U.S. Department of Transportation

Federal Railroad Administration

Joint Bar Failure Study—Field Investigation

Office of Research, Development
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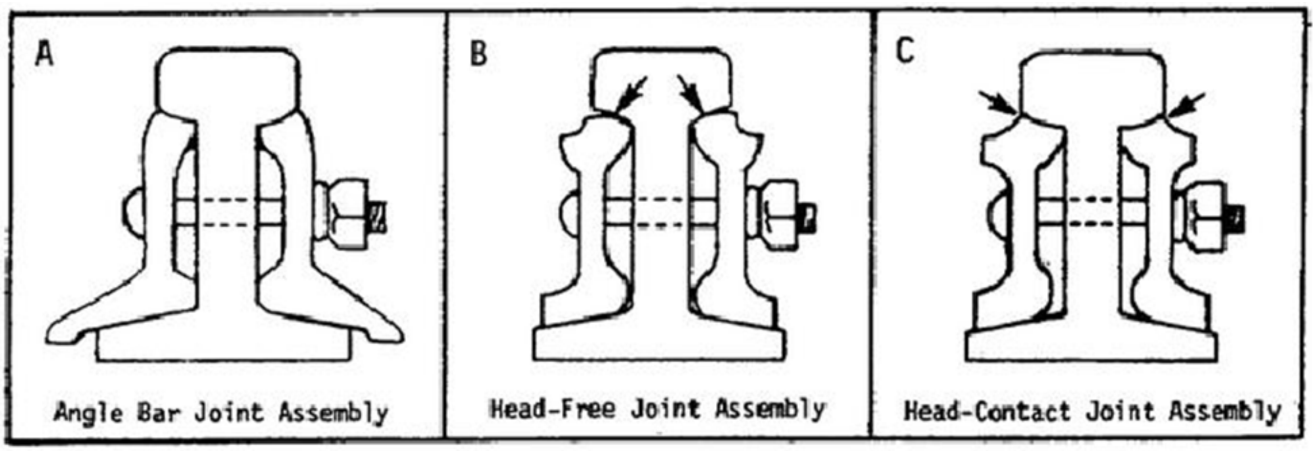
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)
After the Federal Railroad Administration (FRA) accepted a 2011 recommendation by the Rail Safety Advisory Committee (RSAC), the agency directed its Office of Research, Development and Technology (RD&T) to initiate a comprehensive study that would examine the track and operational conditions that contribute to joint bar failures. The goal of the study was to determine the root causes that lead to the failure of joint bars. Field observations and results of analysis of collected data are presented. Also, this study recommends the best track maintenance practices to mitigate the risks of rail joint failures and proposes further research to detect rail joints with high risks of future failures.

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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)

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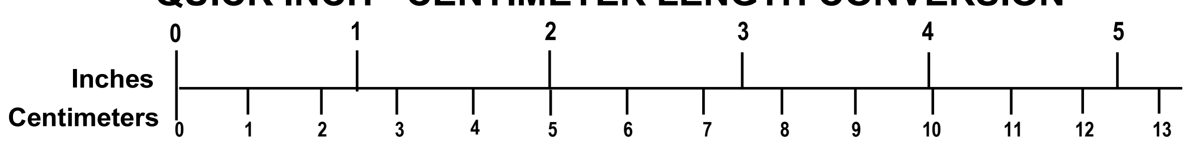

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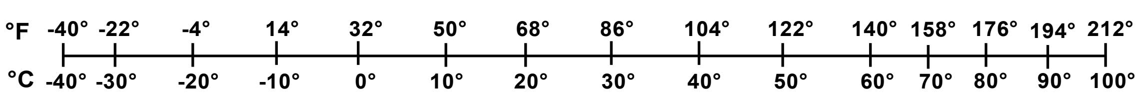

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Executive Summary

After the Federal Railroad Administration (FRA) accepted a 2011 recommendation by the Rail Safety Advisory Committee (RSAC), the agency directed its Office of Research, Development and Technology (RD&T) to initiate a comprehensive study that would determine the track and operational conditions that contribute to joint bar failures. The goal of the study was to determine the root causes that lead to the failure of joint bars. This study was conducted from September 2011 to June 2014.

The study was comprised of three major efforts:

- Field investigations
- Laboratory testing of selected cracked/broken joint bars retrieved at locations of rail joint failures
- Finite element analyses (FEA) to examine structural performance of rail joints under various loading and tie-ballast support conditions with the primary purpose of providing information to help interpret and understand the observations from the field surveys and laboratory testing

This report provides a comprehensive review of the first effort, field investigations, that was assigned to and performed by ENSCO, Inc. Field observations and results of analysis of collected data are presented. In addition, best track maintenance practices to mitigate the risks of rail joint failures are described and further research is proposed to detect rail joints with high risks of future failures.

Scope

The portion of the study addressing field investigations describes:

- Developing of a test and analysis plan and a test procedure for field surveys and the identification of test zones
- Verifying the test procedure
- Collecting field observations and measurements during field evaluation surveys
- Compiling the addition information from participating railroads
- Collecting records from past joint bar inspections
- Analyzing collected field data
- Analyzing past joint bar inspection records to identify repeated rail joint failures
- A preliminary assessment of short mid-chord offsets as a method to detect rail joints with high risk of future failure

Field Survey Timeline, Test Zones and Participants

Seven field evaluation surveys, each encompassing approximately 1 week of evaluation, were conducted on representative test zones from 2012 through 2014 with the cooperation of three Class I railroads. ENSCO personnel and engineers from Transportation Technology Center, Inc.

(TTCI), a subsidiary of the Association of American Railroads (AAR), helped verify and refine the test procedure at the facility in Pueblo, CO, and participated in the test team during the first three initial field surveys.

Test zones included a wide range of track inspection frequencies, track classes, tonnages, rail and crosstie types, as well as joint bar designs in Continuous Welded Rail (CWR) and jointed track (JNT) territories from various geographical regions.

Six of the seven evaluation surveys were conducted in tandem with Optical Automated Joint Bar Inspection System (JBIS) surveys that were conducted as part of the participating railroads' regular testing activities. One survey was done in conjunction with a scheduled railroad walking inspection. JBIS technology was successfully developed by the FRA RD&T several years ago to automatically identify cracked or broken joint bars, and several major railroads employ JBIS in their track inspection programs.

Measurements and Observations Recorded

The field survey team investigated a set of identified failed joints and examined randomly selected locations with intact joints. The intact joints served as a control group. Detailed measurements and observations were made at each site, including rail end conditions and bolting; vertical and lateral joint movement; track geometry; type and condition of crossties and fasteners; ballast and drainage conditions; rail size; type and design of joint bars; rail and ambient temperatures; geographical information; class of track; and several other parameters.

Methodology for Analysis

Joint bar data collected in CWR and JNT territories were separated and analyzed independently from one another due to the inherent differences in the thermal stresses and the installations in each type of territory.

The analysis of the collected data consisted of addressing questions regarding the potential contribution of various track conditions to the mechanism of joint bar failure. Statistical methods were used to evaluate the distribution of defect types and various crack/break patterns and also to analyze the occurrence and magnitudes of the various track conditions found at each joint bar location. The analysis included a statistical T-test to determine what conditions were more prevalent or severe at failed joint locations than conditions at intact joint locations. Records of past JBIS surveys were also analyzed to identify potential repeated rail joint failures.

Sample Composition and Observed Failure Modes

A total of 636 miles of track were surveyed during the seven field visits. Field measurements and observations were recorded on 230 joints (128 failed and 102 intact joints):

- Sample CWR territory (Class 3, 4 – tonnage 21–194 million gross tons [MGT]):
  - 5 defect locations
  - 53 intact bar locations
- Sample JNT (Class X, 1, 2 and 3 – tonnage 0.1–15 MGT):
  - 123 defect locations
  - 49 intact bar locations

The most frequent failure modes were top center cracks and breaks that occur between the middle two bolt holes on standard design joint bars, or full quarter breaks that occur outside of the middle two bolt holes on long toe (angle) bars.

Analysis Results

Vertical movement generated by deteriorating joint support was the most significant factor for joint bar failure in all track classes. Lateral joint movement was also a factor but was less prominent. Many failed joints had vertical movements exceeding 1/2 inch. This threshold would indicate the possibility of joint failure where maintenance efforts would extend the life of a rail joint. In addition, identified repeat joint failures showed vertical movements exceeding 1.5 inches. Immediate remedial action at this threshold would reduce the risks of imminent joint failure.

Rail end condition is a significant factor in Class 3 and above track, especially when the rail end condition is combined with vertical movement. Many failed joints from Class 4 track showed rail end batter or tread mismatches exceeding 1/8 inch or abrupt rail end ramp exceeding 1/8 inch with ramp angles of 2–7 degrees. On Class 3 track, many failed joints exhibited either tread mismatch, rail end ramp or batter, both with slopes over 1 degree that exceeded 3/16 inch. Rail end conditions should be maintained within the currently defined regulatory limits on rail end mismatches (3/16 inch on Class 3 track; 1/8 inch on Class 4 track) and within the non-regulatory maintenance standard for rail end batter (3/16 inch) currently used by several railroads for Class 4 track and above. This limit, however, should also apply on Class 3 track. These values also represent appropriate thresholds for locations with a risk of rail joint failure. Also, the ramps' abruptness should stay within the current non-regulatory maintenance standard requirements used by several railroads for maximum rail end ramp slope of 0.012 per inch slope (0.7 degrees).

Non-contributing factors include longitudinal rail movement, longitudinal joint bar movement, bolting conditions, marginal crossties, suspended/supported rail joint configurations, wide or narrow gage, and alinement, unless they contribute to a lack of vertical support.

After support and rail end conditions were observed at failed temporary joints (joints that are intended to be welded or removed within a short period) indicates that it is important to avoid installing joints in areas of poor crossties and deteriorated support conditions. Repair rails must be selected to avoid rail end misalignment unless the joints are corrected by welding or grinding. Temporary joints with adverse support and rail end conditions should be removed as soon as possible to reduce the risk of joint bar failures.

It is important to maintain good support on all track classes and rail end conditions, especially on track Class 3 and above, to reduce the occurrences of cracked or broken joint bars.

If inspection techniques focus on identifying poor support conditions, they may be able to identify locations that pose a risk to joint bar integrity. For example, shorter chord length track surface geometry measurements, referred to as short mid-chord offsets (MCOs), may be able to successfully identify joint locations with poor support conditions without producing large amounts of exceptions.

1. Introduction

In the recent past, joint bar failures have led to several track related derailments with serious consequences. The Federal Railroad Administration (FRA) has been actively addressing the issue of joint bar failure for many years.

In October 2006, FRA revised the track safety standards (Title 49 Code of Federal Regulations Part 213, Sections 213.119 and 213.343) requiring the inspection of joints in Continuous Welded Rail (CWR) at frequencies up to four times per year. The rule was in response to several accidents associated with the failure of joint bars in revenue service. When the FRA Office of Railroad Safety published the Final Rule on the detection and prevention of joint failures in CWR, it recognized that new and existing automated inspection technologies, when combined with appropriate maintenance and visual inspection practices, could reduce the risk of joint bar service failure. The Final Rule addressed the need for comprehensive joint inspection, including requirements for inventorying joints, detecting cracks, and identifying track conditions that cause the overstressing of joint bars and may ultimately lead to joint failure. The rule specified that the following items be identified:

1. Cracked joint bars
2. Missing or loose fasteners
3. Conditions associated with wheel impact at joints (excessive rail gaps and rail end batter)
4. Proper rail anchoring
5. Adequate vertical support
6. Missing or loose bolts

The safety standards cited earlier require that field conditions associated with cracked/broken joint bars be documented, but that documentation is often inconsistent. Although important information can be found in the field reports, no strong conclusions regarding the failure mechanism of joint bars have been drawn from these reports.

FRA's Office of Research, Development and Technology (RD&T) also supported the development of an automated methodology to assist field personnel in identifying cracked or broken joint bars by creating the optical automated Joint Bar Inspection System (JBIS). Several railroads have subsequently employed JBIS as part of their regular inspection program. Use of joint bar inspection technologies, such as automated visual inspections systems or systems based on ultrasonic approaches, lead to more efficient detection of cracked joint bars than traditional walking visual inspections and their removal from service prior to the occurrence of full breaks.

In 2011, as a result of the Rail Safety Advisory Committee's (RSAC) activity, RD&T initiated a comprehensive study that determined the track and operational conditions which contribute to joint bar failures, with the ultimate goal of determining the root causes of joint bar failures. The study has three major components:

1. Field investigations, supported by three Class I railroads, to compile detailed field observations and measurements of: 1) track conditions at joint bars locations which have exhibited signs of failure, and 2) randomly selected locations with intact joint bars. The

goal of these surveys was to identify major track conditions associated with joint bar failures.

2. Laboratory testing of selected cracked/broken joint bars retrieved from locations where rail joint failures occurred.
3. Finite element analyses (FEA) that examine the structural performance of rail joints under various loading and tie-ballast support conditions, with the primary purpose of providing information to help interpret and understand the observations from the field surveys and laboratory testing.

1.1 Objective

The objective of this report is to summarize the activities, observations and findings of the field investigations. The report also includes recommended best maintenance practices for mitigating the risk of rail joint failure and proposes further research in the detecting of rail joints with high risks of future failures.

1.2 Organization of the Report

Section 2 outlines a field survey methodology for the data collection process developed for this study. It also summarizes the scope of the field testing and gives an overview of the analysis approach. including the additional information collected from the participating railroads.

Section 3 provides an overview of the conducted field surveys. The overview includes a general description of the test zones, a composition of the collected sample and observed failure modes.

Section 4 outlines most important field observations made during the field surveys both on JNT and CWR territories and presents examples of encountered field conditions.

Section 5 presents the data analysis efforts from the JNT and CWR territory sample. The JNT sample is analyzed as combined dataset for all track classes and also separately based on track class as two distinct groups—Class X, 1, and 2 (lower track class) sample and Class 3 (higher track class) sample. The CWR sample is analyzed as one combined sample.

Section 6 summarizes additional analyses of historical joint bar inspection records, which are used to determine locations of repeated rail joint failures.

Section 7 presents the results of a preliminary analysis showing that shorter chord length track surface geometry measurements, also known as short mid-chord offsets (MCOs), have the potential to identify joint locations with poor support conditions.

Section 8 summarizes the field activities, states key observations, and presents conclusions of the study.

The following appendices provide a detailed description of the field procedures and detailed examples of track conditions that were encountered during the field surveys:

Appendix A: List of Field Tools – Lists all the common inspection tools used by the field team for data collection process.

Appendix B: Field Survey Data Collection Sheet (Part 1): The first part of a form used by the field team to record general information about the test zone and measurements and observations regarding the type and condition of the joint bars and bolts, cracking or break patterns and measurements at the rail ends including batters, ramps and mismatches.

Appendix C: Field Survey Data Collection Sheet (Part 2): The second part of a form used by the field team to record measurements and observations regarding track geometry, type and condition of various track components, and certain special track work and maintenance history.

Appendix D: Instruction Handbook: Contains guidelines and rules for recording all information and definition of all measurements included on the Field Survey Data Collection Sheets.

Appendix E: Rating System for Track Components: Contains a rating system for the condition of ties, fasteners, anchors, drainage and ballast. It also includes definition of various terms related to track conditions such as marginal or effective tie.

Appendix F: Field Survey Guidance Manual: Describes, the data collection procedure and gives guidelines for using the Rating System for Track Components and gives examples of various track component conditions with their appropriate ratings.

Appendix G: Examples of Field Conditions Jointed Track Territory: Presents detailed examples of field conditions encountered during the field surveys at both failed and intact rail joint locations on JNT territories.

Appendix H: Examples of Field Conditions – CWR Territory: Presents detailed examples of field conditions encountered during the field surveys at both failed and intact rail joint locations on CWR territories.

2. Methodology

2.1 Scope

The field investigations portion of the joint bar failure study consisted of:

- Developing a detailed test and analysis plan with a consistent methodology—a test procedure for performing field surveys and identifying suitable test zones
- Verifying the test procedure
- Conducting field evaluation surveys and collecting field observations and measurements
- Obtaining additional information from participating railroads
- Collecting records of past JBIS surveys for previously surveyed test zones where records were available
- Analyzing collected field data and past JBIS survey records
- Reporting

Seven field evaluation surveys were conducted throughout 2012–2014 in close cooperation with three Class I railroads. In Phase 1 of the study, the first three field surveys were conducted during 2012. The field investigation efforts were expanded further in Phase 2 with an additional four field surveys conducted in 2013 and 2014. The surveys were conducted both on CWR and JNT territory test zones with wide variety of different inspection frequencies, track classes (Classes X, 1–4), tonnage (0.5–194 million gross tons [MGT]), rail types, and joint bar designs. One of the surveys was conducted on CWR territory with concrete crossties with the remainder of the test zones containing wooden crossties. One test zone was visited twice (2012 and 2014) to document locations of possible repeat rail joint failures. The study was completed after 27 days of field activities.

The test procedures (described in detail below) were verified and refined during a “practice field survey” conducted on February 15, 2012, at Transportation Technology Center, Inc.’s (TTCI) facility in Pueblo, CO. The “practice field survey” allowed the field team to estimate the time required to measure and record data at each joint bar location. It was initially estimated that collection process would require approximately 30–40 minutes at each identified rail joint location. However, as three field surveys progressed, the team was able to collect all the data in less than 10 minutes per location.

2.2 Test Procedure

A detailed test procedure was developed to ensure that field measurements were collected in a comprehensive and consistent manner. During Phase 1 of the study, the Field Survey Team (team) consisted of two ENSCO and up to two TTCI personnel, but in Phase 2, the team consisted only of two ENSCO members.

In six out of seven field surveys, the team used a hi-rail vehicle provided by the participating railroad to follow an optical automated JBIS vehicle or they travelled in the JBIS vehicle itself. During the field survey on concrete CWR territory the team followed a visual walking inspection, which ultimately did not identify any joint defects. The team stopped at many joint defects that were identified by the JBIS inspection, conducted a detailed field investigation of the joints and collected all the measurements before the repair crews removed and replaced the defective joint bar(s). Not every single identified defect location was investigated by the team due to time constraints, limitations of available track authority, train traffic, etc. During the first three Phase 1 field surveys, selected failed joint bars were collected and transported to TTCI facilities in Pueblo, CO, for additional laboratory inspections and material testing. The results of the laboratory inspections, material testing and additional analyses were covered under separate reports, which were authored by TTCI and Volpe National Transportation Systems Center (Volpe).

The survey team also stopped at randomly selected locations with intact joint bars to collect the same information as they did at the locations with failed joint bars. The intact joints were used to establish a control group that allowed the teams to identify factors that distinguish intact locations from locations with failed joints; this would allow them to gain more insight into the general state of track conditions at temporary joints as compared to more permanent joints on CWR territory.

The team was equipped with inspection tools for collecting all the pertinent information at the appropriate locations. The list of the tools used in the surveys can be found in Appendix A.

All the pertinent information and measurements were recorded on Field Survey Data Collection Sheets. The Data Collection Sheet has two parts (Appendix B and Appendix C). Part 1 of the Data Collection Sheet contains general information about the test zone, the type and condition of the joint bars and bolts, and the cracking or break patterns and measurements at the rail ends including batters, ramps and mismatches. Part 2 contains information related mostly to track geometry, type and condition of various track components, and certain special track work and maintenance history.

Not all the information included in the Field Survey Data Collection Sheet was available at each survey site. The information from the data fields shaded in gray was acquired after the field surveys were conducted, using track charts and other sources obtained from the participating railroads.

The field survey data was collected in accordance with the guidelines outlined in the Instruction Handbook and Rating System for Track Components (which can be found in Appendix D and Appendix E). In addition, a Field Survey Guidance Manual that outlines the general methodology for the field activities, was provided (Appendix F). This document describes, in general, the data collection procedures and gives guidelines for using a Rating System for Track Components developed for the purpose of this study. It also gives examples of various track component conditions with their appropriate rating.

In addition to all the information listed in the Field Survey Data Collection Sheet, the team also gathered photographic evidence of the general areas and the joint assembly at all the failed and intact locations.

Each assessed joint location was given a unique identifier number (see Appendix D). The number allows referencing of all the investigated joints regardless of their geographical location or railroad operator and ties the collected field measurements and photographic evidence.

2.3 Post-Survey Activities and Additional Information Provided by the Railroads

The participating railroads provided additional information for the areas of interest (both intact and failed bar locations) at each test zone. This information included track charts, maintenance history records, data from track geometry measurement system (TGMS) vehicle surveys, ENSCO's Vehicle/Track Interaction (VTI) Monitor data (if available) recorded within 2 years prior to the joint bar failure surveys, and records of past JBIS inspection where applicable. Track charts were provided for all the test zones and after each survey used to collect the remaining data on the Field Survey Data Collection Sheet not acquired during the field activities (for example: MGT, curvature, super elevation or longitudinal grade). The maintenance records, TGMS and VTI data were obtained in detail only for the test zones that did not permit proper analysis and conclusions.

Complete records of past JBIS surveys were provided for three of the test zones, which allowed additional analysis of potential rail joints that have failed repeatedly in a span of only several years and an examination of the track conditions associated with such repeat failures.

All the information acquired via the Field Survey Data Collection Sheet was organized and entered into a database created for the purpose of this study.

2.4 Analysis Approach

Joint bar data from CWR and JNT territories were separated and analyzed independently from one another because each territory type has different thermal stresses and the nature/purpose of joint bar installation is different. For example, some joints found on CWR may exhibit different physical attributes because they are meant to be a temporary installation to repair defective rails found during rail flaw detection surveys or rails that are replaced following service failures. The joint bar data from JNT territories was further divided into datasets collected on lower class track (Classes X, 1, and 2) and higher-class track (Class 3) because rail joints at the two groups experience different train operating conditions such as tonnage, type of and frequency of traffic and most importantly train speed and the impact forces associated with it.

The data was analyzed by examining the potential contribution of various track conditions to the mechanism of joint bar failure. Statistical methods were used to evaluate the distribution of defect types and various crack/break patterns, as well as analyze the occurrence and magnitudes of various track conditions found at each joint bar location. Most importantly, the analysis employed a statistical T-test to identify conditions that were more prevalent at failed joint bar locations than conditions found at intact locations.

The records of past JBIS surveys were also analyzed to identify potential repeated rail joint failures. Available camera images from the JBIS vehicles were used to confirm repeated failures that occurred on the same rail joint. This report summarizes the overall findings and presents track conditions found to be associated with repeat failures.

3. Field Surveys and Collected Data

3.1 Field Surveys Overview

A total of seven field surveys were conducted in 2012–2014. The surveys were conducted over a wide range of territories in eastern and western U.S. that had various inspection frequencies, track classes (Classes 1–4, X), MGT, traffic, and rail types. Test zones included CWR and JNT territories mostly with wooden ties, but one of the surveys took place on concrete tie CWR territory. Table 1 summarizes of the field surveys including information on the total miles surveyed, the proportion of CWR and JNT territories at each survey, track characteristics such as track class, tie, fastener and predominant rail type, magnitude and type of traffic, general location of the test zone and date of survey.

Table 1. Field Survey Summary

Survey #	Miles Tested	CWR	JNT	Ties	Fasteners	Track Class	MGT	Traffic Type	Rail Type	Region	Date
1	75	75 (100%)	0 (0%)	timber	cut spike	4	21-24	mixed	133	High Plains	April 17-19, 2012
2	128	58 (45%)	70 (55%)	timber	cut spike	1,2,3	0.5-3	grain	90-115 132-136	Northern Plains	May 14-18, 2012
3*	129	21 (16%)	108 (84%)	timber	cut spike	3,4	12-15	mixed coal	119 131-136	Central Plains	July 23-27, 2012
4	52	0.5 (1%)	51.5 (99%)	timber	cut spike	3	30	timber mixed	115	South-eastern US	March 25-28, 2013
5	112	112 (100%)	0 (0%)	concrete	elastic	4	36-194	coal	136-141	High Plains	June 17-19, 2013
6	85	51 (60%)	35 (40%)	timber	cut spike	X, 1-4	1-60	coal mixed	80-115 130-136	Great Lakes Appalachian	July 29-August 01, 2013
7*	54	7 (13%)	47 (87%)	timber	cut spike	3	12-15	mixed coal	132-136	Central Plains	May 5 & May 28-30, 2014

Note: *The third and seventh field surveys indicated by an asterisk were conducted on the same territory. Initially investigated in July 2012 the zone was revisited in 2014 in order to look for and document locations of possible repeated rail joint failures. A total of 21 miles between the two visits overlapped and were surveyed both times.*

A total of 636 miles were surveyed during seven field visits. The surveyed miles were approximately evenly split between CWR and JNT territories:

- 324 miles CWR (51%)
- 312 miles JNT (49%)

3.2 Test Zones

In most cases, each field survey was conducted on one subdivision or section of one subdivision which had mostly consistent operational and track conditions. Such territories with consistent conditions can be referred to as a “test zone.” In the case of the second field survey, two separate nearby subdivisions (i.e., two test zones) were visited. During the sixth field survey, five separate shorter sections of multiple subdivisions with very different operating and track characteristics located in two distinct geographical regions were surveyed. Therefore, five separate test zones were established. The various test zones surveyed during the field activities are outlined below:

- Survey #1
  - Test zone A was a single main, mostly Class 4 CWR track with timber ties and cut spike fasteners. The territory consisted primarily of 133 lb. rail and contained approximately 240 joints and 130 turnout joints on both rails. The annual tonnage on test zone was in a range between 21 and 24 MGT. This territory is not regularly inspected by JBIS.
- Survey #2:
  - Test zone B1 was a single main track comprised mostly of Class 1 and 2 JNT and Class 3 CWR with timber ties and cut spike fasteners. Rail sections were mostly 90 lb., 100 lb., 112 lb., and 115 lb. Several CWR segments consisted of 129 lb., 132 lb. and 136 lb. rail sections. The annual tonnage was in the range between 1.3 and 3.0 MGT. This territory is regularly inspected by JBIS two to three times a year and prior to the field survey in 2012 it was inspected two times in 2011 (November and July). The field survey was the first JBIS inspection of the test zone in 2012.
  - Test zone B2 was a single main track comprised of Class 2 JNT and short Class 2 CWR sections with timber ties and cut spike fasteners. Rail sections were mostly 90 lb. for JNT territory and 112 lb. and 132 lb. for CWR segments. The annual tonnage was 0.5 MGT. This territory is regularly inspected by JBIS one to two times a year and prior to the field survey in 2012 it was inspected once in 2011 (June). The field survey was the first JBIS inspection of the test zone in 2012.
- Survey #3 and #7:
  - Test zone C was a single main track (with a few double main sections), consisting of mostly Class 3 JNT and Class 4 CWR track. Both the jointed and CWR segments had timber ties and cut spike fasteners. The test zone consisted mostly of 131 lb., 132 lb., and 136 lb. rail sections on JNT and the CWR segments consisted of 119 lb., and 136 lb. rail sections. The annual tonnage on the test zone was in the range between 12 and 15 MGT for the single main segments.

    On the double main track segments, the tonnage was slightly above 7 MGT. This territory is regularly inspected by JBIS one to three times a year and prior to the field survey in 2012 it was inspected three times in 2011 (January, June and September) and once in 2010 (August).

    The field survey in 2012 was the first and only JBIS inspection of the test zone in that year. The zone was revisited as part of the 2014 study, which was the first inspection of that year. Prior to the field survey in 2014, it was inspected two times in 2013 (February and November).
- Survey #4:
  - Test zone D was two contiguous subdivisions. Since they had almost identical track and operational characteristics, they were considered a single test zone. The test zone

was a single main consisting of Class 3 JNT and very few short CWR sections. Both the jointed and CWR segments had timber ties and cut spike fasteners.

The majority of the test zone consisted of 115 lb. rail sections on JNT. The few CWR segments consisted of 115 lb., 132 lb., 136 lb., and 141 lb. rail sections. The annual tonnage on the test zone was approximately 30 MGT. This territory is regularly inspected by JBIS once or twice a year. Prior to the field survey in 2013 it was inspected once in 2012 (March). The field survey in 2013 was the first JBIS inspection of that test zone for that year.

- Survey #5:
    - Test zone E was a double main (with a shorter section of a single main) consisting of Class 4 CWR track with concrete ties and various types of elastic fasteners (Vossloh or Pandrol). The test zone consisted overwhelmingly of 136 lb. and 141 lb. rail sections. The annual tonnage on the test zone was very high, up to 158 MGT on the double main and 194 MGT on the single main section, since this territory is a heavy coal route. This territory is not tested by JBIS but temporary joints are inspected visually by track inspectors on a weekly basis.
- Survey #6: This survey was conducted on a variety of subdivisions with in two distinct geographical regions (Great Lakes and Appalachia) with very different operating and track characteristics. None of the subdivisions were previously tested by JBIS.
    - Test zone F1 was a single main Class 1 JNT with timber ties and cut spike fasteners. The test zone consisted mostly of 115 lb. with few portions of 80 lb. and 132 lb. rail sections. The annual tonnage on the test zone was 0.2 MGT.
    - Test zone F2 was a single main excepted Class X JNT with timber ties and cut spike fasteners. The test zone consisted overwhelmingly of 90 lb. rail sections. The annual tonnage on the test zone was 0.1 MGT.
    - Test zone F3 was a single main Class 1 and 2 CWR track with timber ties and cut spike fasteners. The test zone consisted overwhelmingly of 132 lb. rail sections. The annual tonnage on the test zone was 23 MGT.
    - Test zone F4 was a single main Class 1 JNT with timber ties and cut spike fasteners. The test zone consisted overwhelmingly of 130 lb. and 132 lb. rail sections. The annual tonnage on the test zone was 0.1 MGT.
    - Test zone F5 was a triple main Class 3 and 4 CWR track with timber ties and cut spike fasteners. The test zone consisted mostly of 136 lb. with few portions of 122 lb. rail sections. The annual tonnage on the test zone was 45–57 MGT. This test zone was a moderately heavy coal route.

3.3 Collected Data and Sample Composition

Over the course of the seven field surveys more than 82,000 rail joints were inspected either by a JBIS vehicle or by a walking visual inspection method when followed by the field survey team. Table 2 below illustrates the breakup of inspected rail joints and the collected sample of investigated locations by individual field surveys.

Table 2. Inspected Rail Joints and Collected Sample by Individual Field Surveys

Survey #	Miles Tested			Defect Locations			Intact Locations			Investigated Locations	Joints Inspected during Survey
	Total	CWR	JNT	Total	CWR	JNT	Total	CWR	JNT		
1	75	75 (100%)	0 (0%)	3	3	0	21	21	0	24	370
2	128	58 (45%)	70 (55%)	31	0	31	16	4	12	47	22,200
3*	129	21 (16%)	108 (84%)	34	0	34	14	0	14	48	28,000
4	52	0.5 (1%)	51.5 (99%)	26	0	26	10	0	10	36	12,900
5	112	112 (100%)	0 (0%)	0	0	0	26	26	0	26	26
6	85	51 (60%)	35 (40%)	13	2	11	9	2	7	22	9,200
7*	54	7 (13%)	47 (87%)	21	0	21	6	0	6	27	9,600

Overall, the following samples totaling 230 locations were collected:

- Sample CWR territory (Class 3; 4—tonnage 21–194 MGT):
  - 5 defect locations
  - 53 intact bar locations
- Sample JNT (Class X, 1, 2 and 3—tonnage 0.1–15 MGT):
  - 123 defect locations
  - 49 intact bar locations

3.4 Observed Failure Modes

Various types of failure modes of joint bars were observed during the field investigations. The prevalence of certain types of failure modes depended on the type of joint bar design. Three joint bar designs were encountered during the field investigations of rail joint defect locations. Those were long toe bars (also called angle bars for purposes of this study) and either head-free or head-contact standard design bars (see Figure 1).

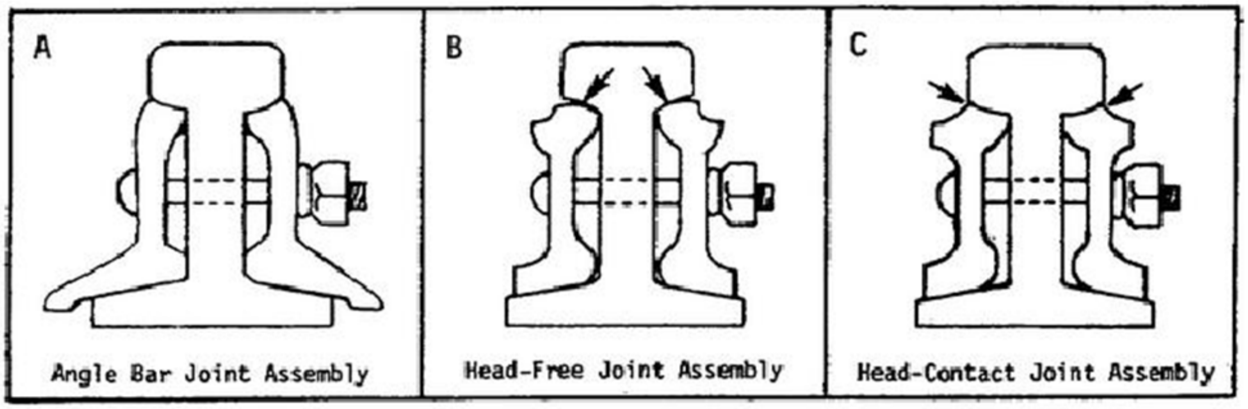

Figure 1. Three Joint Bar Designs Encountered During the Field Investigations

Long toe joint bars are an older design type and are used for smaller rail sizes such as 80 lb. or 90 lb. on lower track classes. All joint bars of this type encountered during the field investigations were located on Class X, 1, and 2 tracks. Long toe joint bars contain square spike holes in the toe on the bottom of the bar. The general notion in the industry is that this type of joint bar design is flawed because the square spike holes cause significant fatigue details, which initiate quarter defect type failures through the spike hole. Crosstie damage can also occur if spikes are driven through the spike holes in the bars and the track moves longitudinally.

Head-free standard design bars come to a single point contact with the bottom of the rail head and also may include an easement, an area in the middle of the joint bar where the material is recessed to prevent contact of the rail ends with the joint bar middle top section. Today, this is the most common bar design for all rail sizes. All joint bars that were encountered on CWR track and on JNT of track Class 3 or higher were this type. This type was also commonly found on Class 1 and 2 tracks.

Head-contact standard design bars come to a full contact with the bottom of the rail head and it is believed that this design provides better support for the rail end and improves ride quality. However, head-contact bars may promote rail failure due to head-web separation. This rail type was only encountered six times, once on Class 1 track and the rest on Class 2 track.

All five defects in CWR territory were top center cracks on standard design head-free temporary joints.

On JNT territory, 123 joint locations with defects were investigated. There were 140 cracks or breaks because both joint bars were broken at 16 locations and 1 joint bar contained multiple cracks. Table 3 summarizes the distribution of all encountered defects.

Table 3. Distribution of Joint Bar Defects on Jointed Track Territory

	LONG TOE (ANGLE)	HEAD-CONTACT	HEAD-FREE	TOTAL
FULL QUARTER BREAK	17	0	4	21
TOP QUARTER CRACK	3	0	2	5
BOTTOM QUARTER CRACK	5	0	1	6
FULL CENTER BREAK	3	1	26	30
TOP CENTER CRACK	10	3	46	59
BOTTOM CENTER CRACK	0	1	6	7
FULL BOLT HOLE BREAK	0	1	6	7
TOP BOLT HOLE CRACK	4	0	0	4
BOTTOM BOLT HOLE CRACK	0	0	1	1
	42	6	92	140

Note: *All defects on JNT territory were identified using the JBIS system. Although the system focuses its search on the top of the joint bar area primarily identifying top cracks and full breaks, it does also view the sides of the bars and is capable of identifying bottom cracks as long as the cracks progressed enough to propagate to the side of the bar. Very small bottom cracks that have not propagated to the exposed side of the joint bar cannot be identified by either a visual walking inspection or an automated inspection because the crack is hidden from view.*

On standard design head-free joint bars the overwhelming majority of the failures were center defects and 59 percent of the center defects were top center cracks.

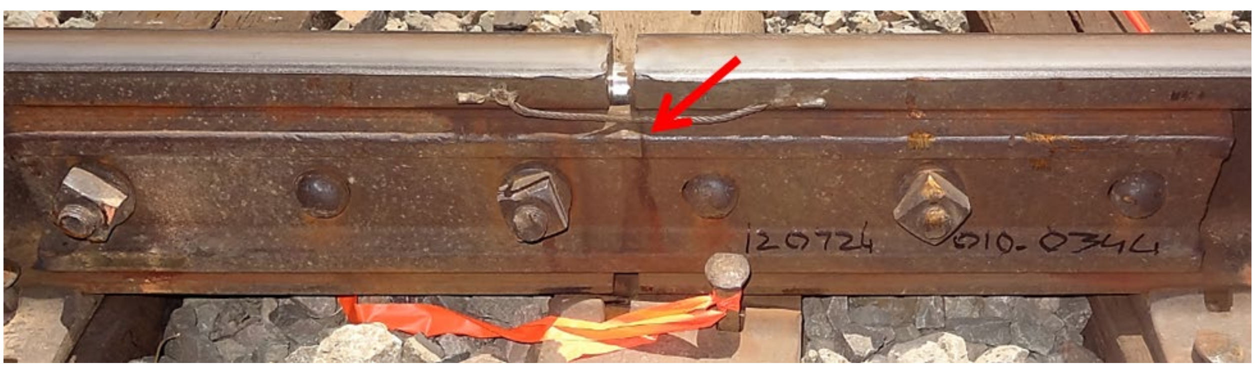

Figure 2. Top Center Defect on a Standard Design Head-Free Bar

On long toe (angle) type bars the predominant failure was a quarter defect, most often a full quarter break—almost 70 percent. Surprisingly, three out of eight partial quarter cracks on the long toe (angle) bars were initiated from the top of the bars and not from the spike hole on the bottom of the bar as expected. When center defects occurred on long toe (angle) type bars, the majority were top cracks (77 percent).

Figure 3. Full Quarter Break on a Long Toe (Angle) Bar

Figure 4. Bottom Quarter Crack on a Long Toe (Angle) Bar Originating at the Corner of the Spike Hole

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Figure 5. Quarter Crack on a Long Toe (Angle) Bar Originating at the Top of the Bar

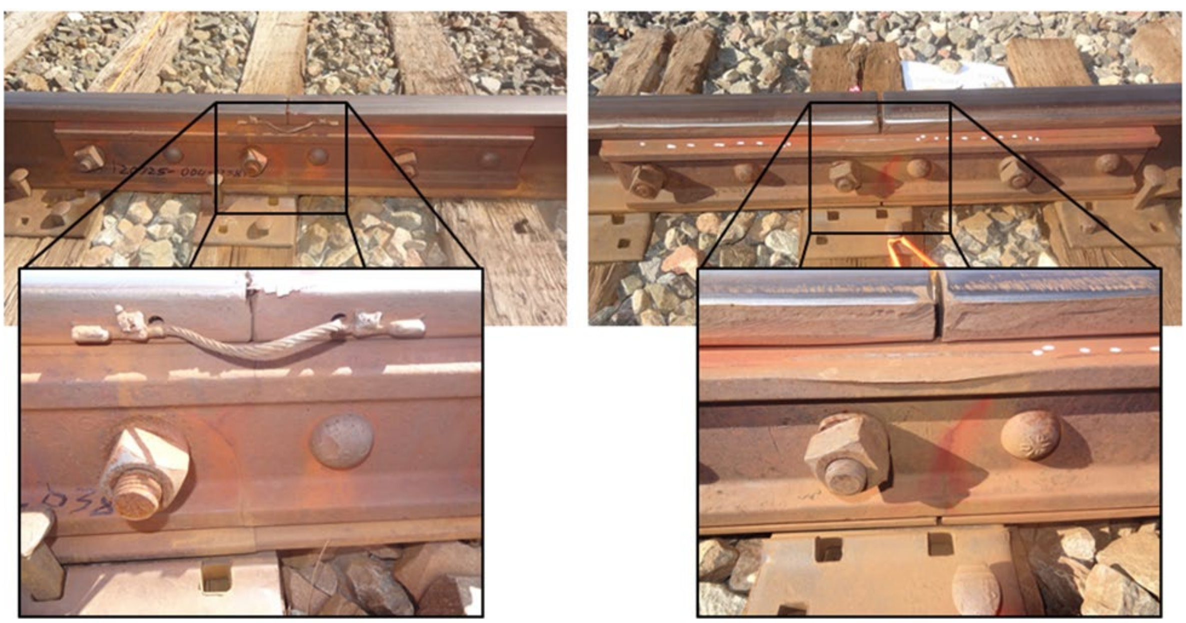
All the head-contact bars in the sample but one failed through the center. One head-contact bar contained a bolt-hole defect. Overall bolt-hole defects were only a marginally occurring defect type on all bar designs. In general, bar defects were evenly distributed between field and gage side bars.

Figure 6. Bolt Hole Defect on a Standard Design Bar

The most common failure mode on the standard design bar was a top center defect and a full quarter break on the long toe (angle) bar.

Two cases of unusual center failures were also found on standard design head-free bars during one of the field surveys. In both instances, the crack in one case and the break in the other case forked into two distinct directions, forming a letter "Y" shape with the split ends directed towards the top of the joint bar.

The photograph a) in Figure 7 below shows the unusual full center break with the "Y" shape pattern. This defect occurred on a field side bar. The photograph b) shows the unusual partial bottom center crack with the "Y" shape pattern. The crack occurred on a gage side bar.



a) Full Center Break with Unusual Pattern

b) Partial Bottom Crack with Unusual Pattern

Figure 7. Unusual "Y" Shaped Crack/Break Patterns

4. Field Observations

4.1 Jointed Track Territory

The most important observation made throughout the field surveys was evidence of localized deteriorated vertical track support conditions at most of the identified failed rail joint locations in contrast to very good vertical track support conditions at intact rail joint locations. Most of the failed rail joint locations also had signs of large vertical joint movements because of the deteriorated support conditions. Even though the deteriorated support conditions were localized to an area of a specific rail joint, they affected several, in many cases three of four, ties in either direction from the joint centerline. Figure 8 shows a typical example of a failed rail joint with deteriorated track support, excessive vertical movement and wide deflection basin. This location was found in test zone C during the 2014 visit.

Figure 8. Large Vertical Movement and Wide Deflection Basin at a Failed Rail Joint Location

It can be noted in the bottom photograph in Figure 8 that a tapered gage used to measure the void between the rail and tie indicated almost a half inch gap on a third tie from the failed joint centerline. Most failed rail joints also appeared to have larger crosslevel under load measurements and, to a lesser extent, profile under load measurements than the intact locations because the larger vertical movement at failed rail joints is an important component of the under load surface and crosslevel measurement.

To a lesser extent, larger lateral movements were also observed ties. Intact locations, however, showed generally better tie conditions than failed bar locations at failed rail joint locations compared to intact joint locations.

Based on the field observations, the leading factors contributing to vertical movement were as follows:

- “Swinging” ties
- Missing, loose, or broken tie plates and plate cutting
- Insufficient ballast (lack of tamping)
- Fouled ballast (mud pumping)
- Rail profile (batter)

Large vertical movements at failed joints were found at locations with good and marginal ties. Intact locations, however, showed generally better tie conditions than failed bar locations.

Adverse rail end conditions at failed rail joints, when compared to intact joint locations, were also observed on higher track classes, specifically at track Class 3. Most of the adverse rail end conditions consisted of moderate and in many cases significant rail end batter. Locations with chipped or otherwise degraded rail ends were also frequently found. However, on jointed territory on all classes, no excessive ramps or tread and gage mismatches were observed at either failed or intact joints. Figure 9 shows an example of a failed joint location with a very significant rail end batter of 0.359 inches magnitude. This location was encountered on test zone D in 2013. The rail ends were also considerably chipped.

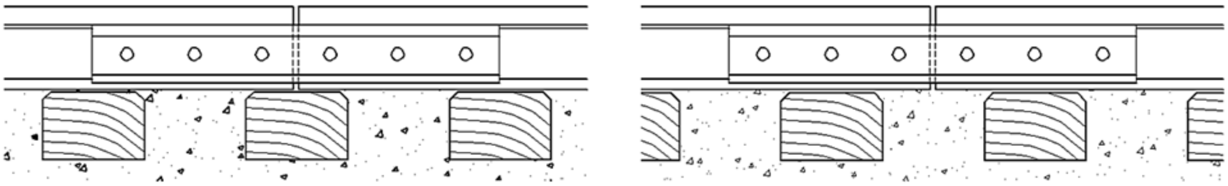
Figure 9. Large Rail End Batter at a Failed Rail Joint Location

Figure 10. Large Rail End Batter at a Failed Rail Joint Location with Straight Edge to Demonstrate Magnitude

Figure 10 illustrates the magnitude of the rail batter at the same rail joint location with a straight edge and tapered gage. Note that the straight edge is positioned this way only to demonstrate the severity of the rail end batter. When actual measurements of rail end batter were taken, a ramp on each rail end is assessed separately according to the procedure outlined in the Instruction Handbook (Appendix D).

Bolt conditions didn't seem to be different between failed and intact locations, since loose or missing bolts were found at both types of locations at comparable rates.

Rail joint failure also appeared to affect both suspended and supported rail joint configurations evenly. Figure 11 defines rail joint configurations. According to field observations, it was the overall support conditions that distinguished failed from intact rail joint rather than the joint/tie configuration. As mentioned above, locations with large vertical movements have fairly wide deflection basins, affecting several ties and determining whether the joint centerline was located directly above a tie or between two adjacent ties did not seem have any effect on the vertical support conditions of such locations as a whole.



a) Supported Rail Joint **b) Suspended Rail Joint**

Figure 11. Rail Joint Configurations

The investigated test zones showed evidence of a wide variety of rail longitudinal movements which mostly ranged between 0.25 and 6 inches. On several occasions, a very large portion of a particular investigated territory (test zone B1) showed evidence of large rail longitudinal movement (up to 9 inches). The longitudinal movement, however, did not seem to have a direct impact on the joint bar failure rate. Significant longitudinal movement was observed to affect long sections of track with both failed and intact joints; while other conditions, such as vertical and lateral movement, were localized to the individual investigated failed locations. However, longitudinal movement often resulted in skewed crossties and narrow (tight) gage at some of the joints, which led to loose fasteners and reduced lateral restraint and/or increased tie spacing under the joints. Figure 12 shows an example of a location with a large longitudinal rail movement (9 inches) resulting in skewed ties and narrow (tight) gage. Two failed rail joints were present at this location.

Figure 12. Large Rail Longitudinal Movement and Skewed Ties

Investigated intact rail joints were overwhelmingly present in locations with very good track support and rail end conditions. A typical intact rail joint (from test zone F1) is shown in Figure 13.

Figure 13. Intact Rail Joint Location

More examples of jointed track field conditions at investigated failed and intact rail joint locations in all test zones can be found in Appendix G.

4.2 CWR Territory

Three distinct CWR territories were visited during the field surveys: test zones A and F5 on wooden ties and test zone E on concrete ties. All the detected failed joints occurred on the two wooden tie zones and no defects were found on the concrete tie zone. In addition, another standalone CWR territory with a lower track Class—test zone F3 and multiple shorter section of CWR territories within the remaining test zones were also investigated, all of them with wooden ties.

The five instances of failed joint bars were all top center cracks that occurred at temporary joints where repair rails were installed in a tangent wooden track. All the identified failed joints except for one exhibited deteriorated rail end conditions, either extensive rail mismatches (both tread and gage), abrupt rail end ramps or rail end batter. Significant lateral and vertical movements, as a result of insufficient joint support, were also present at three of the failed joint bar locations.

Figure 14. Failed Rail Joint at CWR Territory with Deteriorated Support and Rail End Conditions

Figure 14 shows one of the failed locations with battered rail ends and deteriorated vertical support, including heavily fouled ballast resulting in vertical rail joint movement.

One identified defect located in a turnout did not exhibit any significant deviations in geometry, any lateral, vertical, or longitudinal movement. A moderate rail end ramp was present. The turnout appeared to have relatively new and recently replaced switch ties and ballast. It is possible that the initiation of the crack occurred before switch tie replacement and surfacing, or it was due to the recent maintenance work. This location is shown in Figure 15.

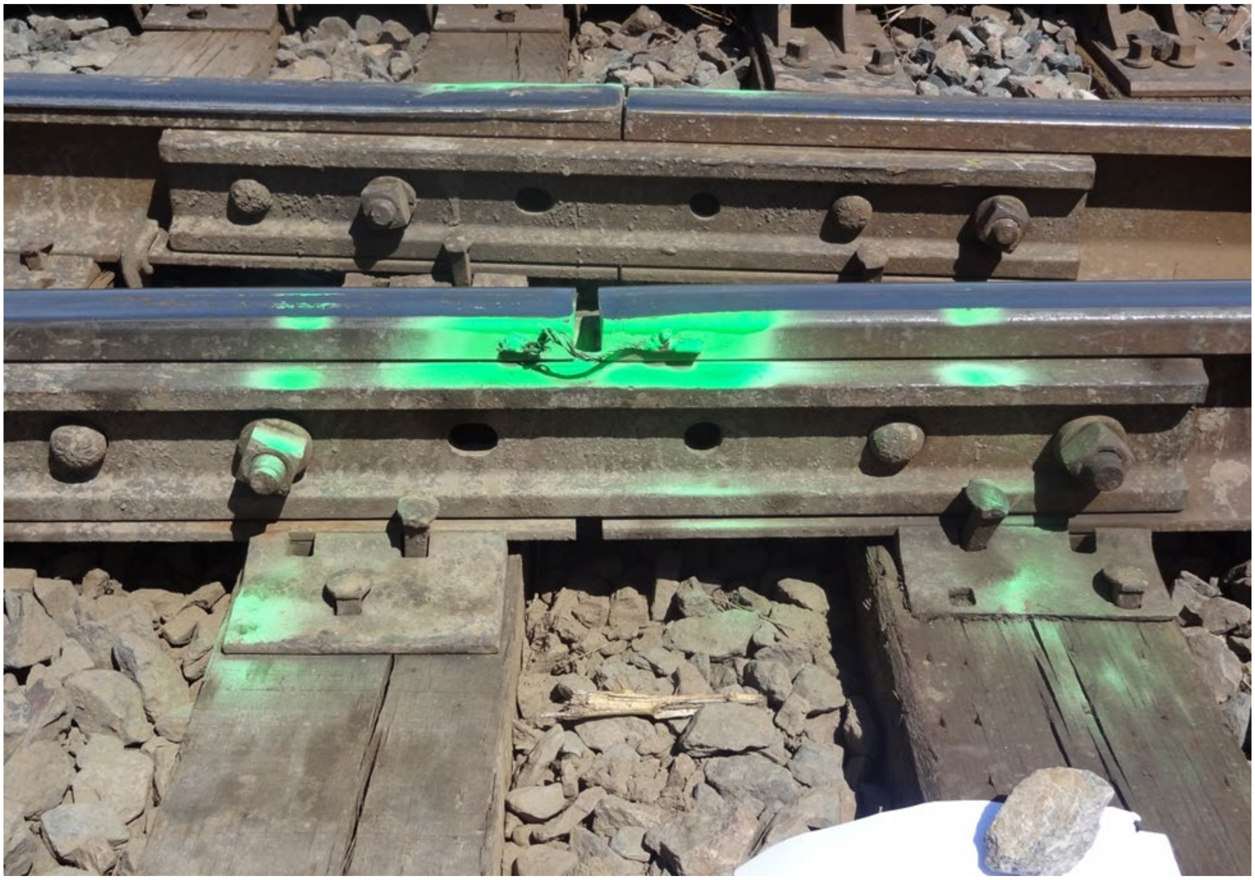


Figure 15. Failed Rail Joint at CWR Territory at Location of Recent Track Work

In general, the encountered track conditions at failed rail joints on CWR territory—the deteriorated vertical support and rail end conditions—were consistent with conditions found at failed joints on Class 3 JNT territory. The conditions of the rail ends on CWR territory, however, seemed to be of different origin.

Deteriorated rail end conditions on Class 3 JNT were overwhelmingly represented by rail end batter, fairly even for both rail ends and developed gradually by repeated wheel impact loads at initially well-matched rail ends. On the other hand, rail end conditions on CWR territory consisted mostly of tread mismatches or abrupt rail end ramps. These mismatches were created when new or full ball repair rail sections were installed in track with worn rail. In some cases, mismatched rail ends were than battered down by repeated wheel impact loads resulting in the short and abrupt rail end ramps. As the head of the new rail was battered down, subsequent rail head widening led to horizontal mismatch on field or sometimes both sides of the rail head. An example of a misaligned, battered down rail end at a failed joint location is in Figure 16. The top view of the same location in Figure 17 illustrates the horizontal mismatches as the battered down rail head results in widening, mostly towards the field side of the rail.

Figure 16. Initially Misaligned Rail End Battered Down into Abrupt Rail End Ramp

Figure 17. Widened Rail Head

The intact joints on wooden CWR track were permanent insulated joints as well as recently installed temporary standard design joints. The insulated joints tended to be in the track for a very long time and the surrounding track conditions were very good with minimum geometry deviations and rail end misalignments. On the other hand, many of the recently installed temporary standard design joints (especially on test zone A), exhibited the same track conditions and larger than normal rail mismatches and abrupt ramps or batters as the failed joint locations. The intact joints, other than insulated rail joints that were evaluated, were installed in the track as a repair for another defect (rail defect or break) and were not intended to remain in the track permanently (i.e., middle bolt holes were not drilled).

Reference marks located on the rail next to the temporary joints made by railroad personnel were documented to get an estimate of how long ago the temporary joints were cut in. The marks are used to keep track of added and subtracted rail whenever a cut is made in CWR (see Appendix F for details). Two welder's reference marks at recently installed temporary joints can be seen in Figure 18. This information confirmed that the intact locations with the large values of joint movements and rail end misalignments were cut in the rail only several weeks or few months prior to the joint bar survey and had not accumulated more than 10 MGT.

Figure 18. Examples of Welder Reference Marks at Temporary Joints on Wooden CWR Track

Neutral temperature was not directly measured during the field surveys. The team, however, looked for indirect signs of rail stress and rail longitudinal movement, such as scratch marks on the base of the rail, shifted rail anchors, skewed ties, etc. Limited longitudinal movement up to 1.5 inches was observed on roughly half the investigated locations on wooden tie track, three of the five defective rail joints did not contain any longitudinal movement.

Rail at four of the failed rail joint locations also appeared to be in compression with the gap between the rail ends fully or almost fully closed even though the measured rail temperature was only between 89 °F and 100 °F in those instances. No defects were found on test zone F3 and track conditions at investigated intact rail joint locations were good.

Conditions observed on the concrete tie CWR territory (test zone E) were very different from the conditions at the various test zones on wooden track CWR. Test zone E was very well maintained and no cases with large vertical movement or geometry conditions were found. All joints, temporary as well as insulated, were well supported. The rail ends were also well maintained. The rail end ramps were negligible and there was only one case with a noticeable tread mismatch (0.125 inches). Elastic fasteners on concrete ties provided sufficient restraint both in the lateral and longitudinal direction. There was no longitudinal and negligible lateral movement across all the investigated locations. Bolt conditions were also excellent as no loose bolts were encountered. All temporary joints, however, were connected by four bolts as the two inner bolt holes were not drilled in preparation for welding.

In most cases where temporary joints were supported by concrete ties, they were not configured with two fasteners on the same rail. The lack of fasteners on one side of the rail or the other, however, did not appear to affect the joint support or geometry conditions. Joint supporting ties equipped with Vossloh fasteners were fully configured with two fasteners per rail. See Figure 19 and Figure 20 for illustrations.

Figure 19. Temporary Joint on Concrete Ties Not Configured with Two Fasteners on the Same Rail

Figure 20. Temporary Joint on Concrete Ties Fully Equipped with VOSSLOH Fasteners

To estimate when temporary joints were installed, reference marks located on the rail next to the temporary joints were also documented on concrete tie track. An example of observed welder's reference marks at recently installed temporary joints on concrete tie track can be found in Figure 21.

Figure 21. Example of Welder Reference Marks at Temporary Joint on Concrete Tie CWR Track

The reference marks revealed that most of the temporary joints were cut in the track very recently, 1 to 2 months prior to the survey date, but in that time accumulated up to 27 MGT because of the high tonnage on that particular test zone.

Figure 22. Example of Rail Joint Location on Concrete Tie Track with Good Support Conditions

Even though no defects were found on the concrete tie CWR territory, the field survey showed that well supported rail joints with minimal rail end misalignments can survive for months in high tonnage Class 4 track. An example of a well-supported temporary rail joint on concrete track territory is shown in Figure 22.

More examples of various CWR track field conditions were found at failed and intact rail joint locations with both wooden and concrete ties can be found in Appendix H.

5. Analysis of Field Survey Data

All data collected on CWR and JNT territories were separated from each another and analyzed independently due to the inherent differences in thermal stresses and the nature/purpose of joint bar installation in each type of territory.

The analysis was designed to determine how various track conditions contributed to the mechanism of joint bar failure. Distribution of defect types, various crack/break patterns, failure rates and also occurrence and magnitudes of various track conditions found at each joint bar location were investigated. Statistical methods, most importantly the statistical T-test, were used to find conditions which were more prevalent at failed joint bar locations than conditions found at intact locations.

5.1 Jointed Track Territory

Several distinct observations were made during the field surveys at lower and higher track classes. Therefore, to gain insight into what conditions are contributing factors to joint bar failure might be class (speed and tonnage) related and what trends apply regardless of class, the sample was analyzed independently for lower track classes (Class X, 1, and 2), for higher track class (Class 3), and the entire JNT sample as a whole.

The collected data samples were also divided into three distinct categories:

1) Intact Joint Locations
2) Type A defect locations – This category consists of all defects through preexisting fatigue details which are part of the joint bar design such as spike holes on long toe (angle) bars and bolt holes on all bars. It assumed that these failures modes are initiated from the preexisting fatigue details and they include full quarter breaks, partial bottom quarter cracks on long toe (angle) bars with spike holes, and all bolt hole cracks and breaks on all bar designs.
3) Type B defect locations – This category includes all other failure modes such as full center breaks and partial center cracks on all bar designs, partial top quarter on long toe (angle) bars and full quarter breaks and partial quarter cracks on head-contact and head-free bars.

In cases where both failed bars, one with a Type A and the other with a Type B defect are found in one joint location, the Type B defect takes precedent.

Defects initiated from preexisting fatigue details, which are part of the joint bar design grouped under defect type A, may have a different failure mechanism from the other failures in defect Type B. Type A defects may also require less energy to fail, as stress concentration associated with the manufactured fatigue details exist in the bar throughout the lifetime of the bar. If this assumption is correct, any track condition contribution to joint bar failure should be present at type A defects at lower magnitudes. The failed bar sample was divided into two defect categories to find out whether this hypothesis is supported by field data collected during the surveys and determine whether track and operational conditions affect various defect types differently.

5.1.1 Jointed Track Class X, 1, and 2

JNT Class X, 1 and 2 contains 42 failed and 19 intact rail joint locations, for a total of 61 locations. The different defect types are distributed in the sample as follows:

- Intact locations (19 locations)
- Type A defects (21 locations)
- Type B defects (21 locations)

There was a total of 49 failed bars because 7 locations with both bars failed were encountered. The sample includes a total of 50 defects because 1 of the bars contained 2 distinct cracks. The defect distribution can be seen in Table 4.

Table 4. Defect Distribution on Track Class X, 1 and 2 Jointed Territory

	LONG TOE (ANGLE)	HEAD-CONTACT	HEAD-FREE	TOTAL
FULL QUARTER BREAK	17	0	0	17
TOP QUARTER CRACK	3	0	0	3
BOTTOM QUARTER CRACK	5	0	0	5
FULL CENTER BREAK	3	1	1	5
TOP CENTER CRACK	10	3	0	13
BOTTOM CENTER CRACK	0	1	1	2
FULL BOLT HOLE BREAK	0	1	0	1
TOP BOLT HOLE CRACK	4	0	0	4
BOTTOM BOLT HOLE CRACK	0	0	0	0
	42	6	2	50

Long toe (angle) bars were the predominant bar design encountered on the lower track classes and they were most often, in almost two thirds of the cases, affected by quarter defects, mostly by full quarter breaks. The other third of the failures were center defects, the majority of them top center cracks. Bolt hole defects rarely occurred.

The chart in Figure 23 provides an overview of vertical, lateral and longitudinal movements recorded at the investigated rail joint locations. The locations are sorted by the magnitude of the vertical movement. The displayed longitudinal movement is scaled down in a magnitude of 10. We can observe that the locations with failed joint bars exhibit much larger vertical movement measurements than the evaluated intact locations.

The chart in Figure 24 gives an overview of three track geometry measurements: crosslevel under load, profile under load and alinement. The locations are sorted by the magnitude of the crosslevel under load. In four instances, profile under load and alinement were not measured because extreme wind prevented the team from executing a reliable stringlining procedure. The chart shows that the locations with failed joint bars exhibit much larger crosslevel under load measurements than intact locations. To a lesser extent, profile under load measurements also seem to be larger at failed joint locations.

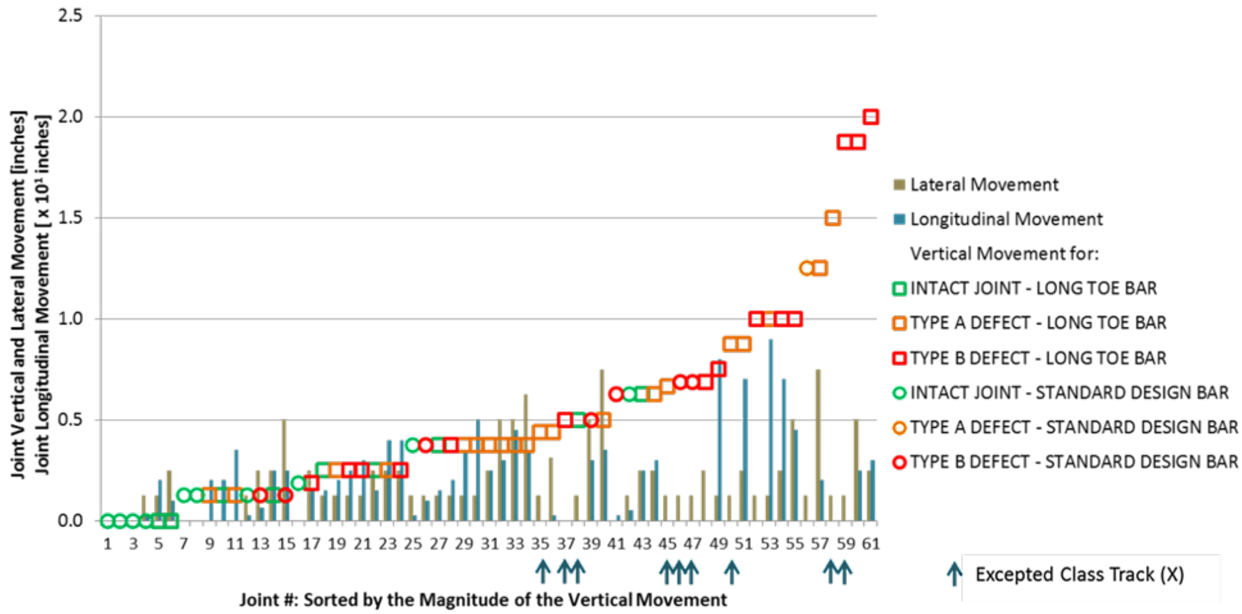


Figure 23. JNT Sample Track Class X, 1 and 2—Overview of Joint Movements

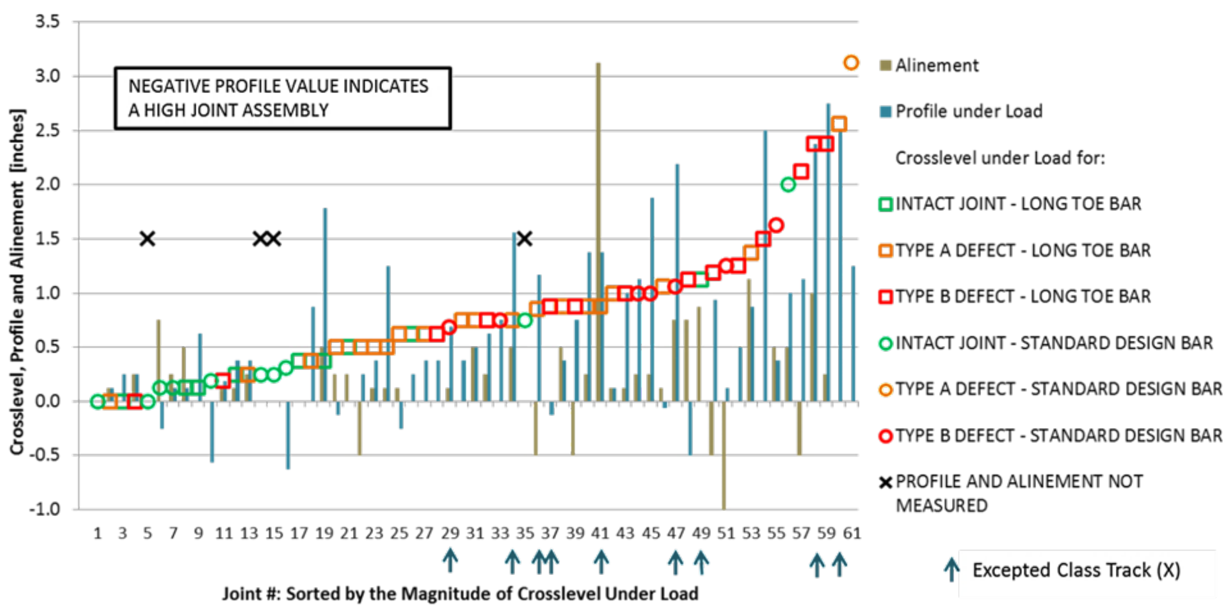


Figure 24. JNT Sample Track Class X, 1 and 2—Overview of Selected Track Geometry Parameters

During the field survey, it was observed that many intact locations had comparable or higher magnitudes of rail end batters, ramps or mismatches in the horizontal and vertical direction than locations with defects. The following chart in Figure 25 provides an overview of rail end conditions with overlaid vertical joint movement confirming the observation. The locations are sorted by the value of rail end vertical misalignment, which is defined as a sum of tread mismatch and rail end ramp and is a calculated parameter that evaluates the overall conditions of the rail ends in vertical direction.

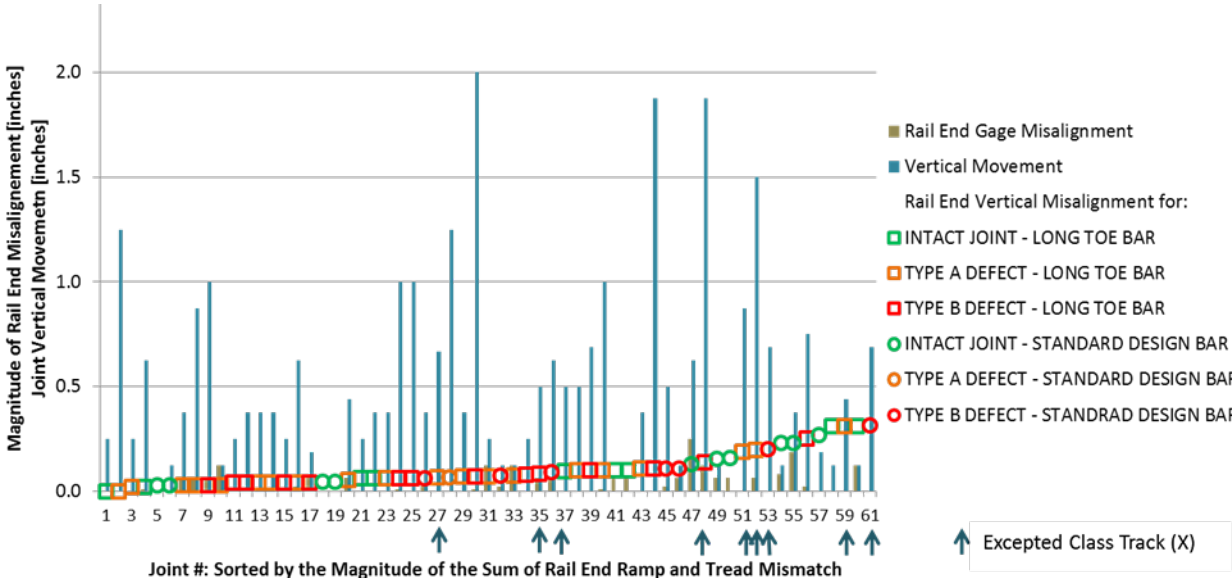


Figure 25. JNT Sample Track Class X, 1 and 2—Overview of Rail End Conditions

In general, most adverse track conditions were found at excepted track—Class X, as expected. This is especially true for rail end misalignments at failed rail joints. The two most deteriorated rail end conditions at failed locations were in track Class X. If these two locations were excluded from the sample, the three highest values of rail end misalignments would have been present at intact rail joints.

The next two plots in Figure 26 and Figure 27 illustrate the distribution of rail end gaps and the measured distance to the first effective tie. Locations with defects show slightly larger magnitudes of rail end gap than evaluated intact joint locations, while the distance to the first effective tie doesn't seem to be significantly different between the intact and failed locations.

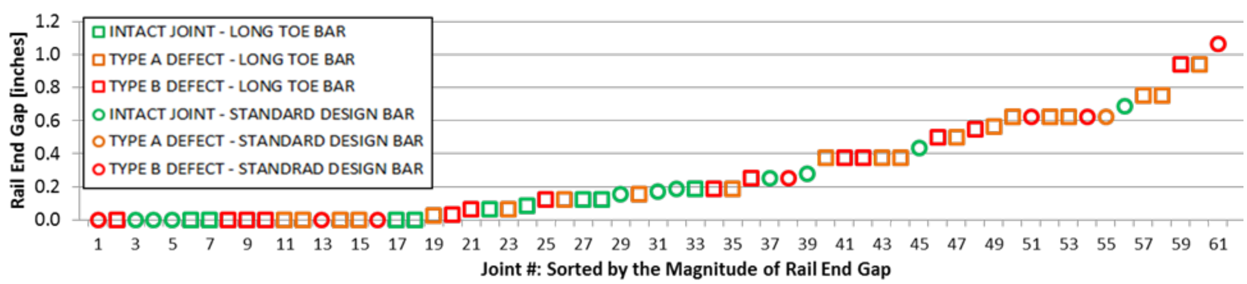


Figure 26. JNT Sample Track Class X, 1 and 2—Overview of Rail End Gaps

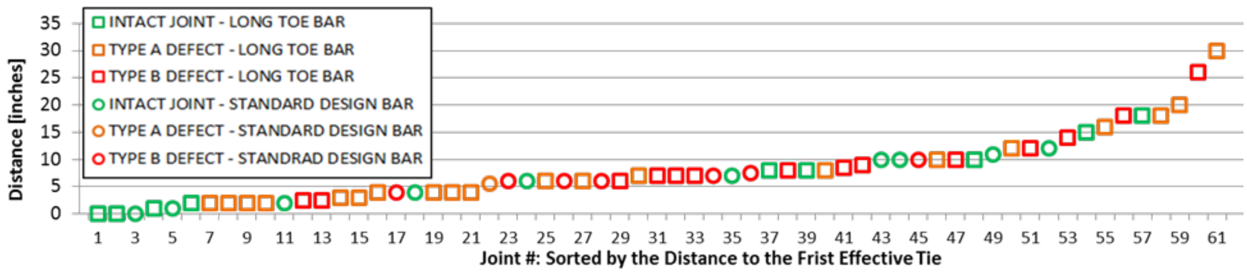


Figure 27. JNT Sample Track Class X, 1 and 2—Overview of Distance to First Effective Tie

Figure 28 displays the longitudinal bar movement encountered during the study. This parameter reflects the relative movement between the joint bar and the rail end, and it is an indirect sign of the effectiveness of longitudinal restraint, rail stresses and responses to rail temperature fluctuations. In this plot, each entry represents an individual joint bar rather than the rail joint location (as in the previous figures). Both intact and failed joint bars show comparable values of longitudinal bar movements.

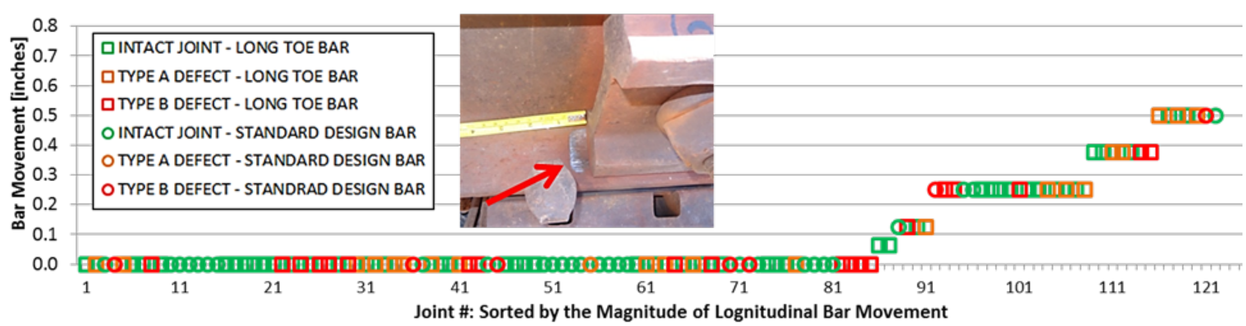


Figure 28. JNT Sample Track Class X, 1 and 2—Overview of Longitudinal Bar Movement

Also, bolt conditions (see Table 5) do not appear to influence joint bar failure. The bolt conditions are comparable at both intact and defect location of both types, and failed locations have a slightly higher proportion of intact bolts.

Table 5. JNT Sample Track Class X, 1 and 2—Summary of Bolt Conditions

	ALL BOLTS INTACT		ONE OR MORE BOLTS LOOSE		ONE OR MORE BOLTS MISSING		AT LEAST ONE BOLT MISSING & LOOSE		TOTAL
INTACT BARS	7	37%	9	47%	2	11%	1	5%	19
TYPE A DEFECTS	9	43%	11	52%	1	5%	0	0%	21
TYPE B DEFECTS	11	52%	6	29%	3	14%	1	5%	21
ALL LOCATIONS:	27	44%	26	43%	6	10%	2	3%	61

A statistical T-test was used to evaluate whether various parameters representing encountered track conditions differ significantly at failed and intact locations. This allows determining which conditions are contributing factors to rail joint failure. Three sets of T-tests were performed for each parameter, between the intact sample and defect type A, B, and all defects combined. A test for unequal sample sizes and unknown variances was used. A 5 percent significance level was chosen.

Table 6 summarizes the results of the T-tests. The table lists the means, standard deviations and the resulting p-value for the test. In our case, the smaller the p-value was, the more likely the track conditions are different at failed and intact locations when extrapolated to the entire population. The particular track condition represents a more significant contribution factor for rail joint failures.

Table 6. JNT Sample Track Class X, 1 and 2—Summary of T-Test Results

T-Test	Sample 1	Mean	StDev	Sample 2	Mean	StDev	p-Value	Level	Pass T-Test
Vertical Movement	Intact	0.20	0.21	Type A	0.59	0.39	0.00036	0.05	YES
				Type B	0.72	0.57	0.00064	0.05	YES
				A & B	0.66	0.49	0.00000	0.05	YES
Lateral Movement	Intact	0.11	0.10	Type A	0.26	0.23	0.00649	0.05	YES
				Type B	0.22	0.16	0.00805	0.05	YES
				A & B	0.24	0.19	0.00049	0.05	YES
Longitudinal Movement	Intact	1.18	0.79	Type A	3.13	2.09	0.00051	0.05	YES
				Type B	2.42	2.09	0.01802	0.05	YES
				A & B	2.78	2.09	0.00007	0.05	YES
Static Crosslevel	Intact	0.34	0.46	Type A	0.54	0.42	0.14917	0.05	NO
				Type B	0.54	0.4	0.14495	0.05	NO
				A & B	0.54	0.41	0.10421	0.05	NO
Crosslevel under Load	Intact	0.39	0.48	Type A	0.89	0.72	0.01387	0.05	YES
				Type B	1.13	0.62	0.00016	0.05	YES
				A & B	1.01	0.67	0.00019	0.05	YES
Static Profile	Intact	0.38	0.45	Type A	0.38	0.38	0.95414	0.05	NO
				Type B	0.4	0.45	0.88924	0.05	NO
				A & B	0.39	0.41	0.96124	0.05	NO
Profile under Load	Intact	0.40	0.48	Type A	0.74	0.64	0.07593	0.05	YES
				Type B	1.01	0.83	0.00934	0.05	YES
				A & B	0.87	0.74	0.00791	0.05	YES
Static Alinement	Intact	0.29	0.31	Type A	0.39	0.68	0.24023	0.05	NO
				Type B	0.34	0.32	0.14818	0.05	NO
				A & B	0.37	0.53	0.51493	0.05	NO
Alinement under Load	Intact	0.40	0.28	Type A	0.63	0.71	0.19248	0.05	NO
				Type B	0.46	0.25	0.52620	0.05	NO
				A & B	0.55	0.53	0.20238	0.05	NO
Static Gage	Intact	56.44	0.34	Type A	56.4	0.24	0.48943	0.05	NO
				Type B	56.2	0.22	0.01748	0.05	YES
				A & B	56.3	0.24	0.09865	0.05	NO
Gage under Load	Intact	56.56	0.33	Type A	56.8	0.4	0.04228	0.05	YES
				Type B	56.6	0.31	0.48473	0.05	NO
				A & B	56.7	0.36	0.10387	0.05	NO
Vertical Rail End Misalignement	Intact	0.13	0.10	Type A	0.08	0.07	0.12288	0.05	NO
				Type B	0.10	0.07	0.38032	0.05	NO
				A & B	0.09	0.07	0.18865	0.05	NO
Gage Rail End Misalignement	Intact	0.05	0.07	Type A	0.03	0.05	0.40438	0.05	NO
				Type B	0.03	0.03	0.26237	0.05	NO
				A & B	0.03	0.04	0.30355	0.05	NO
Rail End Gap	Intact	0.15	0.18	Type A	0.37	0.3	0.00751	0.05	YES
				Type B	0.28	0.33	0.10104	0.05	NO
				A & B	0.32	0.31	0.00630	0.05	YES
Distance to First Effective Tie	Intact	6.58	5.43	Type A	8.02	7.37	0.48190	0.05	NO
				Type B	8.76	5.34	0.20839	0.05	NO
				A & B	8.39	6.36	0.25952	0.05	NO
Bar Longitudinal Movement	Intact	0.08	0.14	Type A	0.14	0.19	0.14521	0.05	NO
				Type B	0.09	0.15	0.70641	0.05	NO
				A & B	0.11	0.15	0.37500	0.05	NO

Figure 29 and Figure 30 show the 95 percent confidence intervals for the parameters summarized in Table 6. The charts can be also viewed as a graphical interpretation of the T-test.

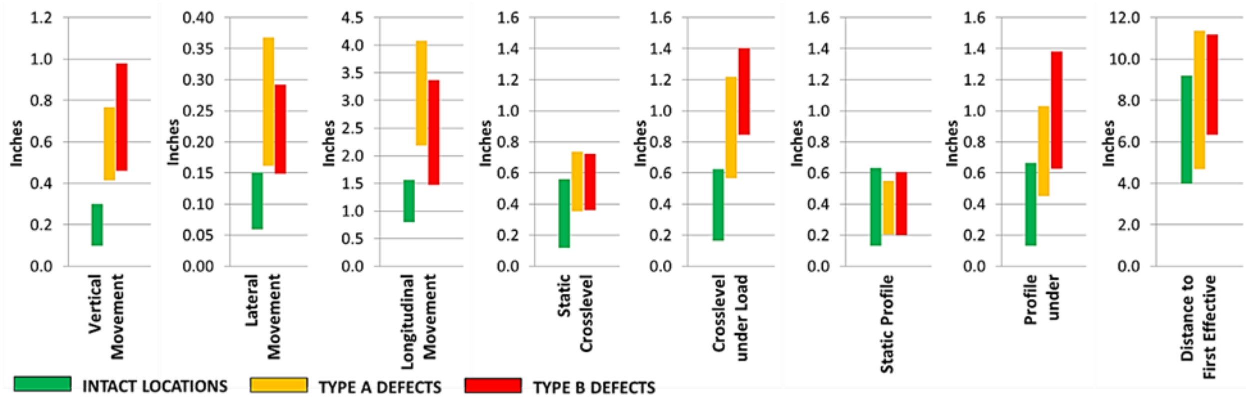


Figure 29. JNT Sample Track Class X, 1 and 2—95% Confidence Intervals of Field Condition Measurements, Part 1

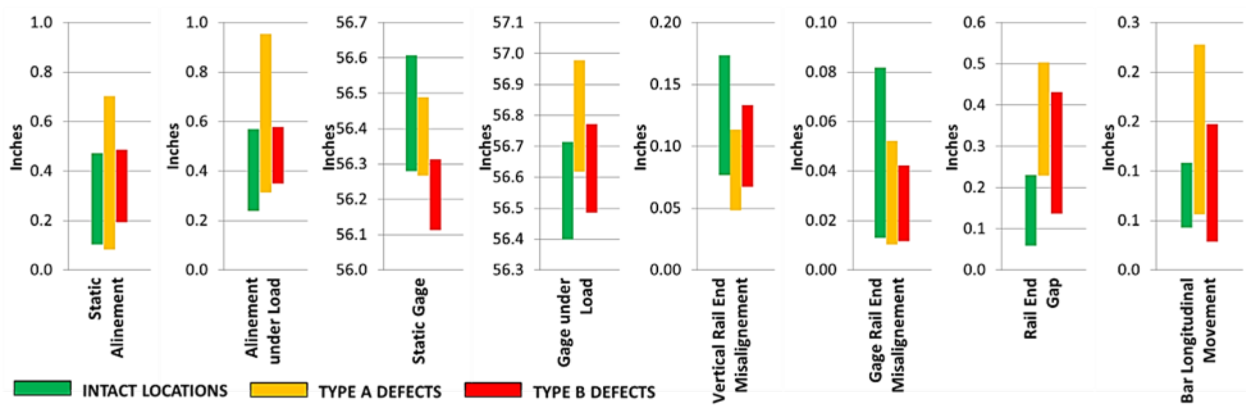


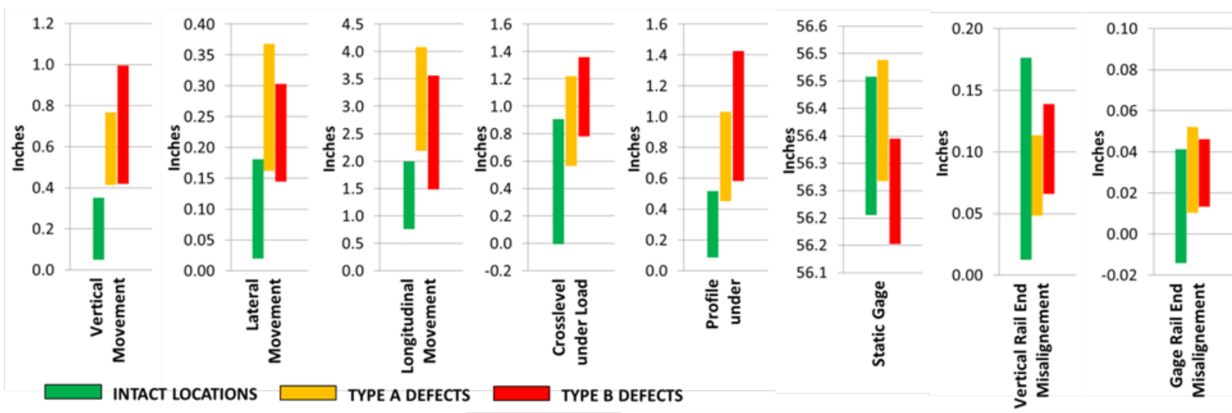
Figure 30. JNT Sample Track Class X, 1 and 2—95% Confidence Intervals of Field Condition measurements, Part 2

The T-test results mostly confirm the observations made during the field surveys. Vertical movements followed by lateral movements are significantly larger at both failed locations with defect types A and B than at intact locations. Values of static crosslevel and profile measurements are not statistically different, however, under load measurements are. This is most likely the consequence of the statistically different vertical movements, which make up a significant portion of each under load measurement. See Appendix D for details of determining the under load measurements.

Other parameters such alinement, rail end conditions, and distance to the first effective ties are not significantly different in the lower track classes. Rail end gaps were significant factor only for defect type A. Static gage was statistically different for defect type B with larger values at intact locations. Under load gage measurements only barely passed the 5 percent significance threshold for defect type A. This suggests that tight static gage and the consequent loosening of the lateral restrain and lateral movements rather than wide gage could be a factor. Definite conclusion about gage is not possible with the given sample size collected on lower track classes.

The T-test also identified longitudinal movement as a possible significant factor contrary to field observations. The longitudinal movements did not seem to have a direct impact on the joint bar failure rate because significant longitudinal movements appeared to affect long sections of track with both failed and intact joints. Other conditions, such as vertical and lateral movement, were localized to the individual failed locations. It is important to note here that the intact joint sample contains locations in the vicinity of failed rail joint locations, as well as random locations where the team stopped and no defects were identified.

Additional analysis was performed to determine if the results summarized in Table 6 would hold when "stand-alone" intact locations were removed from the sample. There were nine such intact locations further than 10 miles from an identified defect on the same test zone or located in a separate test zone altogether. The T-test was repeated and 95 percent confidence intervals were reconstructed for a subset of the data sample with only intact locations located at most 10 miles within an identified defect on the same test zone. T-test results for such a sample subset show that longitudinal movements as well as static gage are not statistically significant for defect group B, while results for other parameters hold even though the significance of lateral movement is diminished. Figure 31 shows the 95 percent confidence intervals and T-test results for rail joint movements, as well as several other selected parameters for the modified standalone sample.



p-value	p-value	p-value	p-value	p-value	p-value	p-value	p-value
Intact vs. Type A	Intact vs. Type A	Intact vs. Type A	Intact vs. Type A	Intact vs. Type A	Intact vs. Type A	Intact vs. Type A	Intact vs. Type A
0.00120	0.01193	0.00265	0.10203	0.01471	0.55323	0.74318	0.28142
Intact vs. Type B	Intact vs. Type B	Intact vs. Type B	Intact vs. Type B	Intact vs. Type B	Intact vs. Type B	Intact vs. Type B	Intact vs. Type B
0.00284	0.02644	0.05509	0.05536	0.00421	0.27017	0.84912	0.28715

Figure 31. JNT Sample Track Class X, 1 and 2—95% Confidence and T-Test Results for Selected Parameters on Modified "Stand-Alone" Sample

This suggested that tight gage and longitudinal movements are related (as observed during field surveys). Longitudinal movement therefore cannot be fully ruled out as a factor with at least a limited affect, possibly by resulting at localized adverse conditions at some of the failed joints, such as skewed crossties and narrow (tight) gage, which can lead to loose fasteners and reduced lateral restraint and/or increased tie spacing under the joints. This can add to the development of vertical and lateral movements.

The confidence intervals presented in Figure 29 and Figure 30 were developed to evaluate whether the collected data supported the assumption that type A defects require less energy to fail than type B defects. However, the magnitudes of all the parameters except for static gage are not statistically different between the type A and B defect group. The data does not yield enough evidence to show that track conditions contributing to joint failure would be present at type A defects at lower magnitudes or track conditions affect various defect types differently.

5.1.2 Jointed Track Class 3

JNT Class 3 contains altogether 81 failed and 30 intact rail joint locations, a total of 111 locations. The different defect types are distributed in the sample as follows:

- Intact locations (30 locations)
- Type A defects (5 locations)
- Type B defects (76 locations)

There was a total of 90 failed bars at 9 locations with both bars failed were encountered. The sample includes a total of 90 defects because none of the bars contained multiple cracks. The defect distribution can be seen in Table 7.

Table 7. Defect Distribution on Track Class 3 Jointed Territory

	LONG TOE (ANGLE)	HEAD-CONTACT	HEAD-FREE	TOTAL
FULL QUARTER BREAK	0	0	4	4
TOP QUARTER CRACK	0	0	2	2
BOTTOM QUARTER CRACK	0	0	1	1
FULL CENTER BREAK	0	0	25	25
TOP CENTER CRACK	0	0	46	46
BOTTOM CENTER CRACK	0	0	5	5
FULL BOLT HOLE BREAK	0	0	6	6
TOP BOLT HOLE CRACK	0	0	0	0
BOTTOM BOLT HOLE CRACK	0	0	1	1
	0	0	90	90

All rail joints encountered on the track Class 3 contained standard design head-free bars. They were most often, in almost 85 percent of the cases, affected by a center defect, and 60 percent of center defects were top center cracks. Quarter defects and bolt hole defects were only marginally occurring failure modes.

The chart in Figure 32 contains an overview of vertical, lateral and longitudinal movements recorded at the investigated rail joint locations on Class 3 JNT. The locations are displayed in same format as the low track class JNT samples. Again, we can observe that the locations with failed joint bars exhibit much larger vertical movement measurements than the evaluated intact locations.

Figure 33 presents an overview of three track geometry measurements: crosslevel under load, profile under load and alinement. The chart shows that the locations with failed joint bars exhibit much larger crosslevel under load and profile under load measurements than intact locations. We can also notice a trend in increasing profile under load values with growing crosslevel under load. This trend is very pronounced compared to the Class X, 1 and 2 data where such a trend was not as discernible (see Figure 24).

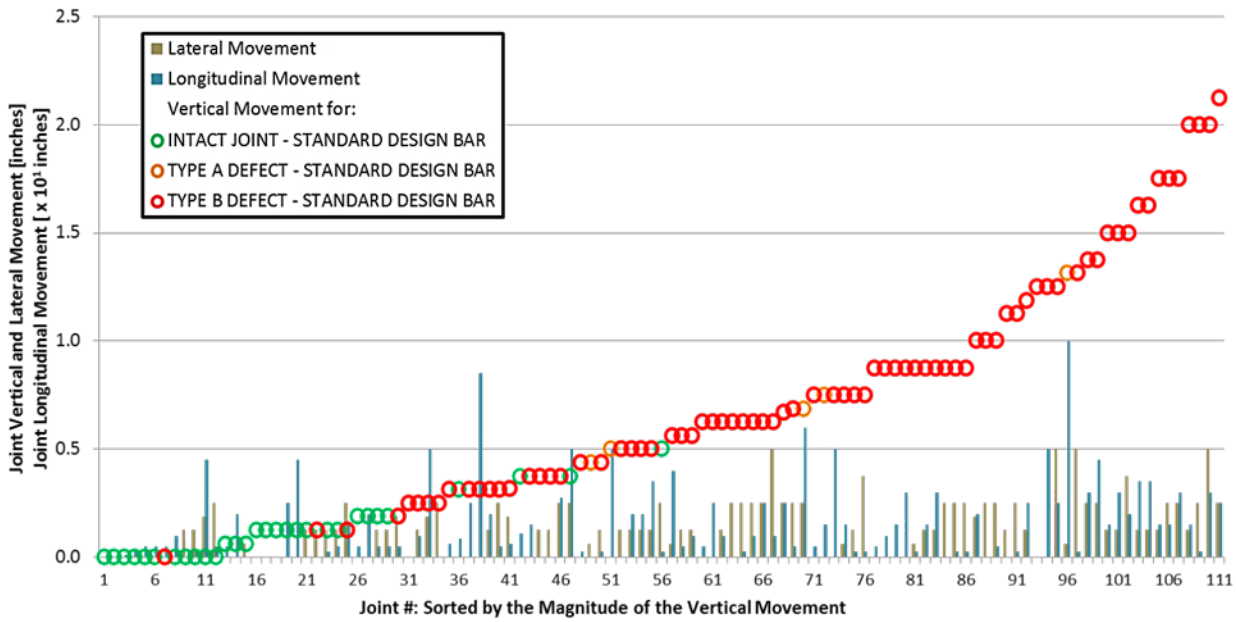


Figure 32. JNT Sample Track Class 3—Overview of Joint Movements

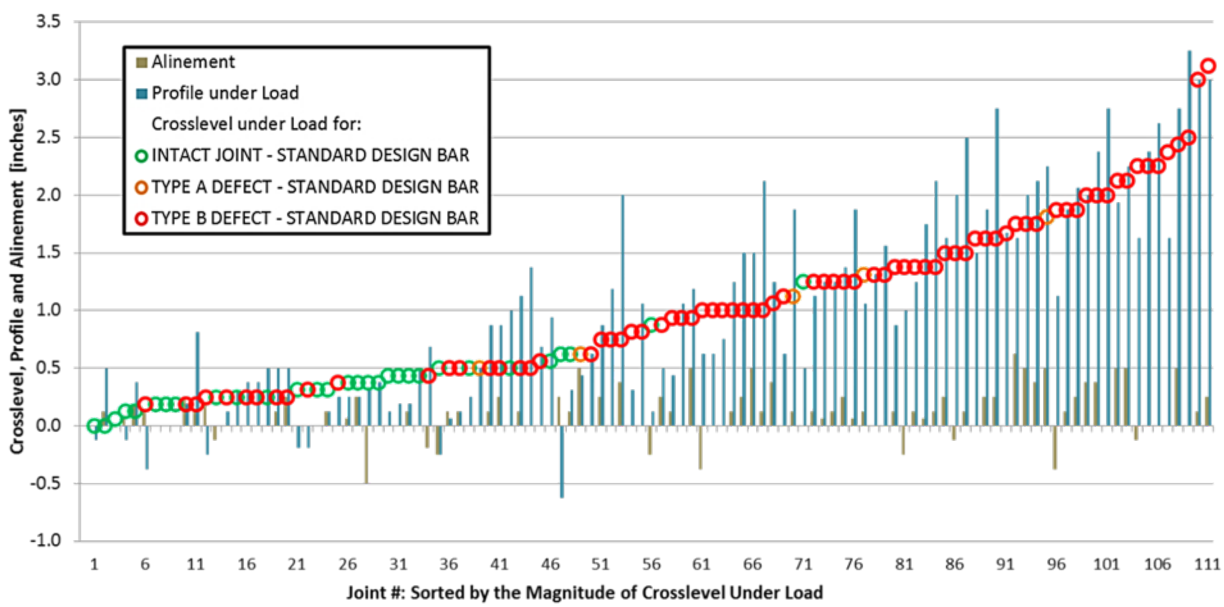


Figure 33. JNT Sample Track Class 3—Overview of Selected Track Geometry Parameters

During the field surveys, it was observed that Class 3 track, unlike lower track classes, had many failed rail joint locations that contained much more deteriorated rail end conditions than investigated intact rail joint locations. The following chart in Figure 34 gives an overview of the rail conditions with overlaid vertical joint movement confirming the observation. The locations are sorted by the value of rail end vertical misalignment. This value is defined as a sum of tread mismatch and rail end ramp and it is a calculated parameter used to evaluate the overall conditions of the rail ends in vertical direction. Most locations with significant rail end misalignments were also accompanied by large vertical movement. The magnitude of the movement, however, did not grow with the magnitude of the rail end misalignment and many locations with no rail end conditions also contain vertical movement.

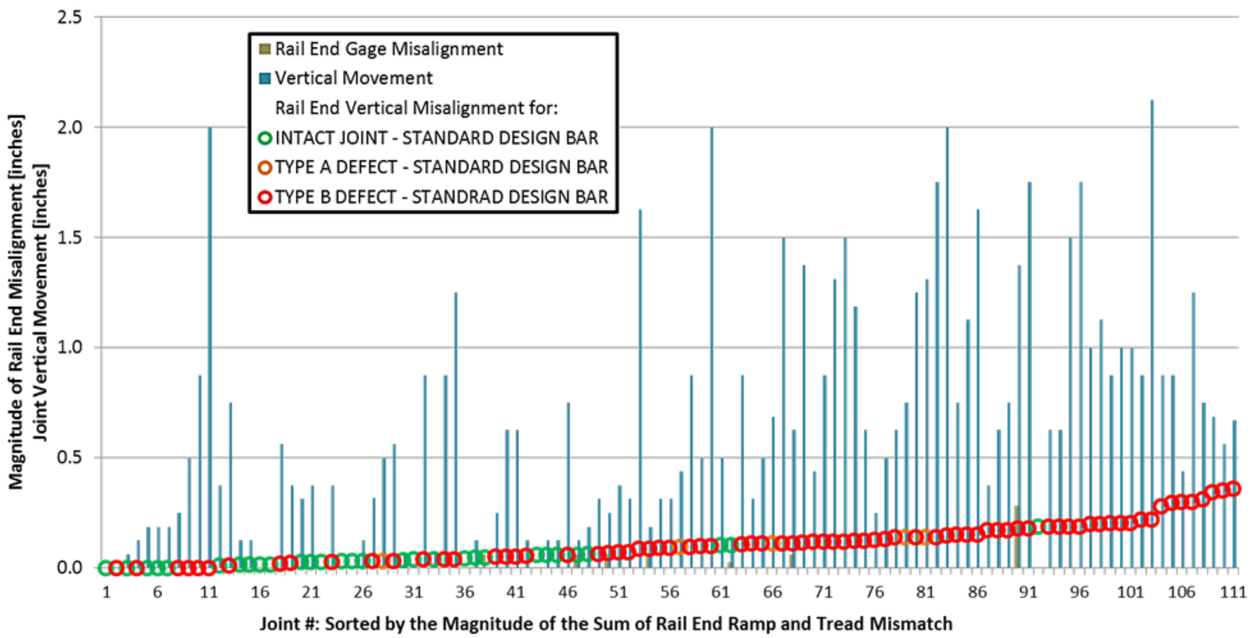


Figure 34. JNT Sample Track Class 3—Overview of Rail End Conditions

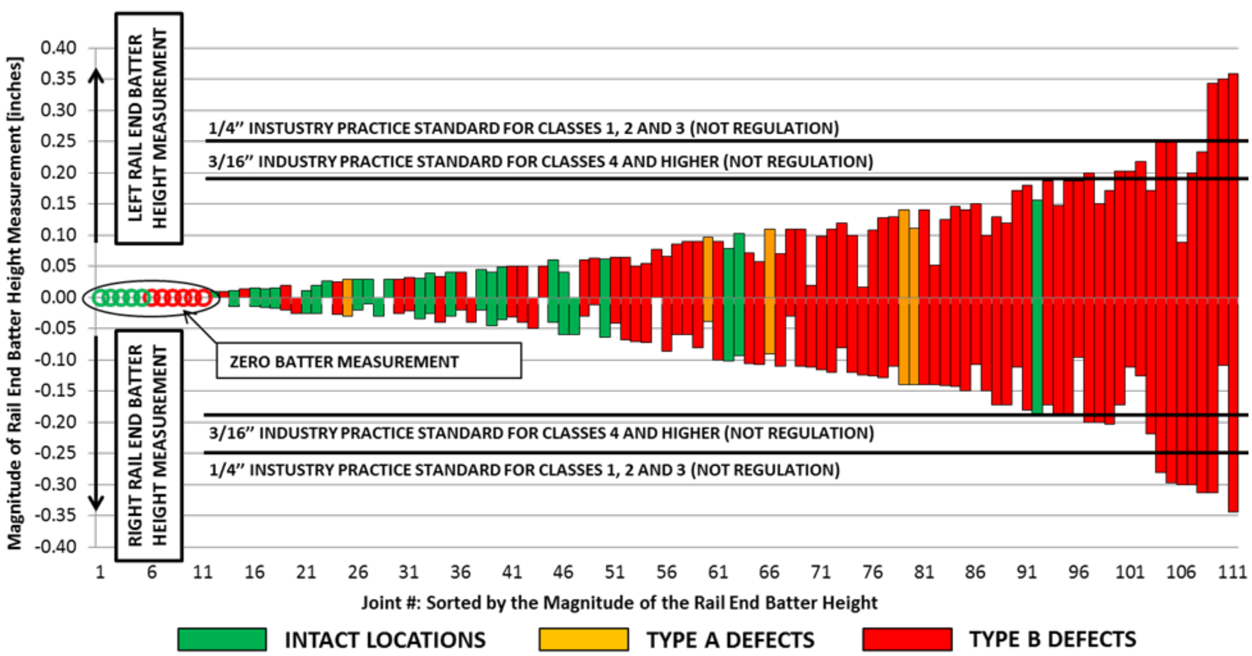


Figure 35. JNT Sample Track Class 3—Overview of Rail End Conditions

Most cases of adverse rail end conditions encountered on Class 3 JNT consisted of moderate or even significant rail end batter of fairly even magnitudes at the opposite rail ends as illustrated in Figure 35. The chart shows that the left and right rail end ramp height measurements are very consistent and that their magnitudes do not exceed the industry practice recommendations, except for several of the most adverse instances of rail end conditions. There were very few cases of tread or gage mismatches encountered on JNT.

Figure 36 and Figure 37 illustrate the distribution of rail end gaps and the measured distance to the first effective tie. Locations with defects do not seem to have different magnitudes of rail end gaps than evaluated intact joint locations. The distance to the first effective tie does not seem to be significantly different between the intact and failed locations (up to around 12 inches). In this sample, distances larger than 12 inches indicate a defective tie at the rail joint location. All such locations contained a failed joint bar.

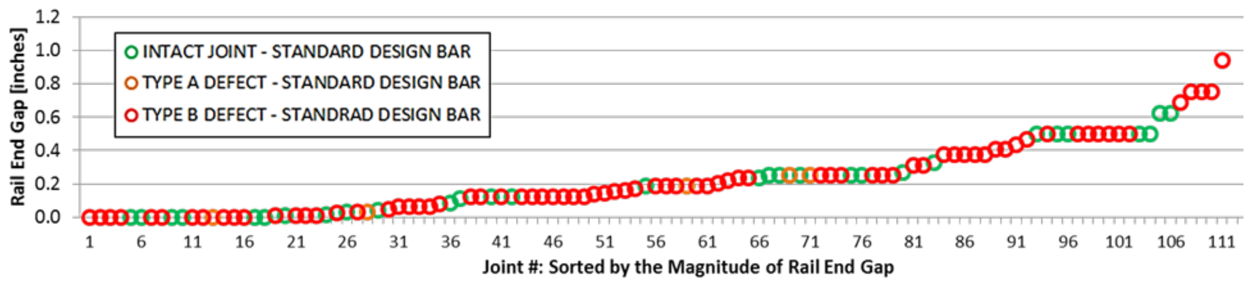


Figure 36. JNT Sample Track Class 3—Overview of Rail End Gaps

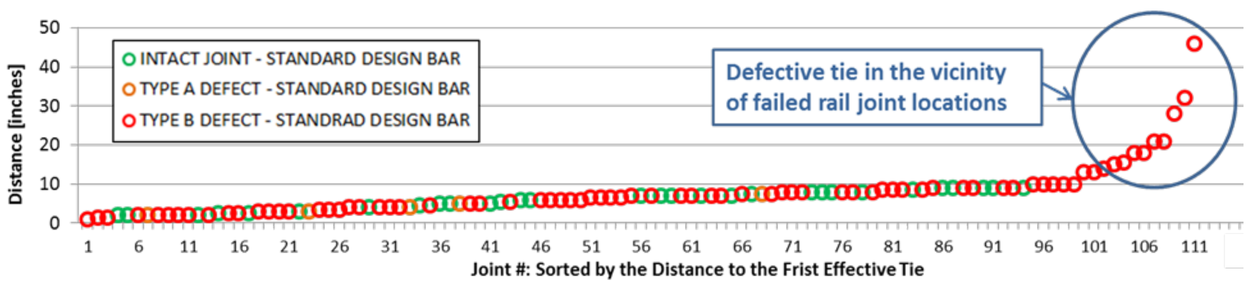


Figure 37. JNT Sample Track Class 3—Overview of Distance to First Effective Tie

Figure 38 displays encountered longitudinal bar movement. This parameter represents a relative motion between the joint bar and the rail ends and it is an indirect sign of the effectiveness longitudinal restraint, rail stresses and response of the joint to rail temperature fluctuations. In this plot, each entry represents an individual joint bar. Both intact and failed joint bars show comparable values of longitudinal bar movements.

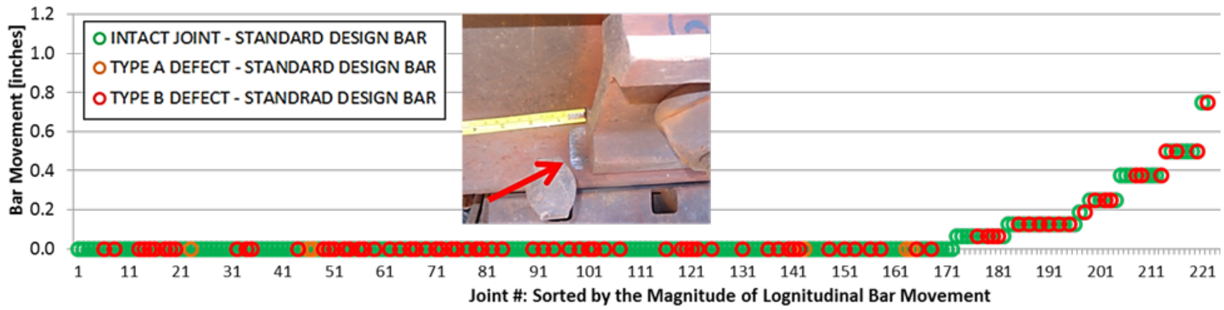


Figure 38. JNT Sample Track Class 3—Overview of Longitudinal Bar Movement

Bolt conditions (as seen in Table 8) do not appear to have an effect on joint bar failure. The bolt conditions are comparable at both intact and defect locations of both types. Overall, bolts were in better condition on Class 3 track than on the lower track classes. The proportion of locations with all bolts intact was 70 percent for track Class 3 compared to 44 percent for lower track classes.

Table 8. JNT Sample Track Class 3—Summary of Bolt Conditions

	ALL BOLTS INTACT		ONE OR MORE BOLTS LOOSE		ONE OR MORE BOLTS MISSING		AT LEAST ONE BOLT MISSING & LOOSE		TOTAL
INTACT BARS	22	73%	4	13%	2	7%	2	7%	30
TYPE A DEFECTS	4	80%	1	20%	0	0%	0	0%	5
TYPE B DEFECTS	52	68%	8	11%	13	17%	3	4%	76
ALL LOCATIONS:	78	70%	13	12%	15	14%	5	5%	111

Data samples of Class 3 track were evaluated with a statistical T-test to determine whether various parameters representing encountered track conditions differ significantly at failed and intact locations and discover the contributing factors to joint failure for this track class. Three sets of T-tests were performed for each parameter, between the intact sample, defect type A, defect type B, and all defects combined. A test for unequal sample sizes and unknown variances was used and a 5 percent significance level was selected.

Table 9 summarizes the results of the T-tests. The table lists the means, standard deviations, and the resulting p-value for the test. The smaller the p-value, the more likely the specific track condition is different at failed and intact locations when extrapolated to the entire population, which suggests more significant contributions by the condition to joint failure.

Figure 39 and Figure 40 show the 95 percent confidence intervals for the parameters summarized in Table 9. The charts can be also viewed as a graphical interpretation of the T-test.

It is important to note that the Class 3 track sample only has five locations with Type A defects. The T-test becomes much more restrictive for smaller sample sizes because more uncertainty exists in estimations of the populations mean and variance and the tails of t-distribution become heavier. This is also reflected in the very large confidence intervals for defect Type A in Figure 39 and Figure 40.

Most the parameters (with few exceptions) do not show significant difference between the intact and the Type A defect locations, even where the difference between intact group and Type B defects is very large. Notably, two exceptions are vertical joint movement and vertical rail end misalignments. For those two parameters, the difference is significant for both defect groups despite the small sample size of defect group A. This confirms two most important observations from the field: 1) Vertical movement at all track classes is a very significant factor that distinguishes intact rail joint locations from failed rail joint locations and 2) Rail end conditions, specifically in the vertical direction, are a contributing factor at Class 3 track, unlike rail end conditions on lower track classes.

Based on the results of the Type B defect group, lateral movement is also shown as a significant factor, even though it is not as large as vertical movement. Longitudinal movement does not show a statistically significant difference between the intact and failed locations for both defect type groups.

Track geometry parameters such as crosslevel, profile, and alinement are statistically different for static and under load measurements. However, the difference is more pronounced for under load values, most likely due to the effect of rail joint movements, which make up a significant proportion of the under load measurements.

Static gage is not significantly different, while gage under loads is, most like again due to the proportion of significantly different lateral movement contained within the under load measurement.

Rail end gaps turned out to be not significantly different. This is an interesting result, especially on the higher track class sample, where large rail end gaps are expected to introduce higher impact loads at the rail joints in a similar manner to rail end batter and mismatches (which were shown as significantly different for the track Class 3 sample). Since the field surveys were conducted in the summer or late spring when rail temperatures were already elevated, the rail end gap results can be influenced by the fact that rail gaps tended to be narrow or closed in general at the time when they were visited and documented. It is hard to estimate the magnitudes of rail end gaps that were present at the investigated locations during the cold weather cycle. Therefore, the effect of the rail end gaps size on joint bar failure is difficult to assess with the available data.

Table 9. JNT Sample Track Class 3—Summary of T-Test Results

T-Test	Sample 1	Mean	StDev	Sample 2	Mean	StDev	p-Value	Level	Pass T-Test
Vertical Movement	Intact	0.12	0.13	Type A	0.74	0.35	0.01519	0.05	YES
				Type B	0.84	0.52	0.00000	0.05	YES
				A & B	0.83	0.51	0.00000	0.05	YES
Lateral Movement	Intact	0.06	0.09	Type A	0.08	0.1	0.80723	0.05	NO
				Type B	0.16	0.13	0.00002	0.05	YES
				A & B	0.16	0.13	0.00004	0.05	YES
Longitudinal Movement	Intact	0.95	1.41	Type A	4.5	3.94	0.11416	0.05	NO
				Type B	1.56	1.59	0.05879	0.05	NO
				A & B	1.74	1.91	0.02081	0.05	YES
Static Crosslevel	Intact	0.26	0.18	Type A	0.38	0.29	0.43484	0.05	NO
				Type B	0.49	0.31	0.00001	0.05	YES
				A & B	0.48	0.31	0.00001	0.05	YES
Crosslevel under Load	Intact	0.38	0.26	Type A	1.08	0.53	0.04105	0.05	NO
				Type B	1.21	0.71	0.00000	0.05	YES
				A & B	1.21	0.7	0.00000	0.05	YES
Static Profile	Intact	0.23	0.25	Type A	0.43	0.47	0.41685	0.05	NO
				Type B	0.57	0.42	0.00000	0.05	YES
				A & B	0.56	0.42	0.00000	0.05	YES
Profile under Load	Intact	0.28	0.26	Type A	1.23	0.81	0.05978	0.05	NO
				Type B	1.35	0.8	0.00000	0.05	YES
				A & B	1.34	0.8	0.00000	0.05	YES
Static Alinement	Intact	0.08	0.12	Type A	0.25	0.23	0.18362	0.05	NO
				Type B	0.17	0.16	0.00491	0.05	YES
				A & B	0.17	0.17	0.00284	0.05	YES
Alinement under Load	Intact	0.11	0.14	Type A	0.33	0.26	0.13991	0.05	NO
				Type B	0.3	0.21	0.00000	0.05	YES
				A & B	0.3	0.21	0.00000	0.05	YES
Static Gage	Intact	56.37	0.18	Type A	56.4	0.31	0.94443	0.05	NO
				Type B	56.4	0.16	0.40195	0.05	NO
				A & B	56.4	0.17	0.44429	0.05	NO
Gage under Load	Intact	56.45	0.19	Type A	56.5	0.27	0.91263	0.05	NO
				Type B	56.6	0.21	0.00500	0.05	YES
				A & B	56.6	0.21	0.00752	0.05	YES
Vertical Rail End Misalignement	Intact	0.04	0.04	Type A	0.1	0.05	0.03053	0.05	YES
				Type B	0.13	0.09	0.00000	0.05	YES
				A & B	0.13	0.09	0.00000	0.05	YES
Gage Rail End Misalignement	Intact	0.01	0.02	Type A	0	0	0.10330	0.05	NO
				Type B	0.01	0.03	0.81317	0.05	NO
				A & B	0.01	0.03	0.86845	0.05	NO
Rail End Gap	Intact	0.22	0.21	Type A	0.14	0.12	0.28472	0.05	NO
				Type B	0.23	0.22	0.81326	0.05	NO
				A & B	0.22	0.21	0.90320	0.05	NO
Distance to First Effective Tie	Intact	6.10	2.39	Type A	4.3	2.11	0.13521	0.05	NO
				Type B	8.26	7.2	0.02259	0.05	YES
				A & B	8.02	7.06	0.03471	0.05	YES
Bar Longitudinal Movement	Intact	0.06	0.13	Type A	0	0	0.00001	0.05	YES
				Type B	0.06	0.14	0.68990	0.05	NO
				A & B	0.06	0.14	0.84765	0.05	NO

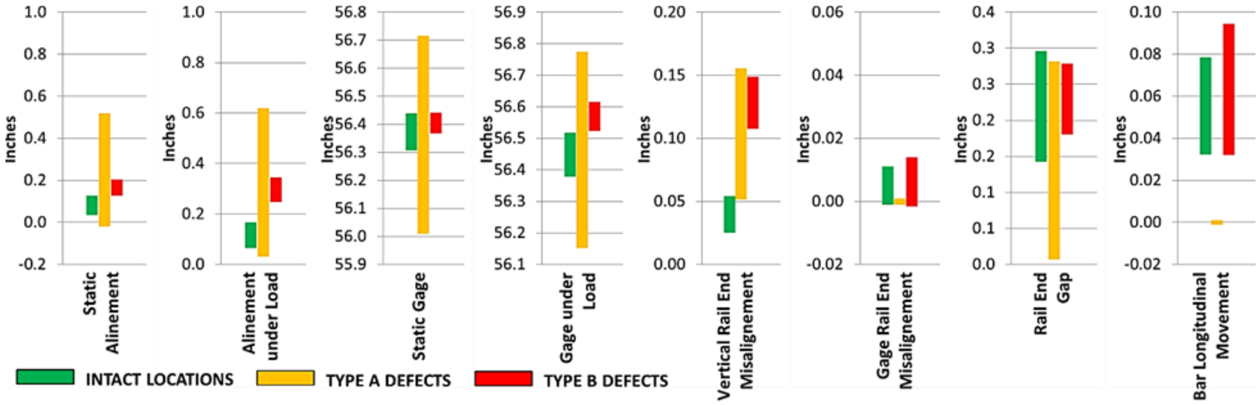


Figure 39. JNT Sample Track Class 3—95% Confidence Intervals of Field Condition Measurements, Part 1

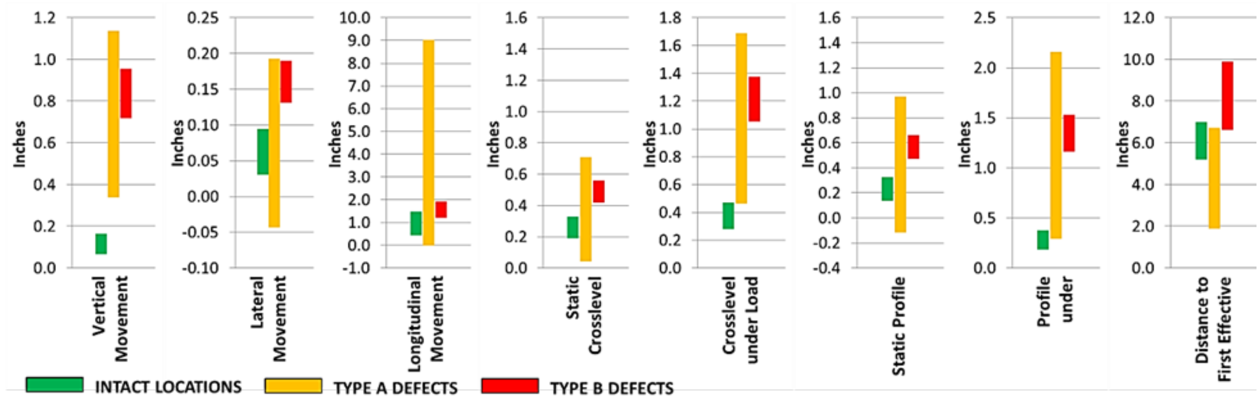


Figure 40. JNT Sample Track Class 3—95% Confidence Intervals of Field Condition Measurements, Part 2

The distance to first effective ties was identified by the T-test as a factor that had significant differences when intact locations were compared to defect locations. The sample contains multiple failed rail joint locations with a distance to first effective tie larger than 12 inches (see Figure 37). Within this sample, this represents locations where there was another tie closer to the joint centerline which was deemed ineffective due to its deteriorated condition as defined in Appendix E. When we repeat the T-test and reconstruct the confidence intervals for a sample with those locations removed, the statistical significance disappears as illustrated in Figure 41. In this case four locations with a distance to first effective tie of 20 inches or larger were removed from the Type B defect sample group.

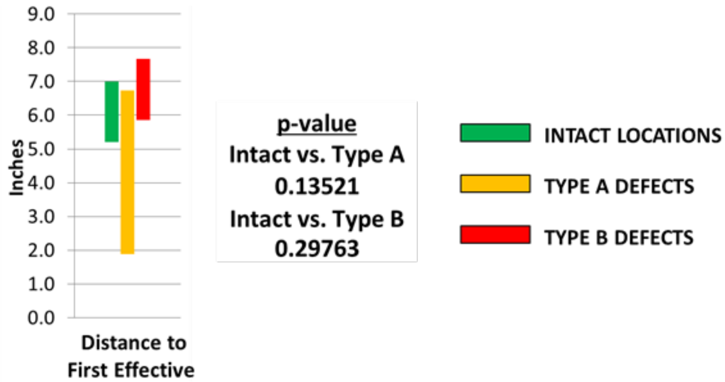


Figure 41. JNT Sample Track Class 3—95% Confidence and T-Test Results for Locations with Distance to First Effective Tie of 20 Inches or Smaller

The result supports the important observation that rail joint failure appeared to affect both suspended and supported rail joint configurations evenly. However, the presence of defective ties contributes to deteriorated overall vertical support condition of the rail joint, regardless of the original tie configuration under the rail joint.

5.1.3 Combined Jointed Track Sample

The combined sample from JNT territory contained 123 failed and 49 intact rail joint locations (a total of 172 locations). The different defect types are distributed in the sample as follows:

- Intact locations (49 locations)
- Type A defects (26 locations)
- Type B defects (97 locations)

There was a total of 139 failed bars and 16 locations had failures with both bars. The sample includes a total of 140 defects in which one of the bars contains two distinct cracks. Defect distribution summarized based on quarter, center, or bolt hole defect type and bar design is presented in Table 10 and further detailed in Table 11.

Table 10. Defect Location and Bar Design Based Defect Occurrence on Combined JNT Sample

	LONG TOE (ANGLE)		HEAD-CONTACT		HEAD-FREE		TOTAL
QUARTER DEFECTS	25	78%	0	0%	7	22%	32
CENTER DEFECTS	13	14%	5	5%	78	81%	96
BOLT HOLE DEFECTS	4	33%	1	8%	7	58%	12

Table 11. Defect Distribution on Combined JNT Sample

	LONG TOE (ANGLE)	HEAD-CONTACT	HEAD-FREE	TOTAL
FULL QUARTER BREAK	17	0	4	21
TOP QUARTER CRACK	3	0	2	5
BOTTOM QUARTER CRACK	5	0	1	6
FULL CENTER BREAK	3	1	26	30
TOP CENTER CRACK	10	3	46	59
BOTTOM CENTER CRACK	0	1	6	7
FULL BOLT HOLE BREAK	0	1	6	7
TOP BOLT HOLE CRACK	4	0	0	4
BOTTOM BOLT HOLE CRACK	0	0	1	1
	42	6	92	140

The distribution of encountered defects on jointed territory is discussed in detail in Section 3.4. In summary, the most common failure mode for a standard design bar was a top center defect and full quarter break on long toe (angle) bars, while bolt hole defects were only marginally occurring failure mode.

Overall, defects were evenly distributed between field and gage side bars (see Table 12 and Table 13).

Table 12. Field/Gage Side Bar Based Defect Occurrence on Combined JNT Sample—Part 1

	FIELD SIDE BAR		GAGE SIDE BAR		TOTAL
FULL BREAK	24	41%	34	59%	58
TOP CRACKS	35	51%	33	49%	68
BOTTOM CRACKS	8	57%	6	43%	14
TOTAL	67	48%	73	52%	140

Table 13. Field/Gage Side Bar Based Defect Occurrence on Combined JNT Sample—Part 2

	FIELD SIDE BAR		GAGE SIDE BAR		TOTAL
QUARTER DEFECTS	13	41%	19	59%	32
CENTER DEFECTS	47	49%	49	51%	96
BOLT HOLE DEFECTS	7	58%	5	42%	12
TOTAL	67	48%	73	52%	140

The plots in Figure 42 through Figure 47 provide an overview of various evaluated parameters such as rail joint movement, track geometry, rail end conditions, etc. in a same manner as for the low and high track class samples in the previous chapters.

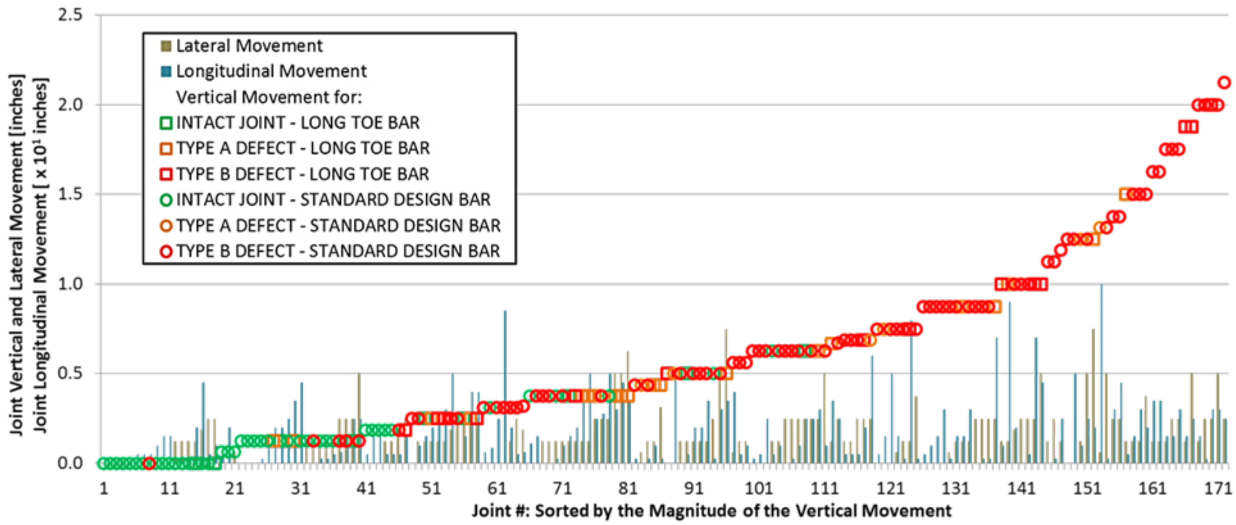


Figure 42. Combined JNT Sample—Overview of Joint Movements

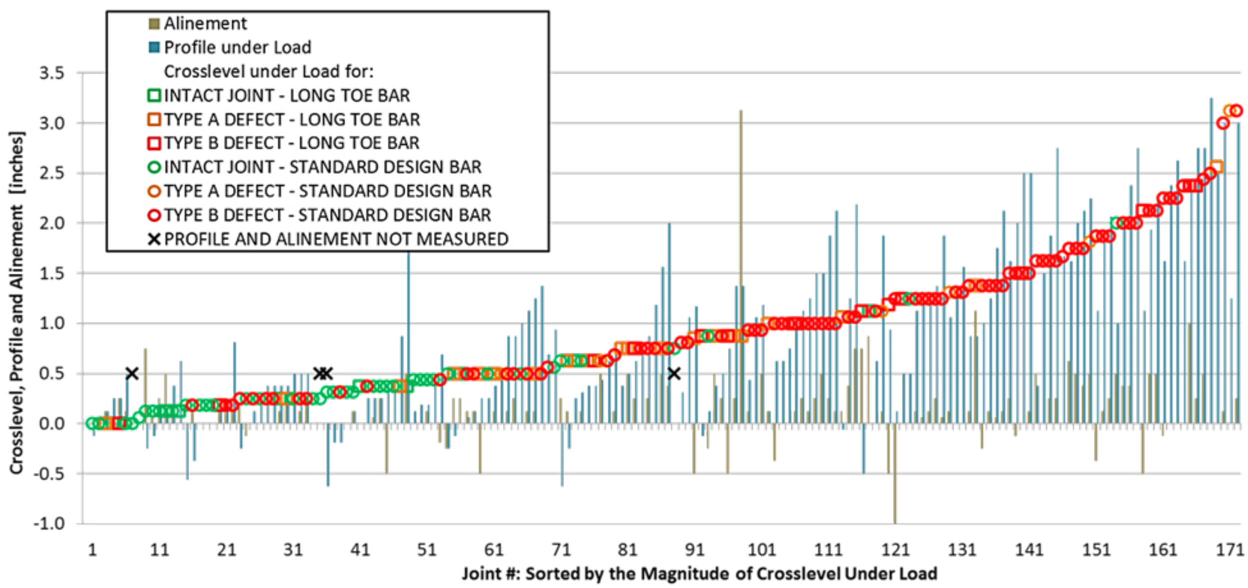


Figure 43. Combined JNT Sample—Overview of Selected Track Geometry Parameters

Joint movements and track three track geometry measurements—crosslevel under load, profile under load and alinement follow the same trends in the combined sample as they did separately in the lower and higher track class samples.

Again, the locations with failed joint bars exhibit much larger vertical movement measurements than the evaluated intact locations (see Figure 42). They also exhibit much larger crosslevel under load and profile under load measurements than intact locations. We can also notice a similar trend as in Class 3 track sample regarding increasing profile under load values with growing crosslevel under load (see Figure 43).

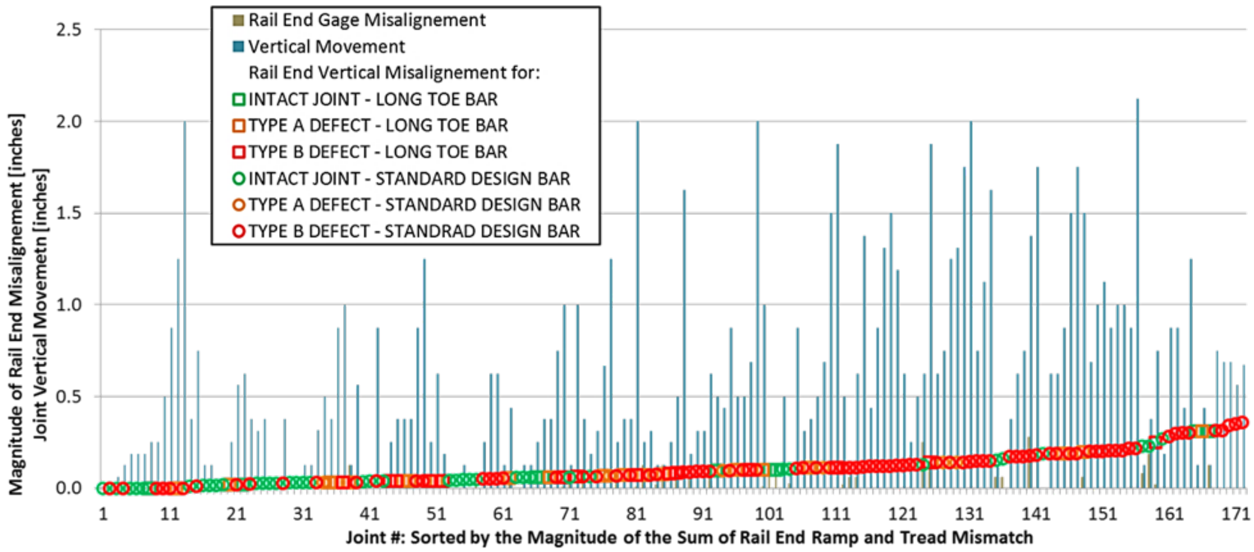


Figure 44. Combined JNT Sample—Overview of Rail End Conditions

Rail end conditions at intact and failed locations are comparable on Combined JNT Sample – Overview of Rail End Conditions the combined JNT sample as seen in Figure 44. The difference in rail end conditions between intact and failed rail end locations was specific to data from Class 3 track.

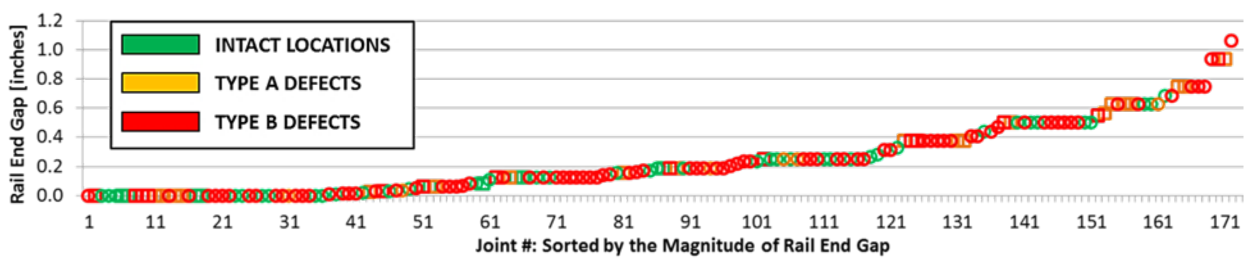


Figure 45. Combined JNT Sample—Overview of Rail End Gaps

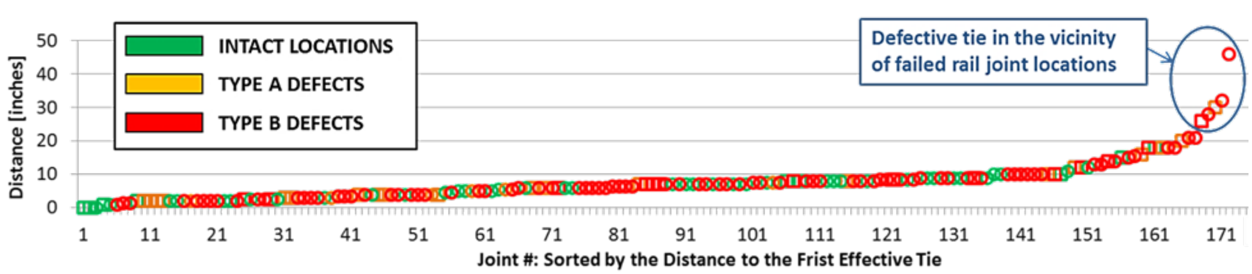


Figure 46. Combined JNT Sample—Overview of Distance to First Effective Tie

Locations with defects do not seem to have magnitudes of rail end gaps than evaluated intact joint locations. The distance to the first effective tie doesn't seem to be significantly different between the intact and failed locations up to distances around 12 inches, see Figure 45 and Figure 46 respectively. This is consistent with the trends on data separated by track class.

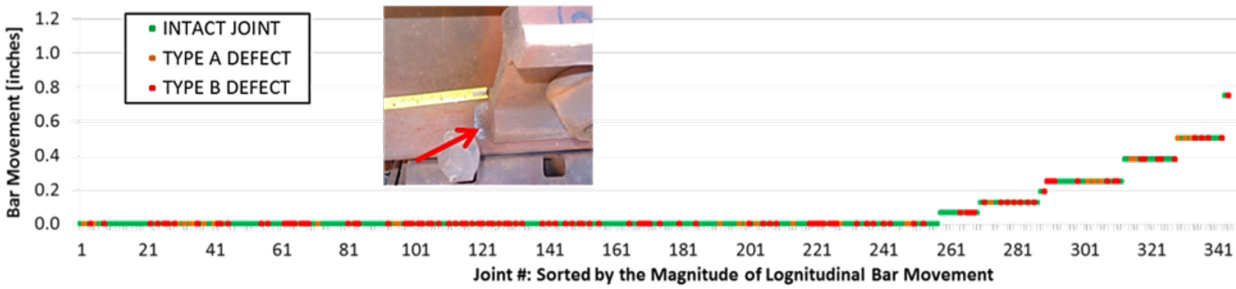


Figure 47. Combined JNT Sample—Overview of Longitudinal Bar Movement

Longitudinal bar movements and bolt conditions are also comparable at both intact and defect locations, see Figure 47 and Table 14.

Table 14. Combined JNT Sample—Summary of Bolt Conditions

	ALL BOLTS INTACT		ONE OR MORE BOLTS LOOSE		ONE OR MORE BOLTS MISSING		AT LEAST ONE BOLT MISSING & LOOSE		TOTAL
INTACT BARS	29	59%	13	27%	4	8%	3	6%	49
TYPE A DEFECTS	13	50%	12	46%	1	4%	0	0%	26
TYPE B DEFECTS	63	65%	14	14%	16	16%	4	4%	97
ALL LOCATIONS:	105	61%	39	23%	21	12%	7	4%	172

When the lower and higher-class samples were analyzed, it was evident that under load measurements of crosslevel and profile are significantly different at intact and defect locations, while their static values are less significantly defect at higher class samples and not at all significantly different at lower class samples. This is due to very significantly different vertical movement, which makes up a significant proportion of the under load measurements, see Appendix D to learn how the under load measurements are determined. Figure 48 and Figure 49 illustrate the relationship between static and under load measurements.

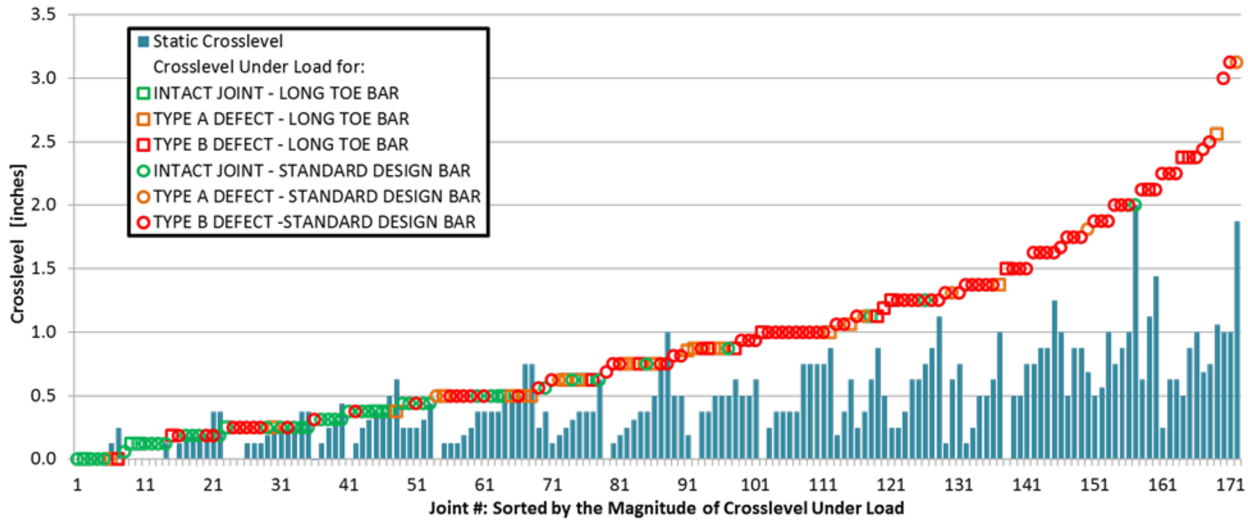


Figure 48. Combined JNT Sample—Overview of Static and Under Load Crosslevel

Figure 48 presents values of crosslevel under load overlaid with its static value. The value of static crosslevel does not appear to be such a distinct indicator of failed joint locations as crosslevel under load, even though a slight trend in the static values can be observed. It can be also observed that since static and under load values do not grow at the same rate, locations with increasing under load values also contain increasing proportion of vertical movements. An almost identical trend can be seen for static and under load profile measurements in Figure 49.

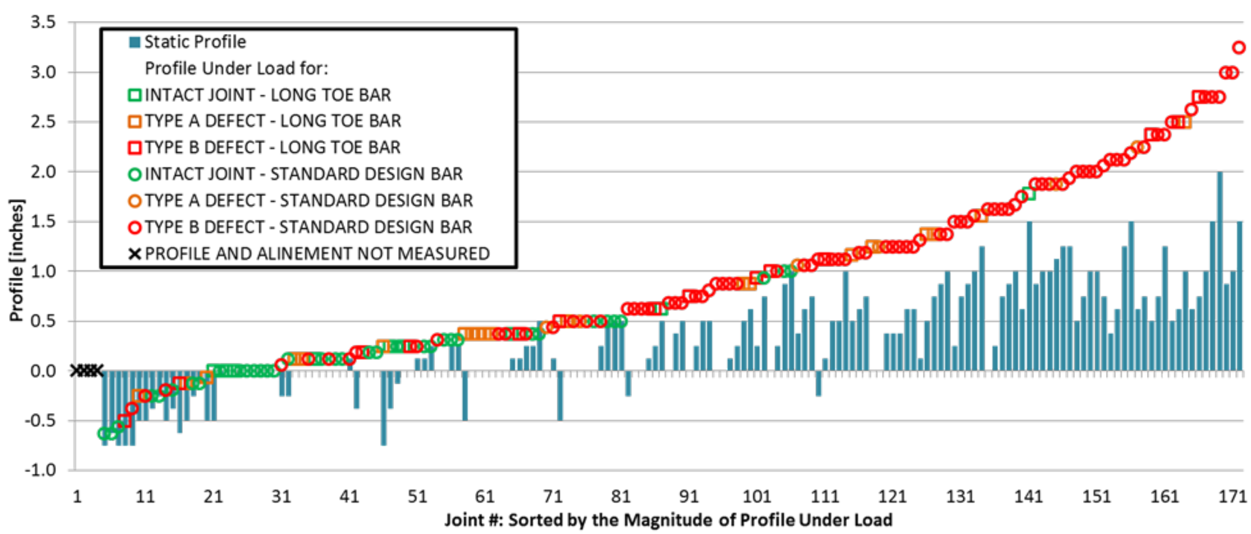


Figure 49. Combined JNT Sample—Overview of Static and Under Load Profile

A closer look was given to alinement because the analysis of the lower track class did not show a significant difference for either static alinement or alinement under load between the intact and failed locations, while the higher-class sample did show a significant difference in the under load alinement parameter.

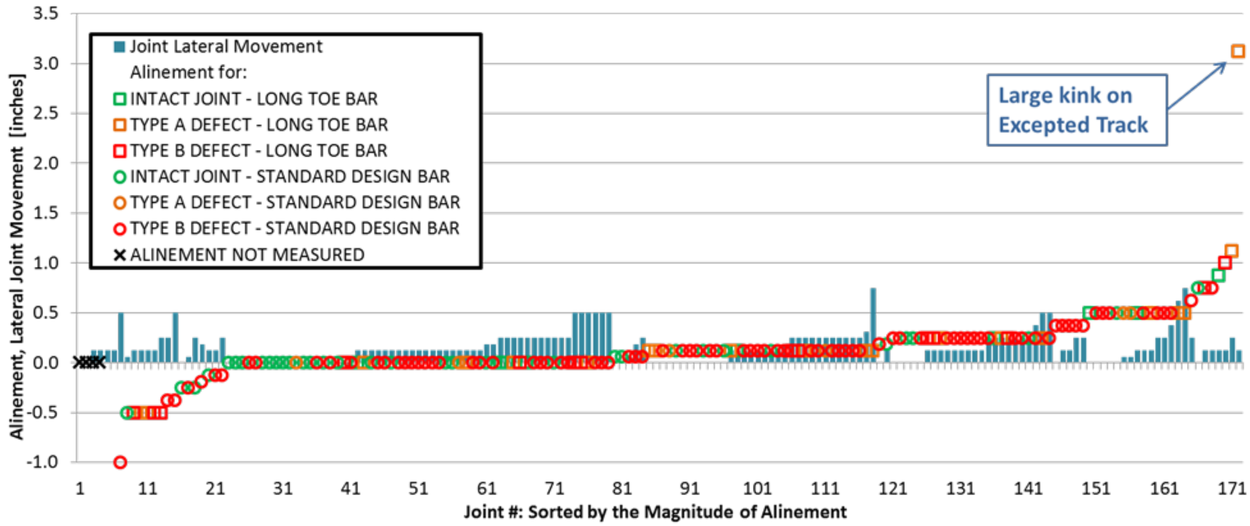
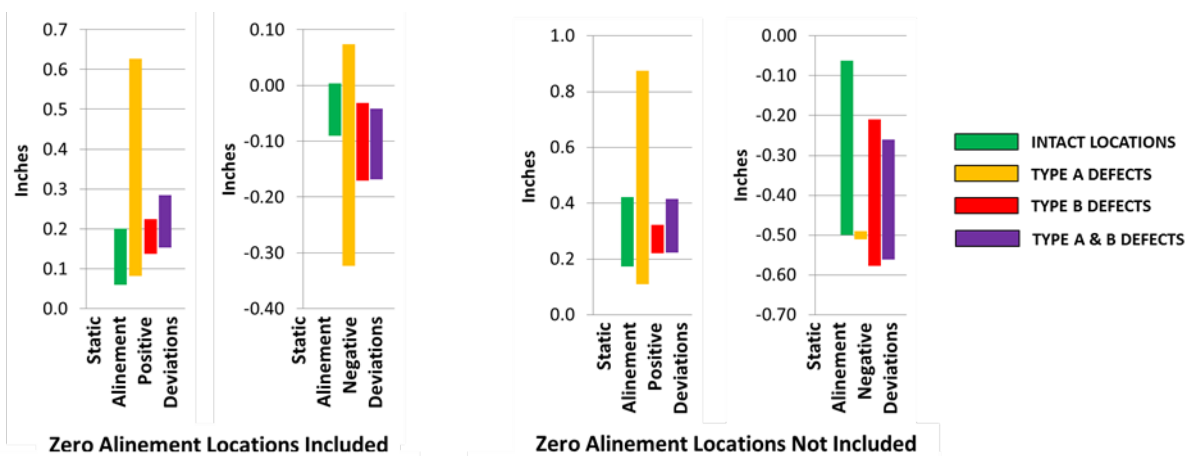


Figure 50. Combined JNT Sample—Overview of Static Alinement

Figure 50 shows static alinement for all locations overlaid with values of lateral movement. A negative value of alinement represents a deviation towards the center of track. The magnitudes of encountered alinement deviations in either direction (positive and negative values) are very small in general and many failed and intact locations do not exhibit any alinement deviation at all. Further statistical analysis was performed to determine if a significant difference between intact and failed joint locations exists separately for positive and negative values of alinement.



T-Test:

Intact vs:	p-value:	p-value:
Type A:	0.111	0.364
Type B:	0.216	0.169
Type A&B:	0.070	0.117

T-Test:

Intact vs:	p-value:	p-value:
Type A:	0.307	0.069
Type B:	0.686	0.348
Type A&B:	0.774	0.248

Figure 51. Combined JNT Sample Track—Detailed 95% Confidence and T-Test Results for Alinement

The T-test analysis was performed and confidence intervals constructed for cases—for positive and negative deviations of alinement with either locations of zero alinement included or not included in the samples. The results summarized in Figure 51 do not support positive or negative alinement as a significant factor contribution to joint failures.

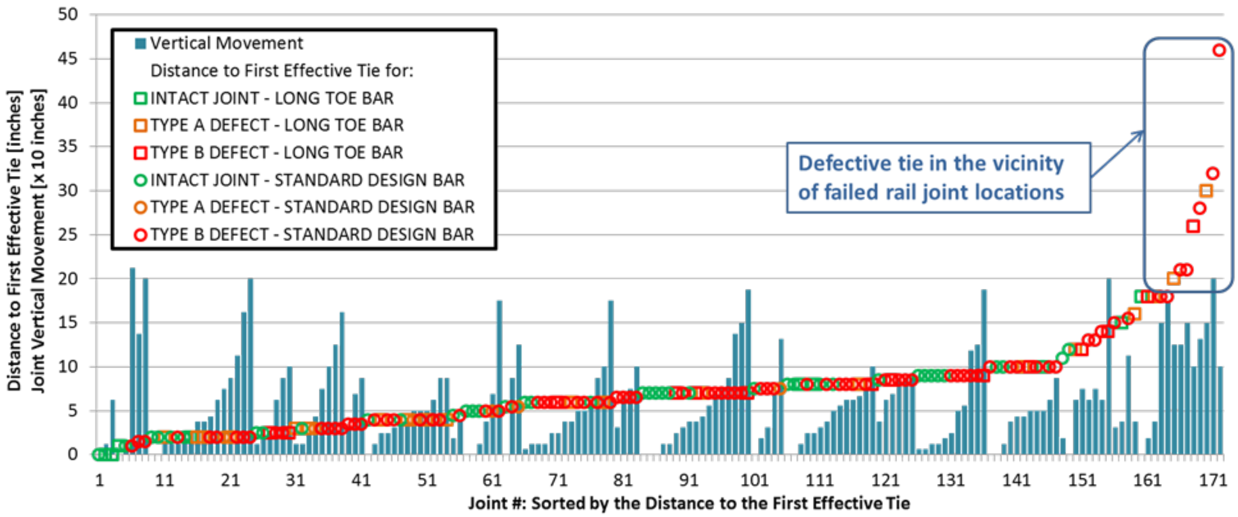


Figure 52. Combined JNT Sample—Overview of Distance to First Effective Tie and Vertical Movement

Figure 52 displays the distance to first effective tie measured on combined JNT samples overlaid with values of vertical movement. The locations are sorted by the magnitude of the distance to first effective tie and the vertical movement is scaled up 10 times. There is no trend in growing vertical movement with increasing distance to the first effective tie. In general, failed locations are accompanied with comparable values of vertical movement regardless of this distance. Locations with a distance to the first effective tie larger than 12 inches, indicating the presence of defective ties under the joint, all contain significant vertical movement. This is comparable to the magnitudes at other failed locations and it is in agreement with the conclusions made separately in lower and higher track class samples and with field observations. Rail joint failure appears to be independent of the original suspended and supported rail joint configurations but it is dependent on deterioration of vertical joint support regardless of the original tie configuration. The presence of defective ties under the rail joints results in and may exacerbate deteriorated vertical support and subsequent vertical movements.

The team also investigated the distribution of vertical movement at locations based on the defect type. Vertical movement was identified as the most significant factor distinguishing intact and failed joint locations. Two arguments for the significance of the vertical movement can be made: 1) the vertical movement preceded the failure of the joint, or 2) vertical movement was a consequence of a reduced bending stiffness in a location with a broken joint bar.

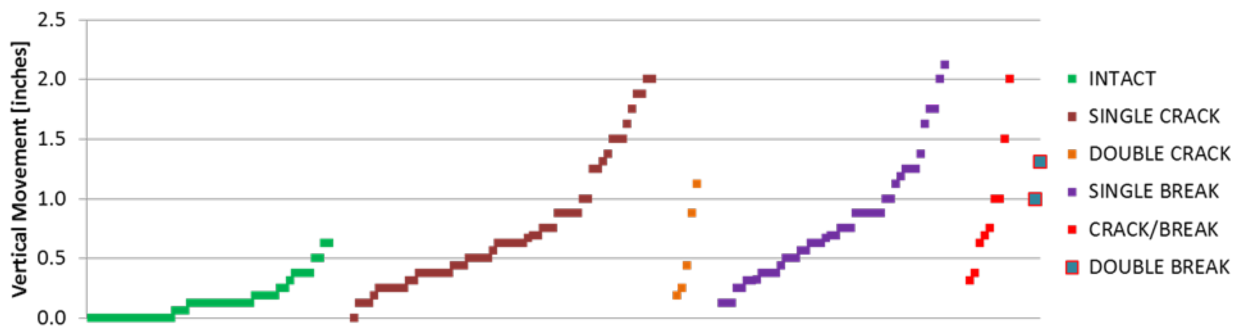


Figure 53. Combined JNT Sample—Overview of Vertical Movement Based on Defect Type

Figure 53 presents the vertical movement for intact locations and locations in the following categories: single crack bar, double crack, single break, crack/break and double break defect. The categories are ordered according to the theoretical decrease in bending stiffness, i.e., the capability to rigidly connect two rail ends at the rail joint for the particular defect configurations. The vertical movements in each group are sorted by their magnitude. Cracked bars (top cracks especially), which offer similar capability to rigidly connect two rail ends as intact bars appear to contain much larger vertical movements than intact bars. Locations with joint bar breaks show comparable vertical joint movements as locations with cracked bars, even though locations with at least one broken bar have reduced cross sectional characteristics at the rail end connection. This is confirmed by 95% confidence intervals shown in Figure 54.

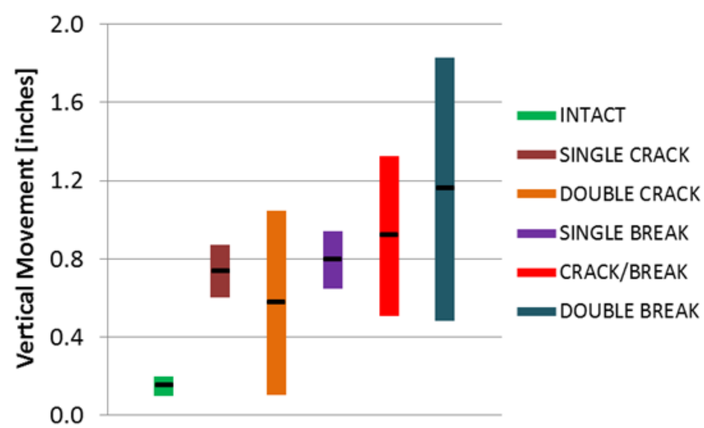


Figure 54. Combined JNT Sample—95% Confidence Intervals of Vertical Movement Based on Defect Type

The difference in the magnitude of vertical movement between the defect locations at intact locations is statistically significant for all defect types except for the double crack category and breaks where the number of sample is very small (five and two locations respectively). The differences are not significant among the defect type combinations, which suggests that joint movements precede the joint bar defects and vertical movements are a factor that contributes to joint failures. The results—due to limited size of crack/break and double break sample groups—do not provide statistically significant evidence to the assumption that vertical movement would grow further once defects develop into full breaks.

The field surveys also documented the distance between the joint bar and rail end centerline. This measurement quantifies asymmetry in the joint bar placement at the rail ends. Figure 55 illustrates comparable values at intact and defect locations.

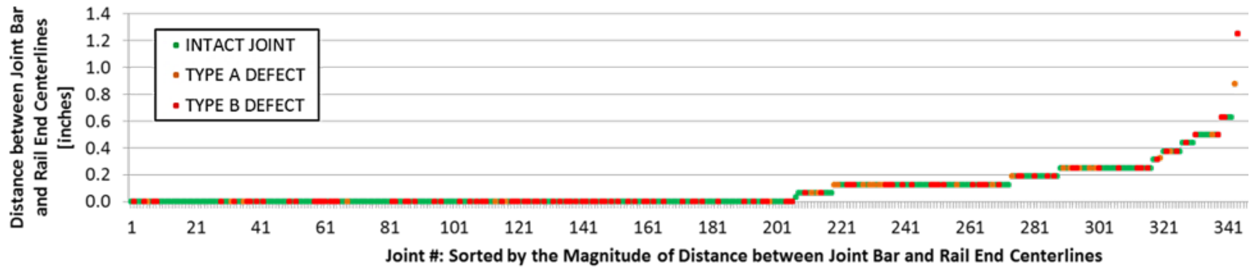


Figure 55. Combined JNT Sample—Overview of Distance between Joint Bar and Rail End Centerline

Easement, a term that describes an area in the middle of the joint bar where the material is recessed to prevent rail ends from coming in contact with the joint bar middle top section, may be present on modern design bars. The easement is supposed to be positioned in the center of the joint bar, which means that the distance between joint bar and rail end centerline distance parameter can evaluate the effect of the easement on joint failure indirectly. Since an easement may be present only in modern-design bars and should affect only failures originating close to the rail ends, a subset of data containing only head-free joint bars either intact or contain center defects was separated from the combined samples. The values at intact and defect locations are again compared (Figure 56). The T-test confirmed that there was no statistically significant difference between the intact and center-failed joint bars with p-value at 0.94. The difference was also found not statistically significant when only failed bars with top center cracks were considered, p-value at 0.20.

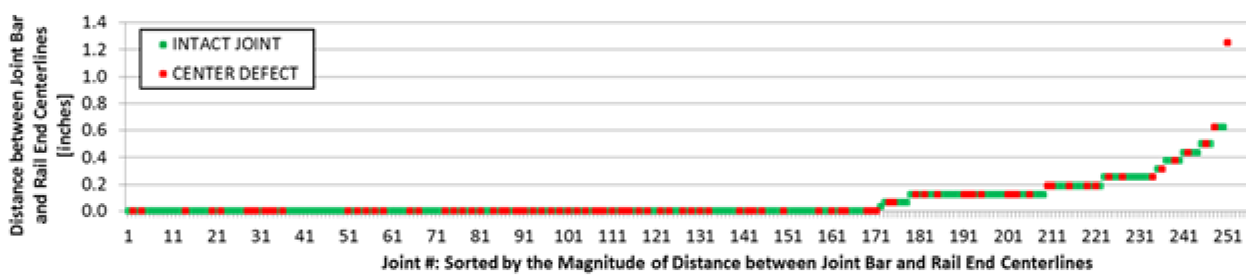


Figure 56. Combined JNT Sample—Overview of Distance between Joint Bar and Rail End Centerline for Head-Free Joint Bars with Center Defects or Intact

These results cannot confirm or rule out definitively any effect of easement on rail joint failure as it is not known to ENSCO whether investigated joint bars truly contained any centrally or otherwise located easement at all. Only selected failed bars were shipped to the TTC for further analysis, where easement presence would be documented.

5.2 CWR Territory

There were 5 failed and 53 intact rail joint locations (a total of 58 locations). All the five defects on CWR territory were top center cracks on standard-design head-free temporary joints on wooden tie track. There were no defects found on concrete tie tracks. Out of the 53 documented intact locations, 12 of them were on concrete tie track and the remainder (41 locations) were on wooden tie track.

Several plots are used to generate an overview of various conditions at the investigated locations in the sample as a whole. Failed locations are shown in red and intact locations in green. To indicate temporary or more permanent joints, the plots also include further differentiation between standard, compromise and insulated joints. Rail joint locations supported by concrete ties are indicated by purple arrows. The plots include overlays of several different measurements to offer insight into possible relationships between these conditions.

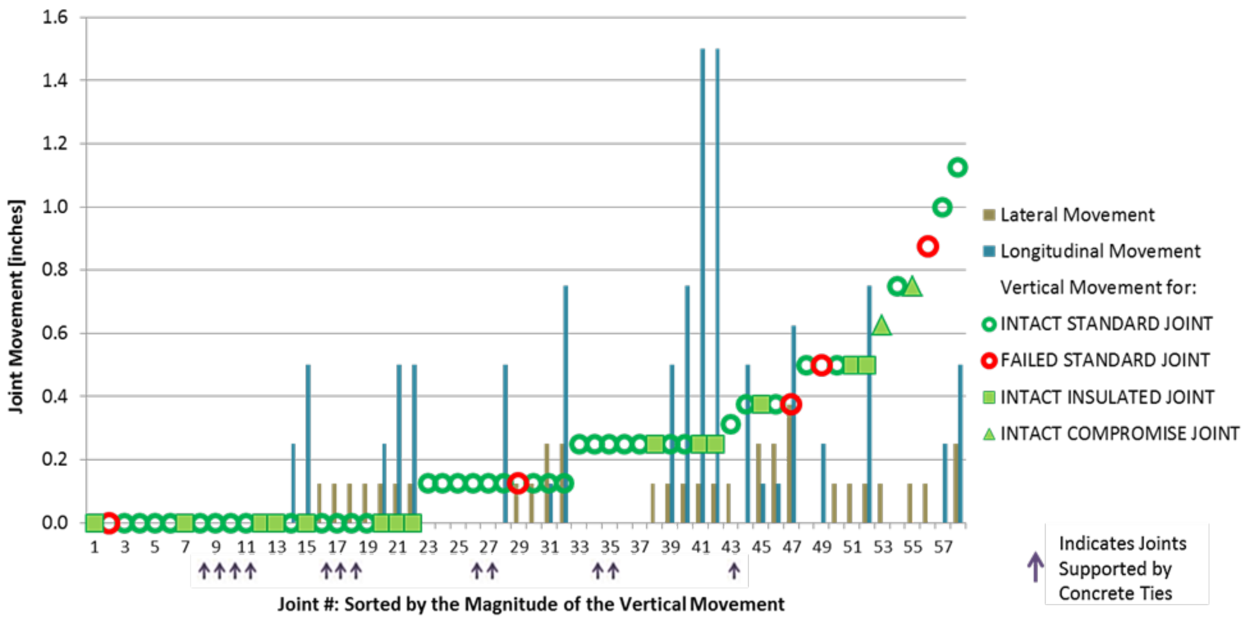


Figure 57. CWR Sample—Overview of Joint Movements

Figure 57 provides an overview of joint movements. The locations are sorted by the magnitude of the vertical movement. Three of the failed locations showed signs of significant vertical movement. One failed location without any measured joint movement may be an outlier, located in a switch with very recent maintenance work. The sample also contains several intact joints with adverse support conditions which were encountered during the first survey at test zone A. These locations were mostly temporary joints, which were very recently installed in track prior to the survey date and did not accumulate significant tonnage (see Figure 63). Permanent rail joint installations have insulated joints that tend to stay in the track for a very long time, and in general have better support conditions than standard temporary joints. Rail joints on concrete tie track including temporary ones had better vertical support than joints on wooden tie track.

Track geometry exhibit very similar trends as joint movement. Selected parameters, crosslevel and profile under load and alinement are presented in Figure 58. It is important to remember that under load crosslevel and profile measurements contain a significant proportion of vertical movement.

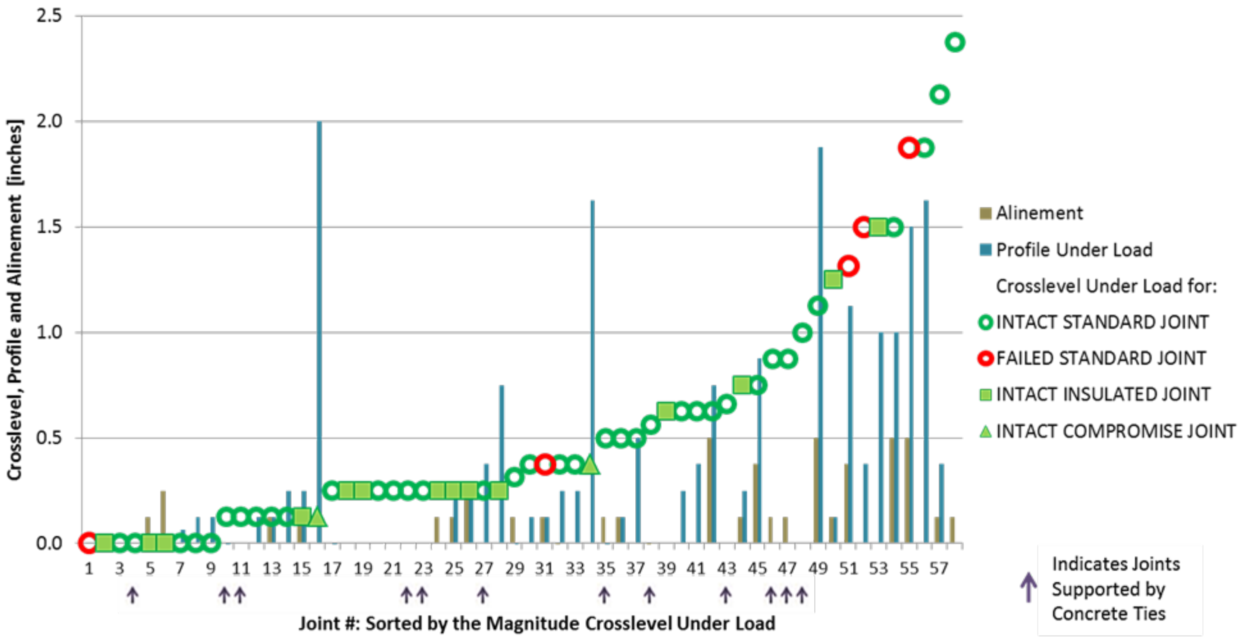


Figure 58. CWR Sample—Overview of Selected Track Geometry Parameters

Figure 59 gives an overview of rail end conditions. The locations are sorted by the value of rail end vertical misalignment, which is defined as a sum of tread mismatch and rail end ramp. This is a calculated parameter used to evaluate the overall conditions of the rail ends in vertical direction. Vertical rail end misalignments are overlaid with vertical movements and gage rail end misalignments, which are defined as the sum of gage ramp and gage mismatch.

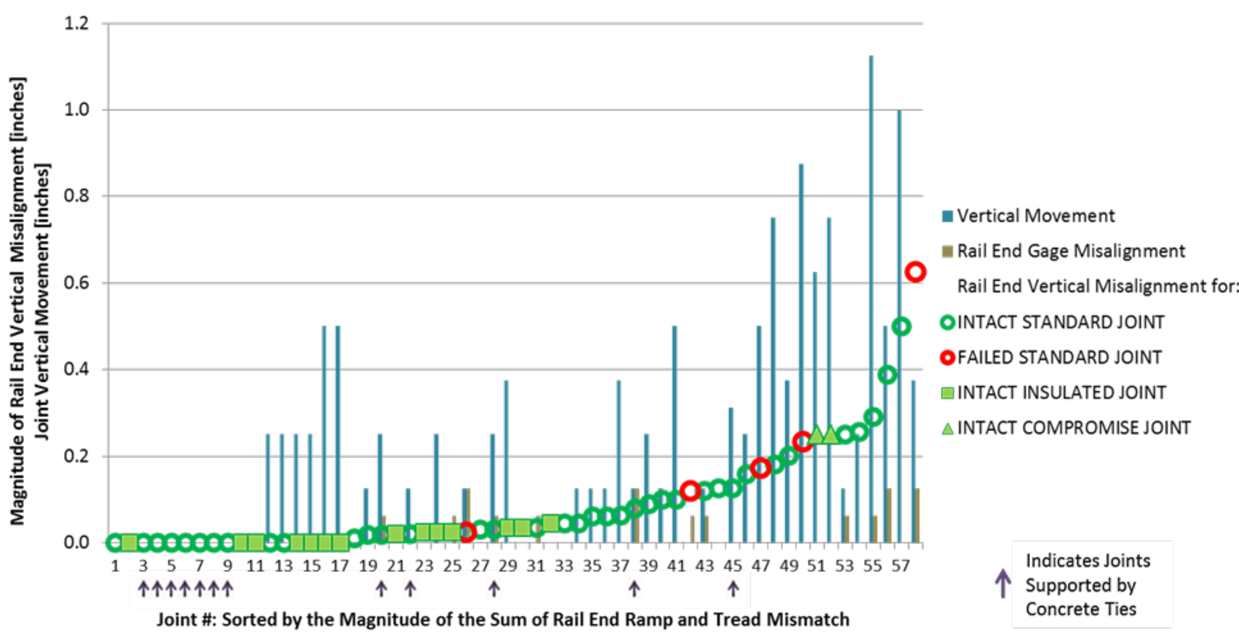


Figure 59. CWR Sample—Overview of Rail End Conditions

Permanent insulated joints in general contained better rail-end conditions than standard temporary joints. Rail joints on concrete tie track, including temporary ones, had better rail end conditions than joints on wooden tie track. Both of those trends are more pronounced than similar trends in vertical joint support observed in Figure 57. Vertical movement seems to increase as the value of vertical rail end misalignment rises. Several intact joint locations contain adverse rail end conditions. Again, these locations were temporary joints that had been recently installed and did not have significant accumulated tonnage; they were encountered during the first field survey on test zone A (see Figure 63). Four failed locations contained significantly adverse rail end conditions. The last failed rail joint location with limited rail end ramp was located in a switch with very recent maintenance work.

During the field surveys, it was observed that CWR deteriorated rail end conditions were overwhelmingly represented by tread mismatches or abrupt rail end ramps, which were caused by the original mismatches being battered down by repeated wheel impact loads. This was especially the case when temporary joints were introduced in places of rail repair that used new or full ball repair rail sections in track with worn rail. Figure 60 displays the proportion of tread mismatch and rail end ramp height contributions to the overall rail end misalignment at the individual joint locations.

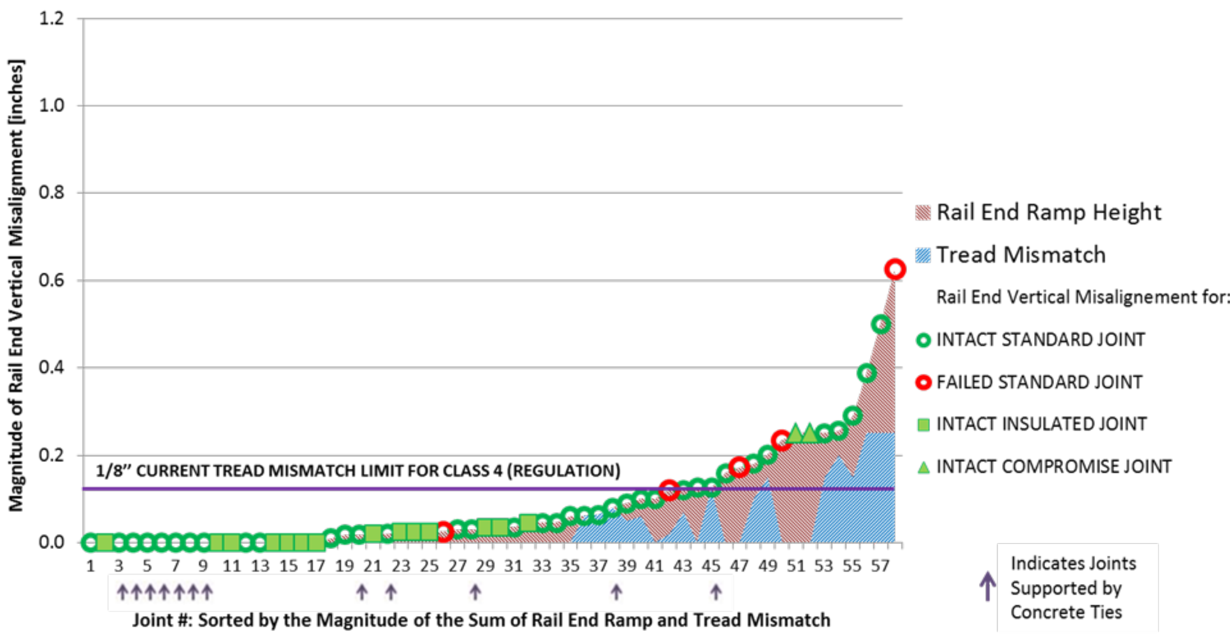


Figure 60. CWR Sample—Composition of Vertical Rail End Misalignments

The proportion of abrupt rail end ramps is often very large, especially at the failed locations. Three out of the four failed rail joint locations with significant rail end misalignments contain mostly rail end ramps as a result of battered down original tread mismatches. This can be also observed in Figure 61 and Figure 62 which present the tread mismatches and rail end ramps at the locations separately.

During the first survey, most intact temporary rail joints with adverse rail end conditions in test zone A were installed in track very recently prior to the survey date and did not accumulate significant tonnage. They predominantly contained tread mismatch, suggesting they did not endure enough traffic for these mismatched rail ends to be battered down yet (See Figure 63).

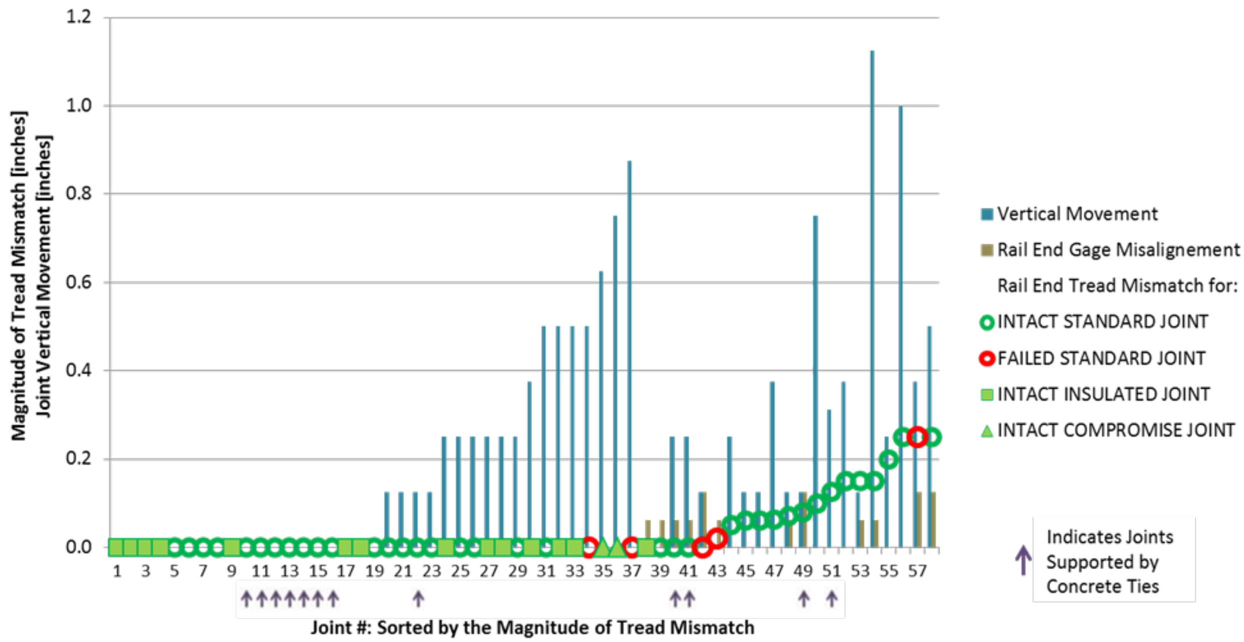


Figure 61. CWR Sample—Overview of Tread Mismatch

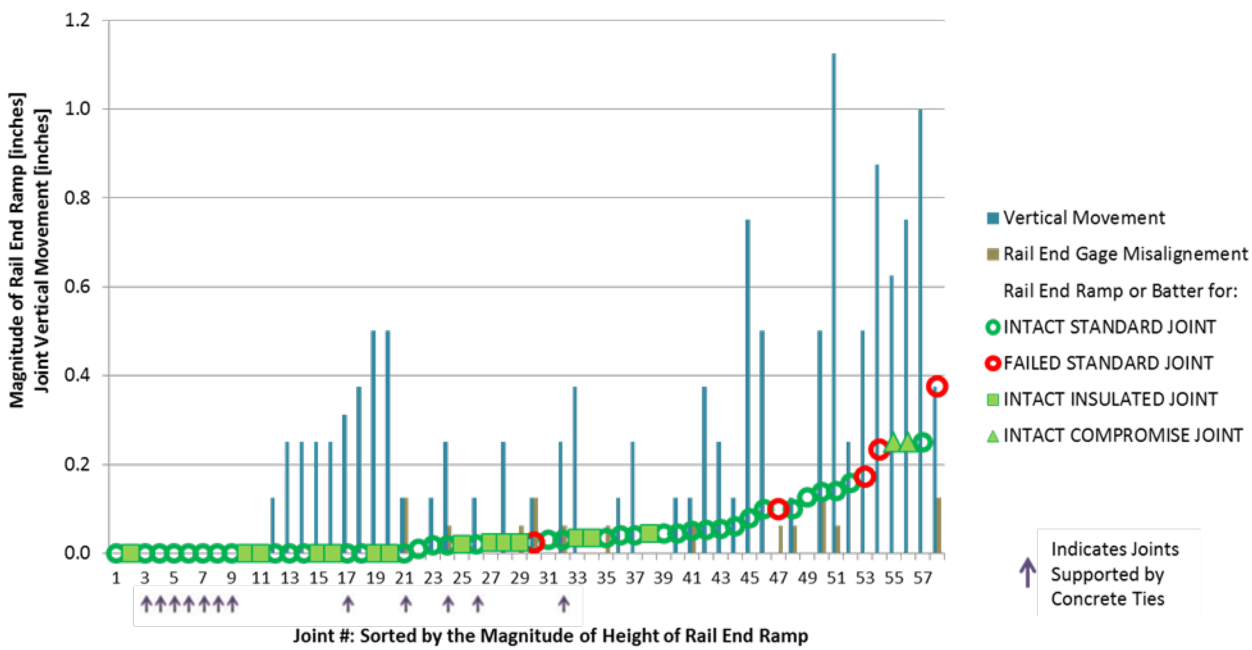


Figure 62. CWR Sample—Overview of Rail End Ramps

Figure 63 shows overall vertical rail end conditions and the proportions of tread mismatches and rail end ramps contributing to the misalignments overlaid with vertical movement on locations investigated during the first field survey on test zone A. As mentioned previously, several intact temporary joints with high value of rail end vertical misalignments were found during the first field survey. These locations are highlighted along with the installation date based on investigation of the welders' reference marks. The first field survey was conducted in April of 2012. All these temporary joints were cut in the track very recently and had not accumulated more than 7 MGT since they were installed in this territory. They also contain a large proportion of tread mismatch contribution to the overall misalignment.

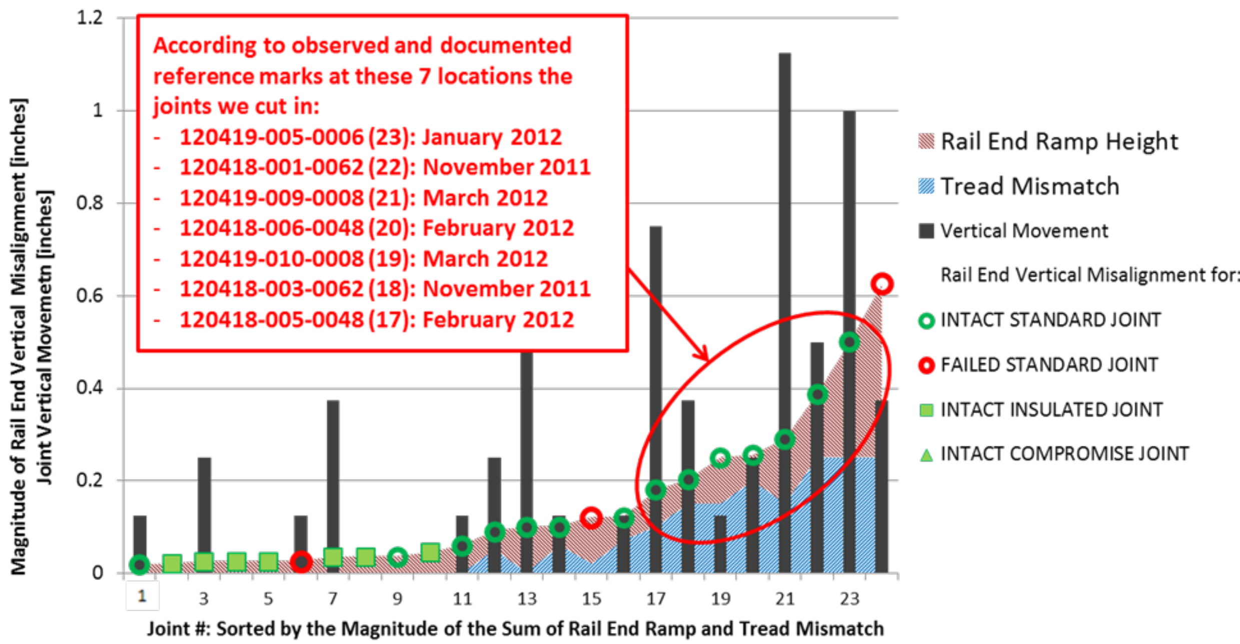


Figure 63. CWR Sample—Composition of Vertical Rail End Misalignments at Test Zone A Locations

The field surveys indicated that most of the rail end ramps at temporary joints were very abrupt and appeared to be originally tread mismatches, which were battered down by wheel impact forces. The plot in Figure 64 provides an overview of the slopes of the measured rail end ramps. Rail end slopes were calculated for both rail ends at each location and the maximum slope for each location was plotted in the order of the growing height of the rail end ramp. The figure also includes the values of gage misalignments at each location.

There appears to be a correlation between the growing magnitude of the rail end ramps and the abruptness of the ramps. At locations where rail end ramps are around 0.1 in. or higher, the ramp slopes are also very steep, between 2 degrees and 7 degrees.

The correlation between the magnitude of the rail end ramps and the abruptness of the ramps supports the observation that many measured ramps at temporary joint were caused by impact loads battering down the rail heads with an originally installed mismatch. Battering down the head in this manner could also cause gage misalignments by widening the rail head. The plot in Figure 64 does not offer a strong correlation between magnitude of the rail end ramps and gage misalignments, as many locations with large rail end slopes do not contain a gage misalignment at all. However, the battering caused the rail head at many such locations to widen towards the field side rather than the gage side of the rail. Refer to Figure 17 for a good example of battered rail head widening towards the field side.

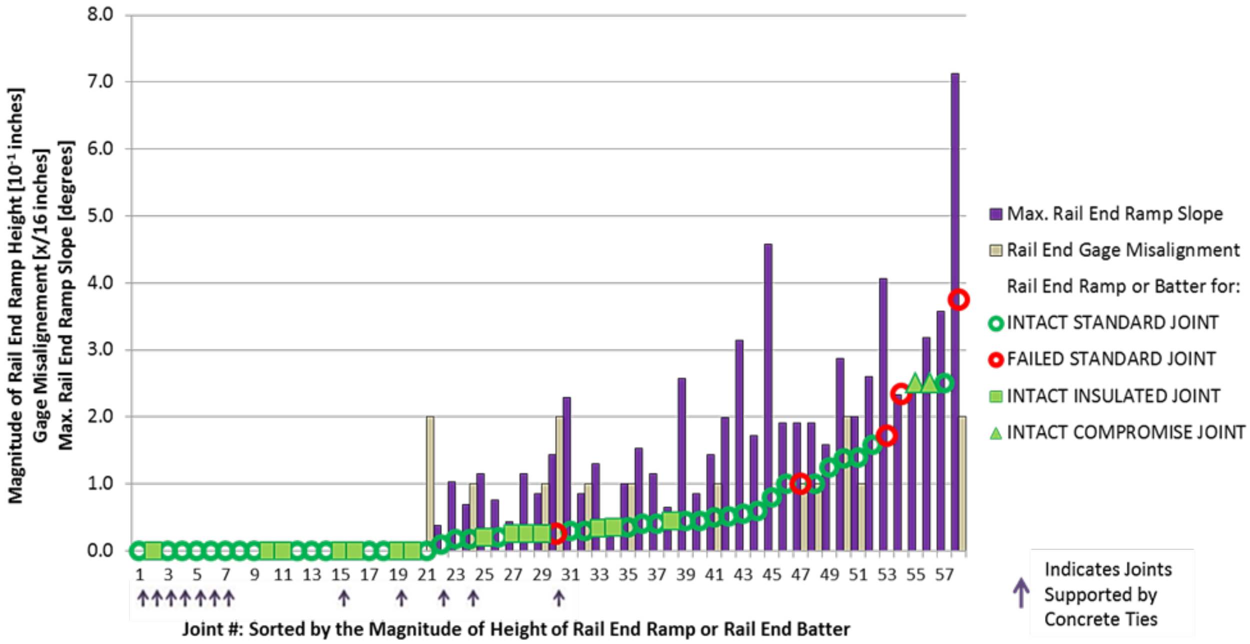


Figure 64. CWR Sample—Overview of Rail End Slopes

Rail joint locations on concrete tie track were very well maintained, with no or minimal rail joint movements and rail end misalignments were found. Investigation of welder's reference marks revealed that most of the temporary joints on the concrete tie territory on test zone E were cut in the track one to two months prior to the survey date and, in that time, accumulated more than 27 MGT while installed in that particular location, based on the annual MGT of the territory as shown in Table 5. The field survey on test zone E took place in June 2013. This shows that well-supported joints with maintained rail ends can survive for weeks (or even months) in high tonnage track (almost 200 MGT) with a large accumulated MGT.

Table 15. Accumulated Tonnage by Joints on Concrete Tie Territory

ID	TRACK MGT	CUT IN: (date)	DURATION (days)	MGT Accumulated
130617-001-0369	36	10/8/2012	252	24.9
130617-002-0369	36	10/8/2012	252	24.9
130617-004-0386	158	4/15/2013	63	27.3
130617-005-0411	158	5/23/2013	25	10.8
130617-006-0411	158	5/23/2013	25	10.8
130617-007-0413	158	5/26/2013	22	9.5
130617-008-0413	158	5/26/2013	22	9.5
130617-009-0428	158	5/22/2013	26	11.3
130617-010-0428	158	5/22/2013	26	11.3
130618-001-0453	194	6/7/2013	11	5.8
130618-002-0453	194	6/7/2013	11	5.8
130618-003-0449	158	5/20/2013	29	12.6
130618-004-0449	158	5/20/2013	29	12.6
130618-005-0437	158	5/22/2013	27	11.7
130618-006-0437	158	5/22/2013	28	12.1
130619-001-0400	158	4/16/2013	64	27.7
130619-002-0400	158	4/16/2013	64	27.7

The CWR data analysis confirms that the maintenance of track conditions at permanent joints (insulated joints) was significantly better than the maintenance at temporary joints which were intended to be eventually welded. Rail joints supported by concrete ties were found to be better maintained than rail joints on wooden tie track. Also, a relationship might exist between rail end misalignments and deteriorated track conditions at temporary joints.

Although the sample is limited in the number of failed joint bar locations and contains only five locations, all except one were found in location with either deteriorated vertical support conditions, compromised rail end conditions or combination of both. This is in agreement with a conclusion made on much larger sample from Class 3 JNT territory.

The analysis of the intact joint bar sample showed the value in collecting data at these locations as well. Even though the exact amount of accumulated tonnage at the investigated intact joint bars cannot be obtained since many of temporary joints may be reused many times for rail defect repairs, the analysis showed a correlation between the deteriorated track and rail end conditions and the duration that temporary joints existed in the specific location of track.

5.3 Comparison of Failure Rates

A comparison of failure rates in the CWR and JNT territories where longitudinal rail stresses are expected to be significantly different can be used to evaluate the possible influence of rail stresses on joint bar failures. Rail joint on CWR territories are subjected to significantly higher tensile stresses than joints on JNT territories. Therefore, if tensile stresses are a significant contributing factor, the rail joint failure rates on CWR should be significantly higher.

During the field surveys, the total number of rail joints inspected and defects identified by JBIS or walking visual inspection were:

- ~800 rail joints inspected and 6 defects identified on 324 miles of CWR
- ~81,500 rail joints inspected and 415 defects identified on 312 miles of JNT

Note that the numbers of total identified defects during the survey inspections are higher than the number of investigated defect locations where field conditions were documented by the survey team—5 defect locations in CWR and 123 defect locations on jointed track. Some identified defect locations could not be investigated by the team due to various time constrains, limitations of available track authority, train traffic, etc. Many of these locations were not repaired on the day of the inspection for the same reason, a slow order was placed on the location and defect was left to be repaired at later time.

In CWR territory, one defect was found per every 800/6 = 133.3 rail joints (0.75% failure rate). In JNT territory, one defect was found per every 81,500/415 = 196.4 rail joints (0.50% failure rate). The failure rate in CWR was roughly 50 percent higher than in surveyed JNT territory.

Field observations and analysis of the collected field data did not indicate that longitudinal rail movements or stresses had a direct impact on joint failure. Longitudinal rail movements affected long sanctions of track with both failed and intact joints, while other conditions, such as vertical and lateral movement, were localized to the failed locations. However, longitudinal movement often resulted in skewed crossties and narrow (tight) gage at some of the joints, which led to loose fasteners, reduced lateral restraint, and increased tie spacing under the joints. In addition, the rail at four of the failed rail joint locations in CWR appeared to be in compression with the gap between the rail ends fully or almost fully closed even though the measured rail temperature was only between 89 °F and 100 °F in those instances.

Track and rail end conditions, especially at temporary joints created by the installation of repair rails or other maintenance activities at significant portions of CWR territory were poor despite these zones (mainly on test zone A and part of test zone F5) being overwhelmingly Class 4 track. Specifically, documented rail end conditions at temporary joints in CWR (with the exception of test zone E) were more significant than in jointed territory composed of lower track classes. Figure 65 presents 95% confidence intervals calculated from all data, both intact and failed locations combined for the JNT and CWR samples. Even when permanent rail joints and all joints from test zone E with very good track and rail end conditions were included, the CWR sample showed comparable influence of rail end misalignments.

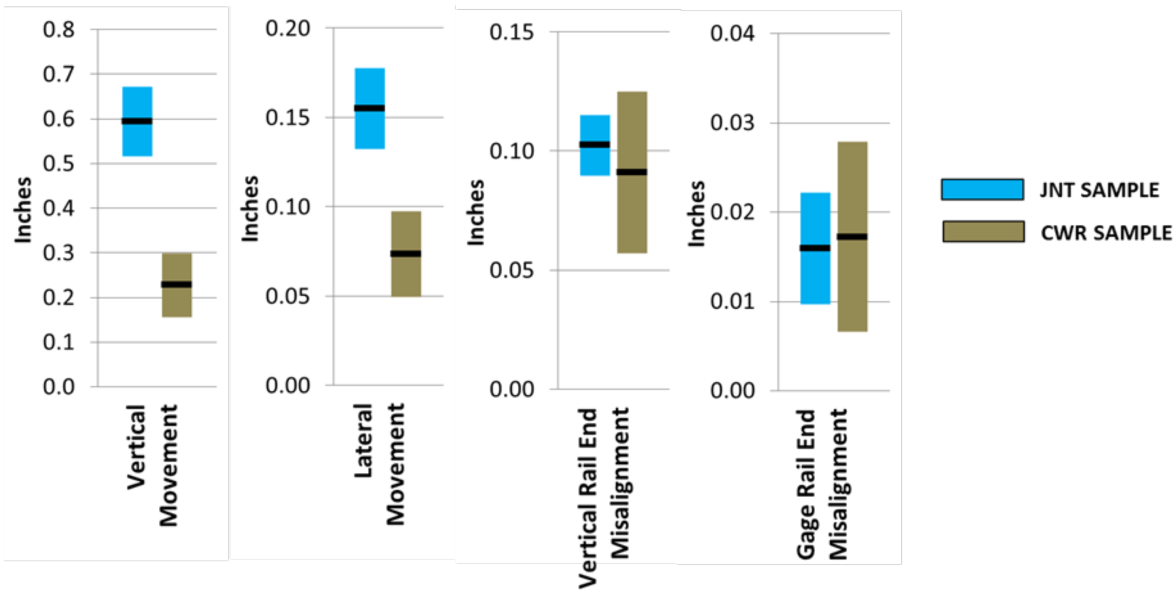


Figure 65. Comparison of Joint Support and Rail End Conditions on JNT and CWR Samples

Although failure rates at CWR were indeed higher, it may be also a result of the less than optimum support and especially rail end conditions at temporary joints that were created in CWR by the installation of repair rails or other maintenance activities.

Therefore, a definite conclusion regarding possible influence of rail stresses on joint bar failure may not be drawn from the available data.

6. Investigation of Repeated Joint Failures

One of the most important aspects of the study into the role of various track and operational factors contributing to joint bar failure was to monitor field conditions at locations where rail joints fail repeatedly. For this purpose, the seventh and last field survey in May 2014 was conducted on test zone C, where the third field survey took place in July 2012, even though the surveyed territories in 2012 and 2014 did not completely overlap. In this manner, the field conditions were documented each time a potential repeated failure was detected and repaired. However, no repeat rail joint failures were identified during the field investigations.

In addition, two of the participating railroads provided records of past JBIS inspections for selected territories that were visited during the study's field activities. The records were analyzed to determine whether the investigated joint locations with joint bar defects had failed repeatedly before or after the survey. Also, field conditions associated with repeat failures are known and documented at one point of the repeat failure cycle. This chapter presents highlights of the analysis and summarizes the results. A separate report was produced by ENSCO to provide more detailed descriptions of the past JBIS inspection records analysis.

The records were provided for test zones B1, C, and D. The testing history and record availability for these zones is:

- Test zone B1 – field survey conducted in May 2012:
    - August 2013 (Records available)
    - October 2012 (Records available)
    - May 2012 (Records available) – Field Survey Conducted
    - November 2011 (Records available)
    - July 2011 (Records available)
    - *November 2010 (Records not available)*
    - June 2010 (Records available)
- Test zone C – field surveys conducted in July 2012 and May 2014:
    - May 2014 (Records available) – Field Survey Conducted
    - November 2013 (Records available)
    - February 2013 (Records available)
    - July 2012 (Records available) – Field Survey Conducted
    - September 2011 (Records available)
    - June 2011 (Records available)
    - *January 2011 (Only partial records available)*
    - August 2010 (Records available)
- Test zone D – field survey conducted in March 2013:
    - August 2013 (Records available)

- March 2013 (Records available) – Field Survey Conducted
- March 2012 (Records available)

The JBIS records contain information about the location of detected joint bar defects as milepost-foot and as GPS coordinates. They also include the type of detected defect (center, quarter, bolt defect), the approximate magnitude of the defect (full break of length of the crack), and specify the affected joint bar (left or right rail, field or gage side). System camera images of the individual joint bars were available for the most recent inspections in test zones B1 and C.

First, candidate locations for repeat failures were identified with GPS coordinates. Locations of defects investigated during the field surveys and defects listed in the JBIS inspection records with distance between them calculated from GPS coordinates is less than 40 feet, roughly a length of one rail segment, are considered candidate failure locations. A total of 27 candidate locations were identified. The candidate locations were confirmed or rejected based on occurrence on left or right rail and review of available camera images to ensure the defect was actually present on the rail joint. In addition, all 14 candidate locations containing quarter defects on Class 2 track were rejected.

The reason to exclude quarter defects on Class 2 track from the list of possible repeat failures is that it is not possible to definitively confirm that they are truly repeat failures. Federal regulation does not require the track owner to replace quarter defects in Class 1 or 2 track. If a double full quarter break defect occurs, with quarter full breaks present both on gage and field side bars, a bolt behind the defect is not effective. Since two bolts on each rail are required on Class 2 and higher by Federal standards, railroads can reduce the track to Class 1 or replace the failed bars.

All the repeat failure candidates, including quarter defects, were located at test zone B1. Since the test zone was Class 1 and 2 tracks, single quarter breaks were not replaced and double quarter breaks defects were only replaced when found in the Class 2 section of the test zone. This practice was probably followed during other JBIS inspections as well. Also, JBIS system sometimes do not report detected single quarter defects on Class 1 and 2 at all. Whether single quarter defects are reported or not by JBIS system on Class 1 and 2 tracks is based on a decision of local track owner personnel on a particular day of the inspection. Therefore, it is very likely that the candidate locations containing quarter defect locations are actually the same defects detected again rather than repeated failures.

Candidates with defects on opposite rails were rejected. Candidates with calculated distances larger than 10 feet where accuracy of GPS receiver could mean that two different rail joints were paired were also excluded, unless system camera images were available for review to confirm the defects occurred on the same rail joint. Defects on opposite bars at the same rail joint were considered as repeat rail joint failures. The number of confirmed repeat failures was reduced to four cases listed in Table 16.

Table 16. List of Identified Repeat Rail Joint Failures

Repeat Failure ID	Joint ID	Rail End Batter	Vertical Movement
01-B-2	120516-006-0571	0.06x2 & 0.07x3	2
02-C-3	120726-001-0404	0.18x6 & 0.18x8	1.75
03-C-3	120726-006-0411	0.1x8 & 0.12x6	1.5
04-D-3	130326-006-0690	0.1875x23 & 0.096x1.75	1.75

TEST ZONE TRACK CLASS

Figure 66 shows the time line of JBIS inspections and identified defects at the four repeat failure locations. In repeat failure ID 02-C-3, the rail joint failed three times in a span of only 3 1/2 years. All four repeat failures occurred in jointed track territory.

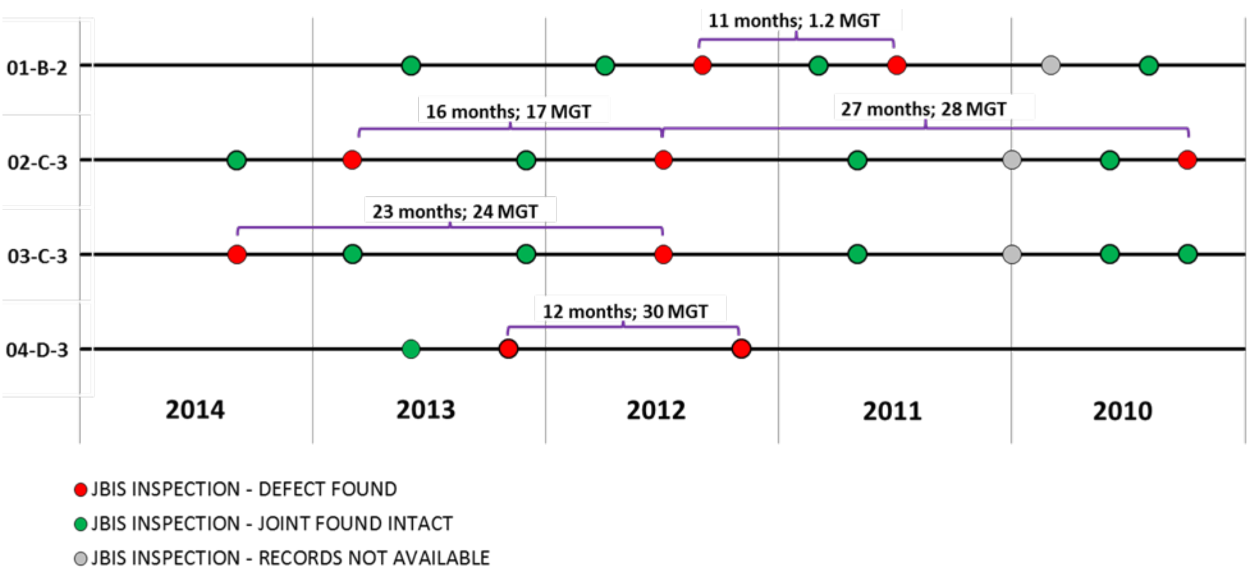


Figure 66. Timeline of Repeat Failures

A repeat failure (ID 02-C-3) is confirmed by a review of system camera images in Figure 67 through Figure 71.

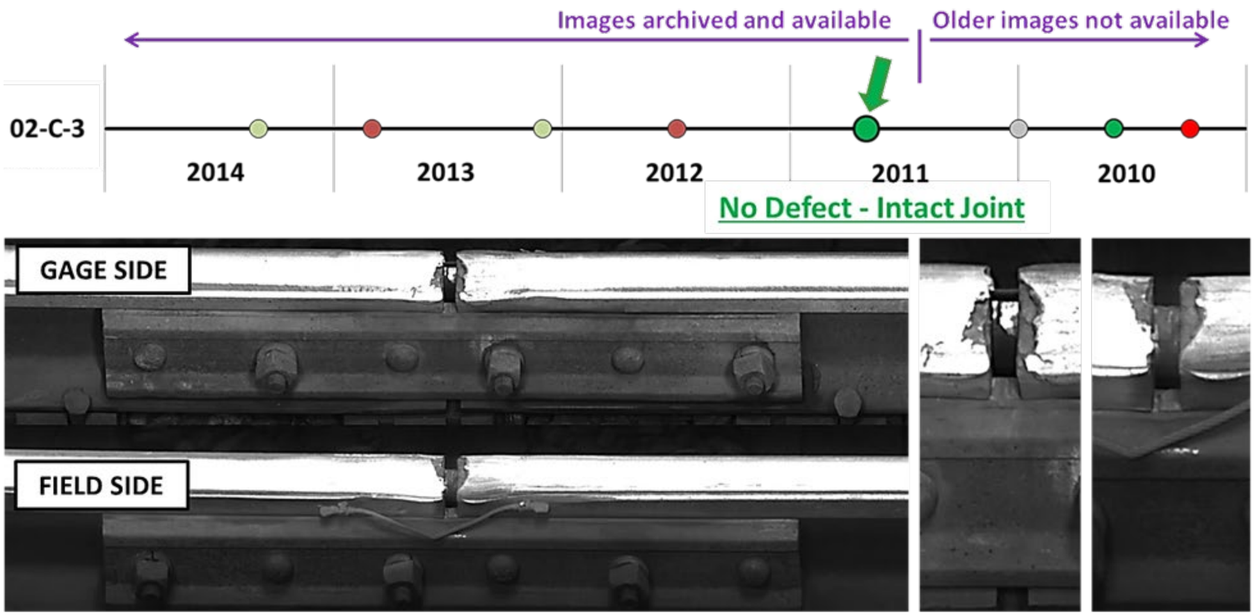


Figure 67. Repeat Failure Location 02-C-3—September 2011 JBIS Camera Image, Joint Intact

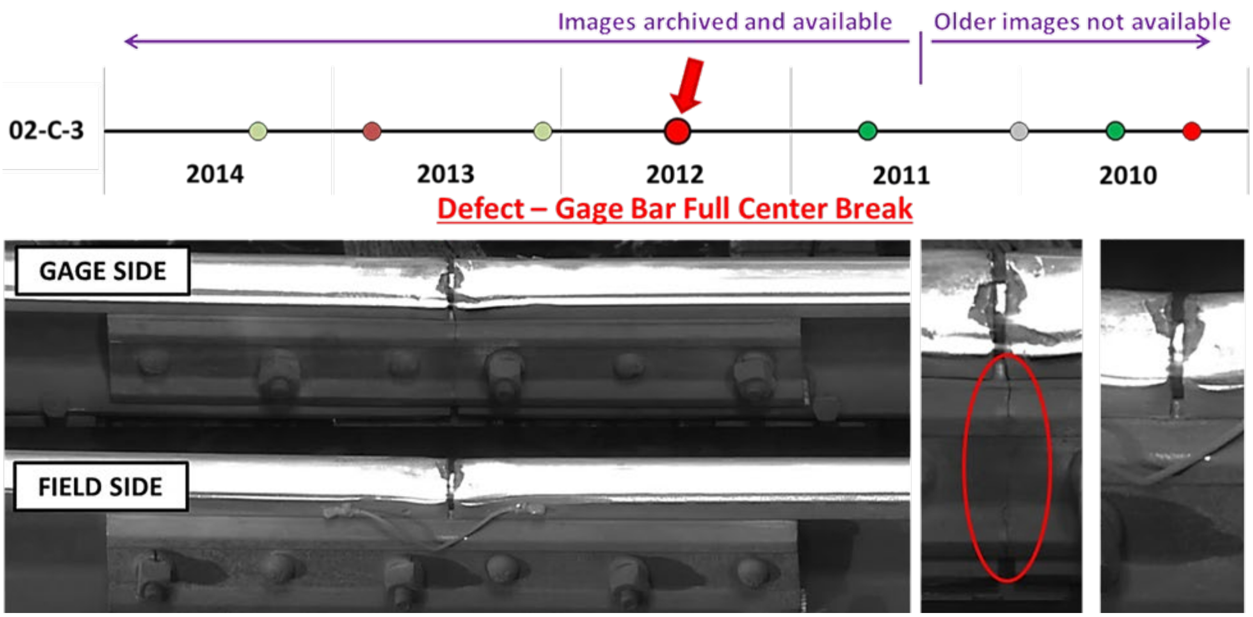


Figure 68. Repeat Failure Location 02-C-3—July 2012 JBIS Camera Image, Joint Failed

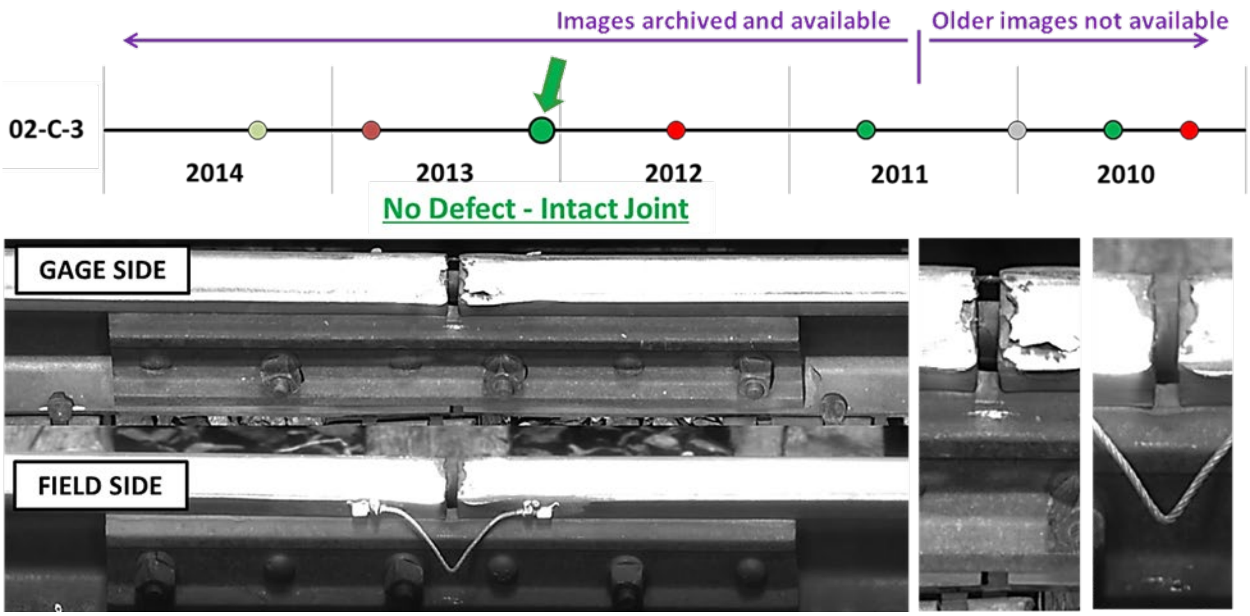


Figure 69. Repeat Failure Location 02-C-3—February 2013 JBIS Camera Image, Joint Intact

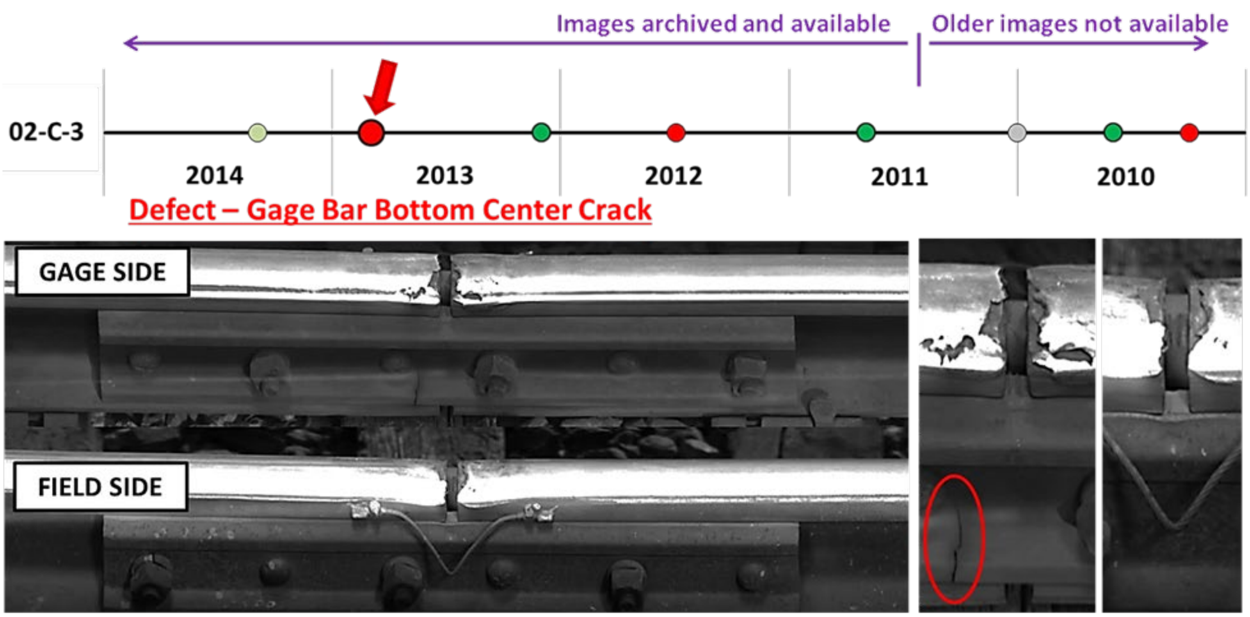


Figure 70. Repeat Failure Location 02-C-3—November 2013 JBIS Camera Image, Joint Failed

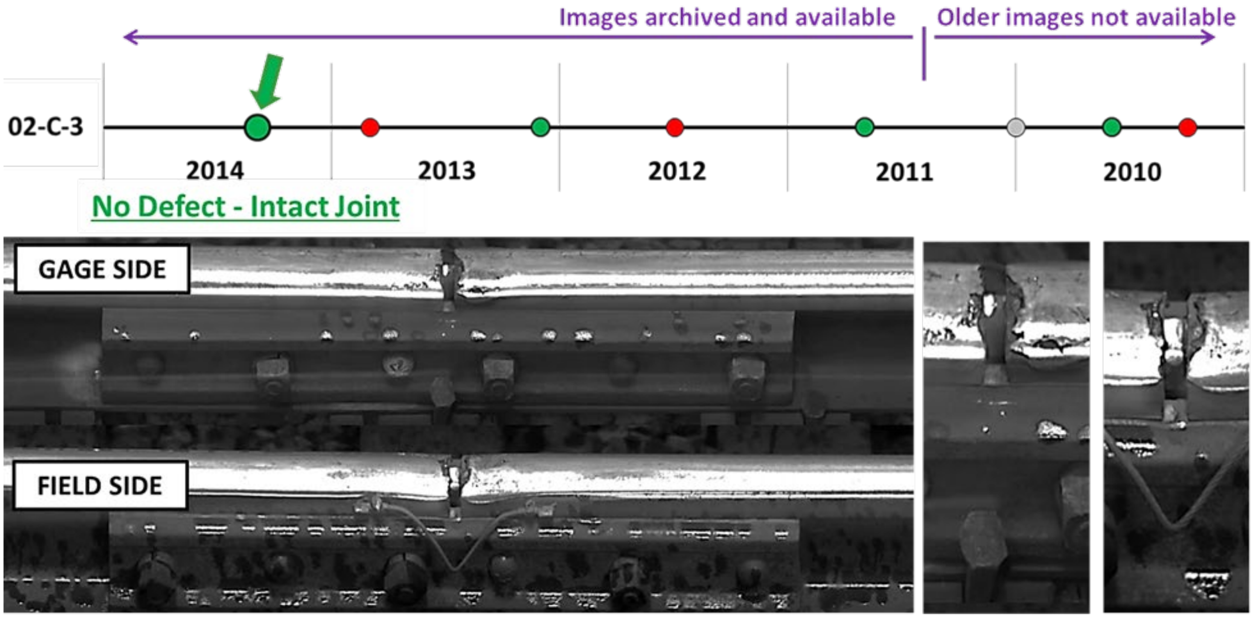


Figure 71. Repeat Failure Location 02-C-3—May 2014 JBIS Camera Image, Joint Intact

On the other side, one example of a rejection of a possible candidate location on Class 3 jointed track at test zone C is given in Figure 72 through Figure 75. This location was chosen as an example because during the review of the system camera images another interesting finding was made.

Figure 72 and Figure 73 show the gage and field side views of the candidate location as documented during July 2012 (the third field survey), when a top center crack on a gage side bar was detected. In Figure 73, the presence reference mark indicates that the rail joint was introduced into the track when a rail plug was installed as a repair for a rail defect. The two middle bolts missing and the absence of bolt holes indicated the temporary nature of joint intended to be welded in the future. The rail end battered down into an abrupt ramp from originally mismatched rails can be also seen both figures.

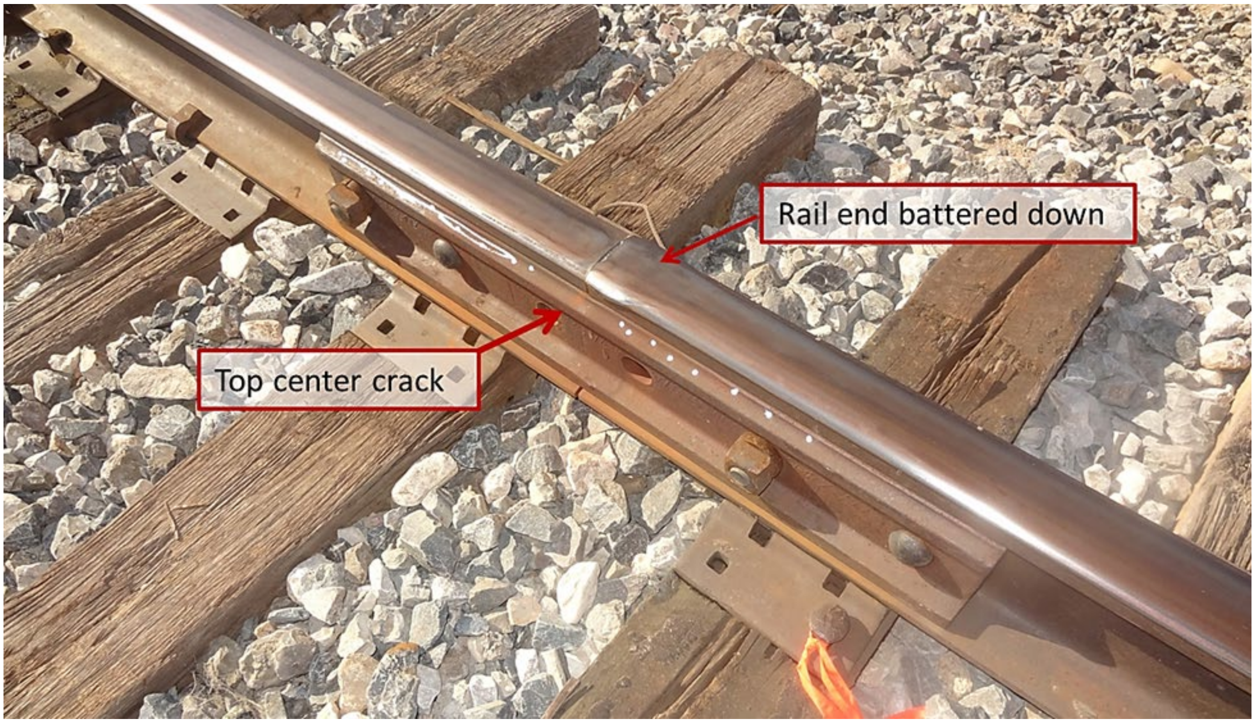


Figure 72. Repeat Failure Candidate 120727-004-0458—Field Conditions, Gage Side View

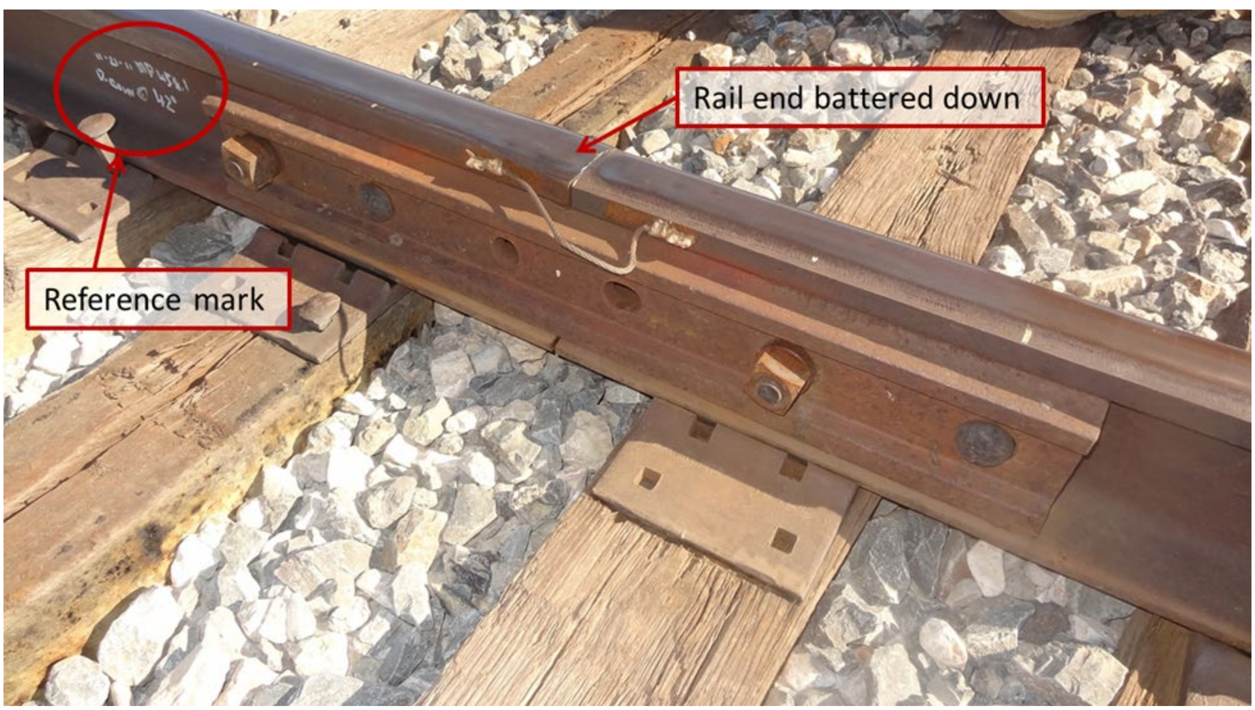


Figure 73. Repeat Failure Candidate 120727-004-0458—Field Conditions, Field Side View

Analysis of JBIS inspection records reveal a joint failure in November 2013 at a location approximately 10 feet away from the with GPS coordinates of the defect location that had been documented in July 2012. Figure 74 shows the JBIS camera image of the failed joint taken during the November 2013 inspection.

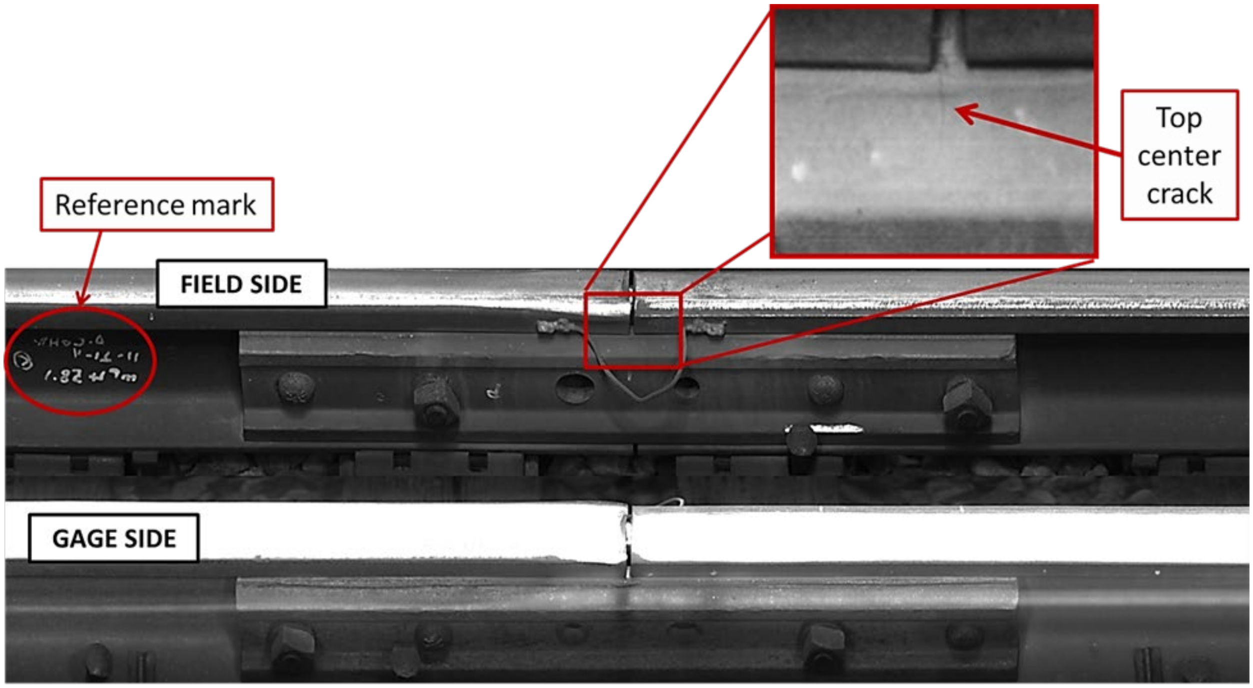


Figure 74. Repeat Failure Candidate 120727-004-0458—November 2013 JBIS Camera Image, Failed Joint

It is obvious that the November 2013 defect occurred at a different rail joint than the July 2012 defect. Most importantly, the reference mark does not match the one documented in Figure 73. A JBIS camera image of an adjacent intact rail joint to the November 2013 failure is presented in Figure 75. This intact location is the actual rail joint that failed in July 2012 as indicated by the matching reference marks.

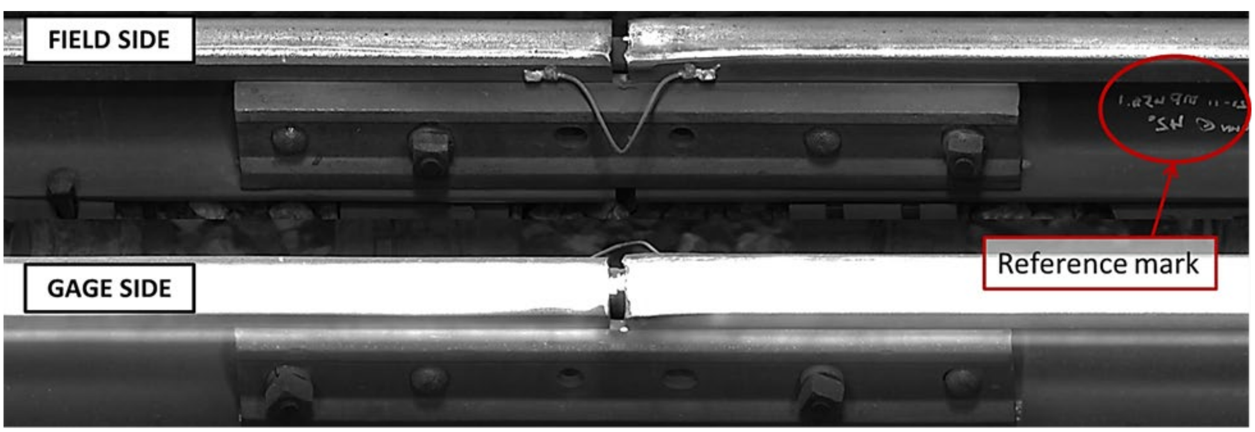


Figure 75. Repeat Failure Candidate 120727-004-0458—November 2013 JBIS Camera Image of Adjacent Intact Rail Joint

This repeat failure candidate was therefore rejected. During the process, however, it was discovered that two temporary rail joints cut into track most likely as a consequence of rail repair failed within a relatively short time period since the rail plug installation. A closer look at the documented reference marks revealed that the repair rail plug was installed in November 2011, only 8 months prior to the first temporary joint failure. The second temporary rail joint failed exactly 2 years after it was cut in the rail. The two temporary joints therefore failed after accumulating only ~7 MGT and ~24 MGT, respectively while installed in this particular location.

Figure 76. General Field Conditions in the Vicinity of a Recently Installed Rail Plug

Figure 76 illustrates the general field conditions at the rail plug and both the temporary rail joints as encountered during the July 2012 field survey. The first failed rail joint contained 0.5-inch vertical movement in combination with 0.13 inches of an abrupt rail end ramp. The second rail joint, which subsequently failed in November 2013, also appears to contain significant rail end ramp and insufficient ballast, which suggests at least some vertical movement based on the pictures in Figure 74 and Figure 76. Insufficient vertical support in combination with deteriorated rail end conditions, specifically abrupt rail end ramps resulting from an original tread mismatch battered down by repeated wheel loads appear to be the main contribution factor to failure in this case.

The same contributing factors were identified on the CWR sample, based on the analysis of the temporary and permanent joints (both failed and intact). In addition, it is interesting to note in Figure 76 that the rail ends were fully closed. The air temperature on the day of the survey was 95 °F. The rail plug was installed in November 2012 at a temperature of only 42 °F based on the rail reference markings. When we consider that that the location was at JNT territory and the joints allowed rail ends to move throughout the annual temperature cycle as visible in in Figure 72 through Figure 75 it is safe to assume that the two failed temporary joints were not subject to significant tensile stresses while installed in this particular location.

Returning to the four-identified rail joint failures, reviews of the July 2012 surveys shows that all the joints were at locations that had significantly deteriorated vertical support with large vertical movements and large values of profile and crosslevel under load. Three of them, all at Class 3 JNT, contained significant rail end batter. The remaining repeat failure with much lesser magnitude of rail batter was located on Class 2 JNT. The four locations also contained 0.125

inches to 0.25 inches lateral movement. Bolt conditions were good; only one location had one bold missing. The four locations are shown in Figure 77 through Figure 80.

a) Field Side View

b) Gage Side View

Figure 77. Repeat Failure 01-B-02—Field Conditions

Figure 77 shows field conditions at repeat failure 01-B-02. The same defect, a full center break, occurred at a field side bar in July 2011 and May 2012. Survey in November 2011 did not find a defect at this rail joint. The joint accumulated ~1.2 MGT between the two failures in 11 months. It is most likely that an older previously long toe bar recovered from a different joint location was used when the original failed bar was replaced. This defect was found at a location with much deteriorated support conditions. The ballast was extremely contaminated, ties were split with large plate cutting and pumping, and tie plates were loose. Vertical movement was 2.0 inches at this location. This location contained the most severe support and track surface geometry conditions encountered during the second field survey in test zone B1. Moderate rail end batter 0.07 inches high and gage mismatch of 0.01 inches was recorded. Bolts conditions were good with all bolts intact.

a) Field Side View

b) Gage Side View

Figure 78. Repeat Failure 02-C-03—Field Conditions

Figure 78 shows field conditions at failure location 02-C-03, where the joint failed three times within 3 1/2 years. One defect, a full center break, occurred on gage side bar in April 2010 and July 2012, while in November 2013, a 50 percent bottom center crack occurred on gage side bar. The joint accumulated ~28 MGT between the first two failures in 27 months and ~17 MGT in the 16 months between the second and third failure. This defect was also found at a location with deteriorated support conditions. The ballast was moderately contaminated, ties were affected by plate cutting and pumping, and tie plates were loose. Vertical movement was 1.75 inches at this location and significant rail end batter 0.18 inches high was recorded, but bolt conditions were good with all bolts intact. This location contained one of the most severe geometry, track support and rail end conditions encountered during the third field survey in test zone C.

a) Field Side View

b) Gage Side View

Figure 79. Repeat Failure 03-C-03—Field Conditions

Figure 79 shows field conditions at repeat failure 03-C-03. Two different defects occurred, a full quarter break on gage side bar in July 2012 and a 20 percent top center crack on field side bar in May 2014. The joint accumulated ~24 MGT between the two failures in 23 months. Support conditions were again deteriorated in this location. The ballast was fouled, ties were split and pumping, one tie plate was missing, and other plates were loose. Vertical movement was 1.5 inches at this location. Significant rail end batter (0.12 inches high) was also measured. Bolt conditions were good with all bolts intact. This location again contained one of the most severe geometry, track support and rail end conditions encountered during the third field survey on test zone C.

a) Field Side View

b) Gage Side View

Figure 80. Repeat Failure 04-D-03 – Field Conditions

Figure 80 shows field conditions at repeat failure 04-D-03. Two different defects occurred: 1) A full center break on field side bar combined with a 20 percent top center crack on gage side bar in March 2012 and 2) a 10 percent top center crack on field side bar in March 2013. The joint accumulated ~30 MGT between the two failures in 12 months. Support conditions were also deteriorated in this location. The ballast was heavily fouled, ties were split and pumping, and tie plates were loose. Vertical movement was 1.75 inches and significant rail end batter (0.188 inches high was also measured. One bolt was missing. This location contained one of the most severe geometry, track support and rail end conditions encountered during the fifth field survey on test zone D.

Plots in Figure 81 through Figure 84 present the field conditions encountered at the locations of repeat failures in respect to conditions at the other documented rail joints.

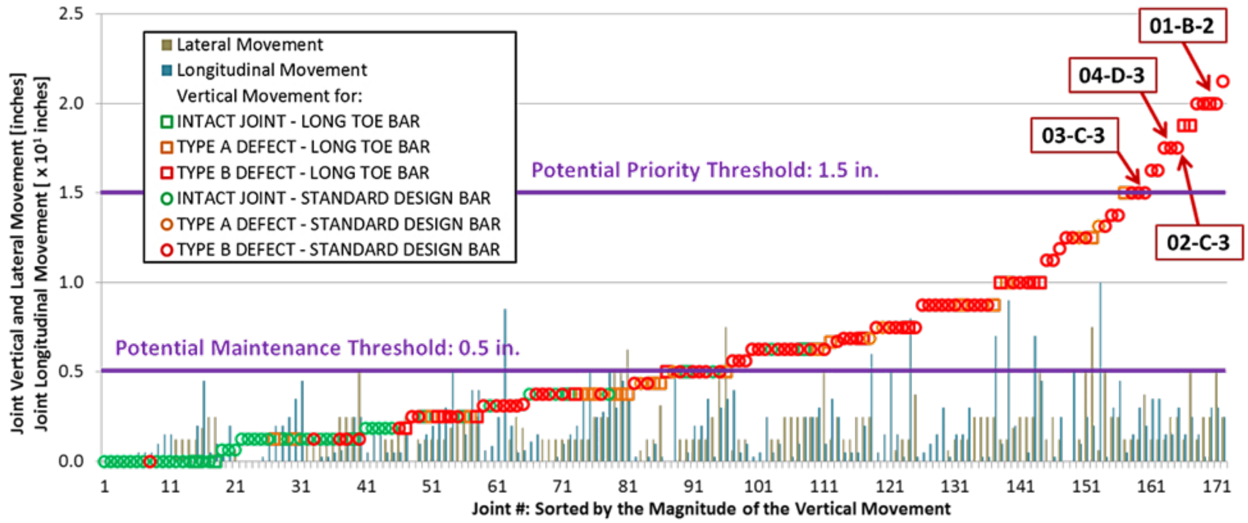


Figure 81. Joint Movements at Repeat Failure Locations in Respect to Combined JNT Sample

Rail joint movements are summarized in Figure 81. The four repeat failures occurred at locations with the highest vertical movements (magnitudes above 1.5 inches) encountered during the entire study. There appears to be a very distinct separation between intact and failed joint locations. Except for two intact rail joints with a vertical movement of 0.7 inches, all the locations with vertical movement larger than 0.5 inches contained a failed joint bar. Therefore, two purple lines in the plot represent two vertical movement levels of concern regarding rail joint failure. The first potential maintenance threshold of 0.5 inches indicates locations where a possibility of a joint failure exists and maintenance efforts would be beneficial. The second potential priority threshold (1.5 inches) identifies locations where the risk of imminent joint failure is much higher and more immediate remedial action or maintenance efforts should be performed.

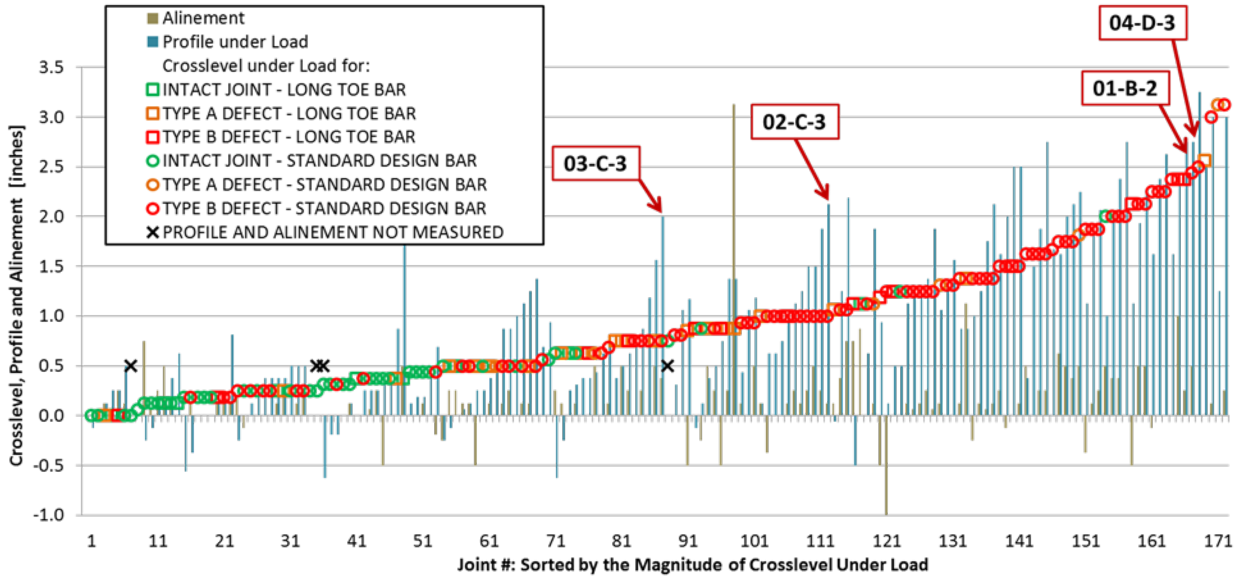


Figure 82. Track Geometry Parameters at Repeat Failure Locations in Respect to Combined JNT Sample

Figure 82 presents three track geometry parameters; crosslevel under load, profile under load, and alinement. The four repeat failure locations contain adverse profiles under load and in lesser extent crosslevels under load as well. Alinements do not exceed the values found at the majority of the other investigated locations.

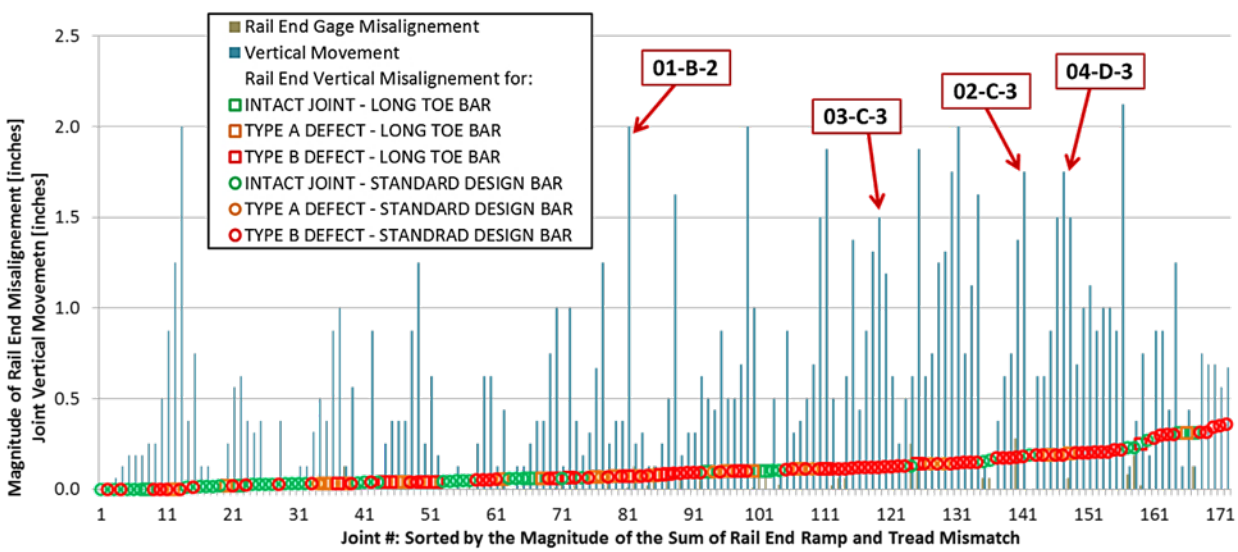


Figure 83. Rail End Conditions at Repeat Failure Locations in Respect to Combined JNT Sample

Figure 83 illustrates the state of rail end conditions at the four repeat failure locations in comparison to rail end conditions encountered throughout the surveys. Three repeat joint failures in Class 3 track contain significant rail end misalignments at the top 30 percent of locations with the combined JNT sample.

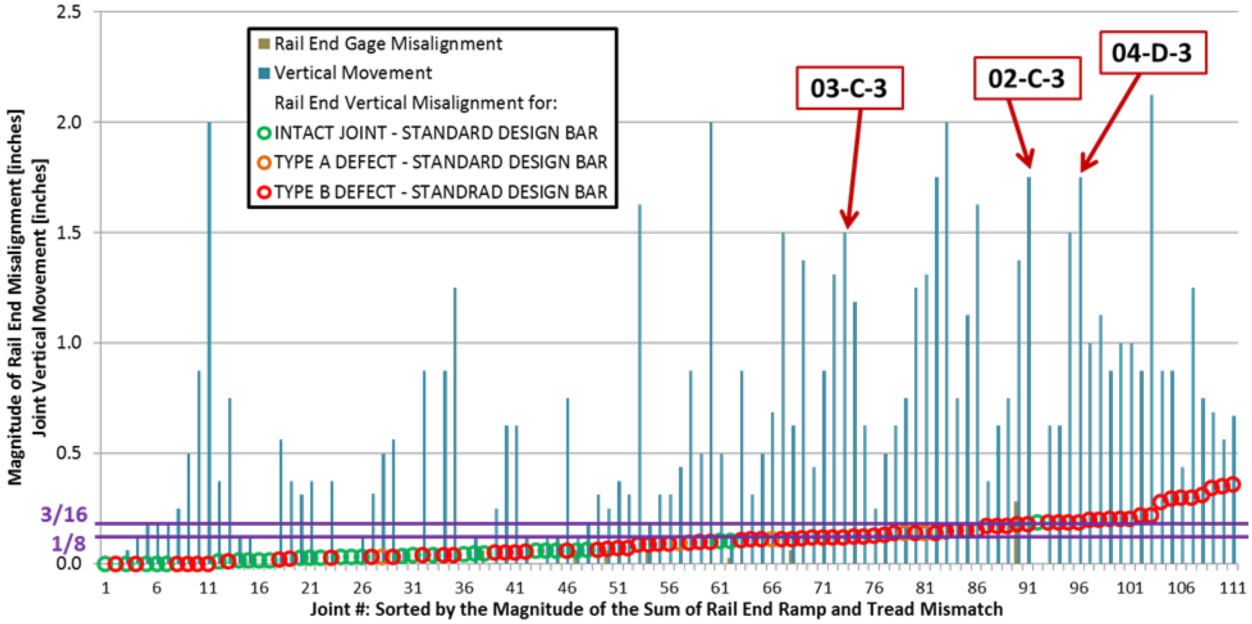


Figure 84. Rail End Conditions at Repeat Failure Locations in Respect to Class 3 JNT Sample

When we look at rail end conditions at Class 3 repeat failure locations as compared to the Class 3 track JNT sample (Figure 84), again the misalignments belong to the top third of observed values. They do not, however, belong to the absolute highest encountered values as was the case with magnitudes of joint vertical movements. Two of the repeat locations contained rail end misalignments roughly at 3/16 inches, which is the current industry practice rail end batter standard for Class 4 track and above. Based on the analysis results this appears to be an appropriate priority threshold indicating higher risk of imminent joint failure when applied at track Class 3 and above.

The findings of repeat rail joint failures analysis agree with the overall conclusions from the analysis of the field survey data. Deteriorated joint support resulted in large vertical movements regardless of track class and compromised rail end conditions at Class 3 JNT and CWR territories were identified as major contributing factors to joint bar failure.

7. Short Chord MCO at Failed Joint Locations

Vertical movement due to deteriorated joint support was identified as an important track-related factor that contributed to rail joint failure regardless of track class. Identifying locations with excessive localized vertical movement could help railroads prioritize maintenance efforts. Improving deteriorated track support conditions would reduce the risk that joint failures will develop and help prevent repeated joint failures in places where defects were already present and joint bars were replaced.

A very preliminary analysis of track geometry data, which was collected as part of the FRA Office of Railroad Safety's Automated Track Inspection Program (ATIP) in test zone C 3 months prior to the July 2012 field survey, showed that shorter chord length track surface geometry measurements, or short MCOs, have the potential to successfully identify joint locations with poor support conditions without producing large amounts of exceptions.

Short MCO measurements are not identical to vertical movements but contain a significant proportion of vertical movements, especially at locations where deteriorated track support and vertical movements are localized. Unless very large static short chord track surface deviations are present, short MCOs usually return values smaller than vertical movements, since end points of the chord are subject to some vertical movement as well. This is especially true at joint locations where the deflection basin is wide affecting multiple ties on either side of the joints centerline as observed frequently during the field investigations. A 10-foot MCO set at a 0.675 inches trigger threshold was able to identify over 50 percent of rail joint locations with measured vertical movement of the same magnitude. This represents 165 events over the surveyed portion of test zone C, which is an acceptable amount. If the short MCO was geared only towards detecting locations of extreme vertical movements, for example vertical movements larger than 1.5 inches where the risk of imminent joint failure or repeat failure is much higher (as shown in Section 6), the threshold can be increased and then reduce the number of triggered events.

So far, analysis with the short MCO is encouraging, despite the fact that the ATIP survey took place approximately three months prior to the site field visit where the ground truth data was gathered. The delay has a negative impact on the correlation between the short chord MCO and vertical movements because vertical track support conditions and track surface are subject to rapid progression, especially at joint locations where adverse track surface is already present and increased vertical wheel loads can be anticipated. Track surface can deteriorate in a matter of days or weeks. Therefore, many joint locations with poor support probably developed higher vertical movements during the field visit than they exhibited while the ATIP survey was conducted, and therefore could not be detected by the short chord MCO. In addition, at locations where ballast was contaminated with fine soil particles and where track drainage system may be compromised (such as chronic mud spots) weather conditions and moisture levels may have had a significant influence on the recorded surface measurements, in part because the subgrade can provide improved support during dry conditions.

Two examples of the 10-foot short chord MCO as it was calculated from the ATIP data for both rails are in Figure 85 and Figure 86. The first example shows the short chord MCO at a failed joint location with a vertical movement which was measured as 1.75 inches 3 months later. This is also the location of the identified triple repeated joint failure described in Section 6. The second example shows short chord MCO at another failed joint location with measured movement at 1.5 inches 3 months after the collection of ATIP data.

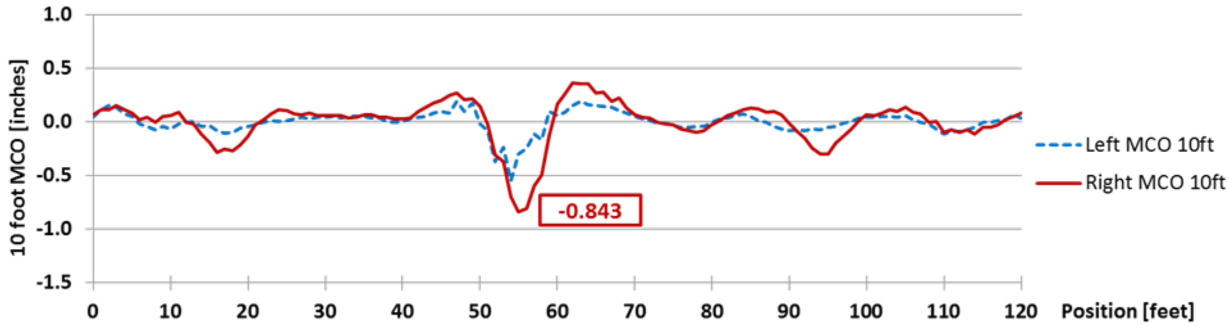


Figure 85. 10-Foot MCO at a Failed Joint Location—Example 1

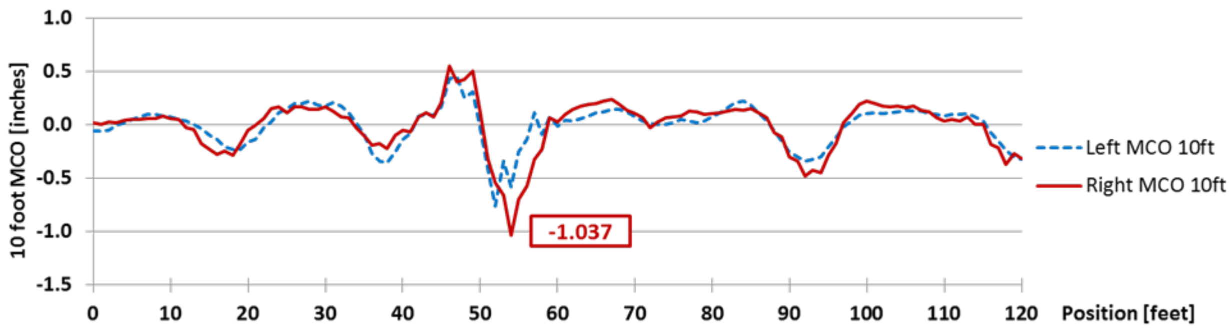


Figure 86. 10-Foot MCO at a Failed Joint Location—Example 2

Although the preliminary results are promising and demonstrate that the short chord MCO may be able to identify locations with deteriorated rail joint vertical support, additional work would be necessary to conclusively confirm that the short chord MCO is a detection method. To properly evaluate the correlation between vertical movement and chord MCO, it is necessary to analyze track geometry data field measurements. These measurements need to be collected within a short time frame of one another to minimize possible rapid deterioration of vertical track support at rail joints where adverse track and rail end conditions already exist. More analysis would also be required to determine the appropriate chord length and detection thresholds to achieve the highest detection rates while resulting in a minimal amount of triggered events.

8. Conclusion

During the initial stages of the study, a detailed methodology for the field data collection process and data analysis was developed and refined.

Seven field evaluation surveys were conducted in 2012–2014 in close cooperation with three participating Class I railroads. Surveys took place in a wide range of territories in eastern and western US with various inspection frequencies, track classes (Classes 1–4, X), MGT, traffic, and rail types. A total of 636 miles were covered, with an approximate even split between CWR and JNT territories.

Overall, a sample of 230 locations was collected:

- Sample CWR territory (Class 3, 4—tonnage 21–194 MGT):
  - 5 defect locations
  - 53 intact bar locations
- Sample JNT (Class X, 1, 2 and 3—tonnage 0.1–15 MGT):
  - 123 defect locations
  - 49 intact bar locations

Joint bar data on CWR and JNT territories were separated and analyzed independently from one another due to the inherent differences in the thermal stresses and the purpose of the installation on each type of territory.

Detailed measurements and observations were recorded at each failed or intact joint examined. The information collected includes:

- Rail end conditions such as rail end gap, batter, ramp, and gage and tread mismatch
- Joint lateral and vertical movement
- Track geometry such as gage, crosslevel, and profile
- Bar type (head-free, head-contact, or long toe), bar design (standard, compromise, or insulated) and length
- Bolt condition
- Failure mode and location of cracks or breaks
- Longitudinal bar and rail movement
- Joint bar offset from rail ends
- Physical location such as tangent, curve, super elevation, and proximity to turnouts, culverts, bridges, highway/rail grade crossings, etc.
- Track speed, class of track, global positioning system (GPS) coordinates, tonnage and other general information
- Rail and ambient temperatures and related data such as information from rail installation reference marks

- Crosstie type (timber or concrete) and crosstie condition
- Distance to first effective tie
- Fastener and anchor type and condition
- Ballast and drainage conditions
- Maintenance history where available

Analysis of the data reveals the following:

- All five encountered defects on CWR territory were top center cracks on temporary rail joints with standard design bars, which were introduced to repair the rail.
- On JNT territory's standard design head-free joint bars, the overwhelming majority of the failures were center defects and 59 percent of the center defects were top center cracks.
- The quarter defect was the predominant failure mode on long toe (angle) type bars. Most often a full quarter break (almost 70 percent) typically initiated from the spike holes of this particular design was found. Surprisingly, three out of eight partial quarter cracks on the long toe (angle) bars were initiated from the top of the bars and not from the spike hole at the bottom of the bar as expected.
- Vertical movement as a result of deteriorated joint support conditions was identified as the most prominent contributing factor to rail joint failure, regardless of track class. The most important observation, which was made consistently throughout all the field surveys and supported by the data analysis, was that localized deteriorated vertical track support was present at the majority of failed rail joint locations, compared to very good vertical track support conditions at random intact rail joints. Based on the field observations, the leading factors contributing to the vertical movement were as follows:
    - "Swinging" ties – spaces between the bottom of the rail and the top of the tie plate or crosstie
    - Missing, loose, or broken tie plates and plate cutting
    - Insufficient ballast (lack of tamping)
    - Fouled ballast (mud pumping)
    - Rail profile (batter)
- A large number of failed joints showed vertical movements exceeding 0.5 inches, which indicates that a maintenance threshold at this level could reduce the possibility of joint failure and extend joint life. Four identified repeated rail joint failures contained excessive vertical movements exceeding 1.5 inches, which indicates that a remedial action at this priority threshold would reduce the risk of imminent joint failure.
- To a lesser extent, lateral movement also appears to be contributing factor at failed joint locations regardless of track class.
- Rail end conditions such as rail batter, ramp, and rail end mismatch were identified to be contributing factors to joint bar failures at higher track classes (Class 3 and above).

- Deteriorated rail end conditions on jointed track were overwhelmingly represented by rail end batter, fairly even for both rail ends, developed gradually by repeated wheel impact loads at initially well-matched rail ends. On the other hand, rail end conditions on CWR territories consisted mostly of tread mismatches or abrupt rail end ramps. These mismatches were created by installing new or full ball repair rail sections in track with worn rail.

  In some cases, mismatched rail ends were than battered down by repeated wheel impact loads, which resulted in short and abrupt rail end ramps. Static crosslevel and track profile does not appear to be an indicator of joint bar failure. However, larger crosslevel and track profile under load measurements were observed at failed joint locations as consequence of vertical deflections of the rail at these locations.

- Most failed joints were found that showed tread mismatches or abrupt rail end ramp with ramp angles of 2–7 degrees exceeding 1/8 inch on Class 4 track. On Class 3 track, many failed joints exhibited either tread mismatch, rail end ramp or batter both with slopes over 1 degree exceeding 3/16 inch.
- Rail end conditions should be maintained within the currently defined regulatory limits on rail end mismatches (3/16 inch on Class 3 track; 1/8 inch on Class 4 track) and within the current non-regulatory maintenance 3/16-inch standard for rail end batter used by several railroads on Class 4 track and above. The results indicate that this rail end batter threshold value should also be applied on Class 3 track.
- The abruptness of the ramps should also stay within the current non-regulatory maintenance standard requirements used by several railroads for maximum rail end ramp slope of 0.012 per inch slope (0.7 degrees).
- The aforementioned values of rail end conditions also represent appropriate thresholds identifying locations with a risk of rail joint failure.
- Longitudinal movement was not identified as a significant indicator of joint bar failure. Observed longitudinal rail movements affected long sections of track with both failed and intact joints; while other conditions, such as vertical and lateral movement, were localized to individual failed locations. Longitudinal movement, however, can contribute to adverse local conditions such as skewed ties and increased tie spacing affecting joint support.
- Longitudinal bar movement relative to the rail and the offset of the bar to the rail joint centerline were not statistically different at failed and intact rail joint locations.
- A definite conclusion regarding the magnitude of rail end gaps as a contributing factor to joint failure cannot be made with the available data samples. Analysis did not reveal a significant difference between intact and failed rail joint. Field surveys, however, were conducted in summer or late spring when rail temperatures were already elevated and rail gaps narrowed or closed. The rail gap size throughout the cold weather cycle was unknown.
- Intact and failed locations contained comparable values of alinement deviations towards the field side (positive value). A limited number of rail joint locations with alinement deviations towards the gage side were also found. Alinement deviation towards the gage

side appeared to occur more frequently at failed joint locations. However, the overall sample size of locations with alinement deviation towards the gage side was too small to result statistically significant difference between failed and intact rail joints. This suggests that alinement deviations towards the center of the track may be a factor, although less important than joint movements or rail end conditions even if confirmed with larger sample.

- Bolt conditions were not significantly different at failed and intact locations. Intact locations actually had slightly higher proportion of intact bolts. Therefore, bolt conditions did not appear to significantly affect joint bar failure. Joints examined in the study in general did not have extreme occurrences of missing or defective bolts.
- Rail joint failures evenly affected both suspended (crossties at each side of the joint centerline) and supported (crosstie directly under the joint centerline) rail joint configurations. However, the results suggest that while the supported/suspended joint configuration is not a significant factor in joint bar failure, the presence of deteriorated vertical support and the associated vertical movement that can be accompanied by defective ties is a factor.
- The findings from investigating repeated rail joint failures agree with the analysis of the field survey data, which concluded that deteriorated joint support resulting in large vertical movements (regardless of track class) and compromised rail end conditions at Class 3 JNT and CWR territories were major track related factors that contributed to joint bar failure.
- Inspection techniques that focus on identifying poor support conditions may identify locations that pose a risk to joint bar integrity. Short chord MCOs may be able to successfully identify joint locations with poor support conditions without producing large amounts of exceptions. More analysis would be required to confirm correlations between short chord MCOs and vertical movements determine appropriate chord lengths and detection thresholds to achieve the highest detection rates while resulting in a minimal amount of triggered events.

Areas of further research may be directed at instrumentation of joint bars at areas with adverse support and rail end conditions in revenue service and evaluation of short chord track surface measurements as means to identify locations with risk of rail joint failure.

Abbreviations and Acronyms

Abbreviations & Acronyms	Definition
AAR	Association of American Railroads
ATIP	Automated Track Inspection Program
CWR	Continuous Welded Rail
FRA	Federal Railroad Administration
FEA	Finite Element Analyses
JBIS	Joint Bar Inspection System
JNT	Jointed Track
MCOs	Mid-Chord Offsets
MGT	Million Gross Tons
RD&T	Office of Research, Development and Technology
RSAC	Rail Safety Advisory Committee
TGMS	Track Geometry Measurement System
TTCI	Transportation Technology Center, Inc.
VTI	Vehicle/Track Interaction
Volpe	Volpe National Transportation Systems Center

Appendix A.
List of Field Tools

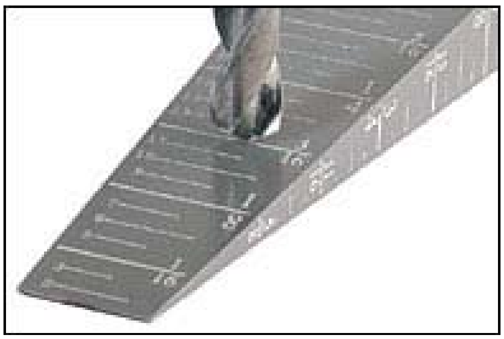
1. Track Level/Gage to measure track gauge and cross level;

2. Tapered gauge to measure rail end batter and rail end ramp;

3. 18" Single Bevel, Non-Graduated welders straight edge for measurements at joints;

4. Step Gauge to measure distance from base of rail to swinging/hanging tie. Can also be used to measure rail end batter, etc.;

5. Taper Gauge to measure distance from base of rail to swinging/hanging tie. Can also be used to measure rail end batter, etc.;



6. 25'L Magnetic Tip tape measure;

7. **Measuring wheel;**

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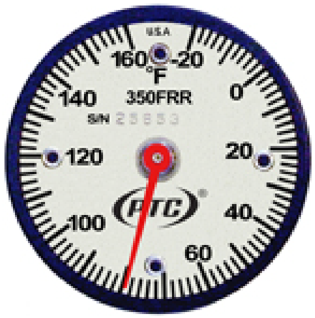
8. **Stringlining kit for measuring track geometry at joints;**

9. **Aluminum Cutting Guide to establish rail plane for geometry measurements at curves;**

10. **Rail thermometer;**



11. Set of magnifying glasses for close up investigation of joint bar cracks.

12. Hand held mirror for close up investigation of joint bar cracks.

13. Handheld GPS unit

14. GPS digital camera

Appendix B.
Field Survey Data Collection Sheet (Part 1)

JOINT ID: [ ] – [ ] – [ ]

1 RAILROAD:	2 SUBDIVISION:		3 MILEPOST:
4 DATE:	5 ANNUAL MGT:	6 TRACK #:	7 TRACK CLASS:
8 SPEED PASSENGER:	9 SPEED FREIGHT:		10 ☐ CWR ☐ JOINTED TRACK
11 GPS COORDINATES:			

12 GAP BETWEEN RAIL ENDS:	.... inches	
RAIL END BATTER OR RAMP:		
LEFT RAIL END (from field side view)	.... inches HIGH	.... inches LONG
RIGHT RAIL END (from field side view)	.... inches HIGH	.... inches LONG
TREAD MISMATCH:	.... inches	
GAGE RAMP:	.... inches OUT	.... inches LONG
GAGE MISMATCH:	.... inches	

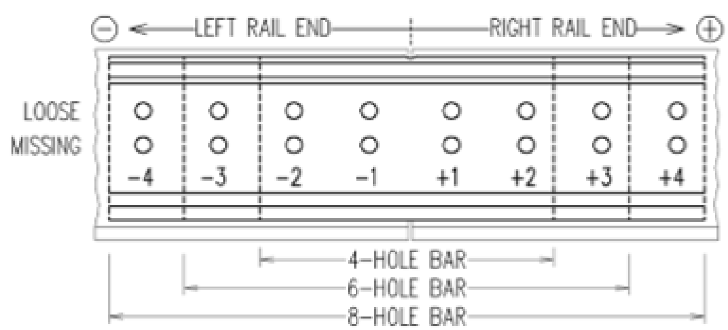
(All data to be collected in curves or spirals as well as tangents)

BAR TYPE & LENGTH (check all that apply)	13 ☐ STANDARD ☐ INSULATED ☐ COMPROMISE NO. OF HOLES: ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8	14 ☐ 36″ ☐ 48″ ☐ OTHER: ....
15 ☐ ANGLE ☐ HEAD-FREE ☐ HEAD-CONTACT ☐ OTHER:		16 BAR INCONGRUITY: ☐ YES ☐ NO

17 BOLT CONDITION:

(if bolts are loose or missing then specify which ones on the provided sketch)

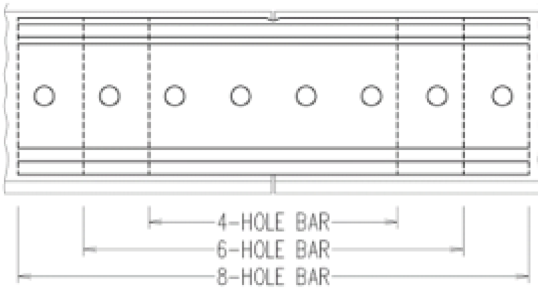
Bolts are numbered from left to right when **looking** at the joint assembly **from the field side.**

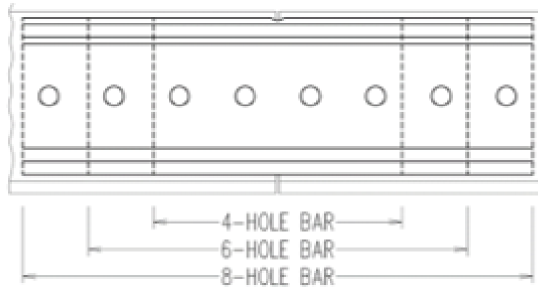


18 MIDDLE BOLTS HOLES DRILLED:

☐ YES ☐ NO

[19] **FIELD SIDE BAR:** ☐ BROKEN THROUGH ☐ CRACKED ☐ INTACT	[20] **GAGE SIDE BAR:** ☐ BROKEN THROUGH ☐ CRACKED ☐ INTACT





[21] LONGITUDINAL BAR MOVEMENT: .... inches	[22] LONGITUDINAL BAR MOVEMENT: .... inches
[23] BAR OFFSET FROM RAIL ENDS: .... inches	[24] BAR OFFSET FROM RAIL ENDS: .... inches

[25] ☐ TANGENT	[26] ☐ CURVE .... degrees ☐ LOW/INNER RAIL ☐ SPIRAL ☐ HIGH/OUTER RAIL DESIGN SUPERELEVATION:	[27] RAIL SECTION(S): LEFT RAIL (from field side view): .... RIGHT RAIL (from field side view): ....
[28] ANNUAL JOINT INSPECTION FREQUENCY FOR THE SEGMENT: ☐ 1x ☐ 2x ☐ 3x ☐ 4x ☐ OTHER:		[29] DATE OF LAST JOINT INSPECTION: ....

FIELD SIDE BAR:	**GAGE SIDE BAR:**
[30] IF BROKEN THROUGH: indicate location of break ☐ CENTER ☐ INNER BOLT HOLE ☐ OTHER	[31] IF BROKEN THROUGH: indicate location of break ☐ CENTER ☐ INNER BOLT HOLE ☐ OTHER
[32] IF CRACKED: indicate location(s) and record length(s) ☐ TOP CENTER .... inches ☐ BOTTOM CENTER .... inches ☐ INNER BOLT HOLE .... inches ☐ OTHER BOLT HOLE .... inches ☐ OTHER (describe) .... inches	[33] IF CRACKED: indicate location(s) and record length(s) ☐ TOP CENTER .... inches ☐ BOTTOM CENTER .... inches ☐ INNER BOLT HOLE .... inches ☐ OTHER BOLT HOLE .... inches ☐ OTHER (describe) .... inches ....
[34] BAR REMOVED: ☐ YES ☐ NO	[35] BAR REMOVED: ☐ YES ☐ NO
[36] MARKED AS REPLACED: ☐ YES ☐ NO	[37] MARKED AS REPLACED: ☐ YES ☐ NO
[38] ARRIVED FOR LAB TESTING: ☐ YES ☐ NO	[39] ARRIVED FOR LAB TESTING: ☐ YES ☐ NO

[40] ADDITIONAL COMMENTS: ....
....
....
....

Appendix C.
Field Data Collection Sheet (Part 2)

JOINT ID: ☐ – ☐ – ☐

41 STATIC GAGE:	42 JOINT LATERAL MOVEMENT:	43 GAGE UNDER LOAD:
44 STATIC CROSS LEVEL:	45 JOINT VERTICAL MOVEMENT:	46 CROSS LEVEL UNDER LOAD:
47 STATIC PROFILE:	48 PROFILE UNDER LOAD:	
49 ALINEMENT:	50 GRADE:	

51 RAIL TEMP:	52 AIR TEMP:	53 CLIMATE - YEARLY AIR TEMPERATURE RANGE:
54 TARGET RAIL LAYING TEMPERATURE:	55 REFERENCE MARKS OBSERVED: ☐ YES ☐ NO	
56 NEUTRAL RAIL TEMP MEASURED: ☐ YES .... ☐ NO	57 OTHER RECORDS TO OBTAIN: ☐ YES ☐ NO	

58 TIE TYPE: ☐ TIMBER ☐ CONCRETE ☐ STEEL ☐ COMPOSITE ☐ OTHER ....

59 TIE CONDITION: ☐ 1 ☐ 2 ☐ 3 ☐ 4 | 60 DISTANCE OF JOINT FROM FIRST EFFECTIVE TIE:

61 FASTENER TYPE: ☐ CUT SPIKE ☐ ELASTIC ☐ OTHER .... | 62 FASTENER CONDITION: ☐ 1 ☐ 2 ☐ 3

63 ANCHOR PATTERN – BOX ANCHOR: ☐ NOT PRESENT ☐ EVERY TIE ☐ EVERY OTHER TIE ☐ EVERY THIRD TIE ☐ OTHER ....

64 ESTIMATE OF RAIL LONGITUDINAL MOVEMENT: | 65 ANCHOR CONDITION: ☐ 1 ☐ 2 ☐ 3

66 BALLAST CONDITION: ☐ 1 ☐ 2 ☐ 3 ☐ 4 Comments: ....

....

....

....

67 DRAINAGE CONDITION: ☐ MAINTAINED ☐ NOT MAINTAINED Comments: ....

....

....

....

68 TRACK ON: ☐ CUT (....................feet) ☐ FILL (....................feet) ☐ NONE

69 **CULVERT** : ☐ NO ☐ WITHIN 100 FEET OF JOINT ☐ JOINT ON CULVERT

70 DISTANCE OF JOINT TO CLOSEST CULVERT END: ....feet,

73 **GRADE CROSSING**: ☐ NO ☐ WITHIN 100 FEET OF JOINT ☐ JOINT ON CROSSING

74 DISTANCE FROM JOINT TO CLOSEST CROSSING END: ....feet CROSSING LENGTH: ....feet

CONDITION: ☐ GOOD ☐ BAD Comments: ....

....

....

....

MATERIAL: ☐ STEEL ☐ CONCRETE ☐ COMPOSITE ☐ OTHER ....

TYPE: ☐ PIPE ☐ BOX ☐ SLAB ☐ ARCH ☐ OTHER ....

[71] **RETAINING WALL** (located directly under the joint bar) : ☐ YES ☐ NO

[72] HEIGHT: .... feet, CONDITION: ☐ GOOD ☐ BAD Comments: ....

....

....

....

[73] **GRADE CROSSING** : ☐ NO ☐ WITHIN 100 FEET OF JOINT ☐ JOINT ON CROSSING

[74] DISTANCE FROM JOINT TO CLOSEST CROSSING END: ....feet, CROSSING LENGTH: ....feet

CONDITION: ☐ GOOD ☐ BAD Comments: ....

....

....

....

[75] **BRIDGE** : ☐ NO ☐ WITHIN 100 FEET OF JOINT ☐ JOINT ON BRIDGE

[76] DISTANCE FROM JOINT TO CLOSEST BRIDGE END OR SUPPORT: ....feet, TRUSS: ☐ YES ☐ NO

MATERIAL: ☐ STEEL ☐ CONCRETE ☐ PRESTRESSED ☐ COMPOSITE ☐ TIMBER
☐ OTHER ....

SUPERSTRUCTURE: ☐ BEAM ☐ TRESTLE ☐ ARCH ☐ SLAB ☐ CANTILEVER
☐ OTHER ....

[77] DECK POSITION IN RESPECT TO SUPERSTRUCTURE: ☐ ABOVE ☐ BELOW ☐ INTERMEDIATE

[78] DECK TYPE: ☐ OPEN ☐ BALLASTED

[79] KNOWN ISSUES: ☐ YES ☐ NO Comments: ....

....

....

....

....

[80] **SWITCH:** ☐ NO ☐ WITHIN 100 FEET OF JOINT | [81] DISTANCE TO SWITCH END: ....feet

[82] **MAINTENANCE HISTORY:** LAST TIME JOINT BAR REPLACED:

[83] INDICATE RECENT WORK PERFORMED IN THE VICINITY SINCE LAST TIME JOINT REPLACED

TIE REPLACEMENT: ☐ YES ☐ NO, IF YES INDICATE DATE(S): ....

OUT OF FACE SURFACING: ☐ YES ☐ NO, IF YES INDICATE DATE(S): ....

SPOT SURFACING: ☐ YES ☐ NO, IF YES INDICATE DATE(S): ....

BALLAST CLEANING: ☐ YES ☐ NO, IF YES INDICATE DATE(S): ....

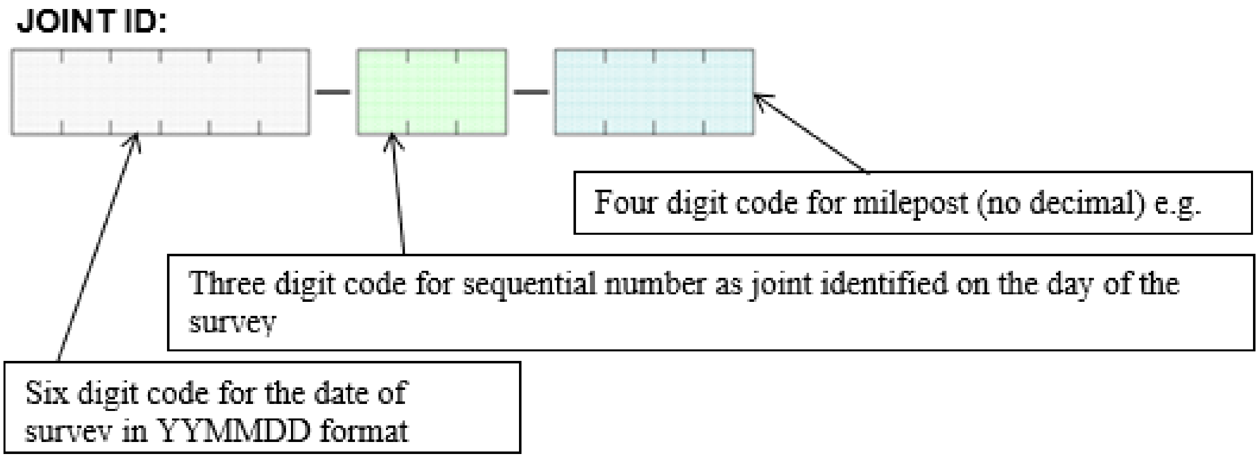
OTHER (indicate what work performed and when): ....

....

....

[84] ADDITIONAL COMMENTS: ....
....
....
....
....
....
....
....
....
....

Appendix D.
Instruction Handbook



PART 1

1. FRA railroad reporting code, (e.g., CSX or NS).
2. Railroad's subdivision or district. If none enter "system."
3. Railroad's designated milepost at the location of the joint.
4. Date of the field survey the joint was identified.
5. Million Gross Tons (from previous calendar year) for the specific track with the identified joint bar.
6. Specify track number by railroad designation.
7. FRA Class for track with the identified joint bar.
8. Maximum Speed limit for passenger traffic [mph].
9. Maximum Speed limit for freight traffic [mph].
10. Specify CWR or Jointed Rail. Use FRA definition. Rail originally installed as CWR remains CWR regardless of joints cut in.
11. GPS coordinates: Latitude, Longitude in decimal format.
12. Measure and record (even if found to be zero) all of the following in inches (record all measurements in curves spiral as well as tangents):
13. Gap between rail ends—measure the distance between rail ends. If joint is pulled apart or separated, estimate the gap before separation.
14. Rail end batter or ramp (length and height)—one set of measurements for each rail end. See Figures 1 and 2 for method of measurement.
15. Tread mismatch. See Figure D-3 for method of measurement.

16. Gage ramp (length and height). See Figure D-4 for method of measurement.
17. Gage mismatch. See Figure D-5 for method of measurement.
18. Indicate bar type: standard, insulated, or compromise bar and number of holes (at least two (2) boxes (one in each row) must be checked.
19. Length of the joint bar as 36," 48," or other. If other is checked then specify.
20. Indicate bar type as Angle bar, Head-free bar, Head-contact bar or other. If other is checked then specify. See Figure D-6 for schematics.
21. Indicate whether a bar incongruity exists in the joint bar assembly. This refers to cases where there are different types of bars installed on the field and gage side of the same joint, bars not corresponding with the rail type (i.e., 119 lb. bar installed on a 136-lb rail) or any combination of such situations. If such condition exists check all the applicable boxes in the fields 13, 14 and 15 and describe the condition in detail in field 40 "ADDITIONAL COMMENTS."
22. Describe bolt condition. If any of the bolts are loose or missing then check the appropriate box on the provided sketch (upper row of round boxes for loose bolts and lower row of round boxes for missing bolts). Bolts are numbered from -4 to +4 from left to right looking at the joint assembly from a field side.
23. Indicate whether middle bolt holes were not drilled in preparation of welding.
24. Indicate whether **field** side bar is broken through, cracked or intact. If joint bar is cracked or broken through then record the crack pattern on the provided sketch in a way that fields 30 and 32 can be filled out later.
25. Indicate whether **gage** side bar is broken through, cracked or intact. If joint bar is cracked or broken through then record the crack pattern on the provided sketch in a way that fields 31 and 33 can be filled out later.
26. Regardless of the bar condition (broken through, cracked or intact) measure and record longitudinal movement of the **field** side bar relative to the rail (inches).
27. Regardless of the bar condition (broken through, cracked or intact) measure and record longitudinal movement of the **gage** side bar relative to the rail (inches).
28. Measure and record (even if found to be zero) the distance between the centerline of the **field** side joint bar and the centerline of gap between the rail ends. Note the sign of the measurement as negative when the gap between the rail ends is towards the left of the joint bar centerline and as positive if the gap between the rail ends is towards the right of the joint bar centerline when looking at the installed joint bar. See Figure D-7 and D-8 for details and method of measurement.
29. Measure and record (even if found to be zero) the distance between the centerline of the **gage** side joint bar and the centerline of gap between the rail ends. Note the sign of the measurement as negative when the gap between the rail ends is towards the left of the joint bar centerline and as positive if the gap between the rail ends is towards the right of the joint bar centerline when looking at the installed joint bar. See Figure D-7 and D-8 for details and method of measurement.

30. Check box if identified joint is in tangent.
31. Indicate if identified joint bar is in a spiral or in a curve. If curve is checked specify the degree of curvature and design super elevation. In both cases indicate whether identified joint bar located on low/inner or high/outer rail.
32. Indicate each rail section comprising the joint, Record the rail section for both left and right rail ends (looking at the joint assembly from field side view)
33. Number of times per year that joint bar inspection (JBIS, walking or any other method) is performed. If more than 4 times per year then specify.
34. Date the last joint bar inspection (JBIS, walking or any other method) was performed.
35. If **field** side bar is broken through check appropriate box to indicate the location of the break (through the center, through inner bolt whole or other location).
36. If **gage** side bar is broken through check appropriate box to indicate the location of the break (through the center, through inner bolt whole or other location).
37. If **field** side bar is cracked but not completely broken through check appropriate box(es) to indicate the crack location(s) and corresponding lengths (any number of boxes can be checked, enter length in inches).
38. If **gage** side bar is cracked but not completely broken through check appropriate box(es) to indicate the crack location(s) and corresponding lengths (any number of boxes can be checked, enter length in inches).
39. Indicate whether identified **field** side joint bar has been removed from the joint assembly.
40. Indicate whether identified **gage** side joint bar has been removed from the joint assembly.
41. Indicate whether **field** side bar was properly marked after being replaced. If **field** side bar was not replaced check NO box.
42. Indicate whether **gage** side bar was properly marked after being replaced. If **gage** side bar was not replaced check NO box.
43. Indicate whether **field** side bar was received by TTCI for further lab inspection and material testing.
44. Indicate whether **gage** side bar was received by TTCI for further lab inspection and material testing.
45. Other comments, including narrative of overall conditions of the location and any other factors that may have contributed to the fracture of the bar(s). Describe in detail incongruity in the joint bar assembly if it exists (see field 16). Include the extent of photographic evidence taken.

PART 2

1. Measure and record static gage at the identified joint in inches.
2. Measure and record lateral movement of the joint under load in inches.
3. Determine gage under load as combination of static gage and lateral movements of the joint and the opposite rail.

4. Measure and record static cross level at the identified joint in inches.
5. Measure and record vertical movement of the joint under load in inches.
6. Determine cross level under load as combination of static cross level and vertical movements of the joint and the opposite rail.
7. Measure and record 62-foot chord length static profile at the identified joint in inches.
8. Determine profile under load as combination of static profile and joint's vertical movement.
9. Measure and record 62-foot chord length alinement at the identified joint in inches.
10. Note for geometry measurements above: In addition to the static (unloaded) geometry measurements taken, the amount of visually detectable dynamic (loaded) deflection that occurs under train movement must be considered. This includes the amount of vertical or lateral rail deflection occurring between rail base and tie plate, a tie plate and crosstie, from voids between the crosstie and ballast section resulting from elastic compression, or any combinations of the above. Each deflection under the running rails must be measured and properly considered when computing the collective deviations under load. It is very important that consideration be given to both rails when measuring these deflections and determining the under load geometry measurements.
11. Measure and record longitudinal grade of the track in the vicinity of the identified joint in percent with two decimal places accuracy.
12. Rail temperature measured at the time of inspection in the proximity of the identified joint [°F].
13. Air temperature measured at the time of inspection in the proximity of the identified joint [°F].
14. If known, define the climate cycle by specifying the yearly minimum and maximum air temperatures achieved in the area (e.g., -10 °F; 95 °F). Otherwise leave blank and retrieve information during data processing.
15. Record the target or designated rail laying temperature for the territory obtained from railroad [°F].
16. Indicate whether there are reference marks present in the vicinity of the joint bar. If so, photograph reference marks to retrieve information on rail such as rail temperature, date, rail added or rail subtracted. Reference marks should be located within 50 ft. in both directions from the joint.
17. Indicate whether the neutral rail temperature was measured using Verse ™ or other method. If so, record the measured value [°F].
18. Indicate whether any follow-up records regarding neutral temperature should be retrieved from the railroads due to unusual circumstances at vicinity of the railroads such sign of rail overstressing. Such record can contain information of the rail temperature of CWR when the rail was originally installed, record of addition or subtraction where rail has been pulled apart, broken, or been cut for defect removal or welding, record of de-stressing of rail or record of curve movement.

19. Indicate the type of crossties. If other, then specify.
20. Indicate the condition of the crossties in the vicinity of the joint by checking appropriate box. See manual for crosstie rating system.
21. Measure and record the distance between the joint centerline and the closest effective tie in inches.
22. Indicate the type of fasteners. If other, then specify.
23. Indicate the condition of the fasteners in the vicinity of the joint by checking appropriate box. See manual for fastener rating system.
24. Indicate an anchor pattern at the distance of at least 195 feet in both directions from the identified joint by checking appropriate box. If no anchors are present then indicate so. If other then listed pattern is present (including other then box anchors) then check OTHER then specify in detail.
25. Record an estimate of the rail longitudinal movement at the location of the identified joint in inches. Record even if the value is 0.
26. Indicate the condition of the anchors in the vicinity of the joint (if present) by checking appropriate box. See manual for anchor rating system.
27. Indicate the condition of the ballast in the vicinity of the joint by checking appropriate box. See manual for ballast rating system. Include any additional description of the situation of the ballast if necessary.
28. Indicate the condition of drainage in the vicinity of the joint by checking appropriate box. See manual for drainage rating definition. Include any additional description of the situation of the drainage if necessary (including of condition of culverts if present).
29. Indicate whether the track in the vicinity of the identified joint is located in a cut (then specify depth in feet) or on a fill (then specify height in feet) or neither of those. Both CUT and FILL boxes can be checked if track is built on a hillside partially in a cut and partially on a fill. See Figure D-9 for details.
30. Indicate whether there is a culvert within 100 feet the identified joint or if the joint is directly on the culvert.
31. In either of the two cases when culvert is present, specify the distance of the joint to the closest culvert end in feet. Specify the material and type of the culvert (if other, then specify further). Any structural or drainage issues with the culvert should be mentioned in the Field 62 Comments.
32. Indicate whether track is supported by a retaining wall on either side directly under the identified joint.
33. If the answer is YES, then define its height in feet and its structural condition as GOOD or BAD. If its condition is BAD then specify the issues in comments (i.e., wall crumbling, tilting outwards…).
34. Indicate whether there is a grade crossing within 100 feet the identified joint or if the joint is directly on the grade crossing.

35. In either of the two cases when grade crossing is present, specify the distance of the joint to the closest crossing end and the length of the crossing in feet. Also indicate the structural condition of the crossing as GOOD or BAD. If its condition is BAD then specify the issues in comments.
36. Indicate whether there is a bridge within 100 feet the identified joint or if the joint is directly on the bridge.
37. In either of the two cases when bridge is present, specify the distance of the joint to the closest bridge end in feet. Indicate whether the bridge has truss superstructure. Also indicate the material of the bridge and the structural type of superstructure (if other, then specify further).
38. Indicate the bridge deck position in respect to the superstructure. See Figure D-10 for details and examples.
39. Indicate the bridge deck type as OPEN or BALLASTED.
40. Report whether there are any known structural or other issues with the bridge that effect vertical or lateral deflection of the joint. If so, specify in detail.
41. Indicate whether there is a switch within 100 feet the identified
42. If joint is located within 100 feet of a switch end then measure and record its distance to the switch end.
43. Indicate date of the last time when the identified joint bar was replaced.
44. Indicate whether any of the listed maintenance works was performed in the vicinity of the joint bar since the last time the identified joint bar was replaced. So, specify all the dates of the maintenance. If any other unlisted maintenance was performed specify what kind and when it was performed. If this information is not readily available at the time of the field survey leave blank. The information must be then collected later during the data processing in cooperation with the railroad.
45. Other comments, including narrative of overall conditions of the location and any other factors that may have contributed to the fracture of the bar(s).

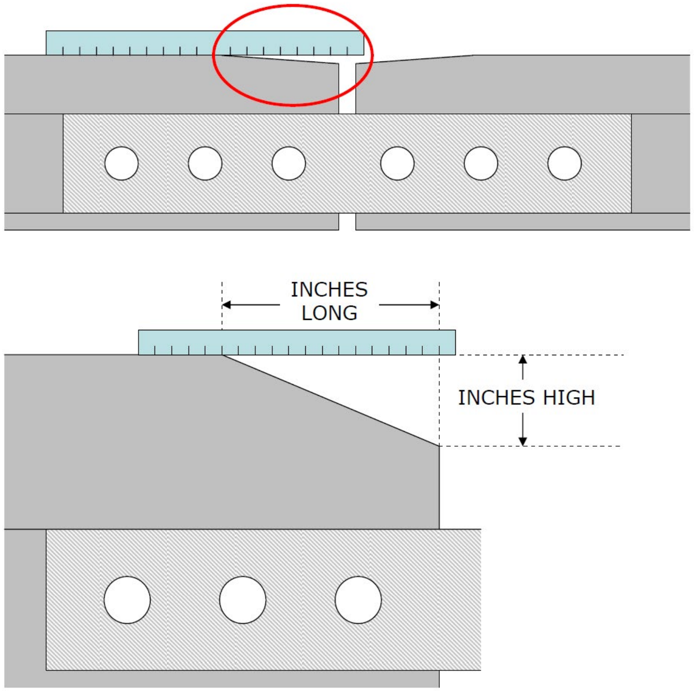


Figure D-1. Method for measuring RAIL END BATTER (Measurement to be made on each rail end). (NOT TO SCALE)

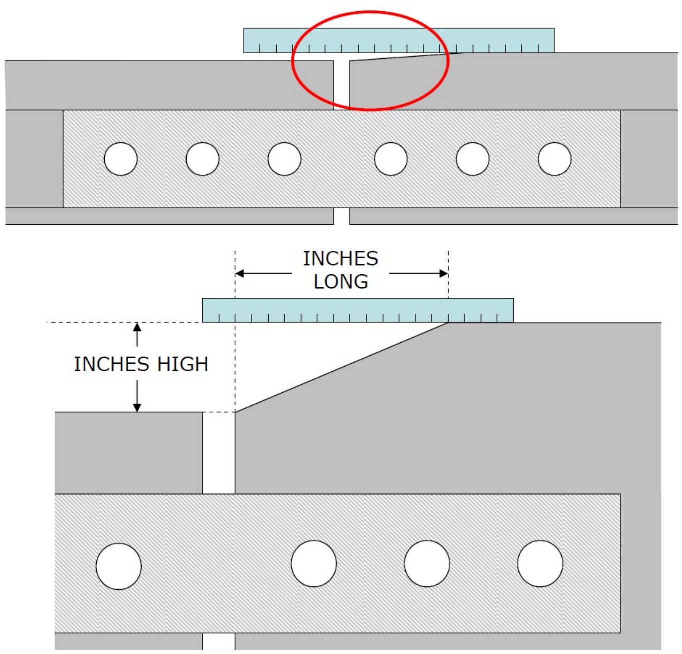


Figure D-2. Method for measuring RAIL END RAMP. (NOT TO SCALE)

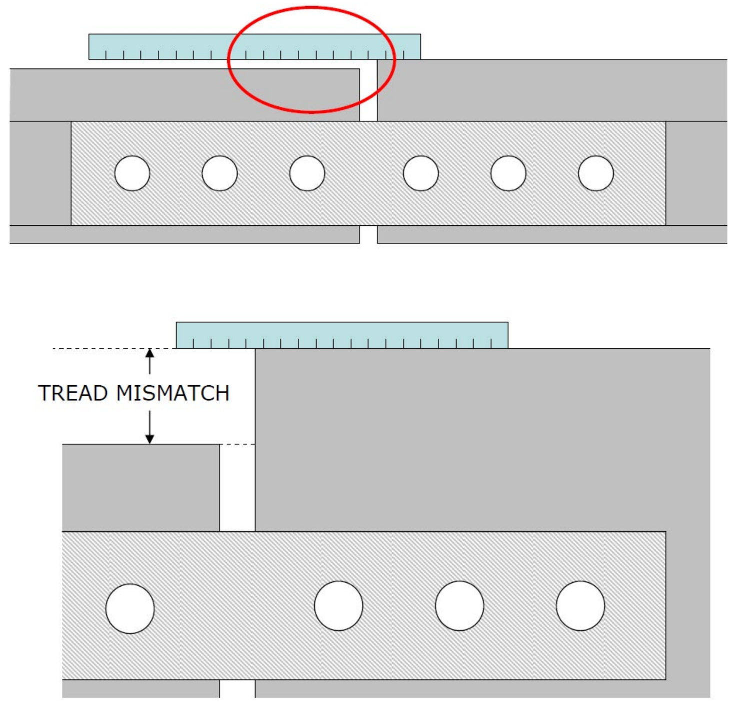


Figure D-3. Method for measuring TREAD MISMATCH. (NOT TO SCALE)

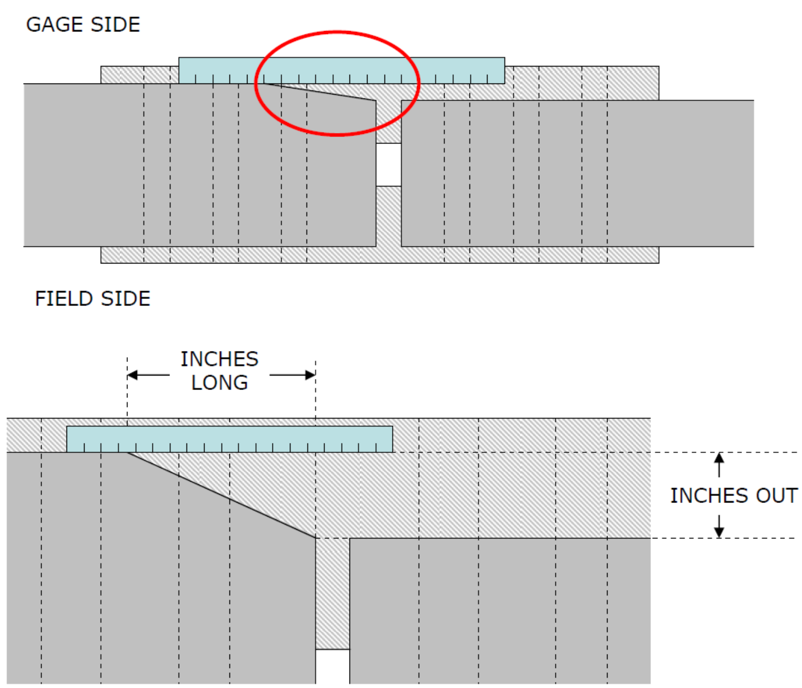


Figure D-4. Method for measuring GAGE RAMP. (NOT TO SCALE)

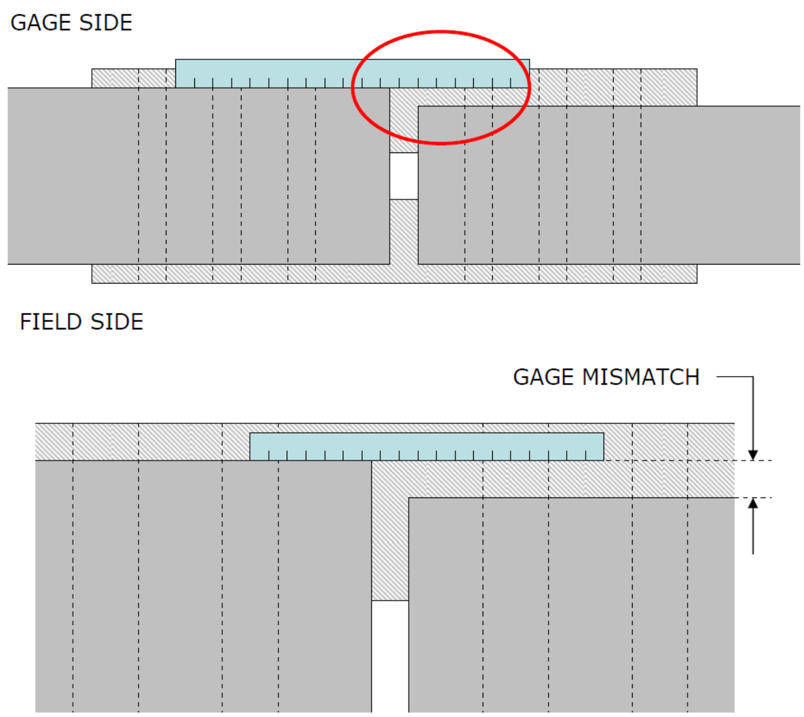


Figure D-5. Method for measuring GAGE MISMATCH. (NOT TO SCALE)

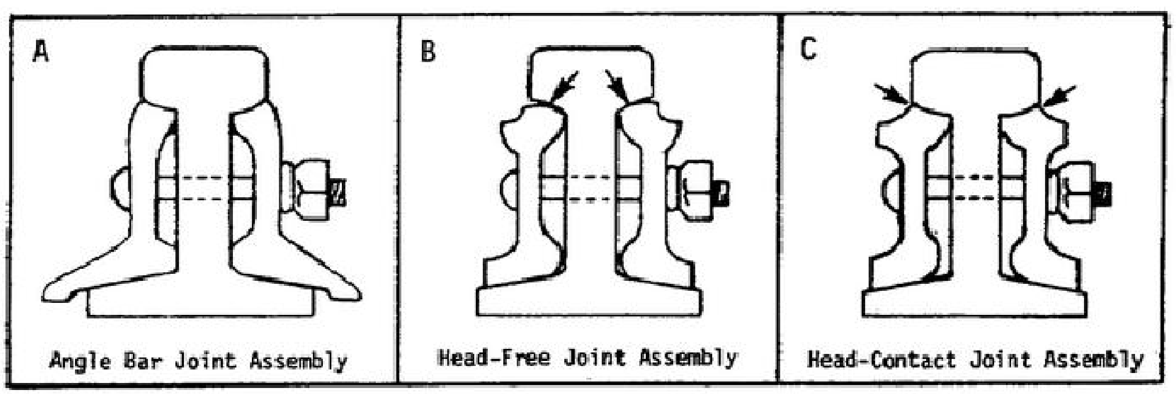


Figure D-6. Three most common joint bar types

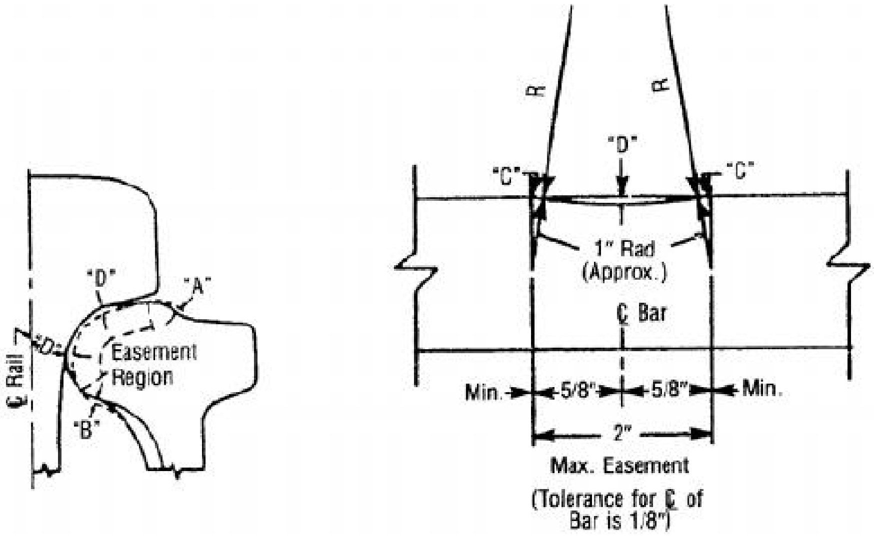


Figure D-7. Typical easement schematics

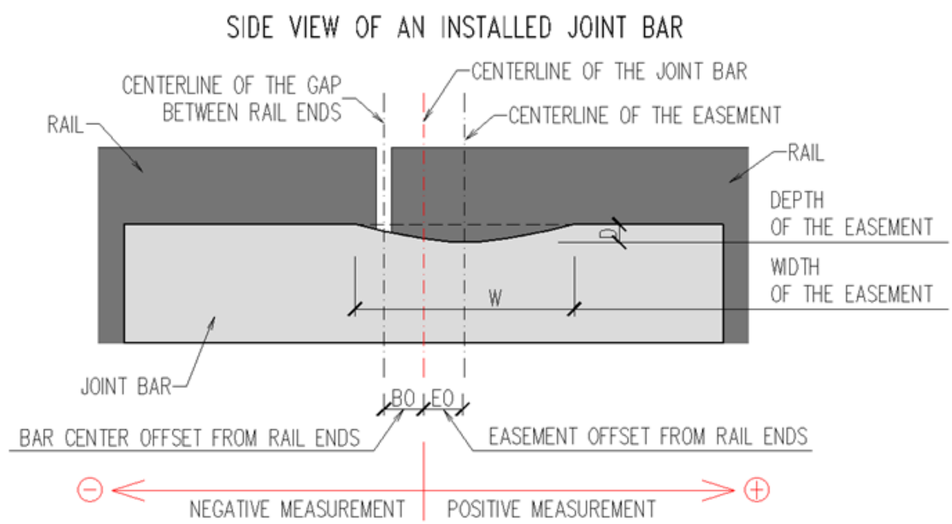


Figure D-8. Method for measuring easement depth, bar center offset from rail ends and easement offset from bar center (NOT TO SCALE)

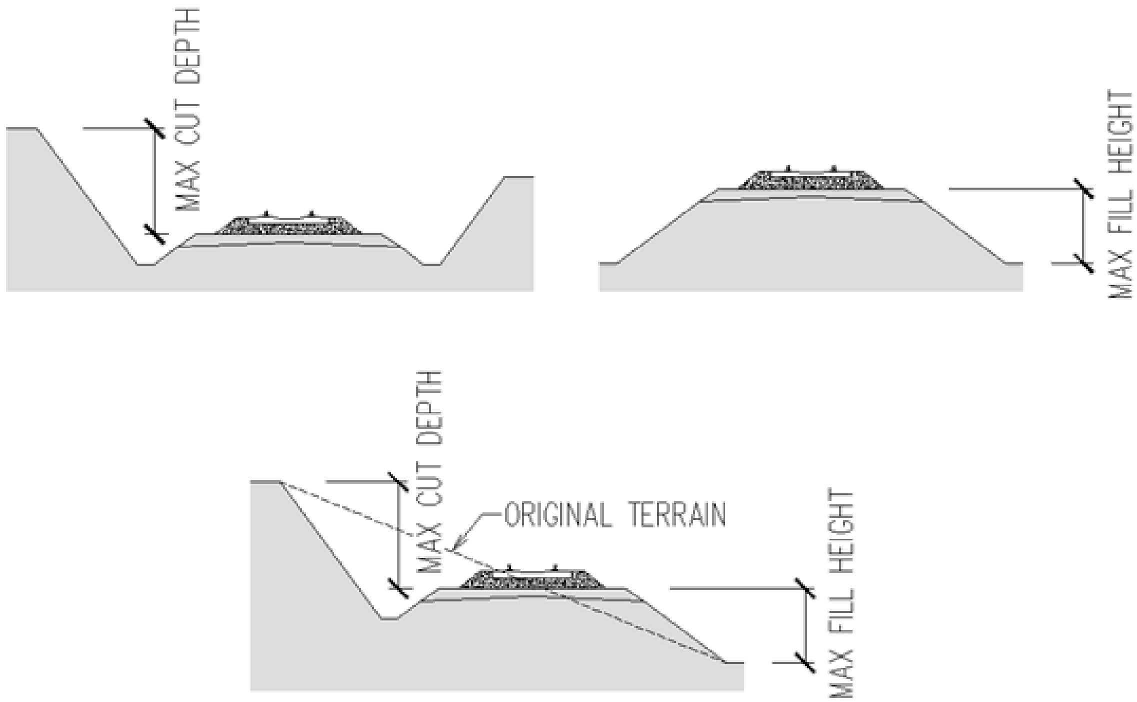


Figure D-9. Method for measuring the depth of a cut and height of a fill. If track located partially in a cut and on a fill as indicated, record both measurements. (NOT TO SCALE)

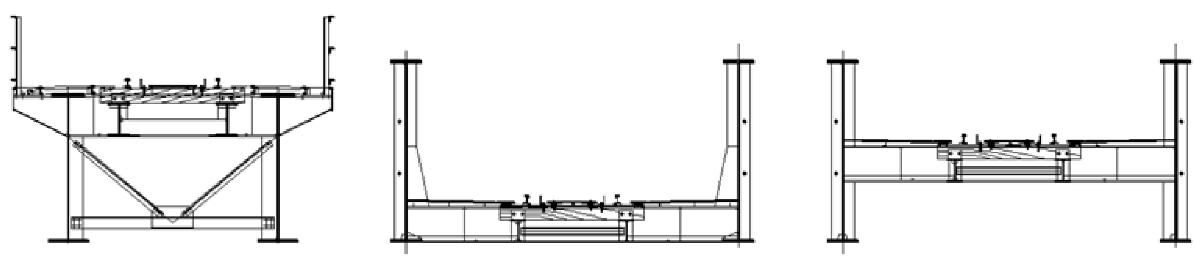


Figure D-10. Location of bridge deck in respect to superstructure.

Appendix E.
Rating System for Track Components

Timber Crossties: Rating ranges from 1 through 4

For purposes of this rating system, an effective crosstie is not broken through, split to the extent that ballast may work through, will not hold spikes or fasteners, so deteriorated that the plate or base of rail can move laterally more than ½ inch, or plate cut more than 2 inches.

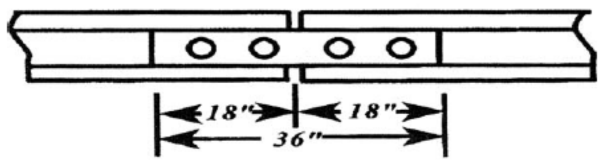


Figure E-1. Illustration of 36-Inch Joint Bar with 18-Inch Limits from Joint Centerline

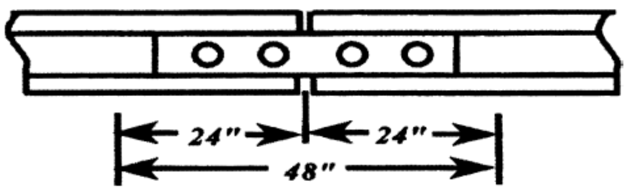


Figure E-2. Illustration of 36-Inch Joint Bar with 24-Inch Limits from Joint Centerline

Rating	Timber Crosstie Configuration Description
1	Centerline of an effective crosstie is not found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties, one on each side, whose centerlines are not found within 24 inches of the joint centerline (Figure E-2).
2	Centerline of an effective crosstie is found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties are found whose centerlines are within 24 inches of the joint centerline (Figure E-2). However, the effective tie(s) used to meet these requirements exhibit marginal characteristics such as plate cutting more than ¾ inches, missing or loose fasteners, track geometry conditions that are beginning to appear, or noticeable splitting but not to the extent that ballast can work through.
3	Centerline of an effective crosstie is found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties are found whose centerlines are found within 24 inches of the joint centerline. However, the effective tie(s) used to meet these requirements do not exhibit the marginal conditions described in rating number 2.
4	All ties within 24 inches of the joint centerline in either direction are effective.

Concrete Crossties: Rating ranges from 1 through 4

For purposes of this rating system, an effective concrete crosstie is not broken through or deteriorated to the extent that prestressing material is visible; deteriorated or broken off in the vicinity of the shoulder or insert so that the fastener assembly can either pull out or move laterally more than 3/8 inch relative to the crosstie; deteriorated such that the base of either rail can move laterally more than 3/8 inch relative to the crosstie on curves 2 degrees or greater, or can move laterally more than ½ inch relative to the crosstie on tangent track or curves less than 2 degrees; deteriorated or abraded at any point under the rail seat to the depth of ½ inch or more;

deteriorated such that the crosstie's fastening or anchoring system is unable to maintain longitudinal rail restraint, or maintain rail hold down, or maintain gage due to insufficient fastener toeload; or configured with less than two fasteners on the same rail except that where fastener placement impedes insulated joints from performing as intended, the fastener may be modified or removed, provided that the crosstie supports the rail.

Rating	Concrete Crosstie Configuration Description
1	Centerline of an effective crosstie is not found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties, one on each side, whose centerlines are not found within 24 inches of the joint centerline (Figure E-2).
2	Centerline of an effective crosstie is found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties are found whose centerlines are within 24 inches of the joint centerline (Figure E-2). However, the effective tie(s) used to meet these requirements exhibits marginal characteristics such as a condition where the concrete tie is broken off but the fastener assembly has not shown evidence of pulling out or moving laterally relative to the crosstie. A marginal condition would also include evidence where some abrasion or deterioration under the rail seat is apparent, but the deterioration is not ½ inch or more.
3	Centerline of an effective crosstie is found within 18 inches of the joint centerline (Figure E-1) OR two effective crossties are found whose centerlines are found within 24 inches of the joint centerline. However, the effective tie(s) used to meet these requirements do not exhibit the marginal conditions described in rating number 2.
4	All ties within 24 inches of the joint centerline in either direction are effective.

Fasteners: Rating ranges from 1 through 3

As used in this rating system a gage geometry condition means a gage measurement irregularity that does not exceed the allowable threshold for the designated track class, but exists due to the reduced or non-existent capability of one or more track structural components to hold the track into its preferred geometric position.

Rating	Fastener Description
1	Track exhibits a gage geometry condition where the system of components does not effectively maintain gage. This rating also includes any occurrence where, if rail anchors are applied to concrete ties, the combination of ties, anchors, and fasteners does not provide effective longitudinal restraint. Where fastener placement impedes insulated joints from performing as intended, the fastener may be modified or removed, provided that the crosstie supports the rail.
2	No gage geometry condition is evident. Where fastener placement impedes insulated joints from performing as intended, the fastener may be modified or removed, provided that the crosstie supports the rail. If rail anchors are applied to concrete ties, the combination of ties, anchors, and fasteners provide effective longitudinal restraint.
3	No gage geometry condition is evident. All fasteners are in place and effective, including at an insulated joint. There is no evidence that the fastener/anchor system fails to provide effective longitudinal restraint.

Drainage: Rating ranges from 1 through 2

Drainage facilities include bridges, trestles, culverts and ditches under or immediately adjacent to the roadbed. A drainage condition will be reported only when the drainage may affect the stability of the specified joint.

Rating	Drainage Description
1	Drainage facility is not maintained. This rating applies when a water-carrying facility is obstructed by debris, silt or vegetation; or is collapsed; or allows subgrade saturation. If the drainage condition affects the lateral stability of the joint, include a description of condition such as a blocked or collapsed culvert or bridge, a deteriorated drainage structure, or uncontrolled water which is undercutting the track structure or embankment at the track joint. Standing water should be noted.
2	Drainage facility is maintained

Fouled Ballast or Insufficient Ballast: Rating ranges from 1 through 4

Ballast may consist of crushed slag, crushed stone, screened gravel, pit-run gravel, chat, cinders, scoria, pumice, sand, mine waste, or other native material, and is an integral part of the track structure. Because ballast conditions can be subjective in nature, other indicators such as a geometry condition must be present at the track joint for fouled ballast to be critical. Evidence of fouled ballast at a track joint is poor drainage or track which demonstrates a geometry condition. For purposes of the rating system, a geometry condition means a track surface, gage, or alinement irregularity that does not exceed the allowable threshold for the designated track class. It exists due to the reduced or non-existent capability of one or more track structural components to hold the track joint into its preferred geometric position.

Rating	Description
1	Insufficient ballast as evidenced by the lack of ballast under the ties or at the ends of ties which may contribute to vertical or lateral deflection and geometry condition in the immediate vicinity of the track joint.
2	Fouled ballast with a geometry condition or poor drainage in the vicinity of the track joint which affects the stability of the track joint.
3	Ballast exhibits fouling. However, no geometry condition or poor drainage occurs in the vicinity of the track joint.
4	Ballast transmits and distributes the load of the track and railroad rolling equipment to the subgrade and restrains the track laterally, longitudinally, and vertically under dynamic loads imposed by railroad rolling equipment and thermal stresses imposed by the rails. Joint area does not demonstrate fouled ballast with a geometry condition or poor drainage.

Anchors: Rating 1 through 3

Joints with elastic fasteners serve the function of rail anchors to restrict longitudinal movement. If anchors are present, rate the anchors at the rail joint as follows:

Rating	Description
1	Anchors allow longitudinal movement of 2 inches or more.
2	Anchors allow up to 2 inches of longitudinal movement. Record anchor pattern and anchor effectiveness as discussed in Rating 1.
3	Anchors are functional and have not allowed noticeable longitudinal movement. Record anchor pattern as described in Rating 1 and 2.

Appendix F.
Field Survey Guidance Manual

Bar Type

Joint bars are used to connect two rail ends. There are many types of joint bars in use. Bars are sometimes described as fish plates or angle bars. Historically, flat fish plates were designed to fit the web area of each rail. Later, the bars were modified to provide support under the rail head and were called "angle bars." In fact, many people in the industry would refer to all bars, except for fish-plate type designs as "angle bars." Regardless of the design, most suppliers categorize bars as standard, compromise, or insulated joint bars. Other suppliers use categories such as long-toe (full-toe), splice, or short-toebars. Others type the bars as angle, head-free, or head-contact joint bars.

Some of these different categories are overlapping. For example, a bar may be a head-free, short toe bar.

In order to be consistent in collecting information, one box should be checked to identify the bar as a standard, compromise, or insulated bar and one box should also be checked to describe the bar as angle, head-free, head-contact, or other. The other category would refer to a flat fish plate or other more unusual design. Although an angle bar could be described as a short-toe or long-toe bar, for the purposes of this study, an entry as an "angle bar" would refer specifically to a long-toe bar as described below.

Compromise joints are used to connect two different sizes of rail. It is important that compromise joints be installed correctly. They are often stamped as "gage" or "out" or "left hand" or "right hand." If compromise joints are not installed correctly, a gage side or tread mismatch can occur which can contribute to joint bar failure. Figure F-1 shows one convention that is sometimes used to make sure the bars are installed correctly.

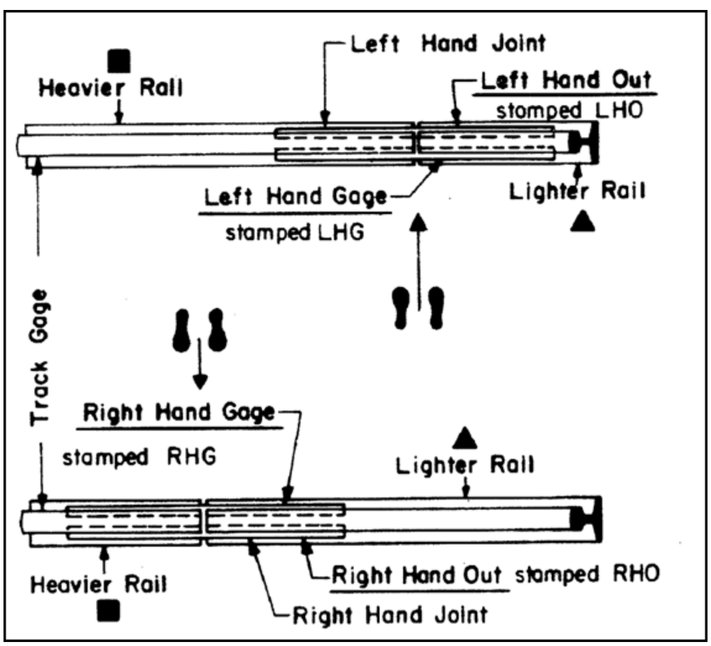


Figure F-1. Convention Used to Make Sure Joint Bars are Installed Properly

Insulated joints are used at signals and other locations. One common type of insulated joint is basically a standard joint with an insulated material (epoxy) which coats the bar and provides insulation. Another common insulated joint is a bonded insulated joint. Bonded insulated joints are typically built at a manufacturing facility and then installed in the rail, but a process exists to rebuild bonded insulated joints in the field. On occasion, regular track bolts have been improperly used in the field to replace the original bolts that were used to construct the bonded insulated joint. The use of track bolts rather than the bolts that were designed have contributed to a loss of insulation or a loss of joint integrity.

Figure F-2 shows a type of insulated joint where an insulated material coats the bars.

Figure F-2. Insulated Joint with Insulation Material Coating Bar

Figure F-3 shows an example of a bonded insulated joint:

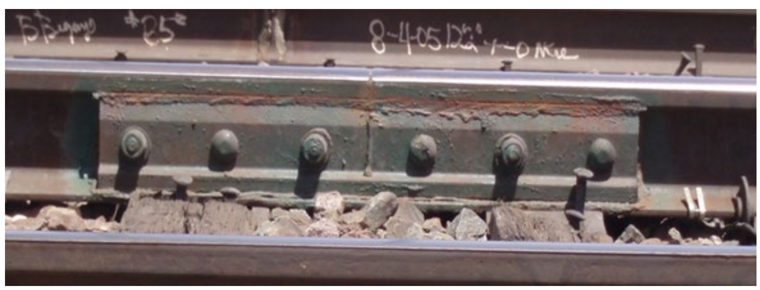


Figure F-3. Bonded Insulated Joint

Joint bars are often described as head-free, head-contact, or angle bars. Figure F-4 shows the different types of design.

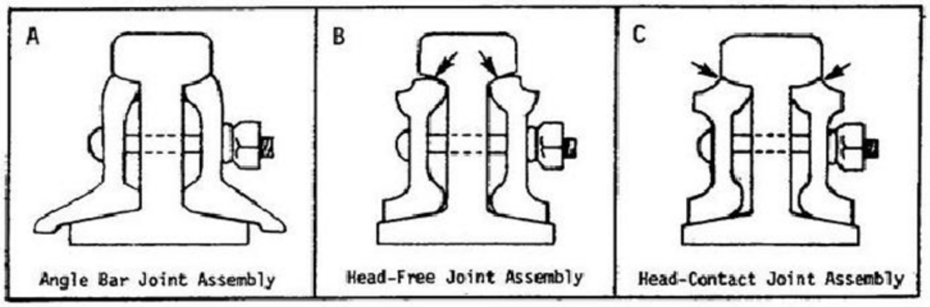


Figure F-4. Illustrations of Head-Free, Head-Contact or Angle Joint Bars

Head-free bars are the most common design and fit into the upper fillet between the web and head of the rails.

Joint bars are sometimes categorized as full (or long) toe, short toe, splice bars, or flat fish plates. The use of a flat fish plate or splice bar would be unusual. Long-toe bars extend out from the base of the rail. Figure F-5 shows three types of bars that one manufacturer uses to describe bar types.

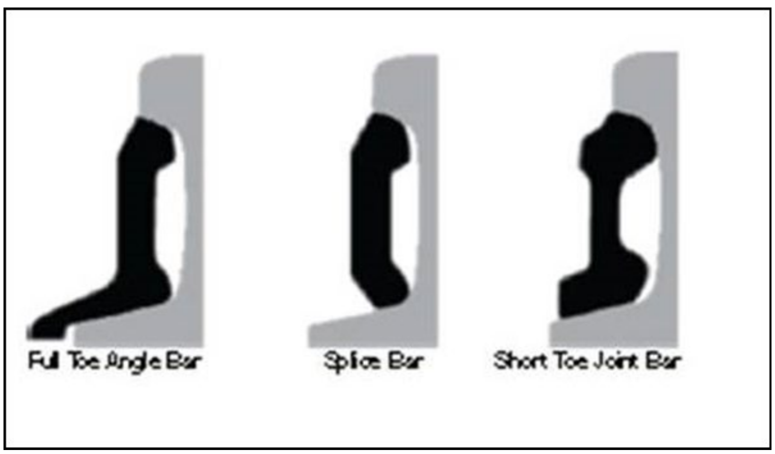


Figure F-5. Illustrations of Full Toe Angle Bar, Splice Bar and Short Toe Joint Bars

Figure F-6 provides an example of a center cracked long toe angle joint bar. Some long toe joint bars are manufactured with slots to accommodate spikes. Cracks and breaks at or near the slot holes have been found. In addition, the spikes in the slots have been found to split timber crossties when the rail moves longitudinally. Common practice now is to install spikes at the edge of the slotted bar and avoid using the slots. If a failed slotted bar is found to be spiked in the manufactured slots, photographs should be taken to document the occurrence.

Figure F-6. Illustration of Long Toe Angle Joint Bar with Center Crack

Joint Bar Easement

The American Railway Engineering and Maintenance-of-Way Association (AREMA) currently recommends an easement on the top of the joint bar to reduce the possibility of a rail end contacting the top of the joint bar. Figures F-7 and F-8 show the requirements of AREMA for an easement in head free joint bars.

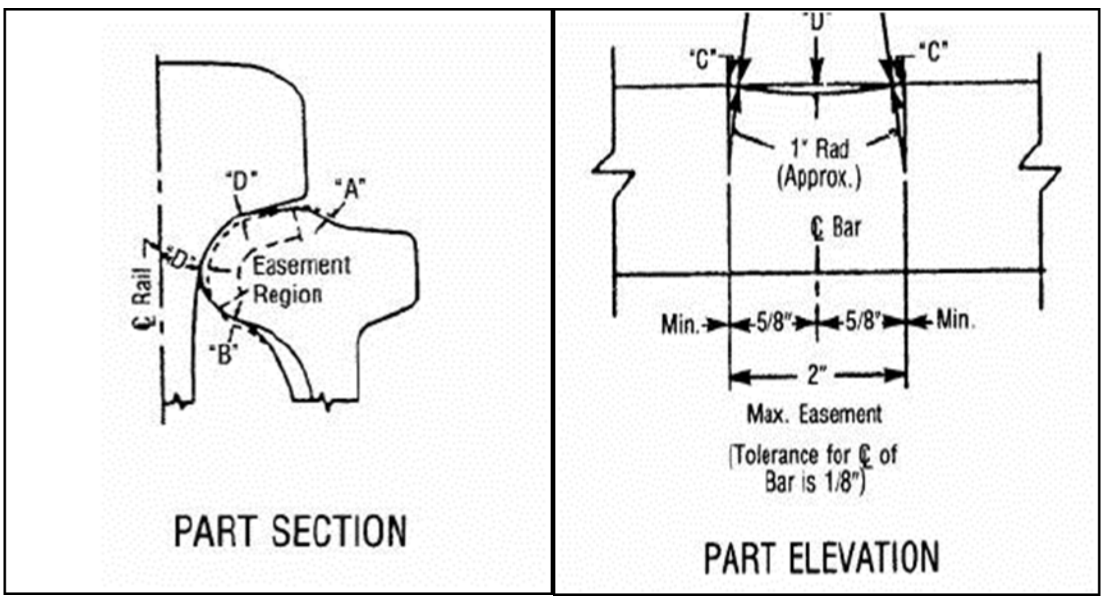


Figure F-7. AREMA Requirements for Easement of Head Free Joint Bar

In order to evaluate the position of the rail ends relative to the easement, take a measurement of the distance from the centerline of the bar to the centerline of the gap between the rail ends before the bar is removed from the track. Together with the dimensions of the easement that are measured after the bar is removed, the relationship of the rail ends to the easement can be identified.

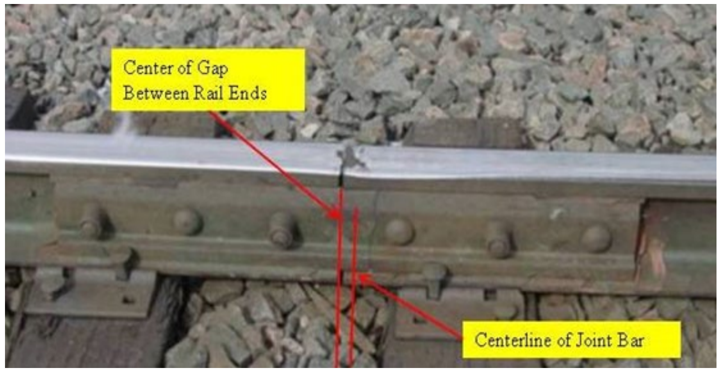


Figure F-8. Illustration of Center of Gap of Joint and Centerline of Joint Bar

After the failed bar is removed from the track, look for signs that the rail ends have been rubbing the top of the joint bar. Photographs of the condition before and after the joint bar is removed should be taken.

Longitudinal Bar Movement

Worn joint components such as elongated bolt holes or worn out bolts may result in longitudinal movement of the rail in relation to the joint bars. If movement occurs, the rail end may rub the easement area of the joint bar. An indication of joint bar movement is a shiny area in the web of the rail.

A measurement of the length of the shiny area provides an indication of the amount of longitudinal bar movement. Figure F-9 illustrates this condition.

Figure F-9. Illustration of Evidence of Longitudinal Bar Movement

Evaluation of Anchors at Failed Joint and Rail Longitudinal Movement

Different anchor patterns are found on the rail system. Elastic fasteners serve the same purpose to restrict longitudinal movement, as well as rail hold down and gage properties. On some occasions, both elastic fasteners and anchors are found at the same location. Whatever the anchor arrangement, it is important to evaluate the ability of the anchors to restrict longitudinal movement.

For continuous welded rail, typical anchor patterns are to “box” anchor every tie, every other tie, or every third tie. Typically, railroads apply 8 to 16 anchors per rail on jointed track. To evaluate anchors at a failed joint, look for signs of longitudinal movement. A rating of 1 is assigned to a condition where longitudinal movement is 2 inches or more, a severe condition. A rating of 2 is appropriate when some longitudinal movement is observed. Signs of longitudinal rail movement include evidence of plowing of the ballast in the cribs of crossties where the rail and ties are moving longitudinally. Other signs of rail longitudinal movement include observations that rail anchors are not tight against the sides of crossties. The amount of movement can often be determined by measuring from the anchors to the sides of the crossties. Sometimes, rail longitudinal movement is shown by markings on the top of the base of rails where spikes or other fasteners have rubbed the base of the rail when the rail moved longitudinally.

Figure F-10 shows a lack of anchors which caused crossties to become skewed with longitudinal movement. The amount of longitudinal movement can be estimated by determining how much the ties would have to be moved to restore their original perpendicular position.

Figure F-10. Results of Lack of Rail Anchors

Evaluation of Track Geometry at Failed Joint

Gage, crosslevel, profile and alinement geometry measurements should be taken at failed joint bars. Static measurements of these parameters are combined with measurements of vertical and lateral deflections to determine the values of these parameters under train loads. Methods to determine vertical deflection include measuring the space between the base of the rail and tie plates or ties and evidence of vertical movement of the ties in the ballast section. Evidence of lateral deflection includes the measurement of lateral plate movement and the movement of the base of rail in the tie plate. The following examples illustrate common techniques to evaluate under load geometry parameters.

Track Gage:

Figure F-11 shows evidence of lateral deflection as determined by the amount of the tie plate movement on the tie. In addition, any space between the base of the rail and the shoulder of the tie plate is also added to the static gage measurement. The gage under load value recorded is the sum of the static gage measurement and the amount of lateral deflection.

Figure F-11. Evidence of Tie Plate Movement

Appendix G.
Examples of Field Conditions Jointed Track Territory

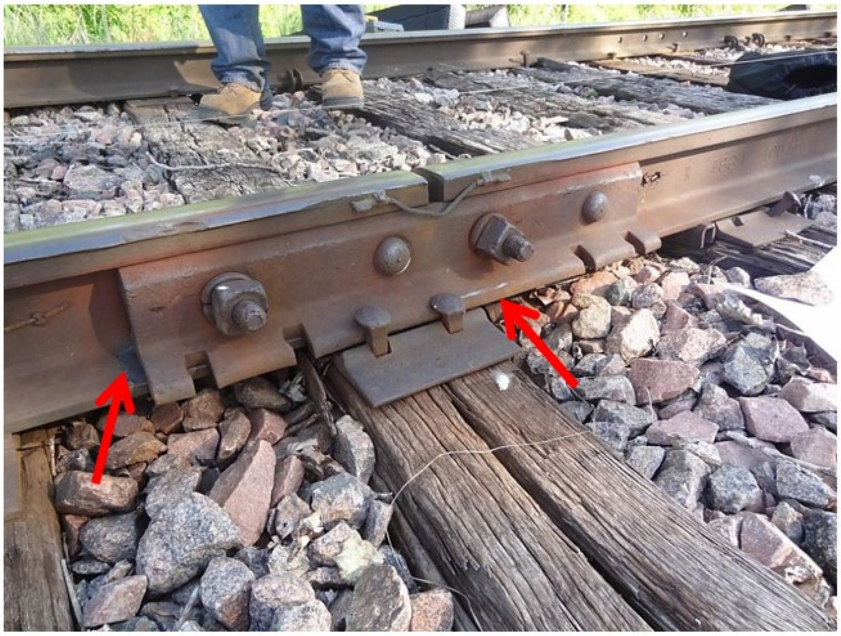
Examples of field conditions encountered during field investigations on jointed track territory are shown.

a) Gage Side View of a Rail Joint Defect in the Area of Large Longitudinal Movement

b) General View of Skewed Ties

Figure G-1: Test Zone B1 – Example of Large Rail Longitudinal Movement and Skewed Ties

Figure G-1 shows an example of a Class 2 location at test zone B1 with a large longitudinal rail movement (9 inches) resulting in skewed ties and narrow (tight) gage. There were two failed joints (#120516-010-0570 and #120516-010-0570) present in this area and the one shown on the photograph had a 56.25 inches static gage measurement with 0.25 inches of lateral movement and 1.0-inch vertical movement.



a) Field Side View of Signs of Longitudinal Bar and Rail Movement

b) Detail of Scratch Mark on Rail Base **c) Detail of Scratch Mark on Rail Head**

Figure G-2: Test Zone B1 – Example of Both Rail and Bar Longitudinal Movement

Figure G-2 shows an example of a Class 2 location at test zone B1 with longitudinal rail movement (3.5 inches) as well as joint bar longitudinal movement. There was a failed joint (#120516-001-0573) present at this location. The ballast and drainage were in good condition. However, marginal (split) ties were found under the joint. The location had a 56.25 inches static gage measurement with 0.75 inches of lateral movement and 0.5-inch vertical movement. The location also showed signs of a large joint bar movement (measured 0.5 inches).

a) Field Side View of a Defect in with Large Longitudinal Movement and Ineffective Tie

b) Detail of Gap between Rail Base and Tie Plate

Figure G-3: Test Zone B1 – Example of Location with Large Vertical Movement and Insufficient Joint Support

Figure G-3 illustrates a Class 2 case at test zone B1 (#120516-001-0573) with a large vertical joint movement rail movement (1.25 inches) and insufficient tie support. The tie under the joint was fully broken through and there was gap under the rail. The tie itself also showed signs of vertical movement due to fouled ballast in the area. The longitudinal rail movement was also present (2 inches), the static gage was 56.5 inches and lateral movement was measured to be 0.75 inches.

a) Broken Tie under a Failed Joint

b) Fouled Ballast in a Vicinity of a Failed Joint

Figure G-4: Test Zone B1 – Example of Fouled Ballast and Broken Tie in a Location with Large Vertical Movement

Figure G-4 shows the general condition of the location (#120516-001-0573) shown in Figure G-3 with a broken tie under the failed joint and fouled ballast in its vicinity.

a) Field Side View of an Intact Joint

b) Overall Track View

Figure G-5: Test Zone B1 – Example Intact Joint Location with Good Vertical Support and Longitudinal Movement Present

Figure G-5 gives an example of a typical Class 2 intact rail joint location at test zone B1 (#120515-005-0602) with very good vertical support conditions leading to no vertical movement. Even though the tie under the rail joint was marginally deteriorated it appeared to offer, in combination with ballast in good condition, a sufficient vertical support. Longitudinal rail movement of 2 inches was, however, present, and resulted in slightly skewed ties. The static gage was subsequently also slightly below nominal at 56.375 inches and lateral movement was measured to be 0.125 inches. Rail ends were in good condition.

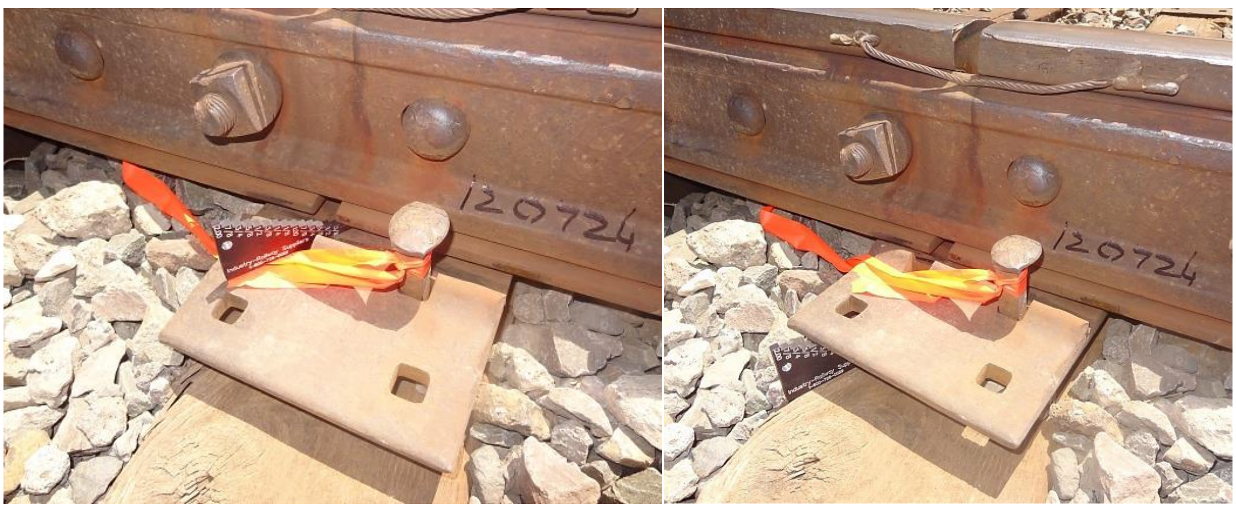
a) Rail End Batter at Location #120726-001-0404

b) 40'' Tie Spacing at Location#120723-010-0232

Figure G-6: Test Zone C – Example of Rail End Batter and 40'' Tie Spacing

Photograph a) in Figure G-6 shows an example of a 0.18-inch rail end batter in combination with "swinging ties" and the photograph b) in the same figure shows an example of skewed ties resulting in 40-inch spacing between ties under the rail joint. The photographs document two different Class 3 failed bar locations and #120726-001-0404 and #120723-010-0232 respectively, both located at test zone C.

a) Gage Side View



b) Measurement of Gap between Rail Base and Tie Plate c) Measurement of Gap between Tie Plate and Tie

Figure G-7: Test Zone C – Example 1 of a Failed Bar Location with a Large Vertical Movement

Figure G-7 shows an example of a Class 3 failed bar location (#120724-010-0344) at test zone C with a vertical movement of 2 inches. The factors contributing to the vertical movement were "swinging ties," a loose tie plate, plate cutting and pumping ties. The static gage in this location was 56.5 inches, lateral movement was 0.125 inches and longitudinal movement was 1.5 inches. No rail end batter was measured but the gap between the rail ends was 0.75 inches.

a) Gage Side View

b) Skewed Ties and Fouled Ballast

Figure G-8: Test Zone C – Example 2 of a Failed Bar Location with a Large Vertical Movement

Figure G-8 shows an example of a Class 3 failed bar location (#120724-009-0370) at test zone C with a large vertical movement. Plate cutting and pumping ties contributed to the 1.25 inches of vertical movement. The static gage in this location was 56.25 inches. No lateral movement was present while the longitudinal rail movement was 5 inches. Skewed ties were also found in the vicinity of the failed joint. Minor rail end batter (0.04 inches high) was recorded.

Figure G-9 shows another example of a Class 3 failed bar location (#120726-001-0404) with a large vertical movement, measured to be 1.75 inches. Factors contributing to the vertical movement were “swinging ties,” loose tie plates, fouled ballast and pumping ties. The ties were in good condition. The static gage in this location was 56.625 inches, lateral movement was 0.25 inches and longitudinal rail movement was 3 inches. Moderate rail end batter was also present

(0.18 x 6.0 inches).

a) Field Side View

b) Measurement of Gap between Rail Base and Tie Plate

c) Signs of Tie Pumping on the Face of the Tie

d) Signs of Tie Pumping on the Side of the Tie

Figure G-9: Test Zone C – Example 3 of a Failed Bar Location with a Large Vertical Movement

a) Field Side View

b) Measurement of Gap between Rail Base and Tie Plate **c) Signs of Tie Pumping**

d) Sign of Longitudinal Movement **e) Sign Longitudinal Movement near a Fastener**

Figure G-10: Test Zone C – Example 4 of a Failed Bar Location with a Large Vertical Movement

Next example of a Class 3 failed bar location (#120726-004-0410) at test zone C with a large vertical movement is shown in Figure G-10. The measurement was 1.625 inches and the factors contributing to the vertical movement were “a swinging tie,” fouled ballast and a pumping tie (the tie itself in a good condition). The static gage in this location was 56.625 inches, lateral movement was 0.125 inches and longitudinal rail movement was 3.5 inches. Moderate rail end batter was present at this location (0.15 x 3.0 inches) and 0.5 inches longitudinal bar movement was also measured.

Figure G-11 presents one of the Class 3 fail joint locations (#140505-002-0224) on test zone C during the second visit in May 2014. This rail joint is not adequately supported and contains very large vertical movement of 2.125 inches. Lateral and longitudinal movements were 0.25 and 2.5 inches respectively at this location. Marginally deteriorated ties, insufficient ballast at the rail joint and significant rail end batter (0.22 x 5.0 inches) was also present, contribution to the inadequate vertical support.

a) Field Side View

b) Insufficient Ballast at Rail Joint

Figure G-11: Test Zone C – Example 5 of a Failed Bar Location with a Large Vertical Movement

a) Field Side View

b) Gage Side View

c) Signs of Tie Movements **d) Chipped Rail Ends**

Figure G-12: Test Zone C – Crowned Failed Joint Location with a Large Vertical Movement

Several crowned[1] rail joints with a joint bar defect and large vertical movement were also encountered during the second visit to test zone C. Figure G-12 illustrates one those locations (#140528-004-0504) at Class 3. The vertical movement in this case was 1.375 inches and static

[1] "Crowning" is a term for a procedure where a rail joint has been previously left slightly higher (humped) during tamping with intention to result in a zero-surface condition after train traffic.

profile was -0.25 inches (high joint). Tie plate was missing on the tie directly under the joint centerline and adjacent ties exhibited signs of significant plate cutting. Deteriorated rail ends were also observed, containing rail end batter of 0.116x2.75 inches and large portions the rai material chipped away.

a) Field Side View

b) Gage Side View

c) Top View of Rail Ends

Figure G-13: Test Zone C – Example 1 of an Intact Bar Location

A typical example of a documented Class 3 intact joint location at test zone C (#120723-005-

0229) with very good track conditions and minimal or no rail end batter is represented in Figure G-13. Good support and tie conditions (no vertical and lateral movement, longitudinal movement 0.5 inches), minimal geometry deviations (0 alinement and profile under load, crosslevel under load 0.3125 inches) and minimal rail end batter (0.03 x 3.0 inches) were observed.

a) Field Side View

b) Gage Side View

c) Top View of Rail Ends

Figure G-14: Test Zone C – Example 2 of an Intact Bar Location

Another example of a Class 3 intact joint location at test zone C (#140530-007-0533) this encountered in 2014 with very good track conditions and minimal or no rail end batter is represented in Figure G-14. Good support and fair tie conditions (minimal tie splitting, vertical and lateral movement both 0.125 inches, longitudinal movement 0.5 inches), and minimal rail end batter (0.015 x 0.75 inches) and no geometry deviations were observed.

a) Gage Side View

b) Rail End Batter Magnitude Illustration

c) Signs of Longitudinal Movement

d) Gap between Rail and Tie Plate

Figure G-15: Test Zone D – Example a Failed Bar Location with a Large Rail End Batter

Figure G-15 illustrates one of the Class 3 failed joint locations (#130325-017-0681) on test zone D with very large rail end batter (0.359 x 14.0 inches). This rail joint also contains 0.67 inches vertical, 0.25 lateral, and 2.5 inches longitudinal movements. Ties are in good conditions. Note that the straight edge in photograph b) of Figure G-15 is positioned in a way to demonstrate the severity of the rail end batter. When actual measurements of rail end batter were taken, a ramp on each rail end is assessed separately according to the procedure outlined in the Instruction

Handbook described in Appendix D of this report.

a) Gage Side View

b) Field Side View

Figure G-16: Test Zone D – Example a Failed Bar Location with a Large Vertical Movement

Figure G-16 shows one of the Class 3 fail joint locations (#130325-002-0675) on test zone D with very large rail vertical movement of 2.0 inches. Deteriorated, split and pumping ties with significant plate cutting are present in this location. Mildly fouled ballast also contributes to the insufficient support conditions. Lateral movement of 0.25 inches and rail end batter of 0.146 x 7.5 inches were also measured.

a) Gage Side View

b) Chipped Rail Ends

Figure G-17: Test Zone D – Example a Failed Bar Location with Good Tie Conditions

Several failed joint locations with good tie conditions were also encountered during the field surveys. Figure G-17 shows one of those Class 3 locations (#130325-010-0678) on test zone D. Vertical movement of 0.675 inches was still recorded, however, due to gaps between rails and tie plates and the movement of the ties themselves. Lateral movement of 0.25 inches and rail end batter of 0.125 x 7.0 inches were also measured. No longitudinal movement was recorded. This location also contained deteriorated rail ends with significant chipping.

a) Field Side View

b) Gage Side View

c) Top View of Rail Ends

Figure H-18: Test Zone D – Example of an Intact Bar Location

An example of a documented Class 3 intact joint location at test zone D (#130326-004-0688) with very good track conditions and minimal rail end batter is represented in Figure G-18. Good support and tie conditions (minimal tie splitting, vertical and lateral movement 0.125 inches and 0.187 inches respectively, and longitudinal movement 0.5 inches), minimal geometry deviations and minimal rail end batter (0.064 x 5.75 inches) were observed. One of the rail ends was, however, significantly chipped.

a) Gage Side View

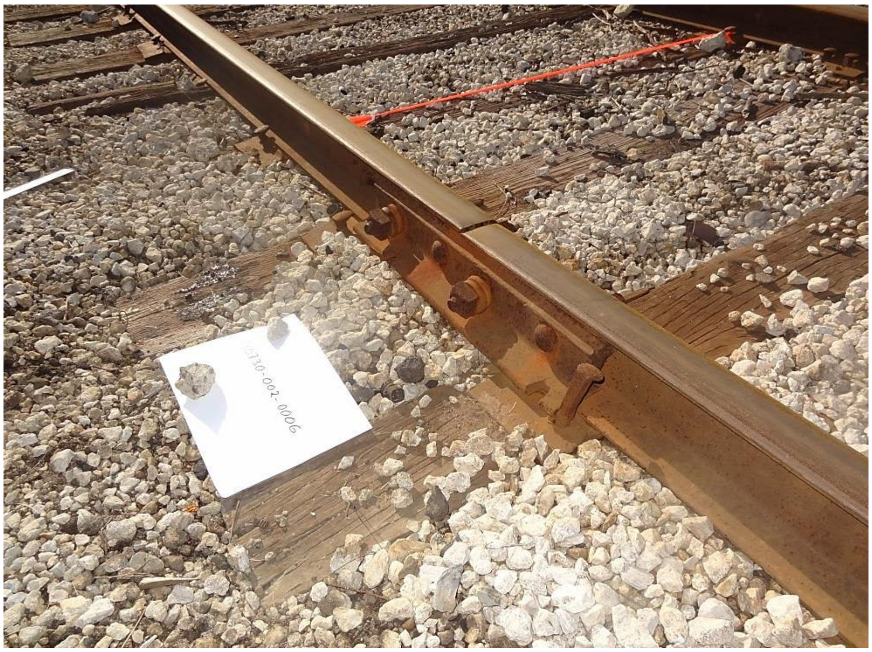
b) Field Side View

c) Gap between Rail and Tie Plate

d) Signs of Tie Pumping

Figure G-19: Test Zone F1 – Example a Failed Bar Location with a Large Vertical Movement and Crosslevel under Load

An example of a Class 1 failed joint on test zone F1 (#130729-003-0011) with large vertical movement and crosslevel under load is presented in Figure G-19. Void between rail and tie plate and extensive tie pumping contributed to vertical movement of 1.25 inches. This location was a low joint with crosslevel under load of 3.125 inches. Lateral and longitudinal movement of 0.123 inches and 1.0 inches respectively and rail end batter of 0.068 x 6.625 inches were measured. The tie directly under the rail joint was in a very good condition compared to the surrounding ties and appeared to be recently replaced.



a) Field Side View

b) Gage Side View

c) Spike in Bar Slot Causing Tie Split

Figure G-20: Test Zone F2 – Example a Failed Bar Location with a Large Tread Mismatch

Class X failed joint on test zone F2 (#130730-002-0006) with large tread mismatch of 0.235 inches is shown in Figure G-20. Additional rail batter of 0.75 x 4.625 inches was also measured. Vertical movement of 0.4375 inches was observed at this location. Spike in a bar slot caused a spit at one of the ties.

a) Field Side View

b) Gage Side View

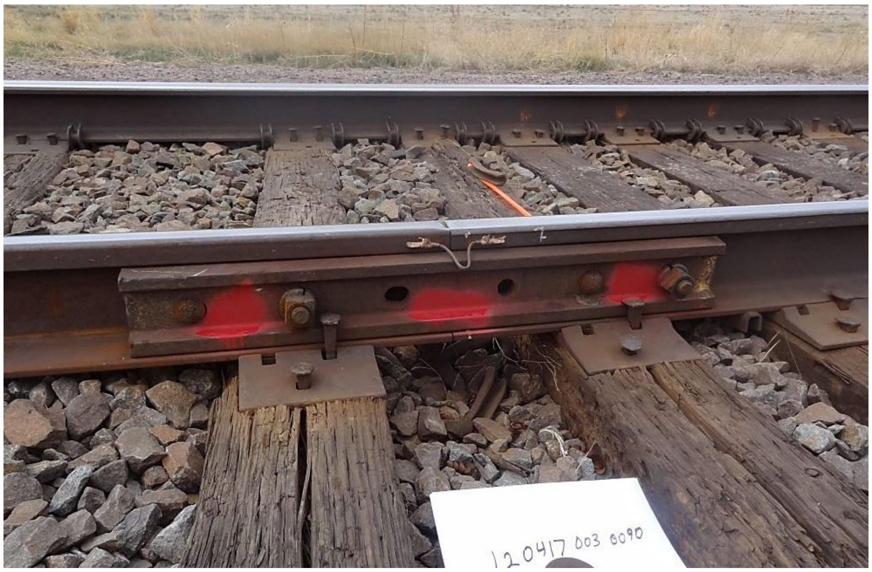
c) Top View of Rail Ends

Figure G-21: Test Zone F1 – Example of an Intact Bar Location

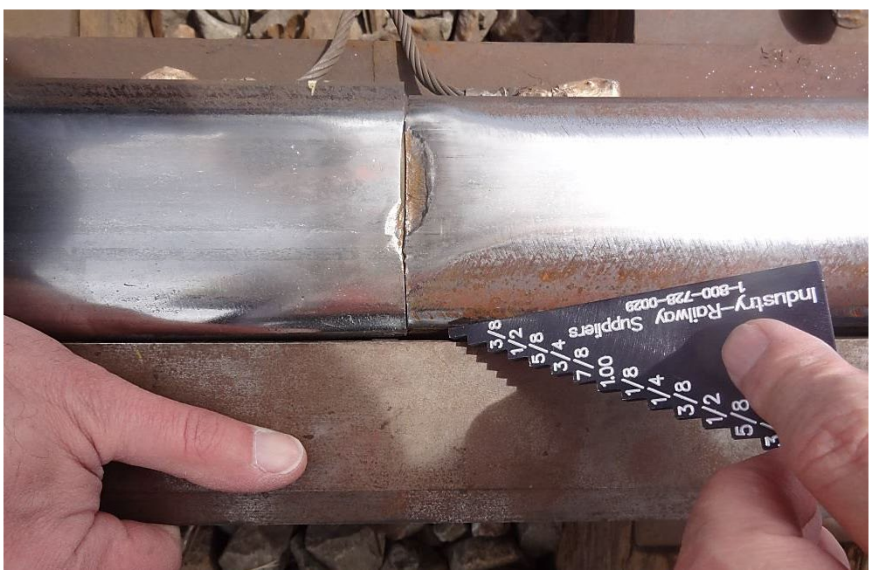
The last example of encountered field conditions is a Class 1 intact joint location at test zone F1 (#120729-005-0008) with very good track conditions and minimal rail end batter represented in Figure G-21. Good support and tie conditions (no vertical and minimal lateral movement), minimal geometry deviations and minimal rail end batter (0.043 x 5.75 inches) were observed.

Appendix H.
Examples of Field Conditions CWR Territory

Examples of field conditions encountered at all five failed and selected intact rail joint locations during field investigations on CWR territory are shown.



a) Field Side View



b) Measurement of Gage Mismatch

Figure H-1: Test Zone A – General Field Conditions at Frist Failed Rail Joint

Figure H-1illustrates the general conditions in the vicinity of the first encountered defect on test zone A (location #120417-003-0090) and shows a measurement of a 1/8-inch gage mismatch. The two middle bolts were not installed, and the bolt holes were not drilled indicating that the joint was a temporary joint and intended to be welded in the future. The joint exhibited good ballast and drainage conditions with marginal ties (see Appendix E for the definition of track conditions such as good or bad drainage, marginal or ineffective ties, etc.). Vertical and lateral movement, profile under load, and alignment were all measured to be 1/8 inch. Crosslevel under load was 0.375 inches low and gage under load was 56.625 inches (see Appendix D for the definition of profile and alinement measurements (using 62-foot cord length in all cases) and method for obtaining under load values). Signs of longitudinal movement were not observed. Vertical rail end ramp was measured to be 0.025 inches high and 1 inch long.

Figure H-2 and Figure H-3 illustrate the general conditions at the next encountered defect on test zone A (#120417-004-0061), which exhibited rail end ramp, mismatch, and evidence of lateral movement.

a) Field Side View

b) Battered Down Rail Head

Figure H-2: Test Zone A – General Field Conditions at the Second Failed Rail Joint

Figure H-2 illustrates the overall conditions in the vicinity of this defect. Also shown is an abrupt rail end ramp that apparently resulted from repeated wheel impact loads that caused the rail end to be battered down when a repair rail with a significant tread mismatch was installed. The two middle bolts were missing, and bolt holes were not drilled indicating the temporary nature of the joint.

a) Rail End Ramp Measurement

b) Measurement of Lateral Movement

Figure H-3: Test Zone A – Selected Measurements at the Second Failed Rail Joint

Figure H-3 illustrates the measurement of rail end ramp and lateral movement. Good ballast and drainage conditions were present at the location. One ineffective tie was found under the joint. Vertical and lateral movements were measured to be 0.375 inches, and the longitudinal movement was 0.625 inches. Crosslevel under load was 1.5 inches low, profile under load 0.375 inches, and gage under load was 56.75 inches. As mentioned above, the head of the new rail was battered down, creating a 1/16-inch gage mismatch and a 1/16 gage ramp. A 0.375-inch-high and 3 inches long rail end ramp and a 0.25-inch tread mismatch were measured at this location. Overall, the joint exhibited a large rail end misalignment.

a) Field Side View

b) Sign of Longitudinal Bar Movement

Figure H-4: Test Zone A – General Field Conditions at the Third Failed Rail Joint

Figure H-4 shows the third and last failed bar location found at test zone A (#120418-004-0053). This joint was located in a turnout and didn't exhibit any significant deviations in geometry, lateral or vertical movement, although the joint exhibited signs of longitudinal bar movement. A moderate rail end ramp was present. The turnout appeared to have relatively new switch ties and ballast. Missing middle bolts and bolt holes not drilled again indicated a temporary joint. The ballast, drainage and ties were in very good condition. No vertical movement or lateral movement was found. The gage under load was a nominal 56.5 inches and crosslevel under load, profile under load and alinement were all zero. The bar longitudinal movement was measured to be 0.1875 inches. Rail end ramp was 0.1 inches high and 3 inches long and a 1/16-inch gage ramp was also present which may have increased the wheel impact loads at the joint. A gap between rail ends of 0.75 inches was also measured. It is possible that the initiation of the crack occurred before switch tie replacement and surfacing or was a consequence of the maintenance work.

a) Field Side View

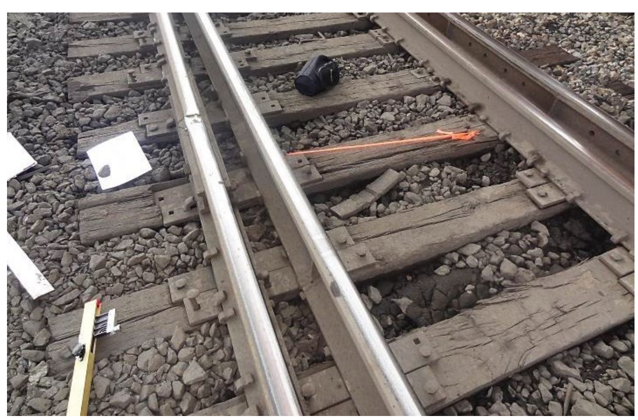
b) Deteriorated and Battered Down Rail Ends

Figure H-5: Test Zone F5 – General Field Conditions at the Fourth Failed Rail Joint

Figure H-5 shows the first failed joint found at test zone F5—fourth failed joint overall on CWR (#130801-003-0520). Missing middle bolts and bolt holes not drilled indicated a temporary joint. Insufficient and mildly fouled ballast, tie pumping and slight plate cutting contributed to vertical movement of 0.875 inches. Lateral movement of 0.125 inches was measured, no longitudinal movement was recorded. Profile under load and crosslevel under load and alinement were 1.5 inches, 1.875 inches and 0.5 inches respectively. Rail ends at this location were significantly chipped and battered down—rail end ramp of 0.234 x 5.75 inches was measured.

a) Field Side View

b) Gage Side View



c) Deteriorated and Battered Down Rail Ends **d) Fouled Ballast**

Figure H-6: Test Zone F5 – General Field Conditions at the Fifth Failed Rail Joint

Figure H-6 shows the second failed joint found at test zone F5—fifth and last failed joint overall on CWR (#130801-004-0516). Missing middle bolts and bolt holes not drilled indicated a temporary joint. Heavily fouled ballast, significant tie pumping, compromised drainage and plate cutting contributed to vertical movement of 0.5 inches despite no measurable gap between the rail and tie plate. No lateral movement was measured; 0.25 inches longitudinal movement was recorded. Profile under load and crosslevel under load and alinement were 1.125 inches, 1.312 inches and 0.375 inches respectively. Rail ends at this location were again significantly chipped and battered down – rail end ramp of 0.172 x 5.875 inches was measured.

a) Field Side View

b) Gage Side View

Figure H-7: Test Zone A – Example of Intact Insulated Joint – Good Track Conditions

Figure H-7 shows an intact permanent insulated joint location (#120419-002-0006) at test zone A with very good track conditions and minimal rail end misalignments. Negligible lateral and longitudinal movement were present. Zero vertical movement, profile under load and alinement were measured. Crosslevel under load was 0.25 inches low and gage under load was nominal

56.5 inches. Very small rail end batter was also measured at this location (0.025 x 3.0 & 0.015 x 1.0 inches).

Figure H-8 and Figure H-9 illustrate deteriorated track conditions at an intact temporary joint location on test zone A (#120419-009-0008).

a) Field Side View

b) Gage Side View

Figure H-8: Test Zone A – Example an Intact Joint Location – Deteriorated Track Conditions

Figure H-8 shows fouled ballast, split and plate cut ties, and loose or missing fasteners. The measured lateral movement was 0.25 inches, longitudinal movement was 0.5 inches and vertical movement was 1.125 inches. Gage was nominal at 56.5 inches, crosslevel under load was 1.125

inches low and profile under load was 1.875 inches. The gap between rail ends was 0.75 inches. An abrupt rail end ramp of 0.14 x 3.0 inches was measured in combination with a 0.15 tread mismatch and a 1/16 x 1.0-inch gage ramp. In addition, the joint exhibited signs of 0.375 inches of joint bar longitudinal movement on both the gage and field side bar.

a) Gage Side View

b) Fouled Ballast

Figure H-9: Test Zone A – Example an Intact Joint Location – Fouled Ballast

Figure H-9 shows missing or pulled up fasteners in the vicinity of the rail joint and fouled ballast in the general surrounding area.

a) Field Side View

b) Rail End Conditions

Figure H-10: Test Zone F3 – Example an Intact Joint Location – Good Track Conditions

Figure H-10 shows intact temporary rail joint location from test zone F3 (#130731-003-0047) with very good track support. Ballast and ties were both in good condition. No vertical movement and geometry conditions were recorded. Only moderate rail end batter of 0.125 x 6.75 inches was measured.

Investigated intact temporary rail joint locations on concrete tie track, test zone E, were characterized by very good support and rail end conditions. One example (#130617-007-0413) is shown in Figure H-11. No joint movements, rail end or geometry conditions were observed.

a) Field Side View

b) Gage Side View

c) Overall View

Figure H-11: Test Zone E – Example 1 of an Intact Joint Location on Concrete Tie Track

a) Field Side View

b) Gage Side View

c) Overall View

Figure H-12: Test Zone E – Example 2 of an Intact Joint Location on Concrete Tie Track

Another example (#130619-003-0407) of such location is shown in Figure H-12. No joint movements, rail end or geometry conditions were observed despite the joint being equipped with only one fastener.