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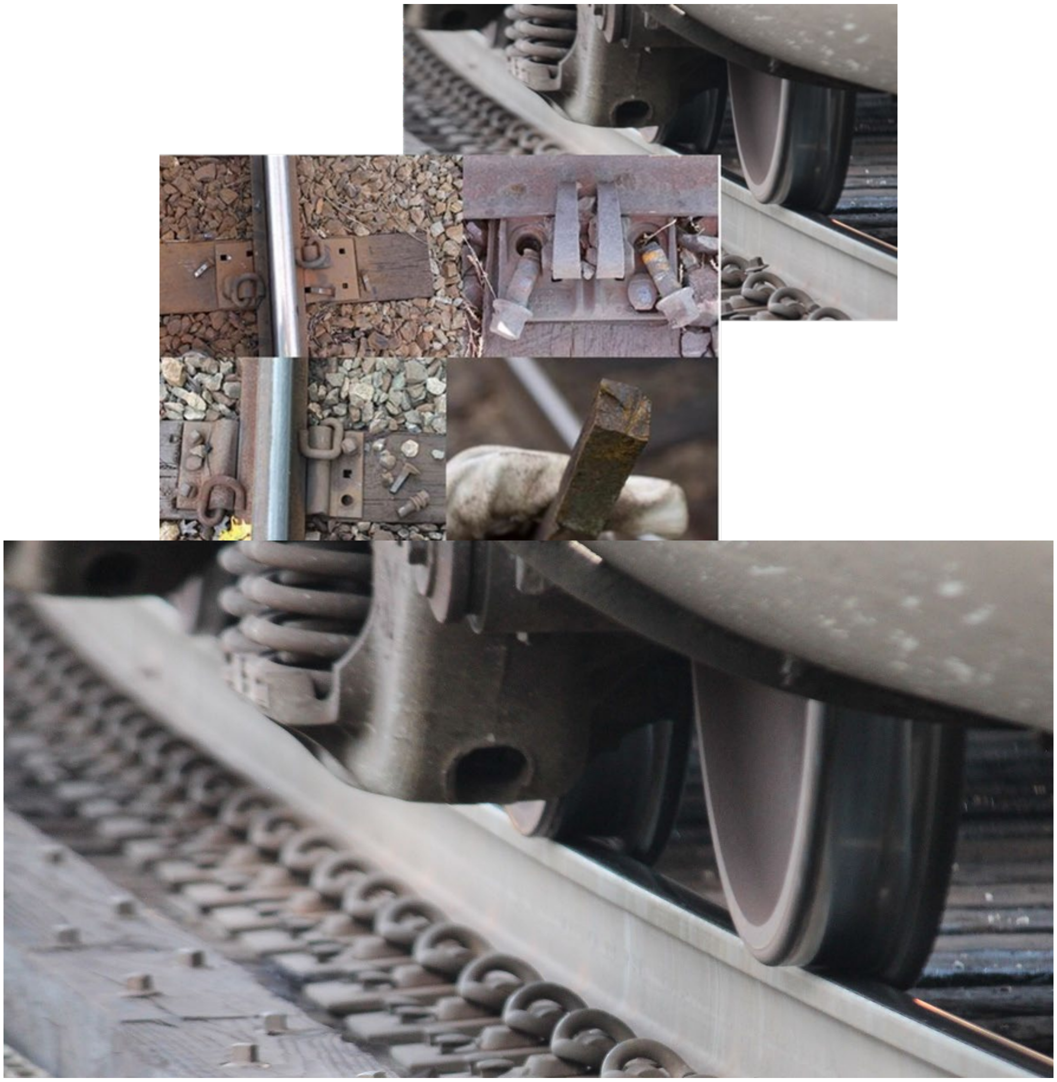
Washington, DC 20590

Mechanistic Investigation of Timber Crosstie Spike Fastener Failures – Phase I: The Magnitude of the Spike Failure Challenge



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13. ABSTRACT (Maximum 200 words)

The Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) performed a literature review, conducted an industry-wide survey, and arranged multiple field visits to examine and quantify the challenges North American railroads are facing with broken spikes in timber crosstie track. Research was conducted between January and October of 2018. This report summarizes the project objectives, reviews fastening system designs for timber crossties, examines multiple broken spike derailment reports, reviews published literature regarding spike breakage, documents the results of a rail industry survey, summarizes field visits to multiple Class 1 locations experiencing broken spikes, and documents interviews with railroaders conducted in relation to these field visits. The research data concludes that spike failures are difficult to inspect for in track, are the cause of at least 10 derailments and are an ongoing issue in curves on at least 5 Class I railroads. The report offers a set of hypotheses to explain why spikes fail in certain areas of timber-tied track and proposes additional research to isolate the root cause(s) of these failures through laboratory experimentation and analytical finite element modeling (FEM).

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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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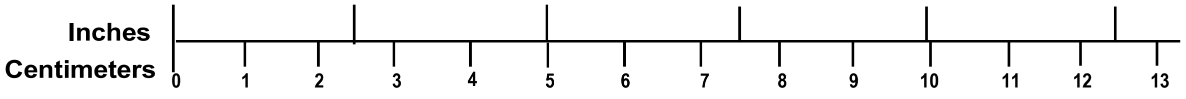

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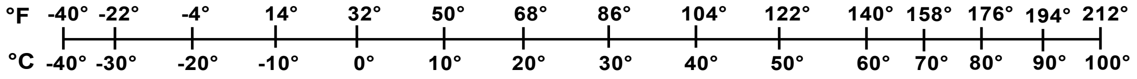


Contents

Illustrations

Tables

Executive Summary

This report documents the first phase of a project funded by the Federal Railroad Administration (FRA), titled *Mechanistic Investigation of Timber Crosstie Spike Fastener Failures*. The Rail Transportation and Engineering Center (RailTEC) at the University of Illinois Urbana-Champaign (UIUC) performed a detailed literature review, conducted an industry-wide survey, and arranged multiple field visits to examine and quantify the problems North American railroads are facing with broken spikes in timber crosstie track. The project was executed between January and October of 2018.

This report summarizes the project objectives (Section 1) and gives a brief introduction to fastening systems for timber crossties (Section 2). Section 3 examines multiple broken spike derailment reports and reviews published literature regarding spike failures in heavy axle load (HAL) freight train environments. The research team found limited published literature documenting prior broken spike research and noted inconsistencies in current best practices regarding the selection and use of fastening systems.

Section 4 documents a rail industry expert survey that was developed and executed by the UIUC research team. The research team designed the survey to clarify the challenges caused by broken spikes. Class I railroads and other participants provided valuable insight into the severity of the broken spike problem, the characteristics of broken spike locations, and the current inspection practices used to locate broken spikes in track. The survey found that broken spikes are often found in premium fastening systems in curved track with new crossties, but the problems do occur in other track types. Also, inspecting for broken spikes can be time- and labor-intensive. Respondents identified the rapid gage deterioration associated with broken spikes as one of their key safety concerns.

UIUC researchers also visited multiple field locations to characterize the magnitude of the problem. The field visits were designed to better understand the nature of the locations where spikes fail, including traffic characteristics, track design, and local maintenance practices. The results from field visits are documented in Section 5. In general, the field visits aligned with prior findings (survey and literature) in that spike breakage occurs in a variety of types of territories with different types of fastening systems and spikes. The most severe case found during the field site visited was a curve having 121 broken spikes. Section 5 also includes several interviews with railroaders.

The consensus from the literature review, survey, and field visits is that spike breakage is leading to wide gauge derailments and has become an inspection challenge on North American Class I railroads. Based on the research presented in this document, the authors propose continuing to Phase II of project to better understand the mechanisms leading to spike breakage and what can be done to prevent it in future fastening system designs, Section 6. Section 7 offers a complete set of hypotheses regarding the causes of spike breakage as well a proposed path forward for testing through laboratory experimentation and analytical finite element modeling.

1. Introduction

This report documents the first phase of a project funded by the Federal Railroad Administration (FRA), titled *Mechanistic Investigation of Timber Crosstie Spike Fastener Failures*. Between January and October of 2018, the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois Urbana-Champaign (UIUC) performed a detailed literature review, conducted an industry-wide survey, and arranged multiple field visits to examine and quantify the problems North American railroads are facing with broken spikes in timber crosstie track. This project was originally designed to be split into three distinct phases, corresponding to the following three overarching questions, with each phase addressing each question:

1. How large of a problem are spike failures? (subject of this Phase 1 report)
2. What is causing broken spike failures?
3. What can be done to prevent broken spike failures?

1.1 Background

Approximately 94 percent of railroad track is supported by ballast. A ballasted track system consists of the rail, fastening systems, crossties, ballast, sub-ballast, and subgrade. Rail fastening systems, in conjunction with the crosstie, secure the rail to maintain gauge, transmit thermal and service loads, and anchor the rail-crosstie structure against lateral and longitudinal movements. Fastening systems must transmit vertical, lateral, and longitudinal loads.

Timber crosstie fastening systems employing elastic fasteners (e.g., e-clip, tension clamp, etc.) and spikes (e.g., cut, screw, drive, etc.) have proven benefits in preventing rail rollover derailments in curves. However, elastic fastening systems have also been the source of broken spike derailments. There has been an increased focus on quantifying the mechanics of these spike failures and on developing failure mitigation strategies to increase the safety of the track system.

1.2 Objectives

The objective of Phase 1, and the focus of this report, is to quantify the magnitude of the broken spike problem and determine if it is a major, nationwide issue that threatens the safety of train operations, or a small, localized issue that occurs infrequently.

1.3 Overall Approach

To achieve the objectives of Phase 1, researchers:

- Examined reports documenting broken spikes derailments
- Reviewed and authored relevant literature
- Conducted a survey of railroads (and other organizations) to glean more information and to better quantify its nature and severity
- Conducted numerous field visits to locations where spikes were known to break (or not break) to better understand the characteristics of these locations

    - These field visits provided an opportunity to interview railroaders to gather first-hand accounts on spike breakage
- Summarized the findings in this report, which suggest that spike breakage is a serious and potentially dangerous problem that merits further investigation

1.4 Scope

This report documents the findings from each activity listed in Section 1.3 as well as the proposed future work to be executed in future phases.

1.5 Organization of the Report

This report is divided into seven sections, including this introduction. Section 2 provides additional details into the background of the problem and definitions for this report. Section 3 provides a detailed review of previous accidents and relevant literature. Section 4 presents findings from the industry survey. Section 5 summarizes the field visits and in-person interviews. Section 6 provides the conclusions from Phase 1, and Section 7 presents recommendations for future work.

2. Introduction to Timber Crosstie Fastening Systems

This section introduces the fastening systems used on North American heavy-axle load (HAL) timber crosstie track and describes the mechanistic functions these systems are designed to fulfill.

2.1 Traditional Fastening Systems

For the purposes of this report, "traditional fastening systems" refers to those that use a standard rolled tie plate (e.g., AREMA 14-inch plate) with cut spikes and rail anchors to secure the rail to a timber crosstie, as shown in Figure 1. This is by far the most common fastening system design used by U.S. railroads.

Figure 1. "Traditional" fastening system

One variation on the traditional fastening system are plates with curve blocks. Curve blocks are designed to prevent rail rollover without clamping the rail to the tie plate. They are typically installed on every third or fourth crosstie in curves, depending on the individual railroad's standard. Plates with curve blocks still use rail anchors, as with the typical traditional system. An example is shown below in Figure 2.

Figure 2. Traditional fastening system with curve blocks installed

2.2 Premium Fastening Systems

Premium fastening systems clamp the rail to the tie plate with elastic clips. These systems come in many varieties. Common types include e-clips, McKay clips, and SKL clips. The tie plate may be a rolled plate, a Victor plate, a cast plate, or other. The spikes also vary, and include cut spikes, screw spikes, lag screws, lock spikes (i.e., "hair-pins"), and others.

Many Class I railroads have installed these systems in their most demanding territories, typically areas with high degree curves and/or steep grades, or areas within special track work. There are several reasons railroads are installing these premium fastening systems, including:

- They provide greater rail-rollover restraint as compared with traditional fastening systems.
- They do not require rail anchors to provide longitudinal restraint because the clamping force of the elastic clip provides sufficient resistance. [1]
- They provide greater gage strength as compared with traditional fastening systems. [2]
- They may help prevent spike-kill of crossties [1]in demanding territories, where increased rail wear leads to more frequent rail changes. Traditional fastening systems are usually replaced with the rail, requiring re-spiking. Premium fasteners offer the possibility to remove the clip and leave the plate in place, thus eliminating the need to re-spike the crosstie. However, railroads reported that this is not a standard procedure.

Photos of common premium fastening systems are shown below in Figure 3.

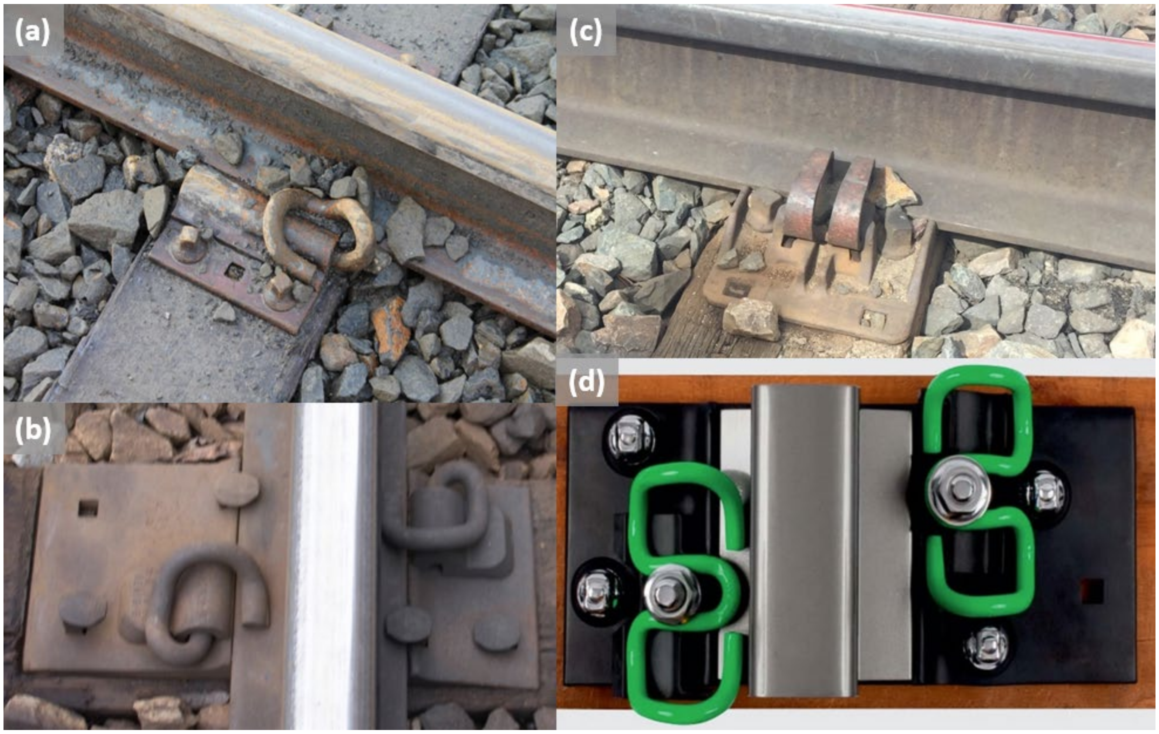


Figure 3. Examples of premium fastening systems: (a) Pandrol rolled plate ("double-shoulder plate") with PR clips, (b) Victor plate (c) McKay clip system (d) Vossloh BT-30

3. Review of Derailment Reports and Published Literature

Broken spikes were the cause of wide gauge derailments in several recent incidents. In this section the team summarizes the findings from a review of available reports and other data sources to illustrate the characteristics of spike failures and the severity of the derailments caused by broken spikes. Table 1 summarizes the incidents reviewed.

Table 1. Summary of known accidents involving broken spikes

Railroad	Year	Location	Fastener Type	Source
TRRA	2001	Sauget, IL	Unknown	FRA Accident Data
CN	2005	Cusson, MN	Unknown	FRA Accident Data
BNSF	2006	Glacier Park, MT	Unknown	Field Interview
UP	2006	Dingle, ID	Unknown	FRA Accident Data
BNSF	2008	Bridgeport, NE	Unknown	Industry Survey
NS	2009	Hammond, IN	Unknown	FRA Accident Data
CN	2011	Montreal, QC	Traditional	TSB Canada
CN	2012	Fabyan, AB	Pandrol plates with screw spikes	TSB Canada
NS	2014	Vandergrift, PA	Victor plates with cut spikes	WRI Presentation
NS	2015	Cincinnati, OH	Victor plates with cut spikes	Field Interview
UP	2016	Mosier, OR	McKay clip system with screw spikes	FRA Accident Brief

3.1 Fabyan, AB

On January 21, 2012, Canadian National Railway (CN) manifest freight train M30141-20 was traveling 41 mph between Winnipeg and Edmonton when it derailed in a curve on a bridge approach near Fabyan, AB. Thirty-one cars derailed, 17 of which fell off the bridge and into the Battle River below.

The accident and subsequent investigation are documented in the Transportation Safety Board of Canada (TSB Canada) report R12E0008 [3]. The train weighed 12,724 tons and was using dynamic braking as it descended a 0.4 percent grade. The temperature at the time was -25° C. Train handling and mechanical issues were eliminated as causes.

The 4° curve was superelevated 3.6 inches with a posted 40-mph track speed. The track had contained a mix of softwood and hardwood crossties until 2004, when all crossties were changed to hardwood. The rail was secured to the crossties using a premium fastening system comprised of 16-inch rolled plates and elastic clips. The rolled plates did not have a ribbed bottom designed to embed into the crosstie, as some other less common cast plate designs do. Four screw spikes in each plate held the plates to the crossties, as shown in Figure 4.

Figure 4. Broken screw spikes (left) and rolled plates (right) [3]

The report claimed the rail was box-anchored at every crosstie, but no photos are available showing these anchors.

Plate cutting of the ties suggested wide gauge as a possible cause of the derailment. Track geometry car reports from the previous summer and fall showed that the curve had registered several "near-urgent" defects for wide gauge up to 1.125 inches (below the Canadian regulatory requirement for Class 3 track), thus indicating that gage widening had been an ongoing issue in the curve. Further, the high rail rolled over in the derailment, and in some places the plates had pulled screw spikes out of the crossties as the rail rolled over.

The curve was found to have many broken screw spikes. The report does not give the exact number of broken spikes but does mention that 74 were retained for investigation. These screws had two threads per inch and were either 7.5 or 8.5 inches long. They originated in four different batches from three different manufacturers. CN used multiple spike manufacturers because of ongoing problems with spikes breaking in service. The screw spikes met all relevant specifications.

Investigators found that the spikes had fatigue failures, with fatigue cracks starting in the upper portion of the threaded shank. The report states that multiple fatigue origins suggested the failures were due to "general stress conditions rather than any material defect," that is, their failure was a mechanism problem, not a material problem. Further, the age of the cracks in the screws varied from several years to just days before the accident.

The report states,

> "In this occurrence, a number of lag screws in the vicinity of the POD broke off in the tie. The breaks, which occurred over a considerable period of time, were due to fatigue at the transition point between the shank and the threads, where the cross-sectional area is reduced. Even with broken lag screws, there was little indication that the curve was under stress, as track gauge was maintained by the lag screws that did not break. The remaining (intact) lag screws experienced much higher lateral curving forces. The derailment occurred when the remaining screw fasteners were insufficient to resist the lateral curving forces; the high rail then rolled under the train, resulting in wheels falling into gauge at the east end of Fabyan Bridge. Signs of wide gauge are normally more apparent in curves with conventional spike fasteners. If a track with conventional fastenings is under excessive lateral stress, the rail will cant, spikes will rise and stay up, and plate cutting on the field side will be more pronounced. These conditions would likely be noted during routine track inspections."

In conclusion, the broken spikes in the track allowed gage widening and reduced rail-rollover restraint, both of which were relatively challenging to detect. Following the derailment, CN updated its track inspection standards to require that during walking inspections of curves, turnouts, and bridge decks with screw spikes, crosstie plates be struck with a lining bar to determine if they are loose or if spikes rattle. CN also required that, for every tenth crosstie, an attempt be made to physically pull screw spikes out of the crosstie.

3.2 Vandergrift, PA

In February 2014, an eastbound Norfolk Southern (NS) train carrying crude oil derailed at Vandergrift, PA. The train was traveling on the Conemaugh Line, a route that curves along the Allegheny and Kiskiminetas rivers.

The information presented here was obtained from a presentation made by Brad Kerchof (Director of Research and Tests at NS) at a Wheel-Rail Interface conference in May 2017 [4], as well as from the accompanying article "WRI 2017 – Heavy Haul: Condition Monitoring at the Component Level" in *Interface, the Journal of Wheel/Rail Interaction* [5]. No formal report about the accident was published by either FRA or NTSB

The train derailed on a 30-mph, 8.3° curve on a river grade (0 percent–0.3 percent) constructed with timber crossties and Victor plates. A Victor plate uses cut spikes and e-clips, and on NS it is typically installed with two hold-down-spikes and two line-spikes. The NS investigation found that the curve had many broken spikes, and at the four crossties near the point of derailment, 7 of the 16 spikes were broken. The spikes were broken 1.0 to 1.5 inches below the top of the crosstie and showed signs of fatigue. The fracture pattern suggested that both lateral and longitudinal forces were involved in the breakage. These broken spikes had allowed the gauge to widen under the train, causing the low-side wheels on the first derailing car to drop into the gauge.

Some of the crossties had experienced multiple broken spikes in the same location, as shown in Figure 5. In this example, a broken spike had been located by engineering personnel and the top half removed. Because the bottom half of the spike cannot easily be removed while the crosstie is still in track, a new spike was driven above it, pushing the bottom half of the original spike through the bottom of the crosstie. This indicated that the location saw repeated broken spikes. As the journal article states, the investigation "found numerous broken spikes, including multiple broken spikes on top of older broken spikes – indicating a long-term, systematic issue."

Figure 5. Broken spikes (left) and rail seat cross-section (right) [4]

The journal article describes the challenges NS faces regarding broken spikes:

- Broken spikes are found on the high rail on both gauge and field sides, and in both rail and anchor spike positions.

- Broken spikes are found in solid ties, including new ties.
- Broken spikes appear in curves with standard 8×18 tie plates but appear more frequently in curves with Victor tie plates.
- Spikes typically break 1 to 1.5 in. below the tie surface, making them difficult to detect.
- Tie plate movement can be minimal until a cluster of ties with broken spikes develops.
- Broken spikes appear on curves greater than 6 degrees and timetable speeds < 35 mph.
- Broken spikes tend to be associated with non-uniform alignment in the high rail.
- Longitudinal force, such as imparted by heavy braking and high tractive effort, plays a significant role in the development of broken spikes." [5]

These problems will be discussed in more detail in Section 4 and Section 5.

3.3 Mosier, OR

In the afternoon of June 3, 2016, a Union Pacific (UP) crude oil train derailed at Mosier, OR as it travelled down the Columbia River Gorge. In the FRA Preliminary Factual Findings Report [6], the investigation found that "multiple lag bolts in this section of Union Pacific track were broken and sheared, leading to tie plates loosening from ties. The loosened tie plates allowed for the rails to be pushed outwards as trains moved across them, eventually resulting in an area of wide gauge, leading to the derailment." An example of the broken lag bolts can be seen in Figure 6.

Figure 6. Broken lag bolts at the Mosier derailment site [6]

UP also published a diagram (reproduced by Oregon Public Radio), which can be seen in Figure 7, to explain to the public how the wide gauge occurred. In the aftermath of the derailment, four tank cars caught fire and a significant amount of crude oil was spilled into the Columbia River Gorge. FRA initiated special inspections of the UP and BNSF track in the area and took enforcement action against UP.

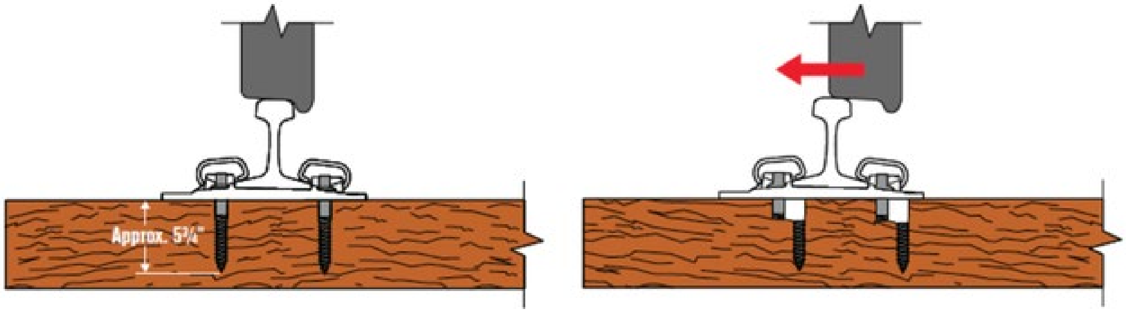


Figure 7. Union Pacific diagram showing spike failure and resulting wide gauge [7]

No further official details about the accident are publicly available as of this writing. The report does mention that FRA "conducted a data search of FRA databases for tie fastener trends across the rail industry" and sent broken lag bolts to the Volpe National Transportation Systems Center for metallurgical testing, although these results are not currently publicly available.

3.4 Montreal, QC

In December 2011, a Montreal commuter train derailed on Track 22 in Montreal Central Station [8]. Although the derailment was not directly linked to broken spikes, an inspection of the curve in neighboring Track 21 revealed numerous broken spikes, as shown in Figure 8. A Transportation Safety Board of Canada report states that laboratory work on these broken spikes "determined that:

- the spikes did not break at the same height;
- the broken spikes failed in fatigue;
- the fatigue cracks varied by their age; and
- the shiny surfaces of the spikes, deformation, and fatigue cracks suggest that there was some significant relative movement of the spikes and tie plates."

Figure 8. Spikes found in Track 21 of Montreal Central Station [8]

3.5 Other Derailments

FRA databases record rail equipment accidents, casualties or injuries, and highway-rail grade crossing accidents. If a rail equipment accident exceeds a set monetary threshold, it must be reported to the FRA with form FRA F 6180.54, recording the circumstances of the accident, the cause of the accident, physical damages to rolling stock and infrastructure, etc. [9]. A search through this database was undertaken to look for accidents attributed to broken spikes, lags, screws, etc. For this study, accidents in the years 2001–2016 were examined.

There is no FRA derailment cause code specifically for failed spikes. The two most likely codes for a broken spike derailment are T111 – "Wide gage (due to defective or missing spikes or other rail fasteners)" and T206 – "Defective spikes or missing spikes or other rail fasteners (use code T111 if results in wide gage)." From 2001 to 2016, at least 531 accidents from all track types were assigned one of these cause codes. However, these derailments could have been caused by any type of fastener failure, and it is not possible to know what subset of them were due to broken spikes. The only way to know if a derailment was caused by broken spikes is to look at the accident narrative and see if broken spikes are specifically mentioned. In most cases, accident narratives note the circumstances of the accident and offer no details about the cause. For example, the Vandergrift, PA accident narrative makes no mention of broken spikes. The Mosier, OR derailment narrative mentions "defective spikes." Further, since accidents must meet a certain cost threshold to require reporting, inexpensive broken spike derailments may have gone unreported.

The examples below were considered broken spike derailments based on their accident narratives. They include the location, date, and railroad where the accident occurred and the reporting railroad's entire narrative section on the circumstances of the derailment.

- Sauget, IL, 2001; TRRA of St. Louis

  > "BROKEN LAG BOLTS CAUSING WIDE GAUGE UNDER MOVEMENT AND THEN DERAILMENT PULLED ONTO THE ALS PROPERTY CAUSING DAMAGE."

- Cusson, MN, 2005; CN

  > "TRAIN A43981-10 WAS TRAVELING AT 50 MPH AT MP 117 WHEN CN414465, 35TH CAR, DERAILED THE LEAD WHEEL OF THE TRAILING TRUCK. CAUSE WAS WIDE GAGE AT A JOINT DUE TO BROKEN SPIKES. CN414465 TRAVELED APPROXIMATELY 2.5 MILES TO MP 119.5 BEFORE LEAD WHEEL CAME OUT FROM UNDER CAR DERAILING CN414465 AND 4 OTHER CARS."

- Dingle, ID, 2006; UP

  > "IDUS3-17 WAS WESTBOUND ON WHEN 41 PLATFORMS/WELLS DERAILED DUE TO WIDE GAUGE CAUSED BY BROKEN SPIKES. 15 ARTICULATED CARS WERE DERAILED WITH A TOTAL OF 41 PLATFORMS/WELLS. CAR BNSA-E240345 WAS DESTROYED."

- Hammond, IN, 2009; NS

  > "AMTRAK 49 WITH 2 UNITS 11 LOADS AND 1 EMPTY OPERATING WEST ON CHICAGO MAIN 2 WHEN THE REAR 3 CARS DERAILED. A CONCENTRATION OF UNDETECTED BROKEN SPIKES ALLOWED HIGH RAIL TO CANT AND ROLL UNDER AMTRAK 49T IN BODY OF 3.2 DEGREE CURVE."

Surveys and interviews with different railroads produced information about other broken spike derailments. An NS derailment in Cincinnati, OH in 2015 was caused by broken spikes. Broken spikes also caused derailments on the BNSF Railway at Bridgeport, NE in 2008 and another at Glacier Park, MT in 2006. In total, researchers found10 derailments caused by broken spikes.

3.6 Published Literature

There is limited research on broken spikes. Most notably, work by Dick et al. in 2007 [10] looked at stresses and fractures in screw spikes, and work by Gao et al. in 2018 [11] looked at cut spike failures with a FEM, as did Dersch et al [12]. Further, spike breakage has been an ongoing problem at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC) in Pueblo, CO [13].

3.6.1 Dick et al., Proceedings of the 2007 Joint Rail Conference

In 2007, Matthew Dick, David S. McConnell, and Hans C. Iwand published work related to broken lag screws titled "Experimental measurement and finite element (FE) analysis of screw spike fatigue loads," sponsored by the UP's methods and research department [10]. This work included a field test that measured the lateral loads going into the screw spikes and found that the lateral loads in a plate were not evenly distributed among the spikes, which could lead to spike failure.

The authors first examined the fractures of the screw spikes, concluding that the "crack growth portion of the fracture indicated a high cycle – low stress condition that allowed the fatigue crack to grow to approximately 80 percent of the cross section. Failed screw spikes are most frequently found in high-degree curves where rail vehicles have their highest lateral wheel loads." An example of a fractured screw spike is seen in Figure 9. Spike metallurgy is also briefly examined.

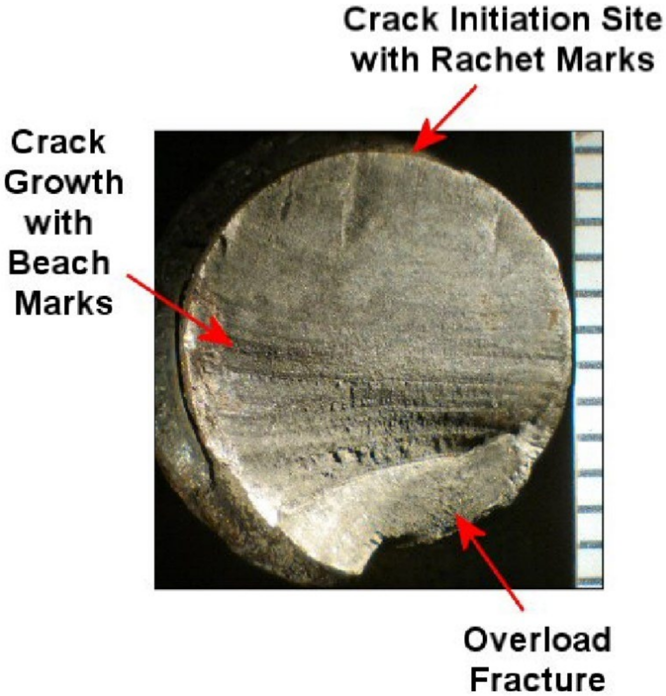


Figure 9. Screw spike fracture surface with notes from Dick et al. [10]

The authors designed an instrumented screw spike that uses a strain gauge mounted on a flexural beam within a hole drilled along the axis of the spike. The instrumented screw spikes were installed in a 10° curve in mountainous territory. One tie plate had all four screw spikes instrumented, and there were several others installed in other locations. A thermocouple was attached to the rail during the testing to gauge the influence of rail temperature on measured lateral loads. The field experimental setup can be seen in Figure 10.

Figure 10. Dick et. al.'s instrumented spike field setup [10]

The test results showed that one screw spike of the four in the plate took the majority (63.1 percent) of the total lateral load going into the spikes from passing trains. Meanwhile, the spike opposite this one, on the gauge side of the plate, experienced very little of the lateral train load (1 percent) but took a large amount of load from decreasing rail temperature. As the rail temperature decreased from 55º to 30°, the rails in the curve want to "suck in," resulting in 5,000 lbs (22.2 kN) of lateral load on the spike.

FE analysis results, shown in Figure 11, found that crosstie stiffness had a significant effect on the stress felt in the spikes, especially at lower crosstie stiffnesses. The authors report that "The FEA model predicted that a lateral load above 8,000 lbs. (35.6 kN) would create stresses above the endurance limit, no matter what the tie stiffness. Likewise, a lateral load below 3,500 lbs. (15.6 kN) would not create stresses above the endurance limit, no matter what the tie stiffness."

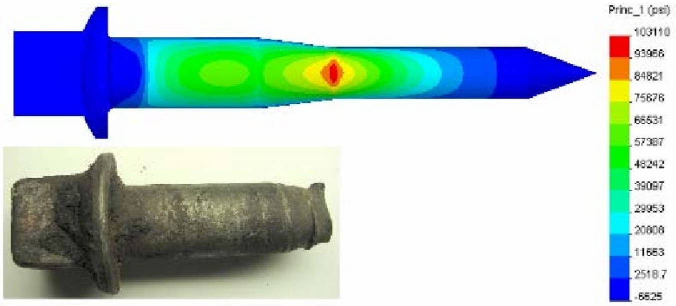


Figure 11. Comparison between location of peak tensile stress from the finite element model and a real failed spike [10]

In summary, this investigation focusing primarily on lateral loads transferred to the screw spikes found:

- The lateral spike load measured ranged from 1 to 63% of the applied rail seat load showing nonuniform loading of the spikes in a plate.
- Temperature changes affected the lateral pre-loading of the spikes.
- Crosstie stiffness has an impact on the load required to exceed the endurance limit.
- The location of maximum stress reported by the finite element model aligns with observations of field failures.

3.6.2 FRA Research Results from FAST at TTC

In 2008, FRA published Research Results RR 08-13 [14], "Update: New Crosstie and Fastening System Test at the Facility for Accelerated Service Testing." This report details the results of tests of several premium fastening systems as part of the HAL program at TTC. These same results were also published by Transportation Technology Center, Inc. as TD-07-027 [13].

The following fastening systems were tested:

- Rolled plates with e-clip and standard No. 5760 screw spikes
- Rolled plates with e-clip and LB&N high strength screw spikes
- Victor plates with e-clip and LB&N high strength screw spikes
- Cast NorFast plates with NorFast clips and standard No. 5760 screw spikes
- AREMA 14-inch plates with cut spikes (traditional fastening system)

Each of these systems was installed on 100 southern yellow pine crossties. Each section of 100 crossties was in a 6° curve with 5 inches of superelevation. During the testing period, the test section accumulated 412 MGT.

At the end of the test period, each test zone experienced broken spikes, except for the control zone with traditional fastening systems. The team created Figure 12 and Figure 13 to illustrate the test results.

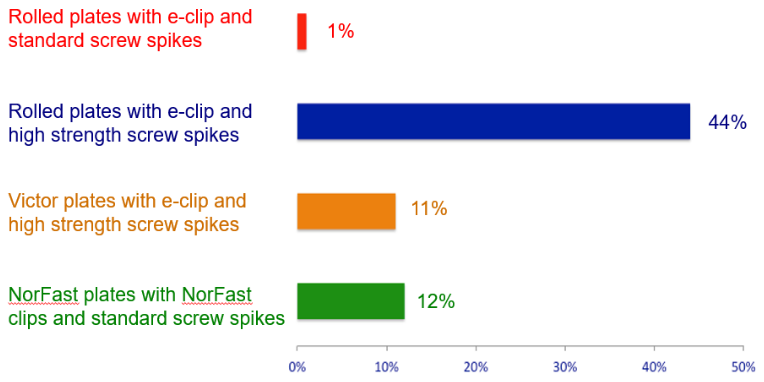


Figure 12. Number of crosstie plates with two or more broken spikes, as a percentage of the total, by test zone

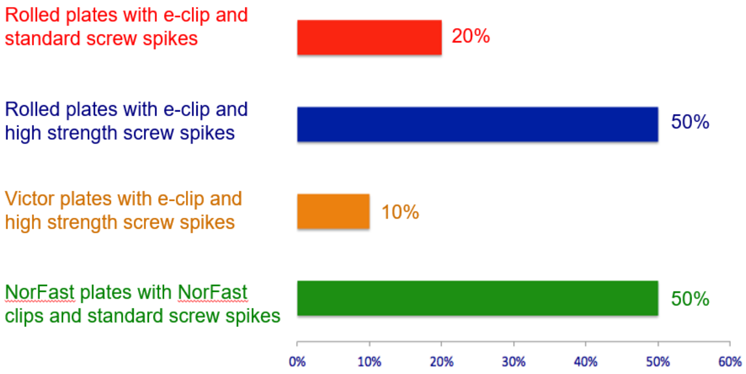


Figure 13. Percentage of each test zone exhibiting gauge widening over 57.25 inches

The report states that the rolled plates had diagonally opposed e-clips on either side of the rail, which can lead to plate skew under the rail. One finding in the zone with rolled plates and high strength screw spikes was that "when two of the four screw spikes break, the screw spike holes in the plate and crosstie become oblong. The plate then is free to skew, subjected to point loading, and ultimately breaks. The remaining screw spikes react against higher per screw spike loads that are introduced by lateral translation of the plates, which may result in spots of weaker track gage, higher per-component loadings, and a higher stress state."

It has been suggested that the broken spike problem is simply due to the use of spikes that do not have high enough strength. However, this report shows that high-strength screw spikes broke at a much higher rate than the standard. This result seems to corroborate the theory that spike breakage is really a mechanism problem (i.e., how the fastening system transfers forces) and not a material problem.

The report concludes that the "14-inch tie plate and cut spike system… performed better than elastic fastening systems… High-strength screw spikes had considerably more failures than conventional screw spikes. The high number of broken screw spikes and/or screw spike uplift in the elastic fastener test zones contributed to the loaded gage-widening degradation seen in those zones."

3.6.3 Gao et. al., Proceedings of the 2018 Joint Rail Conference

Gao, McHenry, and Kerchof's paper [11] presents some background on the issues railroads are facing with broken spikes, as well as the authors' modeling effort to better understand the problem.

The first portion of the paper is devoted to a field investigation of broken spike problems. The data was gathered primarily from one unnamed Class I railroad that has been experiencing issues with broken cut spikes in Victor plates. The investigation was conducted by walking inspections and by studying geometry car data. In general, the findings aligned well with those from the Vandergrift derailment reviewed above, as well as with the findings of UIUC researchers from field visits detailed in Section 5 of this report.

The investigation also found that gauge widening is directly proportional to the number of broken spikes, as shown in Figure 14 below.

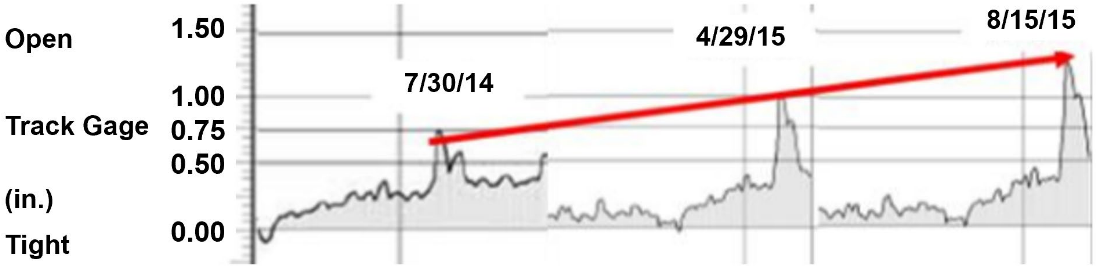


Figure 14. Gauge widening over time at a specific location due to broken spikes [11]

The focus of the paper then shifts to the modeling work conducted to examine the causes of broken spikes. Specifically, the authors deployed a two-part approach: a NUCARS model was used to understand the rigid-body motion at the fastening system due to dynamic train loads, and the results from this were then put into a FEM to understand the loading environment of individual cut spikes. The NUCARS model looked at plate uplift, and the FEM then examined the effect of this on spike stress with different plate/spike contact position scenarios, as seen in Figure 15.

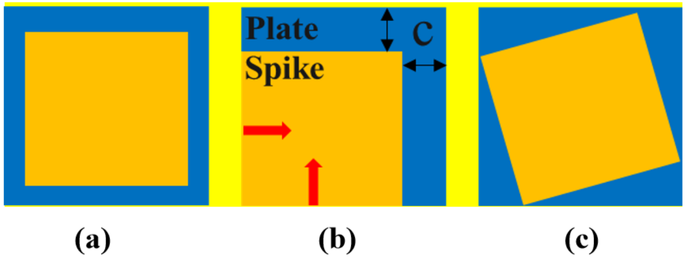


Figure 15. Several potential positions of a spike within a spike hole: (a) centered, (b) two sides in contact with plate, and (c) skewed within the hole [11]

FEM results indicated that the load taken by a spike with two sides in contact was much higher than the others in the plate, a scenario that very likely happens in the real world and is in agreement with Dick's field work. This spike which takes more load is referred to by the authors as the contacting spike. The location of stress in the spikes shown in the modeling results agreed well with the location of fractures in the field, about 1.5 inches beneath the top of the crosstie. The paper closes by discussing the fact that the railroad that conducted the field investigation has been installing rail anchors in their Victor plate curves to help with the longitudinal force transfer, and, in some locations, using Victor plates with screw spikes.

3.6.4 Dersch et. al., 2019, Engineering Failure Analysis

A paper published in Engineering Failure Analysis by Dersch et al. used a FE model of a cut spike in timber to study the effect of certain parameters on spike performance [12]. Three types of timber were modeled for the crosstie: southern red oak, green ash, and yellow birch. These are all common types of timber for crossties, but they exhibit a wide variety of strength properties. The timber tie was modeled with the grain of the timber in the lateral direction, as it is in real crossties. The cut spike was based on AREMA Chapter 5 [15] and the specifications of multiple Class I railroads.

A set of load cases was devised to parametrically alter the lateral and longitudinal loading on the spike and look at the resulting effect on spike stress (Table 2) [12].

Table 2. Load cases from Dersch et al. [12]

Load	Units	Load Case 1	2	3	4	5
Londituginal	kN	22.2	22.2	22.2	11.1	0
	lb	*5,000*	*5,000*	*5,000*	*2,500*	*0*
Lateral	kN	0	11.1	22.2	22.2	22.2
	lb	*0*	*2,500*	*5,000*	*5,000*	*5,000*

From Figure 17, note that a given longitudinal load in the cut spike was more detrimental to spike performance than the same magnitude of lateral load. This was due to the direction of the grain in the timber, and specifically that the longitudinal load put stress on the spike perpendicular to the timber grain direction, whereas the lateral load applies parallel to the grain. Further, the location of maximum stress due to longitudinal load was deeper along the spike shank compared to that from the lateral force. With both lateral and longitudinal forces present, just 1,200 lbs. of force in each direction was enough to exceed the fatigue strength of the spike. The type of timber had little effect on spike performance.

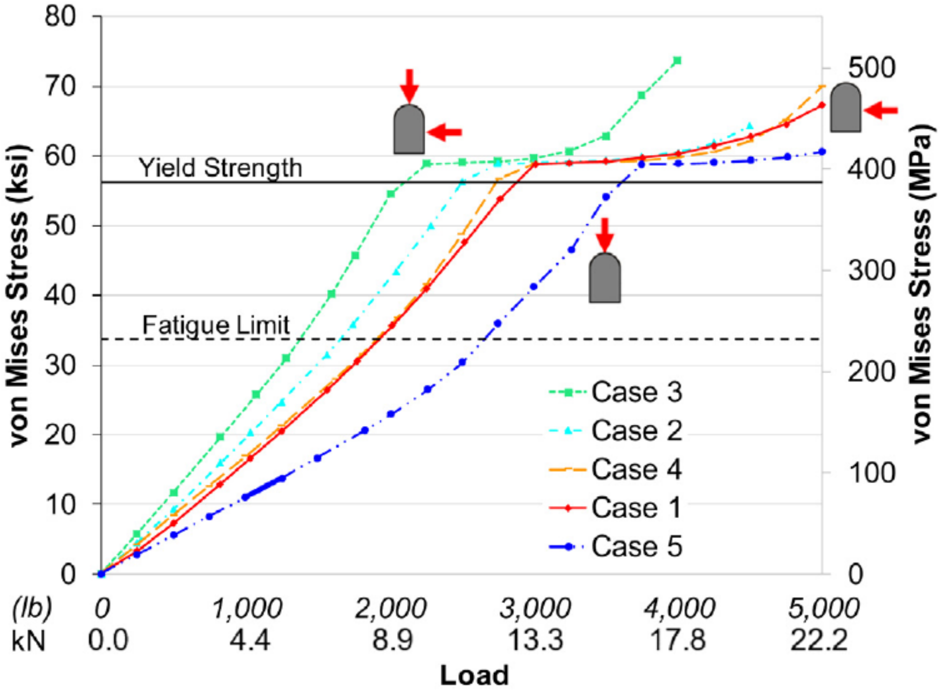


Figure 16. Effect of various lateral and longitudinal loads on maximum spike stress [12]

4. Industry Broken Spike Survey

Given the limited amount of information publicly available regarding failed spikes, the research team decided to conduct an industry survey to collect more basic information about the prevalence and characteristics of broken spike problems.

The primary objective of the broken spike survey was to poll North American railroads on their experience (if any) with broken spikes in timber crosstie railroad track. The survey aided the research team in understanding the magnitude of the challenges that railroads are facing with spike breakage, how they are currently inspecting for failed spikes, and the characteristics of locations where broken spikes are found. The information from this survey will inform the proposed Phases II and III (see Section 7) hypotheses about root causes of spike failure and possible mitigation measures.

4.1 Survey Introduction

The survey contained 11 questions: 6 multiple choice questions and 5 short-answer response questions. A complete copy of the survey appears at the end of this report in Appendix A: Survey Questions. The survey was deployed using identical online and paper formats, with the bulk of respondents using the online format.

The team collected 24 responses from 9 different organizations. The organizations are listed below, with the number of responses from each in parentheses:

- Amtrak (1)
- BNSF (6)
- CN (3)
- CSX (2)
- Kansas City Southern (1)
- LA Metrolink (1)
- Norfolk Southern (4)
- TTCI (1)
- UP (5)

4.2 Magnitude of the Broken Spike Problem

The survey highlights the magnitude of the broken spike problem. Respondents were asked if their railroad had experienced any broken spike problems. Seven of the nine organizations represented (78 percent) had seen broken spike problems (Figure 18). Note that after the survey was conducted, a railroad that had answered no subsequently found broken spike problems, thus bringing the total to eight of the nine (89 percent) organizations experiencing broken spike problems.

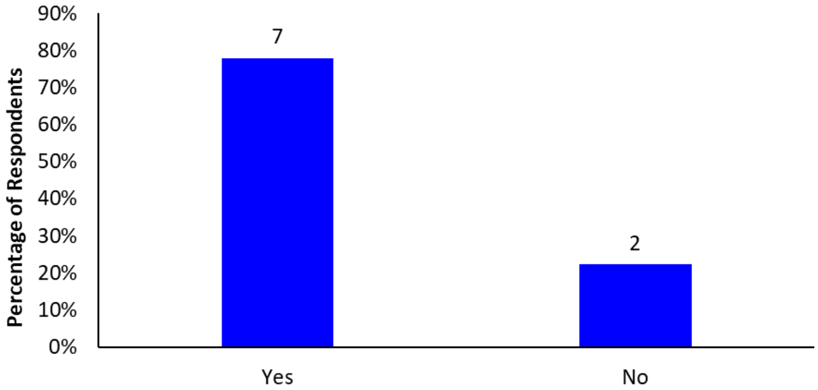


Figure 17. Broken spikes experienced at organization

Respondents who answered "yes" to the broken spike question were subsequently asked for their view of the seriousness of the problem (Figure 19). Note that the one railroad that considered it a "small problem" has not installed timber crosstie elastic fastening systems in track as a standard since the early 1990s. Even so, this railroad has procedures in place to inspect for spike failures caused by seasonal changes.

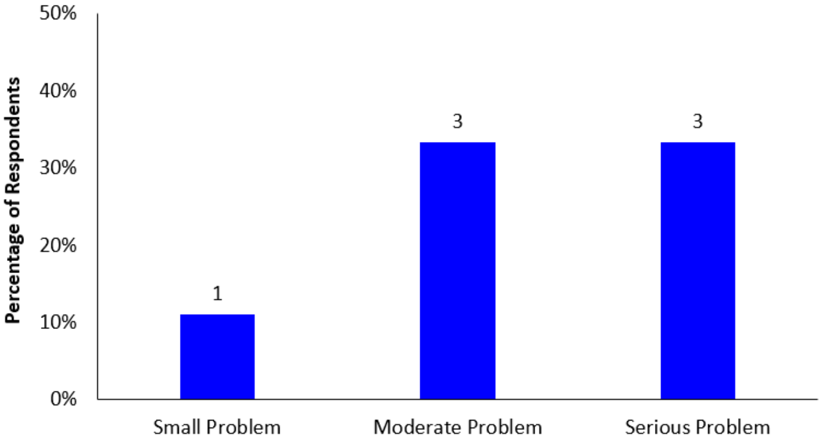


Figure 18. Severity of broken spike problem compared to other track-related problems

The short answer responses to this question help shed light on why different respondents felt the way they did about the magnitude of the problem. A selection of short-answer responses can be found in Appendix B.1: Magnitude of the Broken Spike Problem.

4.3 The Challenges with Inspecting for Broken Spikes

Many respondents commented on how challenging it is to locate broken spikes. The consensus was that gauge restraint measurement system (GRMS) testing is useful in pointing to areas with problems, but walking inspections must be undertaken to find and fix broken spikes. Outward shove of tie plates and false flange markings on the low rail were both mentioned as potential indicators of failed spikes. Some respondents expressed concerns with seeing these indications when track is covered in snow. Others expressed concerns over the dependence on personnel – even those with broken-spike experience – to find and fix issues. Selected responses may be found in Appendix B.2: Challenges of Inspecting for Broken Spikes**.**

4.4 Characteristics of Locations Where Spike Failures Occur

The survey also asked where railroads have been finding broken spikes. Characterizing locations where spikes tend to break is meaningful for two main reasons. First, it helps identify other locations that could potentially be at a high risk for broken spikes. Second, it leads to an improved understanding of the environment in which spikes break and what could be causing breakage.

In one question, respondents were asked to choose all locations where their railroad finds broken spikes. Responses are shown in Figure 20.

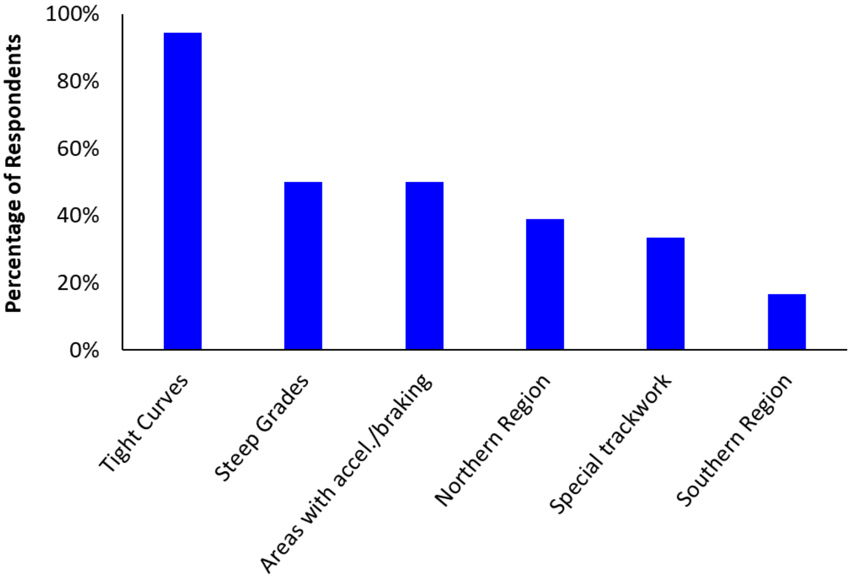


Figure 19. Broken spike locations

All but one respondent chose curves as a location where they have seen broken spikes. This trend also appeared in the short-answer results. There were varying opinions about the critical degree of curvature. This is likely due to different track standard for fasteners, standards for superelevation, and field experiences among the respondents. The high rail of curves was sometimes identified as more of a problem than the low rail, which was also a finding from the field visits (Section 5).

Part of the survey was intended to uncover whether broken spikes are primarily a premium fastening system problem or a more general issue. The three major derailments discussed in Section 3 all occurred on premium fastening systems. A multiple-choice question in the survey asked what percentage of spike breakage occurred in premium fastening systems (Figure 21). Opinions varied about this, and many respondents (33 percent) were not prepared to make an estimate.

The research team found it impossible to draw any clear conclusion from these results because of the high variability and the number of railroaders who were not prepared to make an estimate of the percentage of spike breakage that occurs in premium systems. That said, based on the derailment reports reviewed above and some of the field visits recorded in Section 5, it seems that premium systems are an important part of the spike failure story. The fact that premium systems have been installed in large numbers only recently seems to coincide with the recent emergence of broken spike derailments. However, other recent operating changes (for example, use of AC traction or longer rail lifetimes) could also be responsible. More research is likely needed to better quantify the role of premium fasteners in spike breakage.

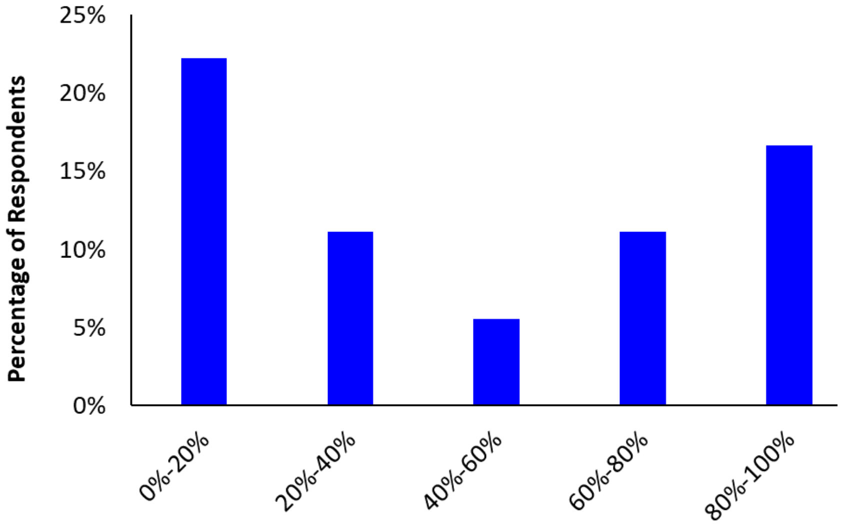


Figure 20. Percentage of broken spikes occurring in premium fastening systems estimate

5. Railroad Field Visits and Interviews

The purpose of the railroad field visits and interviews was to better document the challenges railroads are facing and to compare them across different railroads. Getting into the field on different railroads also provided researchers the opportunity to talk with field personnel to learn more about their experiences with broken spikes and how their local track maintenance crews address them.

The field visits were designed to provide researchers the opportunity to see different locations with different climates, track characteristics, traffic characteristics, inspection practices, etc. These locations had a variety of fastening systems and varying amounts of spike failure reports. A map (Figure 22) of locations visited is provided below along with the 10 known derailments associated with broken spikes.

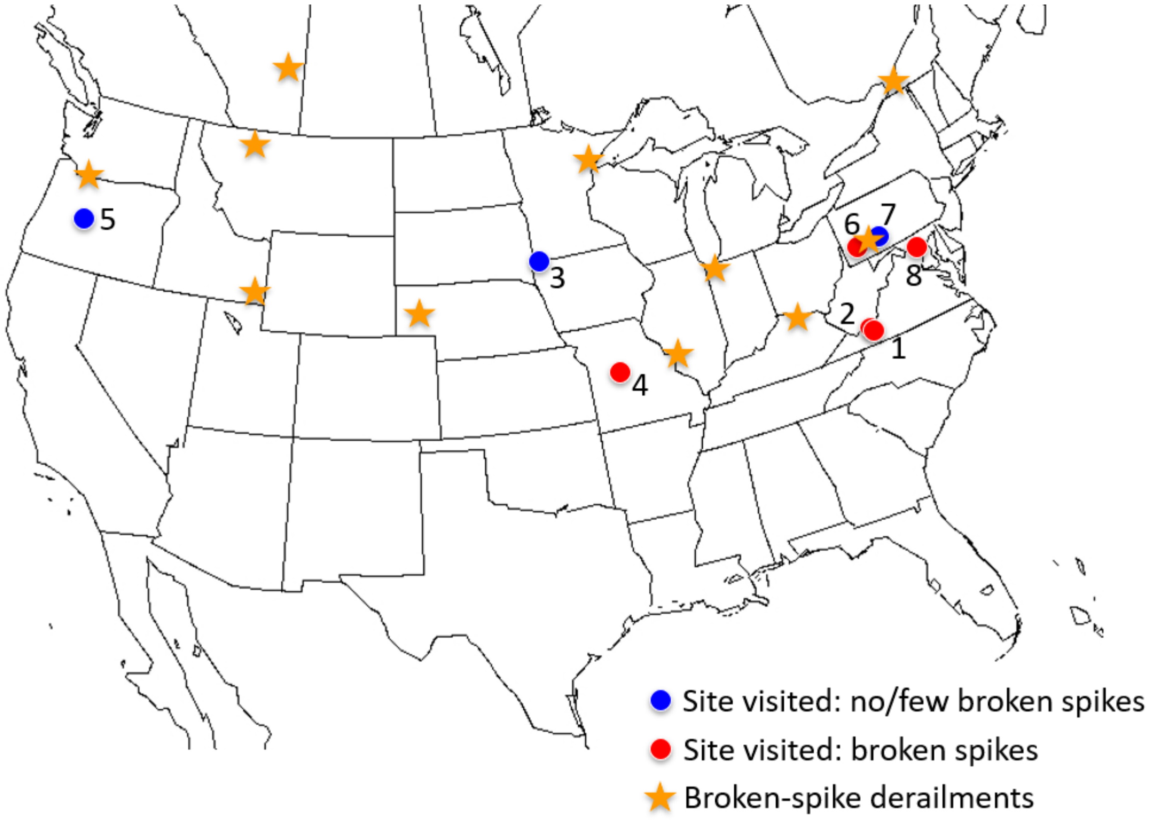


Figure 21. Field visit locations (broken-spike derailment locations added for reference)

5.1 Norfolk Southern – Shawsville, VA

In January 2018, the research team visited curves in the NS Christiansburg District near Shawsville, VA. This section of the district has two main tracks: 25 MGT moves in the downhill direction and 41 MGT moves in the uphill direction annually. The curves varied in curvature from 6.1° to 6.7° and were on a 1.32 percent grade. Six of the inspected curves had Victor plates with e-clips and cut spikes, and one curve had 8- by 18-inch traditional plates with rail anchors and cut spikes.

The researchers walked the curves in a manner typical of NS's usual broken spike inspection method (Figure 23). NS has seen broken spikes primarily in the high rail, and the standard method of inspection included one person walking in the gauge and one person walking on the high rail, field side, each tapping every spike as they walked. The group split into two teams to inspect the seven curves more efficiently. The walking inspections and subsequent spike failure repairs proved time-consuming, requiring the entire morning to complete.

Figure 22. Walking inspection for broken spikes near Shawsville, VA

The curve with traditional cut spikes, plates, and anchors had no broken spikes. Four of the Victor plate curves walked had one to four broken spikes each. One of the Victor plate curves had 25 broken spikes, and 12 additional broken spikes were found in this curve during later repair work. No broken spikes were found on the adjacent track.

Local field personnel said that one way they can identify plates with broken spikes is by looking for plate cutting (Figure 24).

Figure 23. Plate cut/shove suggesting possible broken spikes

Another method is looking for spikes where the spike head leans into the plate, indicating that it is broken. Neither is a perfect method, however, as the group found many plates and spikes that did not exhibit these symptoms. NS also uses geometry car reports, but these do not provide high enough location resolution to call out specific crosstie plates. A walking inspection is still required to isolate broken spikes in a curve with measured wide gauge.

In general, the broken spikes looked no different from the intact spikes. Only upon tapping the head of a broken spike was it apparent that it was broken. Many, but not all, of the broken spikes were found in new crossties.

Figure 25 shows some typical broken spikes after removal. The left spike in the photograph is the rail hold down spike, and the right one is the field spike. The rail hold down spike broke lower down the shank because the tie plate is thicker at the rail location. Both spikes failed at approximately the same depth beneath the top of the crosstie, roughly 1.5 inches.

Figure 24. Typical broken spikes after removal

The spikes exhibit similar fracture patterns, suggesting a fatigue failure caused by both lateral and longitudinal loading from the tie plate, as shown in Figure 26. Most spikes had fracture surfaces that had degraded considerably, likely due to the two broken halves rubbing against each other in the spike hole after failing.

Figure 25. Common spike fracture pattern

NS has installed drive spikes in the Victor plate cut spike holes to restore some failed spike locations because drive spikes were thought to be stronger and might last longer. Several of the broken spikes found were these drive spikes (Figure 27), indicating a repeated spike failure problem at these locations. Local NS personnel mentioned that several of these curves had repeated broken spike problems, and that in one curve they had once found 150 broken spikes.

Figure 26. Broken drive spikes in repeat-breakage locations

In some cases, the broken spikes were found in clusters, as seen in Figure 28. The most extreme cluster had significant curve grease buildup on the gauge face of the high rail and false flange wear on the low rail. Gage widening was noted.

Figure 27. Location with cluster of broken spikes; note gage rod

5.2 Norfolk Southern – Eggleston, VA

The track characteristics at Eggleston differed from those of Shawsville in that the track followed the New River on grades between 0 percent and 0.3 percent. Further, the route here is single track, with 54 MGT per year. The first inspected curve was 5.8° with no broken spikes. The second was an 8.3° curve with 35 broken spikes. The third was a 6.5° curve with 22 broken spikes. All ties in the curves used Victor plates.

The fourth and final curve inspected had previously experienced broken spike issues. It had been gauged and box-anchored every other crosstie in May 2017, and the January 2018 inspection, no broken spikes were found. Local personnel confirmed that since the rail anchor installation, no further broken spikes had been found in the curve. This finding supports the longitudinal force mechanism hypotheses put forth in Section 7 as a root cause of spike failure.

The second and third curves exhibited a spike failure pattern, where spikes broke in clusters at certain intervals, as shown in Figure 29. These clusters were like the one observed at Shawsville, but with less extreme grease buildup and false flange wear. The clusters were spaced at roughly 10-crosstie intervals. The mechanism that leads to this phenomenon is not completely clear. It may be that one cluster of broken spikes develops, leading to a truck hunting pattern that causes impacts at distinct intervals, leading to the regularly spaced clusters. Alternately, it could be a different track irregularity (e.g., a slight misalignment, wide gauge, etc.) leads to this same behavior.

Figure 28. Broken spike clusters appearing at certain intervals, marked by ballast particles on the rail. Note the curve grease marks on the high rail gauge face.

NS repaired broken spike locations during the inspection which gave the team insights into how NS fixes problematic broken spike locations.

When a broken spike is found, the bottom half is typically lodged in the crosstie and cannot be removed. Therefore, new plug wood is placed in the spike hole, cut to the correct height, and a new spike driven in through it, driving the broken spike shank through the bottom of the tie, as shown in Figure 30.

Figure 29. Plug wood and new spikes to be installed in a plate where all four spikes broke.

5.3 BNSF – Doon, IA and Pipestone, MN area

In June 2018, the team visited BNSF Railway's Marshall subdivision linking Doon, IA to the Pipestone, MN area. Derailment reviews, the survey, and the NS visit suggested that spikes break primarily in premium fasteners, and the Marshall subdivision was suggested by BNSF personnel as one of the few locations left on their system with premium fasteners – in this case, Pandrol plates. Since the 1990s, BNSF standards have moved away from Pandrol plates due to cracking at the corner of the shoulder, and the new standard is to install concrete crossties on mainline curves over 3°, or otherwise use tie plates with curve blocks (Figure 2) without elastic fasteners.

The premium fasteners examined on this visit were Pandrol rolled plates with e-clips. Some used cut spikes and some used lock spikes ("hairpins"), shown in Figure 31. The inspection party walked multiple curves with Pandrol plates and examined some curves with the newer curve blocks. The curves ranged from 2° to 4° on mainly level grades between 0 percent and 0.6 percent. Annual tonnage in the area was around 26 MGT.

Figure 30. Pandrol plates using lock spikes (foreground) and cut spikes (background)

The Pandrol plates were all of 1990s vintage or older and showed signs of wear but did not have broken spikes. The local maintenance personnel reported that spike failure was not a major issue in their Pandrol plates, nor in any of their other fastening systems. Only one broken spike, a lock spike, was found in a Pandrol plate. However, it seemed that the movement of longitudinal force from plate to spikes had in some cases resulted in wear of the plate into the spikes instead of spike breakage, as shown in Figure 32.

Curve blocks, shown in Figure 33, provide rail-rollover restraint but not longitudinal restraint, and the track design requires rail anchors. They are not a type of premium fastener, as defined in Section 2. No broken spikes were found in the plates with curve blocks, which are currently installed as BNSF standard on timber crosstie curves.

Figure 31. Wear of plate into cut spikes in the longitudinal direction in Pandrol plates

Figure 32. Example of a traditional tie plate with a curve block

The inspection party also walked two turnouts, and one broken spike was found in one of the turnouts (Figure 34). Though this was not a major issue at BNSF, other railroads in the industry survey reported having turnouts with broken spikes. Like the Pandrol plates, a failure mechanism from longitudinal load where the plate wears around the spike holes was observed (Figure 35), in this case on a 0.6 percent grade.

Figure 33. Broken spike around the frog of a turnout

Figure 34. Longitudinal plate movement with stationary spikes

5.4 Union Pacific – Boonville, MO area

Researchers visited Union Pacific's River Subdivision in July 2018. The River Subdivision uses directional running, moving loaded coal trains and other traffic eastbound from Kansas City to Jefferson City. Current annual tonnage is approximately 50 MGT, though tonnage was around 90 MGT when coal traffic was higher in previous years. The curves walked during the team's visit ranged from 3.2° to 6.5° and were on grades of 0 percent to 0.5 percent. The curves were built with a premium fastening system using cast plates, McKay clips, and screw spikes, which was a

UP standard until 2016. Since 2016, UP has been installing Victor plates with cut spikes and e-clips in curves over 3°.

Broken lags (Figure 36) were typically found individually rather than in clusters. For example, one 3° curve had two broken lags and one 4° curve had seven, but they were spaced far apart rather than in the same plate or within a few crossties of each other. They were typically found on the high rail, on either the gage or field side.

Figure 35. Broken lag screw removed from cast plate, typical of failures observed

Observation of the holes where broken lags were found revealed that some of the timber was visible in the spike hole (see the crescent-shape piece of timber in Figure 37). The visible timber was always on the side of the spike hole in line with longitudinal track loading rather than lateral track loading.

Figure 36. Timber visible in the spike hole, possibly suggesting plate movement and/or severe contact of the plate and spike

Like other field visits, the broken lag screws appeared no different than functioning screws when in the track. Tapping them can reveal which are broken, but if it still had a thread or more engaging the wood above the fracture, it may not feel broken when tapped. Local maintenance personnel had a special tool with which they could feel the torque on the lag screws to identify broken lags.

UP personnel walk the curves with McKay clips at least once every 90 days, and any crossties found with broken lags in them are replaced with Victor plates with cut spikes. This aggressive maintenance strategy has led to replacement of around 100 crossties per month including one problematic curve with 250 new crossties installed.

Maintenance confirmed that they have sometimes found clusters of broken lags where several are broken in a plate or there are several crossties in a row with at least one broken. Several locations were observed where new crossties with Victors had been installed to mitigate a cluster of broken spikes (Figure 38).

Figure 37. A new crosstie with Victor plate, spotted in where there was previously a crosstie with broken lags in the McKay system

One curve observed during the visit had McKay clips with rail anchors, and this curve had no broken spikes when inspected. Two 6° curves were inspected with Victor plates recently installed by a production curve gang. One of these curves also had rail anchors and one did not, but neither had any broken spikes. It was unclear why the curve gang had installed anchors in some curves and not others.

5.5 Union Pacific – Oakridge, OR area

Researchers visited Union Pacific's Cascades subdivision near Oakridge, OR on August 15, 2018. UIUC and UP personnel walked multiple curves, ranging from 2° to 11° on grades from 1.52 percent to 1.87 percent. The annual tonnage at this location is 26 MGT.

In 2016, UP change their design standard to use Victor plates in curves over 3°. Between July and October 2017, UP replaced all the McKay systems in these curves on the Cascades sub, with new Victor plates. Curves greater than 3° and less than 6° have 16-inch Victor plates, while curves over 6° have 18-inch Victor plate. A comparison of both Victor plates can be seen in Figure 39.

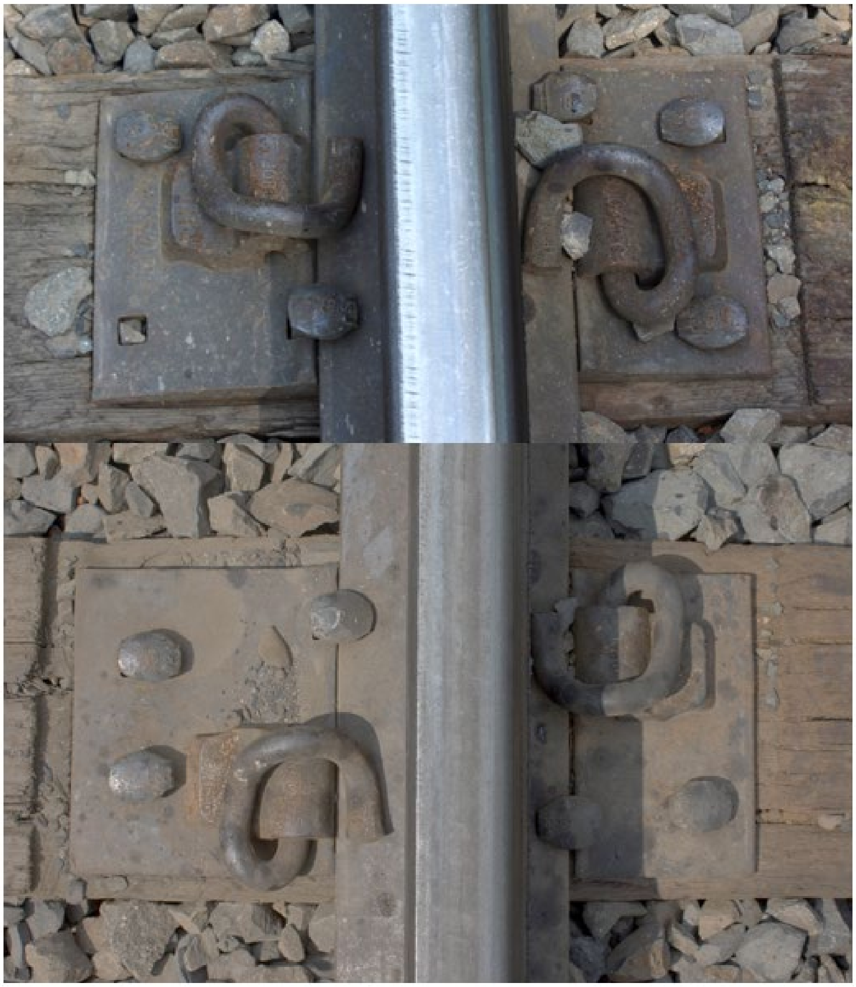


Figure 38. Comparison between 16" Victor plate (top) and 18" Victor plate (bottom)

No broken spikes were found during the field visit. Local maintenance personnel stated that broken lag screws had not been a major problem on the Cascades Subdivision before the change to Victor plates.

5.6 Norfolk Southern – Pittsburgh, PA

On September 4, 2018, the team visited a curve in Pittsburgh, PA. At this location, there are two main tracks coming off a bridge, each with a 12.7° curve. Track speed is 20 mph with 2.5-inch superelevation, and there is no grade, nor do trains regularly accelerate or decelerate at this location. Track 1 sees about 5.1 MGT per year, while Track 2 sees 15.7 MGT. The predominant fastening system is the Victor plate with cut spikes.

The inspection party walked both curves while tapping each spike on each plate on the high side rail, similar in manner to inspections described earlier. Both curves had about 40 broken spikes, typically found individually, one per plate. A few plates were found that had multiple spikes broken (Figure 40), but there were no major clusters of several plates in a row with multiple broken spikes, as was observed at Christiansburg (Section 5.1).

Figure 39. Three broken spikes removed from a bridge timber. The fact that these are drive spikes signifies that all three spike holes previously had cut spikes that broke

In many cases, broken spikes were in "severe contact" with the plate (Figure 41 and Figure 42) and often tough to remove from the plate despite being broken. Per local personnel, this was due to the hot ambient temperature (~92° F), which leads to rail expansion and therefore outward force in a curve, pinning the spikes in a plate against the plate. This was a sharp contrast to the Christiansburg visit, where ambient temperature was around 50° F, and spikes were much easier to remove by hand.

Figure 40. A spike hole with broken spike removed reveals that the spike was in a severe contact position with the plate. Spike hole wear is indicative of longitudinal plate movement to the left

Figure 41. Spike hole and shoulder wear indicates plate rotation and severe contact between plate and spike

NS maintenance personnel stated that every 6 months, they replace 50 crossties in each track on the curve. In some cases, they use a "bridge Victor" (a Victor plate with screw spikes) on these crossties, which has been found to help alleviate broken spike problems, as shown in Figure 43. Further, they recently box-anchored every other crosstie in the curves to try and further reduce spike failures. It is not possible to know whether the broken spikes found during the visit had already begun breaking before the anchors were installed.

Figure 42. New crosstie with "bridge Victors" and rail anchors to help alleviate spike failures

5.7 Norfolk Southern – Conemaugh, PA

An inspection was made of several curves near Johnstown and Conemaugh, PA, on September 5, 2018. The curves are on the NS Pittsburgh Line, which sees around 115 MGT per year on three main tracks. Multiple curves were inspected on Track 2, all of which were on a 0.63 percent grade with curvature ranging from 4.1° to 6.6°. Just one broken spike was found, near an insulated joint. The NS derailment in Vandergrift, PA, in 2014 (see Section 3.2) also found broken spikes around an insulated joint. This is perhaps related to the lateral stiffness of the insulated joint.

Per local maintenance personnel, this area has not had many issues with broken spikes, and in the neighboring territory there are only two curves that have had regular broken spike problems. Locations with excessive curve grease buildup were observed (Figure 44), like those observed at Christiansburg (Section 5.1). However, no broken spikes were found at these locations, nor was there any non-uniform alignment of the high rail. Gage was within standard and there was no evidence of regular gage problems.

Figure 43. Curve grease build-up at Conemaugh, PA

5.8 CSX – Woodstock, MD

On September 24, 2018, research personnel visited the CSX Albany Old Mainline near Woodstock and Marriottsville, MD. Three curves were inspected, all between 9° and 11° in curvature and on grades of 0.3 percent to 0.5 percent. The route is mostly single mainline track with about 23 MGT per year. An earlier CSX standard was to use Pandrol plates with screw spikes in high-degree curves with timber crossties. One curve walked had Pandrol plates in the high rail with Evergrip screw spikes. Recently, CSX has switched their standard to the Victor plate with cut spikes, as have several other Class I railroads. Some locations were seen with Victor plates with either cut spikes or Evergrip screws.

The first curve walked was an 11° curve with Victor plates in the spirals. When local maintenance personnel first discovered broken cut spikes in Victors in the body of the curve, they replaced the entire high rail in the body of the curve with Victor plates with Evergrip screws. The inspection revealed 13 broken cut spikes in the spirals, including at least one plate that had all four spikes broken, as shown in Figure 45. False flange wear was observed on the low rail.

Figure 44. Four broken spikes removed from a Victor plate in the low rail

The second curve was a 9.5° curve with Victor plates in the low rail and Pandrol plates with Evergrips in the high rail. About 60 broken cut spikes were found in the low rail in the curve, and 10 broken Evergrips were found in the high rail, as shown in Figure 46. The number of broken spikes found in the low rail is significant because some survey responses and field interviews indicated that broken spikes are primarily found in the high rail.

Figure 45. A broken Evergrip and a broken cut spike found in a Pandrol plate on the high rail at the second curve

The third curve was a 10° curve with Victor plates on both the high and low rail. Maintenance personnel began spotting in new crossties with Victor plates and Evergrips after broken cut spikes were found in the curve. Maintenance believed there would be no problems with Evergrips failing, as this was not an issue they had previously observed.

However, during this inspection, 121 broken cut spikes were found in the high rail in the span of 150 crossties and 43 of those crossties were newly installed with Victors and Evergrip screw spikes, and the other 107 had cut spikes. Roughly 23 percent of the cut spikes in this section were broken, with Figure 47 showing a representative image. The Victor plates with cut spikes were likely installed in 2008, based on the manufacturer's markings. This was before the change of track standards, and it is likely that the Victors were installed here as a test section before the standards change.

Figure 46. Two broken spikes in a Victor plate on a new crosstie

No significant gage-widening was found at broken spike clusters in each curve during the Woodstock, MD site visit,, and in at least one cluster (Figure 48), gage was found to be one quarter-inch tight (Figure 49). In fact, a geometry car passed over the site on the day of the visit and found no defects. No lubricant buildup was observed here, as was the case at cluster locations at some other sites on other railroads. Indications of false flange contact was observed on the low rail in some locations. Most plates with broken spikes did not have any evidence of lateral plate movement.

Figure 47. Cluster location with multiple plates in a row with broken spikes

Figure 48. Slight tight gage found at one broken spike cluster

5.9 Field Visit Summary

In summary, the research team traveled to eight (8) locations on four railroads (Table 2). The findings from the walking inspections varied widely, from no broken spikes in one curve to clusters of broken spikes in multiple curves. These failures were found in a variety of operating and track conditions, with grades ranging from 0 – 1.9% and curvature ranging from 2 to 11 degrees).

Table 3. Characteristics of field locations visited

Location Number	State	Fastening System	Grades (%)	Curvature (°)	Annual MGT	Spike Failure Findings
1	VA	Victor Plate with e-clip and cut spikes; traditional plates	1.32	6.1 - 6.7	33	Clusters of broken spikes
2	VA	Victor Plate with e-clip and cut spikes	0 - 0.4	6.5 - 8.3	54	Clusters of broken spikes
3	MN/IA	Pandrol Rolled Plates	0 - 0.6	2 - 4	26	Few broken spikes
4	MO	Cast plate with McKay clips and lag screws	0 - 0.5	3.2 - 6.5	50	Individual broken spikes found and evidence of clusters
5	OR	Victor Plate with e-clip and cut spikes	1.52 - 1.87	2.0 - 11.0	26	No broken spikes
6	PA	Victor Plate with e-clip and cut spikes	0	12.7	10	Individual broken spikes found and several plates with multiple
7	PA	Victor Plate with e-clip and cut spikes	0.63	4.1 - 6.6	39	Few broken spikes
8	MD	Victor Plate with e-clip and cut spikes; Pandrol rolled plates	0.3 - 0.5	9 - 11	23	Clusters of broken spikes

6. Conclusion

A review of derailment reports and available literature was undertaken to synthesize available information regarding the broken spike problem. An industry survey and multiple field visits were then conducted to gain more valuable information about the magnitude of the problem and the current practices in place to mitigate it. Based on this work, the authors conclude that the broken spike issue is a serious one that in some regions can jeopardize the safety of train operations and increase infrastructure costs.

Spike failures have caused several major derailments on at least four railroads with at least four different types of fastening systems. This not only shows that the problem is not specific to any railroad or type of spike but also that it is almost certainly a mechanism problem, not a material problem. Further, in each case, all tracks met railroad geometry standards and regulatory requirements before the derailment. It is not unreasonable to assume that such derailments will continue until either a better inspection technique is put in place or until the fastening system design is revised to prevent spike breakage.

The industry survey found that most railroads have experienced some issues with broken spikes, although the severity of issues varies by organization and location. There were differing opinions within each organization about the seriousness of the issues experienced. The survey shed light on where railroads are experiencing their broken spike problems: mainly in tight curves on steep mountain grades, in areas with acceleration and braking, and in special track work. Railroads are primarily finding these broken spikes during walking inspections, but automated technologies like GRMS can also detect these problems. Rapid gage deterioration in broken spike locations was cited as a major concern by respondents.

The field visits collected more scientific data about broken spikes and the characteristics of locations where they occur. The visits also helped better characterize railroads' experiences. Walking inspections are time- and labor-intensive. As a part of these inspections, the head of each spike must be tapped to determine if it is broken. Information about the nature of spike fractures, sample broken spikes, and data regarding locations where spikes are failing was collected for use in future phases of this project.

The consensus from the literature review, survey, and field visits is that spike failures can lead to wide gauge derailments and locating broken spikes in track is an inspection challenge. Based on the research presented in this document, the authors propose continuing to Phase II of project to better understand the mechanisms leading to spike breakage and what can be done to prevent it in future fastening system designs. This effort would align well with FRA's goal of zero track-caused derailments. In the following section, several hypotheses explaining spike breakage and the requisite work to test them are proposed.

7. Spike Failure Hypotheses and Proposed Path Forward

This section outlines current theories related to the root causes of spike failures as well as methods to test them. Section 7.1 discusses spike fatigue failure and how load transfer in fastening systems may lead to higher stresses in spikes. Hypotheses for what factors may cause the higher stresses are divided into factors specific to premium systems (Section 7.2) and general factors for all fastening systems (Section 7.3). Section 7.4 then provides proposed laboratory work to examine the theories given in the preceding sections.

7.1 Spike Failure Hypotheses: Fatigue and General Considerations

The main cause of spike failure is related to how fastening systems transfer forces from rail to crosstie. The fact that multiple types of spikes with different geometries (e.g., cut spikes, screw spikes, lock spikes [hairpins]) have failed, and that they are from different manufacturers, suggests that spike failures are not related to a flawed spike design, material flaws, poor steel metallurgy, etc. Rather, the fatigue fracture surfaces on failed spikes suggests that the spikes are experiencing higher input loads compared to their well-performing counterparts. The hypotheses laid out in the following sections explain factors that could be inducing a higher input stress in spikes that fail.

There are many documented challenges associated with the effective transfer of forces from the fastener to the crosstie. These challenges range from plate cutting in traditional fasteners, to rail seat deterioration on concrete crossties, to broken spikes in premium fasteners or broken fasteners in direct fixation systems. In each scenario, one component in the flow of forces from rail to crosstie is stressed to a failure level. In the case of broken spikes, the spike is this component, and it is therefore important to understand what factors could be leading to a higher stress state in spikes and the resulting effect this has on spike performance.

Because the observed spike failures are fatigue failures, one must first understand how and when higher input loads can lead to spike failures. The fatigue life of spikes can be understood with stress versus number of cycles (S-N) curves. The S-N curves shown below represent the fatigue life of a spike, with number of cycles on the spike on the x-axis and stress felt in the spike on the y-axis. The fatigue limit is the stress level below which steel will never fail in fatigue. There are two distinct possibilities for how the failures relate to the fatigue life of spikes. First, it may be that the stress being felt in well-performing spikes is beneath the fatigue limit of steel, whereas the stresses being felt in the failing spikes is above the fatigue limit (Figure 50). The second possible case is that all spikes are at a stress level high enough that they would eventually fail, but the rail life (in number of cycles) falls between those that break and those that do not. The reason the rail life is important is that when rail is replaced, it is standard to replace fasteners and spikes as well (though there may be cases where this is not done in practice, as will be discussed later) (Figure 51).

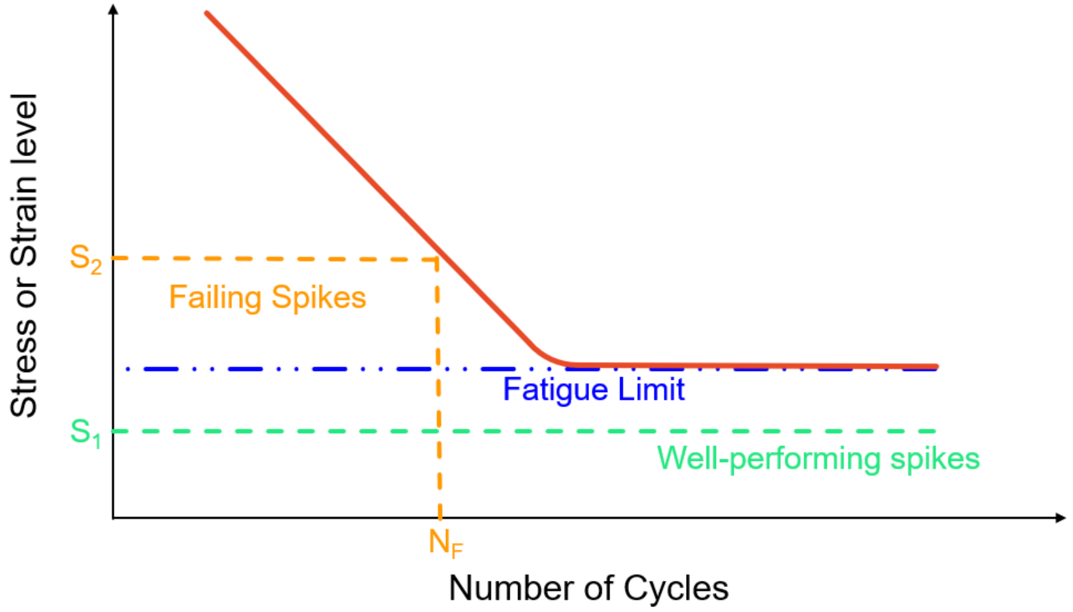


Figure 49. Hypothetical relationship between failing spikes and well-performing spikes on the S-N curve

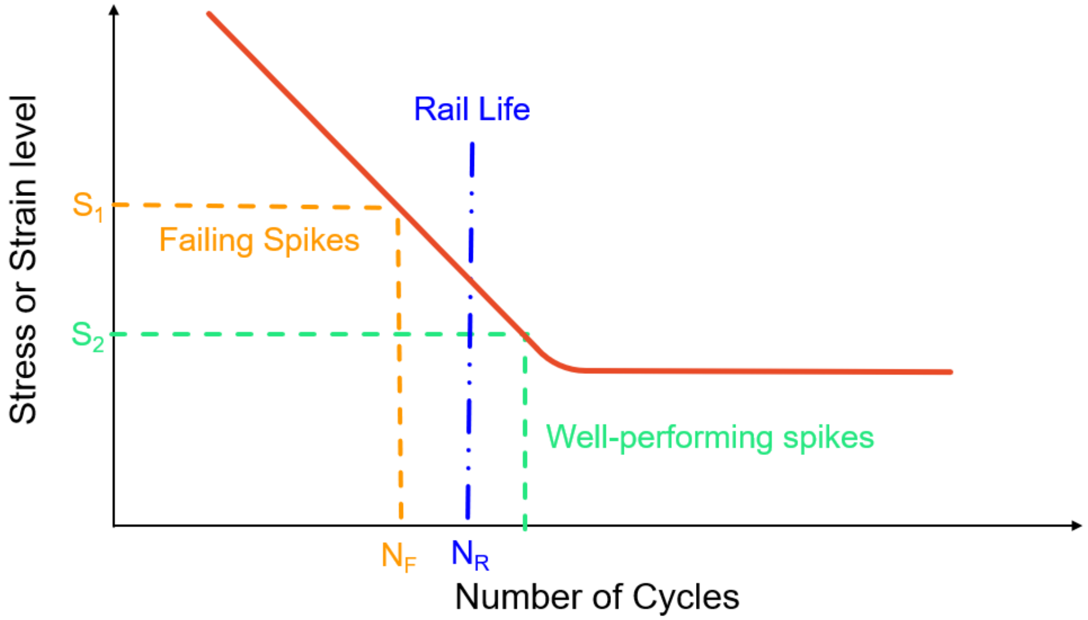


Figure 50. Hypothetical relationship between failing spikes and well performing spikes considering rail/spike replacement on an S-N curve

Because many failures have been observed in premium fastening systems, one set of hypotheses focuses on how these fastening systems transfer forces from rail to crosstie through the spikes. In some cases, broken spikes have been reported in traditional systems as well, and the General Factors section (below) walks through factors that cause greater stress in spikes and in extreme cases could be leading to failures.

Figure 52 shows a conceptual analysis of how different factors that increase spike stress can lead to broken spikes. The x-axis lists several potential environments for a spike, and the y-axis represents the stress in a spike. The dotted orange line across the top of the graph represents the threshold where spike stress is higher than the fatigue limit of the spike steel, or where the spike stress is high enough that the spike will fail before rail replacement.

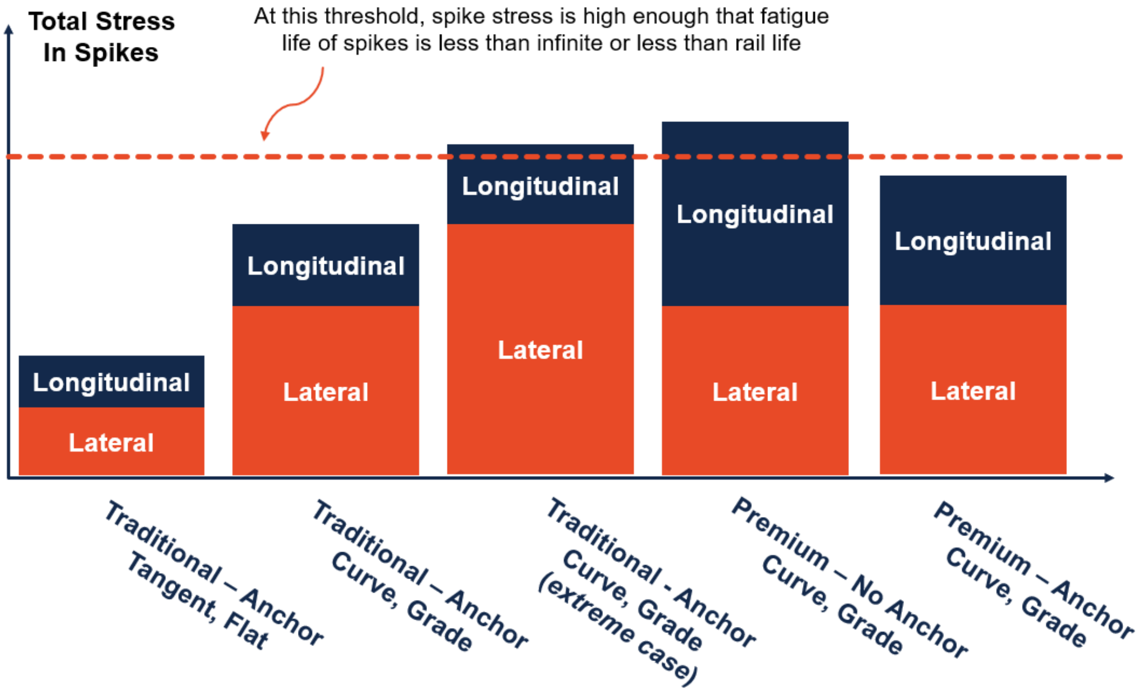


Figure 51. Illustrative example of how general factors and premium fastening systems may affect spike stress and the resulting potential for spike failures

In the case of a spike in a traditional fastening system on flat tangent track (far left in Figure 52), this spike may experience some longitudinal forces (for example, from braking or thermal forces) and lateral loads (e.g., from hunting or track irregularities), but they will most likely not be high enough on a regular basis to lead to broken spikes. A spike in a traditional system on a curve and grade will experience higher lateral stresses due to the curving forces of the train and effects of curve breathing with temperature, and it may also experience higher longitudinal forces from traction or braking (though it is expected that the rail anchor takes most of these forces). In an extreme case, these extra forces could be enough to cause spikes to fail.

Premium fasteners may result in higher spike stresses from longitudinal forces due to a lack of rail anchors, as explained in detail in the following sections. It is therefore expected that a spike in a premium fastener will experience higher longitudinal forces as compared with a spike in a traditional system, and that this added force may be sufficient to cause spike failures (fourth case from the left in Figure 52). NS has begun using rail anchors as a mitigation approach to spike failures, and this has been found to result in fewer failures. This case is shown on the far right of Figure 52, where total spike stresses have receded below the threshold for failure.

7.2 Premium Fastening System Hypotheses

Field visits and interviews, as well as the industry survey, found that broken spikes often occur in premium fastening systems. The following hypotheses focus on the transfer of forces in premium systems and how this can lead to spike failures.

7.2.1 Lack of Rail Anchors and Longitudinal Force Transfer

Longitudinal forces come primarily from train acceleration and braking. In the traditional fastening system, longitudinal forces are transferred from rail to crosstie mainly by rail anchors, which clamp on the base of the rail on either side of a crosstie. Since the rail is not rigidly held to the crosstie plate or the spikes, it is free to move, and the crosstie plate and spikes do not carry a significant portion of the longitudinal load.

One of the main advantages of premium fasteners is that rail anchors are not required where premium systems are in place. The elastic clip in the fastening system has enough clamping force to transfer the longitudinal forces to the tie. These forces are transferred from the rail to the plate, but then must be transferred to the crosstie either through friction between the tie plate and crosstie and/or through the spikes. This extra stress on the spikes may be sufficient to cause failure.

One can imagine the scenario where there is also frozen moisture in the rail seat or tie plate uplift (see Section 7.2.2), reducing or eliminating friction between the plate and tie, forcing all the longitudinal force to move through the spikes. Supporting this theory is one of the findings during the Norfolk Southern field visit, where researchers found that the use of rail anchors with Victor plates reduced the frequency of spike breakage. This situation, shown in Figure 53, is like that of the traditional fastening system in that a rail anchor is present to transfer longitudinal load directly to the crosstie instead of through the spikes. Note that Figure 53 does not show full free-body diagrams. Here the rail and tie plate are considered rigidly connected by the elastic clip. The total longitudinal force being transferred to the crosstie is the same as the sum of the friction, spike, and (if present) anchor reaction forces.

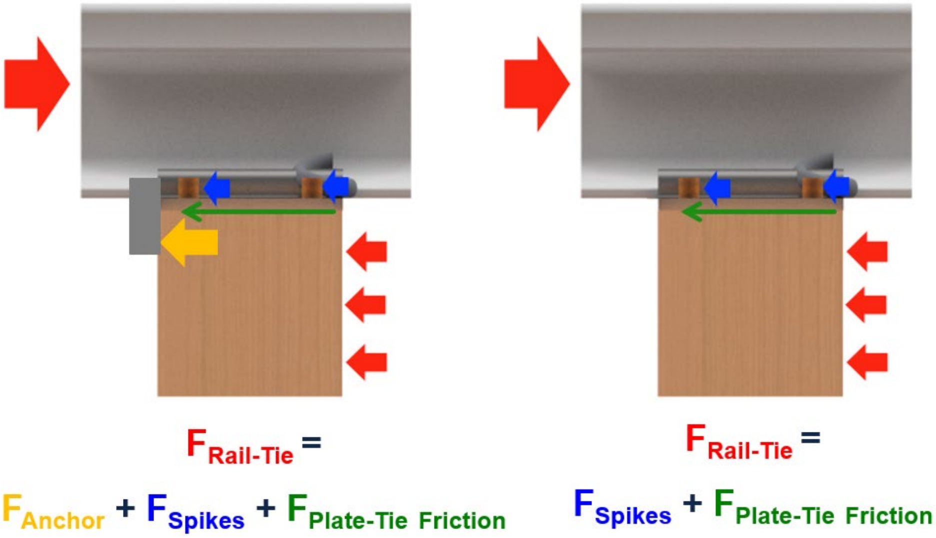


Figure 52. Premium system with and without rail anchors

7.2.2 *Tie Plate Uplift*

In their modeling work, Gao et al. considered the crosstie plate uplift theory, as reviewed in Section 3. Ahead or behind a wheel load (or loading from a set of trucks), a rail uplifts slightly in negative bending, while it deforms beneath the wheel load(s). This negative bending causes a slight uplift of the rail [16].

In the traditional fastening system, this negative bending may raise the line spikes slightly, but will not lift the tie plate or the hold-down spikes. However, in a premium fastening system it is believed that this negative bending will raise the entire plate slightly with the rail due to clamping force of the elastic fastener.

A plate that is lifted off the tie will reduce or eliminate friction between the plate and crosstie, as shown in Figure 54. This in turn will result in a direct force path between the rail and the spikes It is known that there is a significant amount of longitudinal stress in the rail well ahead of a train or axle loads within a train [17] where this uplift occurs.

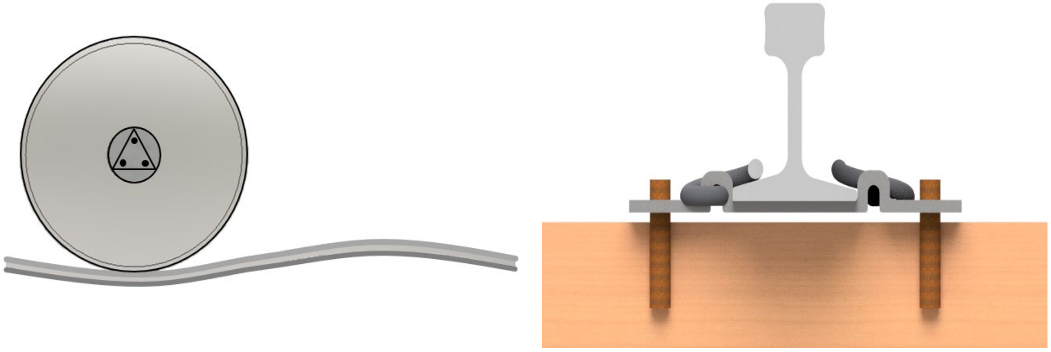


Figure 53. Visual depiction showing rail uplift ahead or behind a wheel load and the accompanying plate uplift in a premium fastening system

The uplift mechanism may explain the spike hole elongation and/or spike neck wear that has been observed in some premium fasteners. In this scenario, uplifting plates carry longitudinal force, which is transferred to the spikes as shown in Figure 55. As the plate moves up and down, it wears against the spike, leading to spike hole elongation in the plate and/or neck wear on the spike (Figure 56).

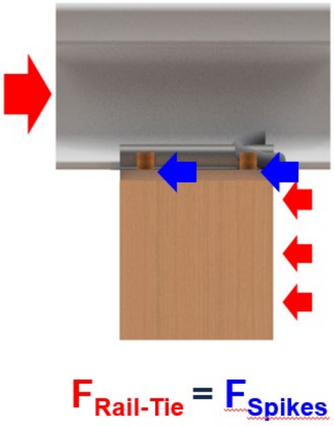


Figure 54. Expected effect of rail uplift on longitudinal force path from rail to crosstie

Figure 55. Left: A Victor plate spike hole showing significant wear in the longitudinal direction. Right: Longitudinal plate movement allowed by spike neck wear

7.2.3 Track Longitudinal Stiffness

The mechanical action of the fastening system affects the longitudinal response of railroad track. If track is modelled as a spring in the longitudinal direction, the fastening system affects the spring constant.

Track with traditional tie plates and anchors allows some longitudinal rail movement through the rail anchor, which results in a wider distribution of the longitudinal forces over adjacent crossties, and thus reducing the fastener-to-crosstie forces on an individual crosstie. This will result in track with a relatively low spring constant (i.e., is longitudinally soft).

Track with premium fasteners, however, restricts this longitudinal rail movement due to the elastic fastener clamping force. This means fewer crossties absorb the longitudinal load, resulting in higher fastener-to-crosstie forces on an individual crosstie. This type of track has a relatively high spring constant (i.e., is longitudinally stiff). The higher fastener-to-crosstie forces expected in the premium fastener case could be a cause of higher spike stress and thus spike failures.

7.2.4 Traction and Braking Forces on Grades

The field visits have revealed that curvature, grade, and tonnage alone do not predict the occurrence of spike breakage. For example, one 12.7° curve on level track had many broken spikes, while an 11° curve elsewhere, on a 1.6 percent grade with twice the tonnage had no issues.

A good example of this problem is one curve discussed during a field interview. The curve is a 9° curve on a 1.8 percent grade with three tracks. The two downhill tracks move most of the tonnage (loaded unit trains) while the uphill track moves the empty trains plus some intermodal and manifest traffic. Yet despite the uphill track having less tonnage and all else being equal, it has regular broken spike problems while the two downhill tracks have never seen major broken spike issues.

A plausible hypothesis is that the downhill trains are using air brakes, meaning the weight of the train and longitudinal forces are equally distributed throughout the train. The force on the fastening system is distributed along the entire length of track supporting the train. Meanwhile, the weight of an entire empty train moving uphill (or an entire intermodal or manifest train) is transferred to the rail and rail seat by only the powered axles of the locomotives. The force on the fastening system is distributed along as short length of track.

7.2.5 Rail Laying Hypothesis

One of the advertised benefits of premium fastening systems is that the plate and spikes need not be removed when doing rail replacement. Instead, the elastic clips can simply be removed to allow the rail to be moved or changed. This prevents the spike-kill of timber crossties.

However, railroads do not typically follow this method, but instead replace plates, anchors, and spikes during a rail change. There are several reasons railroads may not take advantage of this purported benefit of premium systems. One is that it can introduce track irregularities, as illustrated below. Another is a maintenance philosophy that considers the rail and other track components to have similar life cycles. Some railroads take old, removed track components and reuse them elsewhere (e.g., in yard tracks). Practices vary. For example, if a rail gang determines that the premium fasteners are in good shape, they may determine that time and money can be saved by simply removing the clips and laying the new rail.

One potential issue with rail replacement alone is illustrated in Figure 57. If rail in a curve gets worn down sufficiently, the wear, in combination with rail and plate movement, may lead to wide gage (Figure 57a). In this case, maintenance may gauge the rails in the curve to keep the track gage within the standard (Figure 57b), bringing it back to standard. If a rail gang then replaces the rail by only removing the clips and laying the new rail the result would be tight gage (Figure 57c). As long the gage is within standards, then this may not be an issue. In this tight-gage scenario the effect would likely be higher lateral forces on the system, and if the spikes are fatiguing, their reliability would decrease. The spikes are in service much longer than they would have otherwise been in the traditional fastening system.

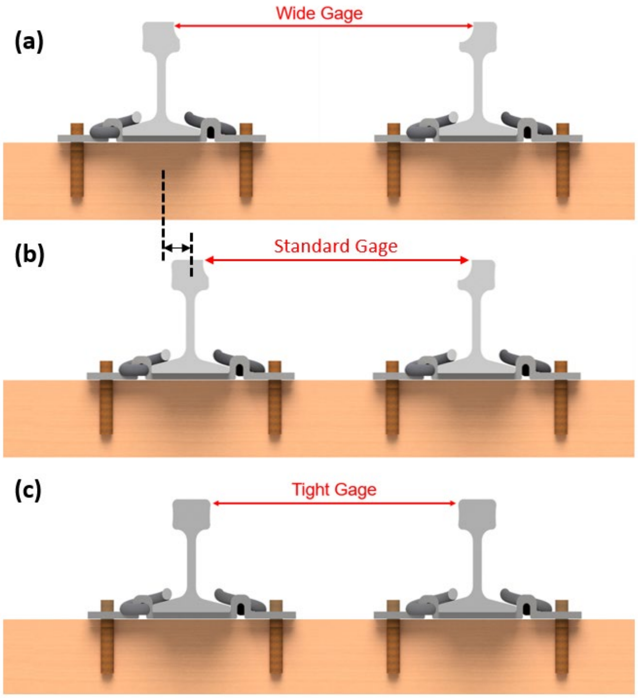


Figure 56. Effect of laying rail over existing premium fasteners

7.2.6 Screw Spike Torque

If screw spikes or lag screws are over-torqued when installed, axial-tensile forces are introduced into the spike. This results in a lower threshold for bending fatigue life for the spikes.

7.3 General Factors

The following hypotheses explain how factors like crosstie age, curvature, temperature, and certain maintenance practices could lead to higher stresses in spikes that are in any fastening system (traditional or premium). In extreme cases, these factors may be enough to lead to broken spikes. These hypotheses are potential factors in the first three cases shown in Figure 52.

7.3.1 New Crossties

Survey results referenced and the field observations confirmed that spike failure often occurs in new crossties. Some have suggested that this is because the new crossties are stiffer and therefore allow the spikes less movement as they are loaded. This induces a greater bending stress in the spikes. However, the FE work done by Dick et. al. showed that increasing crosstie stiffness decreased the maximum stress experienced in the spike and moved the location of maximum stress away from the location where spikes have been breaking. Instead, the reason for more failures in new crossties is more likely because the new, stiffer crossties are required to take more of the load compared to the older, worn, adjacent crossties.

7.3.2 Lateral and Impact Loads in Curves and Turnouts

Railroads overwhelmingly reported that their broken spike problems occur in curves. Several also said they see problems in special trackwork (turnouts, diamonds, etc.). These locations typically see higher lateral loads. Curves steer the vehicle in a different direction. Special trackwork may also steer the vehicle in a new direction, experience higher impact forces, and interrupt the lateral stability of vehicles.

7.3.3 Rail Temperature and Lateral Stress

One finding from the work of Dick et al. was that temperature affected the stress in spikes [16]. Temperature changes cause curves to “suck in,” or pull toward the inside of the curve, in cold temperatures. Rails pulling toward the inside of a curve will put lateral stress on the plates and thus on the spikes. This could be contributing to an increased stress state in the spikes during cold temperatures, which would explain why some railroads have reported their broken spike problems are correlated with temperature.

Dick et. al. found that just the day-to-night temperature change was enough to increase the stress in one spike by 5,000 lbs (22.2 kN). If this is really happening just overnight, then one would expect that in wintertime, when the rail is well below its neutral temperature, the effect would be even more extreme. One can imagine a case where a spike is loaded by this lateral bending stress from cold-temperature curve contraction, and then in addition takes high longitudinal and lateral bending stresses due to being in a premium fastening system during a train pass.

7.3.4 Uneven Distribution of Plate Force among Spikes

The NS field visit and interview found that the company has previously conducted research to investigate stresses in spikes and determined that stresses were unevenly distributed among spikes in the same plate. Dick concluded the same from his field work. One thing that Gao discussed was the spike contact position and the effect of this on the stresses felt in different spikes. Their work suggests that the different stresses seen in different spikes are related to the way each spike contacts the plate. Spikes in close contact with a plate edge are required to take more load than those centered in the spike hole. The spikes that are required to take more load may break, and subsequently require the other spikes to take more load.

7.3.5 Crosstie-Gauging Hypothesis

Another theory regarding why spikes break more often in new crossties relates to how the rail is gauged when new crossties are installed.

Crossties are generally replaced in groups of one, two or three to avoid a track class (speed) restriction that results when there are three bad crossties in a row. This results a mix of older and new crossties in track.

When a new crosstie is installed, spikes and plates are typically removed from the old crosstie to pull it out from under the rail. The new crosstie is then slid under the rail and the rail spiked to the crosstie. When spiking the rail to the new crosstie, the rail should be spiked to “prevailing gauge” (the current gauge of the surrounding track) to prevent the introduction of track irregularities. For example, if the prevailing gauge of a stretch of track is 56.75 inches, the railroad standard is typically to spike to a 56.75-inch gage rather than standard gage (56.5 inches). However, if a spiker operator is not regularly remeasuring the track gage to be sure he or she is spiking to the current prevailing gauge, then gage irregularities could be introduced. If the rail is spiked to standard gauge instead of prevailing gauge, the potential result is shown in Figure 58. This creates a track irregularity that could lead to higher lateral dynamic forces into the spikes at these locations as trains pass over. This may help to explain why broken spikes are experienced more frequently in new crossties.

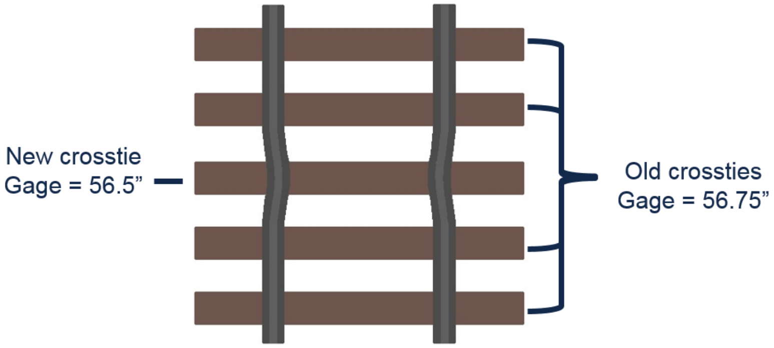


Figure 57. Exaggerated schematic showing a new tie with rails spike to standard gauge while the surrounding track has a prevailing gage of 56.75 inches

7.4 Proposed Laboratory Work

The proposed laboratory plan is designed to test many of the hypotheses presented in the preceding sections. The plan consists primarily of three laboratory test setups which, together with the proposed FEM work, can provide insight into the cause(s) of spike failures and inform fastener design activities and track maintenance practices. Table 4 shows how each laboratory test directly corresponds to one of the hypotheses presented above.

Table 4. Proposed laboratory tests

Hypothesis Number	Hypothesis Description	Lab Test to Investigate Hypothesis Validity	Lab Test Description
Premium Fastening System Hypotheses			
1	Longitudinal load path	A	Longitudinal load test with instrumented spikes
2	Rail uplift hypothesis	A	Longitudinal load test with instrumented spikes
3	Spike fatigue properties	B	Fatigue test of a spike in timber at various load levels
4	Track longitudinal stiffness	C	Large-scale longitudinal test on TLS
5	Screw spike torque		(No lab tests planned)
6	Traction vs. braking forces	(A, B)	No lab tests planned (tests A and B will provide further insight)
7	Rail installation practices	-	(No lab tests planned)
General Factors			
8	Failures in new ties	B, C	Run test A once with a new tie and once with an old tie. Compare stress in old and new ties in test C
9	Lateral loads in curves/special trackwork	-	(No lab tests planned)
10	Temperature Effects		(No lab tests planned)
11	Uneven distribution of force in spikes	A	Compare forces measured in each spike in test B
12	Track gauging over new ties	-	(No lab tests planned)
13	Liquid spike hole filler vs. plug wood	B	Run test A once with a spike with plug wood and once with a spike with liquid spike hole filler

Test A is a longitudinal load test like that prescribed in AREMA Chapter 30 [18]. The proposed test setup is shown in Figure 59. With this test, a longitudinal load can be applied to a traditional fastening system with a rail anchor, a premium system, or a premium system with a rail anchor. Instrumented spikes (shown in Figure 60) will record the effect on the stress in the spikes in each scenario. Further scenarios will include vertical loads from a wheel load, or an uplift force from rail negative bending. Additional scenarios can test the effect of spike location and angle on spike stress and stress distribution among spikes.

The instrumented spikes to be used were originally developed by Randy Bowman for examining spike failures at NS. The variant currently being developed at RailTEC measures stresses in both the lateral and longitudinal directions and will survive being driven multiple times into virgin timber.

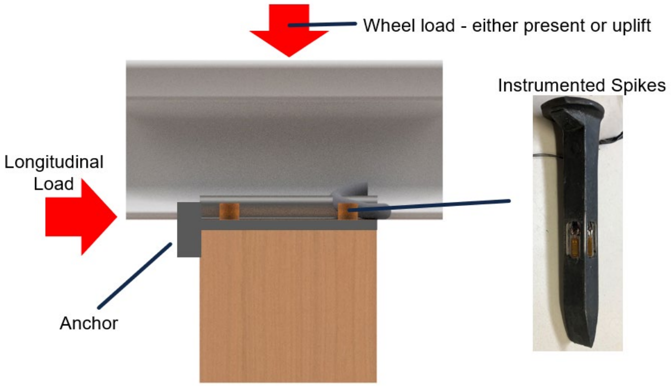


Figure 58. Proposed UIUC laboratory Test A

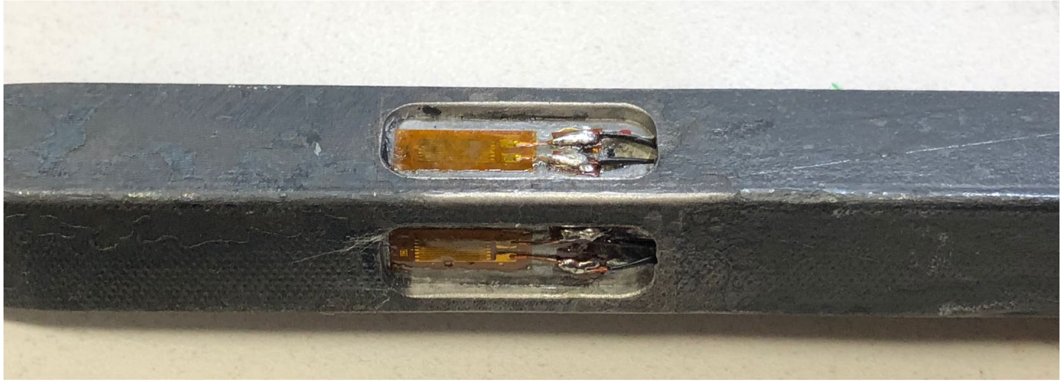


Figure 59. Instrumented spike developed at RailTEC with close-up view of strain gauges before protection layer is added

Test B is a simple laboratory fatigue test on a spike. With this test lateral loads, longitudinal loads, or a combination thereof can be applied to a spike in timber, and the resulting fatigue properties can be confirmed. The results from this test will help researchers understand if the stress increases from other hypotheses (e.g., the lack of rail anchors or rail uplift) is enough to cause the premature spike failures experienced in the field. Further, it will also serve to calibrate the FE models. This test can also be altered to help examine hypotheses presented in Section 7.2.4 and Section 7.2.6.

Test C is a larger test that includes a small track panel of at least 10 crossties on ballast and subgrade that represent common field conditions. This test will be set up on the Track Loading System (TLS) at the RAIL lab at the University of Illinois. Longitudinal loads can be applied to this track panel to test track longitudinal stiffness with different fastening systems and its resulting effect on longitudinal force into each crosstie. The setup is shown in Figure 61.

Figure 60. Proposed UIUC laboratory Test C

8. References

[1] Armstrong, J. H. (2008). The Railroad: What It Is, What It Does, 5th ed., Omaha: Simmons-Boardman Books, Inc.

[2] International Heavy Haul Association (2009). Guidelines to Best Practices for Heavy Haul Railway Operations, Virginia Beach, VA: D & F Scott Publishing.

[3] Transportation Safety Board of Canada (2012). "Railway Investigation Report R12E0008," Transportation Safety Board of Canada.

[4] Kerchof, B. (2017). Writer, *A Derailment Investigation and Broken Spikes.* [Performance]. WRI2017 - Heavy Haul Seminar.

[5] Tuzik, J. (2018). "interface: The Journal of Wheel/Rail Interaction." [Online]. Available: http://interfacejournal.com/archives/2143. [Accessed 24 July 2018].

[6] Federal Railroad Aministration (2016). "Preliminary Factual Findings Report: Derailment of Union Pacific's Unit Crude Oil Train ONETU 02 Transporting Bakken Crude Oil for U.S. Oil: Mosier, Oregon," FRA, Washington, DC.

[7] Schick, T.& Wilson, C. (2016). "How Inspectors Missed Broken Bolts That Caused An Oil Train Derailment," OPB (Oregon Public Broadcasting). [Online]. Available: https://www.opb.org/news/series/oil-trains/how-inspectors-missed-broken-bolts-mosier/. [Accessed 16 August 2018].

[8] Transportation Safety Board of Canada (2011). "Railway Investigation Report R11D0099," Transportation Safety Board of Canada.

[9] Liu, X., Saat, M. R., & Barkan, a. C. P. L. (2012). "Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates," *Transporation Research Record: Journal of the Transporation Research Board,* vol. 2289, pp. 154-163.

[10] Dick, M. G., & McConnell, D. S. I. H. C. (2007). "Experimental measurement and finite element analysis of screw spike fatigue loads," in *2007 ASME/IEEE Joint Rail Conference & Internal Combustion Engine Spring Technical Conference*, Pueblo, CO.

[11] Gao, Y., McHenry, M., & Kerchof, B. (2018). "Investigation of Broken Cut Spikes on Elastic Fastener Tie Plates Using an Intergrated Simulation Method," in *Proceedings of the 2018 Joint Rail Conference*, Pittsburgh, PA.

[12] Dersch, M., , Roadcap, T., , Edwards, J. R., Qian, Y., Kim, J.-Y. & Trizotto, M. (2019). Investigation into the effect of lateral and longitudinal loads on railroad spike stress magnitude and location using finite element analysis. *Engineering Failure Analysis*, 104: 388–398 DOI: 10.1016/j.engfailanal.2019.06.009.

[13] Jimenez R. & Davis, D. (2007). "Technology Digest TD-07-027: Update: New Crosstie and Fastening System Test at FAST," Transportation Technology Center, Inc., Pueblo, CO.

[14] Federal Railroad Administration (2008). "Update: New Crosstie and Fastening System Test at the Facility for Accelerated Service Testing," (Report No. RR08-13).

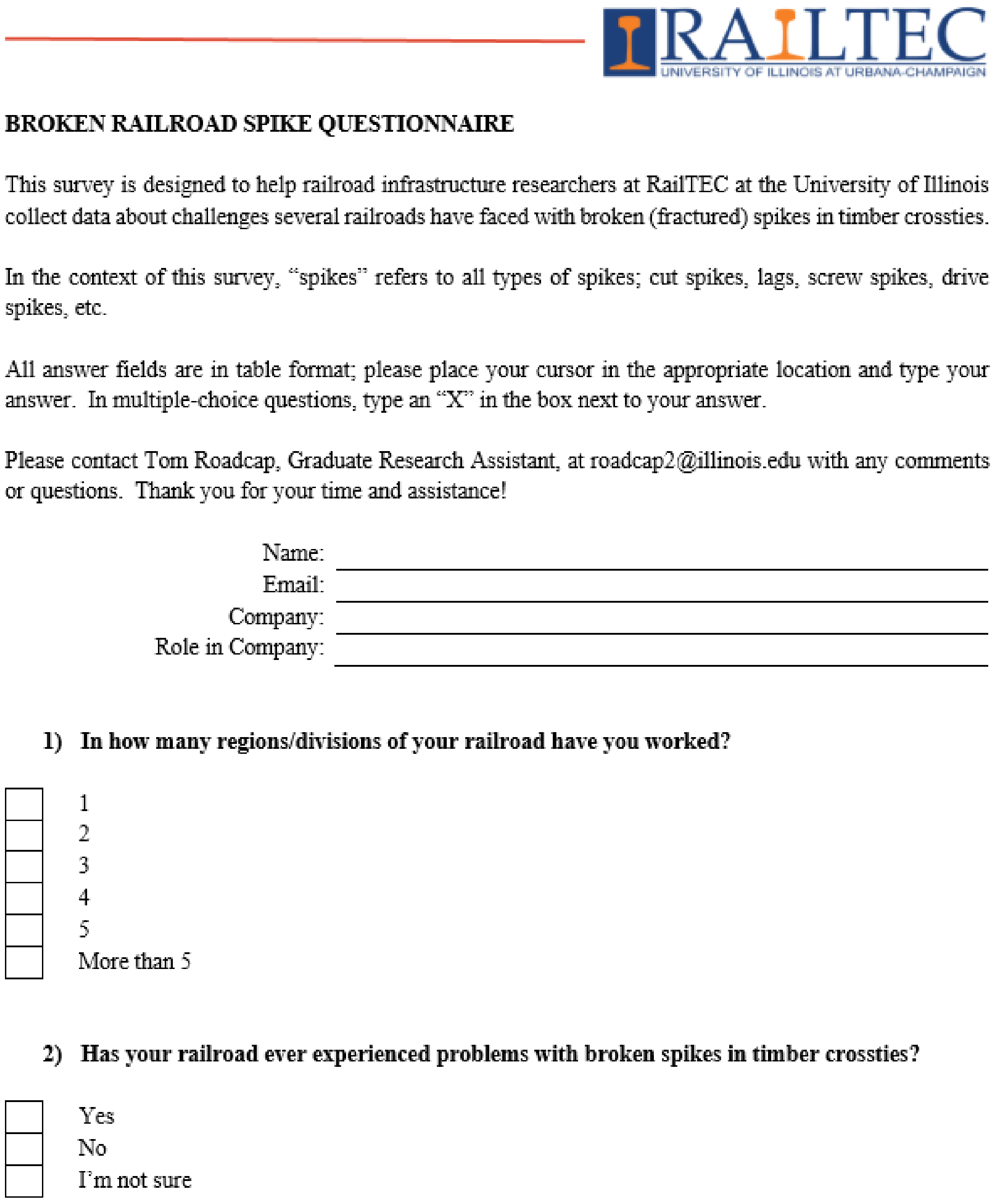
[15] AREMA Manual for Railway Engineering (2017). *Chapter 5 Part 2: Track Spikes,* Landham, MD.

[16] Kerr, A. D. (2003). Fundamentals of Railway Track Engineering, Omaha, NE: Simmons-Boardman Books.

[17] Bose, T., Levenberg E., & Zania, a. V. (2018). "Analyzing Track Responses to Train Braking," *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit,* pp. 1-10.

[18] AREMA Manual of Railway Engineering (2017). *Chapter 30: Ties,* Landham, MD.

Appendix A.
Survey Questions



RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

BROKEN RAILROAD SPIKE QUESTIONNAIRE

This survey is designed to help railroad infrastructure researchers at RailTEC at the University of Illinois collect data about challenges several railroads have faced with broken (fractured) spikes in timber crossties.

In the context of this survey, "spikes" refers to all types of spikes; cut spikes, lags, screw spikes, drive spikes, etc.

All answer fields are in table format; please place your cursor in the appropriate location and type your answer. In multiple-choice questions, type an "X" in the box next to your answer.

Please contact Tom Roadcap, Graduate Research Assistant, at roadcap2@illinois.edu with any comments or questions. Thank you for your time and assistance!

Name: ____________________
Email: ____________________
Company: ____________________
Role in Company: ____________________

1) In how many regions/divisions of your railroad have you worked?

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ More than 5

2) Has your railroad ever experienced problems with broken spikes in timber crossties?

☐ Yes
☐ No
☐ I'm not sure

3) Where do failures typically occur?

☐ Steep grades
☐ Tight curves
☐ Northern region
☐ Southern region
☐ Special trackwork
☐ Areas with acceleration/braking
☐ Other (please elaborate):

4) Please provide any specific details that you can (e.g. specific geographic areas, certain curves, etc.). How does your railroad locate broken spikes?

5) Has locating and addressing broken spikes been a relatively small, moderate, or large problem compared to other track-related problems?

☐ Small problem
☐ Moderate problem
☐ Serious problem

6) Why?

7) Have broken spikes led to wide gage defects or (if you are able to answer) even wide gage derailments? Please provide any details (date, location, etc.) you can.

DEFINITIONS:

Traditional fastening system: cut spike with tie plate and rail anchor

Premium fastening systems: timber tie systems with an elastic clip (examples below)

Premium Fastening Systems:

Progressive Railroading

TTCI

8) Which fastening systems have experienced broken spikes on your railroad?

☐ Traditional plate & cut spike
☐ Pandrol rolled plate
☐ Victor plate with cut spikes
☐ Victor plate with screw spikes
☐ Cast plate with Safelok/SL (Airboss) system
☐ NorFast system
☐ Vossloh BTE30
☐ Vossloh BTC30
☐ Other (please elaborate):

9) Of all broken spikes found on your railroad, how many would you estimate are in premium fastening systems?

☐ 0% - 20%
☐ 20% - 40%
☐ 40% - 60%
☐ 60% - 80%
☐ 80% - 100%
☐ I'm not sure or do not have this data

10) Has your railroad done any internal or contract research or testing regarding broken spikes? If so, would you be willing to collaborate and share findings with the University of Illinois research team?

11) Do you have any other comments you would like to share with us?

Please contact Tom Roadcap, Graduate Research Assistant, at roadcap2@illinois.edu with any comments, questions, or further discussion. Thank you again for your time and assistance!

Appendix B.
Selected Survey Short-Answer Responses

B.1 Magnitude of the Broken Spike Problem

"More of a lessons learned piece- once you identify zones of concern going in and replacing ties- adding additional spikes- BNSF now has a process where we add spikes to high rails when gaging low rail relays/work- removing wood and installing concrete ties- using more data/knowledge/algorithms to help identify zones of concern."

"Mitigated by gage restraint testing. Geometry car and other technology."

"It has not caused too many serious issues."

"The concerns are small but if there is an issue that goes without finding it could cause catastrophic consequences. Once on the ground they are found easily and repaired easily so the issue with locating and addressing are theoretically minute if performing walking inspections of curves on a regular basis."

"I think what makes this such a serious problem is how quickly the deteriorated condition escalates. In Victor plates, broken spikes go from being nearly impossible to detect to FRA defective condition quicker than any gage-widening trends that I've ever seen."

"It's a high-risk issue that is difficult to see especially in snow covered conditions. We've seen more issues over the past few years with longer, heavier trains operating with dynamic braking."

"Cause of significant derailment in the PNW, resulted in FRA sanctions and large-scale capital programs to resolve issues."

"Under normal circumstances, the widening of gage happens gradually and can be monitored by quarterly walking inspections. However, when spikes begin breaking, gage can open much faster and may reach a critical point before the broken spikes are found. This can result in an open gage derailment if these conditions are not detected and corrected soon enough."

"On several heavy tonnage, steep grade territories, broken spikes are the problem that represents the greatest risk to the safety of train operations."

B.2 Challenges of Inspecting for Broken Spikes

"Spikes might not fall out of the tie plates and require tapping to determine if they are broken"

"When walking, the inspector must look for a false flange on the low rail… outward shove of the plates on the high side, and a very good tell-tale sign has been the rotation of the spike head."

"Broken Lags or Broken Spikes are only found by walking inspections. Geometry Car inspections may point to a location that there could be some concern, but you will have to walk to find the issues."

"They are found by looking at the most recent new tie gang locations and tapping the top of the spikes and listening or using a small light weight spike puller and prying upward. A STAR car with a spit axle should also be able to find them or at least point at weak strength locations..."

"Broken spikes are found two ways: 1) by track inspectors making scheduled walking inspections (monthly, or quarterly, depending on circumstances) who check every spike on the high rail in the full body of a curve , or by track geometry cars, which register a gage "spike" (a very short spot of gage wider than prevailing gage). Geometry car spots are confirmed by a walking inspection"

"Depends on the experience and capability of the track inspectors. [One territory on our railroad] does a remarkably effective job finding broken spikes before they have an opportunity to contribute to an open gage defect. Then again, they have a higher frequency of broken spikes than any other territory and have developed this capability because they had to."

"Locating them is the problem. MOST track inspectors, roadmasters, foreman do not follow instructions / requests / advice and test locations."

B.3 Characteristics of Broken Spike Locations

"[On my territory], our most problematic curves for broken spikes are over 8 degrees on steep grade (1.3%-2.3%)."

"Usually see in curves greater than 3 degrees."

"Broken spikes in curves greater that 5 degrees with MGT greater than 50."

"Mainly the high side."

"Specifically, our curves at mileposts 241.7, 244.7, 245.2, and 246.1 have produced most of our broken spikes."

"We also tend to find broken spikes where Victor plates are being used on track with steep grades. We believe this is caused due to the spike holding all forces without the help of snap on anchoring against the ties. Rail grease also seems to play a large role in broken spikes."

"Initially, we found our broken spikes in sharp curves (6° and over) that had Victor plates and that experienced higher tractive effort, under either power or braking, due to a steep grade. Subsequently, we found broken spikes in sharp curves on level grades."

"Locations where there are very good ties sprinkled in with poor ties requiring the good tie to absorb all loads."

"Broken spikes occur on new ties that have recently been replaced in curves. Sharper curves and mt grades (snow=cold) are likely locations. The spikes are broken on the new ties which are taking much of the load when they are adjacent to older ties. The older ties give which does not evenly distribute / share the load."

"Many broken screw lags around turnouts/diamonds."

"Frog plate spikes and point and stock rail plates."

"There are a high number of screw spikes that fail in the front end of the turnouts, likely a higher frequency than in conventional track"