry Measurements

The ATIP geometry car tested the site approximately seven months after the research team's visit. Very little variation in profile or alignment was measured. The maximum gage measured was approximately 56.8 inches.

Appendix C. Grade Crossings

Railroads identified grade crossing as common maintenance locations. Crossings have unique track conditions because they experience train and vehicle loading. This can cause additional ballast breakdown and settlement. Drainage can be difficult to establish at crossings, leading to additional moisture in track and significant ballast fouling. This chapter documents site conditions at railroad crossings.

C.1 Crossing #1: Road Crossing Near Lake in U.S. Inter-mountain West

Researchers visited two track sections located next to a bridge and in a curve in the U.S. Mountain West in June 2016. This mountain location has a Dfb climate (warm summer continental climate) per the Köppen climate classification system. The crossing location has an average annual rainfall of 33.9 in., average annual snowfall of 58 in., an average high temperature of 82 °F in July and average low temperature of 22 °F in January. The concrete ties were replaced a few years before the visit. Ties had a center-to-center spacing of 24 inches. The track maximum speed was 35 mph. Figure C-1 shows (a) satellite view of the site from Google Earth, (b) track-level view of the site location, and (c) a small area near the bridge with ballast churning.

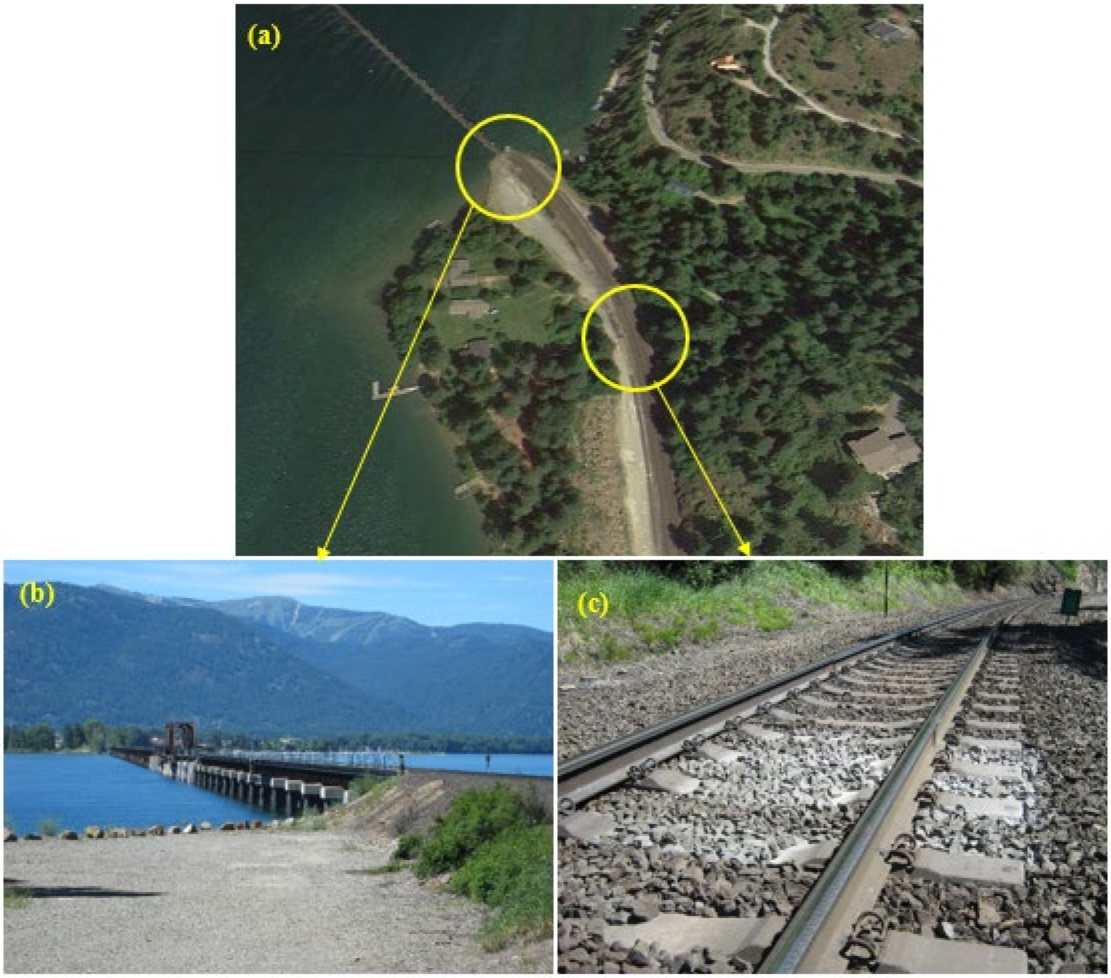

Figure C-1: Satellite view from Google Earth (a), photograph of inspected bridge (b) and (c) small area with ballast churn and fouling, Crossing #1

C.1.1 Track Visual Observations

The concrete ties were relatively new and in good condition. There was a concrete road crossing in track, with 16 wood ties before and 19 wood ties located after the crossing, as shown in Figure C-2. The first tie after the wood transition had mild center-binding cracking.

There were periodic areas of ballast churn and breakdown. These spots are highlighted in Figure C-2 and shown from the reverse angle in Figure C-3. Rail welds were seen at the location of ballast churn, indicating possible previous surfacing issues that led to rail damage. A little more ballast churn was seen on the low rail side of the track. Ballast was removed in the churned area to inspect ballast condition with depth. Ballast fouling and organic matter were seen at the bottom of tie. There were signs of early abrasion wear on the sides of the tie at the ballast level as shown in Figure C-4, but no significant section loss. A discarded tie adjacent to the track showed the potential for tie abrasion damage in this track location, see Figure C-5. This curve had significant abrasion wear before new ties were installed. Railroad officials stated that tamping and ballast maintenance was performed, but no undercutting.

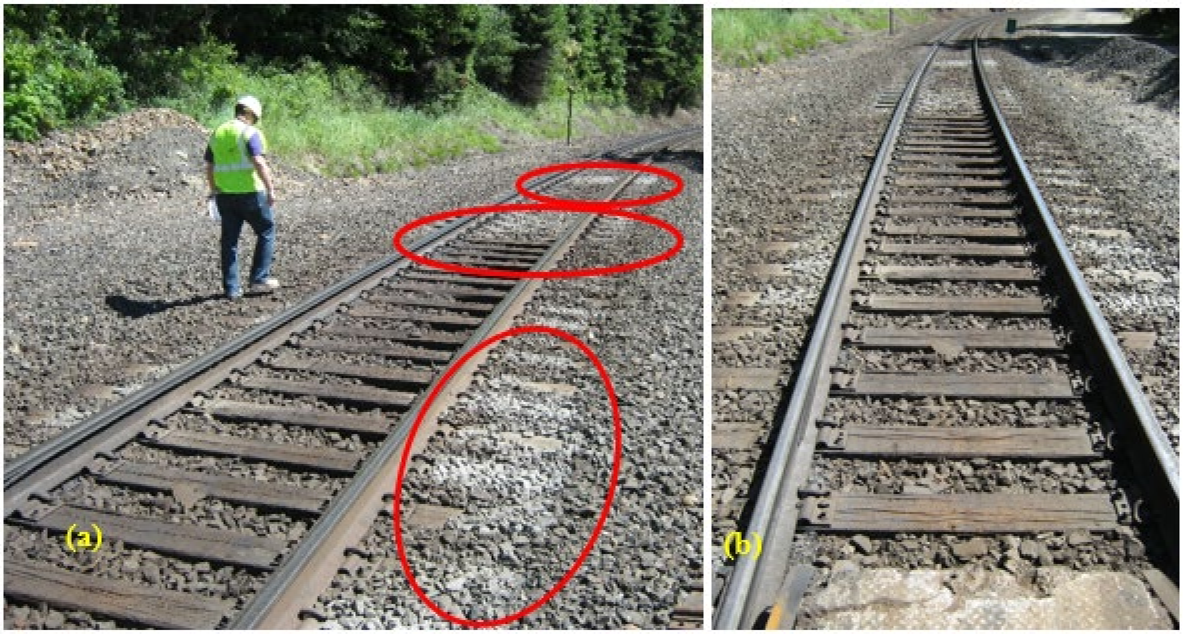

Figure C-2: Replaced concrete ties with wooden ties, Crossing #1

Figure C-3: Pumping area near curve, Crossing #1

Figure C-4: Ballast fouling and beginning of concrete tie wear, Crossing #1

Figure C-5: Tie with abrasion removed from track, Crossing #1

Water was present in this section of track, as evidenced by the moist ballast a few inches below the track surface and by standing water in the ditch, Figure C-6. The nearby vegetation indicates significant water availability. Some sections of track also had issues with grading because of hillside slope conditions, as shown in Figure C-7.

Figure C-6: Standing water and vegetation in ditch, Crossing #1

Figure C-7: Grading issues seen in some locations, Crossing #1

C.1.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to determine the tie surface hardness. The average of the Schmidt hammer readings was 51.

C.1.2 Ballast analysis

Two ballast and subgrade samples were collected. Although the aggregate is a good, hard basalt, it is also vesicular, as shown in Figure C-8. It is unknown what effect the vesicular nature of the ballast played in ballast fouling and concrete wear. Ballast samples were taken at the depth of the bottom of the tie. Table C-1 contains the ballast analysis results. The ballast sample did not show evidence of concrete fines, likely because of track maintenance activities and relatively new ties used. This could indicate that ballast breakdown occurs before concrete bottom tie abrasion at this location.

Figure C-8: Close-up picture of vesicular basalt ballast, Crossing #1

Table C-1: Ballast and subgrade analysis results, Crossing #1

Sample type	Material Types Present:	Sample description
Ballast	Rock	Basalt
Subgrade	Sand, Clay and Cement	No HCl reaction, fines are silicate (e.g., soil); clay to sand size clasts which are silicate minerals (e.g., quartz, feldspar, mafic minerals)

C.2 Crossing #2: Rubberized Crossing

The research team visited a site with a wooden bridge and road crossing in the U.S. Pacific Northwest in June 2016. The local climate is dry-summer subtropical or Mediterranean (Csb). The crossing location has an average annual rain of 14 in. and snowfall of 42 inches. It has an average high temperature of 88 °F in August and average low temperature of 20 °F in January. The concrete ties used in track were manufactured in 1990. The ties had a center-to-center spacing of 24 inches. The track maximum speed was 40 mph. Figure C-9 shows a satellite view of the inspected site from Google Earth and corresponding track-level pictures.

Figure C-9: Satellite view of Crossing #2

C.2.1 Track Visual Observations

The ties were in good condition near the switch. Only three ties with minor center-binding cracking were seen in a few hundred yards of track and no abrasion damage was seen on the bottom or sides. The ballast appeared to be in good shape overall with only one spot with a little gray dust from ballast churn as shown in Figure C-10. A track-level view of the switch is seen in Figure C-11. The drainage was good with built up embankments. There were no water or damp spots in track at the bottom of ties.

Figure C-10: Minor gray dusting of ballast particles, Crossing #2

Figure C-11: Track-level view of the switch, Crossing #2

C.2.2 Tie Measurements

The center thickness of one tie was measured in-track. The ballast around the side of the tie was removed manually to expose the tie. No concrete wear was found, as shown in Table C-2. This was likely because of the excellent ballast condition and maintenance, track support conditions, and drainage.

Table C-2: Tie thickness measurements, Crossing #2

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	6.25	0

C.2.3 Track Geometry Measurements

The ATIP geometry car measured the track geometry nine months before the site visit. The geometry far found little surface profiling issues or gage issues. This data corresponds with the team's visual observations.

C.3 Crossing #3: U.S. Southeast

A section of tangent track was visited in the southeastern part of the United States in July 2017. The track speed was 60 mph but was under a 25 mph the slow order. Track tonnage is 42 MGT. The concrete ties were manufactured in 1997, but were not installed until 2001. The ties had a center-to-center spacing of 24 inches. The site location has an average low temperature of 25 °F in January and average high temperature of 90 °F in July. The local climate is classified as humid subtropical. The average annual rainfall for this site is 52.4 in. and the average annual snowfall is

2 inches. Figure C-12 shows a satellite view of the site investigated. Figure 3-23 shows a view of a portion of the track visited.

Figure C-12: Satellite view of Crossing #3

C.3.1 Track Visual Observations

The railroad reported that some spot undercutting in problem areas was performed 5–6 years ago, with additional undercutting 3–4 years ago. Ballast fouling returned after each maintenance activity. Per the road master, the fouling occurs under the track surface and spreads farther than can be seen at the surface. Ballast fouling and pumping was seen at periodic intervals, as shown in Figure 3-7. The fouled ballast spots were near a crossing and appeared to follow vertical dynamic harmonics of the train on either side of the crossing. Many additional spots were noticed in both directions that were similar in nature to the ones investigated. The road master commented that the track contained many similar spots similar for several miles in each direction. Water was seen ponding in the side of the track near the fouled ballast as shown in Figure 3-7 indicating drainage problems in track. Standing water and plants were seen in and around the ditch, indicating a source of water present near the track. Figure C-13 shows several examples of ties in fouled ballast on site. Figure C-14 shows ties that were damaged at the track locations with pumping. Wear seen was non-uniform across the length of the tie however. Severe center-binding cracking was present in many ties. Damage was seen on the top surface of ties from a broken axle that was dragged by the train for several miles about 10 years prior, Figure C-15. This damage was separate from the center-binding cracking and did not appear to affect the tie abrasion performance. Figure C-16 shows shattered ties that may have resulted from center-binding cracking.

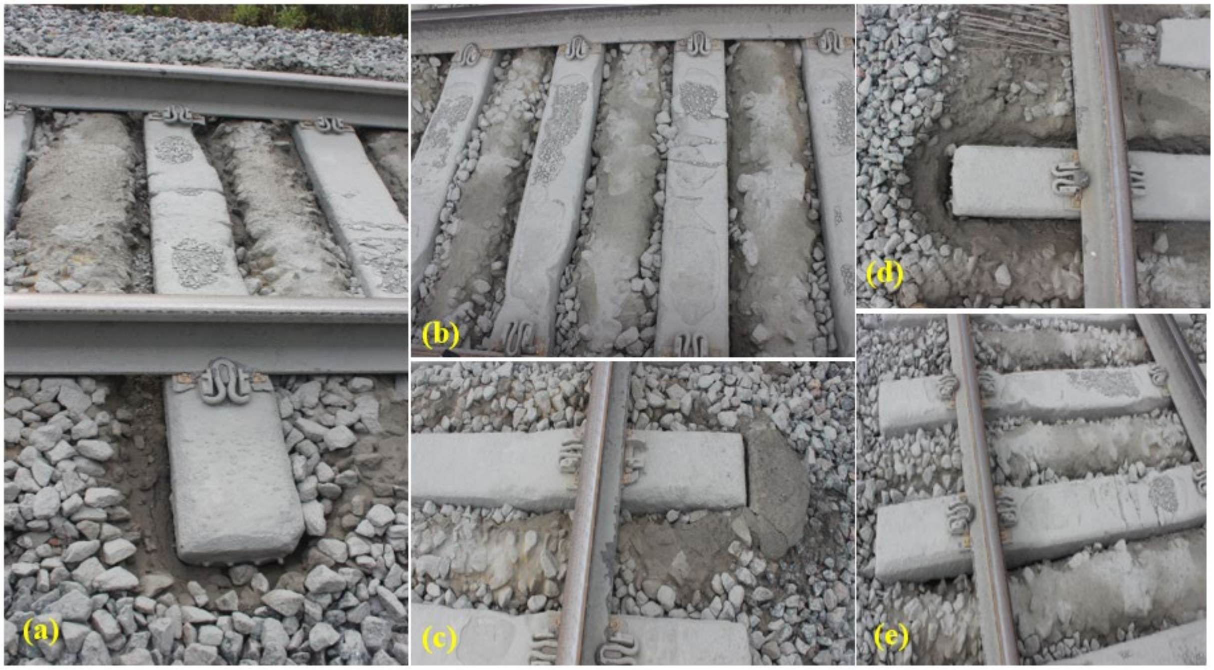

Figure C-13: Severe pumping that led to section loss, Crossing #3

Figure C-14: Ties at locations with mud pumping with severe damage, Crossing #3

Figure C-15: Damaged tie from broken axle derailment, Crossing #3

Figure C-16: Shattered ties that began as center-binding cracks, Crossing #3

C.3.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie in track. The average of the readings taken on the tie was 40. Ballast was removed from the sides and ends of a tie to inspect the tie for abrasion loss. Table C-3 shows the tie thickness measurements taken in track. Significant wear was seen in the ties, as shown in Figure C-17.

Table C-3: Tie thickness measurements, Crossing #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7.25	1.0
Center	7	5.5	1.5
Tie end	8.25	7.25	1.0

Figure C-17: One-inch abrasion on bottom of the tie. Crossing #3

Figure C-18 shows the UPV setup. Table C-4 shows the UPV reading from the same shoulder on the site. UPV measurements show that the UPV readings for center-to-shoulder and shoulder-to-shoulder measurements were lower than the one for the same shoulder because the center-binding cracks reduced the wave propagation speed through the concrete tie.

Table C-4: UPV readings, Crossing #3

	Distance (in)	UPV Reading (ft/s)
Same shoulder	4	6,523
Shoulder-to-center	53.5	1,031
Shoulder-to-shoulder	92	1,790

Figure C-18: UPV measurement setup, Crossing #3

C.3.3 Track Geometry Measurements

ATIP track geometry measurements were made in May 2017. While the track conditions in the nine months between the site visit and the geometry car measurements could have changed significantly, the profile measurements still provide an indication of the track surface profile. The profile measurements on the track that contained the fouled ballast spots visited showed several areas with surfacing issues, with a maximum surface profile downwards of 0.88 in. in the left rail and 1.056 in. in the right rail. ATIP measured a maximum gage of approximately 56.8 inches.

C.3.4 Ballast Analysis

Researchers gathered samples from the subgrade and ballast for analysis. The subgrade sample included sand, mud and clay. There were no HCl reactions for fines (soil). This shows that there were no cementitious materials in the subgrade. The clay-sand fragments in the sample were silicate minerals such as potassium feldspar, mafic, and other rock fragments.

Ballast samples were taken from area around the bottom of the tie. These ballast samples were gray in color, see Figure C-19. The gray color indicates the presence of cement particles from abraded concrete ties. Hydration of the unhydrated cement particles made the ballast stiff and it was difficult to dig through the ballast layer. The ballast sample was composed of granitoid/gneiss rocks and large amounts of fines. The fines reacted strongly with HCl, suggesting that a large percentage of the fines were ground-up concrete particles that came from the tie abrasion.

Figure C-19: Samples taken from subgrade and ballast, Crossing #3

C.4 Crossing #4: Asphalt Crossing in U.S. South-Central

Researchers visited an asphalt crossing in the central southern region of the U.S. in October 2017. The asphalt crossing is in a very rural area with minimal automobile traffic. One side of the crossing was paved with asphalt, the road on the other side of the track was gravel. The ties were fabricated in 2006 or 2007 and were spaced at 24 in. center-to-center. The track maximum speed was 49 mph. The local climate is humid subtropical. The track location has an average annual rainfall of 46 in., no snowfall, an average high temperature of 94 °F in July and an average low of 42 °F in January. Figure C-20 shows a satellite view taken from Google Earth of the asphalt crossing. Figure C-21 shows a track-level view of the crossing.

Figure C-20: Satellite view of Crossing #4

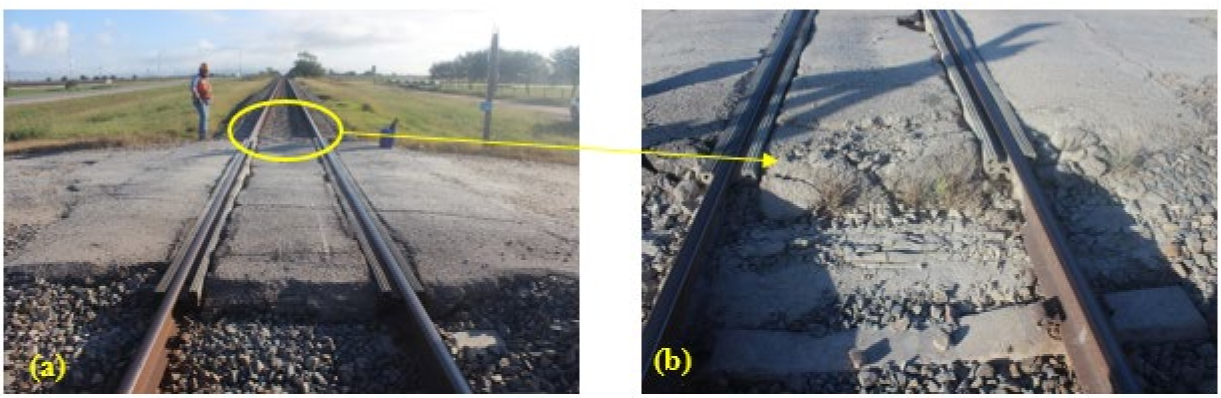

Figure C-21: Asphalt area with mud pumping, Crossing #4

C.4.1 Track Visual Observations

Gray mud was present in track on one end of the crossing. The surface grading on the end with gray mud was not as good as the opposite end, demonstrating how critical good drainage is to the long-term performance of railroad track structures. The railroad maintenance crew reported that the drainage pipes in the crossing require regular cleaning. Grass was growing in track indicating the presence of water, see Figure C-22. The asphalt crossing itself showed evidence of water intrusion, settling, and deterioration, as shown in Figure C-23. This is further evidence that the grading on site was not optimal.

Figure C-22: Excessive pumping and vegetation, Crossing #4

Figure C-23: Asphalt crossing defects, Crossing #4

C.4.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 48. Ballast and gray mud was removed manually from the side of the tie nearest the end with gray mud to measure the tie thickness. Table C-5 details the tie thickness measurements. No wear was seen at the end of the tie, while a small amount of abrasion damage was seen on the tie bottom. It is possible that the ties under the asphalt were severely abraded, producing most of the gray mud, however this was not visually confirmed due to accessibility issues.

Table C-5: Tie thickness measurements, Crossing #4

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	9	8.5	0.5

C.4.3 Track Geometry Measurements

The ATIP geometry system measured track conditions approximately two years before the research team visited the site. The left rail had a maximum profile variation of just over 1 in., while the right rail had a maximum profile variation of 1.459 inches. The maximum measured gage 56.541 inches.

C.4.4 Ballast Analysis

A ballast sample was taken from track at the depth of the bottom of the ties, as shown in Figure C-24. The sample contained some large concrete pieces (>10 mm). Some concrete fines were present. Silicate clasts were also present in the material, indicating some ballast breakdown.

Figure C-24: Subgrade and ballast sample collection, Crossing #4

Table C-6: Ballast Analysis, Crossing #4

Sample type	Material types present:	Sample description
Ballast	Sand, Fines, Rock	Coarse (>10 mm) igneous clasts and concrete pieces. These are surrounded by fines made of carbonate (concrete; strong HCl reaction) and also silt-sized silicate clasts

C.5 Crossing #5: Asphalt Crossing in U.S. Southeast

The researchers visited an asphalt road crossing in the U.S. Southeast in response to reports of ballast fouling and maintenance issues. The local climate is humid subtropical. The crossing location has an average annual rainfall of 50 inch, no snowfall, an average high temperature of 93 °F in July and average low temperature in January of 36 °F. The track maximum speed was 60 mph. The concrete ties were manufactured in 1998 and were spaced at 24 in. center-to-center. A satellite view of the asphalt crossing taken from Google Earth is shown in Figure C-25. Figure C-26 shows a picture of the asphalt crossing taken from eye-level. There are eight ten-foot long wooden ties in the track before and after the crossing. Longer than standard ties were used to attempt to match the track stiffness of the surrounding track.

Figure C-25: Satellite view from Google Earth of Crossing #5

Figure C-26: Crossing #5

C.5.1 Track Visual Observations

Mud pumping was evident at the site, Figure C-27. Figure C-28 shows a schematic view of the site and track condition determined from the visual observations. Figure C-29 shows a closer view of the concrete ties and water ponding in track. The pumping was most likely caused by dynamic forces from the trains passing over track with varying stiffness. Car and truck traffic over the intersection likely caused some ballast settlement and drainage is generally poor. There was a bungalow next to the track with a low grade as shown in Figure C-30, reducing track drainage. Some grass was seen present in track, confirming the regular presence of water and fines in track.

Figure C-27: Concrete-to-wood tie transition, Crossing #5

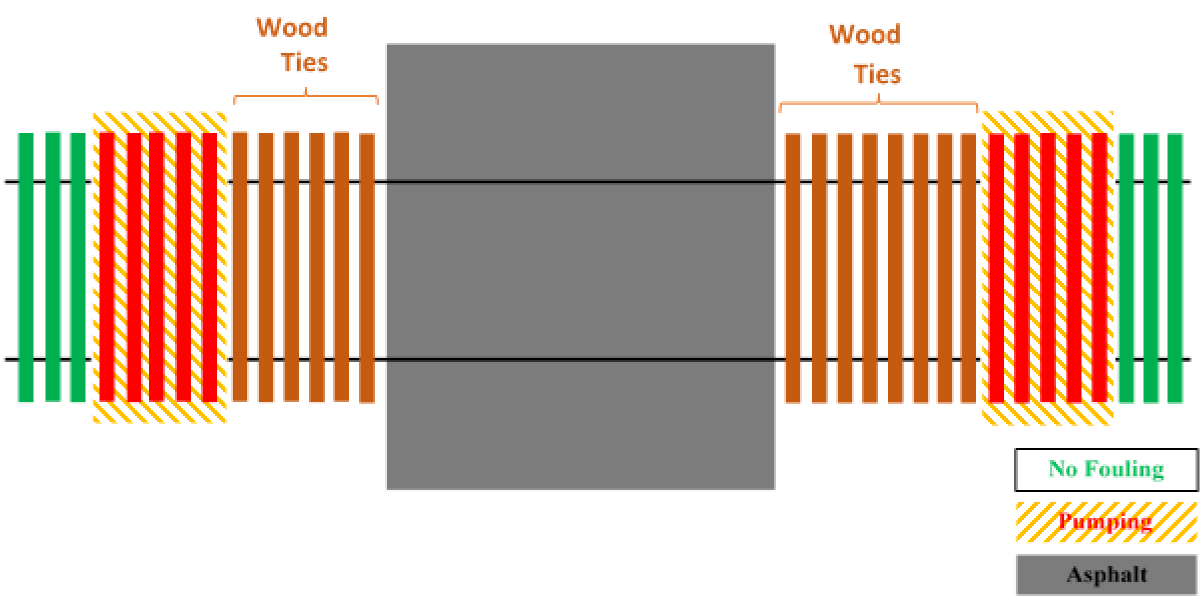

Figure C-28: Schematic view Crossing #5

Figure C-29: Mud Pumping at Crossing#5

Figure C-30: Bungalow next to track, Crossing #5

C.5.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 46. The thickness of the tie used to measure the Schmidt hammer readings was measured at three locations. Researchers removed ballast surrounding the tie by hand to reach the bottom of the tie at both ends and in the center. Table C-7 details the tie thickness data.

Table C-7: Tie thickness measurement, Crossing#5

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7	1.25
Center	7	6	1
Tie end	8.25	6.625	1.625

C.5.3 Track Geometry Measurements

The ATIP geometry car visited the track site a little over 2 months after the research team visited the site. Very little rail profile variation was measured, and the maximum gage was approximately 57 inches.

The vertical deflection of the tie with the most severe pumping was measured using high definition video. The camera was placed on a tripod and focused on a concrete tie, as shown in Figure C-31. The camera and tripod were held in place while the train passed to control vibration. The maximum deflection of the tie was 0.75 inches. Water in track rose with the applied loads and splashed over the tie. Figure C-32 and Figure C-33 are screenshots of the track video during a train pass with the ties in high and low positions in the track, respectively. Figure C-34 shows the tie vertical deflection measured from the high-speed video. An accelerometer was attached to the tie to measure the tie acceleration during loading, as shown in Figure C-31. Figure C-35 shows the measured acceleration of the tie three directions. The high level of vertical acceleration indicates poor ballast support. The lateral acceleration data indicates that the tie moves significantly to the sides of the track. This movement may contribute to abrasion losses on the tie.

Figure C-31: Tie acceleration and deflection were measured using an accelerometer and high-resolution camera, Crossing #5

Figure C-32: Track video screenshot with tie at high position, Crossing #5

Figure C-33: Track video screenshot with tie at low position during train pass, Crossing #5

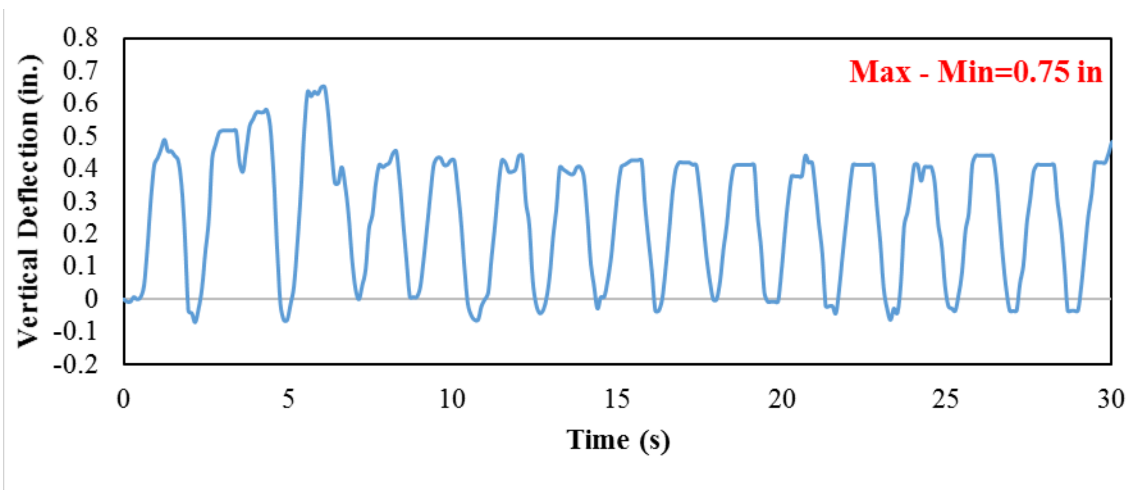

Figure C-34: Vertical deflection of ties measured with high-resolution camera, Crossing #5

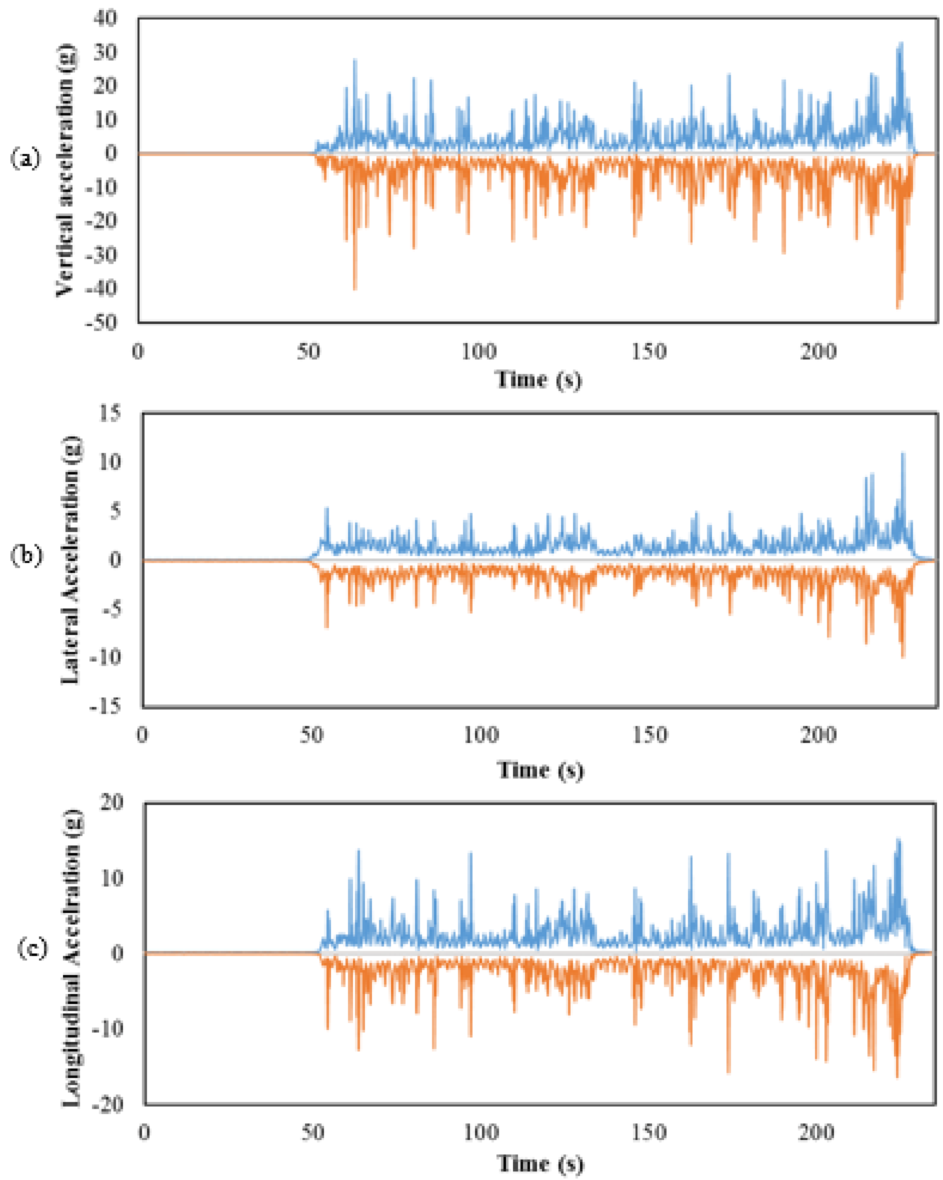

Figure C-35: Acceleration in three directions from Crossing #5: (a) vertical acceleration, (b) lateral acceleration (tie direction), (c) longitudinal acceleration (rail direction).

C.5.4 Ballast Analysis

A ballast sample from the area near the bottom of the ties. Table C-8 details the ballast sample. Some concrete was present in the ballast, however much of the fines are from ballast breakdown.

Table C-8: Ballast analysis, Crossing #5

Sample type	Material types present:	Sample description
Ballast	Rock, Fines	Gneiss and Granite. Weak HCl reaction.

C.6 Crossing #6: Gravel Crossing in U.S. Southeast

The research team visited a gravel railroad crossing in the U.S. Southeast area in August 2016. Gray mud was seen in track from the high-rail vehicle, as well as on ties discarded on the side of the track. The local climate is humid subtropical. The site location has an average annual rainfall of 41.62 in., average annual snowfall of 15 in., an average high temperature of 87 °F in July and average low temperature of 25 °F in January. The concrete ties were manufactured in 1993. Ties had a center-to-center spacing of 24 in. The track has a maximum speed of 35 mph. Figure C-36 shows the satellite view of the site from Google Earth.

Figure C-36: Satellite view Crossing #6 from Google Earth

C.6.1 Track Visual Observations

Ballast fouling was seen in track at four ties, as shown in Figure C-37. The ties were located next to a crossing with poor grading and drainage. There was severe center-binding cracking in the ties. There was a section of track with fines that were produced during pumping as shown in Figure C-38. It rained the day before the research team visited the site. Water was ponding in track, showing the poor drainage on-site. Fines were seen on the ballast shoulders, as shown in Figure C-39.

Figure C-37: Ballast fouling seen in track on four ties, Crossing #6

Figure C-38: Mud pumping adjacent to cracked tie, Crossing #6

Figure C-39: Fines seen on the ballast shoulders, Crossing #6

C.6.2 Tie Measurements

Researchers measured thickness of two ties, one in track and the other found beside the track. Table C-9 shows the tie thickness measured on the tie in track. Figure C-40 shows a picture of a tie beside the track. These ties were made with a relatively soft aggregate. Damage seen with this tie showed less surface roughness than ties made with harder aggregates.

Table C-9: Tie thickness measurement, Crossing #6

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Under Rail Seat	8.25	7.125	1.125
Center	7.0	6.75	0.25

Figure C-40: Tie found beside the track, Crossing #6

C.6.3 Track Geometry Measurements

The ATIP geometry car visited the site approximately 7 months after the research team. Very little variation in profile or alignment was seen (under 0.25 inches). Gage measurements showed a maximum value of just over 57 inches.

C.7 Crossing #7: Asphalt Crossing in U.S. Southeast

The research team visited an asphalt crossing in the U.S. Southeast in August 2016. The local climate is humid subtropical. The location has an average annual rainfall of 41.62 inch, average annual snowfall of 15 in., an average high temperature of 87 °F in July and average low temperature in January of 25 °F. The concrete ties were manufactured in 1993. Ties had a center-to-center spacing of 24 inches. The track has a maximum speed of 35 mph. Figure C-41 shows a satellite view of the crossing from Google Earth.

Figure C-41: Satellite view Crossing #7 from Google Earth

C.7.1 Track Visual Observations

The asphalt crossing showed significant deterioration that appeared to originate underneath the asphalt causing erosion, Figure C-42. Water was seen present in the crossing and in the fouled ballast adjacent to the crossing. Fines from asphalt stripping were seen to have migrated from the asphalt topping in the crossing to the fouled ballast in track. Asphalt fines are cohesive and likely helped contribute to fines sticking together and clogging up ballast pores, enhancing water retention. The gray-colored fines and water are shown in Figure 3-6. Figure C-43 shows a close-up picture of the ballast fouling at the edge of the crossing. Asphalt fines and water are documented in this picture.

Figure C-42: Crossing #7

Figure C-43: Ballast fouling adjacent to Crossing #7

C.7.2 Track Geometry Measurements

Researchers measured 3/4 inches of surface profile deviation in the crossing. The ATIP geometry car visited the site about seven months after the research team. Less than 0.5 in. of profile variation was recorded. The crosslevel measured was close to zero, and the alignment had no significant deviations. The maximum measured gage was approximately 56.8 inches.

C.7.3 Ballast Analysis

A ballast sample was collected from the fouled ballast in the area near the bottom of the ties. Table C-10 details the ballast analysis. The results indicate that a large percentage of the ballast fouling fines were from ground-up concrete. Silicate fine particles were from broken-down ballast.

Table C-10: Ballast analysis, Crossing #7

Sample type	Material types present:	Sample description
Ballast	Fines	Strong HCl reaction (carbonate/concrete fines); silt and smaller clasts surrounded by fines are silicates

C.8 Crossing #8: Removed Asphalt Crossing in U.S. Southeast

The research team visited a location where an asphalt road crossing had been removed from track in the U.S. Southeast in August 2016. The local climate is humid subtropical. The location has an average annual rainfall of 41.62 in., average annual snowfall of 15 in., an average high temperature of 87 °F in July and average low temperature of 25 °F in January. The concrete ties were manufactured in 1993. Ties had a center-to-center spacing of 24 inches. The track has a maximum speed of 35 mph. Figure C-44 shows the satellite view of the site from Google Earth.

Figure C-44: Satellite view of Crossing #8 from Google Earth

C.8.1 Track Visual Observations

A mud spot was seen in track at the location where the road crossing once existed. The site had significant evidence of mud pumping. Figure C-45 shows the areas on the side of the track. Figure C-46 shows an up-close view of some of the ballast fouling. Pieces of asphalt are visible in the fouling. A culvert is located under the fouled track, as shown in Figure C-47. A culvert would likely increase track stiffness.

A culvert, combined with a nearby asphalt crossing, could have created stiff track conditions with drainage issues and high ballast stresses. Fines may have migrated from the crossing into the ballast, increasing fouling.

Figure C-45: Track section with removed crossing, Crossing #8

Figure C-46: Asphalt pieces are present in the fouled ballast, Crossing #8

Figure C-47: Culvert at location of ballast fouling, Crossing #8

C.8.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to determine the concrete surface hardness. The average of the Schmidt hammer readings was 41. The thickness of the tie used to measure the Schmidt hammer readings was measured at the end of the tie. Ballast surrounding the tie was removed by hand to reach the bottom of the tie at both ends and in the center, as shown in Figure C-48. Table C-11 shows the tie thickness measured in track.

Table C-11: Tie thickness measurement, Crossing #8

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	6.75	1.5

Figure C-48: Tie thickness measurement, Crossing #8

C.8.3 Track Geometry Measurements

The ATIP geometry car visited the site approximately 7 months after the research team. Very little variation was seen in the track profile or alignment. The crosslevel was under 1/2 inches. The maximum recorded gage was less than 56.8 inches.

C.8.4 Ballast Analysis

Ballast samples were taken from ballast next to a tie, see Figure C-49. Table C-12 shows the ballast analysis. Fines were principally from concrete and ballast particles.

Figure C-49: Ballast sample collection, Crossing #8

Table C-12: Ballast Analysis, Crossing #8

Sample type	Material types present:	Sample description
Ballast	Sand, Fines, Rock	Strong HCl reaction—fines are carbonate (concrete). Silicate sand-silt sized clasts (mafic minerals, quartz)

C.9 Crossing #9: Combined Asphalt and Gravel Crossing in U.S. Southeast

The research team visited a hybrid asphalt and gravel road crossing located immediately after a switch in the U.S. Southeast in August 2016. The local climate is humid subtropical. The site location has an average annual rainfall of 41.62 in., average annual snowfall of 15 in., an average high temperature of 87 °F in July and average low temperature of 25 °F in January. The concrete ties were installed in 1993. Ties had a center-to-center spacing of 24 in. The track has a maximum speed of 35 mph. Figure C-50 shows a satellite view of the site from Google Earth. A track-level view of the railroad crossing is shown in Figure C-51 and Figure C-52.

Figure C-50: Satellite view of Crossing #9 from Google Earth

Figure C-51: Track-level view facing asphalt side of crossing, Crossing #9

Figure C-52: Track-level view facing gravel side of crossing, Crossing #9

C.9.1 Track Visual Observations

The crossing has a transition from wood-to-concrete ties. Center-binding cracking and shattered tie tops were seen in track right at the transition from wood-to-concrete ties, as shown in Figure C-53(a). Clean ballast appeared to be placed on top of the crossing to allow for better car movement over the tracks. Ballast fouling was seen to be present underneath the new ballast and on the outskirts of the crossing, as shown in Figure C-53(b). Asphalt fines appeared to be present in the ballast fouling in the concrete track. Figure C-54 shows the pumping around the tie immediately after the crossing on the opposite side of the crossing from the wood-to-concrete tie transition. Track grading and drainage appeared to be poor at the crossing as evidenced by the vegetation seen in Figure C-53 and the damp fines seen in Figure C-55, contributing to water retention in-track.

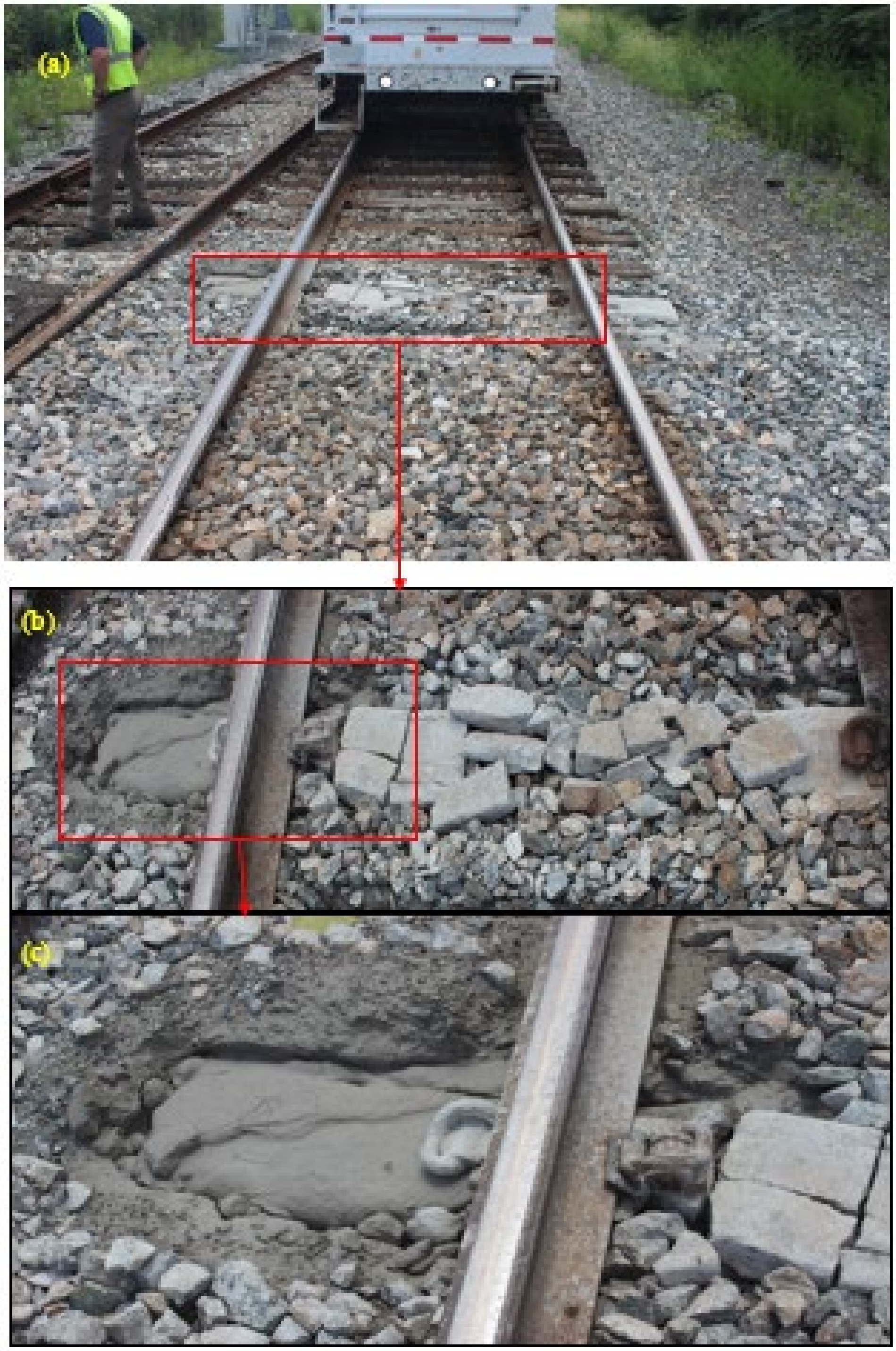

Figure C-53: Shattered tie in transition to wood, Crossing #9

Figure C-54: Mud pumping coming up through crossing ballast and on the edge of Crossing #9

Figure C-55: Mud pumping, Crossing #9

C.9.2 Tie Measurements

Tie thickness was measured at three locations on a tie. Enough ballast surrounding the tie was removed by hand to reach the bottom of the tie at both ends and under a rail seat take the measurements. Table C-13 shows the tie thickness measured on the tie in track.

Table C-13: Tie thickness measurements, Crossing #9

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7	1.25
Rail Seat	8.25	7.25	1.0
Tie End	8.25	7.75	0.5

C.9.3 Track Geometry Measurements

The ATIP geometry car visited the site approximately seven months after the research team. The maximum variation in profile measured in the left rail was approximately 0.8 in. and in the right rail just under 1 inches. Very small variation in alignment and crosslevel were recorded. The maximum measured gage was just over 57 inches.

C.9.4 Ballast Analysis

A ballast sample was collected and analyzed, see Table C-14. The analysis indicates that the fines consist primarily of sand and concrete from abraded ties.

Table C-14: Ballast analysis, Crossing #9

Sample type	Material types present:	Sample description
Ballast	Sand, Fines, Rock	Fines are carbonate/concrete (strong HCl reaction), sand and smaller sized chunks are silicate minerals. Some sand-gravel sized chunks of carbonate-rich material (likely from pieces of ties)

Appendix D.
Curves

Track curves were visited to determine if these locations are more prone to abrasion damage than tangent track. Five curved track sites were investigated in multiple locations around the U.S. This chapter documents track conditions at these locations

D.1 Curve #1: Curve in U.S. Pacific Northwest

The research team visited a curved-track section in the U.S. Pacific Northwest in June 2016. The local climate is a warm summer continental climate. The switch location has an average annual rainfall of 16.5 in., average snowfall of 45 in., an average high temperature of 83 °F in July and average low temperature of 25 °F in January. The concrete ties were manufactured in 1990. Ties had a center-to-center spacing of 24 in. The track maximum speed was 55 mph. Figure D-1 shows a satellite view of the site from Google Earth. Figure D-2 shows a track-level view.

Figure D-1: Site located adjacent to a tangent, Curve #1

Figure D-2: Track view of Curve #1

D.1.1 Track Visual Observations

The ties contained numerous, severe center-binding cracks, Figure D-3. Figure D-3(a) shows a tie with severe center-binding cracking that led to section loss of the tie. Figure D-3(b) and Figure D-3(c) show a tie where center-binding cracks have developed and will eventually spall off, exposing the top row of reinforcements.

The track is in a section cut with higher elevation on both sides of the track. The ballast layer was undercut 3–4 months before the research team visited the site. The railroad claims there was a creek of water flowing through the track during undercutting. Standing water is adjacent to the track, Figure D-4. Figure D-5 illustrates how water could be flowing through the cut sections of hill, allowing for water damage in track. The steep slopes show recent erosion that is further evidence of local water.

Figure D-3: Severe center binding cracking, Curve #1

Figure D-4: Water available on the site, Curve #1

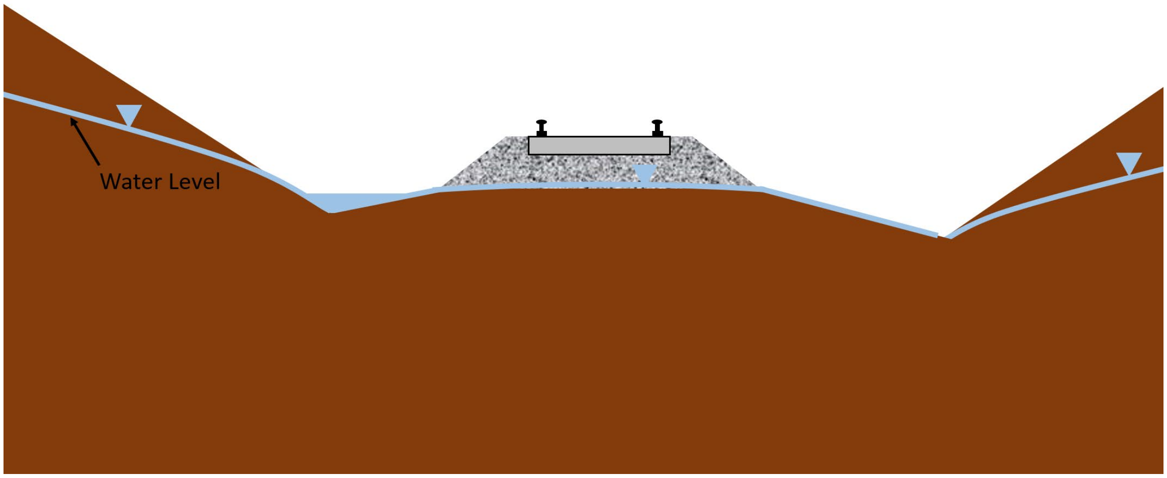

Figure D-5: Schematic cross-section of track, Curve #1

D.1.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 52. The thickness of the tie used to measure the Schmidt hammer readings was measured at three locations. Enough ballast surrounding the tie was removed by hand to reach the bottom of the tie at both ends and in the center to make measurements. Table D-1 details the tie thickness measurements.

Table D-1: Tie thickness measurements, Curve #1

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	5.6875	0.5625
Center	6.25	5.875	0.375
Tie End	8.1875	7.5	0.6875

D.1.3 Track Geometry Measurements

The ATIP geometry car measurements were made within two months of the research visit. The maximum curvature measured was 3.09 degrees with a crosslevel of 1.24 inches. Surface profile and alignment data showed very little variations. The maximum gage recorded in the track segment was 56.922 inches. It is likely that the track measured well due to the recent undercutting operation.

D.1.4 Ballast Analysis

A ballast sample was collected on the site at the depth of the tie bottom. Table D-2 shows the ballast analysis. Very little carbonate-based material was found in the ballast sample, indicating that most of the fouling was from the subgrade. The high amounts of fines seen in the undercutting spoils nearby, along with the infiltration of subgrade material into the track structure indicate that the subgrade material is not tightly compacted and is able to migrate. This is indicative of relatively low track stiffness.

Table D-2: Ballast and subgrade analysis results, Curve #1

Sample type	Material Types Present:	Sample description
Ballast	Sand, Rock	Basalt, vesicular basalt

D.2 Curve #2: Curve in Arid Conditions in U.S. Pacific Northwest

The research team visited a site on a track curve in the U.S. Pacific Northwest in June 2016. The climate is cold semi-arid. The location has an average annual rainfall of 9.8 in., average annual snowfall of 15 in., an average high temperature of 88 °F in July and average low temperature of 25 °F in January. The concrete ties were manufactured in 1991, however railroad records say they were placed in 1998. Tie center-to-center spacing was 24 inches. The track speed was 70 mph for passenger trains and 55 mph for freight trains. Figure D-6 shows a satellite view of the site. A track-level view of the site is shown in Figure D-7. A picture of the track structure is shown in Figure D-8.

Figure D-6: Satellite view of Curve #2 from Google Earth

Figure D-7: Track view, Curve #2

Figure D-8: Photograph of track structure, Curve #2

D.2.1 Track Visual Observations

Figure D-6 shows gray mud present in some track segments. Three fouled-ballast patches were seen during the site visit. The ties had minor center-binding cracking and some had minor splitting cracks. Figure D-9 shows an example of the minor center-binding cracking present on the ties, while Figure D-10 shows vertical splitting cracks found on some ties. The site had been undercut 3 years before this inspection, and fouling had returned at three locations. There were rail welds near the fouled area, indicating potential surfacing issues and/or elevated rail stress.

Figure D-9: Minor center-binding cracks, Curve #2

Figure D-10: Vertical splitting crack, Curve #2

The track superelevation is shown in Figure D-11. The arid environment limits the amount of water in track. The minor center-binding cracking may be due to high wheel loads, or poor support conditions. Researchers noticed mud flat cracking on the embankment, see Figure D-12, indicating the presence of clay particles.

Figure D-11: Track profile, Curve #2

Figure D-12: Mud-flat cracking on track embankment, Curve #2

D.2.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 50. Researchers also measured the thickness of this tie, see Table D-3. The tie had only minor abrasion damage.

Table D-3: Tie thickness measurement, Curve #2

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.1875	7.9375	0.25
Center	6.25	6.125	0.125

D.2.3 Track Geometry Measurements

The ATIP geometry car inspected this track two months of the research team visit. The maximum curvature was 1.05 degrees and maximum crosslevel was 1.572 in., with minimal profile deviation.

D.3 Curve #3: Curve in U.S. Pacific Northwest

The research team visited a curve site in the U.S. Pacific Northwest in June 2016. The local climate is cold, semi-arid. The location has an average annual rainfall of 9.25 in., average snowfall of 7 in., an average high temperature of 89 °F in July and average low temperature of 30 °F in January. The concrete ties were installed in 1992. The ties had a center-to-center spacing of 24 inches. The track maximum speed was 70 mph for passenger train and 60 mph for freight train, but had a 25-mph slow order at the time visited. Figure D-13 shows a satellite view from Google Earth.

Figure D-13: Satellite view of Curve #3 from Google Earth

D.3.1 Track Visual Observations

The railroad reported that the ballast was regularly maintained, however the site had not been undercut recently, only built up. Figure D-14 shows a picture of the track site with visible gray fouling present on ballast. The railroad was in the process of replacing individual ties in order to improve track conditions and remove the slow order, see Figure D-15. The tie shown in Figure D-15 has some abrasion damage on the sides. The railroad plans to replace all ties in the future due to center-binding cracking and cracks near of the fasteners. Figure D-16 is an example of the center-binding cracking.

Figure D-14: Gray-colored fouling present on ballast, Curve #3

Figure D-15: Removed tie, Curve #3

Figure D-16: Center-binding cracking, Curve #3

There were two ties found in track that showed extreme abrasion loss on their adjacent sides. Figure 3-22 shows a picture of the damage. Upon inspection, the team found the remnants of an old tie not removed from track in the ballast between these ties, Figure 3-21. It is likely that the presence of the old tie in the crib area contributed to high local ballast stresses. This old tie restricts ballast movement and increases local stresses. The high stresses caused breakdown and ballast fouling. The tie fines contribute to water retention and increased friction during loading, causing tie breakdown.

D.3.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 51. The thickness of this tie was measured at two locations. Table D-4 shows the tie thickness data. Very little abrasion loss was seen on this tie. It appears that abrasion loss in this section of track was in isolated areas such as the two ties shown in Figure D-14.

Table D-4: Tie thickness measurements, Curve #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	6.125	0.125
Tie End	8.1875	8.125	0.0625

D.3.3 Track Geometry Measurements

The ATIP geometry car measured track conditions a little over a month after the research team visited the site. The track had a maximum curvature of 2.08 degrees, a maximum gage of approximately 56.9 in., maximum crosslevel of 4.79 in., and only minor variations in profile and alignment.

D.4 Curve #4: U.S. West

A section of track near a curve and signal in the U.S. West was visited in October 2016. The ties were manufactured in 1986 and had a center-to-center tie spacing of 24 in. The maximum track speed was 35 mph. The local climate is classified as cold semi-arid per the Köppen classification system. The tangent section location has an average annual rainfall of 13.7 in., average annual snowfall of 37 in., an average high temperature of 89 °F in July and average low temperature of 19 °F in January. Figure 3-18 shows the site.

D.4.1 Track Visual Observations

The ties in this location were scheduled for replacement because the track was not maintaining curvature through rail temperature changes. Some lateral and vertical movement was starting to show at one location near an insulated joint, see Figure D-17. Ballast churn seen at the track surface was limited to the area around five ties. There were also fines seen on the side of track were water usually drains out of the track structure, see Figure D-18. Although the team was not able to walk the track due to sight distance issues, the team found discarded ties on the side of the road about a quarter-mile down the track. These ties did not have scallops along their sides. Scallops may help stabilize the track laterally.

Figure D-17: Ballast churn seen on-site

Figure D-18: Fines on the side of the track

D.4.2 Track Geometry Measurements

The 2011 ATIP track profile measurements showed only minor deviations, see Figure D-19.

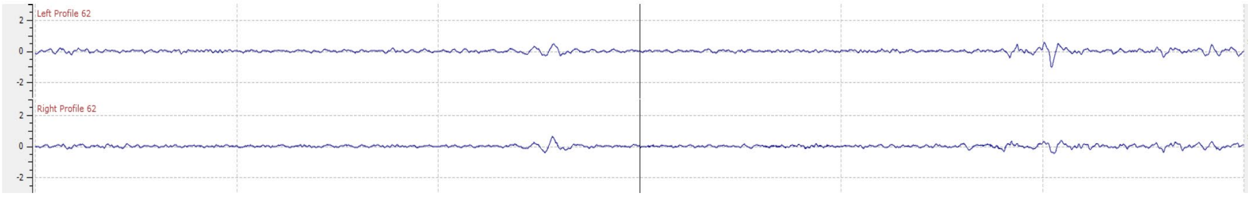

Figure D-19: ATIP profile measurements, Curve #4

D.5 Curve #5: Curve in Canyon

The research team visited a short curve in a canyon site in the U.S. Pacific Northwest in August 2016. The local climate is subarctic, with cool summers. The location has an average annual rainfall of 15.1 in. and snowfall of 76.7 in., an average high temperature of 69 °F in July and average low temperature of -8 °F in January. The concrete ties were manufactured in 2004, and had a center-to-center spacing of 24 inches. The maximum track speed was 25 mph. Figure D-20 shows a satellite view of the site from Google Earth. Figure D-21 shows a track-level view of the site and the pumping zone. The track carries mainly passenger traffic and has low annual tonnage.

Figure D-20: Satellite view of Curve #5 from Google Earth

Figure D-21: Track-level view, Curve #5

D.5.1 Track Visual Observations

The site is an area that frequently has rock slides, as evidenced by the fallen rocks in the drainage ditch and the lack of vegetation on the hillside seen in Figure D-21. Figure D-22 shows a schematic of the tie deterioration in track. There were two sections with surface-visible fouled ballast. The fouled ballast had beige fines from mud pumping around the ties, as shown in Figure D-23 and Figure D-24. The fines were the same color as the surrounding soil, indicating that the majority of fines were from the subgrade. The ties had only minor abrasion wear.

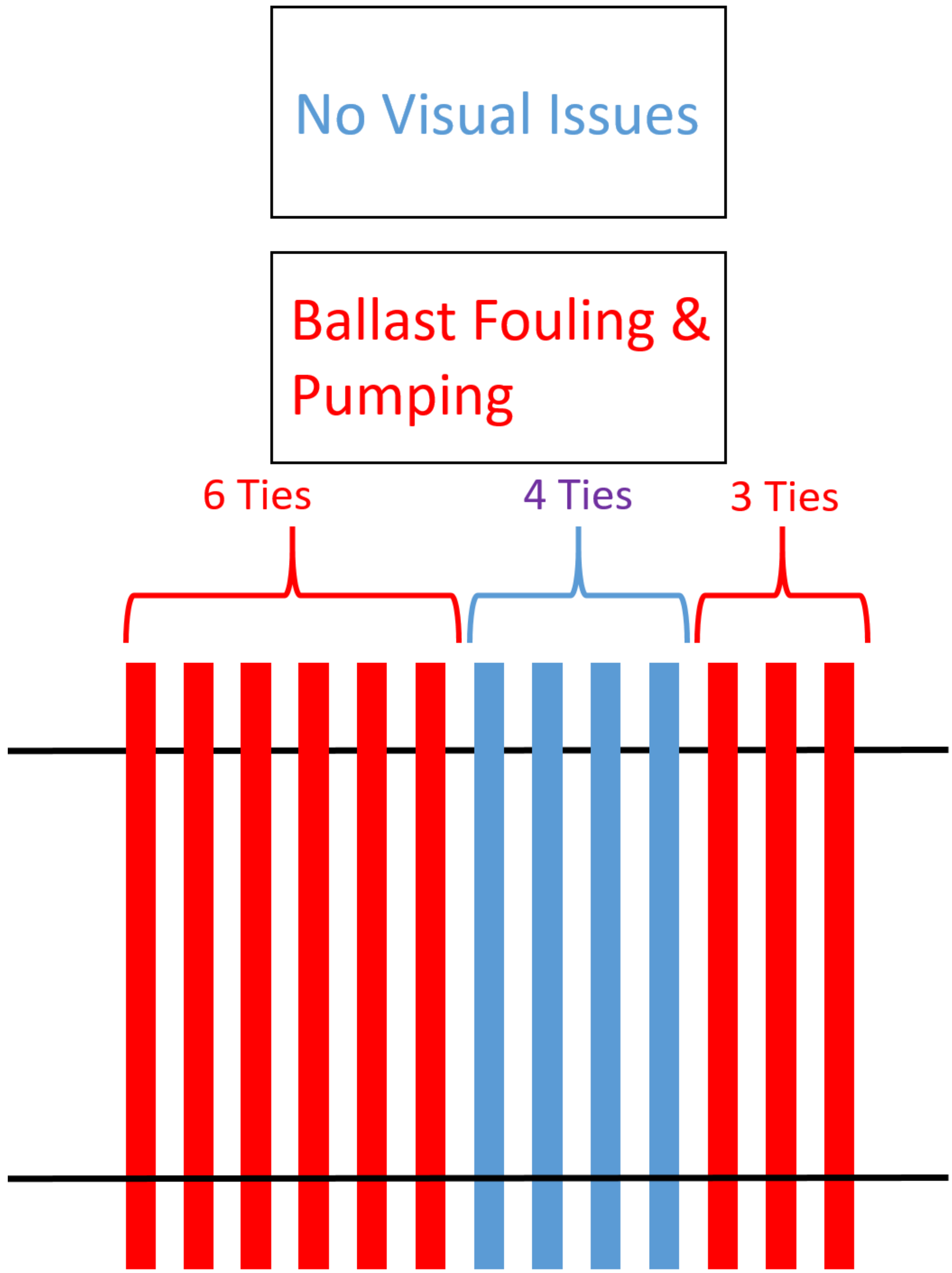

Figure D-22: Schematic of tie condition, Curve #5

Figure D-23: Pumping seen in track, Curve #5

Figure D-24: Fine particles seen at the track surface, Curve #5

Appendix E. Tangent Track

The following sections document the conditions observed at 11 tangent track sites.

E.1 Tangent #1: Tangent Track along a River in the U.S. Pacific Northwest

The research team visited a tangent track site next to a river in the U.S. Pacific Northwest region in June 2016. The local climate is dry-summer subtropical or Mediterranean climate (Köppen climate Csb). The location has an average annual rainfall of 14.52 in., an average annual snowfall of 6 in., an average high temperature of 89 °F in August and an average low temperature in January of 29 °F. The concrete ties were manufactured in 1990 and had a center-to-center spacing of 24 inches. The track speed was 50 mph. Figure E-1 shows a satellite view of the site from Google Earth. Figure E-2 shows a track level view.

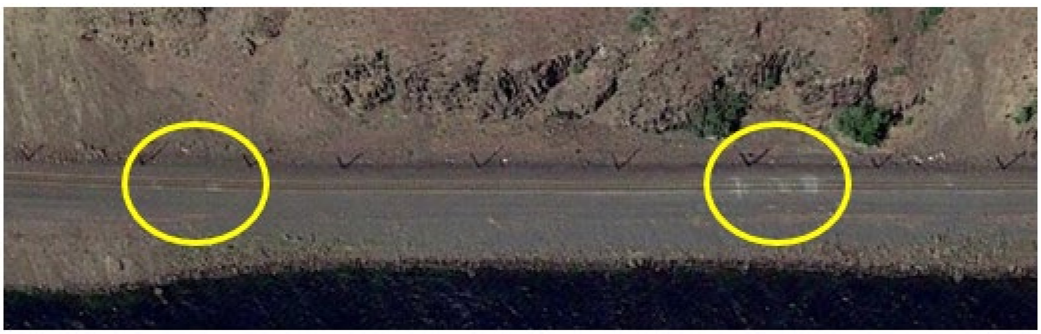

Figure E-1: Satellite view of Tangent #1 from Google Earth

Figure E-2: Track level view of Tangent #1

E.1.1 Track Visual Observations

Researchers observed center-binding cracking over a long section of this track as shown in Figure 3-24. Sone ties had severe center-binding cracking that progressed to full delamination, exposing the steel reinforcements, Figure E-3. Some splitting cracks were also seen at this site.

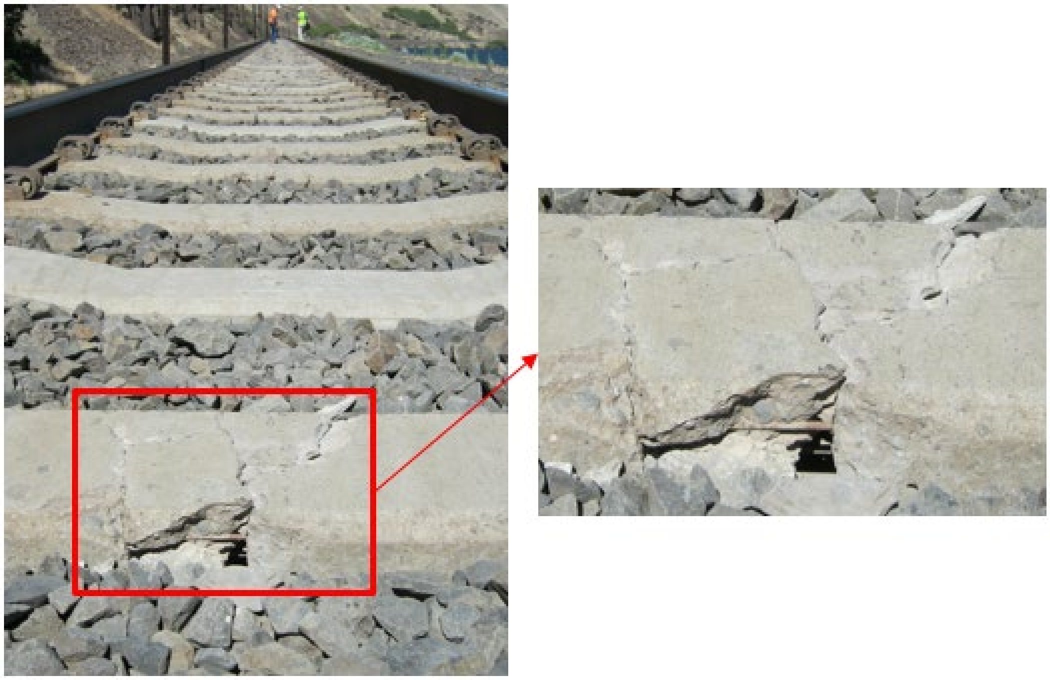

Figure E-3: Severe center binding cracking and exposed reinforcements, Tangent #1

This site was experiencing rapid degradation following a shoulder cleaning operation 1 year prior. The track speed was reduced from 40 mph to 25 mph a couple of weeks before the inspection, and then down to 10 mph immediately following the inspection. Center-binding cracking started within a month after the shoulder cleaning. Track degradation may be the result of a lack of support under the tie ends after shoulder cleaning and/or improper tamping after the cleaning. Figure E-4 shows ties that were removed from track and stored on the side of the road. Very little abrasion was seen on the ties stored on the side of the road.

Figure E-4: Ties removed from track and stored on the side of the road, Tangent #1

E.1.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 48. The thickness of a discarded tie on the side of the road was measured to quantify any abrasion loss. Table E-1 shows the tie thickness data. Very little abrasion damage was measured.

Table E-1: Tie thickness measurements, Tangent #1

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	6.125	0.125
Tie End	8.1875	8.25	0

E.1.3 Track Geometry Measurements

The ATIP geometry car measured the track two months after the research team's visit. The data showed minimal surface profile issues, with a range of deviation of 0.818 and -0.842 in. and 0.725 in. on the left rail and -0.919 in. on the right rail. The maximum rail gage measured was 56.5 inches.

E.2 Tangent #2: Tangent Track along a River in the U.S. Pacific Northwest

The research team visited a tangent track site next to a river in the U.S. Pacific Northwest region in June 2016. This site was located less than a mile from Tangent #1. The local climate is hot-summer Mediterranean climate. The location has an average annual rainfall of 14.52 in., average annual snowfall of 6 in., an average high temperature of 89 °F in August and average low temperature of 29 °F in January. The concrete ties were manufactured in 1990 and had a center-to-center spacing of 24 inches. The track speed was 50 mph. Figure E-5 shows the site from Google Earth.

Figure E-5: Satellite view of Tangent #2 from Google Earth

E.2.1 Track Visual Observations

Some ties were removed from track and stacked nearby, see Figure E-6. There were isolated ties found in track that appeared to have side wear and corner rounding from local ballast conditions, as shown in Figure E-7. The tie did not appear to have any loss in thickness. Center binding cracking was seen on many ties in track. The tie shoulder ballast was cleaned a year before inspection of the research team. Center binding cracking appeared within a month after ballast cleaning, likely because of different stiffness in track under center and the end of the tie. Figure E-8 shows concrete ties with some ballast churn and fouling next to a section of wooden replacement ties next to an insulated joint. The track was elevated and had good grading and drainage, except at the signal location as shown in Figure E-9. The site was very arid with dry grass in the area.

Figure E-6: Ties stored on the side of the road, Tangent #2

Figure E-7: Center binding cracking and tie rounding, Tangent #2

Figure E-8: Pumping on the concrete ties next to wooden ties, Tangent #2

Figure E-9: Poor grading at signal, Tangent #2

E.2.2 Tie Measurements

The thickness of a tie was measured at one location in track. Table E-2 shows the thickness data. Very little change in tie thickness was measured in track, matching the low amount of wear seen on the discarded ties shown in Figure E-6.

Table E-2: Tie thickness measurement, Tangent #2

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	6.125	0.125
Tie End	8.1875	8.125	0.0625

E.2.3 Ballast Analysis

A ballast sample was taken at the depth of the tie bottom. Table E-3 shows the ballast sample analysis. Fines were from ballast breakdown and some from the subgrade. No concrete fines were found in the ballast sample, corresponding to the low amount of tie thickness change in track. Any fines from the tie rounding must have been removed during the shoulder cleaning that occurred within six months of the site visit.

Table E-3: Ballast and subgrade analysis results, Tangent #2

Sample type	Material Types Present:	Sample description
Subgrade	Sand, Fines, Rock	Silicate-rich sand-to clay/silt (no HCl reaction). Gravel to pebble size coarse clasts are igneous rocks

E.3 Tangent #3: U.S. South-Central

The research team visited a tangent section of track located in U.S. South Central region in October 2017. The site is located near a freeway overpass and between two roads. The ties were fabricated in 2007 and were spaced on 24 in. centers. The maximum track speed was 49 mph. The local climate is humid subtropical. The track location has an average annual rainfall of 47 in., no snowfall, an average high temperature of 92 °F in August and an average low of 43 °F in January. A satellite view of the site is shown in Figure E-10.

Figure E-10: Satellite view of Tangent #3

E.3.1 Track Visual Observations

There were ditches on both sides of the track. The ditches were full of vegetation, indicating year-round moisture. The railroad reported that this section of track was undercut about 3 years prior due to surface issues. Significant track fouling was present, as shown in Figure E-11. Figure E-12 shows a schematic of the observed fouling conditions. A potential cause of fouling could be low ballast levels under the ties, leading to high pressures on subgrade and fines infiltration into the track structure.

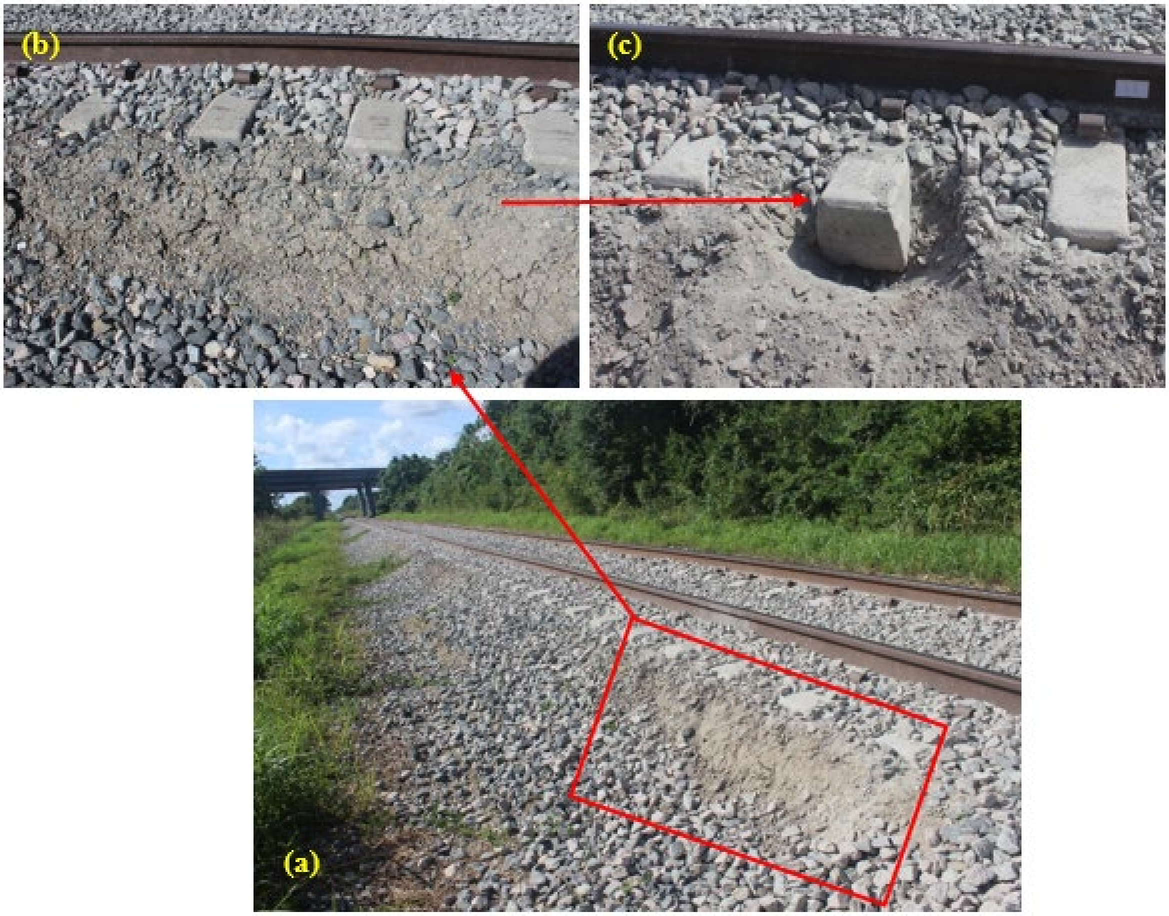

Figure E-11: Pumping on the sides of the track, Tangent #3

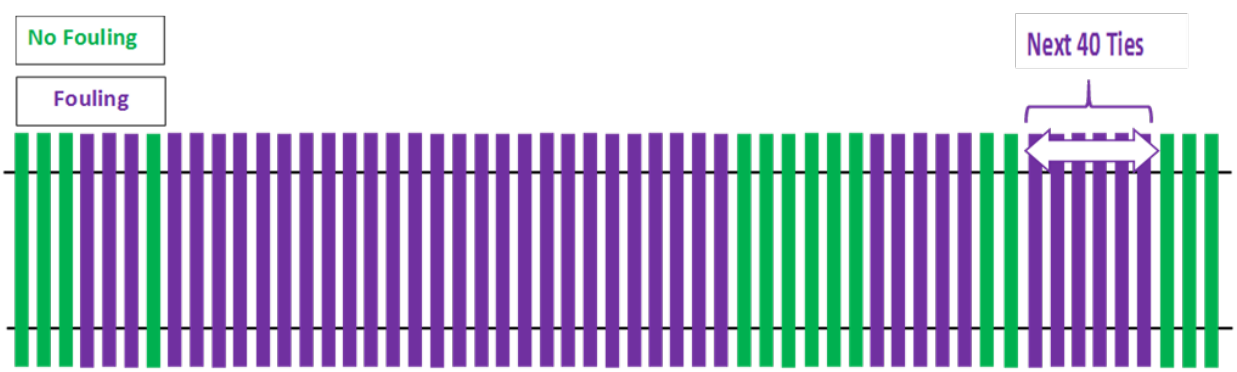

Figure E-12: Schematic view of fouling, Tangent #3

E.3.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 49. Table E-4 shows the tie thickness measured on the site. Only a small amount of abrasion damage was measured.

Table E-4: Tie thickness measurement, Tangent #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	9	8.5	0.5
Center	7	7	0

E.3.3 Track Measurements

Researchers measured the vertical deflection of the tie with the most severe fouling using high definition video during a train pass. The camera and tripod were held in place while the train passed to eliminate vibration in the video images. The deflection was estimated from the vertical movement seen in the images and is shown in Figure E-13. The maximum deflection range o was 0.2 inches. The maintenance personnel told the research team that this location pumps a lot when wet. It is likely that the deflection would be much higher at this site after a rain

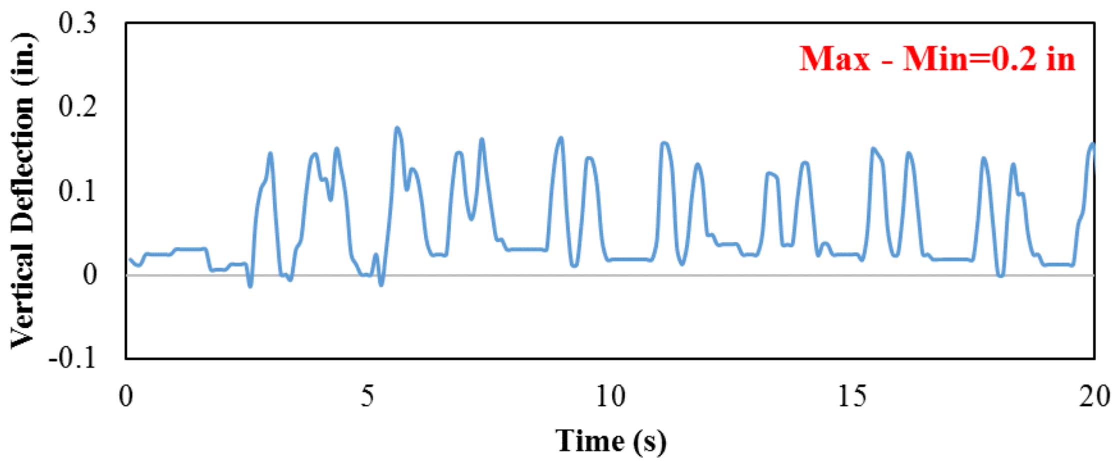

Figure E-13: Vertical deflection of tie measured with high-resolution camera, Tangent #3

E.3.4 Track Geometry Measurements

The ATIP geometry car measured this site 2 years prior to the research team's visit. Profile deviations were slightly less than 1 in. in the left rail and about 1/2 inches in the right rail, with approximately 1 in. of crosslevel, and a maximum gage of approximately 56.75 inches.

E.3.4 Ballast Analysis

A subgrade sample was gathered for analysis. The subgrade showed a strong HCl reaction, see Table E-5, indicating the presence of limestone-bearing material in the subgrade material. This result shows that the acid test is not useful for determining the presence of concrete fines in ballast and subgrade material in areas with limestone. The fouling material found in the ballast had the same color as the subgrade instead of the gray color typically found in locations with large amounts of concrete tie abrasion. This indicates that the fouling material in this case was from the limestone subgrade material pumping up into the ballast.

Table E-5: Ballast analysis, Tangent #3

Sample type	Material types present:	Sample description
Subgrade	Sand, Fines, Rock	Silicate sand and smaller clasts, lots of carbonate fines (strong HCl reaction). Coarse (>10 mm) igneous rock fragments

E.4 Tangent #4: U.S. South-Central

A tangent section of track was visited in the U.S. South-Central region in October 2017. The ties were fabricated in 2007 and spaced at 24 in. centers. The track maximum speed was 49 mph. The local climate is humid subtropical. The track location has an average annual precipitation of 47 in., no snowfall, an average high temperature of 92 °F in August and an average low of 43 °F in January. Figure E-14 shows a satellite view of the site. Figure E-15 shows a track-level view.

Figure E-14: Satellite view of Tangent #4 from Google Earth

Figure E-15: Track-level view of Tangent #4

E.4.1 Track Visual Observations

The ties were in good condition and no abrasion was evident. There appeared to be very little ballast underneath the ties. In the track section with fouling, the concrete tie elevation was only slightly higher than the surrounding subgrade. Other sections of the track without fouling issues appeared to have more ballast under the ties. Ballast was placed on top of the fouled track section, covering 28 ties. The railroad has planned to tamp this section soon.

Insufficient tie support was provided by the track structure, causing fines from the subgrade to pump upwards into the track structure. As shown in Figure E-16, the pumped mud had the same color as subgrade, confirming that there was little ballast under the track and that subgrade fines were infiltrating the track structure. Water and fine subgrade particles present at the site allows grass and other vegetation to grow in the ditches and encroach in the track structure, as shown in Figure E-17.

Figure E-16: Pumping due to the insufficient ballast layer thickness, Tangent #4

Figure E-17: Vegetation encroaching on track, Tangent #4

E.4.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. The average of the Schmidt hammer readings was 52. Table E-6 shows the tie thickness measurements. Little wear was measured.

Table E-6: Tie thickness measurements, Tangent #4

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	9	9	0

E.4.3 Track Measurements

The ATIP geometry car measured this track 2 years before the research team's visit. Profile deviations were -1.118in. in the left rail, and none in the right rail. ATIP measured approximately 1 in. of crosslevel and a maximum gage of 56.54 inches.

E.4.4 Ballast Analysis

Researchers gathered a ballast sample from the ballast at the level of the bottom of the tie. Although the sample showed a strong reaction with acid, see Table E-7, this does not confirm that the fines were concrete. The fines had a reddish tint instead of the usual gray concrete color usually found when large amounts of ground-up concrete fines are present. The reddish tint indicates that there is either hematite or clays present in the fines. The subgrade material from Tangent #3 also had a strong reaction to acid, indicating the presence of carbonate-based material in the subgrade. It is also possible that railcars carrying limestone aggregates deposited limestone dust in the area.

Table E-7: Ballast analysis, Tangent #4

Sample type	Material Types Present:	Sample description
Ballast	Rock, fines	Strong HCl reaction with fines, diorite (igneous) rock fragments.

E.5 Tangent #5: Tangent Track in the U.S. West

Researchers visited a tangent section of track near a bridge and a curve in the U.S. West in October 2016. The ties were manufactured in 1986 and space on 24 in. centers. The track maximum speed was 35 mph. The local climate is cold semi-arid. The site location has an average annual rainfall of 13.7 inch, average annual snowfall of 37 in., an average high temperature of 89 °F in July and average low temperature of 19 °F in January. Figure E-18 shows a track level view of the site. The railroad was in the process of replacing ties.

Figure E-18: Tangent track section near bridge, Tangent #5

E.5.1 Track Visual Observations

Some of the ties removed from track and displayed various wear conditions, as shown in Figure E-19, where (a) shows bottom abrasion, (b) shows exposed steel reinforcements, and (c) shows ties with spalling. Figure E-20 shows ties that were stored next to replacement ties. Overall, the level of abrasion damage seen in ties taken from track on this site was minor.

Figure E-19: Tie abrasion damage, Tangent #5

Figure E-20: Old ties pulled from track, Tangent #5

E.5.2 Tie Measurements

Schmidt hammer readings were taken on the top of a tie in track. The average of the Schmidt hammer readings taken was 45.

E.6 Tangent #6: U.S. Southeast

Researchers visited a tangent section of track near a curve in the U.S. Southeast in December 2016. The local climate is humid subtropical. The crossing location has an average annual rainfall of 50 in., no snowfall, an average high temperature of 93 °F in July and an average low temperature of 36 °F in January. The concrete ties were manufactured in 1998 and were spaced on 24 in centers. The track maximum speed was 60 mph. A satellite view of this location is shown in Figure E-21. A track-level picture of the site is shown in Figure E-22.

Figure E-21: Satellite view of Tangent #6 from Google Earth

Figure E-22: Track-level view of Tangent #6

E.6.1 Track Visual Observations

A small section of fouled ballast was found at this location, as shown in Figure E-23. Fouling and pumping was seen at the surface over a length of five ties shown in Figure E-24. The railroad had removed a few concrete ties during a prior maintenance action shown in Figure E-25. Moderate center-binding cracking was seen in the ties near the fouled ballast, Figure E-26. The center-binding cracking is evidence of track support issues. In addition, Figure E-27 shows one tie with unusual damage. This damage may be the result of ballast particles vibrating on the top of the tie during train passes.

Figure E-23: Mud spot in track, Tangent #6

Figure E-24: Pumping in track, Tangent #6

Figure E-25: Discarded ties stored on the side of the track, Tangent #6

Figure E-26: Center-binding cracking in ties near the fouled ballast location, Tangent #6

Figure E-27: Abrasion damage at unusual location, Tangent #6

E.6.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie. Figure E-28 shows a picture of the tie after preparation to level the tie surface prior to taking the Schmidt hammer readings. The average of the 10 Schmidt hammer readings was 42. Ballast was removed from the side of a tie in track to measure the tie thickness at both ends and at the center. Table E-8 shows the tie measured thickness and estimated wear.

Figure E-28: Preparation of tie for Schmidt hammer testing, Tangent #6

Table E-8: Tie thickness measurements, Tangent #6

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7.5	0.75
Center	7	6	1
Tie end	8.25	7.5	0.75

E.6.3 Track Measurements

Researchers gathered high definition video of one of the ties in the fouled ballast section during a train pass. Video analysis was performed to estimate the tie deflection during loading shown in Figure E-29. The tie with highest level of pumping had 0.7 inch of deflection.

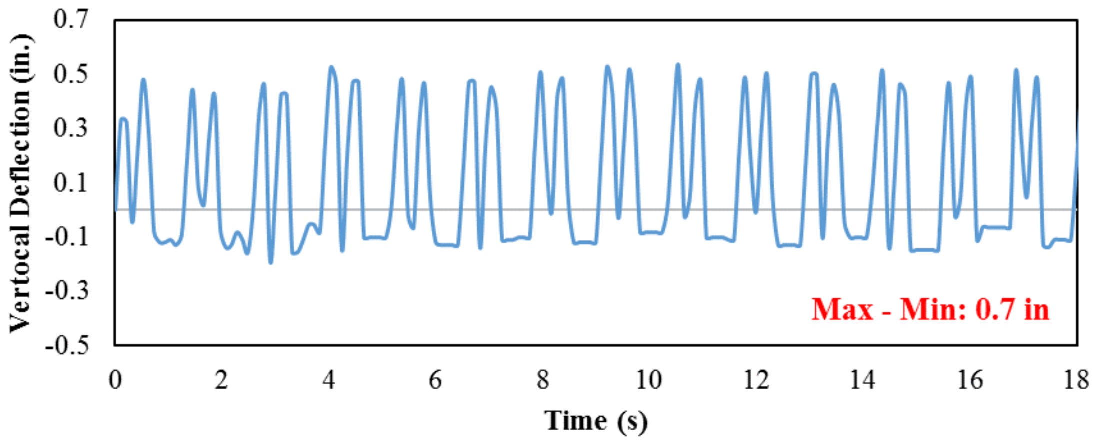

Figure E-29: Vertical deflection of tie with severe pumping, Tangent #6

E.6.4 Ballast Analysis

A ballast sample was taken from track at the depth of a concrete tie bottom. Concrete fines were found in the ballast shown in Table E-9.

Table E-9: Ballast analysis, Tangent #6

Sample type	Material types present:	Sample description
Ballast	Rock, Fines	Gneiss, Schist, and Granite present in the rock. Strong HCl reaction. Fines are carbonate (concrete).

E.7 Tangent #7: Canyon Tangent Track in Subarctic Climate

Researchers visited a section of tangent track near a canyon bridge in the U.S. Pacific Northwest in August 2016. The local climate is subarctic, with cool summers. The location has an average annual rainfall of 15.1 in., snowfall of 76.7 in., an average high temperature of 69 °F in July and average low temperature of -8 °F in January. The concrete ties were manufactured in 2004. The ties had a center-to-center spacing of 24 inches. The track maximum speed was 25 mph. A satellite view of the location is shown in Figure E-30. Figure E-31 shows a picture of the bridge and approach from track-level. The track has a low traffic levels, with mixed passenger and freight trains.

Figure E-30: Satellite view of Tangent #7

Figure E-31: Bridge approach in canyon, Tangent #7

E.7.1 Track Visual Observations

The site had large amounts of ballast fouling. Figure E-32 shows a schematic of the track fouling conditions. Evidence of pumping action was seen in the fine material surrounding the ties. The pore pressure in the fines during loading expels water and fines along the sides of the ties, pushing material away from the tie. Figure E-33, shows the photo of the section of track with severe fouling and pumping action. The fines were removed from the tie top surface as shown in Figure E-34, exposing center-binding cracking. Figure E-35 shows the ties that were shattered from center-binding cracking that delaminated at the top row of reinforcements.

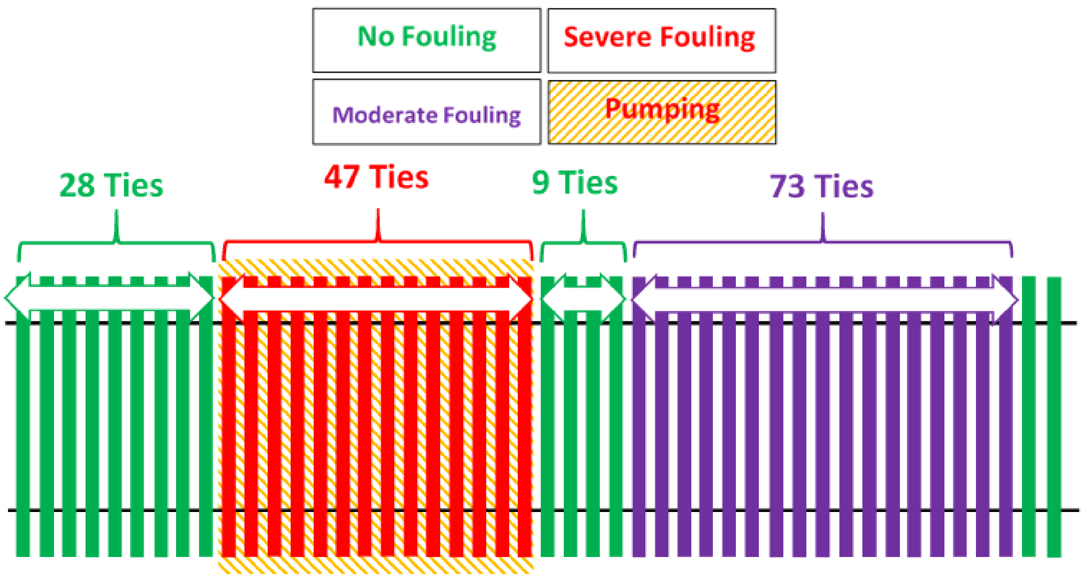

Figure E-32: Schematic view of the fouling, Tangent #7

Figure E-33: Severe pumping, Tangent #7

Figure E-34: Tie cracking, Tangent #7

Figure E-35: Shattered tie, Tangent #7

The area surrounding the track did not appear stable. There is evidence of occasional landslides on to the track, and poor slope stability under the track. In one location, wooden piles with steel cable tie-backs had to be installed in track to prevent further slope erosion, Figure E-36. Many ties appeared to have little or no ballast support. Some ties even appeared to be below grade.

Track drainage issues were apparent. The railroad had dug trenches in track to drain water from the track in pumping locations, Figure E-37. Drainage ditches were clogged by debris in some areas from rack falls, Figure E-38. Algae was also seen covering standing water in the drainage ditch. A drainage pipe was installed in track to further assist with drainage, Figure E-39. One tie was seen with some wear seen on the tie end, as shown in Figure E-40. The damage went up to the ballast level and could have been caused by the ballast movement between the tie and a stiff spot in track to the side of the tie. Track maintenance is difficult in this section due to utility locations.

Figure E-36: Wooden piles with tie-back cables to stabilize the track, Tangent #7

Figure E-37: Trenches dug in ballast to drain water ponding in track, Tangent #7

Figure E-38: Debris and algae covering standing water seen in drainage ditch, Tangent #7

Figure E-39: Drainage pipe crossing under track, Tangent #7

Figure E-40: Tie end wear, Tangent #7

E.7.2 Tie Measurements

Ten Schmidt hammer readings were taken on the top of a tie to measure the concrete surface hardness. The average of the Schmidt hammer readings was 44. Researchers measured the thickness this tie at three locations. Very little ballast was present under the tie. The thickness of a second tie that appeared to have more ballast support had more wear, Table E-10.

Table E-10: Tie thickness measurement, Tangent #7

Ballast Amount Under Tie	Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Low	Tie End	8.25	7.75	0.5
Low	Center	7	6.75	0.25
Low	End	8.25	7.875	0.375
Typical	Center	7	5.75	1.25

E.7.3 Track Geometry Measurements

The ATIP geometry car measured this track eleven months prior to the research team's visit. The geometry car measured profile variations of approximately 3/4 inches in the left and right rails. The system measured very low crosslevel, and no significant gage issues.

E.8 Tangent #8: Small Section of Gray Mud in Subarctic Climate

Researchers visited a section of track near a canyon bridge approach in the U.S. Pacific Northwest in August 2016. The local climate is continental subarctic with cool summers. The crossing location has an average annual rainfall of 16.6 in., average annual snowfall of 75.5 in., an average high temperature of 65 °F in July and average low temperature in January of 8 °F. The concrete ties were manufactured in 2004 and had a center-to-center spacing of 24 inches. The track maximum speed was 60 mph for both passenger and freight trains.

E.8.1 Track Visual Observations

This location was in a tangent track on high embankments. Severe fouling was seen at the surface around six ties at one location. One of the ties was shattered as shown in Figure E-41. Figure E-42 shows the pumping products at one end of the tie. Fines in the track appeared to initiate underneath the surface and come to the top during pumping action.

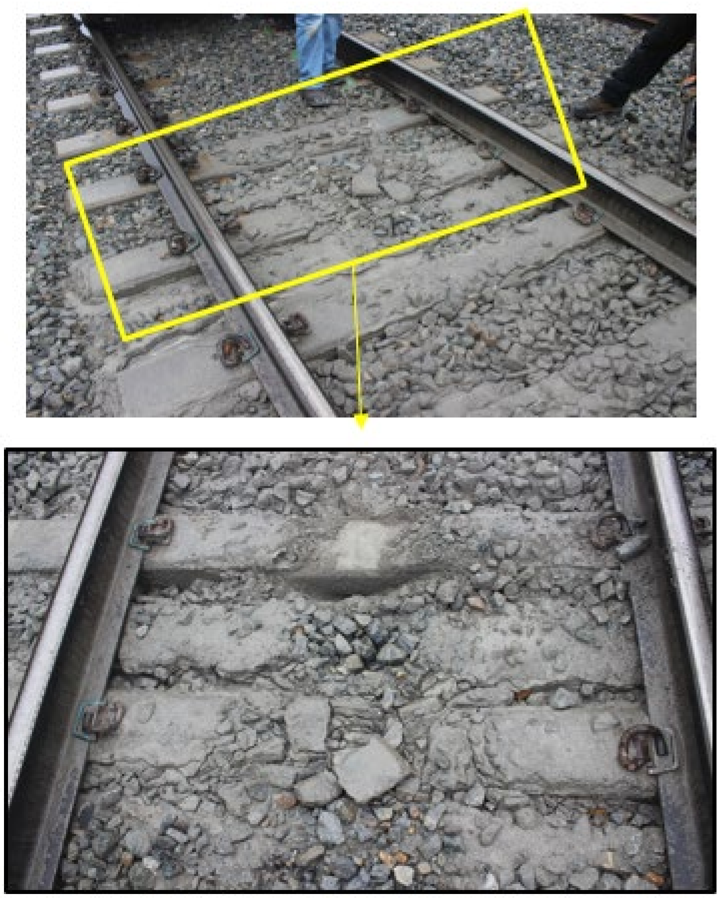

Figure E-41: Shattered ties, Tangent #8

Figure E-42: Pumping produces fine particles around the tie, Tangent #8

E.8.2 Tie Measurements

The tie thickness was measured at two locations, Table E-11. Significant losses were measured.

Table E-11: Tie thickness measurements, Tangent #8

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7	1.25
Center	7	5.5	1.5

E.8.3 Track Geometry Measurements

The ATIP geometry car measured the track 11 months before the research team's visit. The track had very little variation in rail profile. The maximum gage measured was 56.8 inches.

E.9 Tangent Track #9: Tangent Track after Wood Ties in Subarctic Climate

The research team visited a tangent track in the U.S. Pacific Northwest in August 2016. The local climate is subarctic with cool summers. The location has an average annual rainfall of 15.1 inch, average annual snowfall of 76.7 in., an average high temperature of 69 °F in July and average low temperature of -8 °F in January. The concrete ties were manufactured between 2004 and 2006 and had a center-to-center spacing of 24 inches. The track maximum speed was 25 mph. Figure E-43 shows a satellite view of the site through Google Earth. Figure E-44 shows a track-level view. This track has very low annual tonnage consisting primarily of passenger trains and some freight trains.

Figure E-43: Satellite view of Tangent #9 from Google Earth

Figure E-44: Track-level view, Tangent #9

E.9.1 Track Visual Observations

Railroad personnel reported that this location requires routine maintenance. Ballast fouling was seen in track beginning on the sixth tie after the wood-to-concrete tie transition. Figure E-45 shows a schematic of the ballast fouling visible on the track surface. Evidence of severe pumping was also seen in track, as shown in Figure E-46. The fouling had a different color than the typical gray mud typically seen in track locations with concrete abrasion damage. The color of the fines was like that of the soil next to the track. This is most likely because the track had only a thin layer of ballast underneath the ties and was in a low spot. Some ties with shattered top sections were seen in track, as shown in Figure E-47. In areas with excessive fouling and pumping, center-binding cracking was seen after the ties were uncovered as shown in Figure E-48. Figure E-49 shows a picture of welds in the rail after a section of the rail had to be replaced in 2010, only a few years after the concrete ties were installed. There were also small rock slides on the hill above the track, interfering with drainage and causing fouling in track.

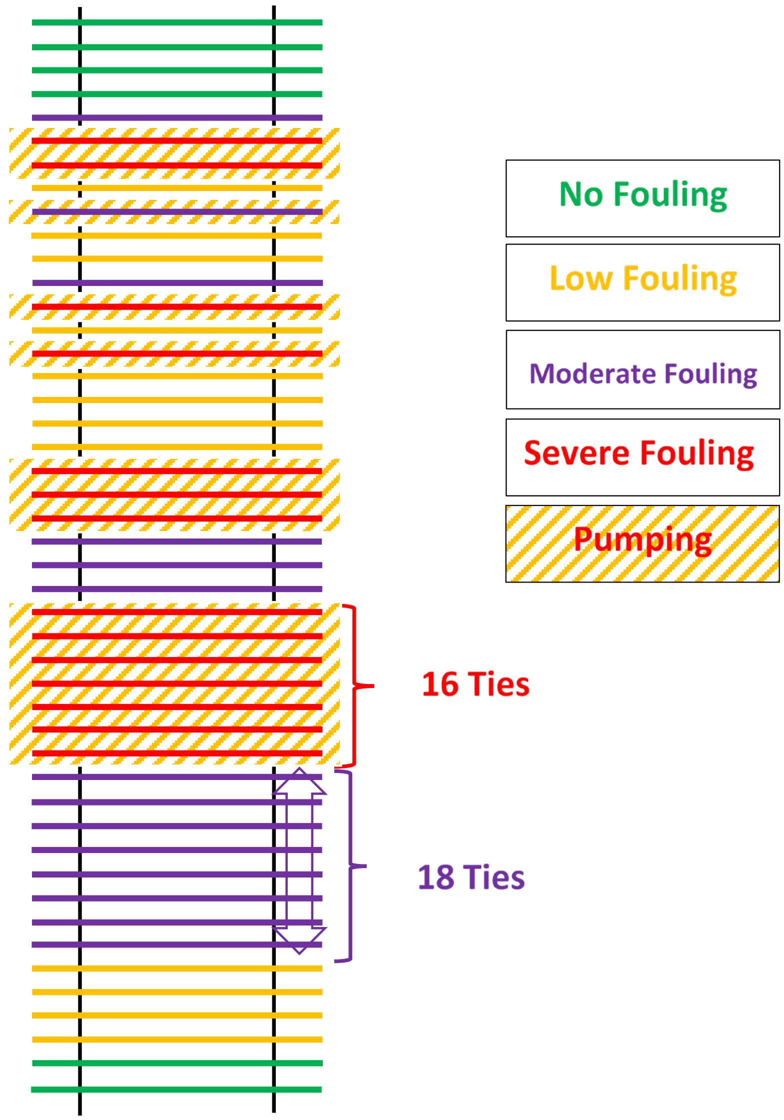

Figure E-45: Schematic view of fouling condition, Tangent #9

Figure E-46: Mud pumping, Tangent #9

Figure E-47: Damaged ties, Tangent #9

Figure E-48: Tie center binding cracks, Tangent #9

Figure E-49: Rail welds, Tangent #9

E.9.2 Track Measurements

The ATIP geometry car tested the track 11 months before the research team's visit. Geometry car measurements showed a maximum profile variation of 1.2 in. in the left rail and 1.2 in. in the right rail. No significant gage widening issues were seen in the measurements.

Ultrasonic pulse velocity readings were taken on a tie in track to measure the tie integrity. Table E-12 shows the UPV readings that were measured on-site. Figure E-50 shows the UPV reading being taken from the same tie shoulder. UPV measurements show that the UPV readings for center-to-shoulder and shoulder-to-shoulder is lower than the one for the same shoulder because of the center-binding cracking. Center-binding cracks impede the pulse movement through the tie, decreasing the velocity. The low shoulder-to-shoulder velocity confirms the visual observations of center-binding cracking.

Table E-12: UPV readings, Tangent #9

	Distance (in)	UPV Reading (ft/s)
Same shoulder	4	6,447
Shoulder-to- center	39	9,280
Shoulder-to-shoulder	89	7,59

Figure E-50: UPV testing, Tangent #9

Tie acceleration measurements were taken on the UPV tested tie UPV during two train passes. A three-directional accelerometer was attached to the tie shoulder using hot glue. The tie acceleration was measured at a 20-kHz sample rate. Figure E-51 shows the acceleration as a passenger train passed, while Figure E-52 shows the tie acceleration as a freight train passed. High accelerations were measured in the vertical direction, indicating poor support under the tie.

The tie showed slightly higher accelerations in the vertical direction from the freight train likely because of the higher loads.

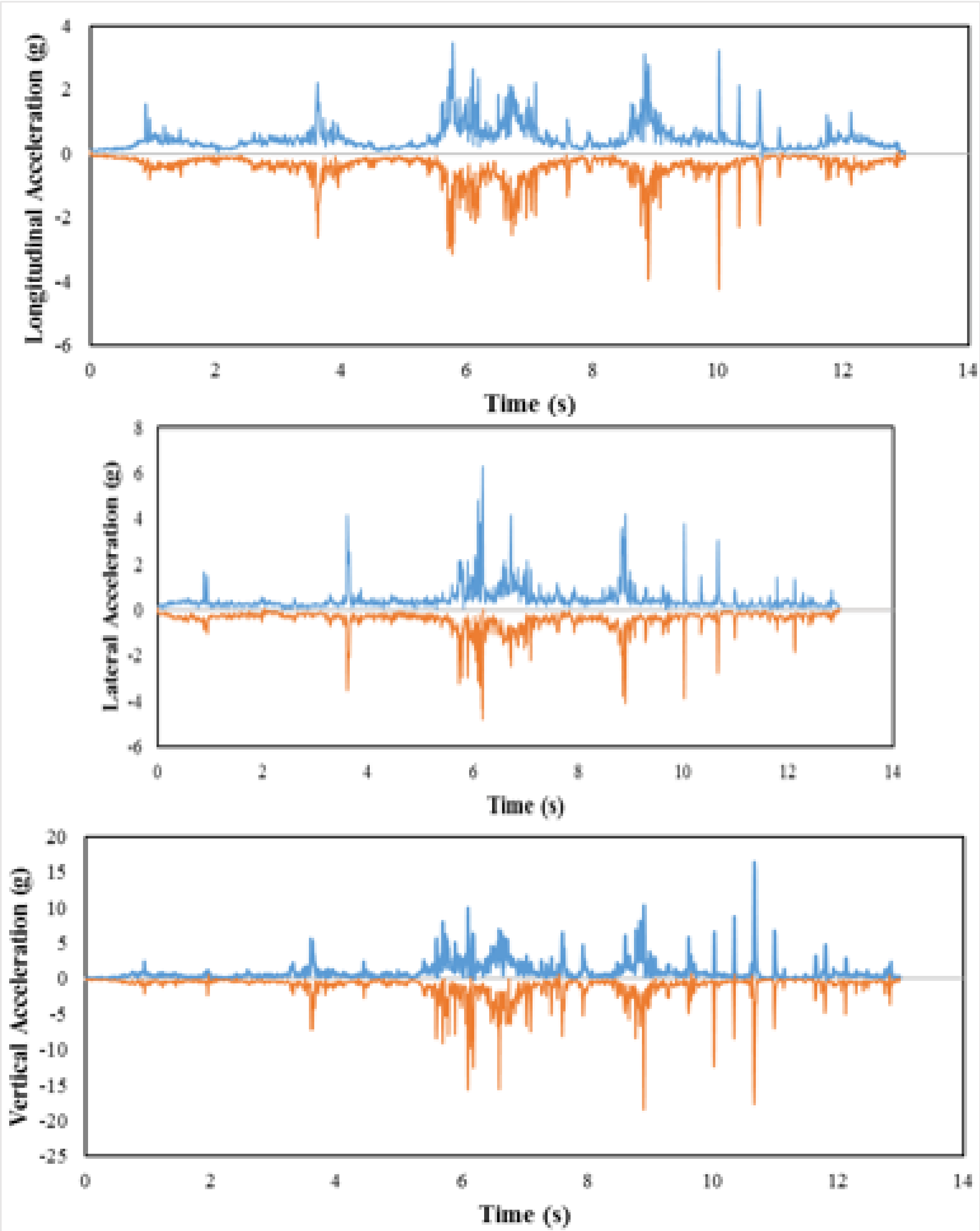

Figure E-51: Measured tie acceleration during a passenger train pass, Tangent #9

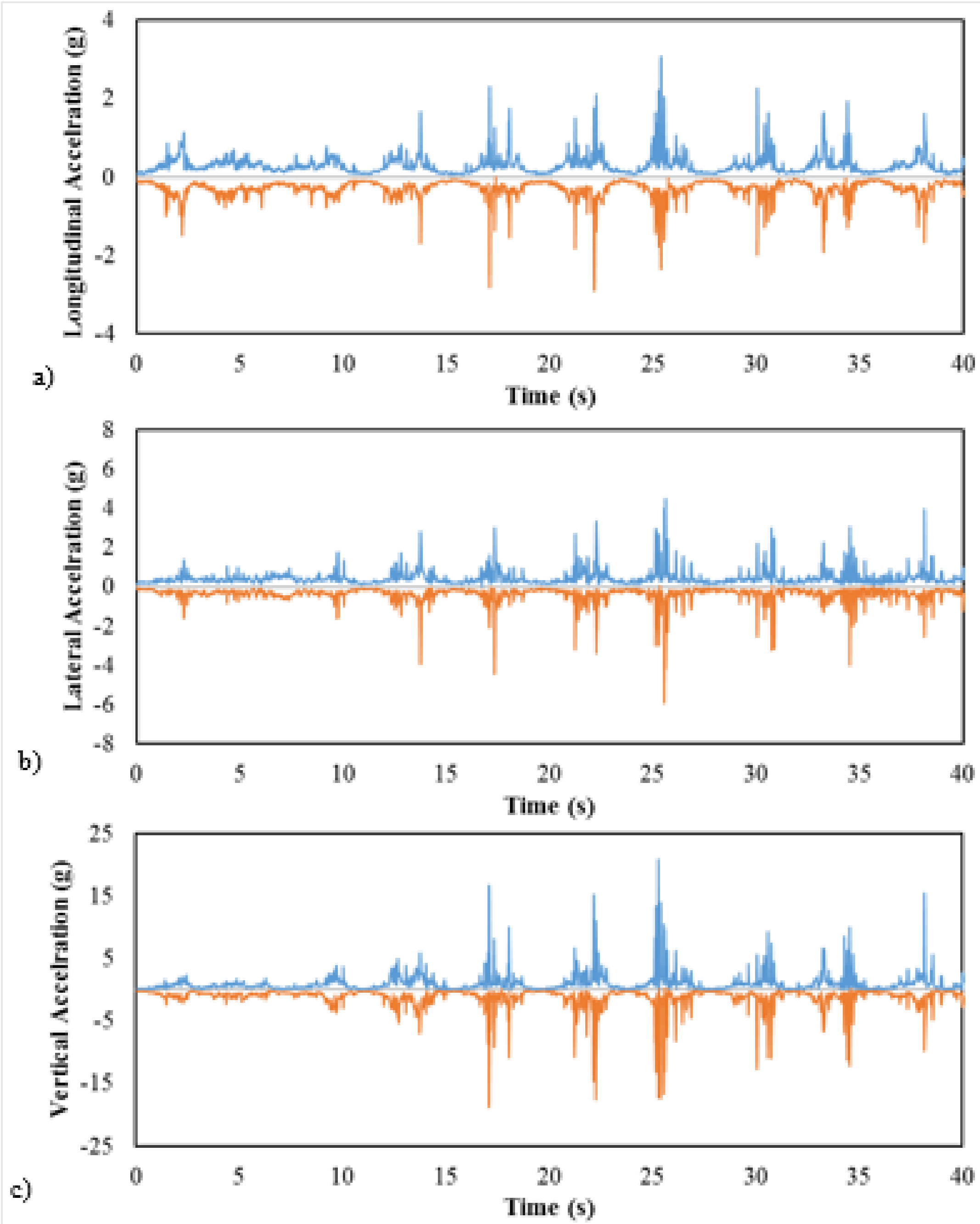

Figure E-52: Measured tie acceleration during a freight train pass, Tangent #9

E.10 Tangent Track #10: Track Section Adjacent to Highway in U.S. Southeast

The research team visited a tangent-track site in the U.S. Southeast in August 2016. The site is next to a highway, as shown in the Google Earth satellite image, Figure E-53. The local climate is humid subtropical. The site n has an average annual rainfall of 41.62 in, average annual snowfall of 15 in., an average high temperature of 87°F in July and average low temperature of

25°F in January. The concrete ties were installed in 1993 and had a center-to-center spacing of 24 inches. The track had a maximum speed of 35 mph.

Figure E-53: Satellite view of Tangent #10 from Google Earth

E.10.1 Track Visual Observations

Gray mud was seen at the surface of the track over three ties, however it is likely the fouling extended farther under the surface. Moderate center-binding cracking was seen in the ties in the fouled-zone. The railroad reported that mud pumping at this site returns following maintenance actions. The grading in track was poor with very little slope away from the track. Water was seen ponding in track and in the ditch between the highway and railroad, as seen in Figure 3-5. Figure E-54 shows the water and gray mud ponding around a tie. Green grass was seen growing in the ditch, indicating that this is a low-spot in the ditch that does not drain well and is consistently wet.

Figure E-54: Fine particles and water in track, Tangent #10

E.10.2 Tie Measurements

The thickness of a tie was measured at both ends and in the center. Table E-13 shows the tie thickness measured in track. The moderate amount of abrasion correlated with the small zone of fouling and pumping, indicating that the site was likely repaired frequently enough to retard the rate of abrasion.

Table E-13: Tie thickness measurement, Tangent #10

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	7.5	0.75
Center	7	6.625	0.375
End	8.25	7.75	0.50

E.11 Tangent Track #11: Track Section in U.S. Southeast

The research team visited a tangent track section in the U.S. southeast in August 2016. The local climate is humid subtropical. The site location has an average annual rainfall of 40.52 in., average snowfall of 14 in., an average high temperature of 87 °F in July, and an average low temperature of 22 °F in January. The concrete ties were installed in the early 1990’s with a center-to-center spacing of 24 inches. The track had a maximum speed of 35 mph. Figure E-55 shows a satellite view of the site from Google Earth.

Figure E-55: Satellite view of Tangent #11 from Google Earth

E.11.1 Track Visual Observations

Recent mud pumping was evident from examining the track conditions, Figure E-56. Moderate center binding cracking was seen on the site. Fines were seen deposited on the edge of the ballast on the side of the road where the water drains out of the track structure, as shown in Figure E-57. Vegetation was also seen encroaching on the track structure, indicating that water is available at least during the summer season. The railroad indicated that they had been stacking trains to run at night. The weather patterns in this region showed that it was more likely to rain while the trains were running at night, increasing the amount of mud pumping.

Figure E-56: Tie pumping, Tangent #11

Figure E-57: Fines and vegetation adjacent to track, Tangent #11

E.11.2 Tie Measurements

The thickness of a tie was measured at two locations. Table E-14 shows the tie thickness measured in track.

Table E-14: Tie thickness measurements, Tangent #11

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.25	6.5	1.75
Center	7	6.25	0.75

E.11.3 Track Geometry Measurements

The ATIP geometry car tested this track approximately 8 months after the research team's visit. The geometry car measured a variation in profile in the left and right rails of approximately 0.5 in., about 0.3 in. of variation in the left and right alignment was measured. The maximum gage was 57 inches.

E.11.4 Ballast Analysis

A ballast sample was collected near the measured tie. Table E-15 shows the ballast analysis results. The fines were found to have high percentages of concrete breakdown material. Larger pieces in the sample were ballast particles.

Table E-15: Ballast analysis results, Tangent #11

Sample type	Material types present:	Sample description
Ballast	biotite, muscovite	Strong HCl reaction to fines (they are carbonate—concrete breakdown). >1 cm frags are igneous rocks

Appendix F.
Concrete Tie Boneyards

Concrete ties are often removed individually from track because of damage, or in mass when the ties in whole sections of track are replaced. The ties are often stacked and stored next to the side of the road until they are shipped to a large collection yard for refurbishment and use in lower-speed track or ground for and disposal. The collection and disposal process can take months or years to complete. Researchers visited concrete tie boneyards to help establish the frequency of bottom-tie abrasion in track. The bottom and sides of ties stacked in boneyards are often exposed, allowing for a more thorough examination of wear patterns.

F.1 Boneyard #1: Intermountain West

Researchers visited a concrete tie boneyard in the U.S. Inter-mountain West to study ties collected s from a Class I railroad. Ties are shipped here from track locations in many states. During discussions with the railroad and boneyard operators it was discovered that many of the ties in poor condition were destroyed just before the research team visit. This led to a skewed view of bottom abrasion prevalence.

Ties were stacked in large piles on dunnage to separate layers of ties, Figure F-1. Out of the thousands of ties stored on site, only 6 were found with severe abrasion damage, and 12 were found with moderate abrasion damage. The ties with abrasion damage were clustered together, indicating that they came from the same location in track. This matches what was seen in track inspections. Ties with abrasion damage in track are clustered in groups. Figure 3-16 shows one tie found in the boneyard with significant abrasion loss. The original center thickness of this tie was 6.25 inches. The tie also had significant center-binding cracking on the top that bifurcated, resulting in delamination in the top. Abrasion damaged ties in this boneyard non-uniform damage, with very rough bottom surfaces, Figure F-2. Figure F-3 and Figure F-4 show pictures of additional ties seen at the boneyard with severe abrasion damage, while Figure F-5 shows a picture of tie ends with minor-to-moderate abrasion damage.

Figure F-1: Ties stacked in large concrete tie boneyard, Boneyard #1

Figure F-2: Tie with significant non-uniform abrasion damage, Boneyard #1

Figure F-3: Picture of tie bottom with severe abrasion damage, Boneyard #1

Figure F-4: Tie ends with moderate-to-severe abrasion damage, Boneyard #1

Figure F-5: Tie ends with minor-to-moderate bottom abrasion damage, Boneyard #1

F.2 Boneyard #2: East Coast

Researchers visited a concrete tie boneyard in the U.S. East Coast in May 2017 to study used ties from a Class I railroad. 3,230 ties were removed from 1.3 miles of track in Maryland and sent to the boneyard for grinding and disposal. The maximum train speed in this location is 110 mph. The maximum gradient in this region is -0.22. There is a 0.73 degrees curve present. This track serves primarily passenger trains. The concrete ties were placed in three stacks on-site for disposal, as shown in Figure F-6.

Figure F-6: Three stacks of used concrete railroad ties, Boneyard #2

The ties in stack 1 consisted primarily of ties made in 1995 with eight smooth reinforcement strands. Most of the ties in stack 1 were in good condition, with very little abrasion damage. Many of the ties still had the original broom finish visible on the bottom, as shown in Figure F-7. Some ties showed a moderate amount of abrasion, such as the tie shown in Figure F-8. Some minor rail seat deterioration was present on several ties. Longitudinal splitting cracks were more common in ties in stack 1 stack than abrasion damage. The cracking extended to the top row of strands, Figure F-9. Cracking was observed in 5–7 percent of the ties in stack one, however, it is not known is these cracks were the result of tie removal and handling process or in-service conditions.

Approximately 10–15 percent of the ties in stack 1 were newer ties made with 24 wires. These ties were used to replace failed eight-strand ties. The newer ties were made with the same coarse aggregate, but with a crushed granite sand instead of a siliceous sand. The newer ties had more abrasion damage than the older ties. This abrasion could be track location specific. Locations with good track support conditions would be expected to cause minimal damage to ties, negating the need for replacement.

Figure F-7: Broom finish still visible on bottom of many ties in stack 1, Boneyard #2

Figure F-8: Minor abrasion present in tie in stack 1, Boneyard #2

Figure F-9: Longitudinal splitting cracking seen in tie in stack 1, Boneyard #2

Stack 2 contained eight strand ties made between 1994 and 1996. Approximately 70 percent of the ties had very minor bottom wear less than 0.5 inches. The remaining 30 percent of ties were newer ties made with 24 wires and showed noticeably more abrasion damage. However, only 10–12 ties in stack 2 had more than 0.75 in. of wear. All the severely abraded ties were newer ties. Three ties were pulled from stack 2 for additional study. These ties were made in 2005, 2006, and 2008. One of the ties had 2 wires exposed and 0.75 in. of wear at the center of the tie, with more severe abrasion at the ends, as shown in Figure F-10. This tie experienced significant rounding of the bottom corners. Per the railroad, these newer ties were usually placed in poor track conditions with standing water in track.

Figure F-10: Tie with severe abrasion wear in stack 2, Boneyard #2

About one third of the ties in stack 3 were of the newer 24-wire variety. Ties in stack 3 showed less abrasion damage that those in stack 2.

F.3 Boneyard #3: Pacific Northwest

Researchers visited a concrete tie boneyard in a maintenance facility in the U.S. Pacific Northwest in June 2016. The ties were taken from unknown locations in the area. The climate near the maintenance yard is classified as Mediterranean, however. the track weather conditions in the mountainous terrain common in this area can be highly variable. The maintenance yard location has an average annual precipitation of 106.7 in., average annual snowfall of 50 in., an average high temperature of 76 °F in July and average low temperature in January of 32 °F. The concrete ties were manufactured in 1988. Figure F-11, Figure F-12, and Figure F-13 are examples of ties found with abrasion damage. Figure F-12 shows an example of tie bottom corner rounding commonly seen in the ties. The tie bottom rounding could indicate either torsional forces on the ties during loading, a rocking action on the ties during loading, or hydro-abrasive effects on the tie during pumping. The difference in tie thickness from abrasion damage is also evident in the middle row of ties in Figure F-13. The tie second from the right in the middle row is considerably thinner than the other ties.

Figure F-11: Abrasion on the bottom of the tie, Boneyard #3

Figure F-12: Tie with some abrasion damage, Boneyard #3

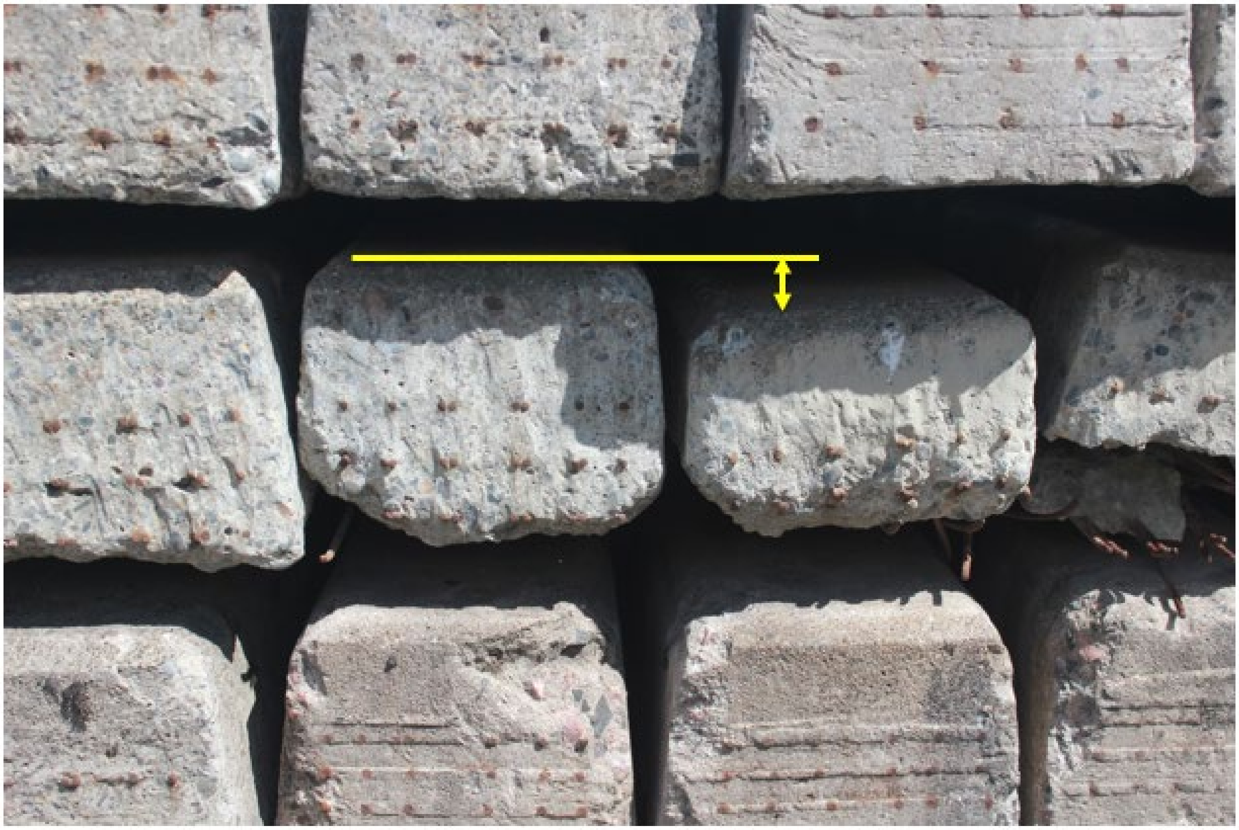

Figure F-13: Rounding of tie bottom corners seen in some ties, Boneyard #3

F.3.1 Tie Measurements

Tie thickness was measured on two ties. A level was used to assist in the tie measurements. Figure F-14 shows one of the ties during thickness measurement. Table F-1 shows the tie thickness measured on the tie in track.

Figure F-14: Tie thickness measurement, Boneyard #3

Table F-1: Tie thickness measurement data, Boneyard #3

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Center	6.25	5.625	0.625
Center	6.25	5.125	1.125

F.4 Boneyard #4: Southeast

Researchers visited a concrete tie boneyard at a maintenance facility in the U.S. Southeast. The ties were taken from unknown locations in the track subsection. This area has an average July high temperature of 90 °F, average January low temperature of 25 °F, average annual rainfall of 53.4 in., and average annual snowfall of 2 inches. The climate is classified as humid subtropical.

Many of the ties stored here had large amounts of bottom and side abrasion. Figure F-15 shows ties with abrasion damage that were stored in the boneyard. As shown in Figure F-15e, abrasion often rounds the bottom of the ties.

Figure F-15: Concrete ties found in the boneyard at a maintenance yard in the U.S. Southeast, Boneyard #4

F.4.1 Tie Measurements

Because of safety concerns with the tie pile, the research team was not able to get concrete tie thickness measurements on abraded ties.

F.5 Boneyard #5: West

Researchers visited a boneyard in the U.S. west in October 2016. The ties at this site were manufactured in 1986. The local climate is classified using the Köppen classification system to be cold semi-arid. The boneyard location has an average annual rainfall of 13.7 in., average annual snowfall of 37 in., an average high temperature of 89 °F in July and average low temperature in January of 19 °F. Figure F-16 shows the boneyard and ties with minor abrasion.

Figure F-16: Ties with minor abrasion, Boneyard #5

F.5.1 Tie Visual Observations

The nearby track carries large quantities of high-value commodities annually and is economically important to the railroads. Per the local road master, the track receives regular maintenance and has good ballast. The boneyard ties had only minor bottom-tie abrasion. Figure F-17 shows different ties with minor abrasion.

Figure F-17: Ties with minor abrasion, Boneyard #5

F.5.2 Tie Measurements

Tie thickness measurements were made during the visit, Figure F-18.

Figure F-18: Abrasion measurement, Boneyard #5

Table F-2: Tie thickness measurement data, Boneyard #5

Location	Design thickness at location (in.)	Measured thickness (in.)	Estimated wear (in.)
Tie End	8.1875	7.5	0.6875
Tie end	8.1875	7.75	0.4375

F.6 Boneyard #6: West

Researchers visited a boneyard in the U.S. West along the side of a track in October 2016. The ties were found in a curve in a canyon, as shown in Figure F-19. These ties were manufactured in 1986. The track had a 24-in. center-to-center tie spacing. The track speed was 35 mph. The local climate is classified as cold semi-arid. This location has an average annual rainfall of 13.7 in., an average annual snowfall of 37 in., an average high temperature of 89 °F in July and an average low temperature in January of 19 °F. Figure F-20 shows a satellite view of this location from Google Earth.

Figure F-19: Discarded ties on the side of the track, Boneyard #6

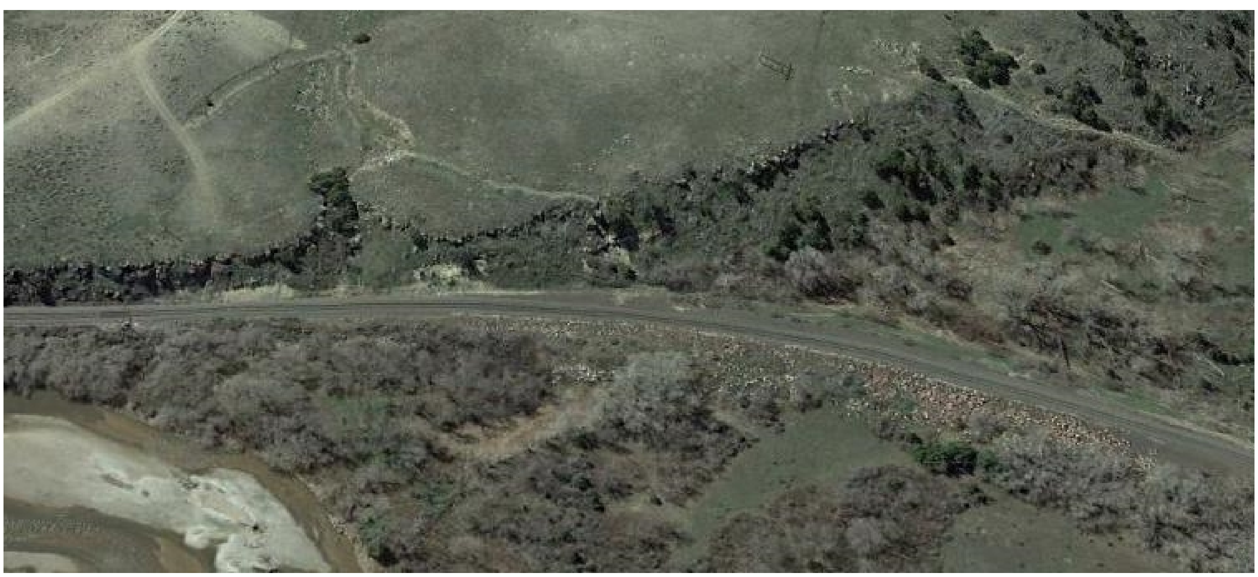

Figure F-20: View of Boneyard #6 from Google Earth

F.6.1 Tie Visual Observations

One tie examined had severe abrasion damage on one end, as shown in Figure F-21. The rest of the ties had no abrasion damage or some minor abrasion damage with corner rounding. Some concrete ties had minor center-binding cracking. The track was in very good condition with good ballast thickness under the ties and proper drainage. Some dry grass was seen at the site, indicating low moisture availability on-site. The dry climate likely contributed to the low numbers of abraded ties at this site.

Figure F-21: Highly abraded concrete tie, Boneyard #6

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ASTM	American Society for Testing and Materials
ATIP	Automated Track Inspection Program
FRA	Federal Railroad Administration
HC1	Hydrochloric Acid
KSU	Kansas State University
PTC	Positive Train Control
UPV	Ultrasonic Pulse Velocity
UBM	Under-Ballast Mats
UTP	Under-Tie-Pads
UF	University of Florida