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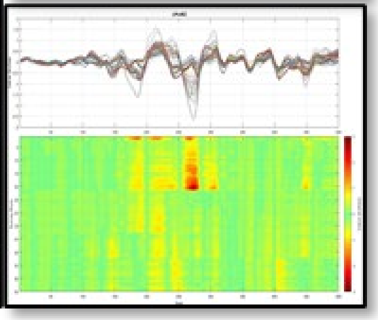
Washington, DC 20590**

Fouled Ballast Waiver Operations and Results



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14. ABSTRACT
Current regulations require locations of noncompliant ballast to be remediated within 30 days or to be taken out of service, regardless of track class. In 2013, the Association of American Railroads (AAR) applied for a waiver to the current regulations that proposed a track class specific approach to managing noncompliant ballast. In 2015, the Federal Railroad Administration (FRA) granted the waiver subject to certain conditions including weekly track geometry measurements. The waiver also initiated a research project to investigate the behavior of reduced performance ballast. BNSF Railway (BNSF) operated safely throughout the waiver period on 340 route miles of its Creston and St. Joseph subdivisions from June 12, 2017, to January 31, 2019. Researchers observed a significant variation in track performance at fouled ballast locations—a strong argument for a performance-based rule for managing noncompliant ballast. The results presented in this report are specific to the conditions on the designated waiver territory which was posted as track class 4 and carried over 100 million gross tons (MGT) of traffic per year. Future projects could be conducted on territory with different traffic, weather conditions, and types of fouling materials.

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Fouled ballast performance, track geometry, degradation, trending, long-term wayside monitoring, waiver operations, enforcement modes, track, Autonomous Track Geometry Measurement System, ATGMS, track

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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)

[(9/5) y + 32] °C = x °F

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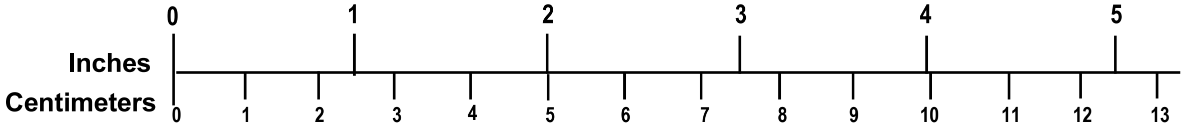

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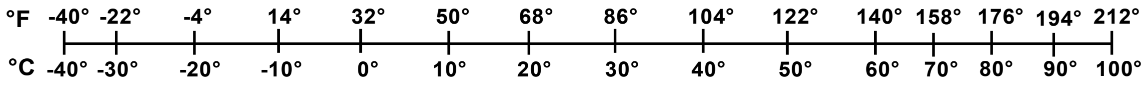

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This project would not have been possible without the help received from BNSF Railway (BNSF). While operating under the fouled ballast waiver, BNSF field personnel on the designated territory took on additional duties and responsibilities including:

- Operating under a different enforcement mode for fouled ballast
- Additional reporting
- Frequent hand measurements at fouled ballast sites
- Recording locations and lengths of new and existing fouled ballast

BNSF organized training sessions for its field track inspectors to:

- Explain the requirements of the weekly compliance procedure and describe field forms
- Introduce the weekly track geometry safety reports

BNSF field and Technical Research and Development (TR&D) personnel also provided invaluable support to the research activities. TR&D personnel assisted with the instrumentation of the long-term wayside monitoring sites during installation and track maintenance. BNSF personnel also supported other tests related to the joint research project such as static vertical loading tests with the DOTX 218.

BNSF was also responsible for the movements of the FRA's DOTX 225 and DOTX 226 Autonomous Track Geometry Measurement System (ATGMS) cars and supported vehicle maintenance by ENSCO, Inc. at the Hobson Yard in Lincoln, NE.

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Executive Summary

This report details the results of operating under a waiver to the current Federal Railroad Administration (FRA) regulations concerning fouled (failed) noncompliant ballast. The results are from the waiver period June 12, 2017, to January 31, 2019, and from post waiver monitoring through early January 2020.

The current regulations require locations of noncompliant ballast to be remediated within 30 days or to be taken out of service, regardless of track class. The current definition of compliant ballast requires inspectors to make decisions based on experience and local knowledge and relies on overall observations of track performance under load.

The Association of American Railroads applied for the waiver in December 2013. The request identified a new approach to managing noncompliant ballast that was track class specific and removed the 30-day requirement. In November 2015, FRA's Safety Board granted the waiver subject to certain conditions including weekly track geometry measurements and analysis at locations with noncompliant ballast. The waiver also initiated a research project to investigate the behavior of reduced performance ballast.

FRA's Office of Research, Development and Technology contracted with ENSCO, Inc. to coordinate the research activities, and analyze and document the results. The John A. Volpe National Transportation Systems Center provided technical guidance and assisted with data analysis. The University of Illinois at Urbana-Champagne (UIUC) collected and analyzed data at six long-term wayside monitoring sites. Instrumentation Services, Inc. assisted UIUC with instrumentation at the wayside monitoring sites.

Burlington Northern Santa Fe Railway (BNSF) operated safely throughout the waiver period on 340 route miles of its Creston and St. Joseph subdivisions. The waiver territory was located in FRA Region 6. The waiver conditions resulted in increased track maintenance to avoid temporary speed restrictions and regulatory monitoring to control risk.

The waiver conditions applied to locations of fouled ballast longer than 10 feet. Analysis of track geometry measurements showed similar degradation rates for fouled ballast locations longer and shorter than 10 feet. Some fouled ballast locations shorter than 10 feet were found to have higher track geometry degradation rates than those at locations longer than 10 feet.

The waiver threshold for vertical profile measured from a 62-foot chord (Profile 62) on track class 4 was found to be adequate. Some fouled ballast locations degraded rapidly, but the frequent geometry measurements provided the data necessary to identify them and schedule timely remediation.

Significant variation in track performance was observed at fouled ballast locations. The variation did not appear to be related to tie type or the properties of the fouling material. The variation in track performance is a strong argument in favor of a performance-based rule for managing noncompliant ballast.

The results presented in this report are specific to the conditions on the designated waiver territory which was posted as track class 4 and carried over 100 million gross tons of traffic per year. The track was mostly continuously welded rail on both concrete and timber ties. The waiver period covered weather typical of all four seasons in Missouri, Iowa, and Nebraska.

Further work is needed to evaluate thresholds for track classes other than class 4 and for track geometry parameters other than Profile 62. Future projects could be conducted on territory with different weather conditions and types of fouling materials.

1. Introduction

This report describes operations under a waiver from noncompliant ballast regulations and the results of a study into the behavior of reduced performance ballast. In June 2015, the Federal Railroad Administration (FRA) contracted with ENSCO, Inc. to support the work and write this report.

ENSCO partnered with the University of Illinois at Urbana-Champaign (UIUC) and Instrumentation Services, Inc. for this effort. Research activities were performed in cooperation with the John A. Volpe National Transportation Systems Center (Volpe) and assisted by personnel from the host railroad Burlington Northern Santa Fe Railway (BNSF) and FRA Region 6 track inspectors.

The fouled ballast waiver ran from June 2017 through January 2019. FRA and BNSF inspection vehicles made weekly track geometry measurements. Weekly track geometry measurements using FRA Automated Track Inspection Program (ATIP) inspection vehicles continued as part of post-waiver monitoring through early January 2020. In addition, researchers performed wayside monitoring at six instrumented sites throughout the waiver period until April 2021.

1.1 Background

The current regulation concerning ballast is defined in Title 49 Code of Federal Regulations § 213.103–Ballast; general, of FRA's Track Safety Standards (Federal Railroad Administration, 2013). In addition to requiring the ballast to sustain loads and maintain track geometry, it requires ballast to provide adequate drainage for the track. FRA inspectors use these requirements, guidance from FRA's compliance manual (Federal Railroad Administration, 2018), and associated track conditions to determine when ballast is noncompliant and therefore defective.

Fouling material in the ballast is the principal cause of noncompliant ballast. It can prevent the adequate drainage required by the regulation. Fouling material can come from above (e.g., spillage from rail cars or blown in from surrounding property), from internal breakdown of ballast particles, and from infiltration from the subgrade below.

The regulations consider a ballast defect as "non-class specific." This means it is a defect regardless of track class. Remedial action for this type of defect is not specified. Some other types of defects in the regulations are "class specific." They depend on track class and may be a defect at one class of track but not at a lower class. For example, a Warp 62 of 2.25 inches is a defect on track class 2, but not on track class 1.

In 2013, the Association of American Railroads (AAR) filed a petition for a waiver from certain provisions of the ballast regulation (Association of American Railroads, 2013). AAR's position was that the current regulation is vague and FRA's Compliance Manual does not contain an objective standard. The waiver would allow the evaluation of a class specific and objective approach to managing ballast defects. FRA assigned the request as Docket Number FRA-2013-0137.

In 2015, FRA's Safety Board granted AAR a waiver from 49 CFR § 213.103 (Federal Railroad Administration, 2015). FRA's Safety Board granted the requested relief for 18 months until

January 31, 2018. The waiver was subsequently extended for a further 12 months through January 31, 2019 (Federal Railroad Administration, 2017).

The FRA Safety Board's conditions for the waiver included a requirement to follow a Reduced-Performance Ballast Plan. This plan described how data on track behavior was to be collected during the waiver period and subsequently analyzed.

1.2 Objectives

The waiver to the current ballast regulation had two principal objectives:

1. To monitor and maintain safe railroad operations under a class specific and objective approach to managing ballast defects
2. To research track behavior when the performance of the ballast is reduced

The results were intended to answer the following:

a. Where should fouled ballast specific geometry limits apply? Is the 10-foot criterion included in the waiver appropriate?

b. What should the geometry limits for fouled ballast be? Are the geometry limits included in the waiver appropriate?

c. Are there other considerations and safety implications?

1.3 Overall Approach

The overall approach was to implement the requirements of the waiver at designated fouled ballast locations and measure the track behavior through complete ballast degradation cycles without exceeding safety thresholds. The data gathered included track geometry measurements, track photographic images, and Ground Penetrating Radar (GPR) measurements. Researchers performed wayside monitoring at six selected sites. They also collected and analyzed some samples of fouled ballast material. Insights from regional FRA track inspectors and local railroad staff were also incorporated.

1.4 Scope

The scope of the work reported here was restricted to the subdivisions to which the waiver was applied. Thus, the results are specific to the type of operations, track construction, geography and climatic conditions in those areas.

1.5 Organization of the Report

The rest of this report is organized as follows:

- Section 2 gives details of the waiver and its conditions. It also describes the reduced performance ballast research project.
- Section 3 describes railroad operations during the waiver period including the procedure developed to ensure safe operations and data collection.
- Section 4 presents the results of the reduced performance ballast research project.
- Section 5 presents results of long-term wayside data collection and analysis.

- Section 6 provides a discussion and gives recommendations for further work.
- Section 7 makes overall conclusions
- Appendix A through C provide additional data and results.

2. Fouled Ballast Waiver Details

The current regulation for ballast is codified as Title 49 Code of Federal Regulations (CFR) § 213.103–Ballast; general. This non-class specific rule requires defective track taken out of service if not repaired within 30 days. Monitoring of complete ballast degradation cycles required relief from the current ballast requirements. FRA granted the relief through formal process defined in FRA's Rules of Practice (Federal Railroad Administration, 2009).

2.1 Current Regulation

The current regulation for ballast (49 CFR § 213.103–Ballast; general) and many other non-class specific rules (e.g., 49 CFR § 213.33–Drainage) are sets of requirements necessary for safe train operations. The current regulation reads:

"Unless it is otherwise structurally supported, all track shall be supported by material which will—

(a) Transmit and distribute the load of the track and railroad rolling equipment to the subgrade;

(b) Restrain the track laterally, longitudinally, and vertically under dynamic loads imposed by railroad rolling equipment and thermal stress exerted by the rails;

(c) Provide adequate drainage for the track; and

(d) Maintain proper track crosslevel, surface, and alinement."

The precondition for this regulation is that the track is supported by material. The nature of the material (or ballast) supporting the track follows in four parts. The first part (a) states that it must transmit and distribute the load to the subgrade. This generally presumes a competent subgrade to distribute the load to and a ballast material with adequate strength to transmit the load.

The second part of the rule (b) states that the ballast must restrain the track laterally, longitudinally, and vertically under dynamic loads and thermal stress. In addition to transmitting the load to the subgrade, the ballast should retain the track in its intended position without excessive deformation. This requires adequate ballast stiffness.

The third part of the rule (c) states that ballast should provide adequate drainage. Since track is an open structure allowing precipitation to enter, this requires ballast with adequate hydraulic conductivity to drain water (from precipitation and infiltration from the subgrade) away from the track.

The fourth part of the rule (d) requires that ballast maintains proper track geometry. This requires an inherent stability of the track structure with limited settlement that could cause track geometry variations.

The first three parts of the rule (a, b, and c) relate to the structural design of ballast layer thickness and properties necessary to limit track settlement and the formation of track geometry variations. Inadequate design, as defined by inability to meet the requirements of parts a, b, and c, means that the track structure might not be able to withstand the applied load. Track geometry variability (part d) is evidence of inadequate design or improper maintenance.

2.2 Ballast Waiver Request

In December 2013, the AAR, on behalf of itself and its member railroads, filed a petition for a waiver from certain provisions of the ballast regulation (Association of American Railroads, 2013). The request included a new definition of noncompliant ballast and proposed a class specific management of track that met this definition.

If granted, the waiver would be applied to designated subdivisions on BNSF's railway.

2.3 Ballast Waiver Conditions

In November 2015, FRA's Safety Board granted the waiver subject to certain conditions, summarized as follows:

1. A BNSF designee serves as a record administrator and point-of-contact to FRA.
2. BNSF designates the waiver territory and informs FRA about the traffic on the designated territory.
3. Noncompliant ballast is defined as conditions in which track drainage in mainline or controlled siding track is impeded for 10 feet or more where the ability of the track structure to maintain an adequate margin of safety is impaired by the presence or evidence of water, ballast fines, or other material.
4. When noncompliant ballast is discovered during a track inspection, the ballast must be cleaned or replaced, otherwise track speed must be reduced in accordance with class-specific safety thresholds. Class 1 track may remain at class 1 speeds.
5. Track geometry at all noncompliant ballast locations must be measured weekly until the ballast is cleaned or replaced, or the waiver period ends.
6. The track geometry measurement data for identified instances of noncompliant ballast must be provided to FRA.
7. AAR, BNSF, FRA's Office of Research, Development and Technology (RD&T), and FRA's Office of Railroad Safety will enact a Reduced-Performance Ballast plan. Upon completion, the results and findings must be reported to FRA and will form the basis for any further recommendations by the AAR.
8. FRA inspectors will monitor ballast performance and assess the safety risk. After consultations with regional and headquarters' managers, the inspectors will have final decision-making authority over continued train operations and train speeds.

The waiver applied for 18 months and expired on January 31, 2018. It allowed AAR to request an extension in September 2017, which was granted in October 2017, extending the waiver through January 31, 2019.

The waiver approval letter included the Reduced-Performance Ballast plan referred to in item 7 above. That plan proposed the class-specific track geometry thresholds shown in Table 1.

Table 1. Fouled Ballast Waiver Track Geometry Thresholds

Parameter	Class 1	Class 2	Class 3	Class 4	Class 5
Alinement 31	N/A	N/A	1 C	0.5 C	0.375 C
Alinement 62	3	1.75	1.5	0.75 T 0.625 C	0.5625 T 0.5 C
Narrow Gage	56	56	56	56	56
Wide Gage	57.75	57.5	57.5	57.25	57.25
Profile 62	2.25	2	1.5	1.25	1
Runoff 31	3	2	1.5	1	1
Crosslevel	2	1.75	1.25	1	0.5
Warp 62	2.25	2	1.75	1.5	1.5
Twist 31	1.5	1.25	1	0.75	0.75

Note: T – Tangent track (curvature < 0.25 degrees), C – Curved track (curvature ≥ 0.25 degrees)

The limits in Table 1 are intentionally more restrictive than those defined for track geometry in FRA's Track Safety Standards (Federal Railroad Administration, 2013). This ensured continued safety during the waiver by anticipating the accelerated deterioration of geometry under fouled ballast conditions.

The definition of noncompliant ballast in the Reduced-Performance Ballast plan (i.e., item 3 above) uses a distance of 10 feet or more. This length was derived from calculations in AAR's waiver petition that considered the length of track that would influence the behavior of a standard truck.

2.4 Designated BNSF Territory

BNSF designated sections of the Creston and St. Joseph subdivisions in the Heartland division for operation under the fouled ballast waiver. The two sections in the waiver territory were:

- Creston: Milepost (MP) 58.87 to MP 0, and MP 475.0 to MP 393.5[1]
- St. Joseph: MP 7.99 to MP 207.0

The waiver territory, shown in Figure 1, totals approximately 340 route miles. It is predominantly posted as class 4 track and consists of a mix of timber and concrete ties with continuously welded rail. Both subdivisions contain significant portions of double main track and controlled sidings, bringing the total track miles in the waiver territory to approximately 506 miles.

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[1] Although there is a gap in the Creston mileage the section is continuous.

Both subdivisions carry over 100 million gross tons (MGT) yearly and BNSF designates it as hazmat and crude oil routes. Creston subdivision is also a passenger traffic route hosting Amtrak's California Zephyr service. The location of the territory is within FRA Region 6.

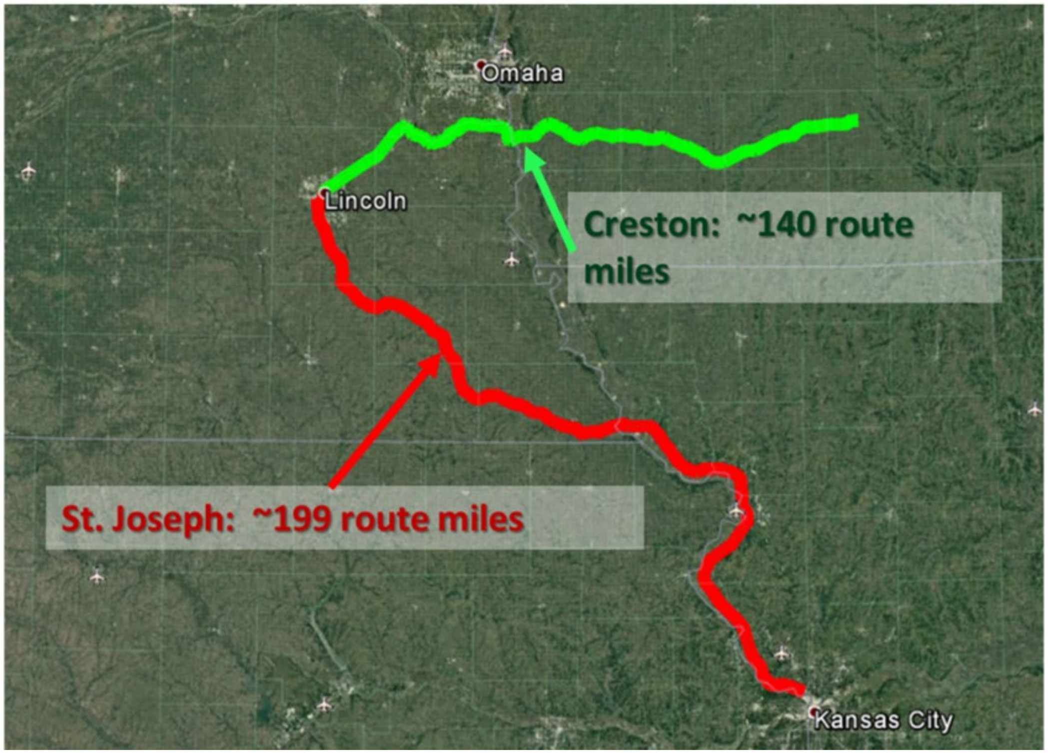

Figure 1. BNSF Designated Ballast Waiver Territory

2.5 Reduced Performance Ballast Research

The Reduced-Performance Ballast plan included in FRA's waiver called for a cooperative research project between BNSF and FRA. In 2015, FRA assembled a team from the government, BNSF, and contractors for this effort. The team members and roles were:

- FRA Office of Research, Development & Technology – Responsible for the overall management of the research project
- FRA Office of Safety Region 6 – Assisted with field inspections, provided locations of fouled ballast and enforced safety on the waiver territory
- Volpe – Provided technical guidance and performed an analysis of track geometry data
- ENSCO – Coordinated research activities with all the stakeholders, maintained a list of fouled ballast locations, coordinated the collection of track geometry measurements, performed track geometry data analysis and weekly reporting to enforce waiver conditions and conducted field investigations
- UIUC – Collected data at six long-term wayside monitoring sites and performed its analysis
- Instrumentation Services, Inc. – Assisted UIUC with instrumentation at the wayside monitoring sites

- BNSF – Hosted the research project and operated under the waiver on two of its subdivisions with field staff supporting the installation and management of instrumentation at monitoring locations

3. Railroad Operations Under the Fouled Ballast Waiver

The reduced performance ballast research team developed a detailed procedure to ensure compliance with the waiver conditions. The procedure ensured safe operations and collection of data to meet the objectives of the reduced performance ballast plan. The weekly compliance procedure was in effect from June 12, 2017, to January 31, 2019. Figure 2 summarizes this in the flow chart.

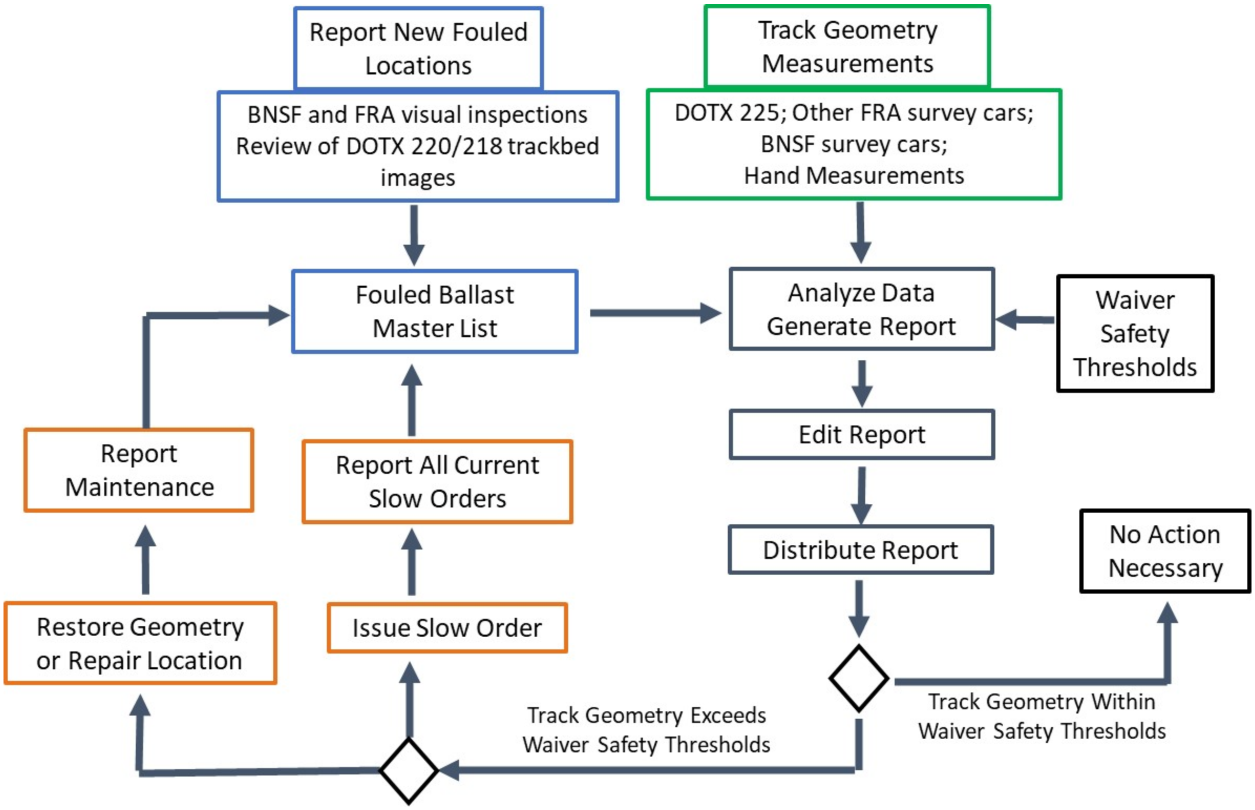

Figure 2. Fouled Ballast Waiver Weekly Compliance Procedure

The following four subsections describe the four different colored regions of Figure 2.

3.1 Fouled Ballast Master List

A central component of the weekly compliance procedure was the master list of fouled ballast locations.[2] The list included the following information for each location:

- ID – A sequential number
- Entry date – When added to the list

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[2] Although the waiver conditions applied to fouled ballast locations longer than 10 feet, the research team agreed to keep records of, and collect geometry data at, all fouled ballast locations, even if shorter than 10 feet. This information allowed the research team to evaluate whether the 10-foot length criterion was appropriate.

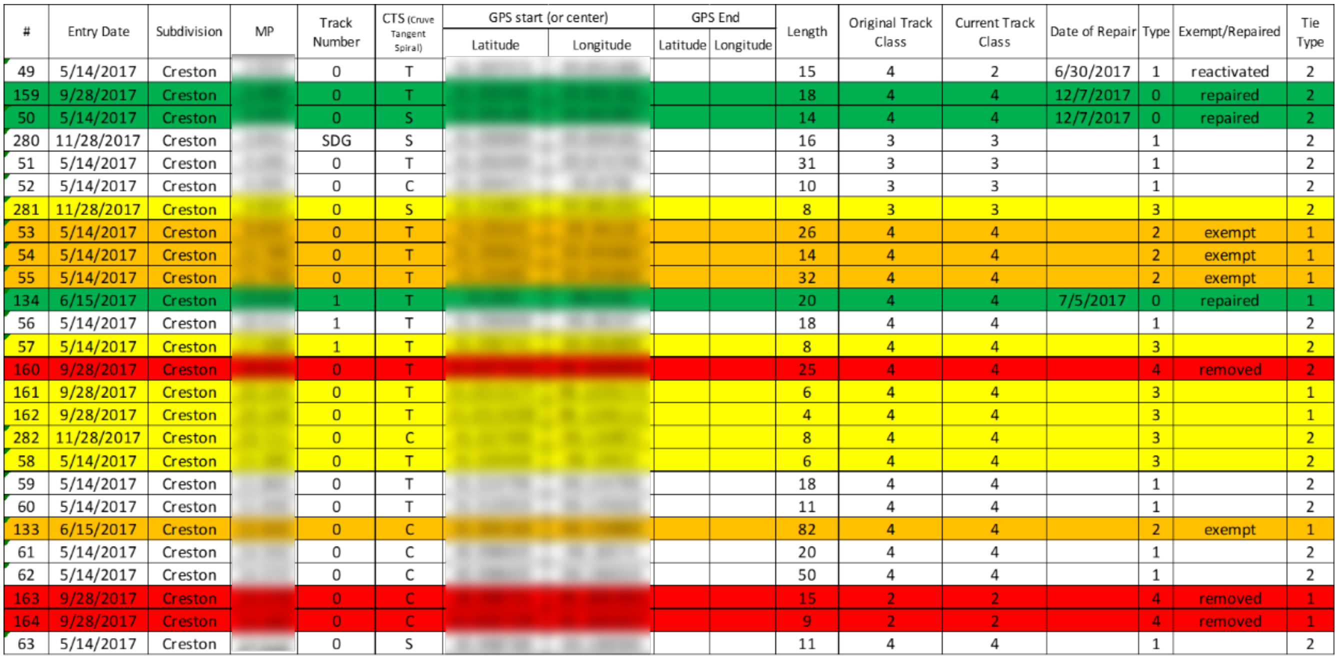
- Location information – Subdivision, Milepost, Track Number
- GPS coordinates of the center of the location
- Curve, Tangent or Spiral
- Length of fouling in feet
- Original posted track class and current track class based on applied slow orders
- Date when remedial action was taken
- Type (see below) and status
- Tie type
- Additional information and notes

ENSCO maintained the list and made it available to all stakeholders including BNSF field personnel. It was initially populated from visual inspections conducted by FRA Region 6 track inspectors in April and May 2017. Subsequently, ENSCO added any new fouled ballast locations discovered by BNSF or FRA Region 6 track inspectors during routine inspections. Track bed images from inspection vehicles were also used to identify fouled ballast locations.

The locations recorded in the master list were divided into four types:

- Type 0 – Green: Locations that were remedied and where fouling was removed
- Type 1 – White: Fouled ballast locations 10 feet or longer per the waiver definition
- Type 2 – Orange: Fouled ballast locations 10 feet or longer per the waiver definition but exempt from the hand measurement requirement due to their proximity to grade crossings
- Type 3 – Yellow: Fouled ballast locations shorter than 10 feet
- Type 4 – Red: Locations entered in the master list erroneously and removed from consideration

Figure 3 shows example entries in the master list.



#	Entry Date	Subdivision	MP	Track Number	CTS (Cruve Tangent Spiral)	GPS start (or center)		GPS End		Length	Original Track Class	Current Track Class	Date of Repair	Type	Exempt/Repaired	Tie Type
						Latitude	Longitude	Latitude	Longitude							
49	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			15	4	2	6/30/2017	1	reactivated	2
159	9/28/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			18	4	4	12/7/2017	0	repaired	2
50	5/14/2017	Creston	[redacted]	0	S	[redacted]	[redacted]			14	4	4	12/7/2017	0	repaired	2
280	11/28/2017	Creston	[redacted]	SDG	S	[redacted]	[redacted]			16	3	3		1		2
51	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			31	3	3		1		2
52	5/14/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			10	3	3		1		2
281	11/28/2017	Creston	[redacted]	0	S	[redacted]	[redacted]			8	3	3		3		2
53	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			26	4	4		2	exempt	1
54	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			14	4	4		2	exempt	1
55	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			32	4	4		2	exempt	1
134	6/15/2017	Creston	[redacted]	1	T	[redacted]	[redacted]			20	4	4	7/5/2017	0	repaired	1
56	5/14/2017	Creston	[redacted]	1	T	[redacted]	[redacted]			18	4	4		1		2
57	5/14/2017	Creston	[redacted]	1	T	[redacted]	[redacted]			8	4	4		3		2
160	9/28/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			25	4	4		4	removed	2
161	9/28/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			6	4	4		3		1
162	9/28/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			4	4	4		3		1
282	11/28/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			8	4	4		3		2
58	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			6	4	4		3		2
59	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			18	4	4		1		2
60	5/14/2017	Creston	[redacted]	0	T	[redacted]	[redacted]			11	4	4		1		2
133	6/15/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			82	4	4		2	exempt	1
61	5/14/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			20	4	4		1		2
62	5/14/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			50	4	4		1		2
163	9/28/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			15	2	2		4	removed	1
164	9/28/2017	Creston	[redacted]	0	C	[redacted]	[redacted]			9	2	2		4	removed	1
63	5/14/2017	Creston	[redacted]	0	S	[redacted]	[redacted]			11	4	4		1		2

Figure 3. Example Entries in the Master List of Fouled Ballast Locations

A location was never taken off once added to the master list. Researchers marked a location as repaired when the ballast was cleaned. It was marked as Type 4 when entered by mistake. BNSF informed ENSCO every week about the maintenance it had performed. The locations where fouling returned after ballast was cleaned were reactivated.

Researchers updated the current track class for all locations in the master list each week based on all slow orders in place on the waiver territory. BNSF sent this information to ENSCO every Friday.

ENSCO also amended the master list based on reviews of track bed images. FRA's DOTX 220/218 manned track inspection consist collected the images during its surveys of the waiver territory as part of the ATIP. Figure 4 shows highlighted an example of a fouled ballast location identified during such a review.

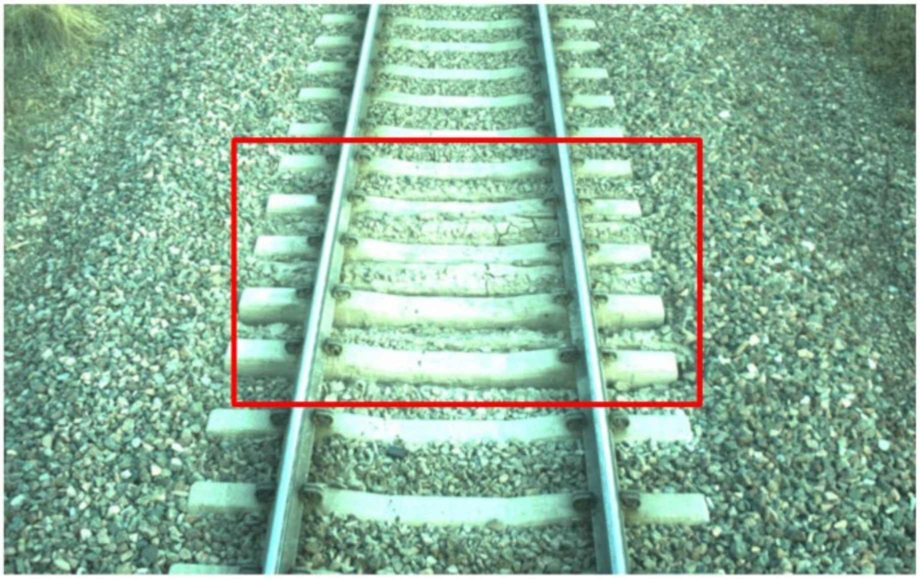


Figure 4. Fouled Ballast Location Identified in DOTX 220/218 Trackbed

At the end of the extended waiver period, the master list contained a total of 405 locations of which 184 were active (i.e., Type 1, Type 2, or Type 3).

3.2 Track Geometry Measurements

The weekly track geometry measurements served two purposes. First, they ensured compliance with the waiver. Second, they provided a large and unique dataset for analysis as part of the research project.

The waiver stipulated that track geometry at fouled ballast locations 10 feet or longer must be measured every week. The research project relied mostly on measurements collected by rail bound inspection vehicles, which are more efficient than several hundred hand measurements every week. In addition, measurement systems on rail bound vehicles produce loaded track geometry that is more consistent and repeatable than hand measurements. Consistency of the track geometry measurement was important for analysis of long-term deterioration trends.

Weekly track geometry measurements at locations shorter than 10 feet were not required. Speed restrictions or remedial action at these shorter locations were subject to individual assessment by BNSF and FRA Region 6 personnel. BNSF field personnel and FRA Region 6 track inspectors could direct protective action at fouled ballast locations of any length and any track geometry condition when those locations were perceived as safety concerns.

FRA provided its DOTX 225 and DOTX 226 for dedicated operation to collect track geometry data on the waiver territory. Both vehicles are refurbished freight box cars with a carbody mounted Autonomous Track Geometry Measurement System (ATGMS) for unmanned operations. Figure 5 shows DOTX 225.

Figure 5. DOTX 225 ATGMS Vehicle

DOTX 225 arrived at Lincoln, NE, in April 2017, where it was turned over to BNSF who was responsible for its movements over the waiver territory. Figure 6 shows two of the most common patterns of DOTX 225 surveys. The first pattern was a loop consisting of a southbound move on the St. Joseph subdivision, followed by a northbound move on St. Joseph and Napier subdivisions and an eastbound move on Creston subdivision west of Pacific Junction. The second pattern covered the Creston subdivision by eastbound and westbound moves. Occasionally the car was also routed through the Omaha and Ottumwa subdivisions. On several occasions, FRA assigned DOTX 226 to the waiver territory to allow DOTX 225 to have system upgrades without interruptions in weekly measurements.

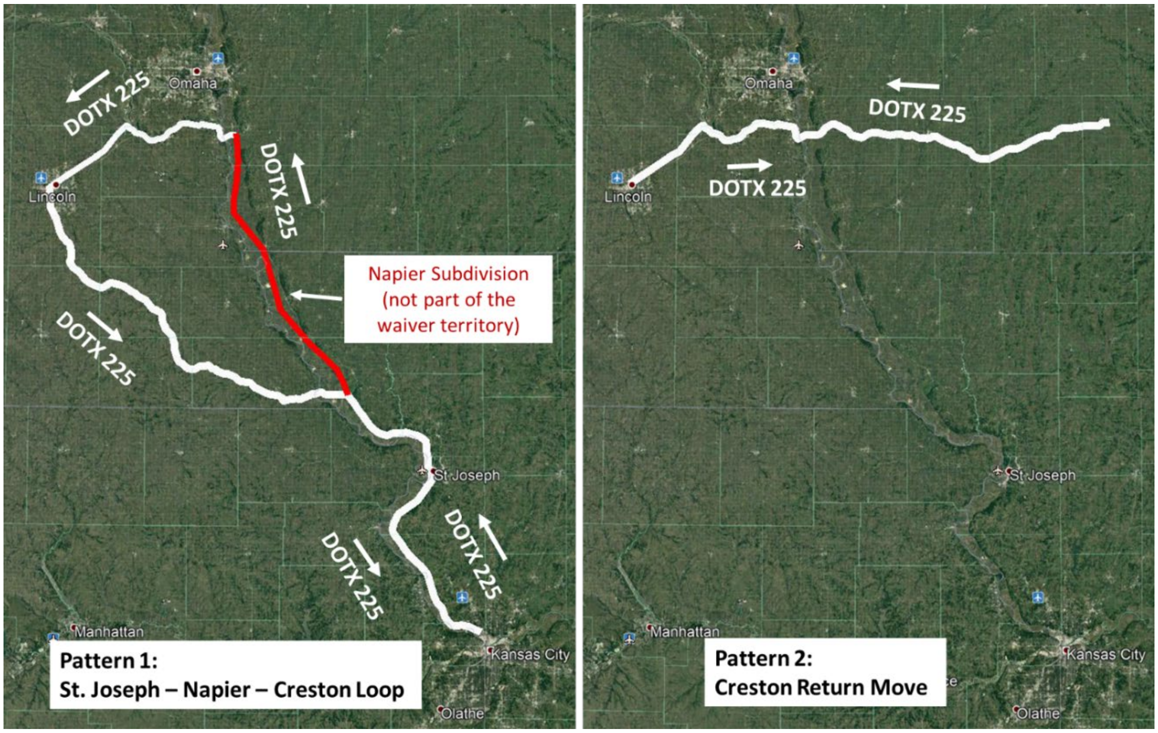


Figure 6. DOTX 225 Survey Patterns

DOTX 225 and DOTX 226 provided approximately 80 percent of the weekly track geometry measurements required by the waiver. Figure 7 shows a weekly summary of the miles surveyed by the two vehicles since they began operation over the waiver territory. The vehicles surveyed over 68,000 miles between April 2017 and January 2020, over 47,000 of which were during the waiver period. Weekly miles surveyed varied for operational reasons.

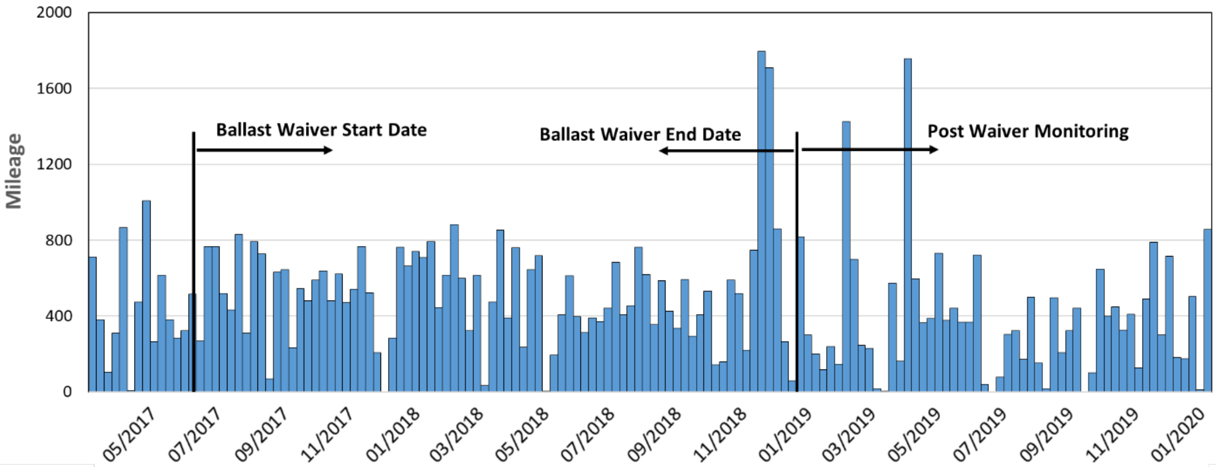
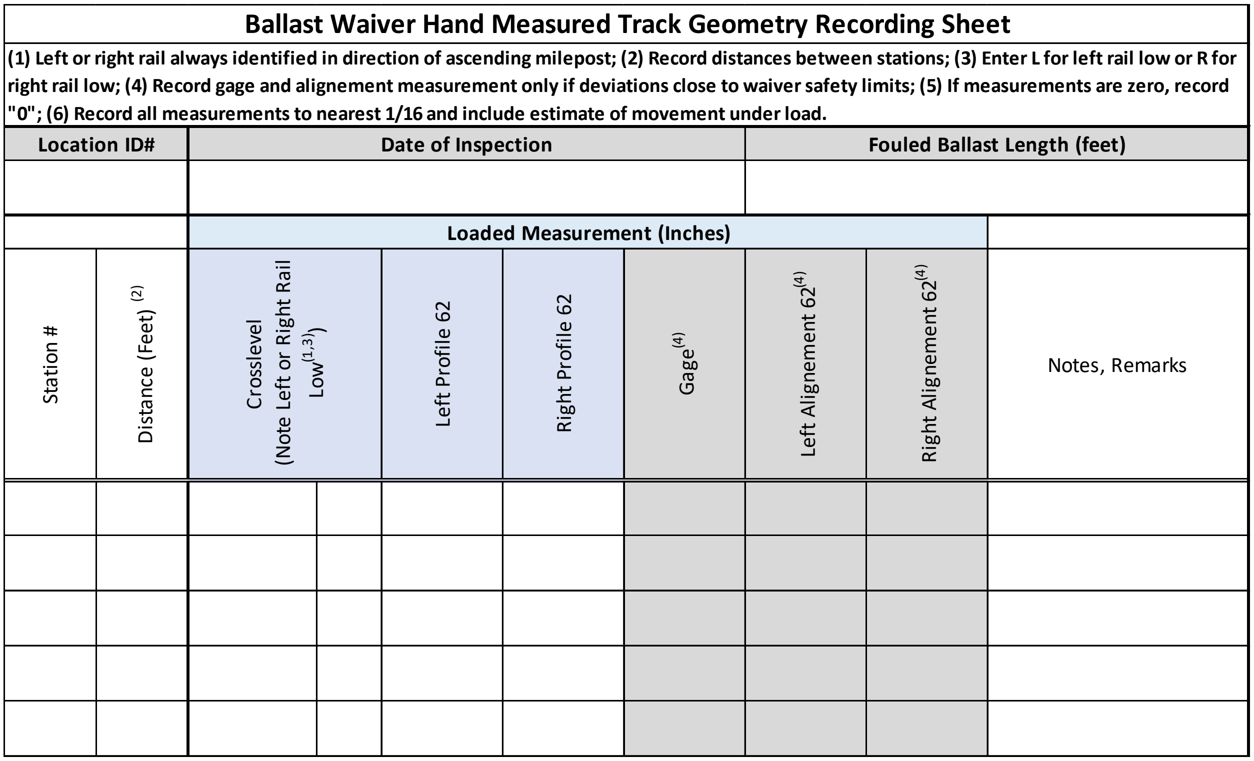


Figure 7. Weekly Summary of DOTX 225 and DOTX 226 Survey Mileage

The track geometry measurements collected by BNSF and other FRA manned and unmanned inspection vehicles complemented the DOTX 225 and DOTX 226 data. BNSF inspection vehicles collected 15,300 miles of measurements over the waiver territory between April 2017 and January 2019. BNSF delivered the survey data to ENSCO using an established data transfer protocol on Monday and Thursday every week.

FRA's DOTX 220/218 manned comprehensive inspection consist, DOTX 219 manned inspection vehicle as well as DOTX 221 unmanned vehicle all surveyed portions of the waiver territory as part of a regular ATIP schedule. DOTX 220/218 collected additional data such as Gage Restraint Measurement System (GRMS), GPR, and track imagery and performed additional tests.

Despite heavy coverage of the waiver territory by inspection vehicles, some fouled ballast locations were missed each week due to various operating conditions and restraints. BNSF field personnel took hand measurements if the missed locations were 10 feet or longer, marked as active, and not near a grade crossing. The research team developed a form, shown in Figure 8, to record hand measured track geometry consistently. BNSF provided the hand measurements to ENSCO every week.



Ballast Waiver Hand Measured Track Geometry Recording Sheet

(1) Left or right rail always identified in direction of ascending milepost; (2) Record distances between stations; (3) Enter L for left rail low or R for right rail low; (4) Record gage and alignement measurement only if deviations close to waiver safety limits; (5) If measurements are zero, record "0"; (6) Record all measurements to nearest 1/16 and include estimate of movement under load.

Location ID#	Date of Inspection	Fouled Ballast Length (feet)

		Loaded Measurement (Inches)							
Station #	Distance (Feet) (2)	Crosslevel (Note Left or Right Rail Low(1,3))		Left Profile 62	Right Profile 62	Gage(4)	Left Alignement 62(4)	Right Alignement 62(4)	Notes, Remarks

Figure 8. Hand Measured Track Geometry Form

3.3 Weekly Analysis and Reporting

The research team compiled all track geometry measurements, current slow orders, reports of new locations, and remedial actions. ENSCO analyzed the information every week to assess compliance with the waiver safety thresholds and other requirements. As a first step, the master list was updated based on a list of current slow orders, reports of new locations, and remedial actions provided by BNSF. Track geometry datasets, including hand measurements, were aligned and processed to identify areas of fouled ballast with concerning track geometry and locations not measured in the weekly reporting period. Manual review of the results removed locations identified due to spikes or otherwise erroneous data signatures.

The outcome was a report distributed to the research team and BNSF field personnel every Monday afternoon via email covering the preceding Sunday to Saturday reporting period. The report listed four types of events:

- ALERT – Fouled ballast locations 10 feet or longer where at least one geometry parameter exceeded the waiver safety threshold. An immediate response, a speed restriction or remedial action had to be taken by BNSF.
- WARNING – Fouled ballast locations 10 feet or longer where at least one geometry parameter exceeded a level 15 percent below the waiver safety threshold.
- ADVISORY 1 – Fouled ballast locations shorter than 10 feet where at least one geometry parameter exceeded the waiver safety threshold.

- ADVISORY 2 – Fouled ballast locations of any length where at least one geometry parameter grew significantly without exceeding or approaching the waiver safety threshold.

In addition to these events the weekly reports included:

- List of fouled ballast locations 10 feet or longer and not exempt from hand measurements where track geometry was not measured by any method in the reporting period (i.e., missed locations)
- List of fouled ballast locations 10 feet or longer and not exempt from hand measurements where track geometry was not measured by any method in the last two consecutive reporting periods
- Foot-by-foot overlay and time history plots of track geometry parameters that triggered the event at reported locations
- Map of the territory with locations of reported events
- Map of the territory covered by survey vehicles and missed locations in the reporting period

3.4 Weekly Actions

BNSF acted on the weekly reports to protect locations of concern with appropriate responses (e.g., slow order or remedial action) as outlined by the waiver. Only ALERT events required immediate action. However, the waiver included WARNINGS and the two ADVISORIES to provide additional information to improve the margin of safety. In these cases, BNSF field personnel and FRA Region 6 track inspectors determined the response, if any, on a case-by-case basis.

3.5 Post-Waiver Monitoring

It is possible that the imposed safety thresholds affected the degradation observed during waiver period monitoring. For example, tighter geometry limits led to more speed restrictions and increased maintanence. Thus, the reseach team agreeed to extend track geometry and wayside monitoring through early 2020 without the waiver in place. This allowed the collection of additional data and study of degradation rates under different enforcement and operating conditions. In the post-waiver monitoring period FRA’s normal Track Safety Standards applied and inspectors treated fouled ballast as a non-class specific defect.

All reporting requirements established by the waiver ceased when it expired on January 31, 2019. A different aproach to track geometry degradation monitoring was adopted. ENSCO analyzed track geometry data on a weekly basis and identified all locations with significant degradation. The source of degradation at these locations was identified by:

- Comparison to the Waiver Master List of Fouled Ballast Locations
- Feedback from FRA Region 6 personnel
- Field visits conducted by ENSCO

- Analysis of track bed images collected by FRA’s DOTX 220/218 manned track inspection consist

Locations were characterized as:

- Fouled ballast locations
- Other degradation source (e.g., broken joint, new fill settlement)
- Unknown (i.e., where a determination could not be made)

Wayside monitoring at six long-term wayside monitoring sites described in Section 5 continued unchanged.

4. Reduced Performance Analysis and Results

ENSCO and UIUC began the research work by investigating definitions and parameters used to describe fouled ballast in the United States and abroad (Bruzek, Stark, Wilk, Thompson, & Sussmann, 2016). This confirmed the definition proposed by AAR in its waiver petition was suitable. This definition is based on visual observation of the presence or evidence of water, ballast fines, or other material originating from the track structure or from train operations.

Section 4.1 describes the method used to analyze track geometry behavior during the waiver period. A similar method was used on data from the post-waiver period. Section 4.2 gives the results of this analysis. Section 4.3 uses these results to evaluate the length of fouled ballast used in the waiver, and Section 4.4 uses them to evaluate the safety thresholds included in the waiver.

4.1 Method of Analysis

Researchers analyzed the track geometry data collected throughout the waiver period in several steps. The analysis method was applied to all locations in the master list, regardless of length.

The first step was to align the data measured on different dates and from different sources. Alignment was achieved by:

1. Using Global Positioning System (GPS) information to make coarse adjustments
2. Analyzing cross-correlation and standard deviations of differences between datasets to make fine adjustments

The second step was to remove spikes and other obvious errors in the data by filtering and manual editing. The filtering algorithm used a combination of median filters, ENSCO proprietary outlier and spike detection, and flat line detection. The filter results were reviewed to check only erroneous signatures were removed.

Figure 9 shows an example of unfiltered and unedited track geometry. Forty recordings of the mid-point offset on a 62-foot chord for the alignment of the left rail (LAlign62) are superimposed. Fouled ballast was present at this location between 200 and 300 feet.

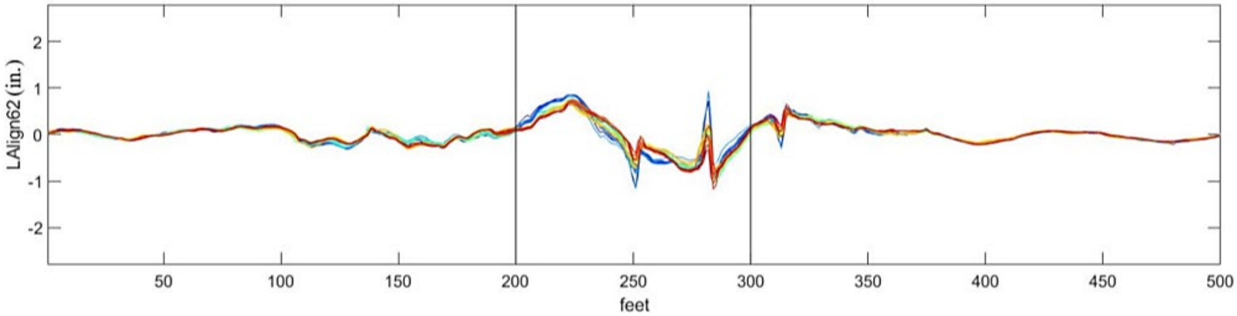


Figure 9. Example of Unfiltered and Unedited Track Geometry Data

Figure 9 shows a pattern of noise in several of the recordings. This was found to be caused by variation in measurements through a turnout. Figure 10 shows the same data after median filtering and manual editing.

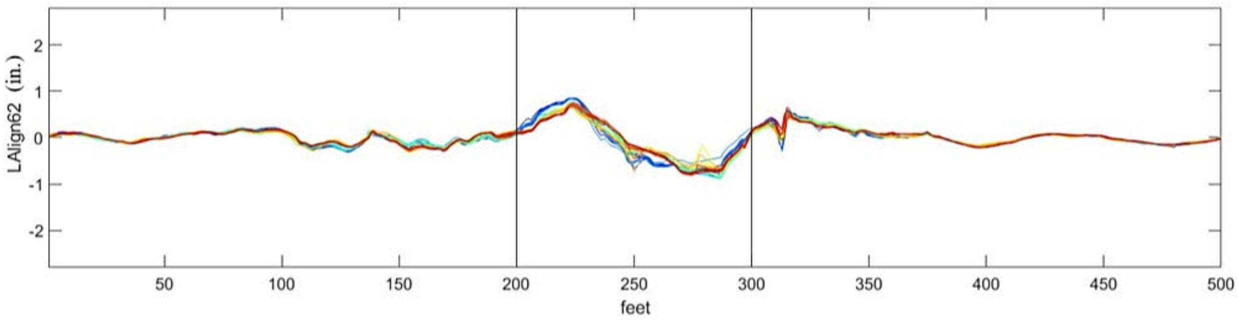


Figure 10. Example of Filtered and Edited Track Geometry Data

Figure 10 shows the noise in the original recordings has been reduced or removed by filtering and editing between 200 and 300 feet. The remaining variation between recordings could be due to real changes in track geometry during the monitoring period.

The third step in the analysis method was to measure the peak for each combination of track geometry parameter and recording. The peak was measured within a window that extended 30 feet either side of the section of fouled ballast. The peaks were then plotted against time and compared with limits in FRA's Track Safety Standards (Federal Railroad Administration, 2013) and the thresholds defined in the waiver.

Figure 11 shows an example of a track geometry peak time history. This graph plots the peaks in 80 recordings against the test date. The peaks are for the 62-foot mid-chord offset for profile of the left rail (LProf62).

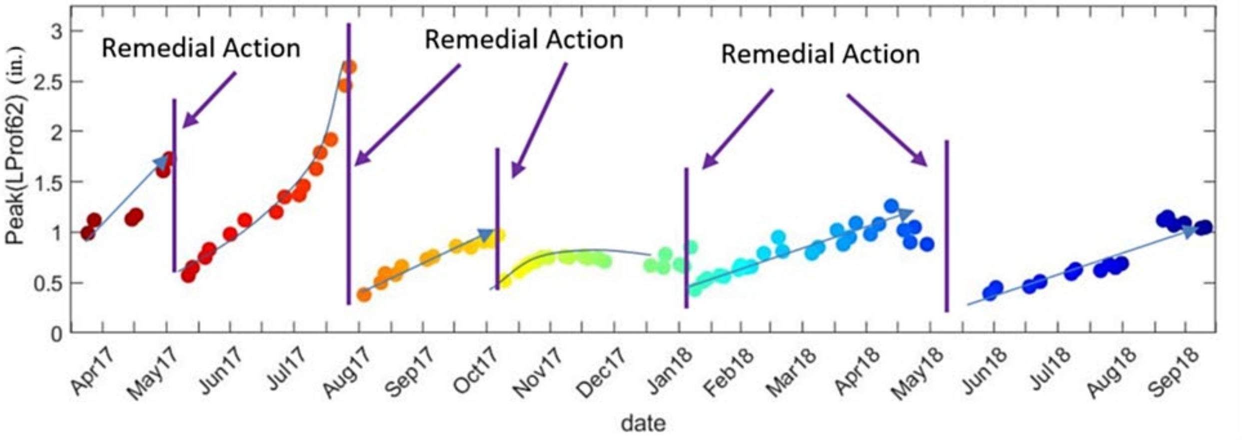


Figure 11. Example Track Geometry Peak Time History

The vertical lines in Figure 11 show the dates when remedial action was taken to improve track geometry. This example clearly shows a repeated pattern of degradation and improvement.

The fourth and final step was to quantify track geometry deterioration rates. The calculation of degradation was for the track inspection interval prior to any track geometry parameter reaching a track geometry safety limit. Figure 12 shows how track geometry deterioration rates were determined. It shows a peak time history with horizontal lines at certain safety limits and thresholds.

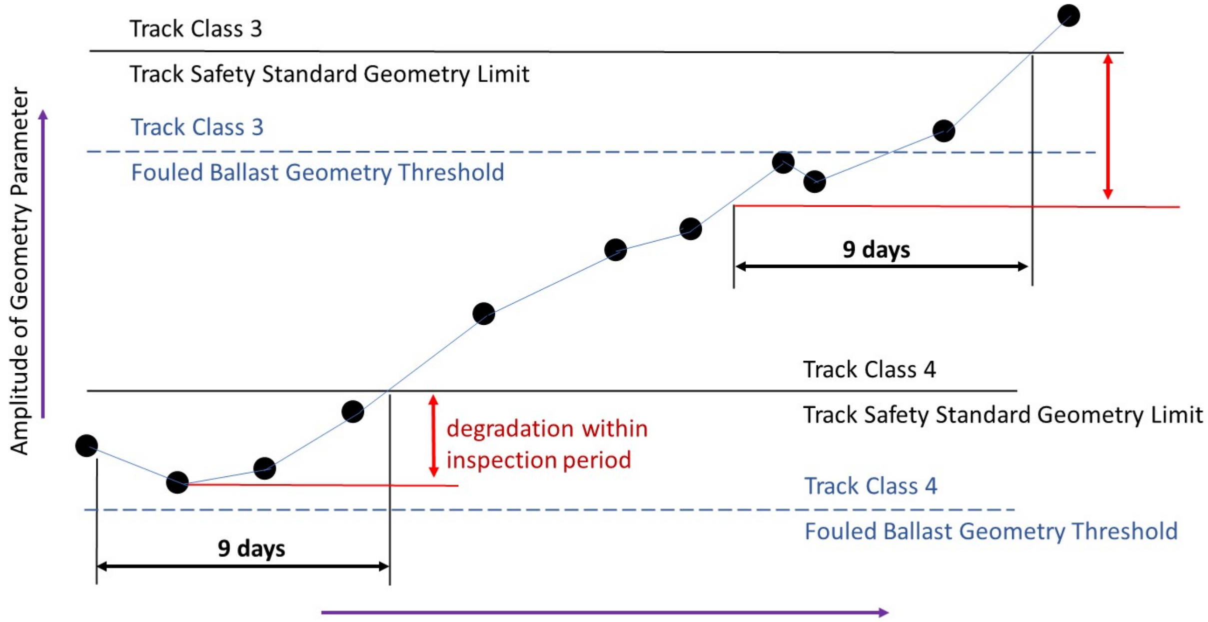


Figure 12. Determination of Track Geometry Deterioration Rates

The waiver territory is predominantly posted as track class 4 and it carries more than 10 MGT of traffic per year. From FRA's Track Safety Standards (Federal Railroad Administration, 2013) the required inspection frequency is twice weekly with at least 1 day between inspections. The maximum allowable interval between inspections is 9 days since a longer interval would not allow four inspections separated by at least a day over a 2-week period.

Figure 12 shows the peak in the track geometry parameter crossed the track class 4 safety limit sometime between the fourth and fifth recording. The estimated time this occurred is found by linear extrapolation between the fourth and fifth recorded values. The 9-day period prior to this time is shown. The degradation during the inspection period is the change from the lowest value (in this case the second recording) to the track class 4 safety limit. In this case the degradation is less than the difference between the track class 4 safety limit and the threshold set by the fouled ballast waiver.

The top right of Figure 12 shows a case when the peak in the track geometry parameter crossed the track class 3 safety limit. The lowest value in the 9 days prior to this event is found by linear interpolation between the seventh and eight recorded values. In this case the degradation is more than the difference between the track class 3 safety limit and the threshold set by the fouled ballast waiver.

As Figure 12 shows, the recorded geometry at a single location can cross more than one safety limit. Thus, although the waiver territory was posted as track class 4, the data allowed degradation to be evaluated at the safety limits for track classes 1 through 5. The results for track classes other than 4 are of interest since they allow analysis of the ballast specific thresholds proposed in the waiver. This analysis is limited because the traffic, maintenance and operations on the waiver corridor is representative of posted track class 4. The degradation rates it generates may not be typical conditions in other posted track classes. This is especially true for results observed at track class 5 safety levels. Trains at posted track class 5 territories would operate at higher speeds than on the waiver territory.

4.2 Degradation Results

Figure 13 shows the degradation results for the mid-point offset on a 62-foot chord for the profile of the left and right rails (Profile 62). These results are for the pre-waiver period from April 2017 to June 2017 and for the waiver period from June 2017 through January 2019. Figure 14 shows the degradation results for Profile 62 in the post-waiver period from January through December 2019. Similar results for the other track geometry parameters are shown in Appendix A.

Figure 13 and Figure 14 have separate charts for track classes 1 through 5. Each chart shows instances when the relevant safety limit for the track class was crossed. Color coding is used to indicate tangent, curved, or spiral track. The units of the y-axis are inches.

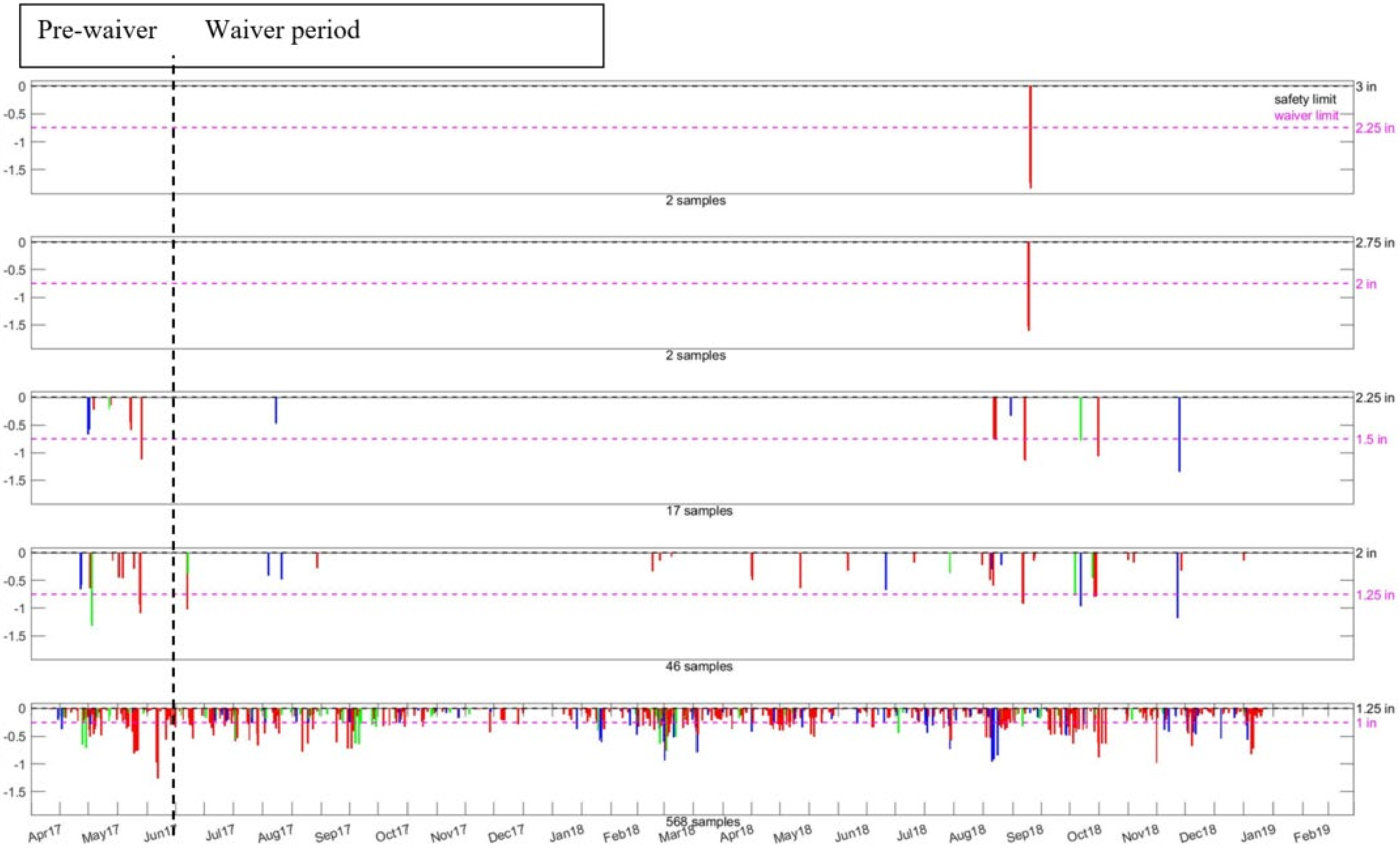


Figure 13. Degradation Results for Profile 62 During the Pre-waiver and Waiver Periods

Color Codes: Red – Tangent, Green – Curve, Blue – Spiral

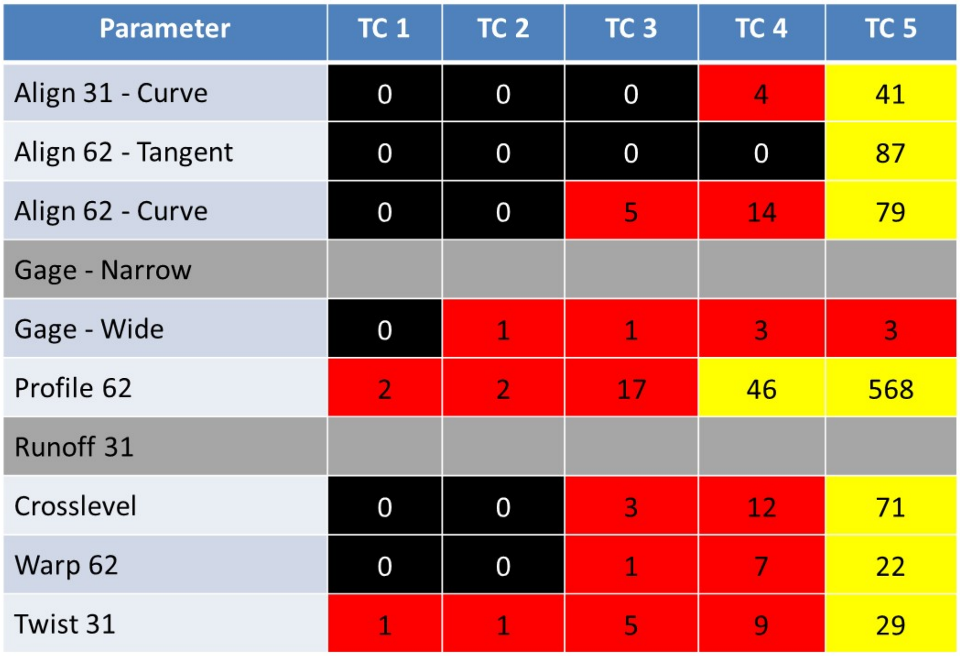
Figure 14. Degradation Results for Profile 62 During the Post-waiver Period

Color Codes: Red – Tangent, Green – Curve, Blue – Spiral

The results in Figure 13 and Figure 14 are grouped by track class. The dashed horizontal lines in these figures show the safety limit and waiver thresholds for track parameter Profile 62. Figure 13 and Figure 14 show most of the calculated degradation results occurred on tangent track. Some results were on curves and a few were on spirals. This is consistent with the lengths of tangents and curves on the waiver territory. The results show some degradation results exceeded the additional safety margin between the waiver threshold and the track safety limit.

Table 2 shows the number of degradation results for each combination of track class and geometry parameter in the pre-waiver and waiver periods. A degradation result means an instance when a given track geometry safety limit was exceeded. Black indicates no results, red indicates 1 to 20 results, and yellow indicates more than 20 results.

Table 2. Counts of Degradation Results for the Pre-waiver and Waiver Periods



Parameter	TC 1	TC 2	TC 3	TC 4	TC 5
Align 31 - Curve	0	0	0	4	41
Align 62 - Tangent	0	0	0	0	87
Align 62 - Curve	0	0	5	14	79
Gage - Narrow					
Gage - Wide	0	1	1	3	3
Profile 62	2	2	17	46	568
Runoff 31					
Crosslevel	0	0	3	12	71
Warp 62	0	0	1	7	22
Twist 31	1	1	5	9	29

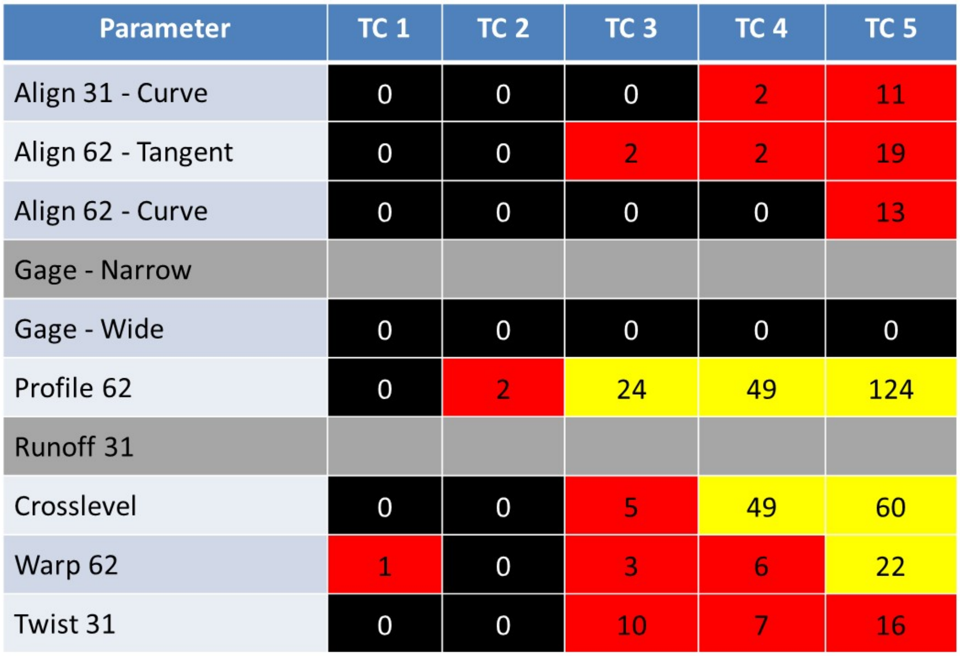
Note: TC = Track Class

Table 2 shows most results were degradation leading up to the track class 5 safety limits being exceeded. Although the data allowed these degradations to be calculated, it should be remembered that the waiver territory was posted as track class 4. Degradation for posted track class 5 territory may be different due to increased train speed.

Table 2 also shows most results were for degradation in the Profile 62 track geometry parameter. Researchers expected this since settlement caused by ballast fouling mainly affects the track's vertical position.

Table 3 shows the number of degradation results for each combination of track class and geometry parameter in the post-waiver period. The color coding is the same as in Table 2.

Table 3. Counts of Degradation Results for the Post-waiver Period



Parameter	TC 1	TC 2	TC 3	TC 4	TC 5
Align 31 - Curve	0	0	0	2	11
Align 62 - Tangent	0	0	2	2	19
Align 62 - Curve	0	0	0	0	13
Gage - Narrow					
Gage - Wide	0	0	0	0	0
Profile 62	0	2	24	49	124
Runoff 31					
Crosslevel	0	0	5	49	60
Warp 62	1	0	3	6	22
Twist 31	0	0	10	7	16

Note: TC = Track Class

In addition to the Profile 62 degradation results Table 3 shows a significant count for the crosslevel track parameter in track class 4. It is important to note that many crosslevel degradation occurrences in the post-waiver period were due to sources other than fouled ballast. Field investigation identified defective joints and uneven settlement on fresh limestone fill at several flood related washout locations as common causes of crosslevel degradation.

4.3 Evaluation of Fouled Ballast Length

The degradation results found in Figure 13 and Figure 14, and in Table 2 and Table 3 are for all fouled ballast locations in the master list regardless of length. Figure 15 compares the variation in degradation between lengths less than 10 feet with the variation for those equal to or greater than 10 feet. These results are for locations where the Profile 62 parameter crossed the track class 4 safety limit during the waiver period.

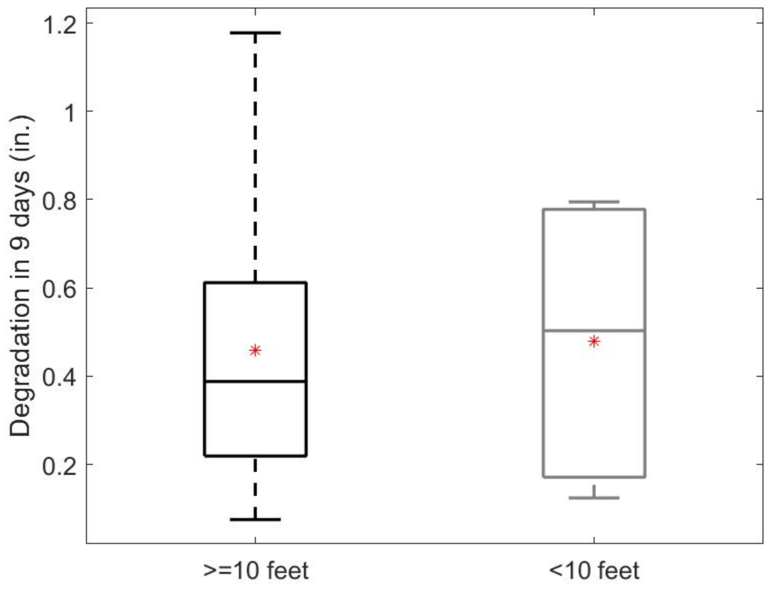


Figure 15. Profile 62 Degradation by Fouled Ballast Location Length – Track Class 4 Safety Limit – Waiver Period

Figure 15 shows box and whisker plots for both categories of fouled ballast length. The means are also shown for comparison with the medians. The mean degradation for locations equal to or greater than 10 feet (28 results) is similar to that for locations less than 10 feet (6 results).

Significant variation can be seen in the degradation results. The standard deviation of the degradation for each category of fouled ballast length is the same and has a value of 0.31 inches.

A statistical analysis confirmed that there is no reason to conclude the degradation is different for these two datasets. Short sections of fouled ballast can be considered together with long sections.

Figure 16 compares the variation in degradation in the Profile 62 parameter between different time periods. Variation is shown for the pre-waiver, waiver, and post-waiver periods. These results are for all lengths of fouled ballast locations crossing the track class 4 safety limit.

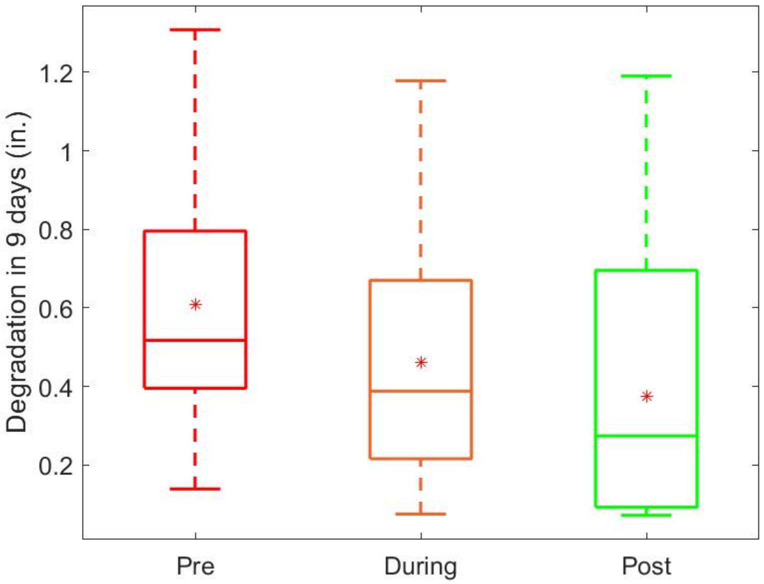


Figure 16. Profile 62 Degradation by Time Period – Track Class 4 Safety Limit

Figure 16 shows box and whisker plots for the pre-waiver, waiver, and post-waiver periods. The means are also shown for comparison with the medians. The degradation in the pre-waiver period (12 results) appears to be greater than in the waiver period (34 results) and the post-waiver period (23 results). However, a statistical analysis of variation did not give any reason to conclude degradation depends on the time period.

Figure 17 compares the variation in degradation in the Profile 62 parameter between different types of tie. These results are for all lengths of fouled ballast locations crossing the track class 4 safety limit and for all time periods.

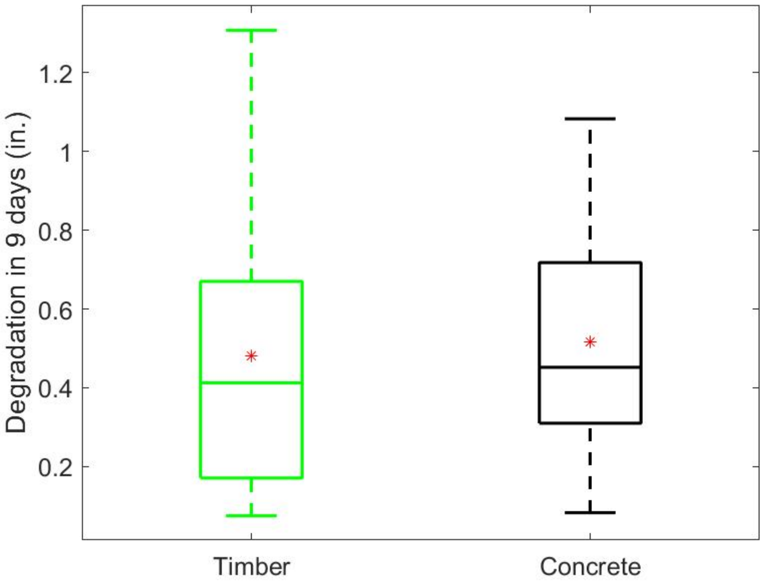


Figure 17. Profile 62 Degradation by Tie Type – Track Class 4 Safety Limit

Figure 17 shows box and whisker plots for both tie types. The means are also shown for comparison with the medians. The mean degradation for timber ties (22 results) is similar to that for concrete ties (24 results). A statistical test confirmed there is no evidence that the degradation is different for these two types of tie.

The maximum degradation for the timber ties, 1.31 inches, is slightly larger than that for the concrete ties, 1.08 inches.

Figure 18 compares the variation in degradation between lengths less than 10 feet with the variation for those equal to or greater than 10 feet. These results are for locations where the Profile 62 parameter crossed the track class 4 safety limit during the pre-waiver, waiver, and post-waiver periods. They are for both types of tie.

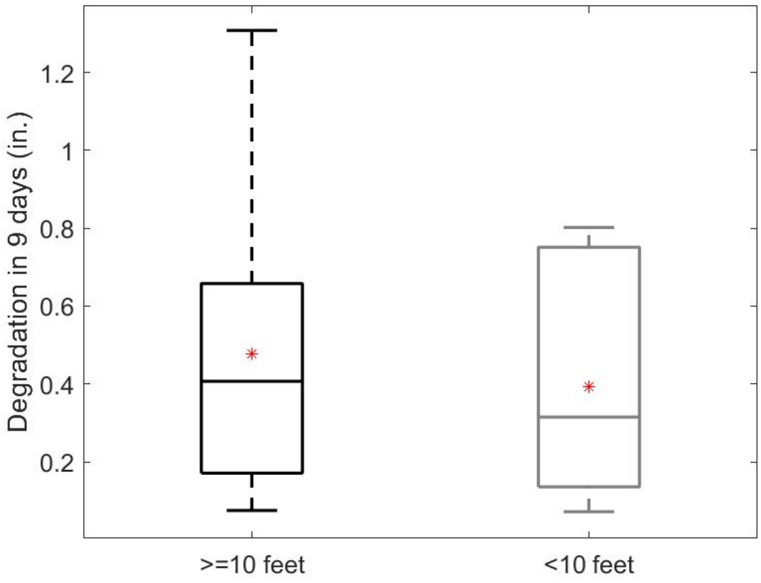


Figure 18. Profile 62 Degradation by Fouled Ballast Location Length – Track Class 4 Safety Limit – All Periods and Tie Types

Figure 18 shows box and whisker plots for both categories of fouled ballast length. The means are also shown for comparison with the medians. The mean degradation for locations equal to or greater than 10 feet (54 results) is similar to that for locations less than 10 feet (15 results). A statistical test showed there is no reason to conclude the degradation is different for these two datasets.

Figure 19 shows the counts of Profile 62 degradation before crossing the track class 4 safety limit for various bins of fouled ballast lengths. Bins that have no results are not included. The results are for all fouled ballast locations regardless of the time period, and tie type.

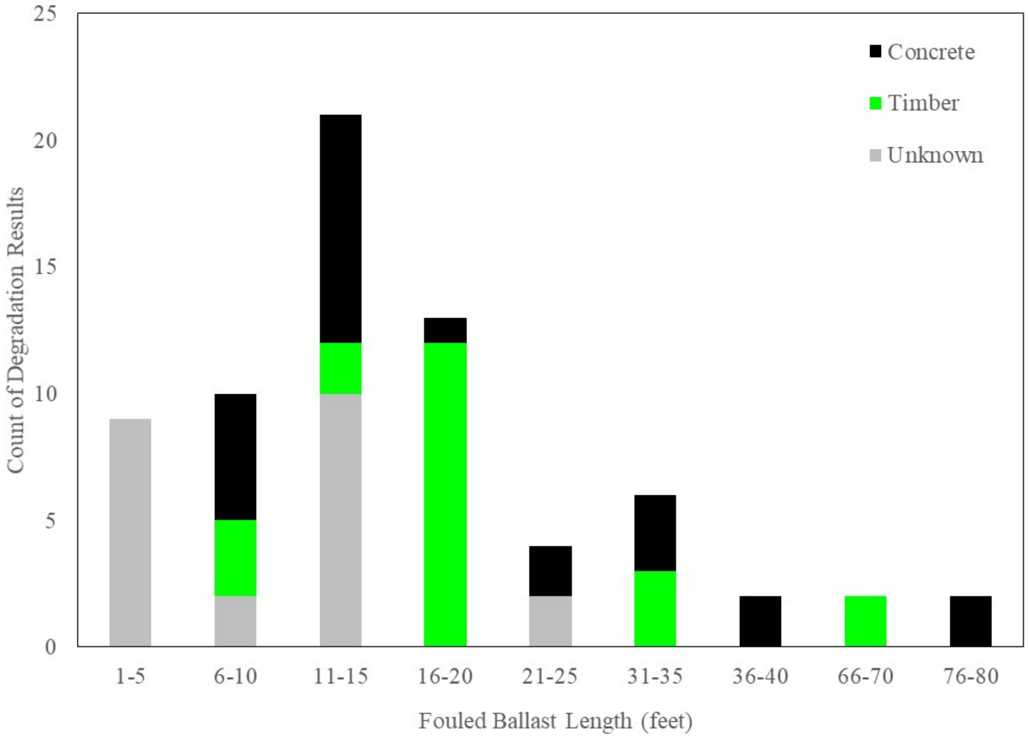


Figure 19. Histogram of Fouled Ballast Lengths – Profile 62 Track Class 4 Safety Limit – All Periods and Tie Types

Figure 19 shows sections of fouled ballast that crossed the track class 4 safety limit varied in length from 5 feet or less up to 80 feet. There does not appear to be any correlation between tie type and fouled ballast length.

Figure 20 shows individual values of Profile 62 degradation before crossing the track class 4 safety limit plotted against fouled ballast lengths. The results are for all fouled ballast locations regardless of the time period. The data points are coded to show the tie type.

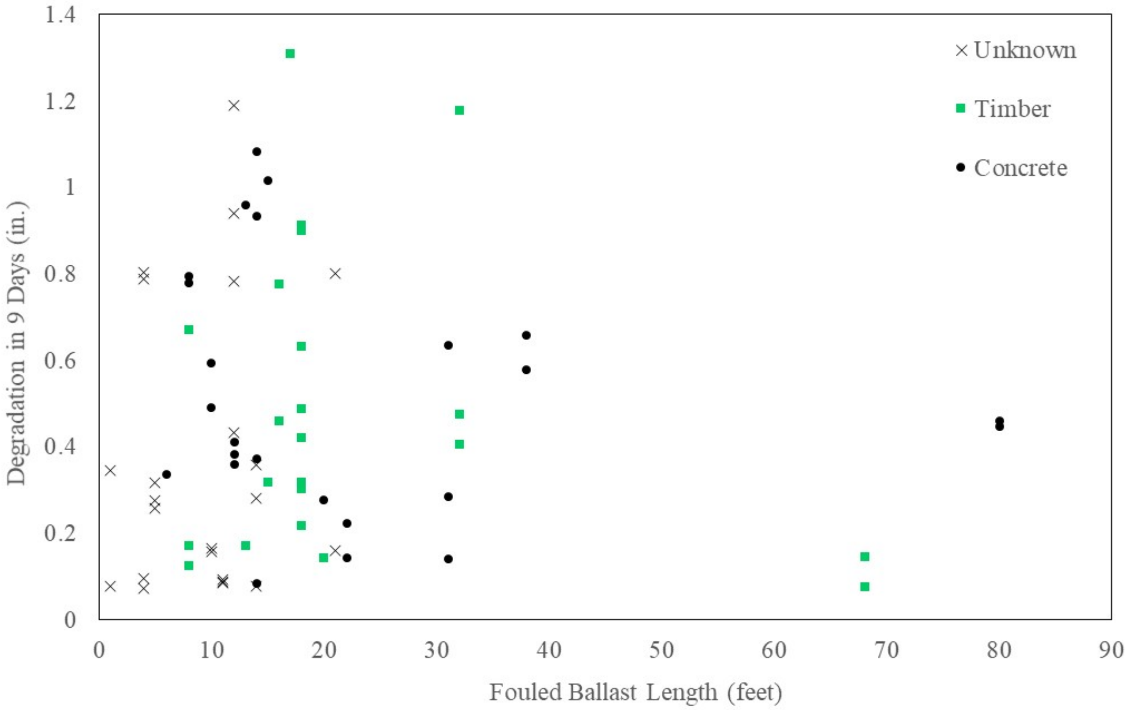


Figure 20. Profile 62 Degradation Statistics by Fouled Ballast Length – Track Class 4 Safety Limit – All Periods and Tie Types

Figure 20 shows the maximum value of Profile 62 degradation at short sections of fouled ballast can be as large as at some longer sections. It also shows no correlation between Profile 62 degradation and tie type.

Figure 21 shows results from locations where the Profile 62 parameter crossed the track class 5 safety limit. It compares the variation in degradation between lengths less than 10 feet with the variation for those equal to or greater than 10 feet. These results are for locations during the pre-waiver, waiver, and post-waiver periods, and both tie types.

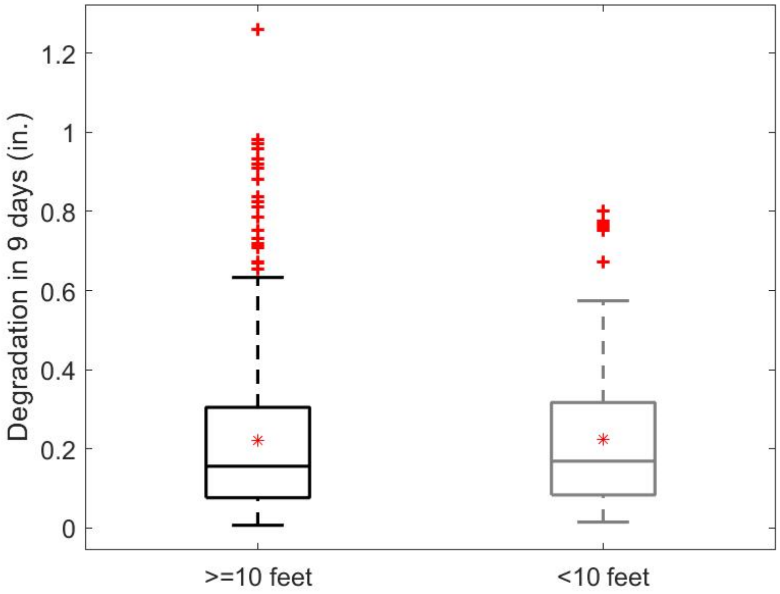


Figure 21. Profile 62 Degradation by Fouled Ballast Location Length – Track Class 5 Safety Limit – All Periods and Tie Types

Figure 21 shows box and whisker plots for both categories of fouled ballast length. The means are also shown for comparison with the medians. Data points that lie outside the fence are also shown. They indicate several locations with exceptionally high degradation. (Note that the previous box plots showed these outliers were not present in the track class 4 Profile 62 degradation results.)

The mean degradation for locations equal to or greater than 10 feet (501 results) is similar to that for locations less than 10 feet (121 results). A statistical test showed there is no reason to conclude the degradation is different for these two datasets.

Comparing Figure 21 with Figure 18 shows mean degradation before crossing the track class 5 safety limit is less than that before crossing the safety limit for track class 4. The variation is similar for short and long locations of fouled ballast.

Figure 22 shows the counts of Profile 62 degradation before crossing the track class 5 safety limit for various bins of fouled ballast lengths. Bins that have no results are not included. The results are for all fouled ballast locations regardless of the time period, and tie type.

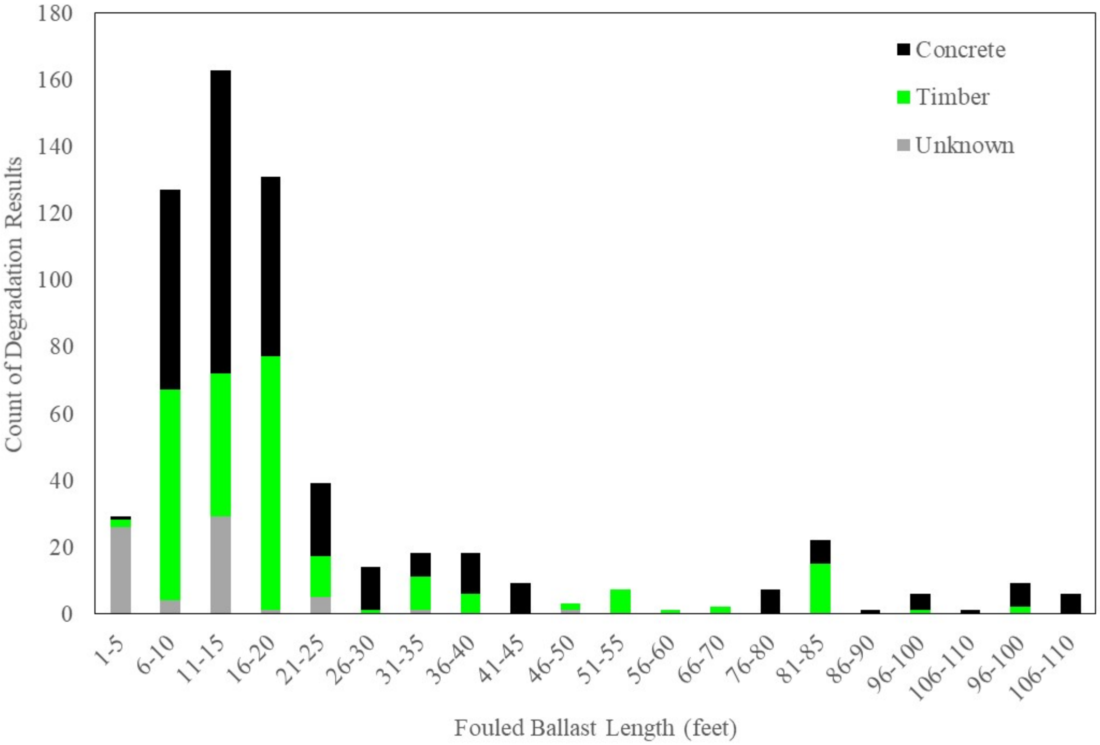


Figure 22. Histogram of Fouled Ballast Lengths – Profile 62 Track Class 5 Safety Limit – All Periods and Tie Types

Figure 22 shows sections of fouled ballast that crossed the track class 5 safety limit varied in length from 5 feet or less up to 110 feet. There does not appear to be any correlation between tie type and fouled ballast length.

Figure 23 individual values of Profile 62 degradation before crossing the track class 5 safety limit plotted against fouled ballast lengths. The results are for all fouled ballast locations regardless of the time period. The data points are coded to show the tie type.

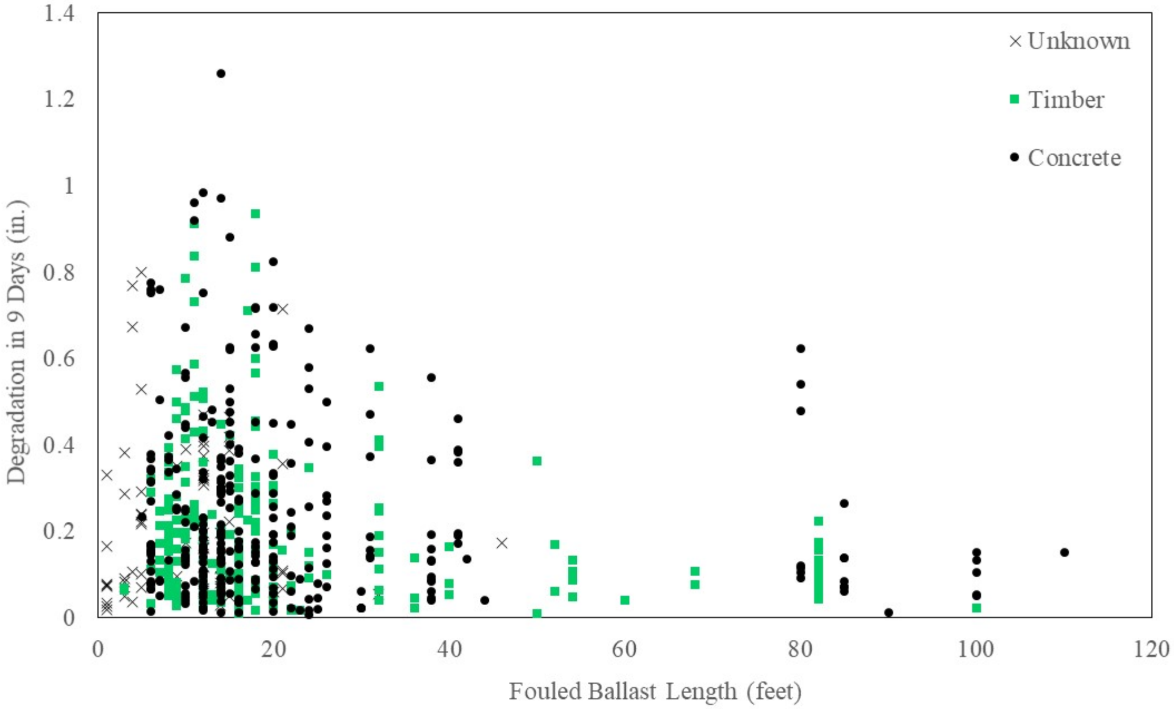
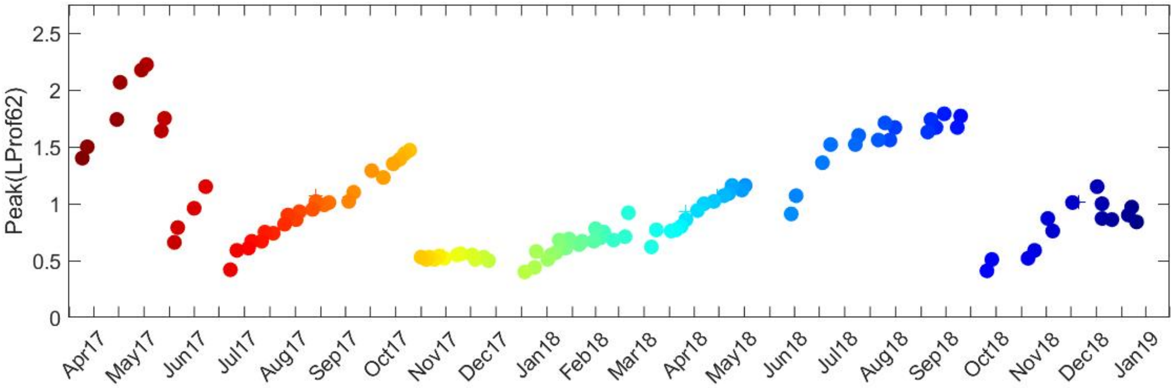


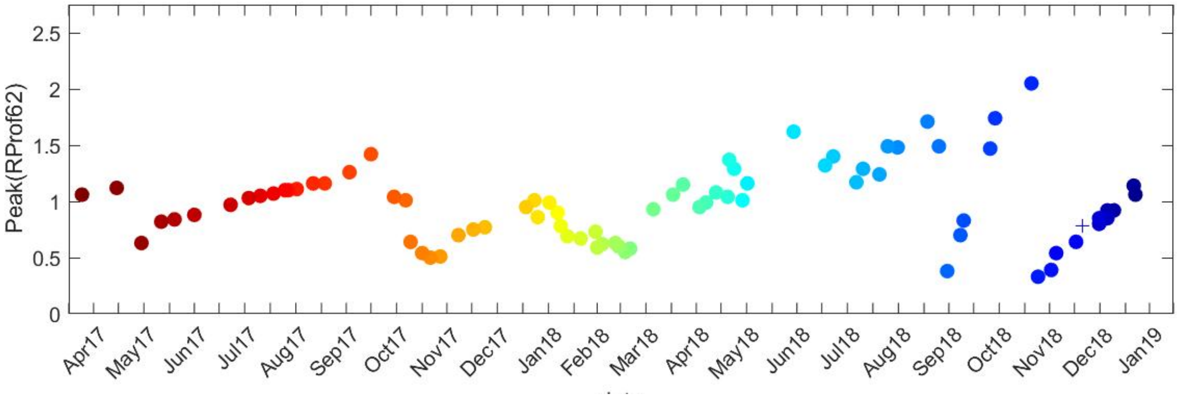
Figure 23. Profile 62 Degradation Statistics by Fouled Ballast Length – Track Class 5 Safety Limit – All Periods and Tie Types

Figure 23 shows the maximum value of Profile 62 degradation at short sections of fouled ballast can be as large as at some longer sections. It also shows no correlation between Profile 62 degradation and tie type.

Figure 24 shows two typical examples of time histories of peaks in the Profile 62 parameter. The upper example is for a location of fouled ballast that is 12 feet long. The lower example is for one that is 8 feet long.



a) 12-foot Section of Fouled Ballast at MP 84



b) 8-foot Section of Fouled Ballast at MP 106

Figure 24. Right Rail Profile 62 Peak Time Histories on St. Joseph Subdivision

Figure 24 shows similar patterns of degradation and improvement for the long and short locations of fouled ballast. In both cases the Profile 62 track geometry parameter crosses the track class 5 and 4 safety limits (1.25 and 2.0 inches respectively).

This subsection studied the effect of fouled ballast length on degradation of the Profile 62 track geometry parameter. Appendix A includes similar results for the crosslevel parameter.

4.4 Evaluation of Waiver Thresholds

Figure 25 shows a histogram of degradation results for the Profile 62 parameter crossing the track class 4 safety limit. The results are for all fouled ballast locations regardless of length, time period, and tie type.

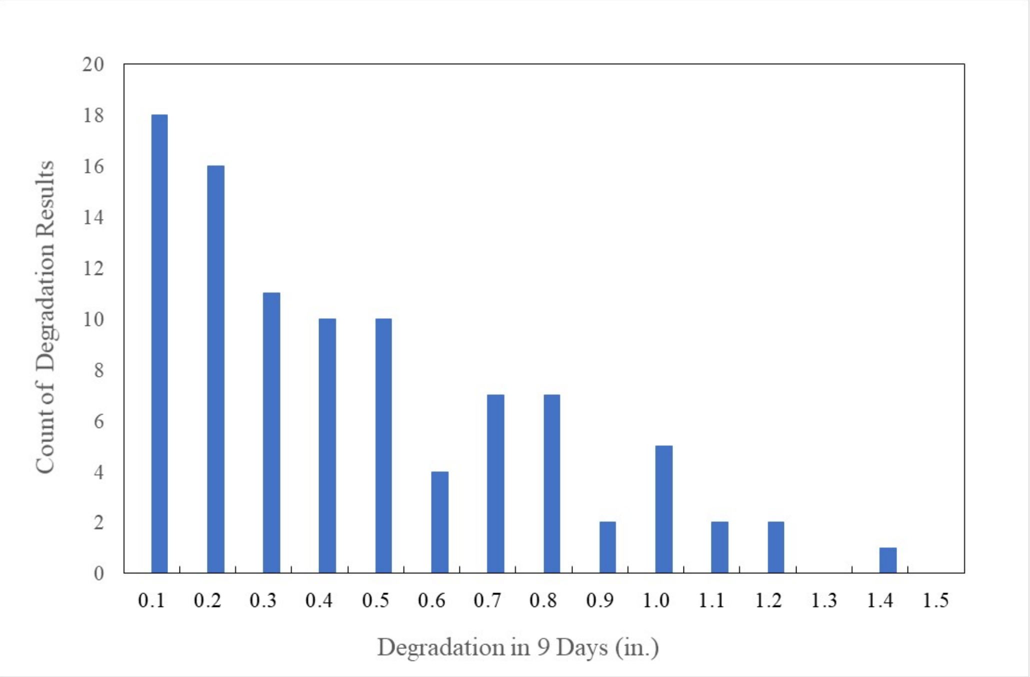


Figure 25. Histogram of Profile 62 Degradation Results – Track Class 4 Safety Limit – All Periods and Tie Types

The additional safety margin between the waiver threshold and the safety limit is 0.75 inches. Figure 25 shows 18 of the total 95 degradation results exceeded this additional safety margin. This means that in 19 percent of cases the degradation in the 9 days prior to the Profile 62 parameter crossing the track safety limit was greater than the additional safety margin included in the waiver.

Figure 26 shows the relationship between the Profile 62 threshold and the number of degradation results within the additional safety margin. The results are for all fouled ballast locations regardless of length and time period.

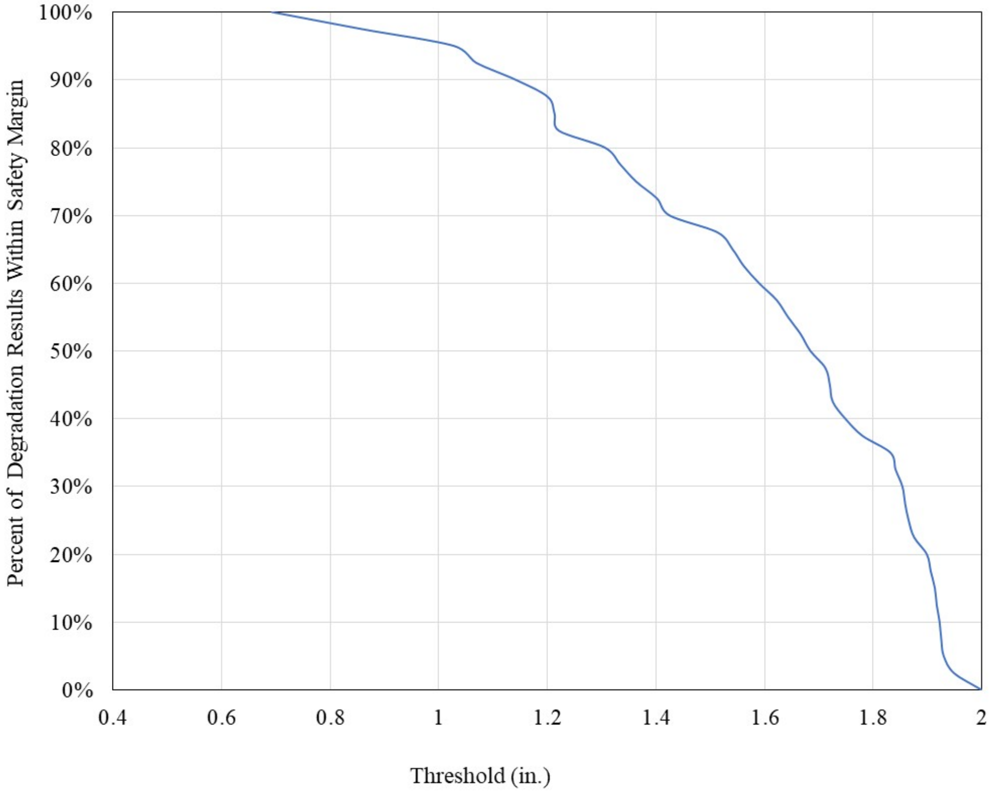


Figure 26. Effect of Profile 62 Threshold on Degradation Results – Track Class 4 Safety Limit – All Lengths, Periods and Tie Types

The Profile 62 safety limit for track class 4 are 2.0 inches and the waiver threshold are 1.25 inches. Figure 26 shows that this threshold means 81 percent of degradation results will be within the additional safety margin between 1.25 and 2.0 inches. All degradation results could be included in the additional safety margin if the threshold is set to 0.7 inches. As another example, 95 percent of the sites fall within a threshold of 1 inch.

Figure 27 shows the same results as Figure 26 with the track class changed to five.

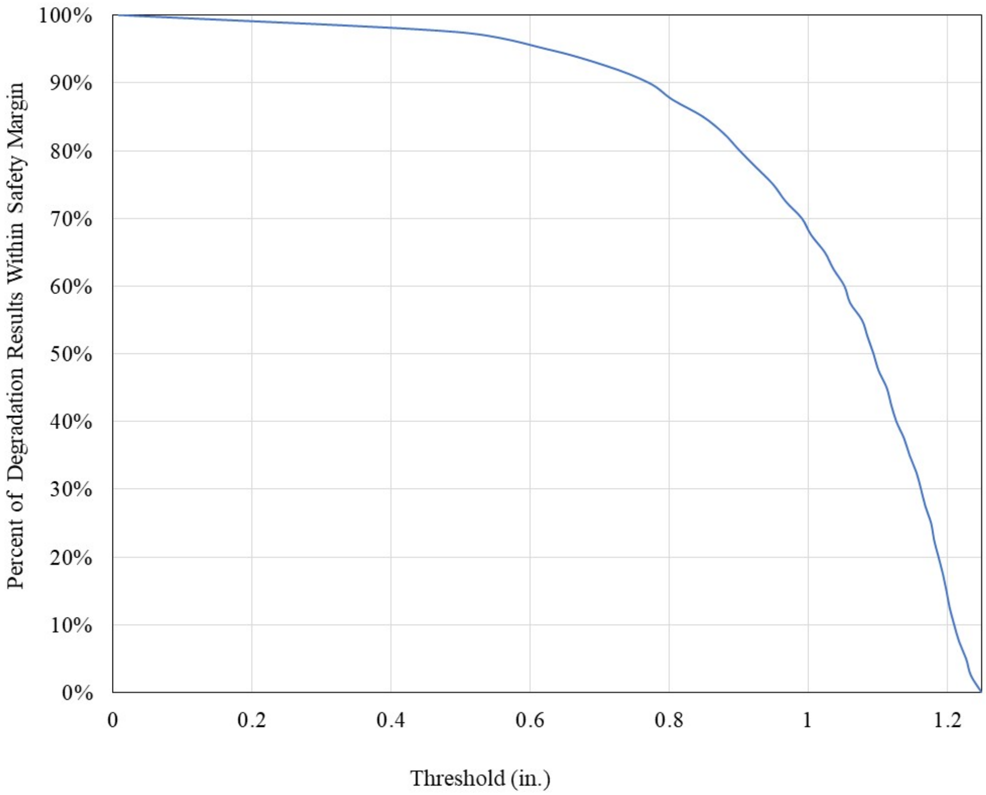


Figure 27. Effect of Profile 62 Threshold on Degradation Results – Track Class 5 Safety Limit – All Lengths, Periods and Tie Types

The Profile 62 safety limit for track class 5 are 1.25 inches and the waiver threshold are 1.0 inches. Figure 27 shows that this threshold means 68 percent of degradation results will be within the additional safety margin between 1.0 and 1.25 inches. All degradation results could only be included in the additional safety margin if the threshold is set to zero. As another example, ninety five percent of results fall within a threshold of 0.6 inches.

Appendix A includes similar results to those shown in Figure 26 and Figure 27 for the crosslevel parameter.

5. Long-term Monitoring

In addition to the weekly analysis and reporting described above, UIUC installed six long-term monitoring sites on the waiver territory. Wayside instrumentation monitored the load environment, support conditions, transient deflections, soil moisture changes, and weather patterns. It observed the physical processes underlying track support degradation and the deterioration of track geometry at the six selected locations.

The location of the six long-term monitoring sites were on the St. Joseph subdivision between Lincoln, NE, and Kansas City, MO. Four sites contained fouled ballast, and two had clean ballast and acted as control sites. Two sites (i.e., one control and one fouled) had timber ties and four sites (i.e., three fouled and one control) had concrete ties.

Table 4 gives the location, track type, tie type, and monitoring dates for the long-term monitoring sites.

All long-term monitoring sites were on tangent track except for Parkville which was on a spiral adjacent to a tangent.

Table 4. Long-term Monitoring Site Details

Site*	MP	Track	Ties	Start Date	End Date
Parkville (F)	9.850	Single	Concrete	11/14/2017	5/16/2019
Waldron (F)	17.200	Single	Concrete	12/20/2017	7/30/2019
Hickman (C)	191.578	Track 2, Double	Timber	12/19/2017	Ongoing
Hickman (F)	192.778	Track 2, Double	Timber	5/5/2017	Ongoing
Roca (C)	196.111	Single	Concrete	9/26/2017	4/29/2020
Roca (F)	196.288	Single	Concrete	9/26/2017	4/29/2020

* - F indicates a fouled ballast site, C indicates a control site

Figure 28 shows the locations of the long-term monitoring sites on a map of the St. Joseph subdivision.

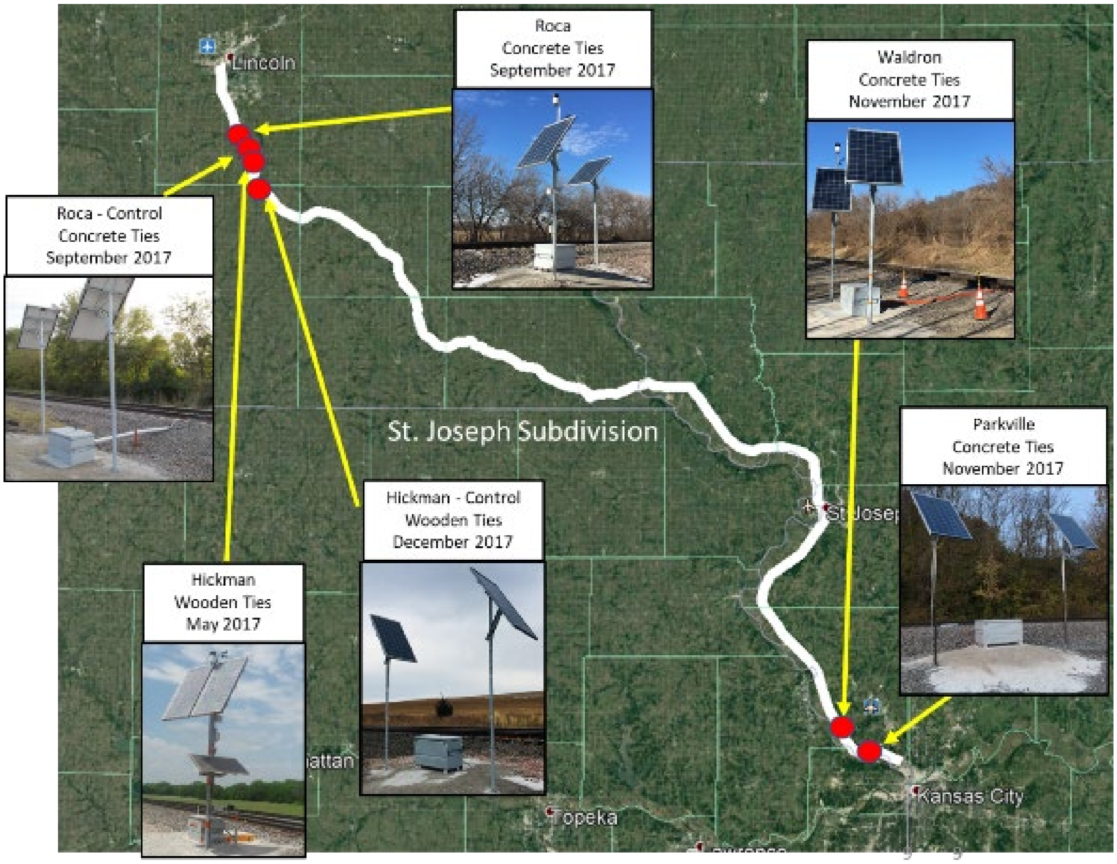


Figure 28. Locations of the Long-term Monitoring Sites

5.1 Equipment Setup and Operation

Figure 29 shows the overall instrumentation setup installed at each of the six instrumented sites. Solar panels were initially installed to provide power to the National Instruments (NI) data acquisition system. The solar panels at each site were augmented with a wind generator to maintain adequate power throughout the range of environmental conditions these sites experienced. In addition, four sites had weather stations mounted on the same pole as one of the solar panels. The weather stations measured rainfall, wind speed, and direction.

Figure 29. Typical Setup of Instrumentation Box, Solar Panels, and Weather Station

Figure 30 is a plan view of the instrumentation installed at a fouled ballast site with concrete ties.

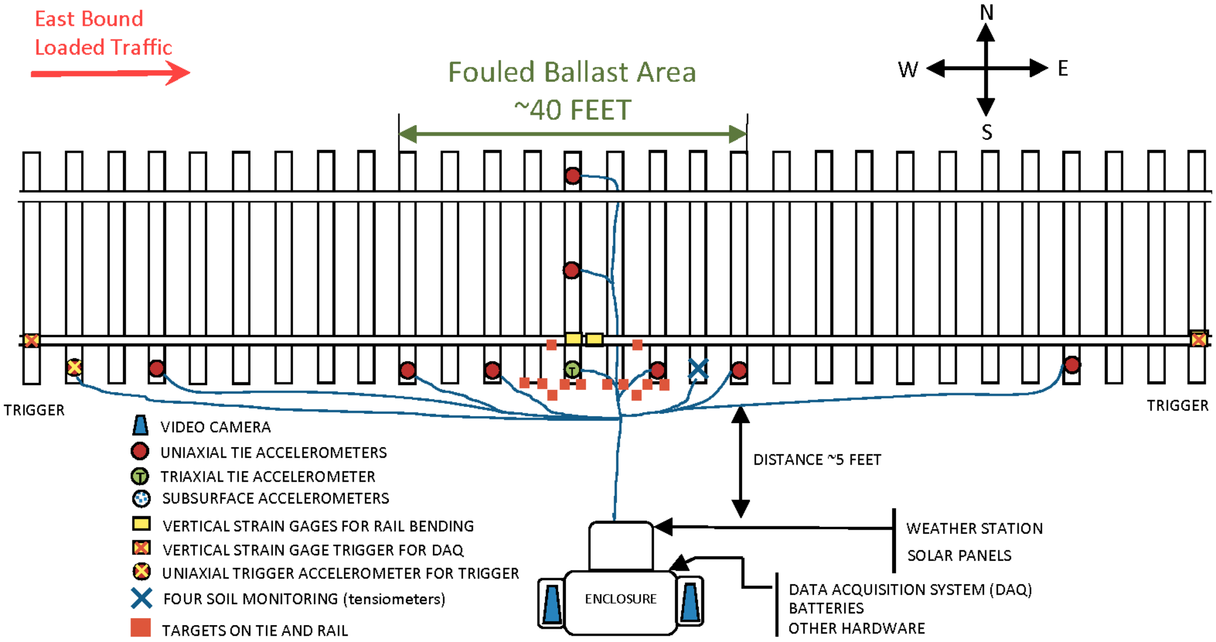


Figure 30. Plan View of Instrumentation at Concrete Tie Sites

Figure 30 shows the following equipment:

- Instrumentation box mounted with two high frequency video cameras

- Orange targets on the rail and two concrete ties per camera and a ground stake
- Two or more rail strain gauges to measure wheel load above a crib and adjacent tie in the fouled ballast area
- Eight strain gauges on each of two concrete ties (i.e., strain gauges were not attached to timber ties)
- Nine uniaxial accelerometers, one of which serves as a trigger for the data acquisition system
- One triaxial accelerometer
- Two rail strain gauges to the left and right of the instrumentation that serve as triggers to activate the data acquisition system depending on the direction of traffic

Not shown in Figure 30 are four or five soil moisture sensors installed in the fouled ballast.

Appendix B has diagrams of the instrumentation layout at all six long-term monitoring sites.

Figure 31 shows the NI data acquisition (DAQ) system in a concrete tie instrumentation box. The main components of the DAQ system are:

- Controller that is programmed to collect and store all the data and where the two video cameras (not shown) are connected
- DAQ chassis (CDAQ) where rail strain gauges, triggers, and accelerometers are connected
- Four TB external hard drive that stores all the data
- Modem that allows the system to be remotely monitored and restarted
- Remote on/off circuit that allows remote restarting after low power shut down or other unexpected events
- Power supply board where the solar panels and four 12-volt deep-cycle, DC batteries are connected
- Sixteen signal conditioners for the 8 concrete tie strain gauges, 2 strain gauge triggers, and 6-wheel load strain gauges

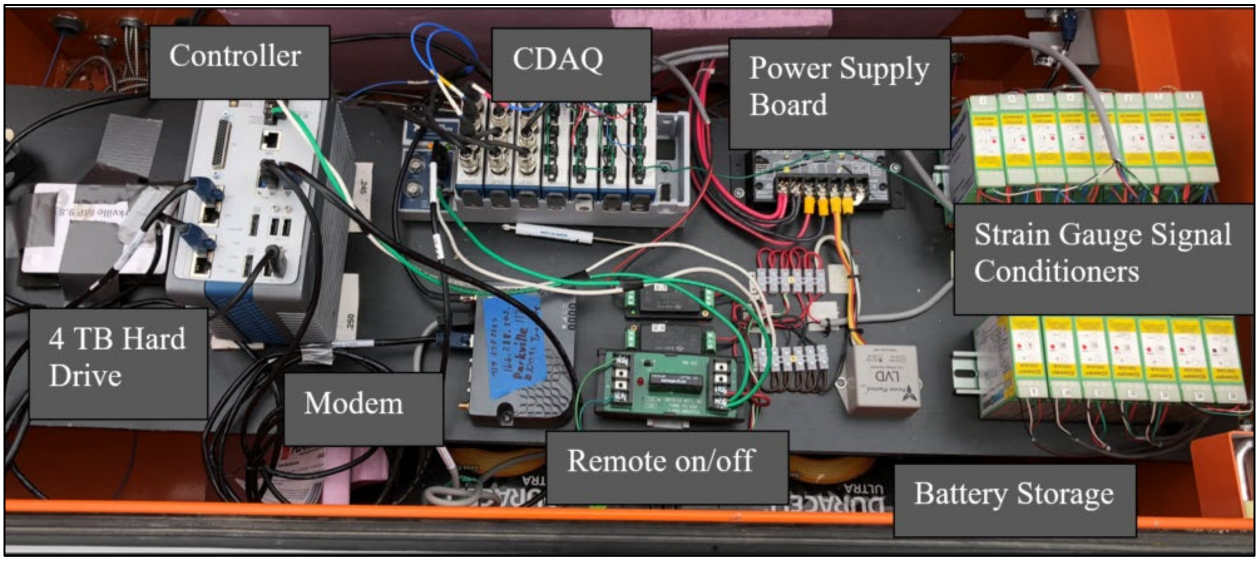


Figure 31. Instrumentation Inside a Weatherproof Box at a Concrete Tie Site

The hard drive was necessary because the modem could not transmit all the data in real time and required too much power. Data from the hard drive was downloaded manually.

Figure 32 shows one of the two high frequency video cameras installed in each instrumentation box. The glass shield that protected each camera is shown on the right of Figure 32. The cameras recorded each train at a rate of 100 frames per second for 3 minutes. For each train, the 4 TB hard drive stored 36,000 frames. Researchers connected the cameras directly to the DAQ controller and recorded the transient and permanent displacements of the orange targets that were installed on the rail and adjacent ties. Each camera monitored two ties and the connecting rail. Each camera also monitored a ground stake that was installed in front of the two ties and responded to the ground vibrations induced by the passing train. The ground vibrations were subtracted from the measured rail and tie displacements to estimate the transient and permanent displacements of only the rail and ties.

Figure 32. High Frequency Video Camera and Glass Shield

Figure 33 shows the system of orange targets installed for one of the cameras. The MATLAB code obtained transient displacement time histories of the rail and tie targets for each train. The use of these time histories estimated the tie-to-ballast gap, rail-to-tie gap, and track stiffness as a function of wheel load. The installed targets were 2-inch metal squares, which were painted orange to distinguish them from the surrounding environment.

The MATLAB code processed the transient displacement data from each camera and target assembly by calculating the relative movement per frame compared to the image of the target immediately before the train arrived. This was possible because a rail strain gauge or a tie accelerometer activated the DAQ system prior to train arrival at the first target.

Figure 33. Targets Attached to Adjacent Crossties, Connecting Rail and Ground Stake

Figure 34 shows a typical rail strain gauge circuit installation. Each circuit consisted of four strain gauges installed along the neutral axis of the rail. Researchers installed two gauges on each side of the rail to measure shear strain—gages were 45 degrees from the neutral axis.

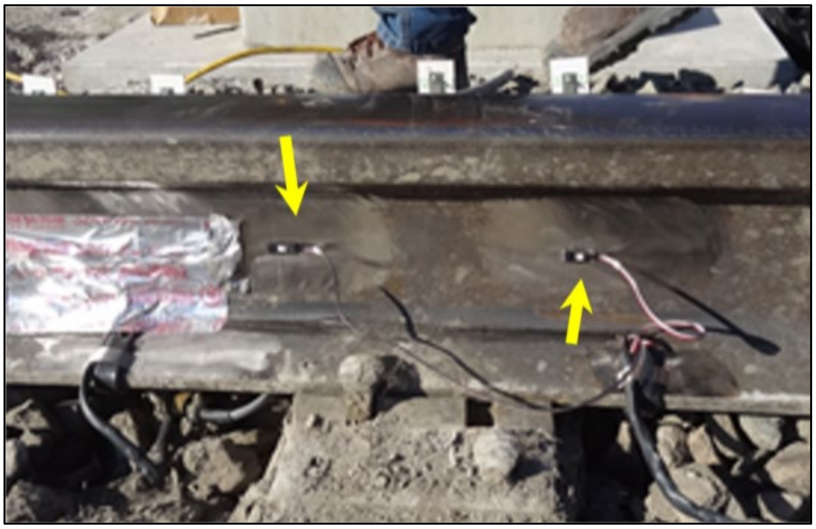


Figure 34. Strain Gauges Attached to the Rail (yellow arrows)

The visible strain gauges in Figure 34 (i.e., indicated by yellow arrows) are part of the circuit above a tie to measure the amount of wheel load transferred to the tie. The silver tape shown to the left in Figure 34 is covering two strain gauges that are part of the crib circuit that was used to measure the unsupported or fully applied wheel load. The crib strain gauge circuit yields the applied wheel load because the change in measured shear strain as a wheel passes over the gage is in direct proportion to the wheel load.

Figure 35 shows the loading fixture used to calibrate the rail strain gauges. During calibration, a load up to 40,000 lb. is applied by a hydraulic jack in the fixture to simulate the maximum wheel load and deflect the rail. The results are used to construct a load-deflection relationship that yields a calibration factor for converting the strain gauge bridge voltage to the applied load. A calculation of the separate calibration factor took place for each crib and tie strain gauge circuit.

Figure 35. Strain Gauge Calibration Frame

Researchers installed soil moisture sensors at the four fouled ballast instrumentation sites. Figure 36(a) shows a soil moisture sensor before installation. Figure 36(b) shows a borehole adjacent to a concrete tie prior to installation of a soil moisture sensor. The installation of moisture sensors was in a similar location at timber tie sites. The installation of four or five soil moisture sensors were at each fouled ballast site. The sensing depths were 1, 4, 7, 10, and 13 inches (i.e., for a five-sensor installation) below the ballast top surface.


11 14 2017

(a) (b)

Figure 36. (a) Soil Moisture Sensor, (b) Borehole for Installing Sensor

Researchers chose the location shown in Figure 36(b) to avoid damage during track maintenance. The soil moisture sensors were removed before any major ballast cleaning operations and reinstalled afterwards. This resulted in the sensors being surrounded by different material and possibly at slightly different depths than before major maintenance.

The work in the laboratory verified the soil moisture sensors by collecting samples of fouled material and measuring the moisture content. Researchers collected the samples approximately every 6 months. The laboratory measured moisture content was then compared with the sensor measured value on the day the sample was collected.

Preliminary data showed that relatively small changes in moisture content could affect the load-carrying capability of the fouled ballast. The load-carrying capability changed soon after an increase in moisture content due to either rain or thaw. Soil moisture and weather readings were taken continuously to compare rain and temperature with moisture levels at various depths in the fouled ballast and underlying subgrade.

Figure 37 shows the three types of accelerometers used in the project. Figure 37(a) is a 10 mV/g PCB 607A60 piezo-electric uniaxial accelerometer. The frequency range is (±3dB) 0.5 to 10,000 Hz. The measurement range is ±500 g (±4,905 m/s^2) and the weight of this accelerometer is 1.1 oz (31 gm).

Figure 37(b) is a 25 mV/g PCB 356A25 piezo-electric triaxial accelerometer. Its measurement range is ±200 g (±1,960 m/s^2) with a frequency range of 1 to 5,000 Hz (±5%). The weight of this accelerometer is 0.37 oz (10.5 gm).

Figure 37(c) is a 4630 direct current triaxial accelerometer from measurement specialties. The sensitivity is 4 mV/g for all three axes. Different from the piezo-electric accelerometers, direct current accelerometers need external excitation. For this accelerometer, the excitation voltage used was 24 volts. The measurement range is ±500 g with a frequency range of 0 to 1,000 Hz (±5%). The weight of this accelerometer is 40 grams.

(a) **(b)** **(c)**

Figure 37. (a) PCB 607A60 Piezo-electric Uniaxial Accelerometer, (b) PCB 356A25 Piezo-electric Triaxial Accelerometer, and (c) Measurement Specialties 4630 Direct Current Triaxial Accelerometer

Since they were intended for long-term monitoring, the accelerometers were weather-proofed and attached rigidly to the ties. For the PCB uniaxial accelerometers, mounting pads were soldered onto metal plates that were then screwed to the ties. Plastic boxes were used as a cover. The triaxial accelerometers were installed in water-proof boxes and conduit was used to protect any vulnerable cables.

Figure 38 shows a typical accelerometer installation.

Figure 38. Accelerometer Attached to a Tie and Covered with a Plastic Box

5.2 Method of Analysis

5.2.1 Wheel and Tie Loads, and Distribution Efficiency

The output from the strain gauge circuit in the crib is proportional to the wheel load P_C. This is because the rail is unsupported in the crib and the change in shear force as the wheel crosses the strain gauge circuit is equal to the applied load. The output from the strain gauge circuit above the tie is typically less than that from the circuit in the crib. This is because the tie typically provides some support and reduces the change in shear force as the wheel crosses the tie. When the output from the strain gauges above the tie is converted to load, it is referred to as the distributed tie load, P_T.

If P_T equals P_C the tie is providing no support (Stark, T. D., Wilk, S. T., Thompson, H. B., & Sussmann, T, 2015). In this case the load must be transferred to adjacent ties. If P_T is less than P_C some of the applied wheel load is transferred to the underlying ballast and less is transferred to adjacent ties. Thus, P_T is a way to measure the support the ballast and substructure gives to the tie.

Distribution Efficiency (DE) is also used to quantify the support given to a tie. It is calculated from the load measured by the rail strain gauges at the instrumented tie (P_T) and in the adjacent crib (P_C). DE expresses the percentage of the wheel load that is transferred to adjacent ties:

$$\text{Distribution Efficiency (DE)} = \frac{\text{Distributed Tie Load } (P_T)}{\text{Wheel Load } (P_C)} \times 100\%$$

If DE equals 100 percent the wheel and tie loads are equal and none of the applied load is transferred to the underlying ballast, i.e., the tie is unsupported. This condition is known as a “hanging tie” and indicates that the tie does not make load-bearing contact with the ballast under load. Conversely, if DE is 0 percent, the applied wheel load is fully transferred to the underlying ballast, which is referred to as a “fixed tie.” Usually an intermediate condition is observed. A well supported tie can be expected to support approximately 40 percent of the applied wheel load (DE = 40%) when the tie-ballast gaps are small and uniform (Wilk, S., Stark, T., & Rose, J., 2015).

5.2.2 Track Stiffness

Researchers calculated track stiffness by comparing rail and tie displacements with wheel load. Figure 39 shows an example of rail transient displacement. The video camera captured this data from monitoring the orange target applied to the rail. It consists of 90 data points that correspond to the largest measured rail displacement every 2 seconds of train passage. This yields values that are always proportional to the average wheel load. For a train with variable wheel loads, the 2-second peak transient displacement accounts for the larger and smaller displacements from the heavier and lighter loads.

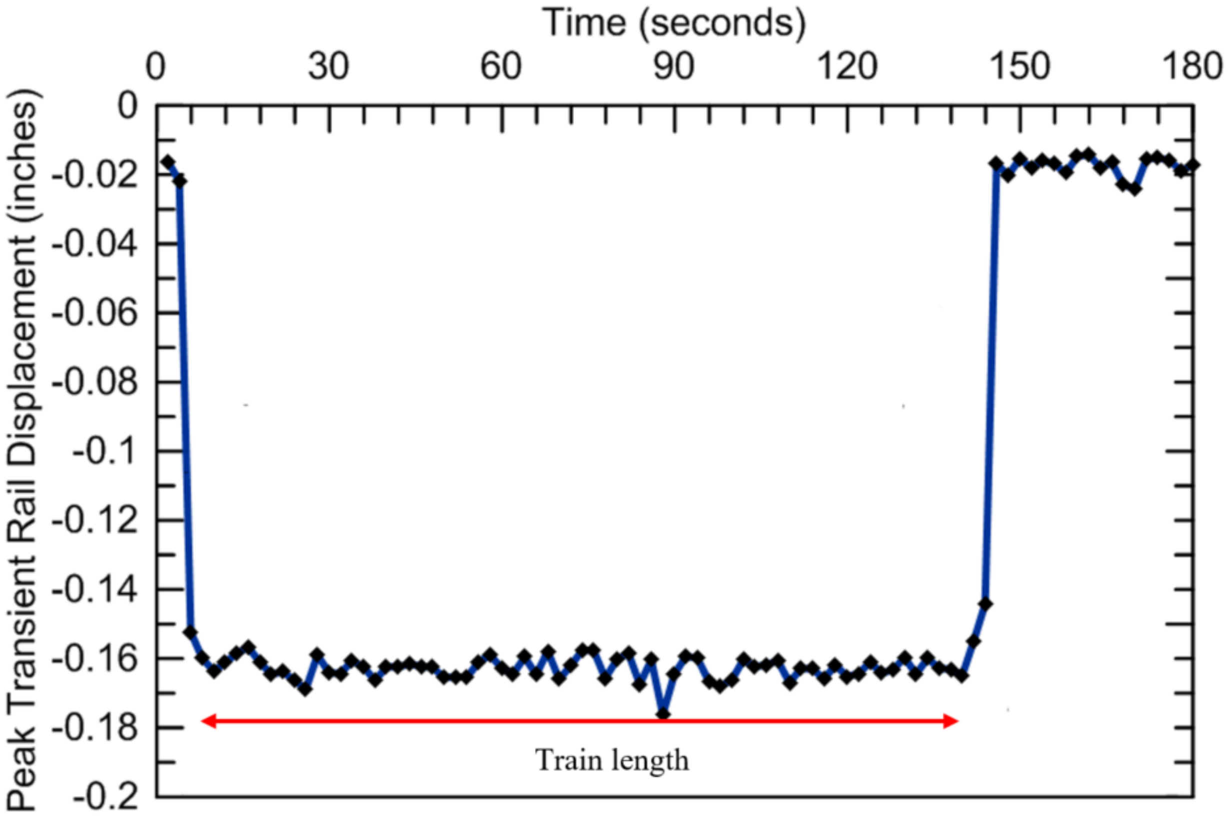


Figure 39. Example Peak Transient Rail Displacement Data

After deleting the points before and after the train pass, the overall peak transient rail displacement is calculated by averaging the 2-second peak displacements. The overall peak rail transient displacement for the train in Figure 39 is 0.16 inches under an average wheel load of 33.4 kips.

Figure 40 shows a typical plot of peak transient rail displacement against wheel load. This data is from February 2018 at the long-term monitoring site at Waldron.

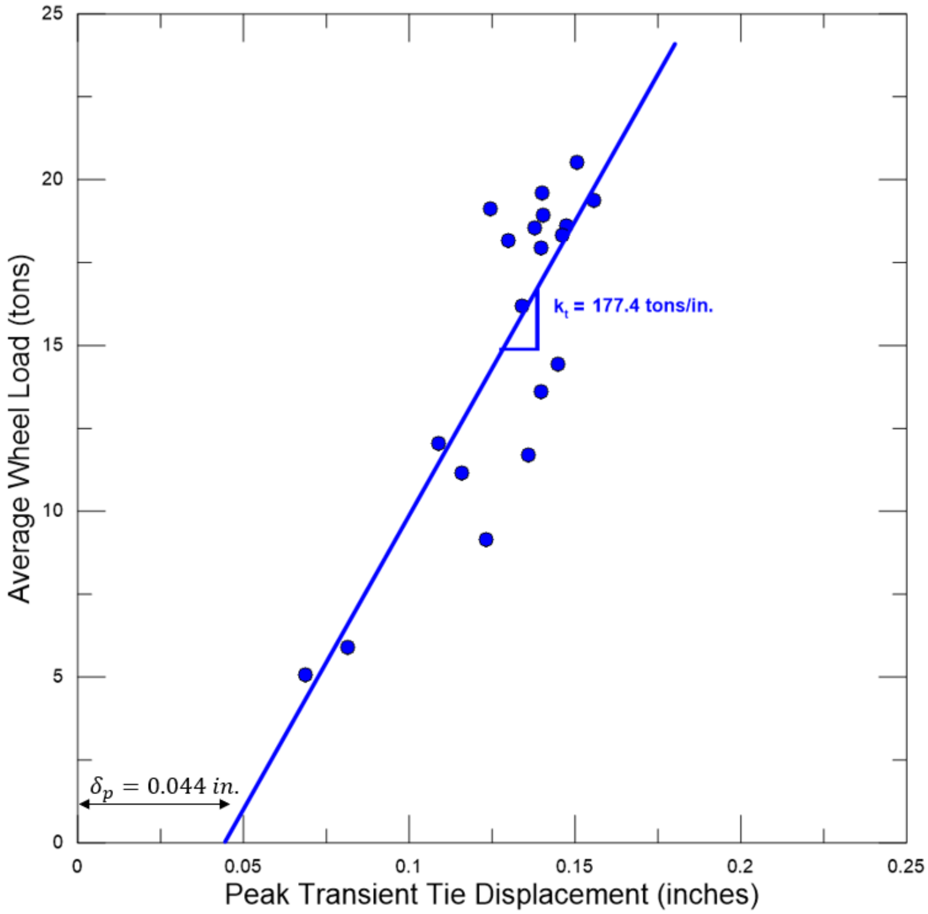


Figure 40. Wheel Load vs. Transient Displacements

Figure 40 shows a displacement, δ_p, of 0.044 inches before displacement increases approximately linearly with wheel load. The requirement of the initial displacement is to close any gap between the tie and the ballast. To calculate the track stiffness, k_t, it is from the slope of the line in the linear part of the relationship.

5.2.3 Tie Accelerations

Time histories from the accelerometers installed on the ties provide insights into dynamic movements under passing trains. Causes of tie accelerations include:

1) Wheel-rail vibrations
2) Wheel-rail impacts
3) Rail-tie impacts
4) Tie-ballast impact
5) Quasi-static wheel loading

Each cause tends to have its own unique signature and can typically be identified by analyzing the measured tie accelerations in both the time and frequency domains. Well-supported track will typically display tie accelerations from only quasi-static wheel loading but can also show wheel–

rail impacts and wheel–rail vibrations. The remaining factors are typically indicative of poorly supported track.

Maximum accelerations at frequencies less than 50 Hz typically range from 1 to 5 g for well-supported track. They can range from 10 to over 100 g for poorly supported track. For this project, an acceleration of 10 g was used to differentiate between well-supported and poorly supported track. Using the number of daily exceedances of 10 g allowed for the quantification of the quality of track support.

5.2.4 Bending Moments on Concrete Ties

Using the measurements of strain on concrete ties allowed the calculation of tie bending moments. Installation of the strain gages took place at the rail seat and the center of the tie.

Figure 41 shows published relationships between measured strain and bending moments on concrete ties (Edwards, J. R., Gao, Z., Wolf, H. E., Dersh, M. S., & Qian, Y., 2017). The red points are the data used to derive the relationships.

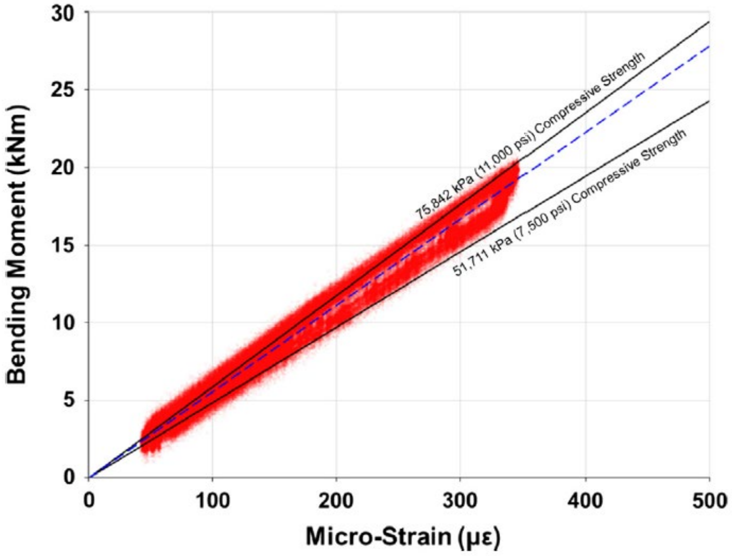


Figure 41. Calibration Factors of Strains to Bending Moments (Edwards, J. R., Gao, Z., Wolf, H. E., Dersh, M. S., & Qian, Y., 2017)

Using a calibration factor from the upper relationship in Figure 41 amounted to avoiding understimating bending moments. The American Railway Engineering and Maintenance-of-Way Association (AREMA) recommended design limits are 200 kip-in for the tie center and 300 kip-in for the rail seat respectively. Using the number of daily exceedances of these limits allowed researchers to quantify the severity of concrete tie bending at a monitoring site.

5.2.5 Track Geometry

The work conducted allowed for an analysis of the weekly track geometry measurements required by the waiver to determine behavior at the long-term monitoring sites. The raw track geometry data assisted with calculating the Track Quality Index (TQI). TQI is the sum of gage, crosslevel, twist, alignment 62, and profile 62 computed over a 100-foot moving window. The result has a range from 0 to 2 inches and Figure 42 presented the magnitude using a color scale.

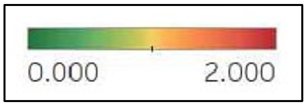


Figure 42. Color Scale for TQI

Figure 43 shows an example of a TQI waterfall plot. Researchers combined the results from several track geometry recordings to show the change in TQI with time. The results from the earliest recording are on the top of the chart and those from the latest recording are on the bottom.

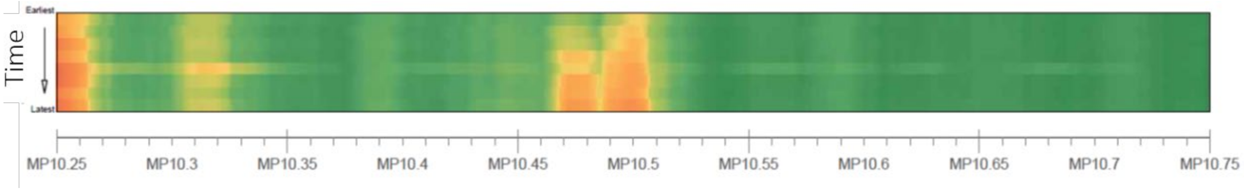


Figure 43. Example TQI Waterfall Plot

Figure 43 shows three locations of degraded track quality (e.g., around MP 10.25 and MP 10.31, and between MP 10.46 and 10.51). The track quality between MP 10.46 and 10.51 appears to have deteriorated with time.

5.2.6 Ground Penetrating Radar

GPR measurements were made throughout the ballast waiver period at the long-term monitoring sites with FRA equipment supplied by Zetica Rail (Zetica Ltd). Calculating the Selig Fouling Index (Selig, E. T., & Waters, J. M., 1994) was from the GPR data and used to derive a Ballast Fouling Index (BFI) using the descriptions and ranges in Table 5. Blue is used for highly fouled ballast to indicate the high likelihood that water is present.

Table 5. BFI Definitions

Category	Description	Selig Index Range
0	Unavailable	n/a
1	Clean	<5
2	Moderately Clean	5 - 10
3	Moderately Fouled	10 - 25
4	Fouled	25 - 30
5	Highly Fouled	>30

Figure 44 shows an example grayscale plot of GPR data filtered at 400 MHz. This type of plot is analyzed to estimate the depth of the ballast and sub-ballast layers. The yellow line indicates the surface of the ballast and the blue line is the estimated interface between the ballast and the sub-ballast. The red line delineates the approximate bottom of the sub-ballast that coincides with the top of subgrade or fill.

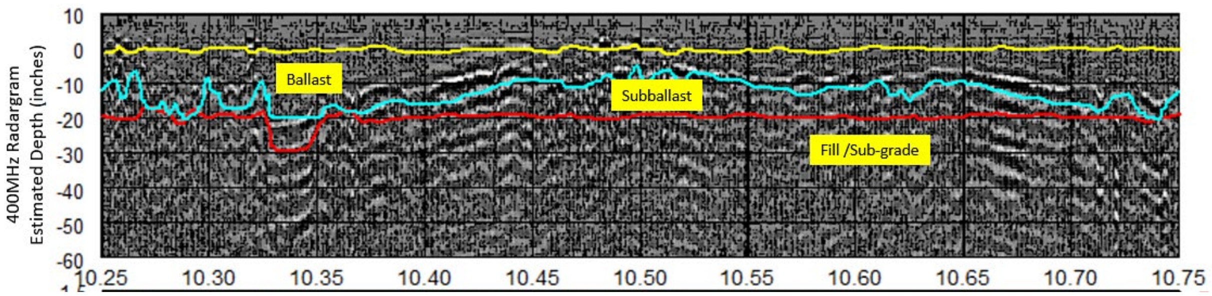


Figure 44. Example Grayscale Plots of GPR Data

Figure 44 shows shallow ballast in similar locations to the locations of degraded track quality shown in Figure 43. In these locations, the ballast extends barely below the bottom of the ties (i.e., typically 8 inches deep).

Figure 45 shows an example of a layer interpretation plot. This is an alternative method to Figure 44 of displaying the boundaries between the layers.

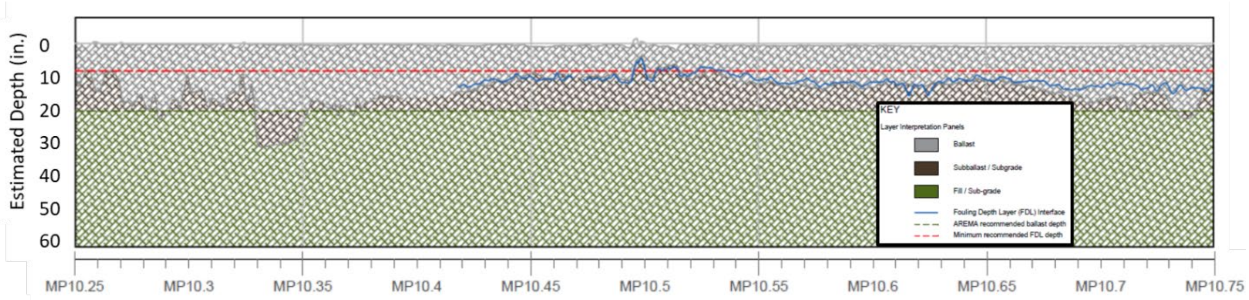


Figure 45. Example Layer Interpretation Plot

The Fouling Depth Layer (FDL) is the depth to a fouled layer, which represents the depth of relatively clean ballast identified by GPR. Table 6 shows the definitions used for FDL. Brown indicates fouling at or above the bottom of the tie, meaning that no clean ballast is expected to be supporting the tie. The horizontal red line at 8 inches in Figure 45 is the typical depth of ties. The horizontal blue line at 20 inches in Figure 45 is the depth of ballast recommended by AREMA.

Table 6. FDL Definitions

*Relative to ballast surface

Fouling Depth Layer (FDL)		
Category	Description	Thickness (inches)*
0	Unavailable	n/a
1	Good	>14
2	Moderate	11 - 14
3	Poor	8 - 11
4	Very Poor	<8

Researchers calculated the BFI and FDL for the left, center, and right positions across the track. The ratings for these parameters are then used to develop the Trackbed Condition Summary (TCS). TCS is generally rated as poor when any parameter is very poor. Table 7 shows the definitions used for TCS.

Table 7. TCS Definitions

Trackbed Condition Summary		
Category	Description	Score
0	Unavailable	n/a
1	Good	<4
2	Moderate	4 - 8
3	Poor	8 - 12

The GPR data is interpreted to highlight sections of track potentially affected by mud spots or ballast pockets. Fouling material approaching the track surface identified the locations susceptible to the formation of mud spots. Variations in the ballast-to-subgrade interface indicating subgrade subsidence identified the locations susceptible to ballast pockets. Table 8 shows the definitions used for these Subsurface Defects (SSD).

Table 8. SSD Definitions

🟧	Subgrade failure / incipient mud spot
🟦	Ballast pocket / track bed subsidence

Figure 46 shows examples of BFI, FDL, TCS, and SSD results between MP 10.25 and 10.75 on the St. Joseph subdivision.

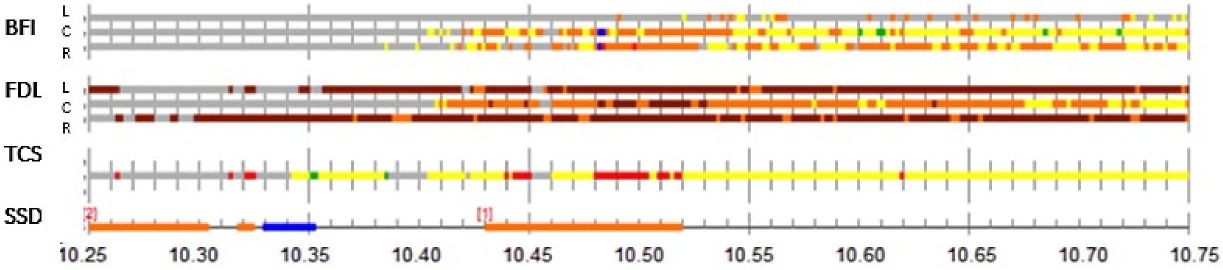


Figure 46. Ballast Conditions Derived from GPR Data

Figure 46 shows the BFI varies significantly over half a mile from Moderately Clean to Highly Fouled with most of the zone labeled Moderately Fouled. The FDL varies through the zone with Very Poor being the predominant rating near MP 10.49 indicating little clean ballast supporting the ties. To indicate that the SSD has mud spots present, the TCS summary rating is Poor at MP 10.49.

5.3 Results

This section first presents results of soil sampling and the GPR survey. This gives an overall assessment of the ballast condition at the long-term monitoring sites. Then the results presented the analysis of DE. The remaining subsections show the effects of rainfall, temperature, and remediation on ballast performance.

5.3.1 Fouling Material Properties

Table 9 gives the properties of samples of fouling material taken at various times from the six long-term monitoring sites. Researchers tested the samples using ASTM D4318 (ASTM, 2017).

Table 9. Site Water Content and Material Properties

Site	Date	Location	Water Content (%)	Fines Content (%)	Liquid Limit (%)	Plastic Index (%)
Parkville	12/5/2017	Ballast surface	17.8	67	39	19
	4/6/2018	Ballast surface	9.4	58	25	20
	5/1/2018	Ballast surface	44.1	83.7	37	14
	5/22/2018	1 inch below subgrade	-	-	33	10
	5/22/2018	9 inch below subgrade	-	-	43	13
	5/22/2018	10 inch below subgrade	-	-	42	22
	11/6/2018	Subgrade pumping	-	-	46	19
	11/6/2018	Subgrade pumping, west tie	-	-	69	45
Waldron	12/5/2017	Ballast surface	24	76	35	14
	5/1/2018	Ballast surface	2.7	71.2	25	14
	5/22/2018	Ballast surface	3.8	45.3	22	6
	5/16/2019	Ballast surface			28.9	8.8
Hickman	3/20/2018	Ballast surface	32.7	94	51	27
	7/30/2018	Ballast surface	59.3	-	51	21
	11/5/2018	Ballast surface	-	-	56	33
	10/31/2019	Ballast surface	-	-	50.6	30.3
	2/13/2020	Ballast surface	46.7	-	45.2	19.5
	5/27/2020	Ballast surface	-	-	42.6	17.5
Roca	2/20/2018	Ballast surface	-	-	46	23
	4/29/2020	Ballast surface	-	-	21.1	3.7

Table 9 shows the water content of the fouling material was at or near the liquid limit at the time of sampling, which is a high water content indicating poor drainage. Since the liquid limit is an indicator of the water content at which a soil behaves as a liquid rather than a solid, this indicates the ballast was not providing much support because of its low shear strength and high compressiblity.

Figure 47 shows a plasticity chart with the results for the 20 fouled ballast samples in Table 9.

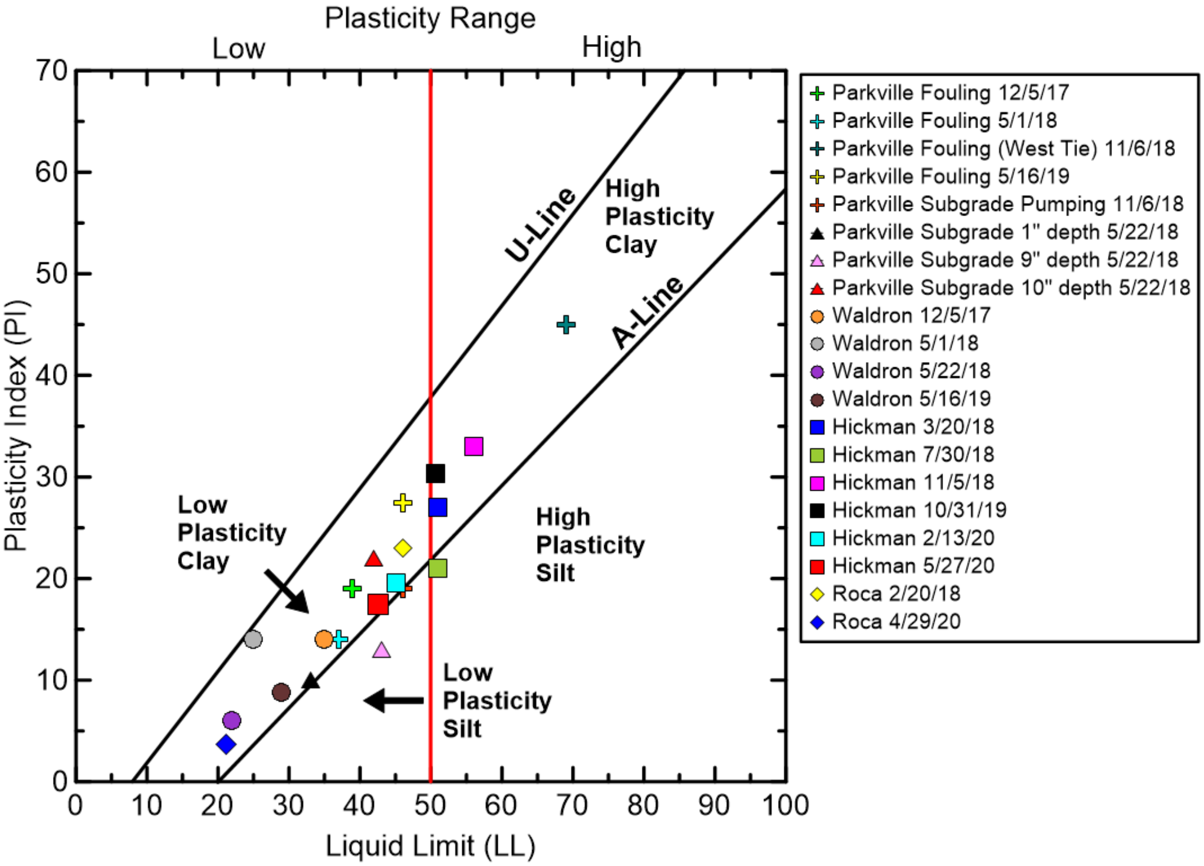


Figure 47. Plasticity Chart for all Sites and Dates

The classification of most fouling samples is a low plasticity clay except for three samples collected from Hickman and one from Parkville, which classify as a high plasticity clay. The classification of high plasticity indicates the soil behaves in a plastic manner over a large range of water contents. The characterization of plastic behavior is by large deformations at constant stress and generally low shear strength.

Figure 48 summarizes the results of the trackbed inspection at the Parkville long-term monitoring site. The location of the wayside instrumentation monitoring site at Parkville is MP 9.85.

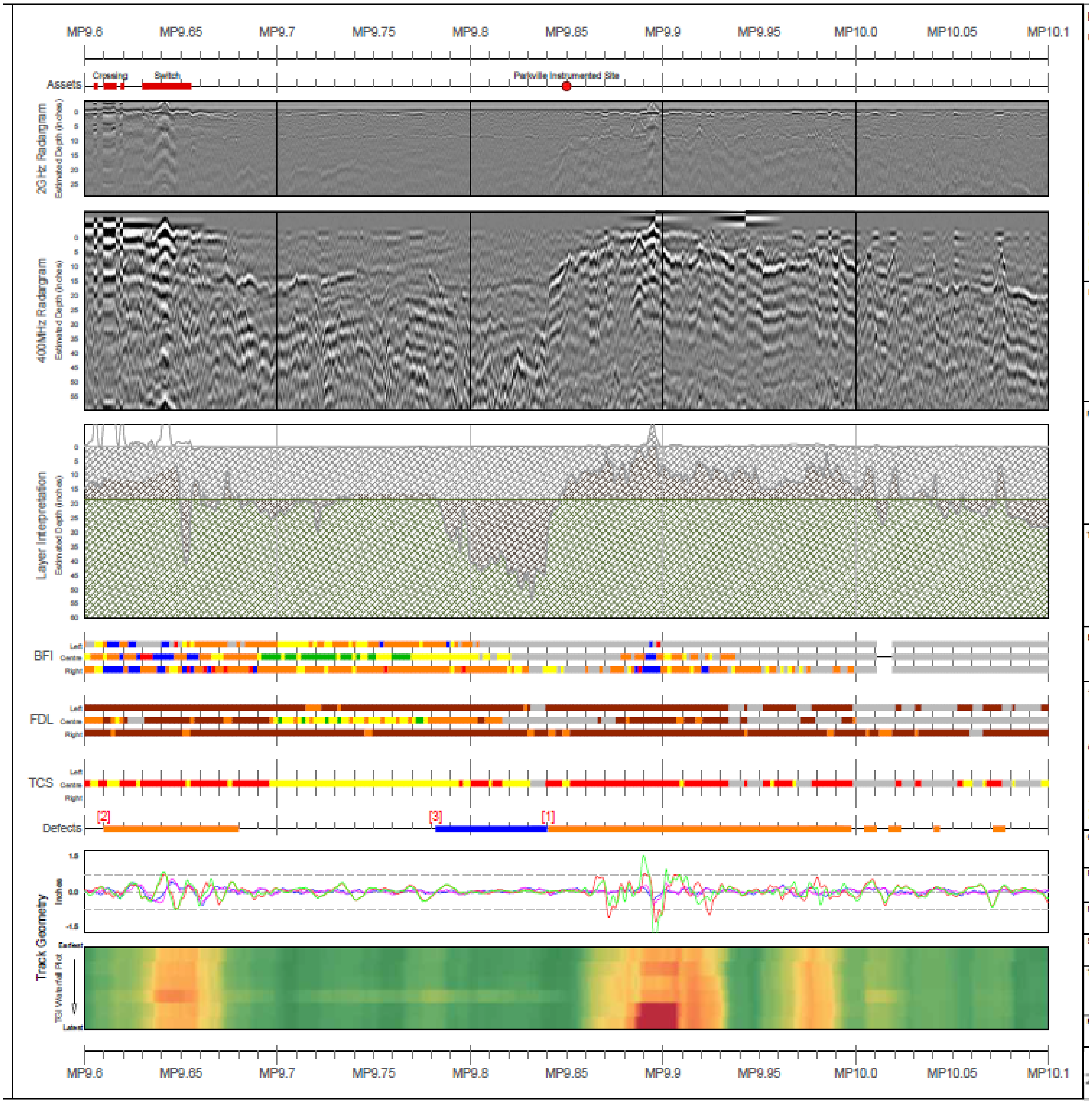


Figure 48. Trackbed Inspection Results at Parkville

The plain grey zone in the 400 MHz GPR data between MP 9.7 an 9.9 in Figure 48 shows the ballast layer near the monitoring site is shallow with clean ballast extending barely below the bottom of the ties. Under the thin layer of ballast there is a zone of mixed sub-ballast and subgrade. The sub-ballast is most likely old fouled ballast. The intermixing of the fouled ballast and the subgrade indicates instability in the track support layers. A deep zone of ballast can be seen between MP 9.78 and 9.83 adjacent to the site.

The BFI data was not available at the site likely due to electromagnetic interference. The FDL data in Figure 48 is consistently Very Poor on the left and Poor on the right side of the track. Data from the track center was not available at the monitoring site. The Track Condition

Summary (TCS) rating is Moderate close to the monitoring site with ratings of Poor on either side. This is consistent with the shallow ballast thickness in the zone. Identified subsurface defects include mud spots and ballast pockets near the monitoring site.

Track geometry profile variations near the monitoring site seem to be localized to a zone between MP 9.86 and 9.93. The TQI waterfall plot shows gradually deteriorating conditions close the monitoring site.

Figure 49 summarizes the results of the trackbed inspection around the Waldron long-term monitoring site. The location of the wayside instrumentation monitoring site at Waldron is MP 17.2.

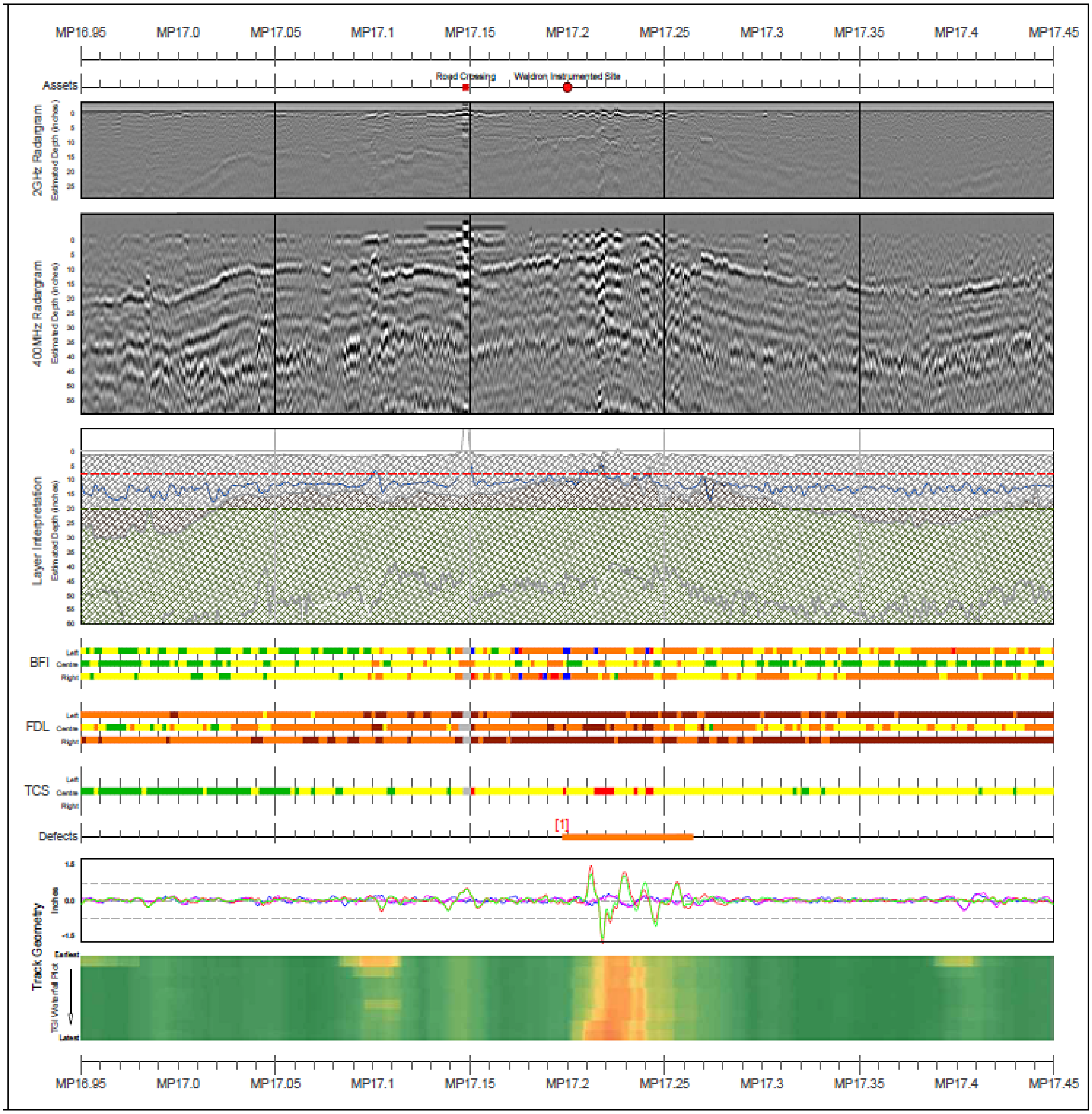


Figure 49. Trackbed Inspection Results at Waldron

Figure 49 shows the ballast layer near the monitoring site at Waldron (MP 17.2) is shallow with ballast extending just over 2 inches below the bottom of the ties. The ballast thickness is a minimum near to MP 17.2. GPR indicates that the interface to the natural soil subgrade is at a depth of 35 to 45 inches along this zone.

The BFI data indicates Moderate ballast fouling, while the FDL rating is Very Poor on both the left and right while varying from Poor to Very Poor in the track center. The TCS rating is Moderate for a short distance with ratings of Poor on either side. Mud spots are indicated between MP 17.20 and 17.26.

Track geometry profile variations are localized to a zone between MP 17.21 and 17.24. This coincides with the zone of thin ballast. There is a slight deterioration of TQI at the monitoring site.

Figure 50 summarizes the results of the trackbed inspection around the Hickman long-term monitoring site. The location of the wayside instrumentation monitoring site at Hickman is just prior to MP 192.8.

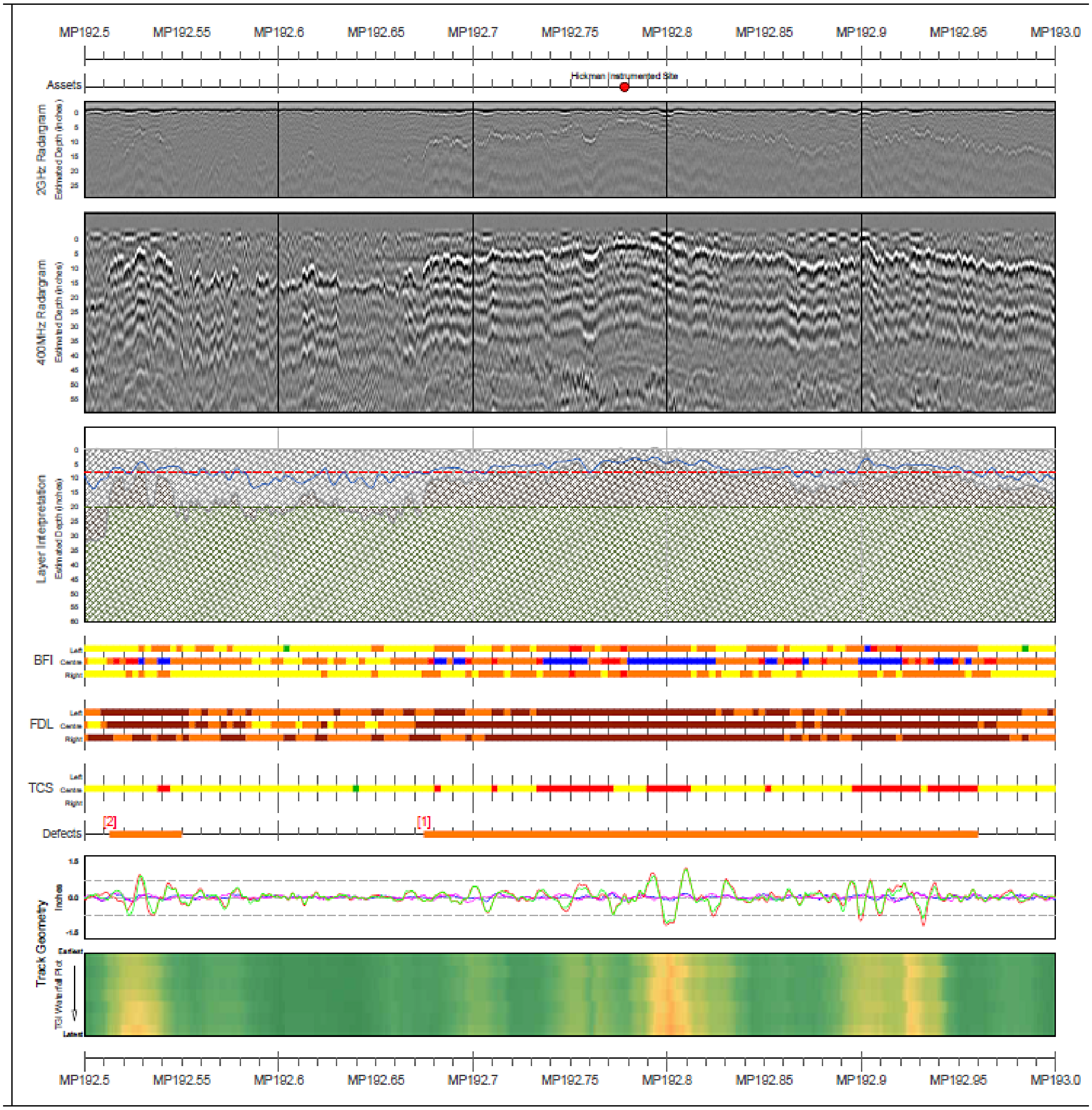


Figure 50. Trackbed Inspection Results at Hickman

Figure 50 shows the ballast layer near the monitoring site (i.e., MP 197.7) is shallow with ballast extending just over 5 inches from the track surface. This means fouled ballast starts 3 inches above the bottom of tie and extends down to the subgrade.

The BFI data shows Moderately Clean ballast shoulders with Highly Fouled ballast in the track center. The FDL is Very Poor and the TCS is Moderate for a short distance with Poor to either side. Mud spots are indicated around the monitoring site.

Track geometry profile variations are present in the area around the monitoring site. They coincide with the section with the thinnest ballast layer. GPR was not recorded at the Hickman control site at MP 196.11.

Figure 51 summarizes the results of the trackbed inspection around the Roca long-term monitoring site. The wayside instrumentation monitoring site at Roca is at MP 196.3. The control site at Roca is at MP 196.1.

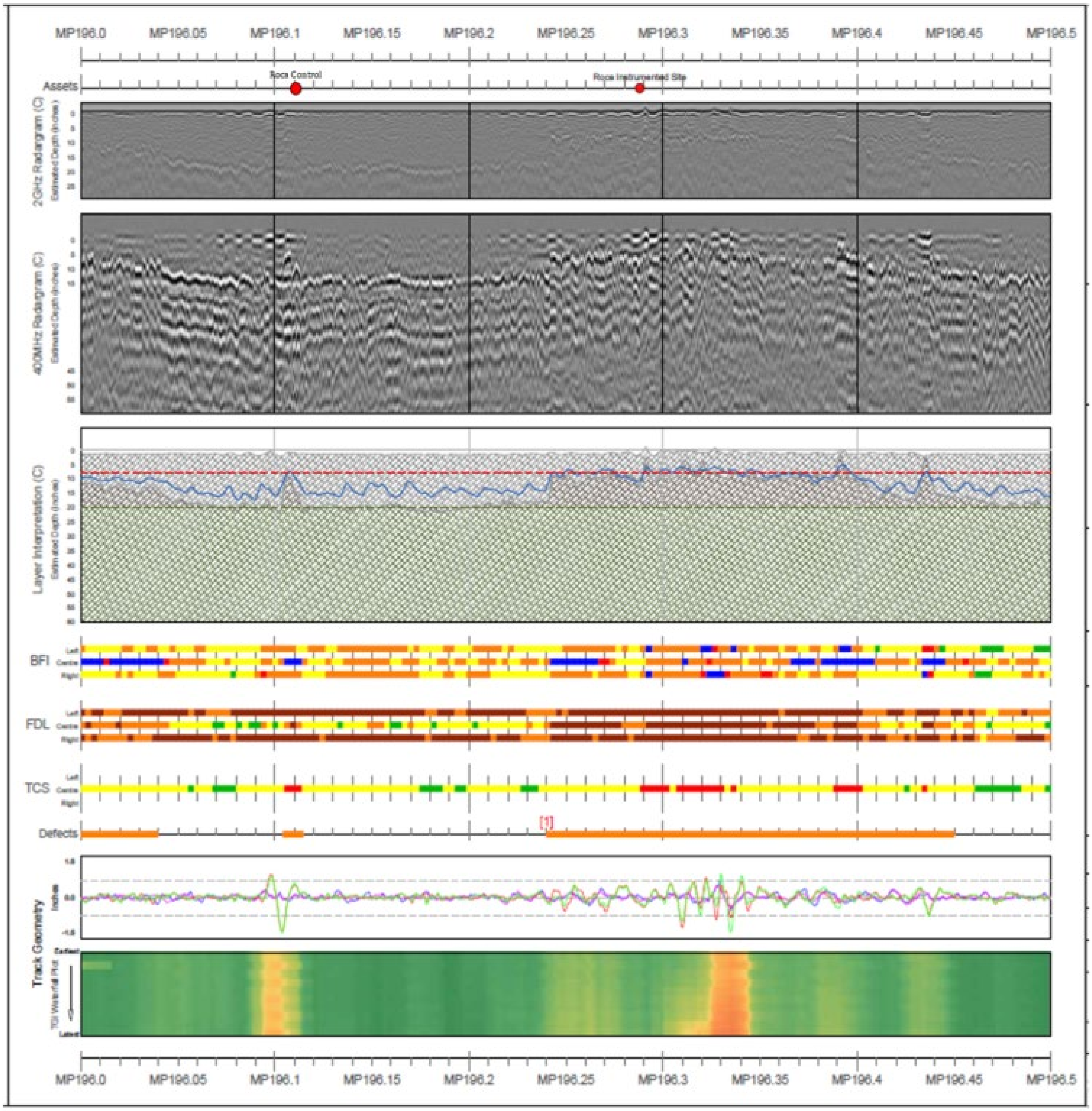


Figure 51. Trackbed Inspection Results at Roca

Figure 51 shows the ballast layer at the control site has Moderate fouling with Very Poor FDL. The TCS changes from Moderate to Poor at this location with mud spots indicated. Track geometry has some variation, but the TQI waterfall plot indicates the geometry at MP 196.1 is stable.

Figure 51 shows the ballast layer around the monitoring site is shallow with ballast extending to about the bottom of tie and a mixture of sub-ballast and subgrade below. The ballast depth changes from approximately 15 inches to approximately 8 inches at MP 196.24.

The BFI data varies significantly over a short distance from Moderately Clean to Highly Fouled, while the FDL is predominantly Very Poor. The TCS is Poor at Roca. Mud spots are present between MP 196.24 and 196.45.

There are track geometry profile variations near the control site and the monitoring site. The extended zone of track geometry variations around the monitoring site coincides with the zone of thinnest ballast.

Table 10 summarizes the condition of the ballast at the six long-term monitoring sites.

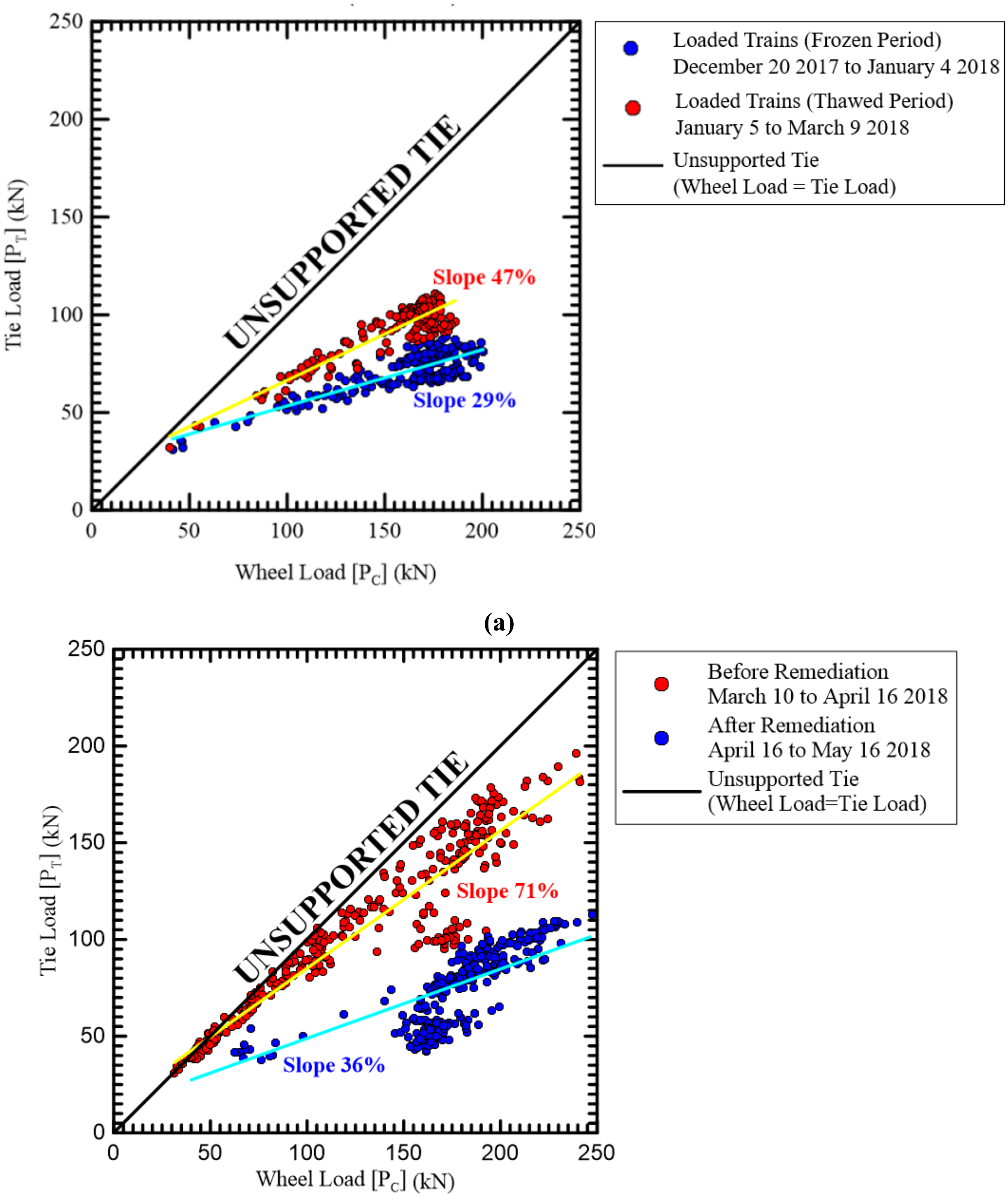
Table 10. Site Ballast Conditions

Site*	Fouling Material	Notes
Parkville (F)	Low and high plasticity clay	Shallow and irregular ballast to sub-ballast interface. Mud spots and ballast pockets. The material pumped up from the subgrade is high plasticity clay. That from the surface of the ballast and various depths in the subgrade is low plasticity clay.
Waldron (F)	Low plasticity clay	Shallow ballast and mud spots
Hickman (C)		No fouling
Hickman (F)	Medium plasticity clay	Shallow ballast, mud spots, and high subsurface moisture content
Roca (C)		No fouling
Roca (F)	Low plasticity clay	Shallow ballast, mud spots, with pockets of high moisture content in the substructure

* - F indicates a monitoring site, C indicate a control site

5.3.2 Distribution Efficiency

Researchers analyzed DE at the Parkville long-term monitoring site to investigate the effects of traffic loading and ballast condition on track stiffness. Figure 52 shows charts of the distributed tie load (P_T) against the wheel load measured at the crib (P_C). DE is the slope of the line in these charts. The diagonal line in the charts represents an unsupported tie for which P_T equals P_C and DE = 100%.



(a)

(b)

Figure 52. Tie Load vs. Wheel Load Change due to Seasonal Variation (a), Tie Load vs. Wheel Load Change due to Ballast Remediation (b)

Figure 52(a) shows the DE when the ballast was frozen (from December 20, 2017, to January 4, 2018) was 29 percent. It changed to 47 percent when the ballast thawed (from January 5, 2018, to March 9, 2018). Frozen fouling material causes a high overall track stiffness as the ballast is more readily engaged and stiffer. On the other hand, the thawing process decreases the tie support by about 18 percent which implies that the rail is distributing more load to adjacent ties instead of transferring it to the tie and ballast.

On March 8, 2018, in a period when ambient temperature was above freezing, the site at Parkville was remediated by surfacing. Comparing the data plotted in red in Figure 52(a) with Figure 52(b) shows that remediation changed DE from 47 to 71 percent. This increase in DE means the track stiffness reduced indicating reduced track support and more load distributed to adjacent ties.

Ambient temperature dipped below freezing in late March and early April 2018. On April 16, 2018, after the spring thaw, the site at Parkville was remediated again by surfacing. Figure 52(b) shows that before remediation the DE was 71 percent. After remediation, the DE changed to 36 percent. The reduction in DE means the ballast support improved and the track stiffness increased.

5.3.3 Effects of Rainfall

Figure 53 shows rainfall and soil moisture from May 2018 to December 2018 at the Waldron long-term monitoring site. This site had concrete ties. Daily rainfall is plotted on a linear scale with rainfall events noted as bars with a peak of 6.5 inches on October 9, 2018. The vertical lines in Figure 53 note the dates of performance when undercutting and surfacing. The filled circles depict the subsurface moisture sensor readings.

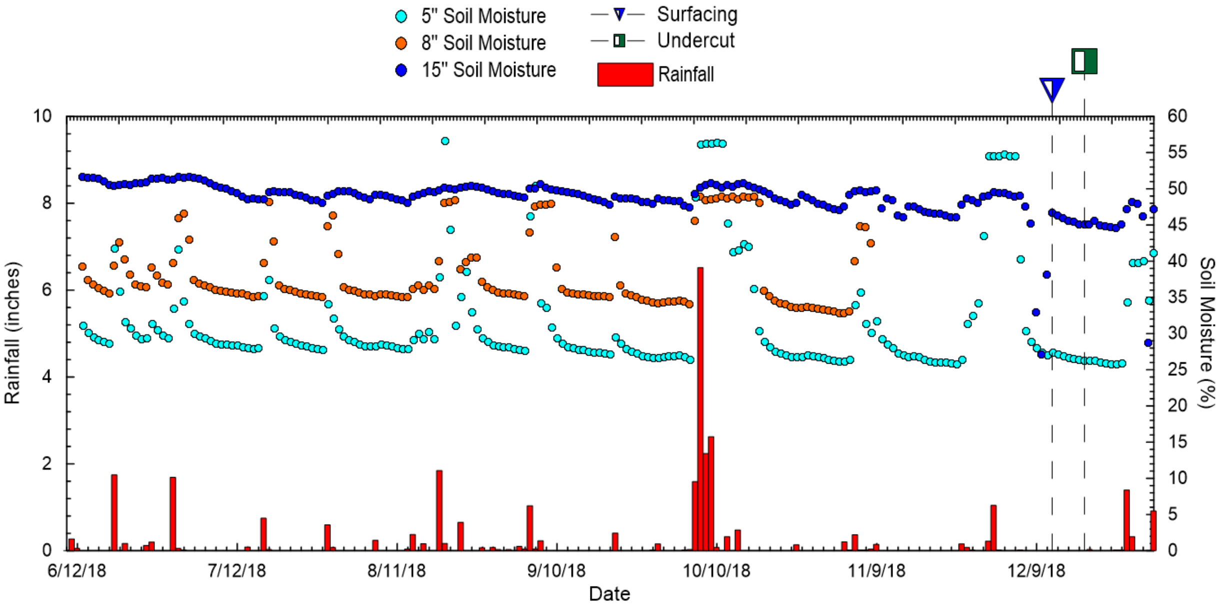


Figure 53. Effects of Rainfall on Soil Moisture at Waldron (concrete ties)

Figure 53 clearly show increases in soil moisture after rainfall followed by gradual drying out until the next rainfall. The rate of reduction in soil moisture at different depths indicates the ballast's ability to drain. In this case the moisture content increases with depth below the surface of the ballast. The increase in soil moisture and rate of reduction after rain are highest near the surface and lowest at the deepest location.

Three time periods in Figure 53 give insights into the effects of rainfall on moisture in the ballast:

- Before and during August 20, 2018, there was moderate rainfall (1.8 inches). Soil moisture measured at depths of 5, 8, and 11.5 inches increased sharply and stayed relatively high for a few days and then decreased gradually over the following days.
- Around September 5, 2018, there was light rainfall (1 inch). This caused soil moisture to increase and stay relatively high for approximately 4 days.
- Starting on October 7, 2018, heavy rainfall occurred for several days. Soil moisture measured at all depths increased and stayed high for 5 days.

This variation in behavior indicates that moisture content in the fouled ballast depends on more than rainfall.

Figure 54 shows changes in soil moisture and distributed tie loads, P_T, at the Waldron long-term monitoring site for the same time period as that shown in Figure 53. The solid pink line in Figure 54 is the average distributed tie load for the control site at Roca, which also has concrete ties. It indicates the support expected at a concrete tie site with clean ballast. The red line is the average wheel load (i.e., measured in the crib) at Waldron. It indicates the distributed tie load for an unsupported tie at this site.

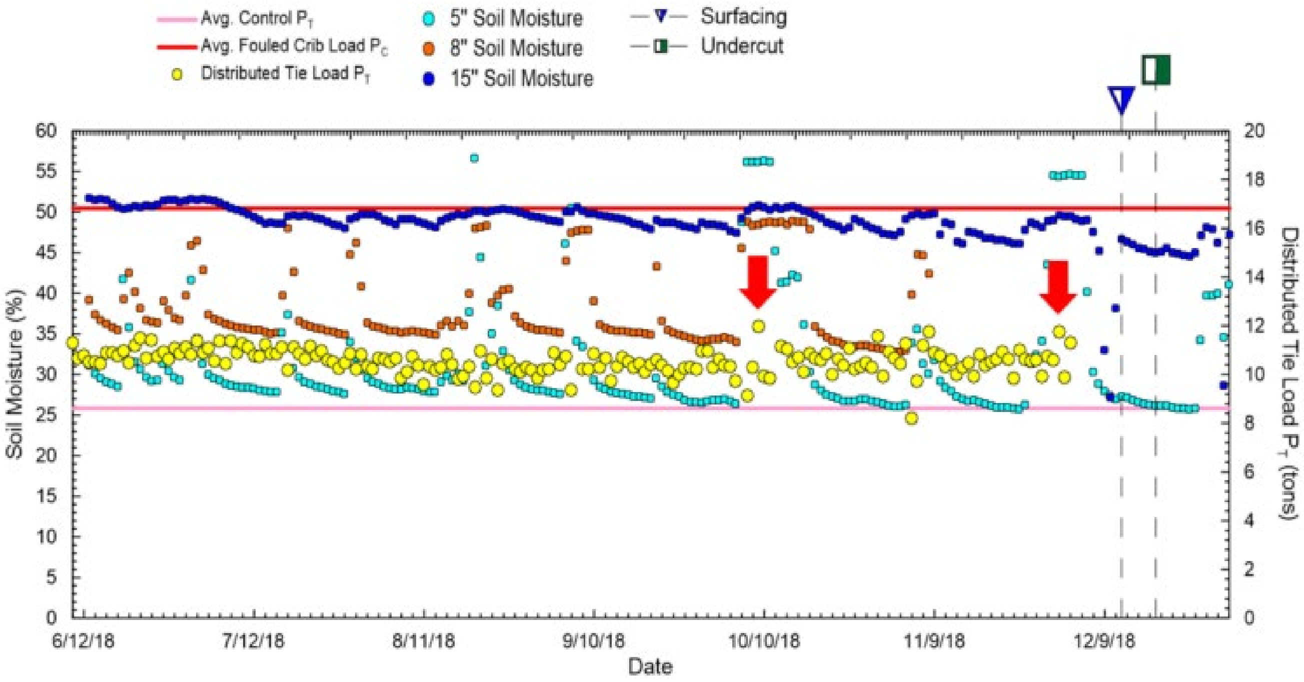


Figure 54. Effects of Soil Moisture on Distributed Tie Loads at Waldron (concrete ties)

Figure 54 shows sustained increase in soil moisture will result in an increase in distributed tie load and hence decrease in support provided by the ballast. This can be observed in the rainfall events in early October 2018 and late November 2018. The distributed tie load increases indicated by the red arrows in Figure 54 correspond to a sustained soil moisture increase measured at 5 inch depth.

Figure 55 shows rainfall and soil moisture from September 2017 to July 2018 at the Hickman long-term monitoring site. This site had timber ties. The vertical line in Figure 55 shows when machine tamping was performed on October 28, 2017.

The variation in moisture content in the winter of 2017/18 is due to freezing and thawing as explained in Section 5.3.4.

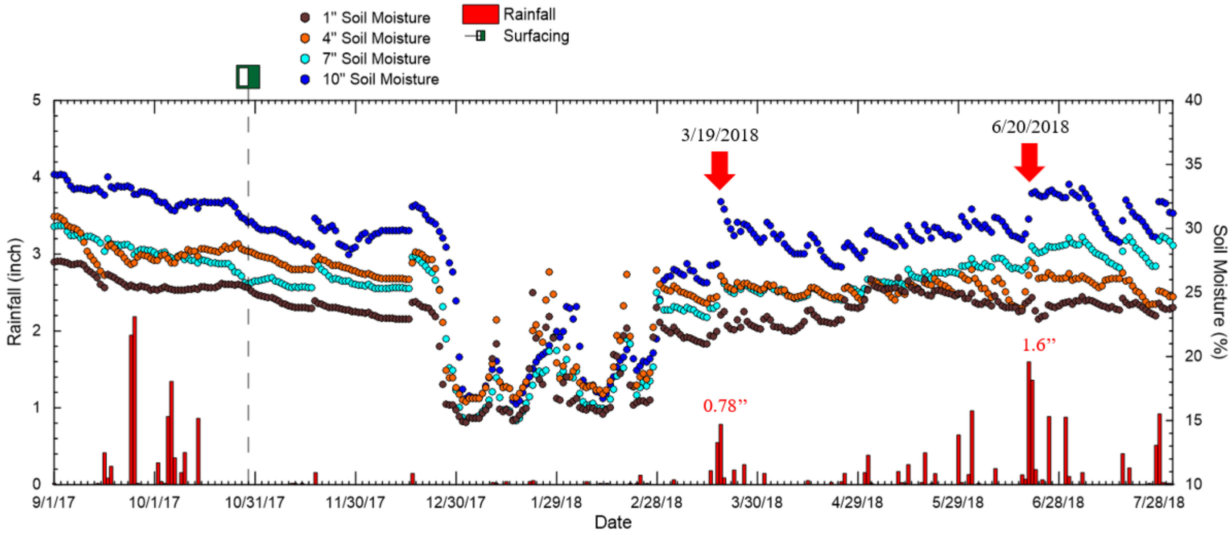


Figure 55. Effects of Rainfall on Soil Moisture at Hickman (timber ties)

In some time periods in Figure 55 the soil moisture did not increase continuously with depth. In November 2017, for example, the soil moisture at 4 inches was greater than that at 7 inches. This is likely due to fouling at intermediate depths below the ballast surface.

Figure 55 clearly shows increases in soil moisture after rainfall followed by gradual drying out until the next rainfall. The periods of heavy rainfall around March 19, 2018, and June 20, 2018, were followed by significant increases in soil moisture, particularly at the lower depths.

Figure 55 also shows the rain in October 2017 did not cause an increase in soil moisture. Before surfacing on October 28, 2017, the ballast was saturated and was not draining. The surfacing caused the ballast to start draining and respond to rainfall in a more natural way.

Figure 56 shows changes in soil moisture and distributed tie load, P_T, at the Hickman long-term monitoring site for the same time period as that shown in Figure 55. The solid pink line in Figure 56 is the average distributed tie load for the control site at Hickman, which also has timber ties. It indicates the support expected at a timber tie site with clean ballast. The red line is the average wheel load (measured in the crib) for the fouled site at Hickman. It indicates the distributed tie load for an unsupported tie at this site.

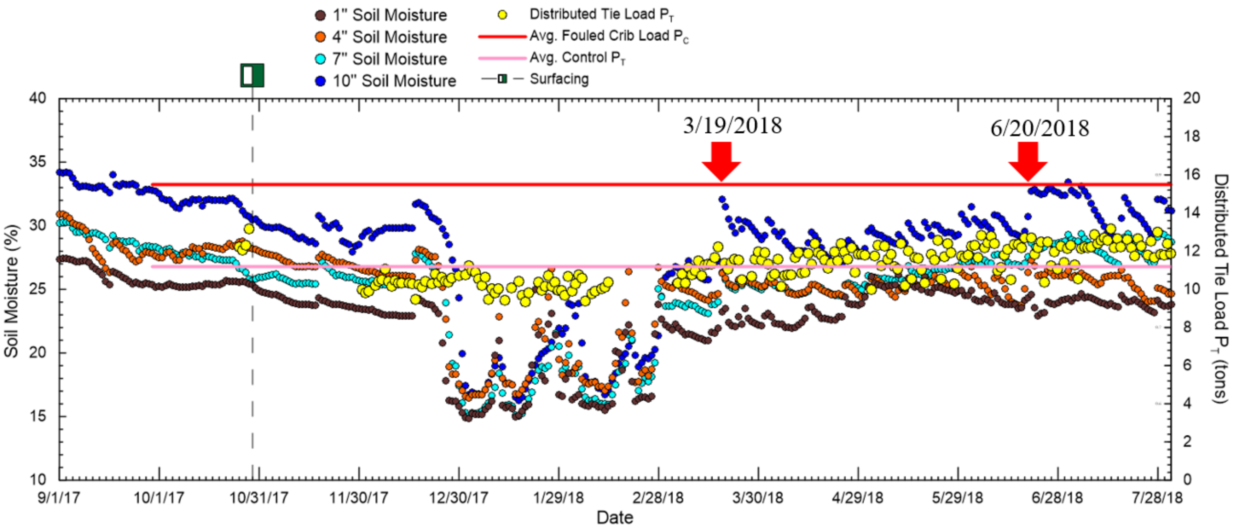


Figure 56. Effects of Soil Moisture on Distributed Tie Loads at Hickman (timber ties)

Figure 56 shows no sudden changes in distributed tie load when the moisture content increased on March 19, 2018, and June 20, 2018. Thus, the distributed tie load results show rainfall and soil moisture did not affect track stiffness at the Hickman timber tie site.

5.3.4 Effects of Freezing and Thawing

This subsection investigates the effects of freezing and thawing on moisture content, distributed tie loads, and track stiffness. The weather stations at the long-term monitoring sites measured the ambient air temperature. The ballast temperature was not directly measured, hence there might be a discrepancy and lag between these two temperatures. In general, field observations showed it takes up to 7 days to freeze the moisture in the fouling material but only 1 to 3 days for it to thaw.

Figure 57 shows temperature and moisture content for the time period between November 2017 and June 2018 at the Hickman long-term monitoring site. This site had timber ties. The dashed pink line is the freeze-thaw boundary at 32 °F.

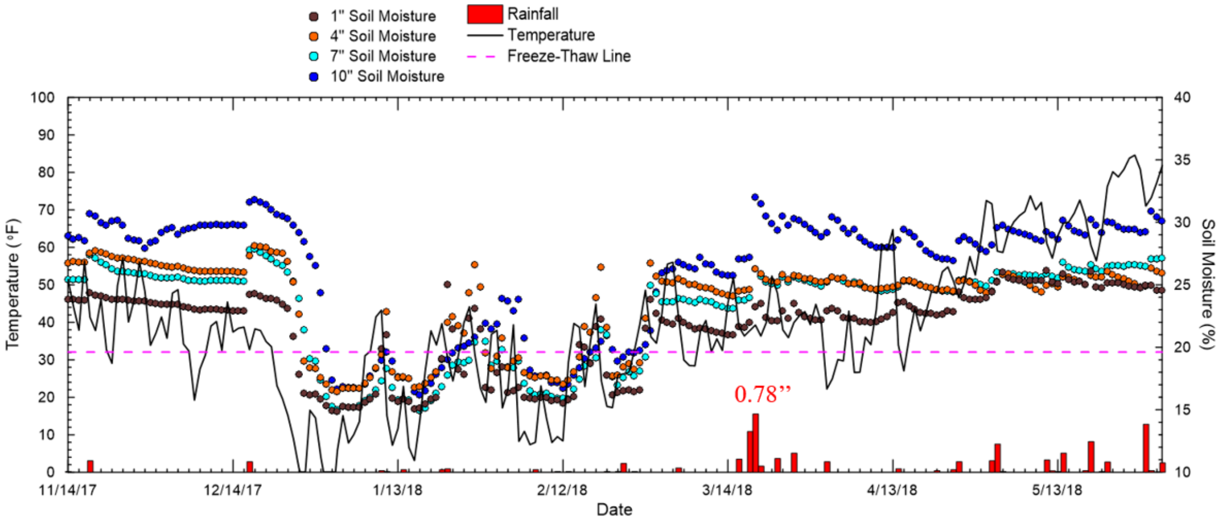


Figure 57. Effect of Ambient Temperature on Moisture Content at Hickman (timber ties)

Figure 57 shows soil moisture measured by the sensors drops during periods when the ambient temperature is below freezing for long enough for the ballast to freeze. This is due to the reduction in output from the sensors when the water in the fouling material goes from the liquid to solid state.

Figure 58 shows temperature and distributed tie load, P_T, for the time period between November 2017 and August 2018 at the Waldron long-term monitoring site. This site had concrete ties. The dashed pink line is the freeze-thaw boundary at 32 °F. Changes to distributed tie loads during freezing in January and February 2018 are indicated by blue dashed lines while the changes during thawing are indicated by the red dashed lines.

The solid pink line in Figure 58 is the average distributed tie load for the control site at Roca, which also has concrete ties. It indicates the support expected at a concrete tie site with clean ballast. The red line is the average wheel load (measured in the crib) at Waldron. It indicates the distributed tie load for an unsupported tie at this site.

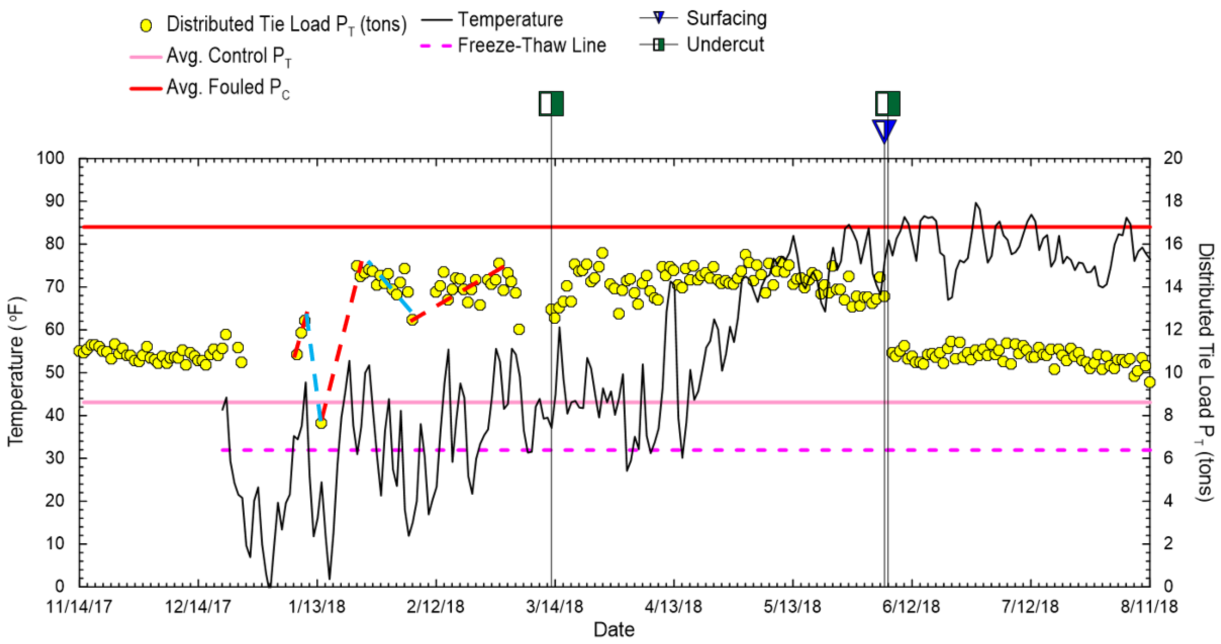


Figure 58. Effect of Ambient Temperature on Distributed Tie Loads at Waldron (concrete ties)

Figure 58 shows the ambient temperature was low for several days around January 13, 2018. This could be expected to cause the ballast to freeze. At this time there was a reduction in distributed tie load. A similar effect can be seen when the temperature dropped for several days before February 12, 2018. Together, these observations illustrate the increase in track stiffness when fouled ballast freezes.

Figure 58 shows the ambient temperature was above freezing for several days after January 13, 2018. This could be expected to thaw the ballast. At this time there was an increase in distributed tie load. A similar effect can be seen when the ballast thawed after February 12, 2018. Together, these observations illustrate the reduction in track stiffness when fouled ballast thaws.

Figure 59 shows the temperature and distributed tie load, P_T, for the time period between September 2017 and April 2018 at the Roca long-term monitoring site. This site had concrete ties, as did the site at Waldron, but the degree of ballast fouling was less than at Waldron.

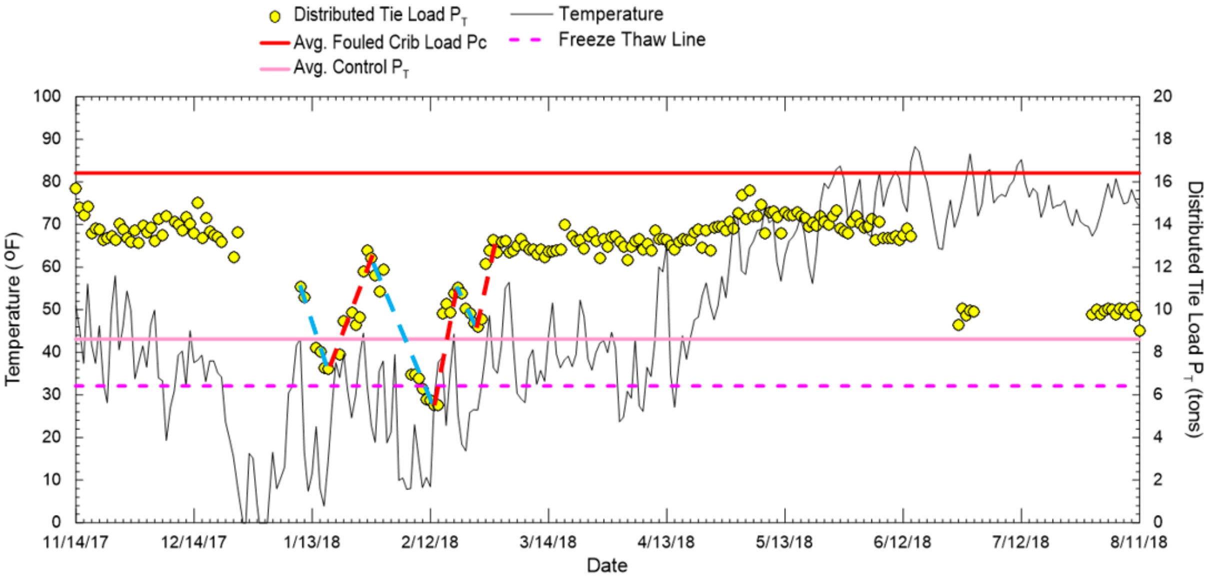


Figure 59. Effect of Ambient Temperature on Distributed Tie Loads at Roca (concrete ties)

Changes during thawing periods are indicated by red dashed lines in Figure 59, while changes during freezing periods are indicated by the blue dashed lines. Comparing Figure 59 with Figure 58 it can be seen that the effects of freezing and thawing on distributed tie load tend to be smaller when the ballast is less fouled. This is attributed to the fact that the plasticity index of the fouling material at Waldron was lower than that at Roca (see Table 9). The higher plasticity index at Roca allowed the fouling material to absorb more moisture than at Waldron. The expectation of the higher moisture content can result in higher stiffness on freezing and higher compressibility on thawing.

Figure 60 shows temperature and distributed tie load, P_T, for the time period between November 2017 and August 2018 at the Hickman long-term monitoring site. This site had timber ties.

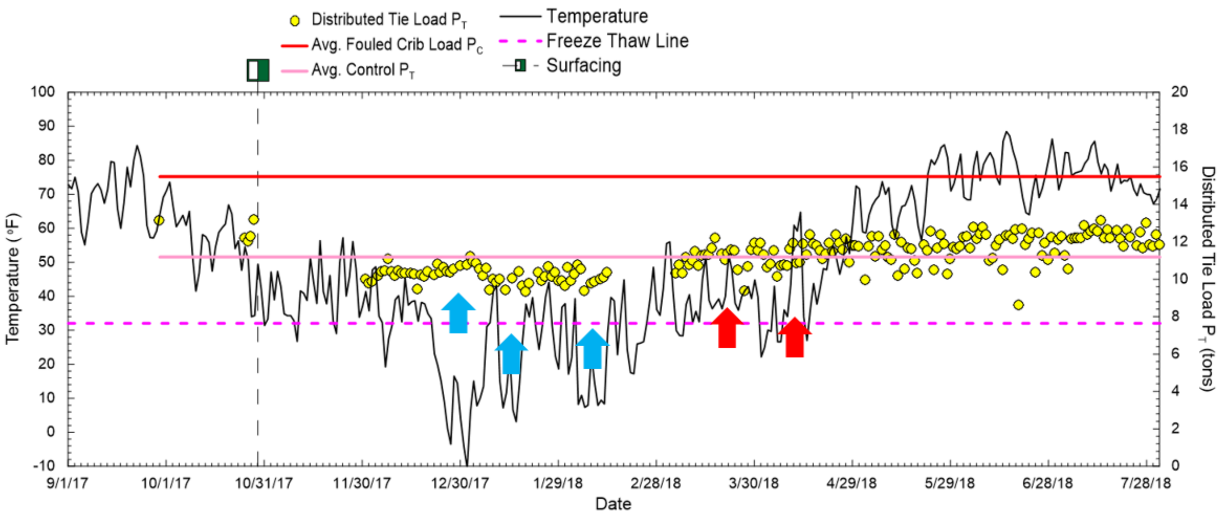


Figure 60. Effect of Ambient Temperature on Distributed Tie Loads at Hickman (timber ties)

The three blue arrows in Figure 60 show periods when the ambient temperature was below freezing for several days and researchers expected the ballast to have been frozen. The two red arrows show periods when the ambient temperature was above freezing for several days and the expectation of the ballast is that it thawed.

Freezing and thawing do not appear to have a significant effect on distributed tie load at the Hickman site on timber ties. Thus, these temperature cycles do not appear to affect track stiffness at this site.

Figure 61 shows wheel loads plotted against transient rail displacements at the Parkville long-term monitoring site. This site had concrete ties and a similar degree of ballast fouling as at Waldron. Results are shown separately for loaded freight cars (blue symbols) and lightly or unloaded freight cars (red symbols) at different periods in the freeze-thaw cycle. The frozen period was from December 20, 2017, to January 4, 2018, when the ambient temperature was continuously below freezing. The thaw period was from February 26, 2018, to April 10, 2018, when the ambient temperature was continuously above freezing.

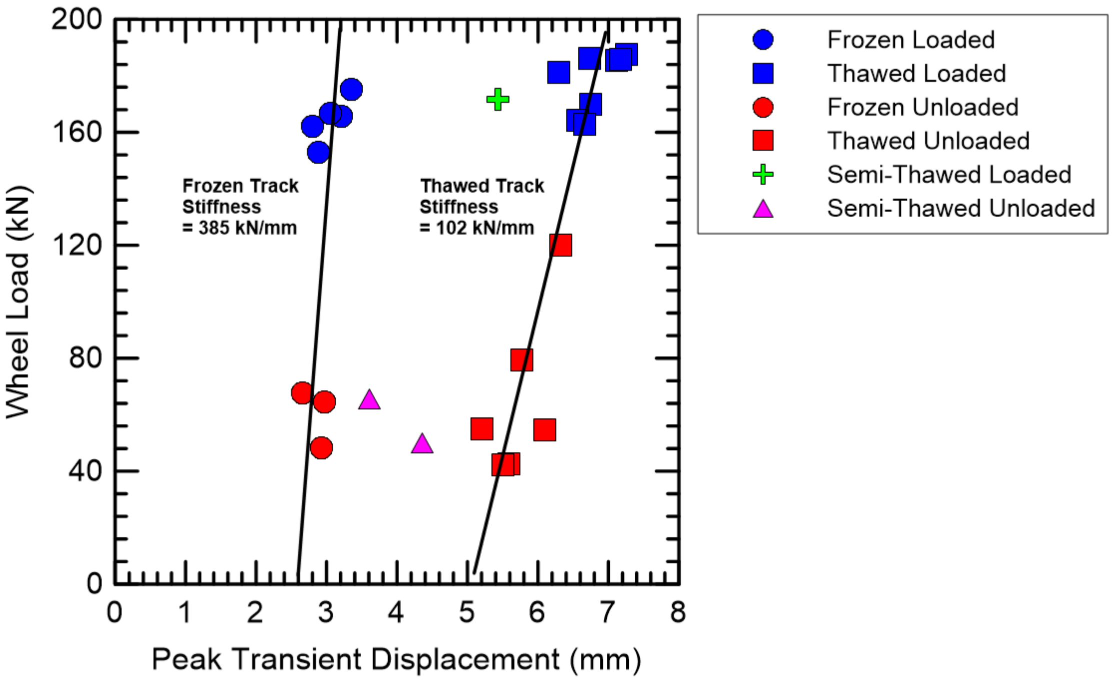


Figure 61. Effect of Temperature on Track Stiffness at Parkville (concrete ties)

Figure 61 shows the calculated track stiffness is four times greater for the frozen period (385 kN/mm) than the thawed period (102 kN/mm), indicating the expected higher track stiffness when frozen.

5.3.5 Effects of Remediation

The research team performed several different types of ballast remediation at the long-term monitoring sites while data was being gathered. These included:

- Undercutting – An on-track machine lifts and holds the rail and ties while a cross-cutting bar removes material from under the track. The material is picked up and separated by particle size to either be returned to the track structure or wasted. Subsequent surfacing is performed to restore track geometry.
- Surfacing – Lifting and lining the track structure with an on-track tamping machine to restore track geometry. Ballast under the ties is repositioned but not replaced. After the tamper has finished, additional ballast may be added to fill in between the ties. The new ballast is subsequently redistributed, compacted and the track bed and shoulder profiles are restored.
- Machine Tamping – A process used during surfacing. It may also be performed independently without lifting the track structure, and usually no shoulder maintenance.

Table 11 shows the remediation performed at the long-term monitoring sites during the waiver period.

Table 11. Track Remediations During Wayside Monitoring

Date	Type of Remediation
Parkville Site	
January 24, 2018	Surfacing
March 8, 2018	Surfacing
April 6, 2018	Broken rail repair with joint bars
April 16, 2018	Surfacing
May 16, 2018	Undercutting and initial surfacing
May 19, 2018	Rail Welded (joint bars removed)
June 6, 2018	Follow-up surfacing
July 22, 2018	Broken rail repair with joint bars
October 5, 2018	Surfacing
December 11, 2018	Undercutting and initial surfacing
December 13, 2018	Final surfacing
Waldron Site	
March 13, 2018	Surfacing
June 5, 2018	Undercutting and initial surfacing
June 6, 2018	Follow-up surfacing
December 12, 2018	Undercutting with initial surfacing
December 18, 2018	Follow-up surfacing
Hickman Fouled Site	
October 28, 2017	Machine tamping only
Roca Fouled Site	
June 21 2018	Surfacing (due to heavy rain)

This subsection discusses the effects of several of the remediations listed in Table 11 on the data gathered at the long-term monitoring sites.

Figure 62 shows the changes in distributed tie load, P_T, during the period between November 2017 and August 2018 at the Waldron long-term monitoring site. This site had concrete ties. The vertical lines and arrows in Figure 62 show when surfacing and undercutting were performed.

The pink line in Figure 62 is the average distributed tie load for the control site at Roca, which also had concrete ties. It indicates the support expected at a concrete tie site with clean ballast and good drainage. The red line is the average wheel load (i.e., measured in the crib) at Waldron. It indicates the distributed tie load for an unsupported tie at this site.

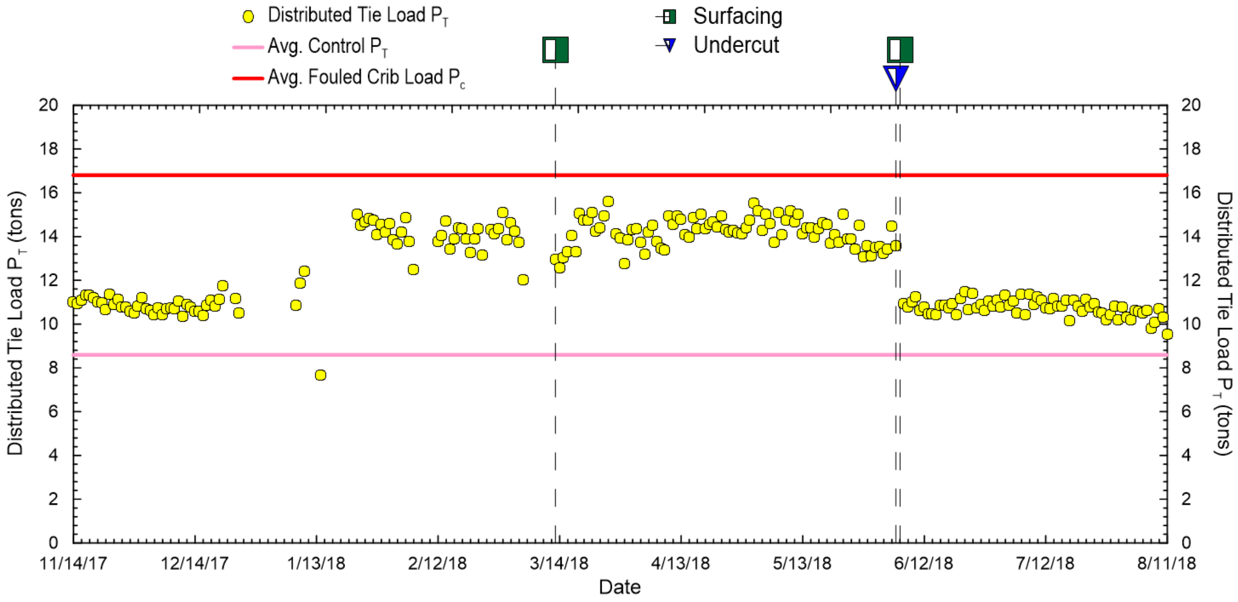


Figure 62. Effects of Remediation on Distributed Tie Load at Waldron (concrete ties)

Figure 62 shows surfacing on March 13, 2018, had little effect on distributed tie load. This remediation did not improve concrete tie support with fouled ballast. Section 5.3.4 discussed the lower value of distributed tie load for the data point just before surfacing was due to the fouled material freezing.

The undercutting and surfacing on June 5, 2018, reduced distributed tie load. This remediation improved the ballast support to the concrete tie. The improved support was close to that provided by clean ballast under the concrete ties at the Roca control site.

Figure 63 shows the changes in soil moisture at the Waldron long-term monitoring site for the same time period shown in Figure 62. Soil moisture is shown at various depths below the surface of the ballast. The variation in moisture content in the winter of 2017/18 is due to freezing and thawing as explained in Section 5.3.4.

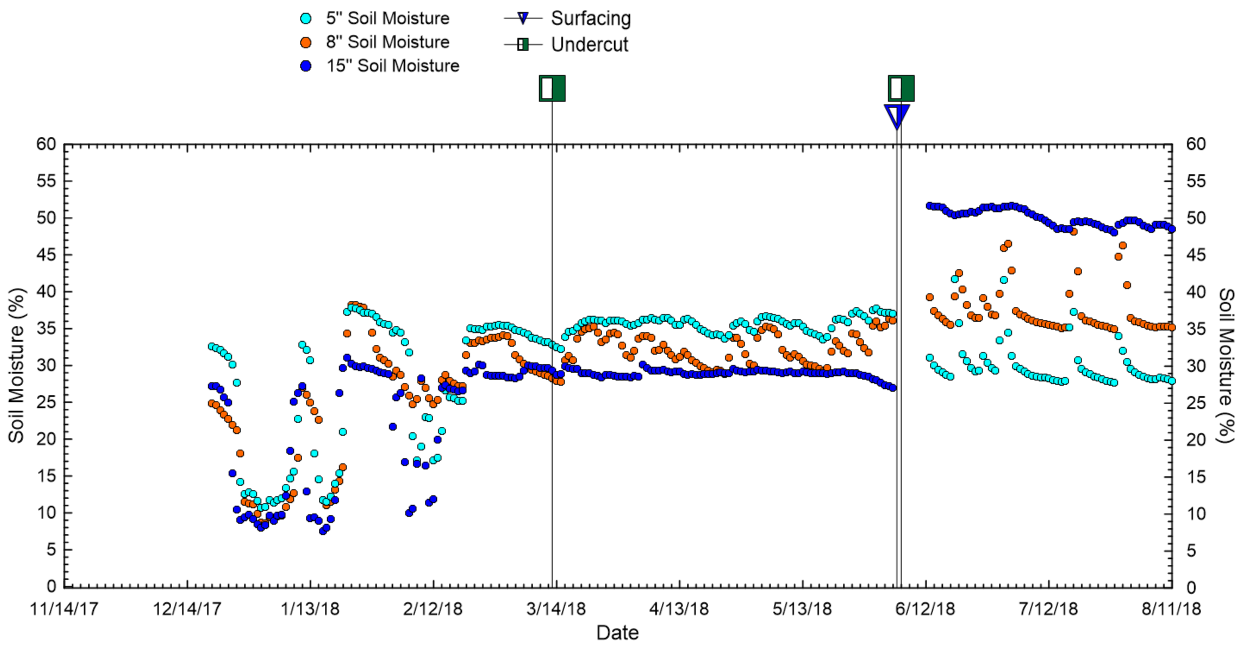


Figure 63. Effects of Remediation on Soil Moisture at Waldron (concrete ties)

Figure 63 shows the surfacing on March 13, 2018, produced little change in soil moisture at all depths. This is expected since the tamping operation during surfacing disturbs the ballast but does not replace it.

The undercutting and surfacing on June 5, 2018, and June 6, 2018, had some effect on soil moisture. Prior to remediation, the soil moisture at 5 inch depth was approximately 35 percent. It changed little after rainfall, which indicates poor drainage. After remediation, it reduced to 30 percent and continued to reduce with the improved drainage provided by the clean ballast.

Figure 64 shows the changes in distributed tie load, P_T, during the period between November 2017 and June 2018 at the Parkville long-term monitoring site. This site had concrete ties. The vertical lines in Figure 64 show when surfacing, undercutting and rail repair was performed.

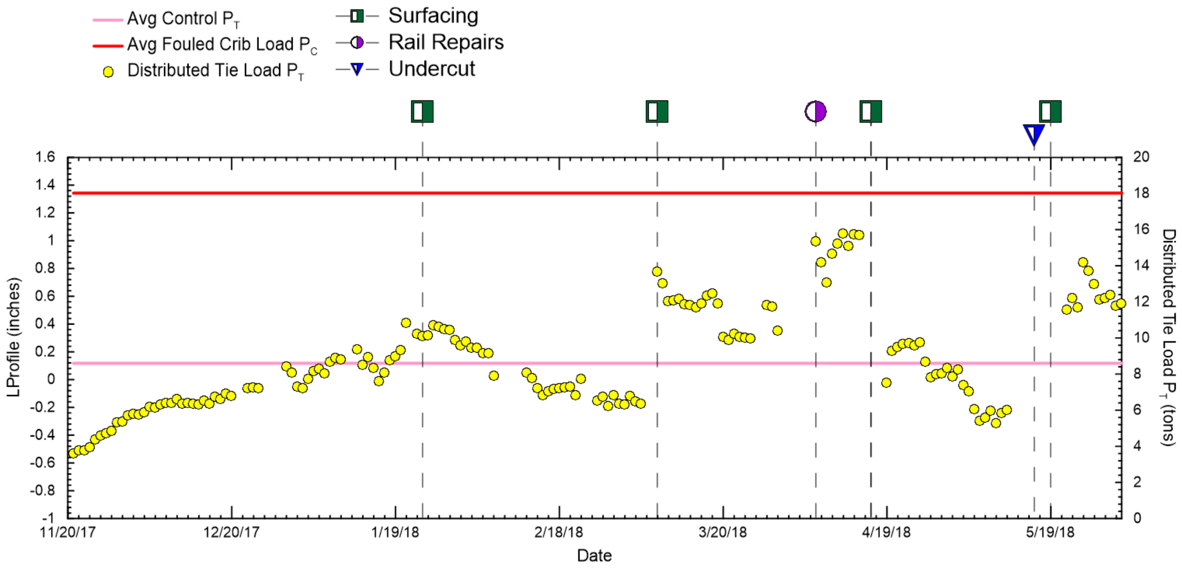


Figure 64. Effects of Remediation on Distributed Tie Load at Parkville (concrete ties)

Figure 64 shows that the performance of surfacing occurred on three separate occasions. On January 24, 2018, it had no effect on distributed tie load. On March 8, 2018, it increased distributed tie load, which indicates a reduction in tie support. On April 16, 2018, it reduced distributed tie load, which indicates an improvement in tie support.

Although data is not available immediately before and after the undercutting on May 16, 2018, it is possible that this remediation led to an increase in distributed tie load. Since final post-undercutting surfacing was not performed until a few weeks later, it is possible the new ballast was not fully compacted. This would explain the reduced support under the concrete ties after undercutting.

Figure 65 shows the changes in soil moisture at the Parkville long-term monitoring site for the same time period shown in Figure 64.

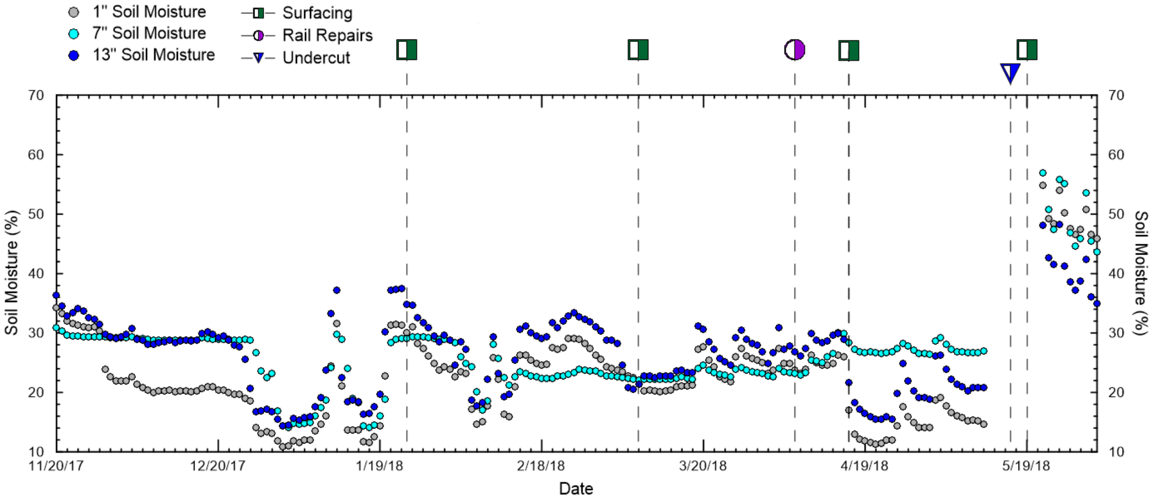


Figure 65. Effects of Remediation on Soil Moisture at Parkville (concrete ties)

Figure 65 shows the surfacing on January 24, 2018, was performed soon after the ballast thawed after being frozen for several days. After this remediation, the soil moisture gradually reduced. The surfacing on March 8, 2018, was at a time when the soil moisture was relatively low and resulted in no measurable difference in soil moisture. The surfacing on April 16, 2018, made a significant reduction in the soil's moisture at 1 and 13 inch depth, but it did not affect soil moisture at 7 inch depth.

Figure 66 shows the number of daily exceedances of 10 g tie acceleration for the same location and time period shown in Figure 64.

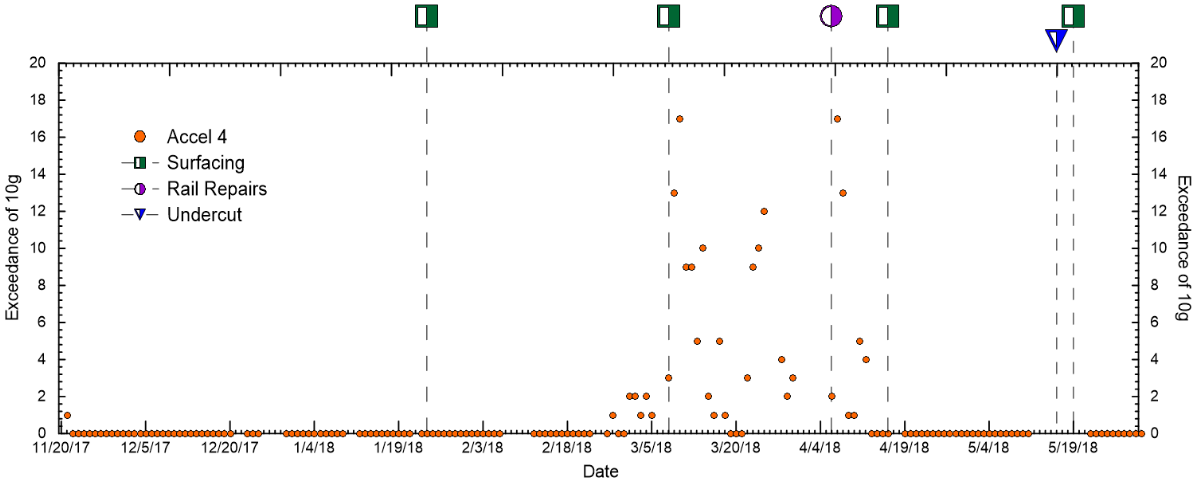


Figure 66. Effects of Remediation on Accelerations at Parkville (concrete ties)

The count of peak accelerations greater than 10 g increased after surfacing on March 8, 2018. This coincides with the increase in distributed tie load shown in Figure 64. It is likely due to the tie having weak support after the surfacing operation.

6. Discussion

Although it is generally agreed that ballast defects may not be an immediate safety hazard, they can degrade under additional traffic and weather conditions such as rainfall and thawing. For this reason, current regulations require remedial action at ballast defects within 30 days regardless of the track class, otherwise the track must be removed from service.

In some cases, operations may safely continue during the 30 days while the railroad monitors the fouled ballast condition and schedules maintenance. However, other fouled locations may experience more rapid degradation and greater displacement under traffic, requiring an immediate speed restriction or removal from service until repaired.

A waiver to the current regulation, granted by FRA and applied to two subdivisions on BNSF, allowed an alternative rule for managing fouled ballast to be evaluated. Railroad operations under the waiver were monitored and the behavior of track when the performance of the ballast is reduced. Railroad operations and the results of the research are discussed below. The discussions refer to the results presented in Sections 4 and 5 and use responses to a post-waiver questionnaire distributed to BNSF and FRA staff involved in the project.

6.1 Railroad Operations

The ballast waiver caused no safety issues during the period it was applied. There were two broken rails near the Parkville long-term monitoring site, but these were not related to the fouled ballast waiver conditions. This safety record demonstrated the conditions of the waiver were sufficient to control the risk of derailment at locations of fouled ballast on the subdivisions in the waiver territory.

The class-specific track geometry limits in the waiver caused some temporary speed restrictions to be applied. Once the track geometry data showed a ballast waiver threshold had been reached, the permitted line speed was reduced to that for the next lower track class. The waiver territory was on track class 4 with a maximum line speed of 60 mph for freight. This speed drops to 40 mph for track class 3.

The more frequent collection of track geometry data combined with the speed restrictions to the next lower track class changed the priorities for maintenance during the waiver period. To avoid speed restrictions that were more severe than under the traditional regulation, track geometry faults were given a higher maintenance priority. Repair of track geometry faults was prioritized to avoid operational delays due to the speed restrictions. Both BNSF and FRA staff involved reported more maintenance than normal during the waiver period.

The inventory of fouled ballast locations and the extra track geometry data that was made available to BNSF may have focused more attention on these sites than would otherwise have been normal.

A consequence of the additional maintenance to avoid speed restrictions was that the behavior of the fouled ballast locations with track geometry elevated above current track safety limits beyond 30 days without maintenance could only be observed in two cases. A statistically significant sample of these observations might be possible on a route with less traffic.

6.2 Variation in Degradation Rate

The results presented in Sections 4.3 and 4.4 show considerable variation in degradation rates at different fouled ballast locations. For locations on timber ties the degradation over 9 days leading up to an exceedance of the track class 4 safety limit for Profile 62 varied from 0.08 to 1.31 inches. For locations on concrete ties the same degradation varied from 0.08 to 1.08 inches.

The track class 4 waiver threshold for Profile 62 was 1.25 inches and the safety limit was 2.0 inches. The variation in degradation results means, having passed the waiver threshold, the worse locations can reach the safety limit in less than 9 days. Whereas some locations could take more than 80 days to reach that limit.

The current regulation requires locations of fouled ballast to be remediated within 30 days. This can be seen as conservative for locations with low rates of degradation but unsafe at others. The variation in degradation rate is the principal reason why locations of fouled ballast should not all be treated the same. Some measure of performance and factors other than the presence of fouling material need to be considered. This would identify locations that require urgent remediation and allow others to be monitored and treated when necessary, i.e., upon additional follow-up for compliance inspections.

Factors that affect degradation rate include local drainage, subgrade condition, properties of the fouling material, discontinuities such as transitions from timber to concrete ties, field welds, track geometry faults, and turnouts. FRA funded research to quantify the effect of some of these factors (Zarembski, A., Yurlov, D., Palese, J., Attoh-Okine, N., 2020). Accounting for these factors may require a more complicated regulation. However, it can be argued that a pure performance-based fouled ballast rule should avoid the need to consider them.

Subgrade was found to be an important factor in track geometry degradation due to fouled ballast. Unstable subgrade was a major factor driving track geometry degradation at Waldron. In addition, some sites suffered from fouling due to subgrade materials infiltrating the ballast layer. In these locations, the type of subgrade had a significant effect on the fouled ballast behavior, with the more plastic and weak clay subgrade materials creating more problematic fouled ballast conditions.

Locations with the higher track geometry degradation rates were also some of the sites with the highest recurrences of track geometry exceptions. In terms of risks to safety, both the rapid degradation rate and frequent recurrence are indicators of high risk.

6.3 Fouled Ballast Length

The degradation results shown in Section 4.3 showed no evidence that fouled ballast locations longer than 10 feet behaved any differently than those that were shorter. The maximum degradation rate (i.e., in terms of inches over 9 days) of the Profile 62 track geometry parameter at short sections of fouled ballast was found to be as large as some longer sections.

Including the 10-foot minimum length criteria in the ballast waiver conditions reduced the number of locations that required maintenance. However, the data showed that shorter sections of fouled ballast can quickly deteriorate to require corrective action. Corrective action on fouled ballast locations shorter than 10 feet was regularly performed by BNSF during the waiver period. Short lengths of fouled ballast at rail joints, welds and turnout components can require special attention.

An argument can be made that short lengths of fouled ballast are not as safety critical as those over 10 feet in length. However, short lengths of poor track support can cause high loads in track components including the rail, tie, and tie-fastener system. These locations often progress to longer zones of fouled ballast, but it is possible that some track component failures may occur while the length is still short.

Under the current regulation, track inspectors use their experience and observations of local conditions to assess the safety of fouled ballast. This is necessary because of the wide variation in degradation behavior discussed above. Length of fouled ballast is one factor taken into consideration. Guidance on how to factor in length could be provided in the compliance manual rather than a minimum length being specified in a revised regulation.

6.4 Waiver Thresholds

Setting thresholds is a risk-based decision. The track geometry trending analysis presented in Section 4 provides information needed for the industry and regulators to make informed data driven decisions regarding performance-based track geometry thresholds for fouled ballast. The discussion in Section 4.2 showed that the waiver threshold would have to be set impractically low to eliminate the risk of the fouled ballast locations with the highest degradation rate reaching the safety limit in a few days. However, reasonable limits could be set with additional controls in place to minimize risk. For example, higher thresholds for fouled ballast could be justified when coupled with increased inspection frequency or use of additional inspection technologies such as GPR.

Having a single set of performance thresholds, regardless of factors that could affect degradation rate, would be clear and promote ease and consistency of enforcement. However, it would require thresholds to account for safety risks at fouled ballast locations with different composition, conditions, and components.

Since many inspectors commit the track geometry safety limits to memory, an alternative to the thresholds in the waiver would be to use the safety limits for the next higher track class. In that case the threshold for the Profile 62 parameter would still be 1.25 inches for track class 4, but the thresholds for lower track classes would be less conservative.

In general, the BNSF and FRA staff involved in the project felt the waiver thresholds were adequate. Having the thresholds gave clear guidance to track inspectors on when ballast was noncompliant.

6.5 Noncompliant Ballast Definition

The definition of noncompliant ballast used for the waiver was, "… conditions in which track drainage in mainline or controlled siding track is impeded for 10 feet or more where the ability of the track structure to maintain an adequate margin of safety is impaired by the presence or evidence of water, ballast fines, or other material." This definition proved useful in the waiver period but needs to be reconsidered if it is to be used for future projects or regulations.

One change favored by several project participants is to remove the 10-foot clause. This would be consistent with the finding that short fouled ballast locations can deteriorate at least as quickly as longer ones.

The current definition requires an inspector to make a subjective decision on whether the track structure could “maintain an adequate margin of safety.” Some of the factors that go into that decision have been discussed above. Guidance on accounting for these factors could be given in the compliance manual. Alternatively, the inspector’s decision could be based on criteria that are more objective. One possible criterion is the number of days before the track safety limit is expected to be exceeded. In turn, the calculation would be from the current track geometry values and the measured degradation rates. It would require at least weekly autonomous track geometry measurements over the route and access to those measurements for inspectors.

6.6 Long-term Monitoring Sites

Tests on ballast samples at the long-term monitoring sites classified the fouling material as low to high plasticity clay. Researchers tested samples of fouling material from the ballast and from the subgrade at Parkville. Thus, the material properties were similar.

The fouling material at the long-term monitoring sites infiltrated from the sub-ballast and subgrade. It was not from other common causes such as breakdown of ballast or coal pollution. This bottom-up fouling is problematic since by the time it is visible on the surface the track geometry, support and drainage are significantly compromised and the potential for rapid degradation of track geometry is increased.

In general, and as expected with fouled ballast, rainfall caused an immediate increase in soil moisture followed by a gradual reduction over several days as the water drained from the ballast. These changes in soil moisture did not usually have a significant effect on distributed tie load, P_T. However, a sustained increase in soil moisture, due to either continued rainfall or poor drainage, was seen to increase P_T and hence decrease the support provided by the ballast.

Freezing and thawing of fouled material in the ballast was seen to have a significant effect on distributed tie load, P_T, and track stiffness. Freezing caused a reduction in P_T and an increase in track stiffness. The opposite effect was seen when the fouled material thawed.

The effects of freezing and thawing on distributed tie load tended to be greater when the ballast contained more fouling material. Higher moisture content in the ballast can be expected to result in higher stiffness on freezing and higher compressibility on thawing.

Thawing was seen to occur within 1 to 3 days resulting in a rapid reduction in track stiffness. Freezing typically took 4 to 7 days, and the effect on track stiffness was more gradual.

Track geometry remediation by surfacing was found to have inconsistent effects on track support. At Parkville, for example, surfacing in January 2018 had no significant effect on distributed tie load, P_T, and track stiffness. In March 2018, it caused a significant reduction in P_T, and in April 2018 it significantly improved track support. Possible reasons for these differences include:

1. Details of the work done in each surfacing operation – For example, the amount of new ballast added is an important variable.
2. State of the fouling material – Recently thawed fouled ballast can respond differently to surfacing than normal.

Undercutting and follow-up surfacing, as expected, significantly improved track stiffness. The improvement was seen to be delayed if the follow-up surfacing was delayed due to the uncompacted new ballast.

Some differences in behavior were seen between long-term monitoring sites with timber and concrete ties. However, the results presented in Section 4.2 show tie type caused no statistically significant difference in track geometry degradation rate. It is likely that the variation in performance at the long-term monitoring sites was due to factors other than tie type.

6.7 Further Work

The discussion and conclusions in this report are based on the specific conditions on the designated waiver territory. The work could be expanded to include locations with higher and lower rainfall, and for locations with clay and other subgrades. This would increase confidence in the approach and the track geometry thresholds used in the waiver.

Track settlement observed at the fouled ballast locations monitored in this project was similar for left and right rails. Thus, a detailed evaluation of the crosslevel thresholds in the waiver was not possible. Further monitoring at locations with inconsistent settlement between left and right rail, such as on jointed track, would enable crosslevel thresholds to be analyzed.

The waiver territory was posted as track class 4, which allowed the waiver thresholds for this class to be evaluated. Some results were obtained for track class 5 by analyzing the geometry degradation as the waiver thresholds for this class were exceeded. These results could be confirmed by extending the work to territory posted as track class 5.

The work could also be extended to territory posted as track class 3. In addition to enabling class 3 waiver thresholds to be evaluated it is likely that this territory would have less traffic. In which case speed restrictions might be less critical and full cycles of ballast degradation could be observed.

Further research could be performed into the relationship between track geometry degradation rates and the properties of fouled ballast. This could lead to properties such as fouling index and material plasticity being used to assess fouled ballast locations. Although some of this data was gathered in this project, more frequent GPR measurements data and lab analysis would be needed to produce useful results.

This project used the inventory of fouled ballast locations to determine where the track geometry waiver thresholds should be applied. If the approach to managing fouled ballast was applied more widely then autonomous inspection systems would need to be modified to apply alternative thresholds at fouled ballast locations automatically, without human interaction.

The methods used for long-term monitoring in this project could be reviewed and recommendations made for further monitoring. Procedures could be developed for coordinating different types of measurements to avoid gaps in data. The types of data most useful to analyzing ballast performance in the future could be identified using the results of this project.

7. Conclusion

BNSF operated safely from June 12, 2017, to January 31, 2019, on two subdivisions under a waiver to the current FRA regulation for fouled ballast. The waiver conditions resulted in increased track maintenance to avoid temporary speed restrictions. Frequent—typically weekly—track geometry measurements were made during the waiver period and a register of fouled ballast locations was maintained. Researchers analyzed and shared this data with BNSF and FRA staff.

The results presented in this report are specific to the conditions on the designated waiver territory on the Creston and St. Joseph subdivisions of BNSF. This territory was posted as track class 4. It carried over 100 MGT of traffic per year. The track was mostly continuously welded rail on both concrete and timber ties. The waiver period covered weather typical of all four seasons in Missouri, Iowa, and Nebraska.

The waiver conditions applied to locations of fouled ballast longer than 10 feet. Analysis of track geometry measurements showed degradation rates were similar for locations longer and shorter than 10 feet. Some locations shorter than 10 feet were found to have track geometry degradation rates higher than those longer than 10 feet.

The track geometry measurements of vertical profile from a 62-foot chord were analyzed in detail. The threshold for this parameter on track class 4 was found to be adequate. Some fouled ballast locations were found to degrade rapidly, but the frequent geometry measurements provided the data necessary to identify them and for remediation to be scheduled.

Significant variation in track performance was observed at fouled ballast locations including those equipped with long-term wayside monitoring. The variation did not appear to be related to tie type—concrete or timber. The properties of the fouling material were found to be similar—low to high plasticity clay. The variation in track performance is a strong argument for a performance-based rule for managing fouled ballast.

This was a pilot project that developed a methodology and identified topics for further work. Further work is needed to evaluate thresholds for track classes other than class 4 and for track geometry parameters other than Profile 62. Future projects could be conducted on territory with different weather conditions and types of subsoil.

8. References

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Appendix A.
Crosslevel Degradation Results

Figure A.1 compares the variation in degradation between fouled ballast lengths less than 10 feet with the variation for those equal to or greater than 10 feet. These results are for locations where the crosslevel parameter crossed the track class 4 safety limit during the pre-waiver, waiver, and post-waiver periods. They are for both types of tie. There is no reason to assume the average degradation differs between the longer (15 results) and the shorter (3 results) lengths of fouled ballast.

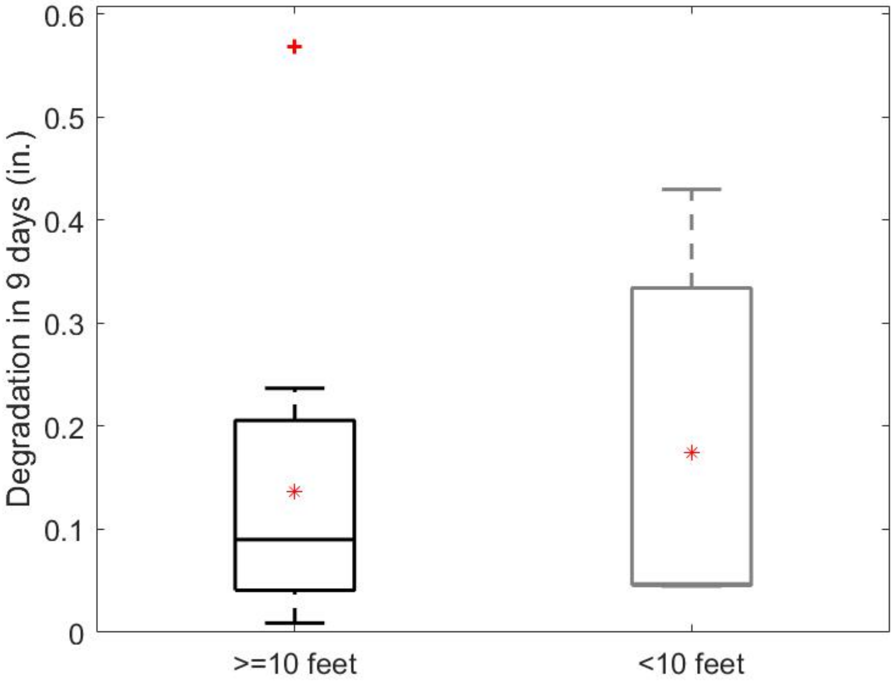


Figure A.1. Crosslevel Degradation by Fouled Ballast Location Length – Track Class 4 Safety Limit – All Periods and Tie Types

Figure A.2 shows the same as Figure A.1 except for the track class 5 safety limit. Again, there is no reason to assume the average degradation differs between the longer (59 results) and the shorter (22 results) lengths of fouled ballast.

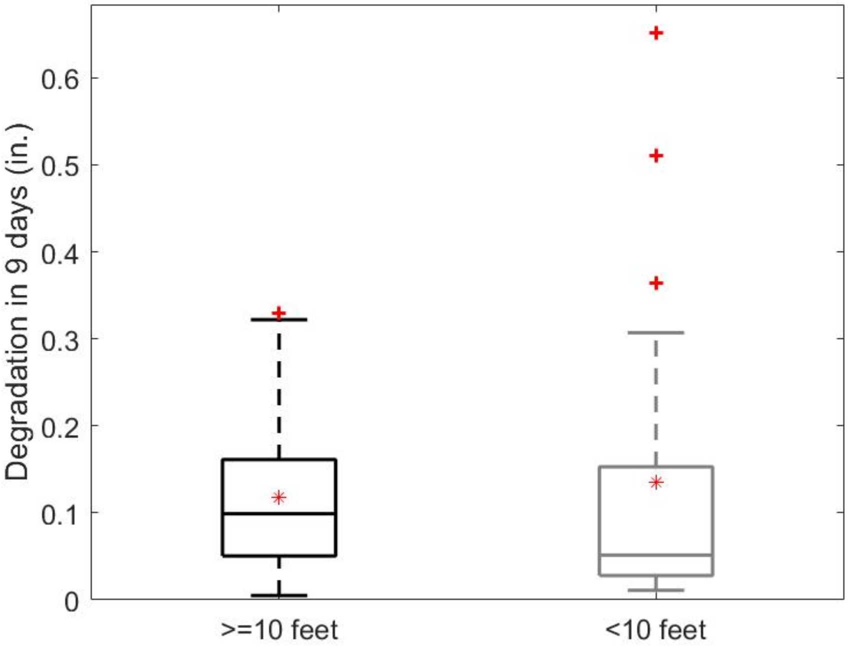


Figure A.2. Crosslevel Degradation by Fouled Ballast Location Length – Track Class 5 Safety Limit – All Periods and Tie Types

Figure A.3 shows individual values of crosslevel degradation before crossing the track class 4 safety limit plotted against fouled ballast lengths. The results are for all fouled ballast locations regardless of the time period. The data points are coded to show the tie type.

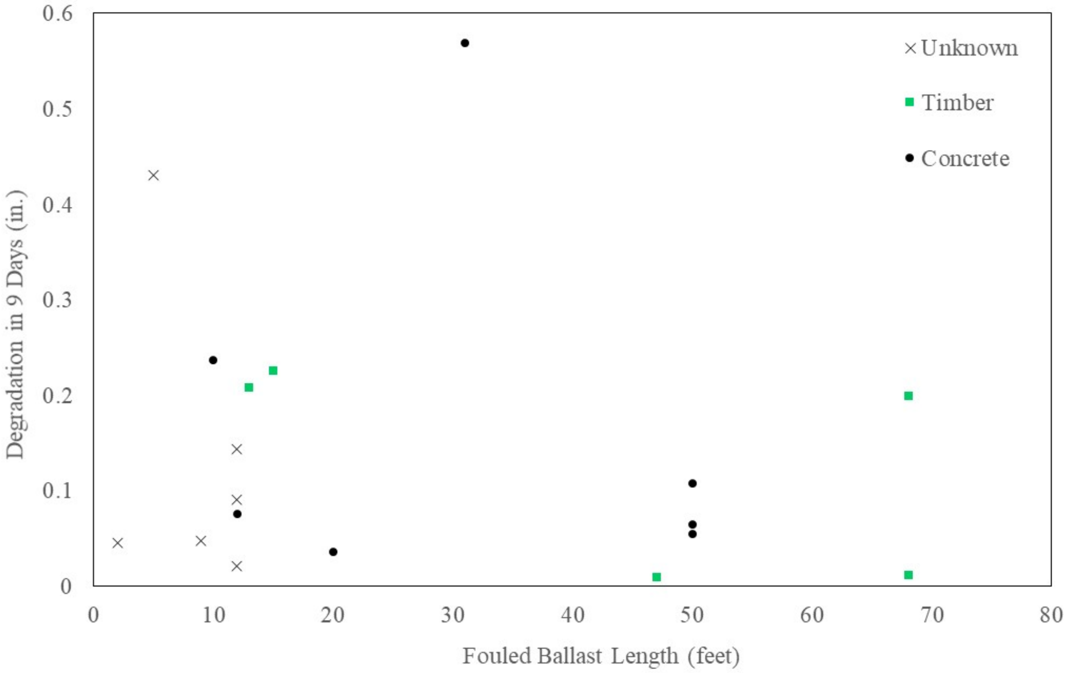


Figure A.3. Crosslevel Degradation Statistics by Fouled Ballast Length – Track Class 4 Safety Limit – All Periods and Tie Types

Figure A.3 shows the maximum value of crosslevel degradation at short sections of fouled ballast can be larger than at some longer sections. It does not appear to show any correlation between fouled ballast length and tie type.

Figure A.4 shows individual values of crosslevel degradation before crossing the track class 5 safety limit plotted against fouled ballast lengths. The results are for all fouled ballast locations regardless of the time period. The data points are coded to show the tie type.

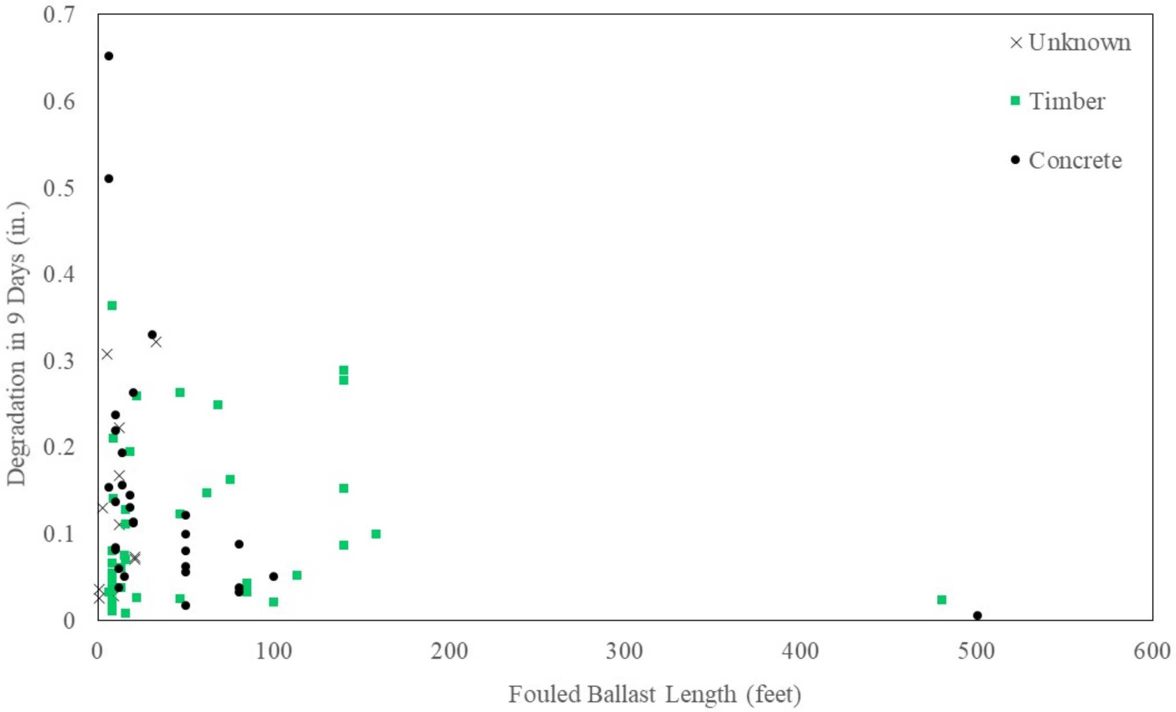


Figure A.4. Crosslevel Degradation Statistics by Fouled Ballast Length – Track Class 5 Safety Limit – All Periods and Tie Types

Figure A.4 shows the maximum value of crosslevel degradation at short sections of fouled ballast can be larger than at some longer sections. It does not appear to show any correlation between fouled ballast length and tie type.

Figure A.5 shows the relationship between the crosslevel threshold and the number of degradation results within the additional safety margin for track class 4. The results are for all fouled ballast locations regardless of length and time period. The crosslevel safety limit for track class 4 is 1.25 inches. The waiver threshold is 1.0 inches for this track class.

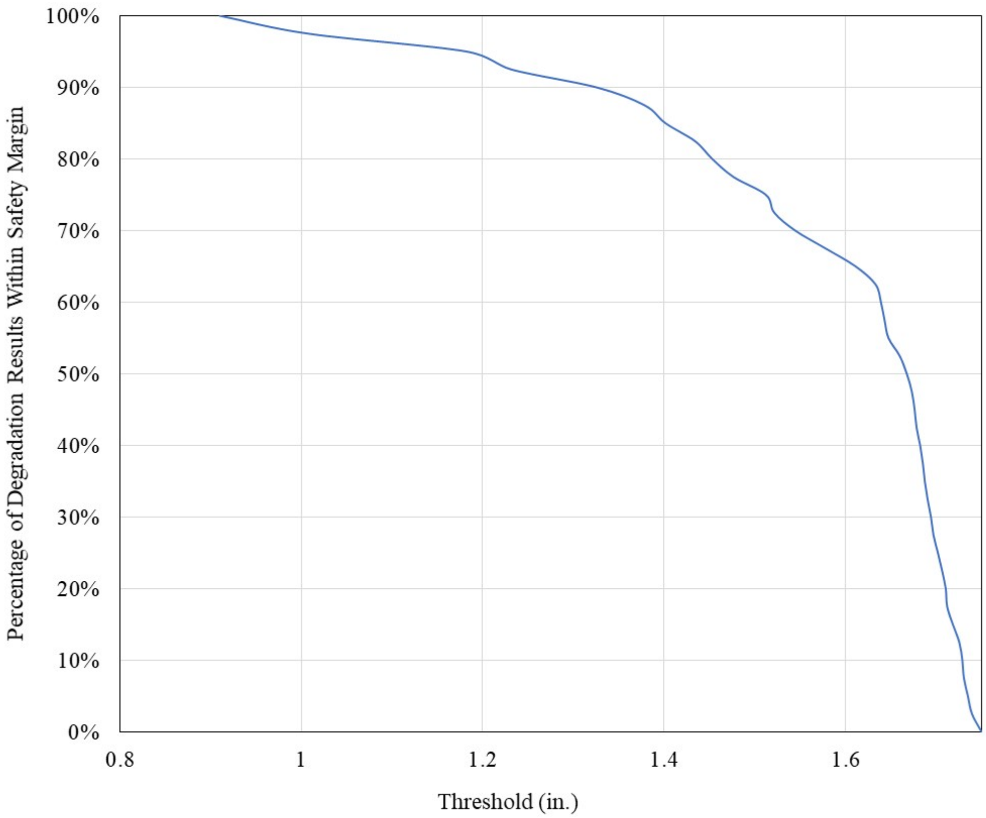


Figure A.5. Effect of Crosslevel Threshold on Degradation Results – Track Class 4 Safety Limit – All Lengths, Periods and Tie Types

Figure A.6 shows the relationship between the crosslevel threshold and the number of degradation results within the additional safety margin for track class 5. The results are for all fouled ballast locations regardless of length and time period. The crosslevel safety limit for track class 5 is 1.0 inches. The waiver threshold is 0.5 inches for this track class.

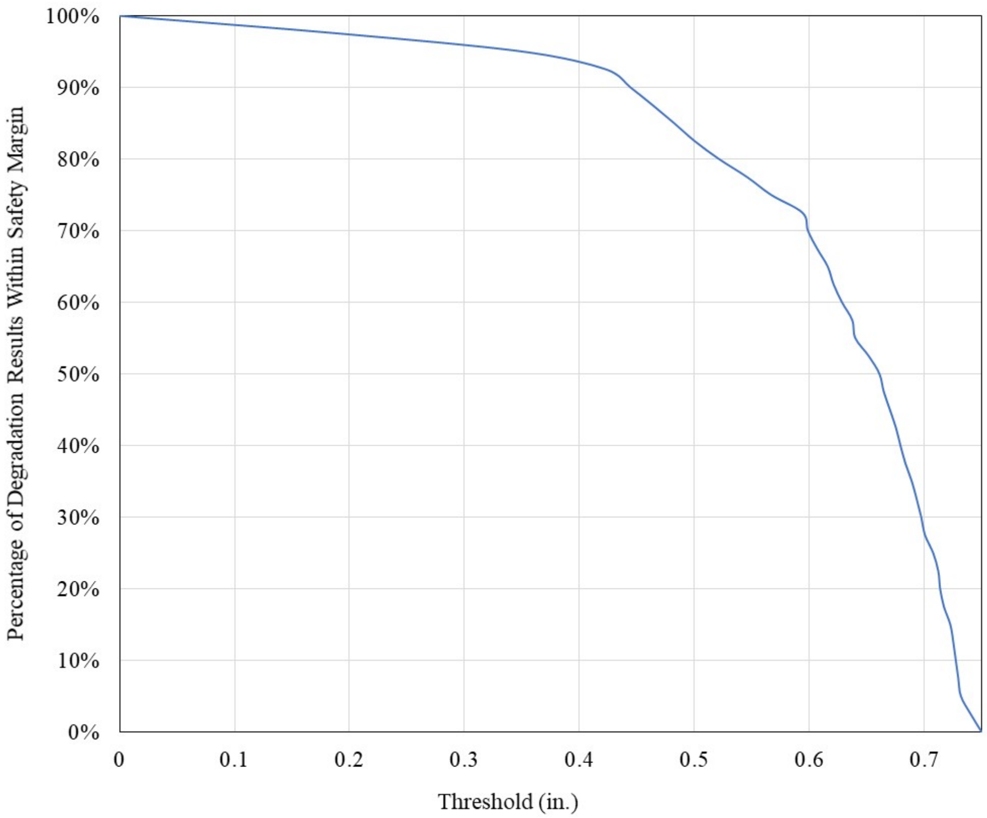


Figure A.6. Effect of Crosslevel Threshold on Degradation Results – Track Class 5 Safety Limit – All Lengths, Periods and Tie Types

Appendix B.
Long-term Monitoring Site Instrumentation Details

This appendix provides the instrumentation details at the monitoring site, featured in Figures B.1 through B.10.

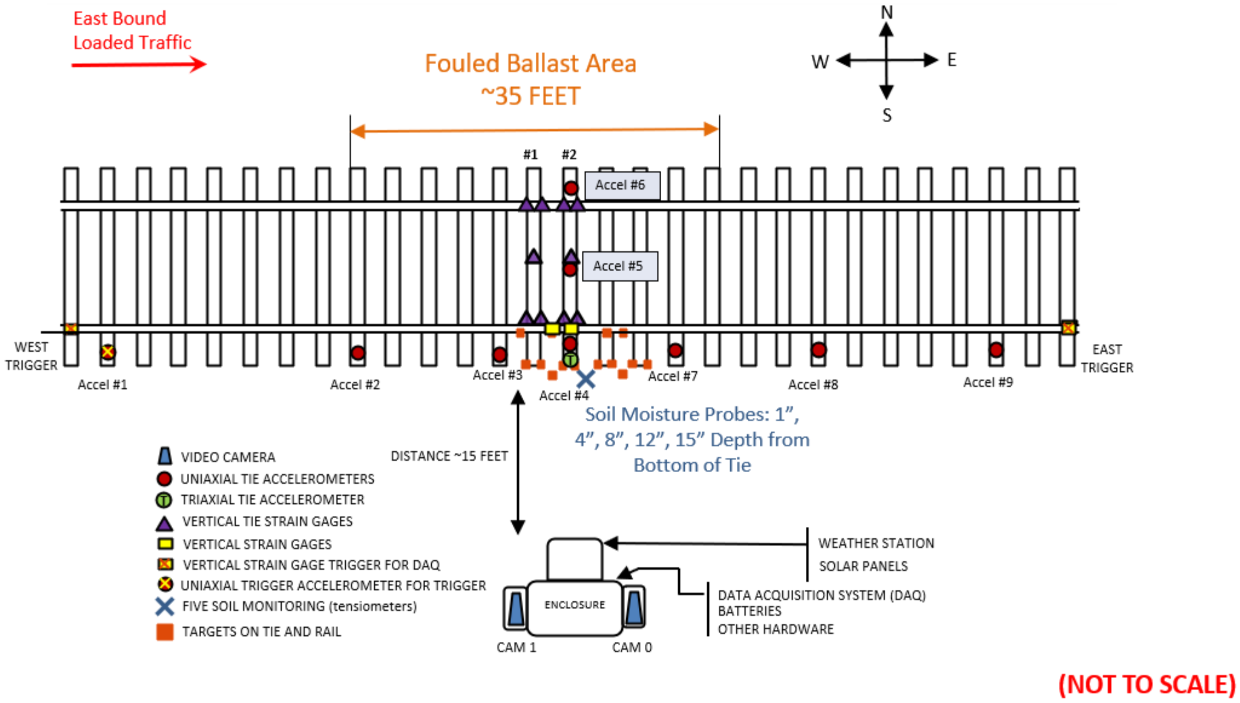


Figure B.1. Instrumentation Layout at Waldron

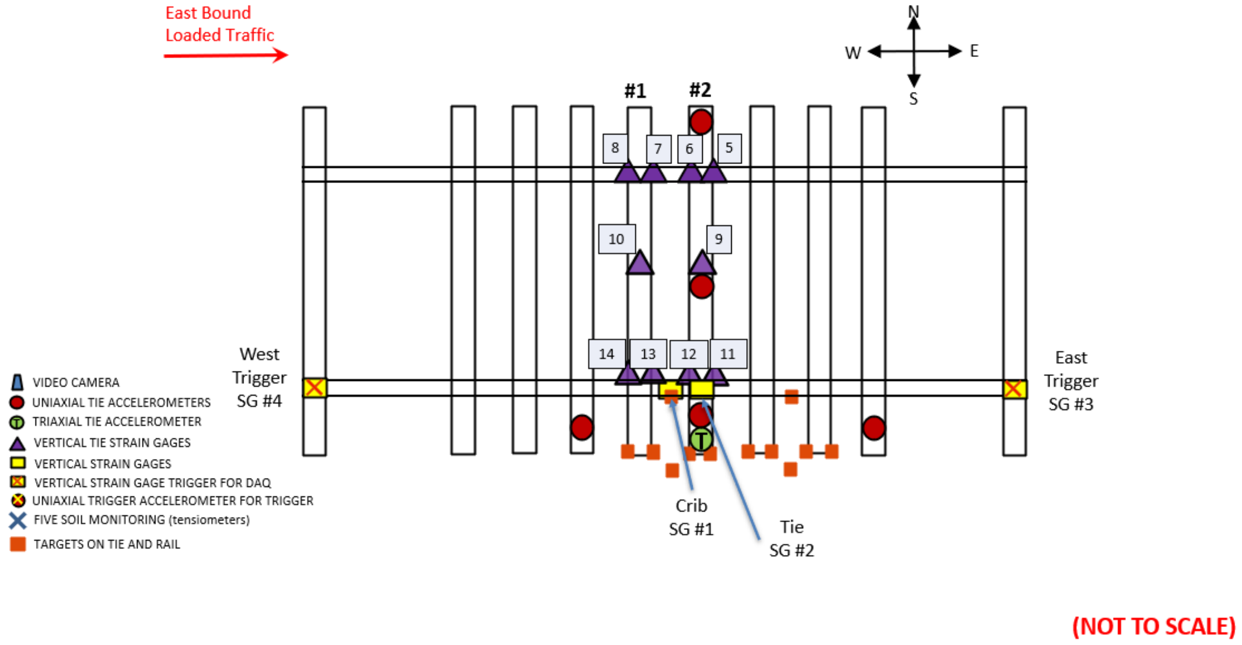


Figure B.2. Strain Gage Layout at Waldron

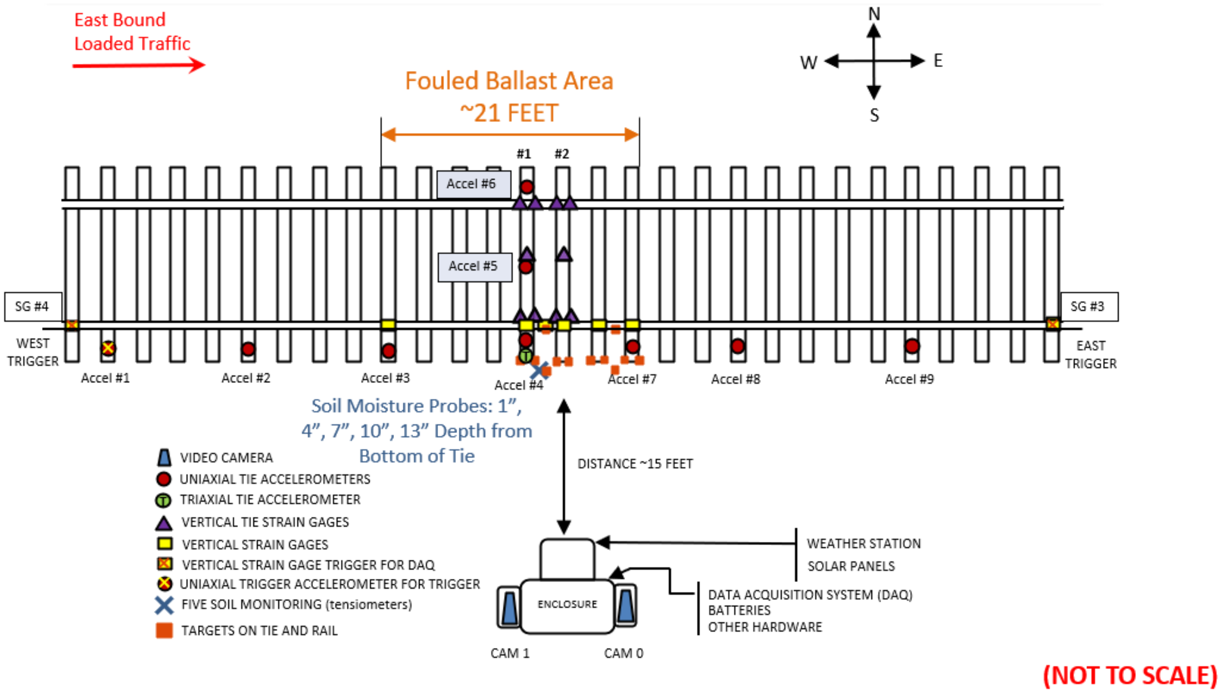


Figure B.3. Instrumentation Layout at Parkville

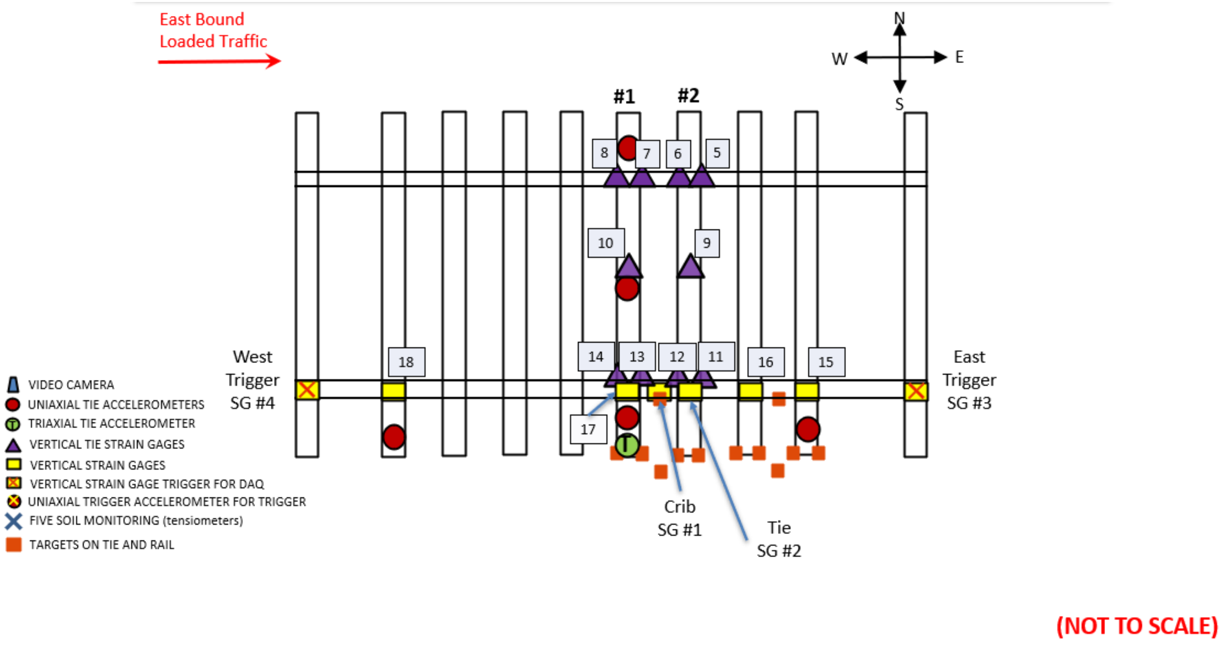
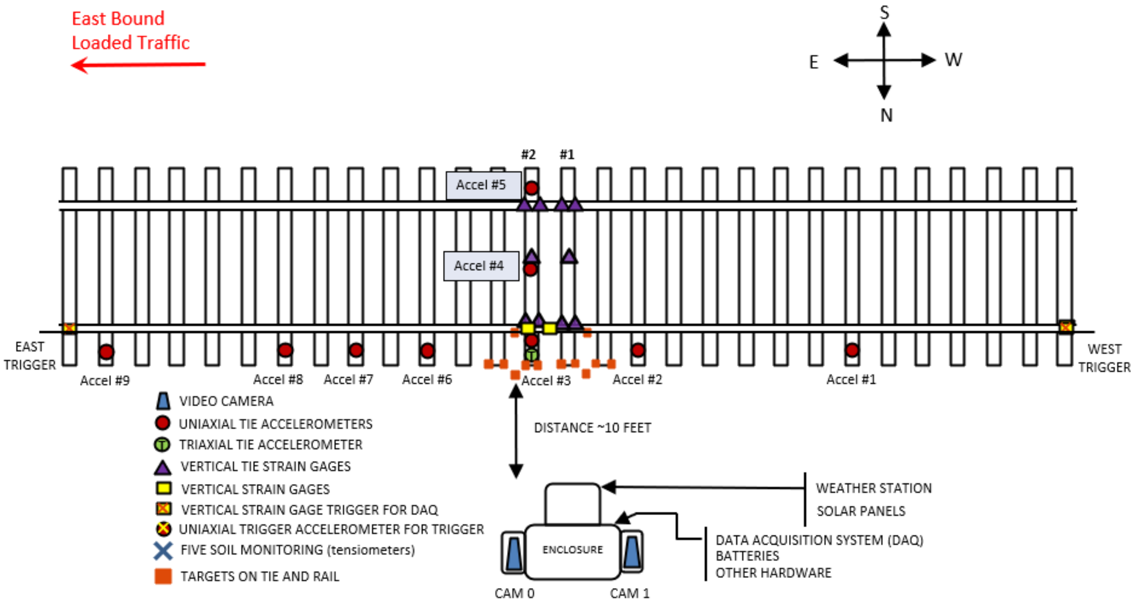


Figure B.4. Strain Gage Layout at Parkville



(NOT TO SCALE)

Figure B.5. Instrumentation Layout at Roca – Control

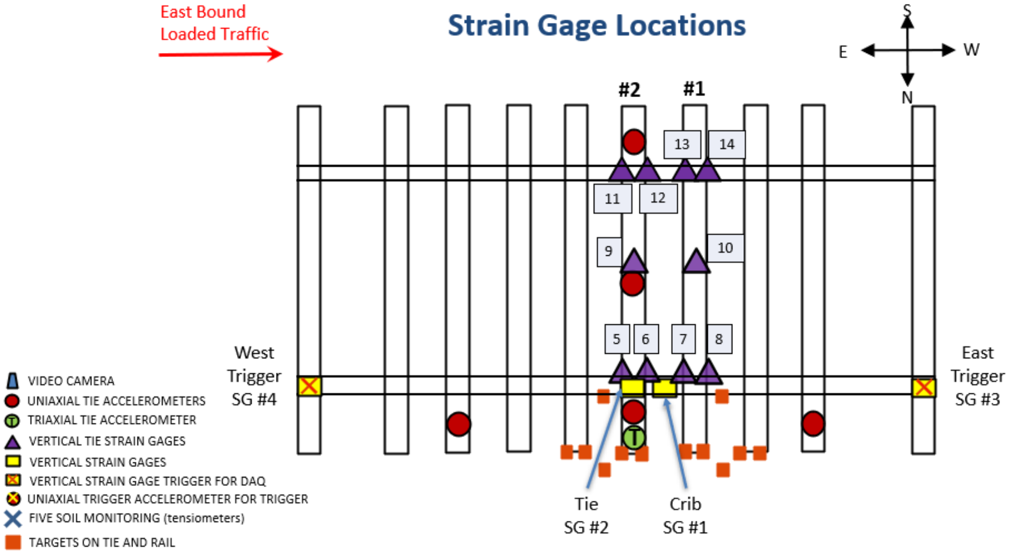


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Figure B.6. Strain Gage Layout at Roca – Control

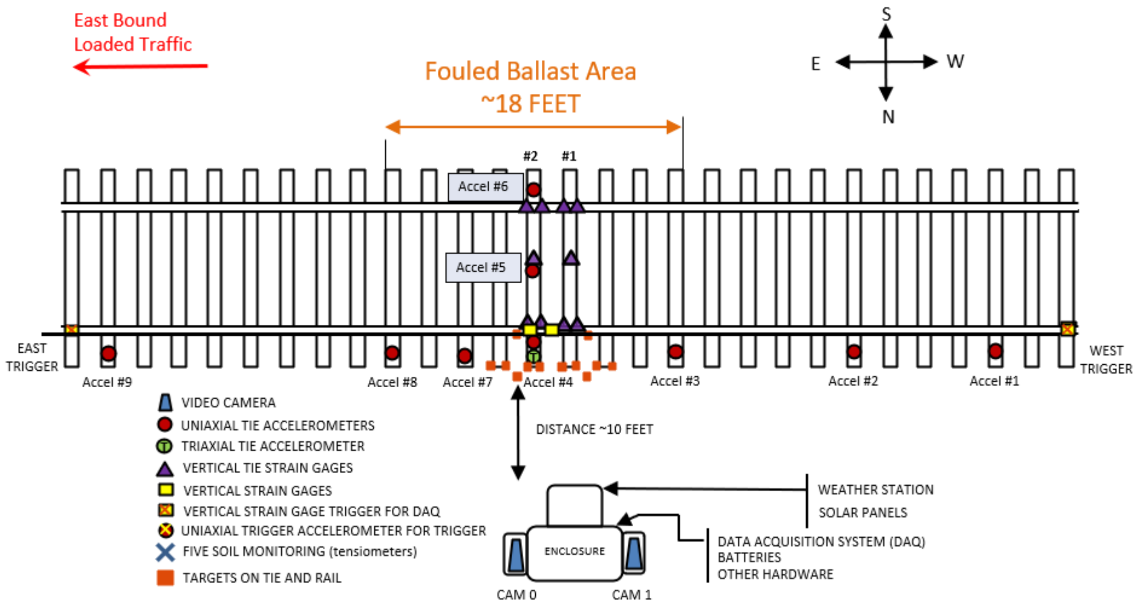

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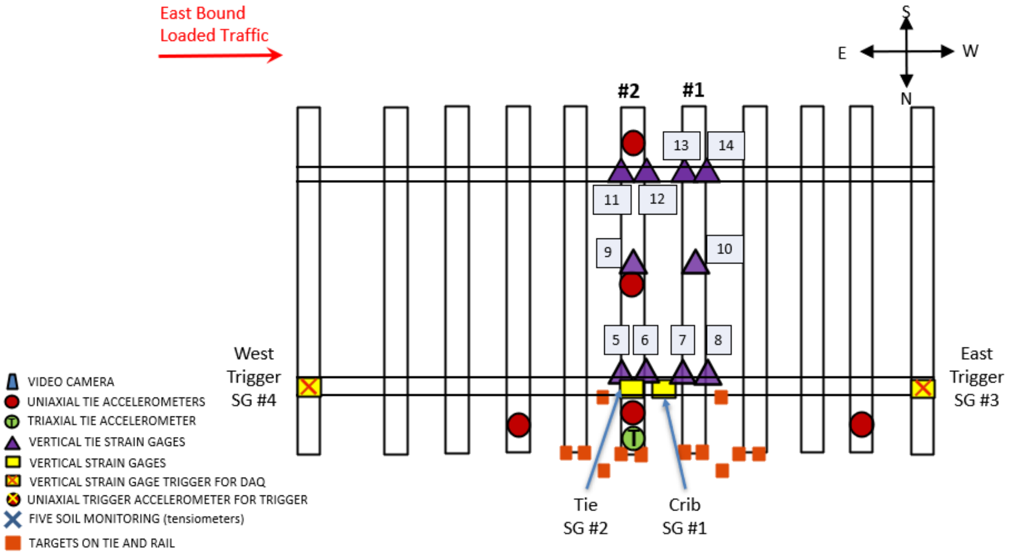
Figure B.7. Instrumentation Layout at Roca – Fouled



(NOT TO SCALE)

Figure B.8. Strain Gage Layout at Roca – Fouled

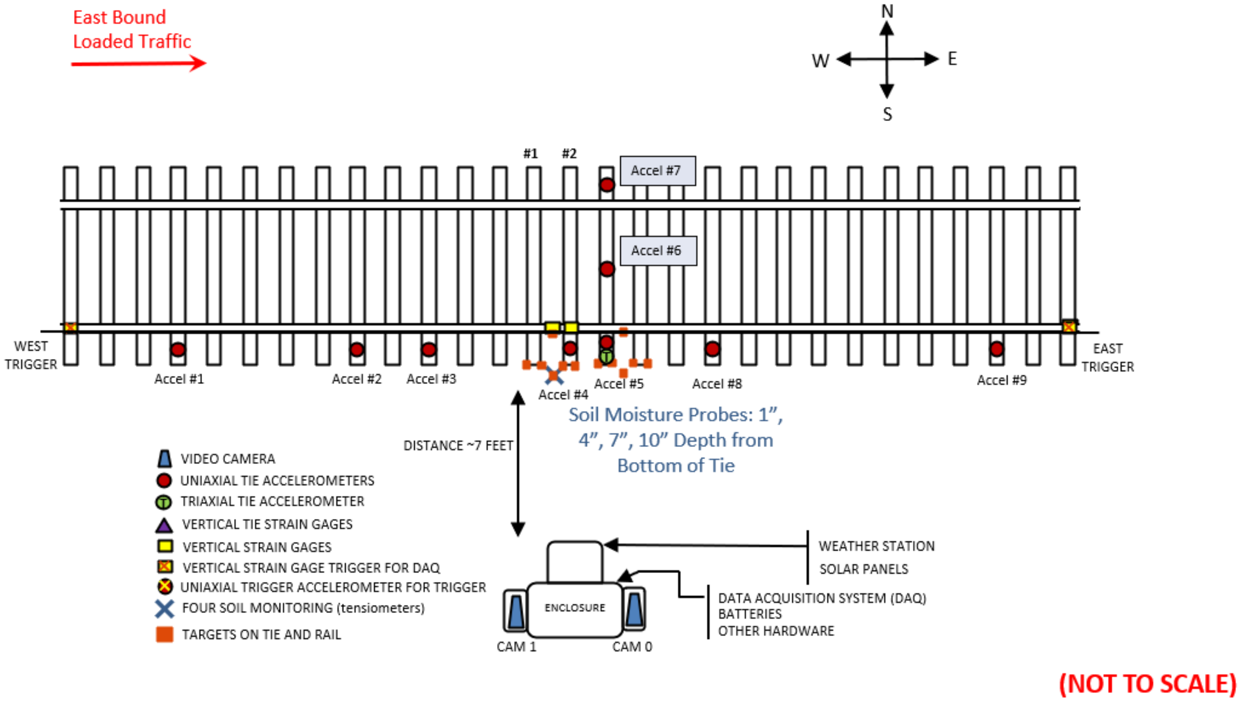


Figure B.9. Instrumentation Layout at Hickman – Control

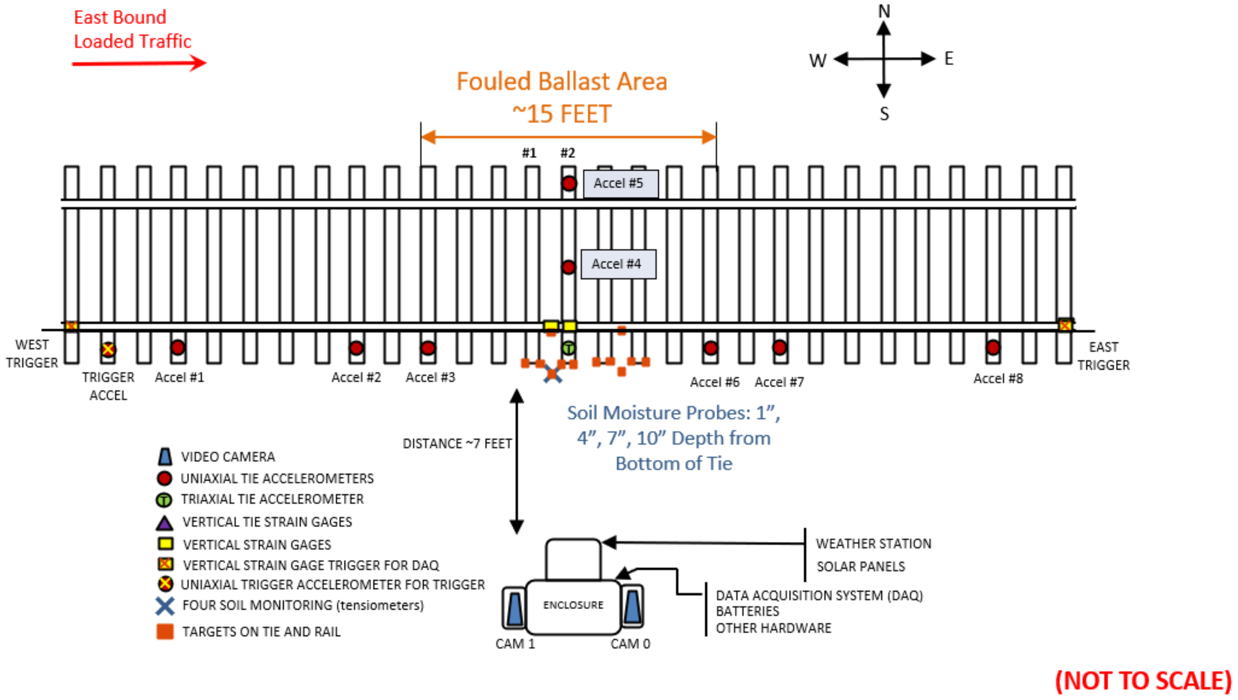


Figure B.10. Instrumentation Layout at Hickman – Fouled

Note, strain gauges were not installed on the timber ties at Hickman.

Appendix C.
Complete Long-term Monitoring Results

The figures in this appendix show all the data recorded at the long-term monitoring sites. They include the track geometry measurements that were required by the waiver. The track geometry parameter shown in the figures is Profile 62. It represents the vertical, mid-chord offset of the rail from a 62-foot chord.

The Profile 62 measurement value is affected by track settlement at the mid-chord as well as movements at the ends of the chord. Thus, Profile 62 data will not always represent local geometry and track deflections at a location of interest. Future analysis of collected data should include comparisons with geometry trends based on profile space curves. Profile space curve trend is more representative of local track settlement with time at a location of interest. The drawback is a higher cut-off speed for space curve measurement compared to Profile 62 resulting in sparser space curve data at the wayside locations.

The long-term monitoring sites are on posted track class 4. The waiver threshold and track safety limit for Profile 62 on track class 4 are 1.25 and 2.00 inches respectively.

Track geometry measurements by FRA's DOTX 225 or DOTX 226 ATGMS vehicles were typically made every week. However, operational constraints occasionally resulted in gaps in coverage of several weeks. In these cases, the waiver's weekly track geometry measurement requirements were satisfied by BNSF inspection vehicles or hand measurements. BNSF track geometry data is not considered for wayside long-term monitoring analysis due to much lower weight of the vehicles and different uniformity filtering than FRA ATGMS vehicles. Similarly, hand measurements were only used for waiver compliance and not used for research purposes.

The calculated value of distributed tie load can be affected by the axle loads of the passing trains. Light axle loads may not close the gap between the tie and ballast if present. This may produce a lower value of distributed tie load than one calculated from a train with heavy axle loads.

The temperature shown in Figures C.1 through C.41 was measured by the weather stations at the long-term monitoring sites. It is the ambient air temperature, which is not necessarily the same as the temperature of the ballast.

The outputs from soil moisture gauges change when the ballast freezes and thaws. These gauges are also removed and replaced when major remediation such as ballast undercutting is performed.

C.1 Waldron

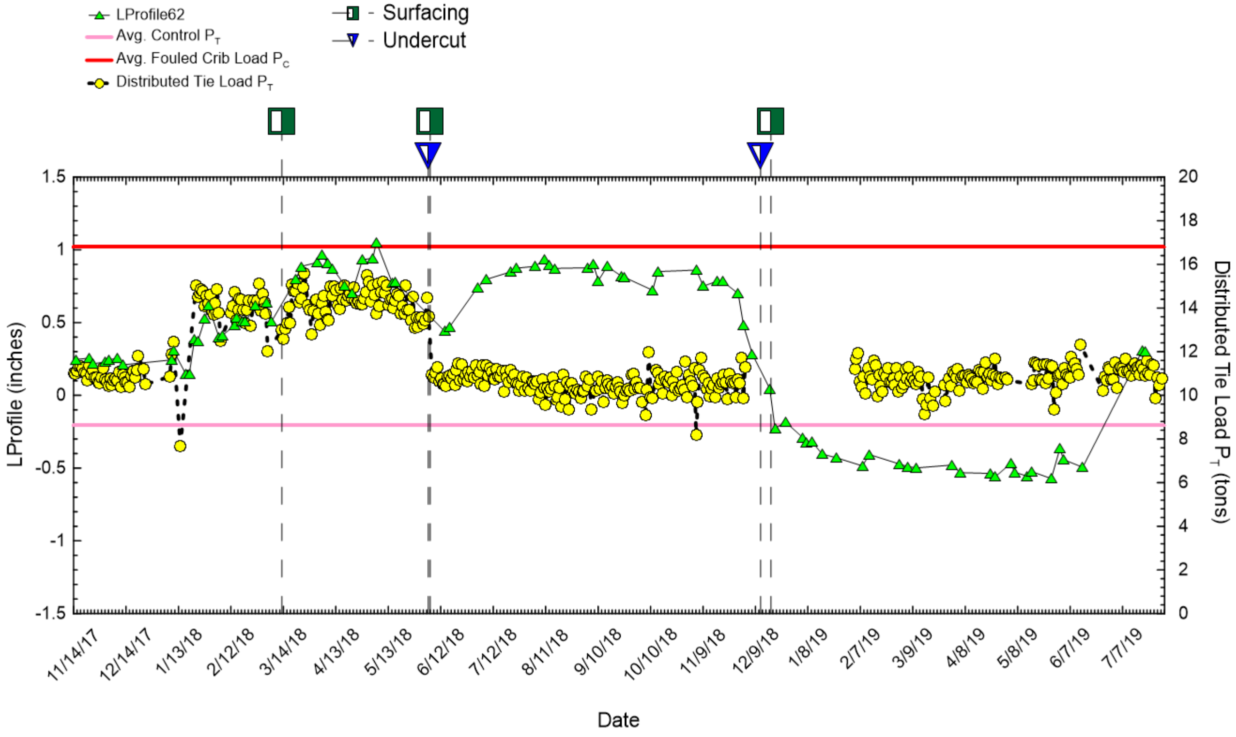


Figure C.1. Distributed Tie Load at Waldron

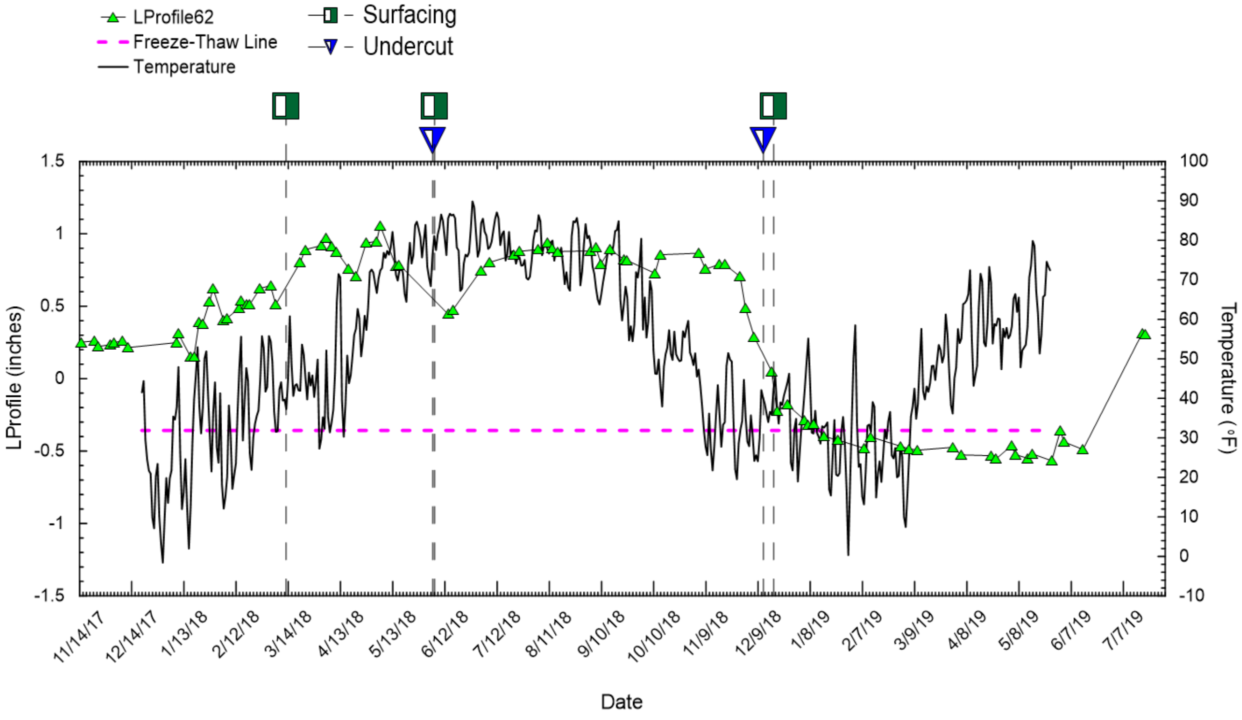


Figure C.2. Temperature at Waldron

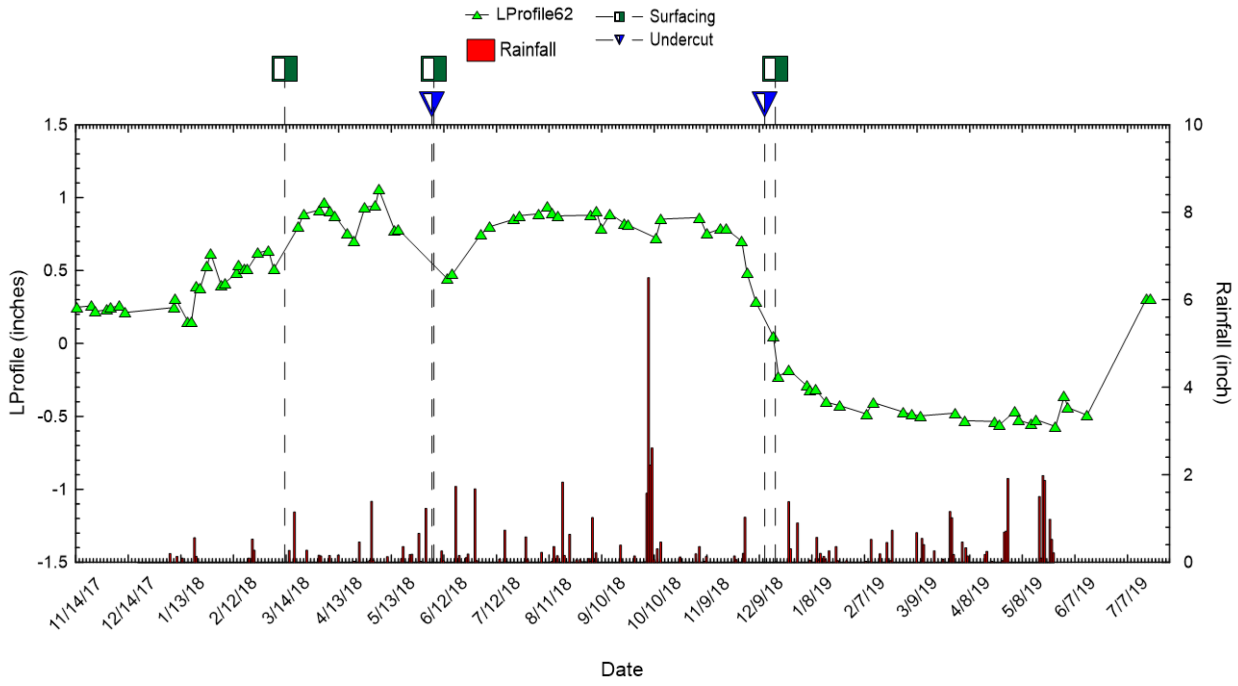


Figure C.3. Rainfall at Waldron

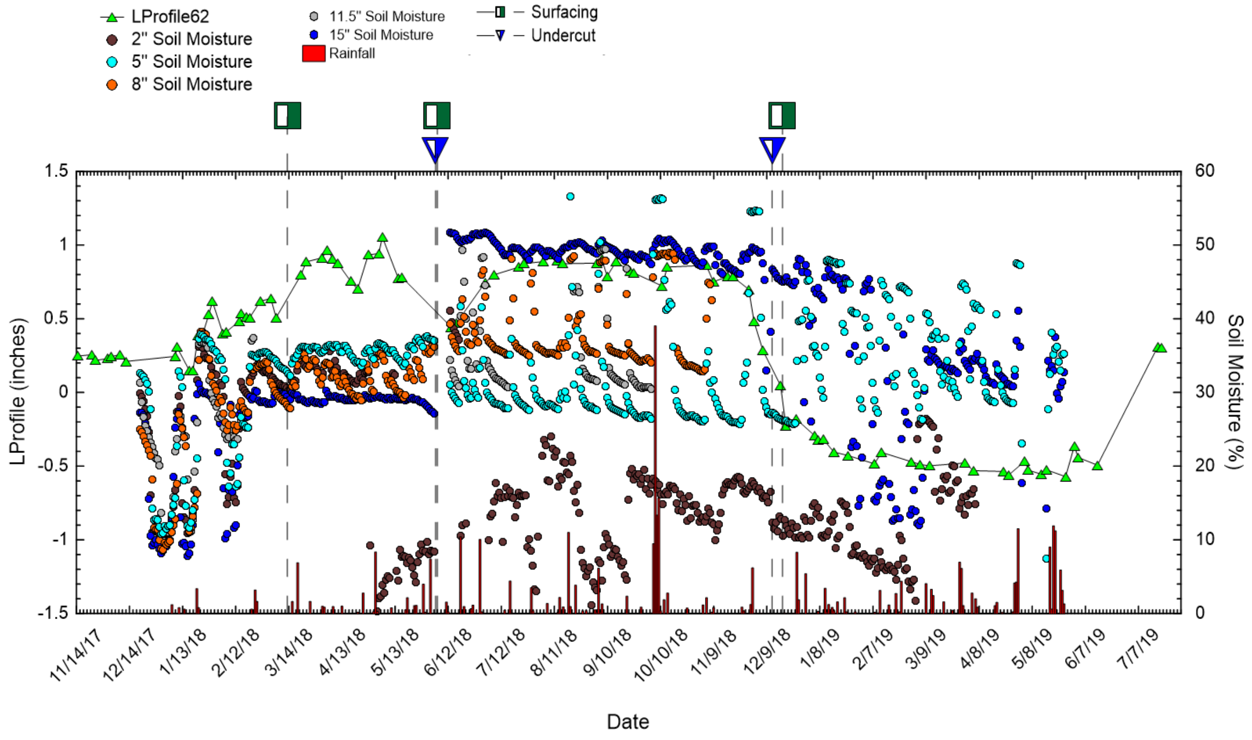


Figure C.4. Soil Moisture at Waldron

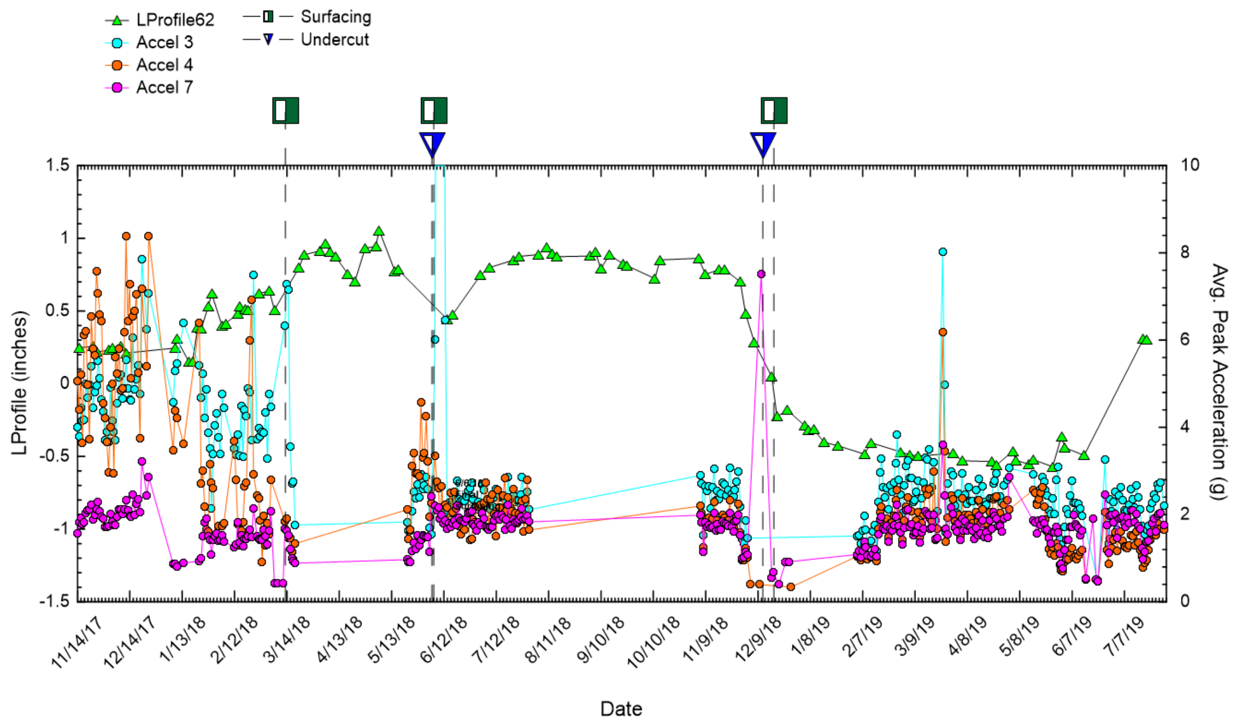


Figure C.5. Average Peak Accelerations at Waldron

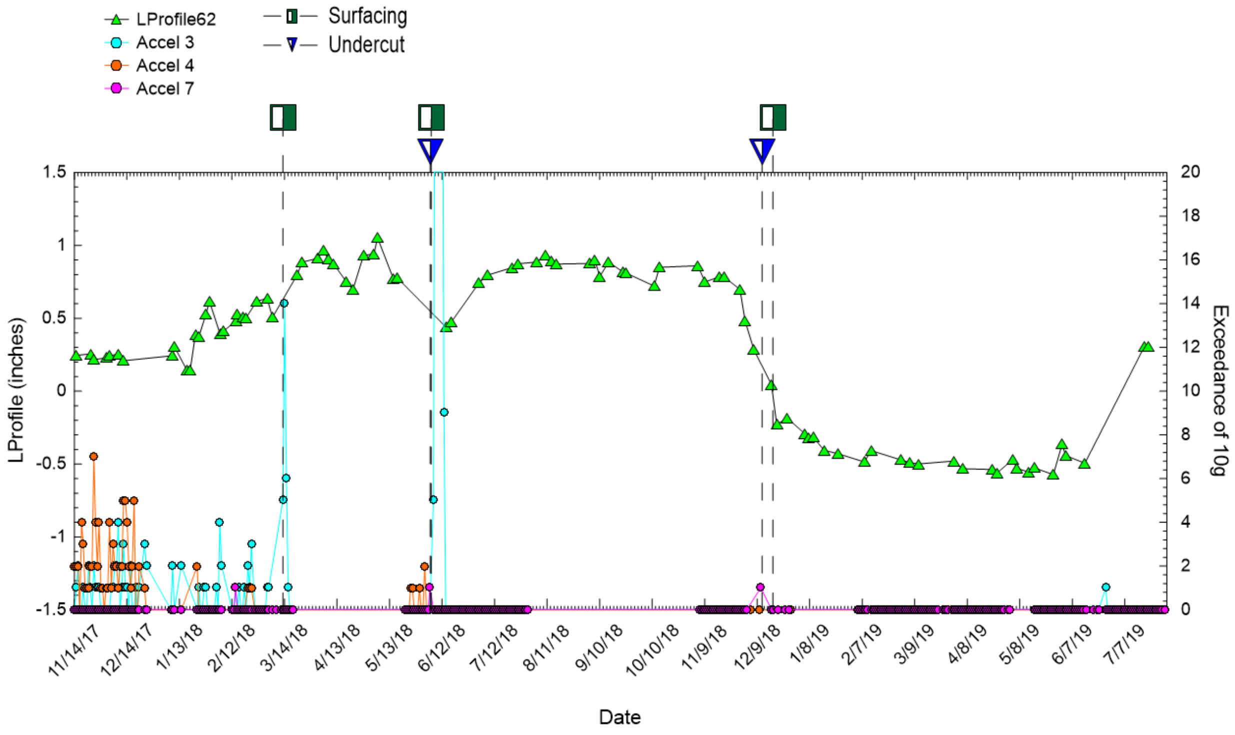


Figure C.6. Acceleration Exceedances at Waldron

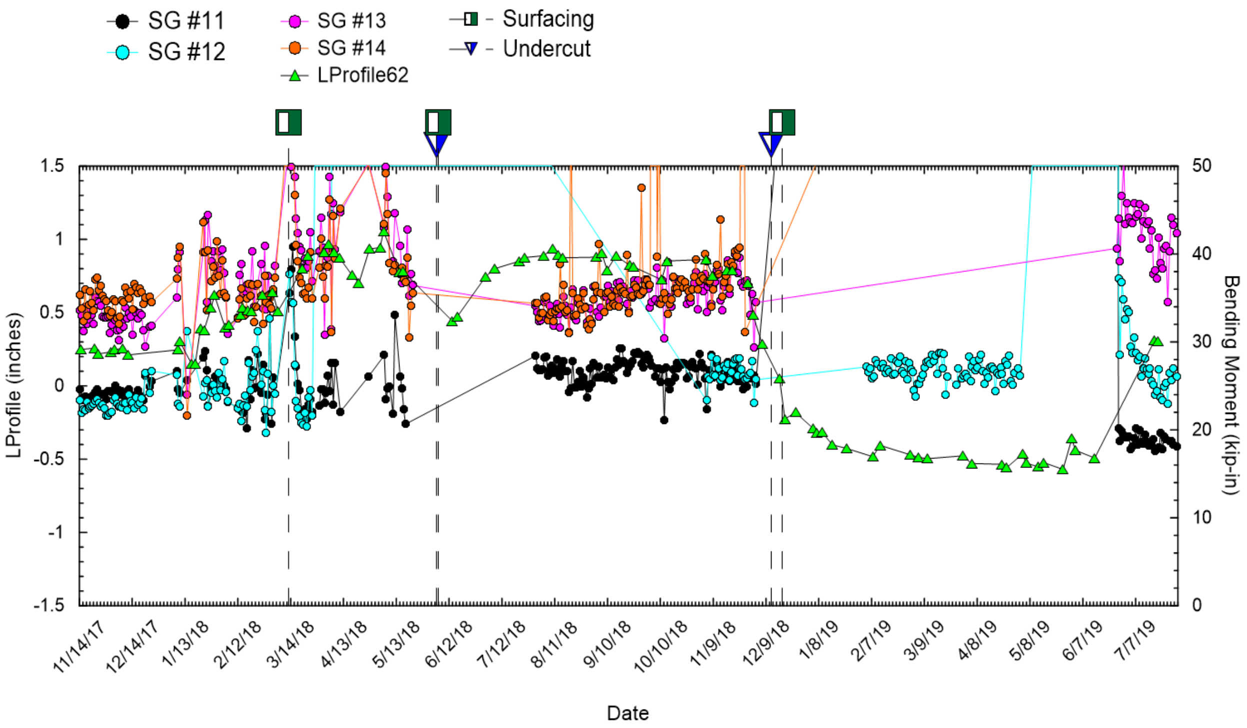


Figure C.7. Bending Moments at Waldron

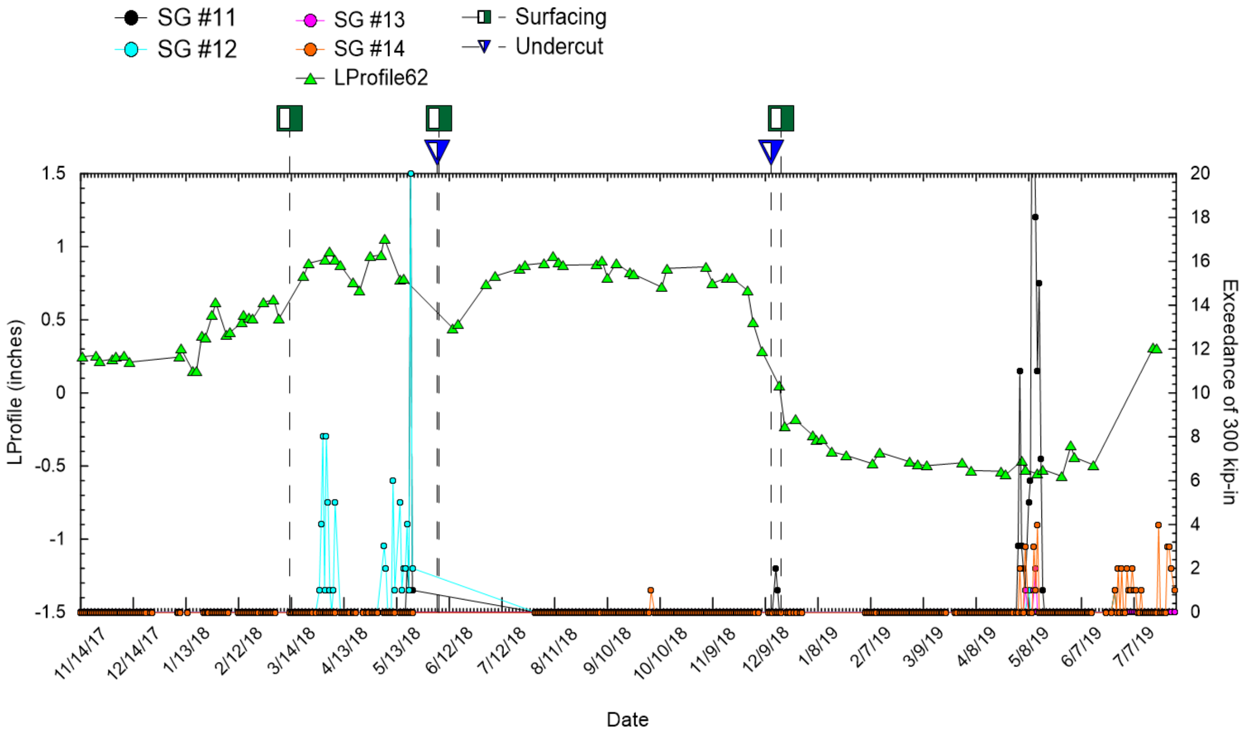


Figure C.8. Bending Moment Exceedances at Waldron

C.2 Parkville

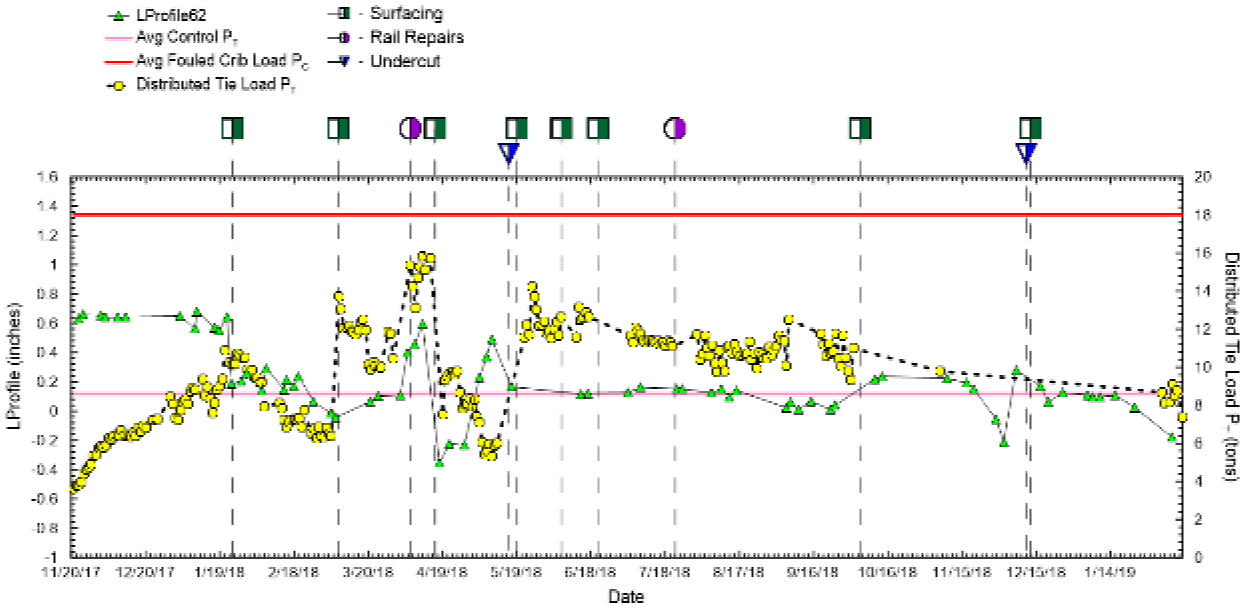


Figure C.9. Distributed Tie Load at Parkville

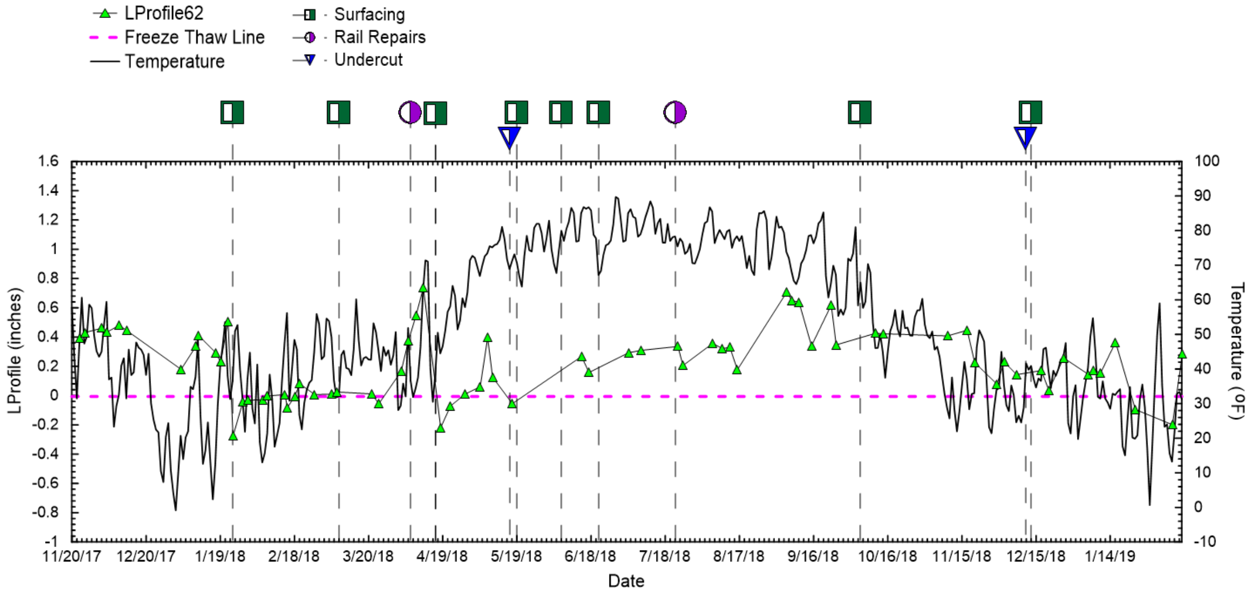


Figure C.10. Temperature at Parkville

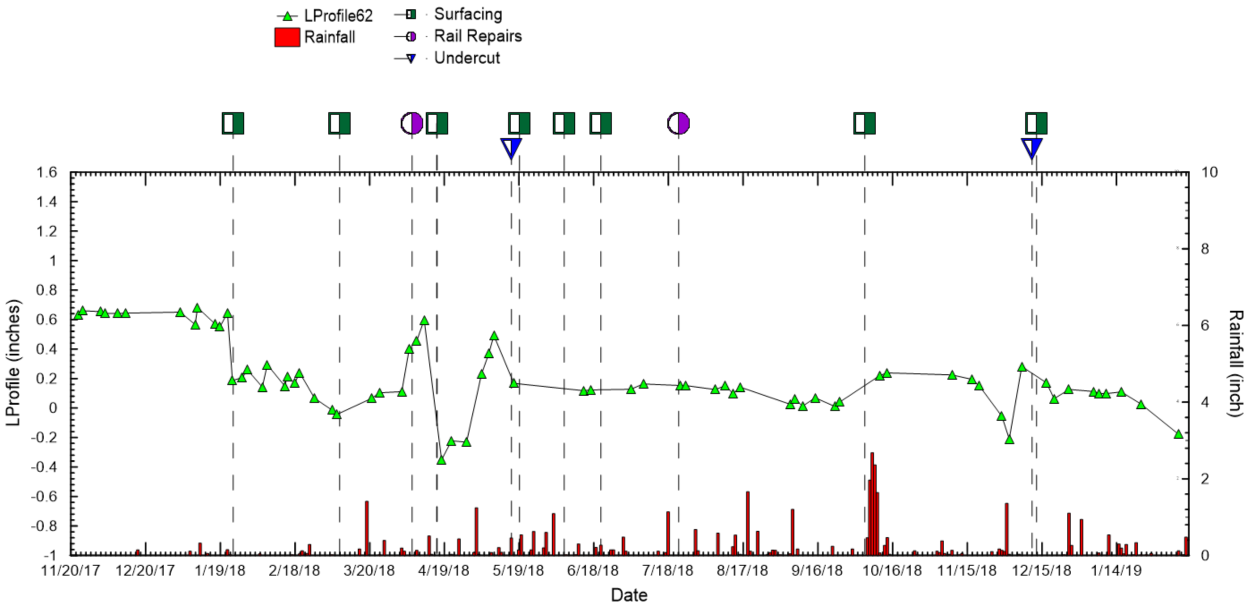


Figure C.11. Rainfall at Parkville

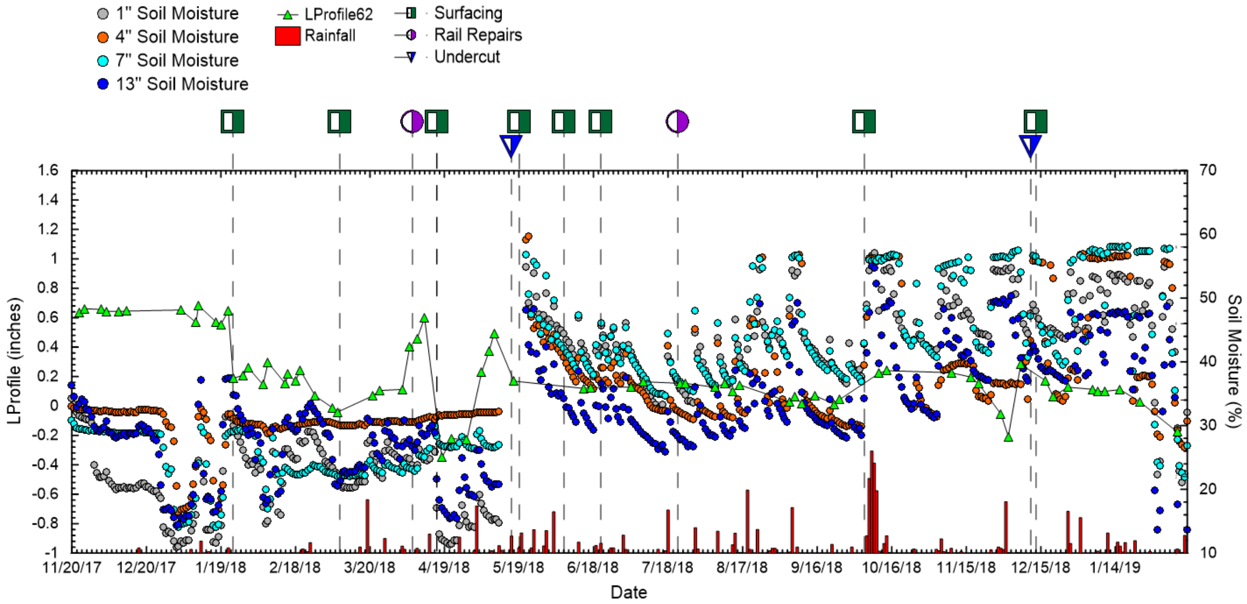


Figure C.12. Soil Moisture at Parkville

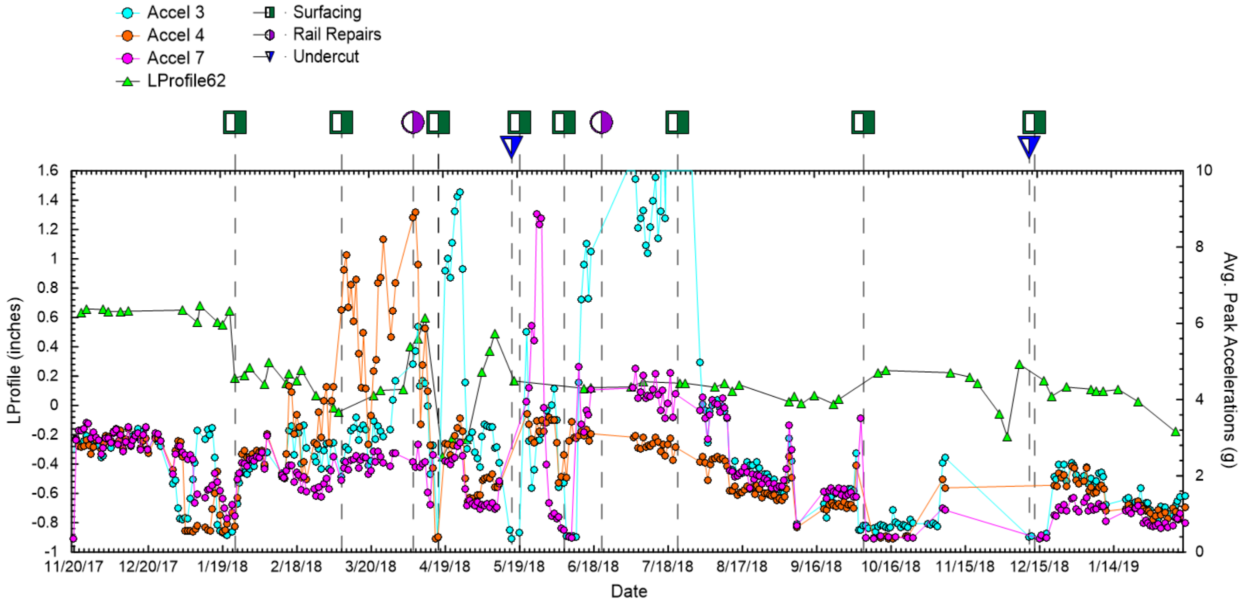


Figure C.13. Average Peak Accelerations at Parkville

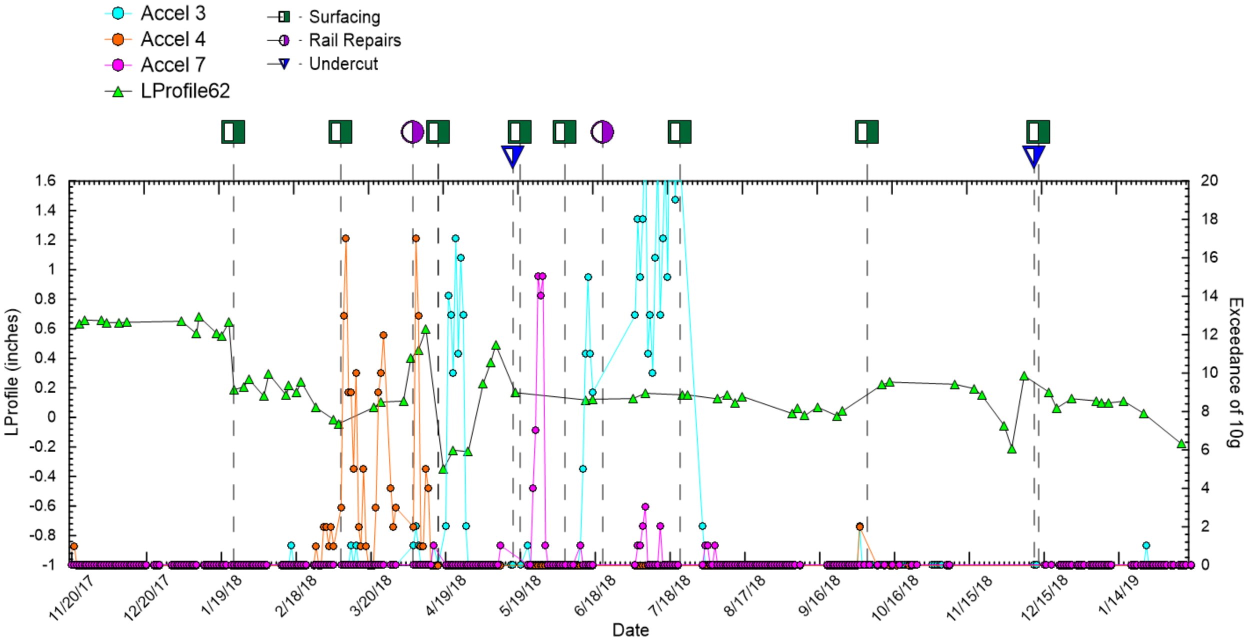


Figure C.14. Acceleration Exceedances at Parkville

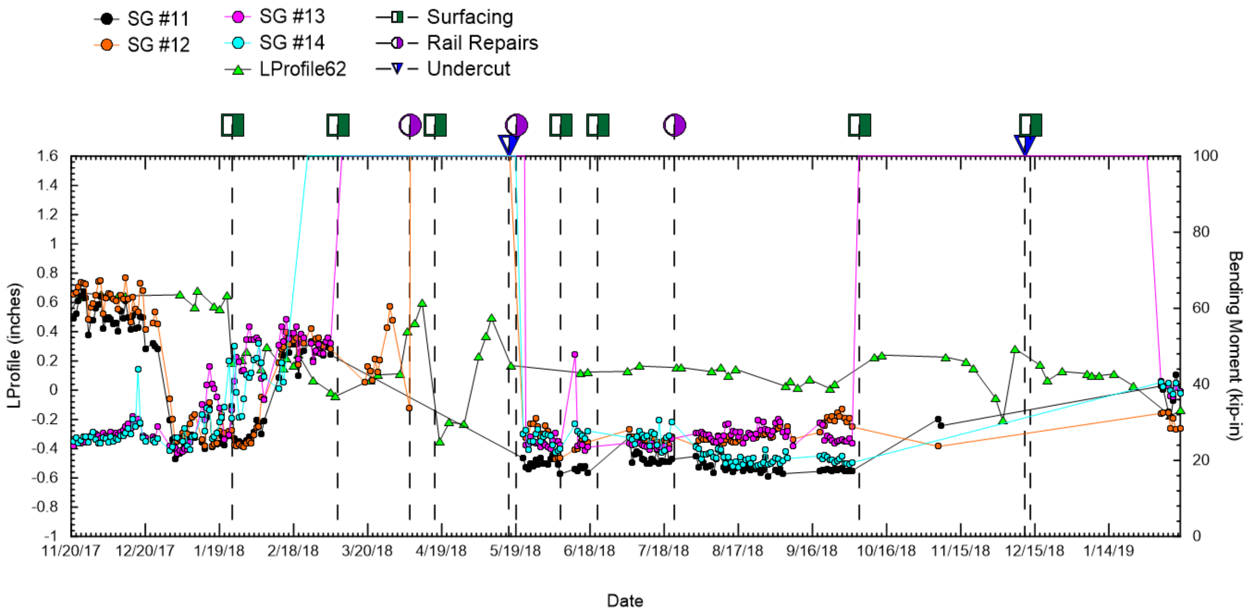


Figure C.15. Bending Moments at Parkville

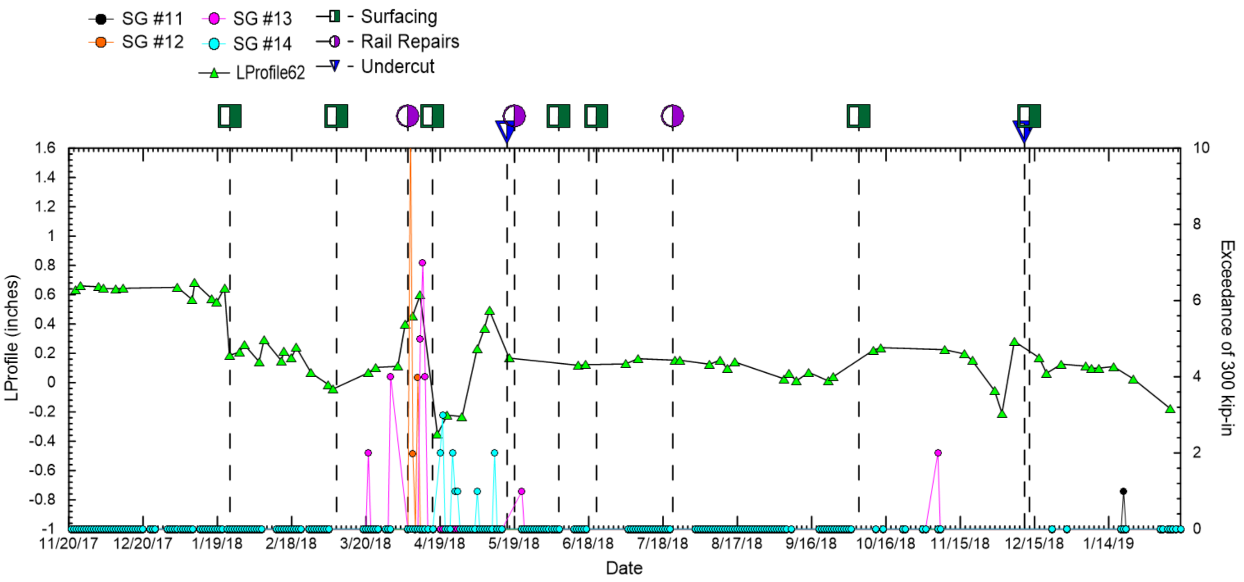


Figure C.16. Bending Moment Exceedances at Parkville

C.3 Roca – Fouled

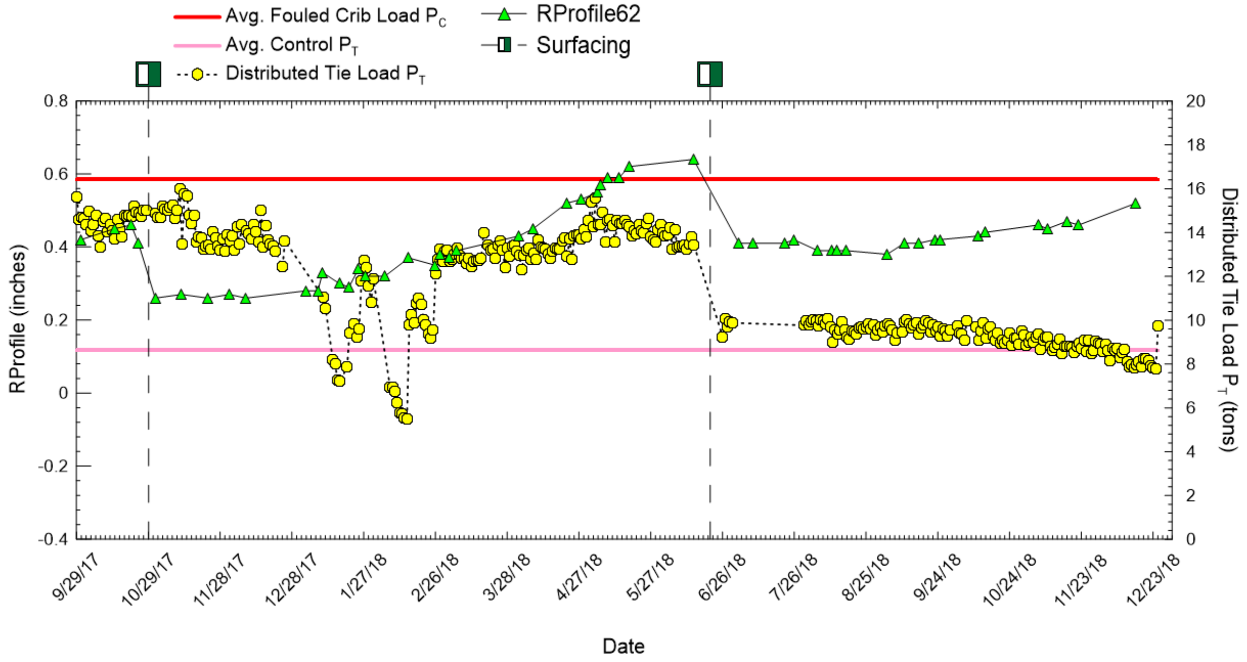


Figure C.17. Distributed Tie Load at Roca – Fouled

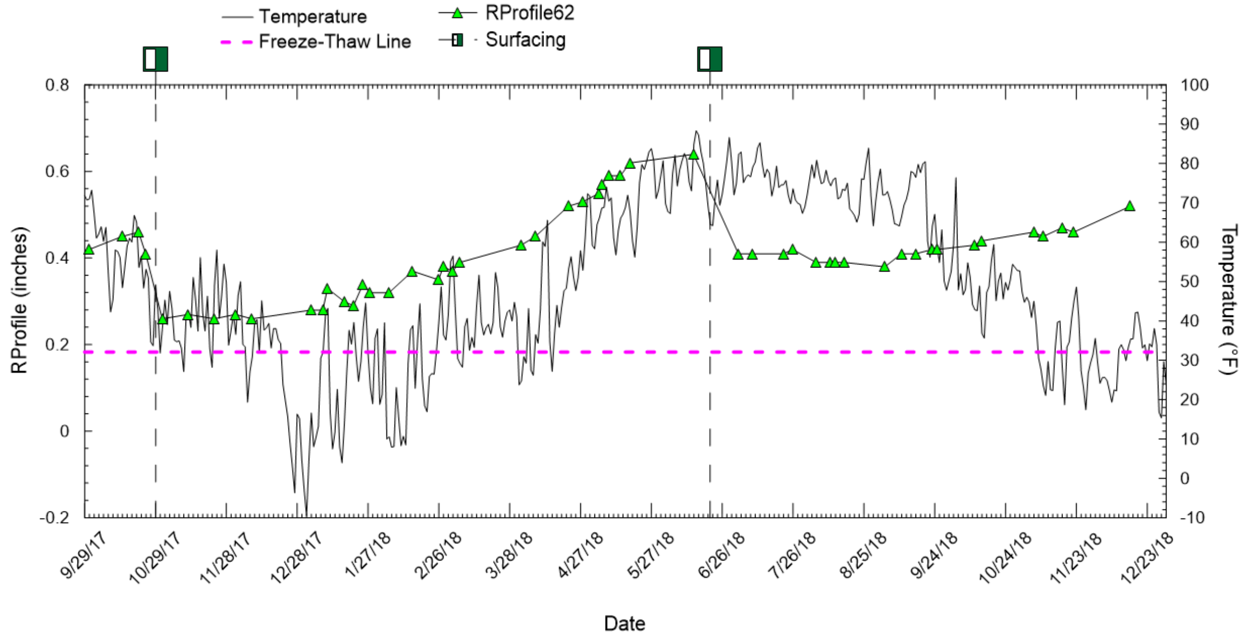


Figure C.18. Temperature at Roca – Fouled

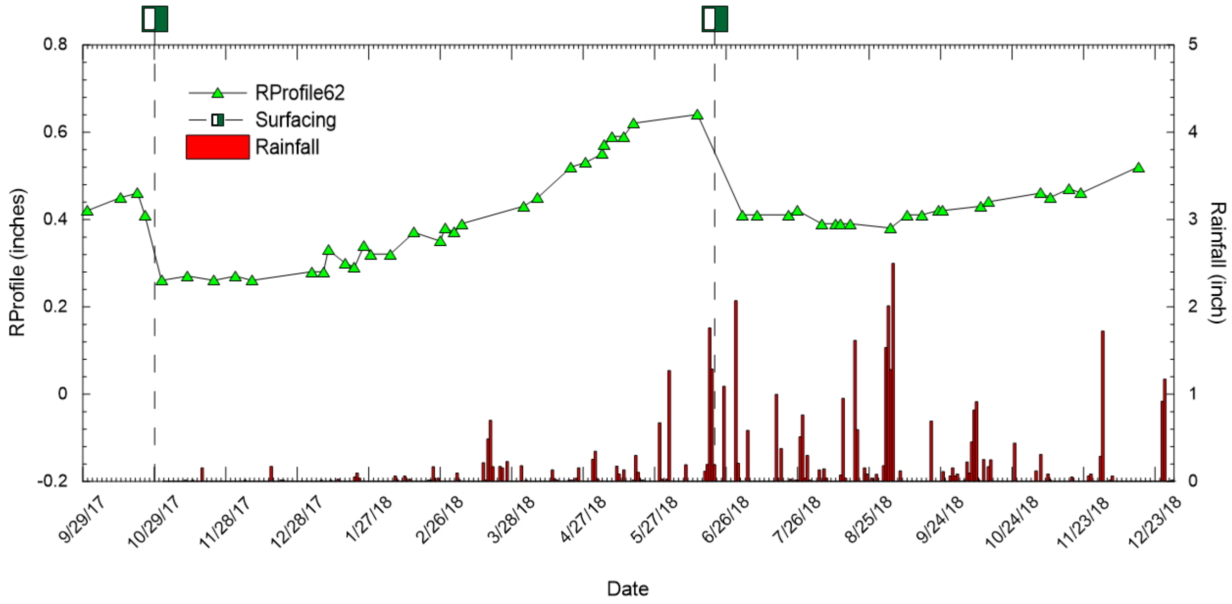


Figure C.19. Rainfall at Roca – Fouled

Note: Soil moisture at the Roca fouled ballast site was inconclusive due to insufficient fouling at the sensor depths resulting in dry conditions.

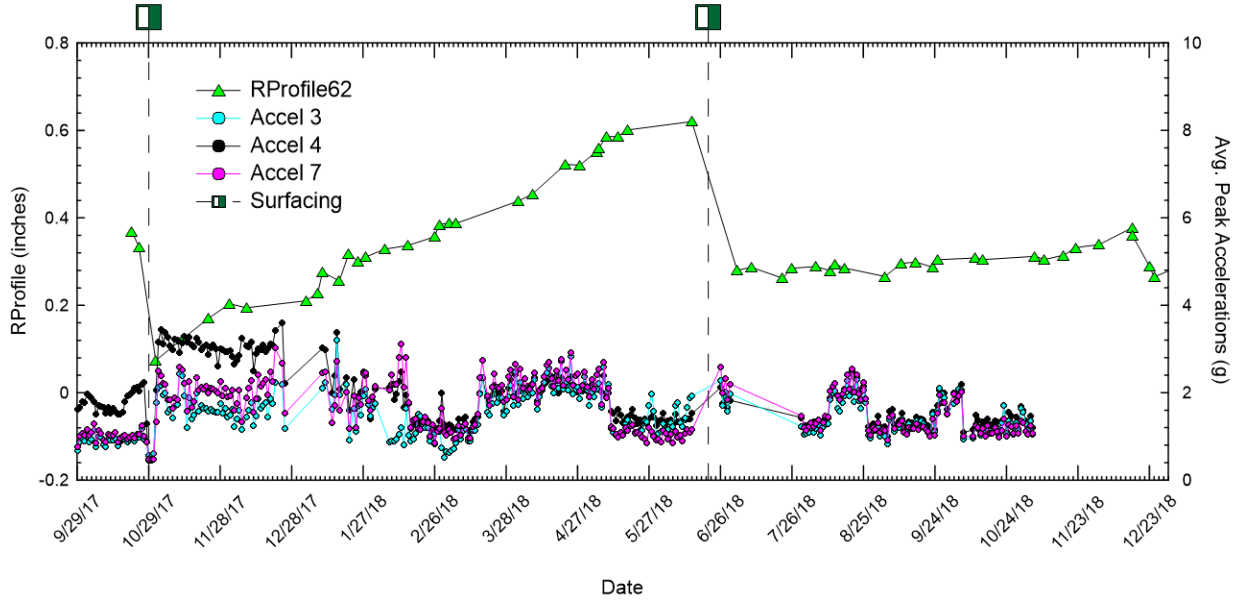


Figure C.20. Average Peak Accelerations at Roca – Fouled

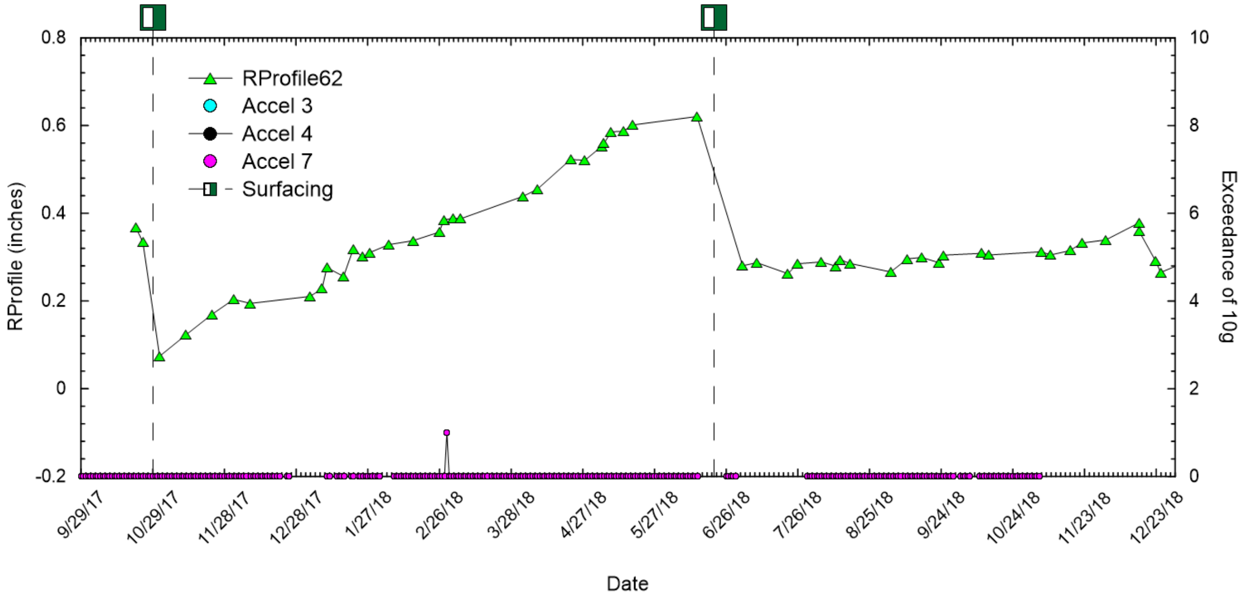


Figure C.21. Acceleration Exceedances at Roca – Fouled

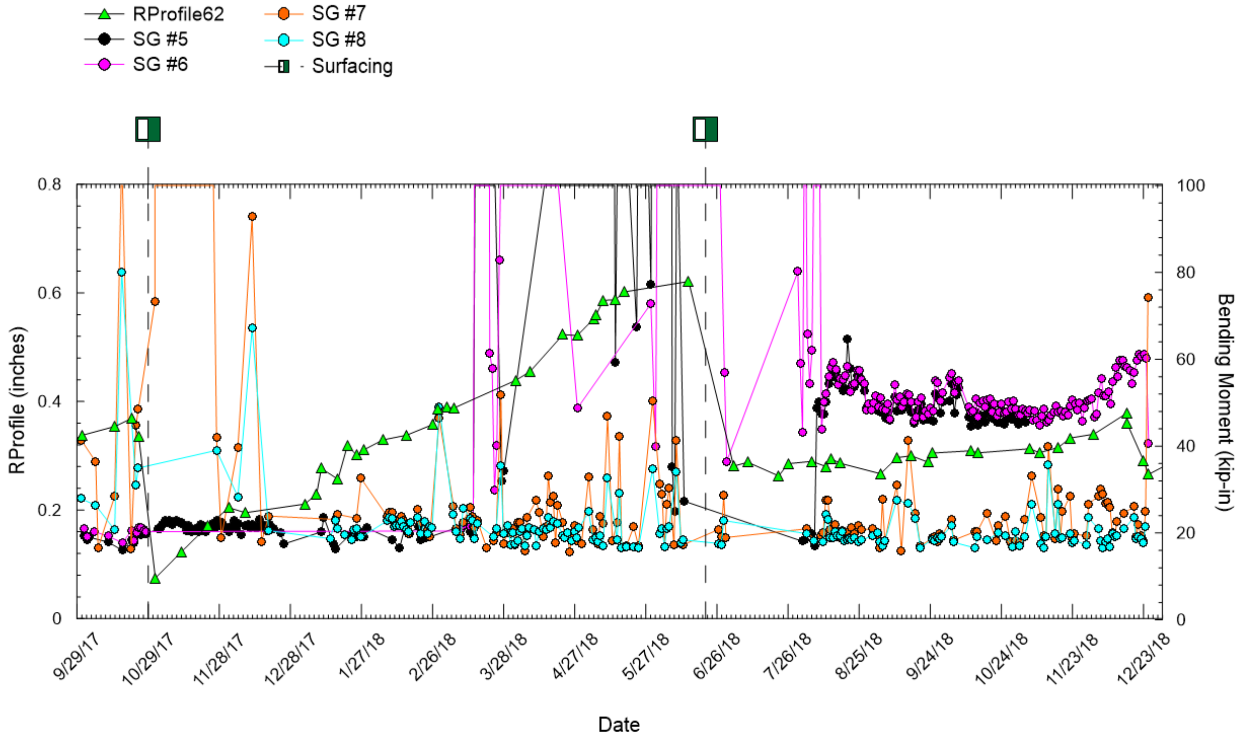


Figure C22. Bending Moments at Roca – Fouled

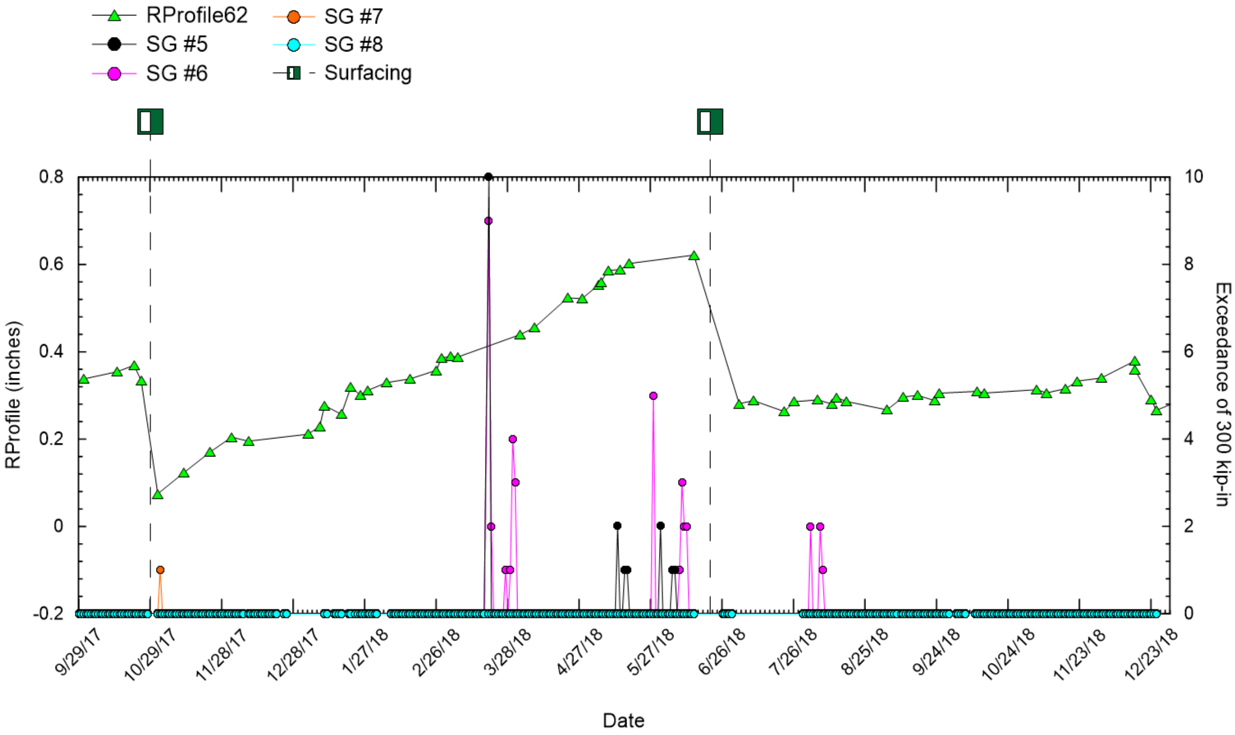


Figure C.23. Bending Moment Exceedances at Roca – Fouled

C.4 Roca – Control

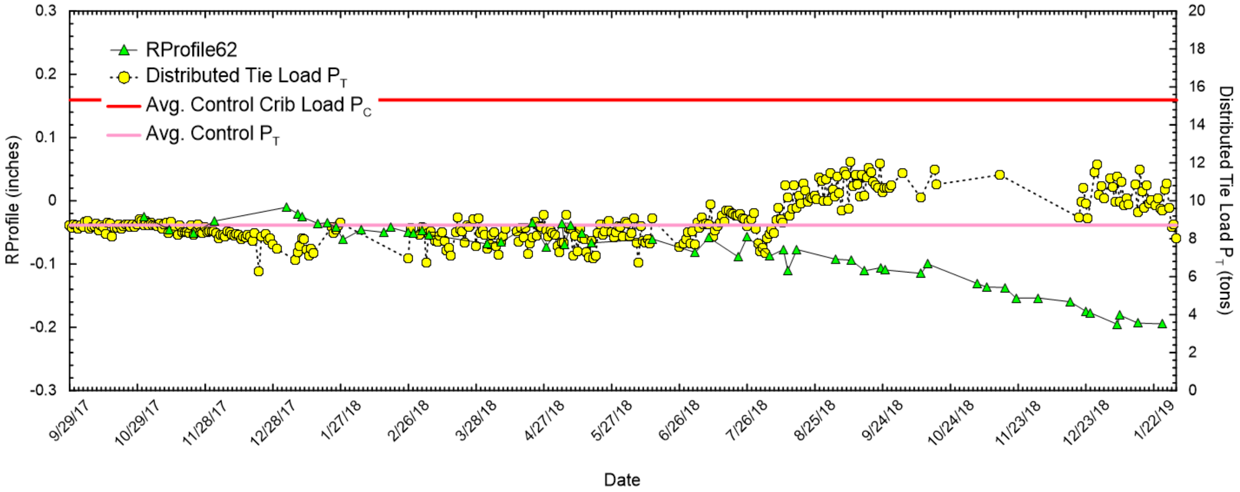


Figure C.24. Distributed Tie Load at Roca – Control

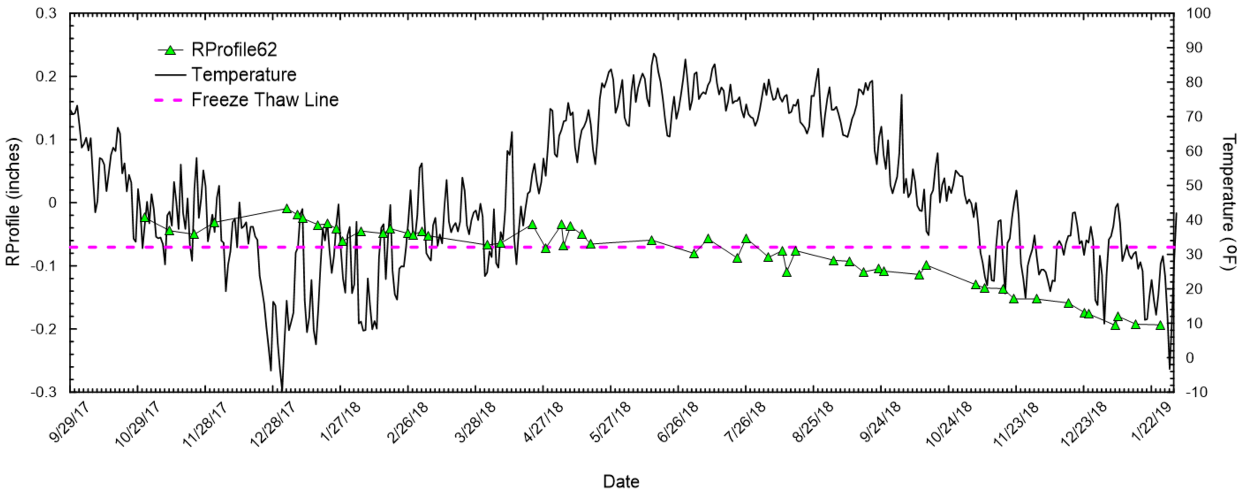


Figure C.25. Temperature at Roca – Control

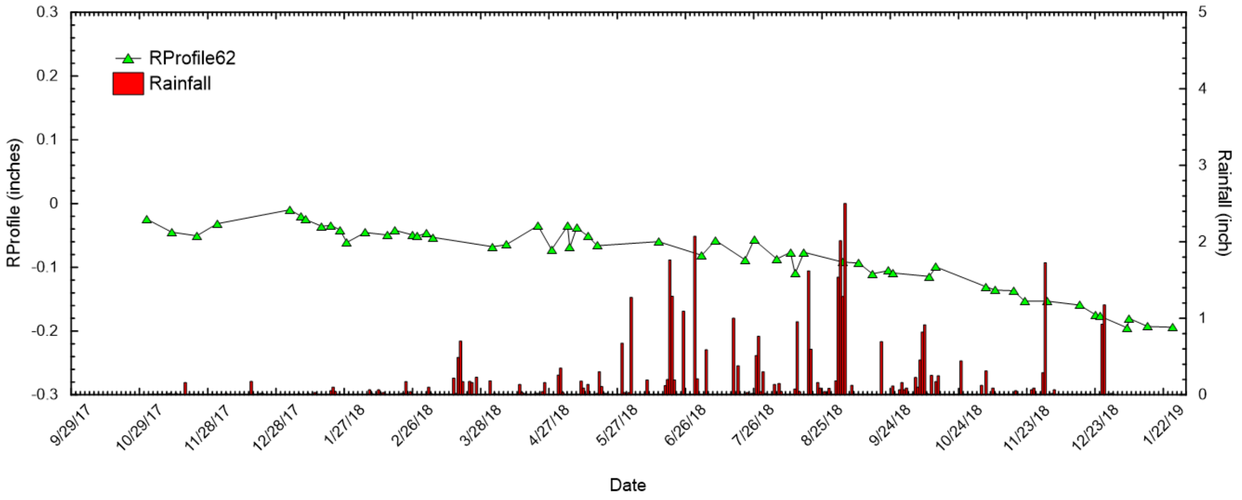


Figure C.26. Rainfall at Roca – Control

Note: Soil moisture at the Roca control site was not measured due to the dry conditions preventing the moisture sensors from working.

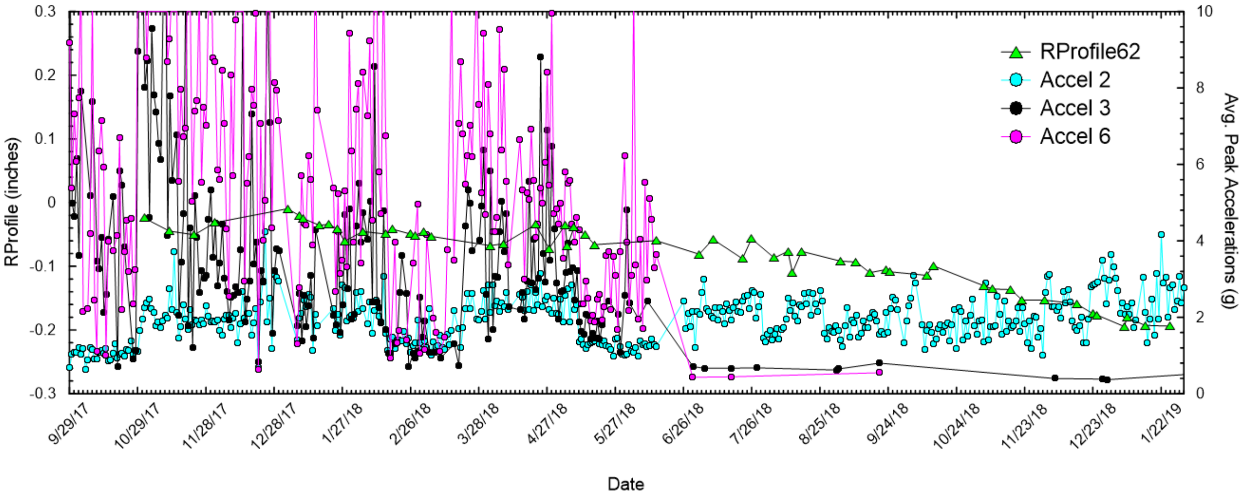


Figure C.27. Average Peak Accelerations at Roca – Control

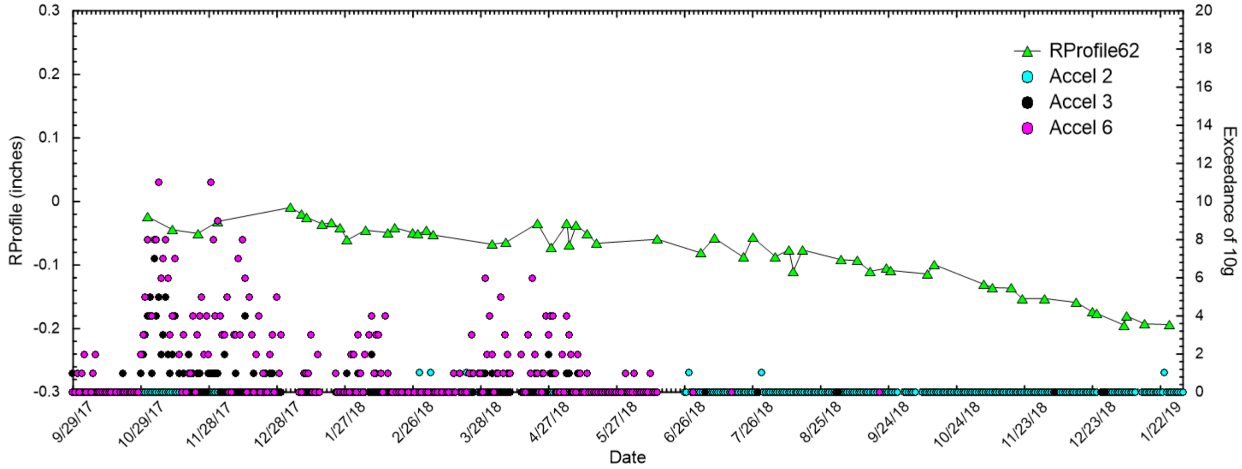


Figure C.28. Acceleration Exceedances at Roca – Control

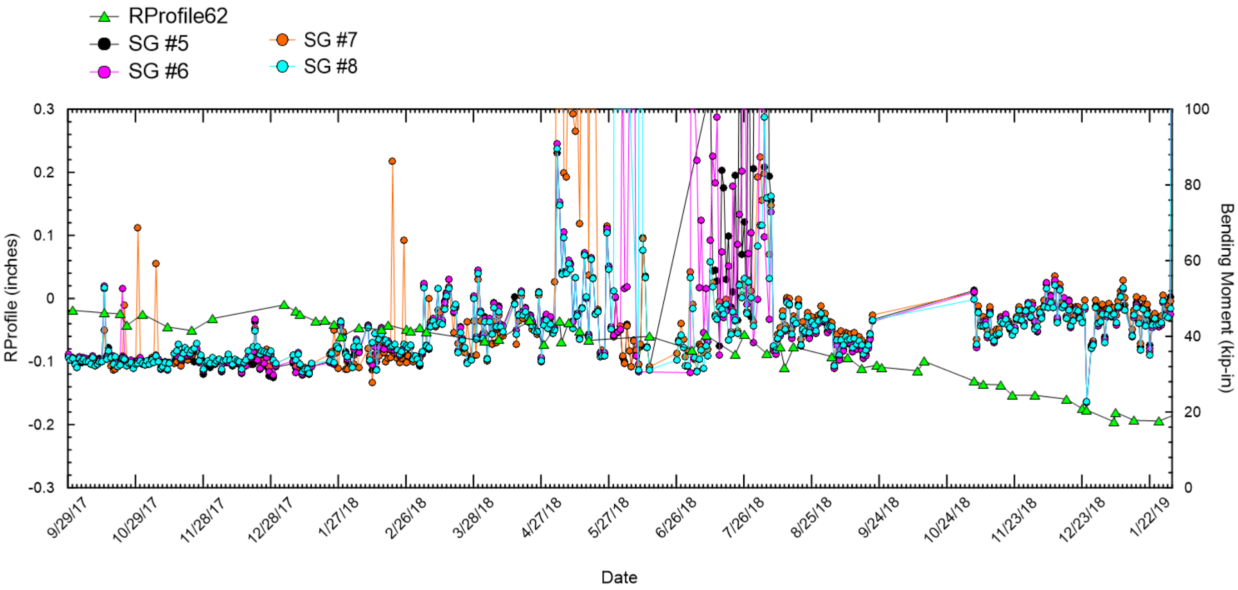


Figure C.29. Bending Moments at Roca – Control

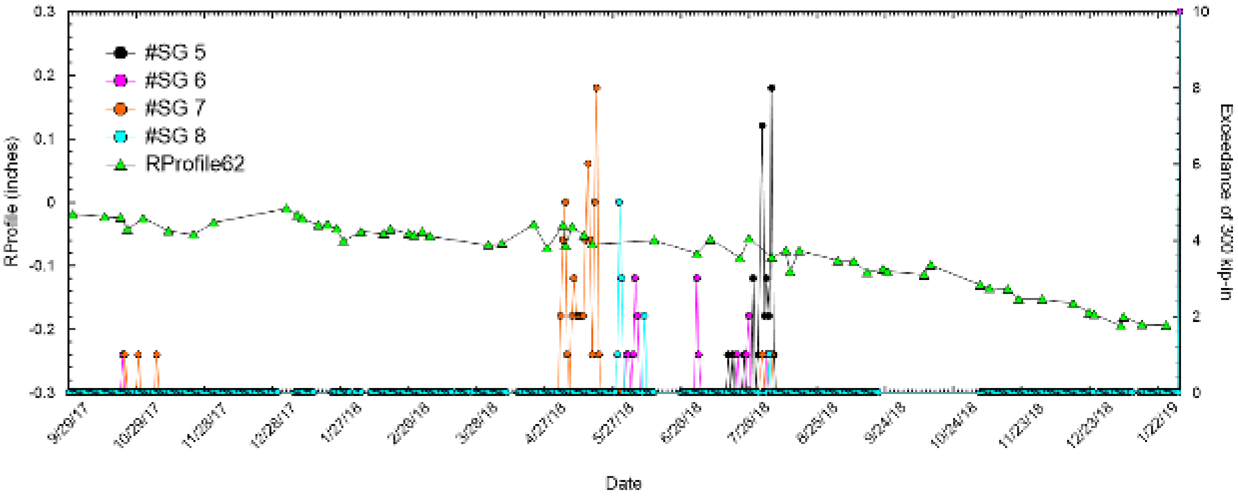


Figure C.30. Bending Moment Exceedances at Roca – Control

C.5 Hickman – Fouled

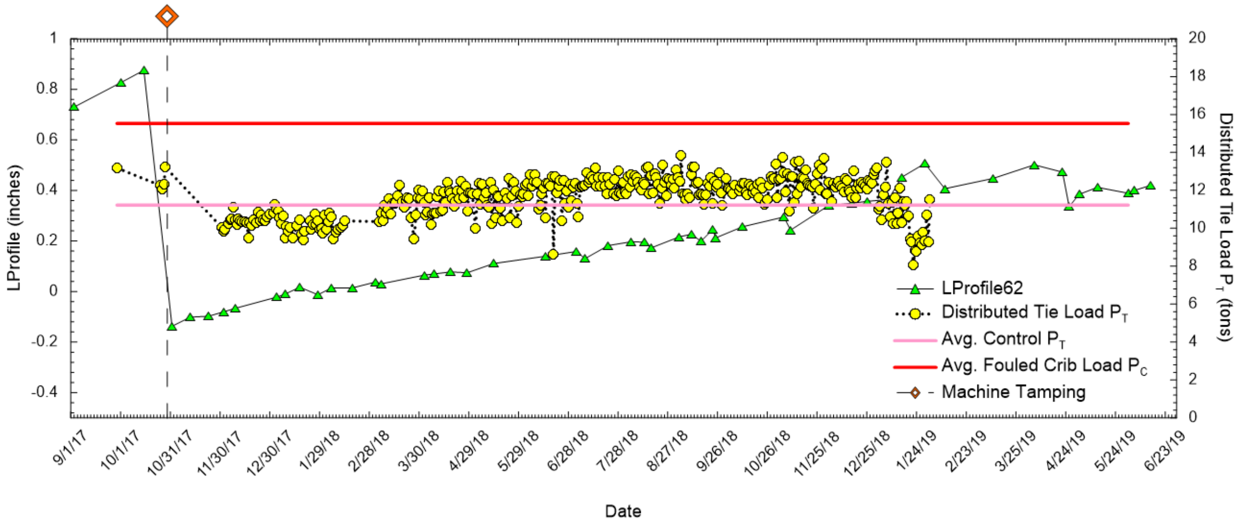


Figure C.31. Distributed Tie Load at Hickman – Fouled

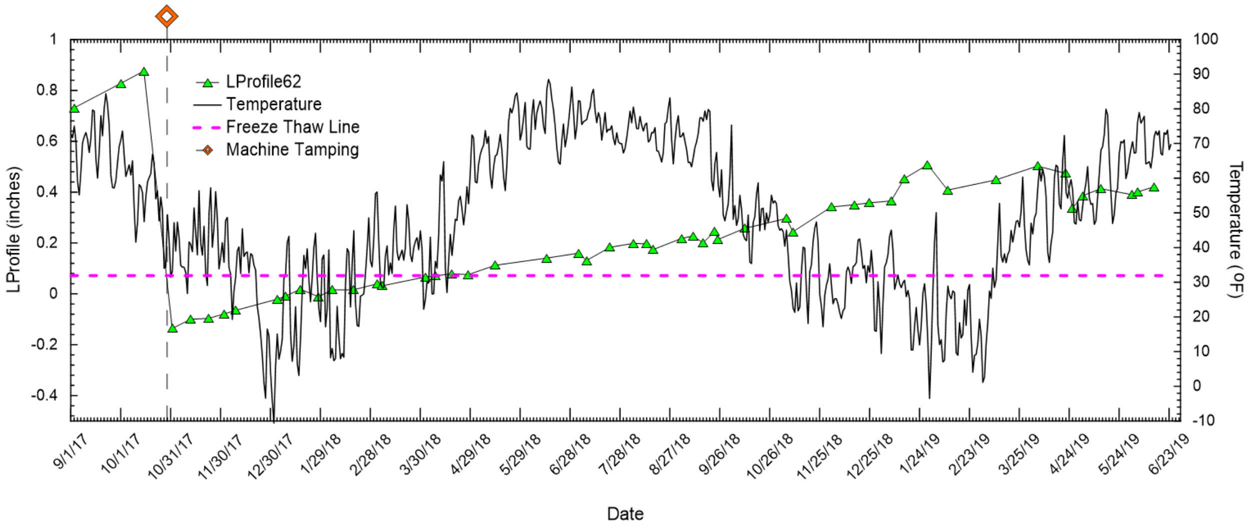


Figure C.32. Temperature at Hickman – Fouled

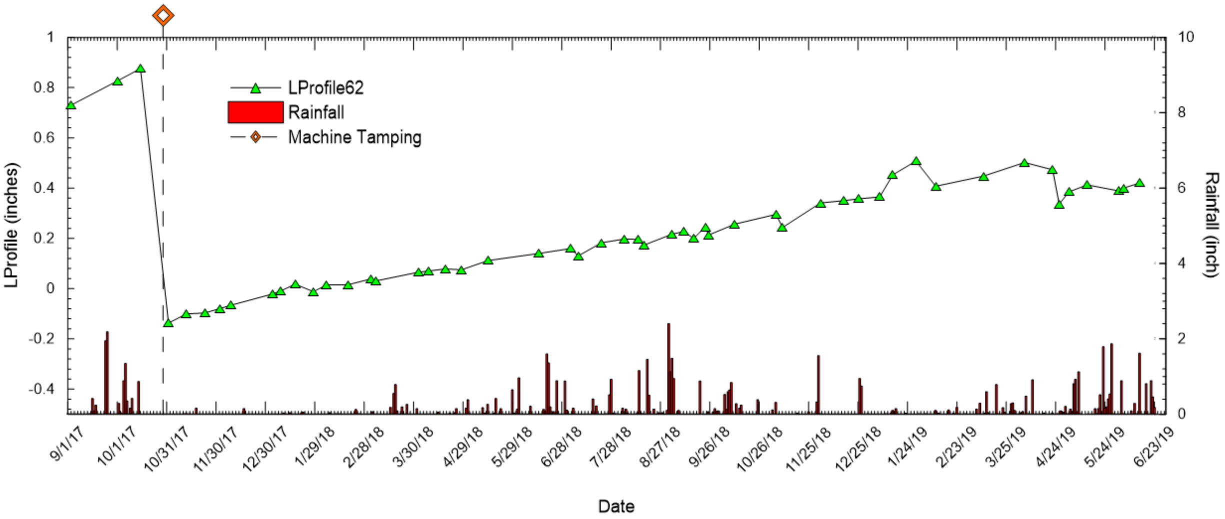


Figure C.33. Rainfall at Hickman – Fouled

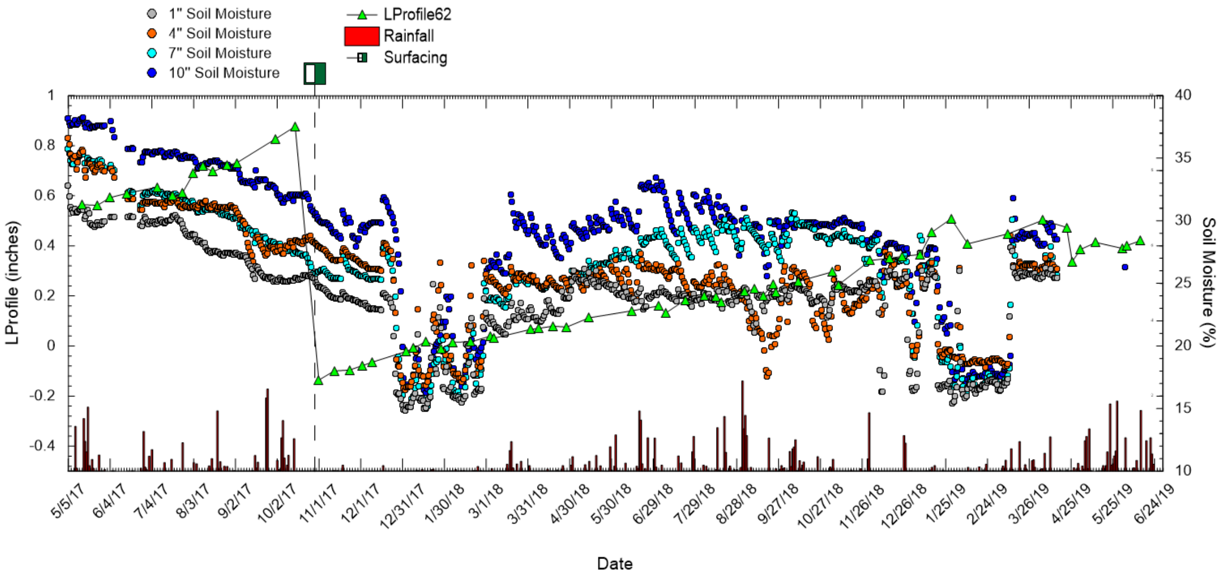


Figure C.34. Soil Moisture at Hickman – Fouled

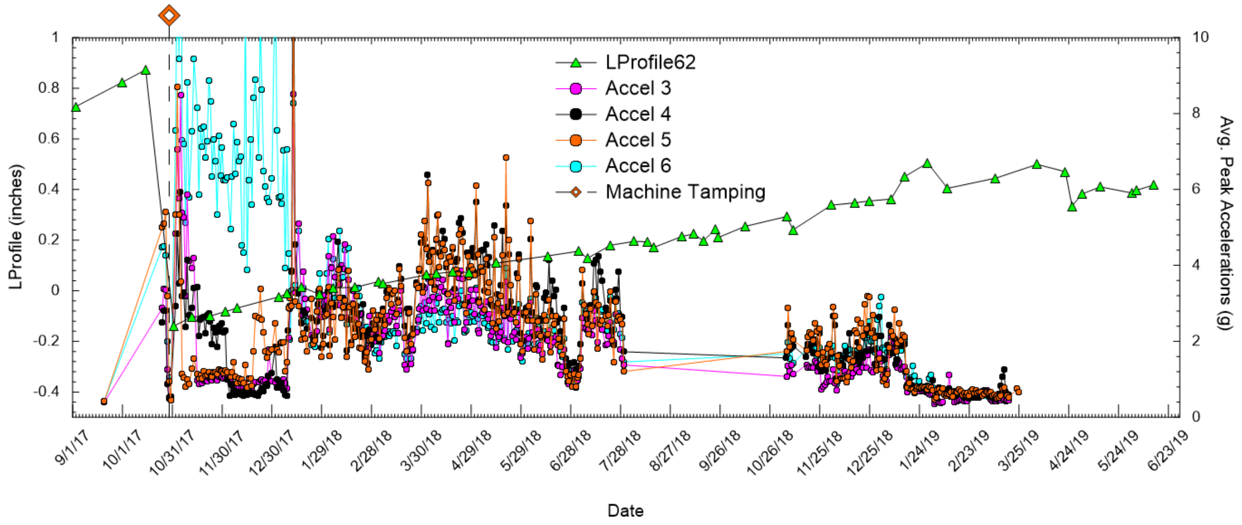


Figure C.35. Average Peak Accelerations at Hickman – Fouled

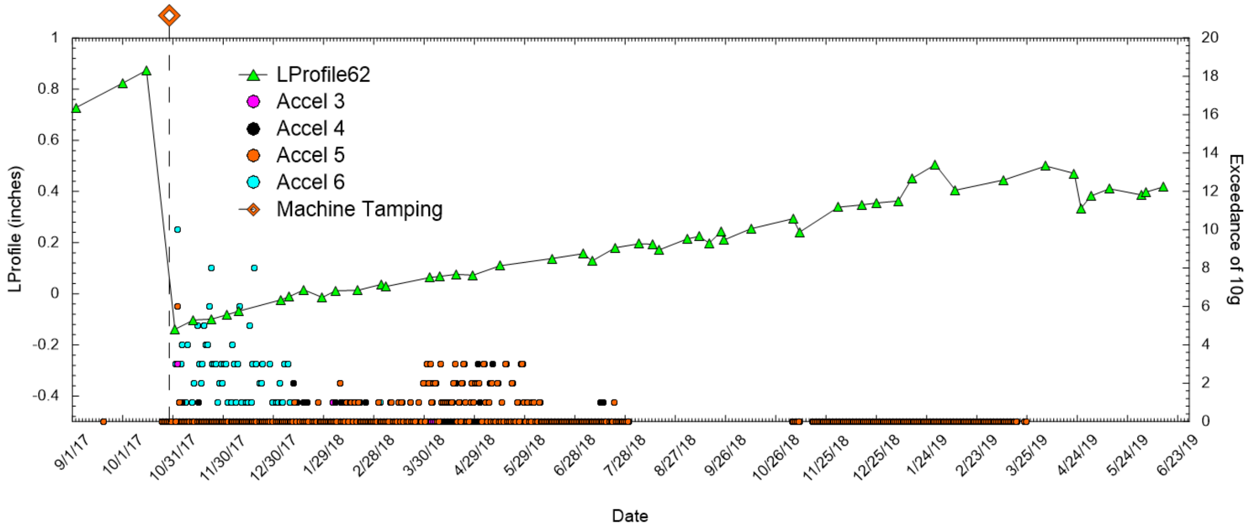


Figure C.36. Acceleration Exceedances at Hickman – Fouled

Note that bending moments are not available at the Hickman fouled ballast site because this site had timber ties. Tie strain gages were only installed on concrete tie sites.

C.6 Hickman – Control

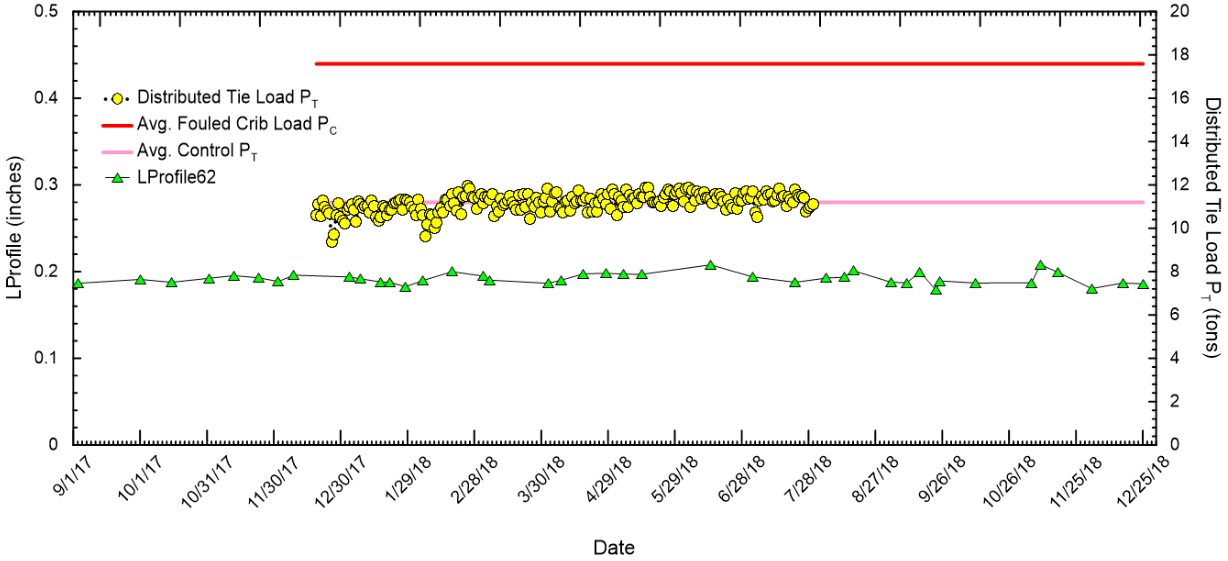


Figure C.37. Distributed Tie Load at Hickman – Control

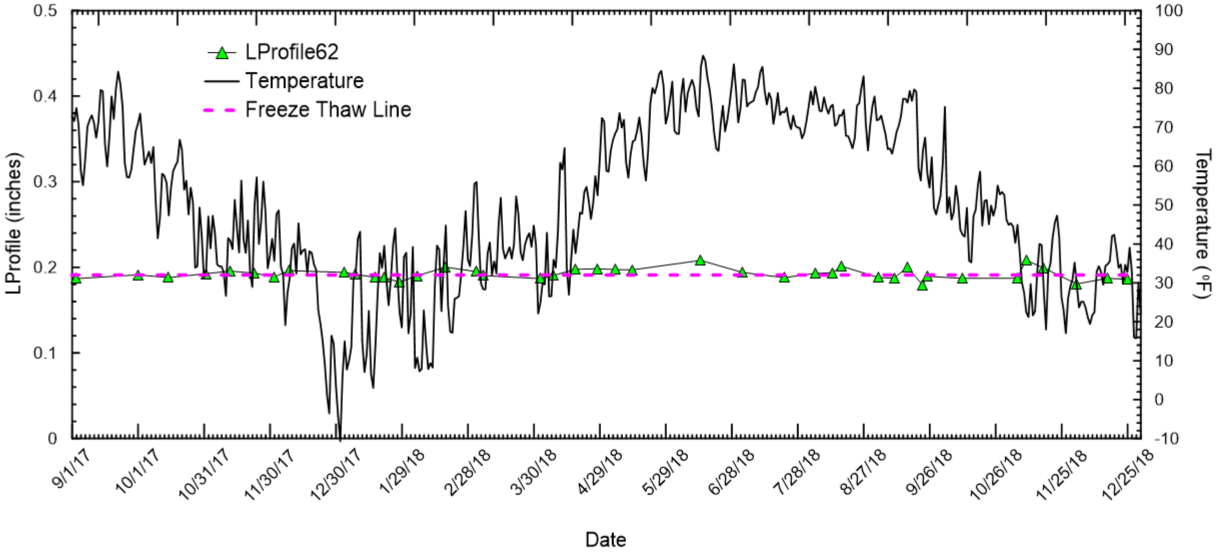


Figure C.38. Temperature at Hickman – Control

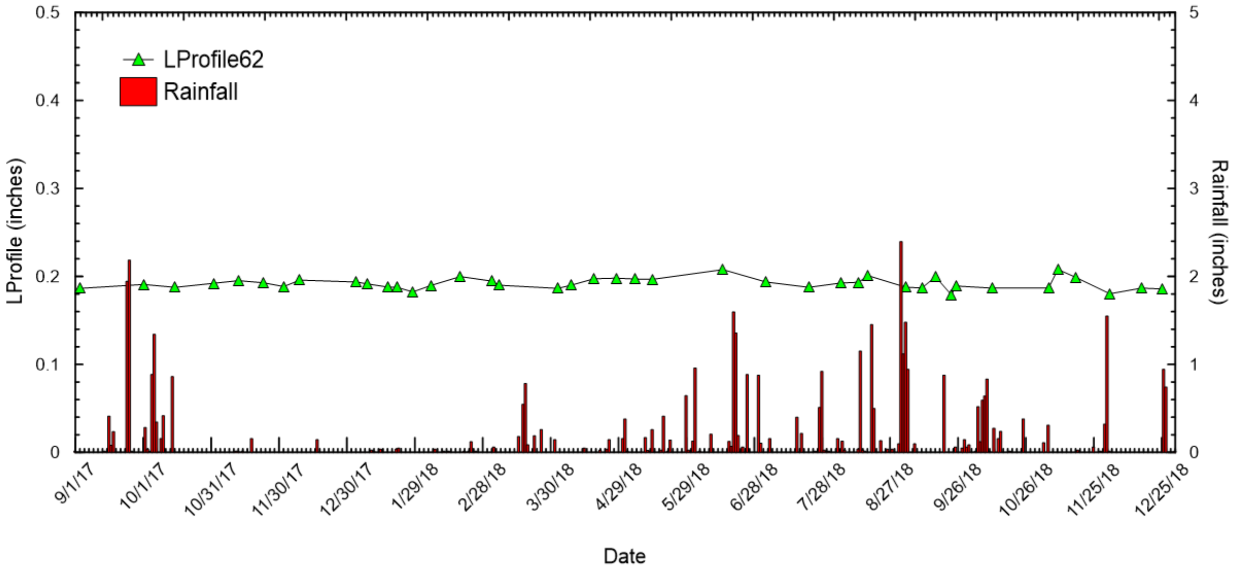


Figure C.39. Rainfall at Hickman – Control

Note: Soil moisture at the Hickman control site was not measured due to the dry conditions preventing the moisture sensors from working.

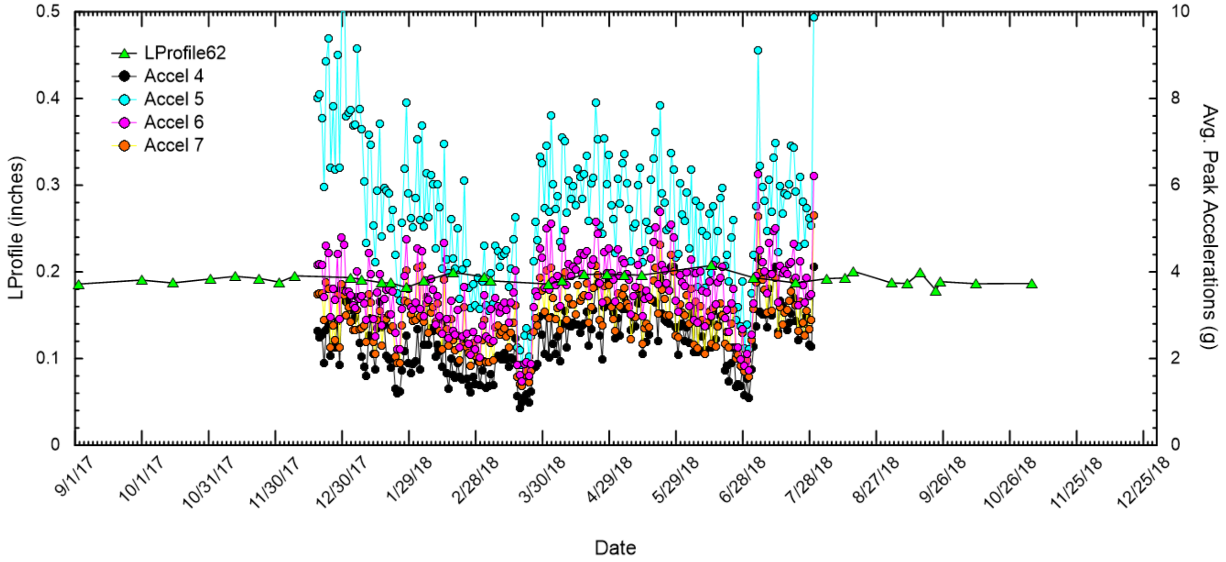


Figure C.40. Average Peak Accelerations at Hickman – Control

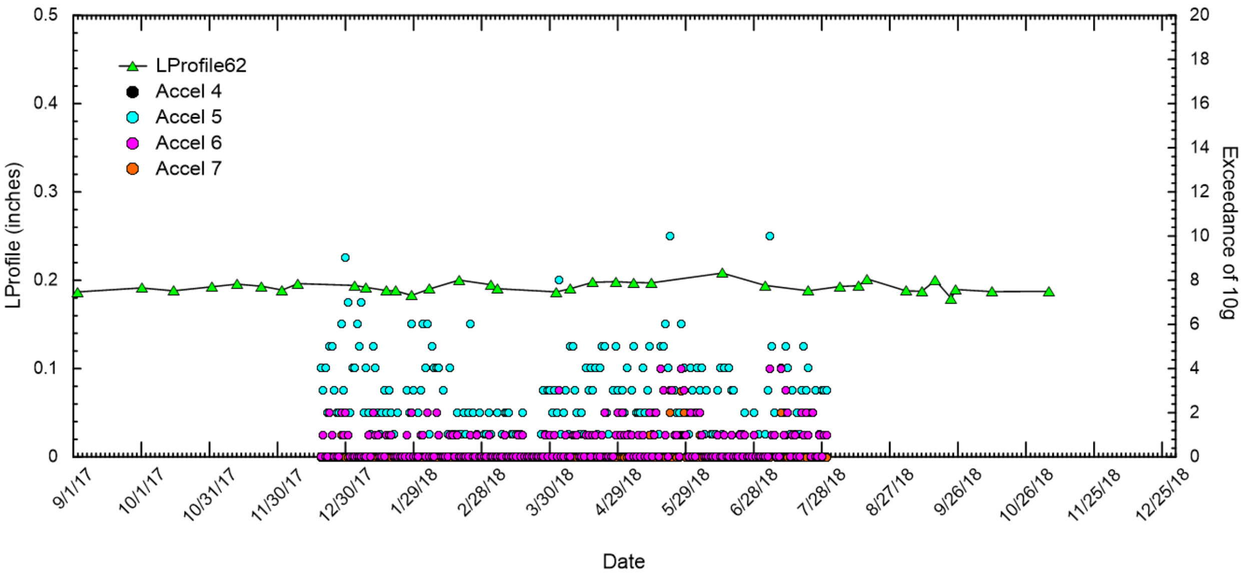


Figure C.41. Acceleration Exceedances at Hickman – Control

Note that bending moments are not available at the Hickman control site because this site had timber ties. Tie strain gages were only installed on concrete tie sites.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AREMA	American Railway Engineering and Maintenance-of-Way Association
AAR	Association of American Railroads
ATGMS	Autonomous Track Geometry Measurement System
ATIP	Automated Track Inspection Program
BFI	Ballast Fouling Index
BNSF	Burlington Northern Santa Fe Railway
CFR	Code of Federal Regulations
DAQ	Data Acquisition
CDAQ	Data Acquisition Chassis
DC	Direct Current
DE	Distribution Efficiency
FRA	Federal Railroad Administration
FDL	Fouling Depth Layer
GRMS	Gage Restraint Measurement System
GPS	Global Positioning System
GPR	Ground Penetrating Radar
Volpe	John A. Volpe National Transportation Systems Center
MP	Milepost
MGT	Million Gross Tons
NI	National Instruments
RD&T	Office of Research, Development and Technology
PCB	PCB Piezotronics, Inc.
SSD	Subsurface Defects
TR&D	Technical Research and Development
TB	Terabyte
TCS	Trackbed Condition Summary
TQI	Track Quality Index
UIUC	University of Illinois at Urbana-Champagne