Mechanistic Investigation of Timber Crosstie Spike Failures

Industry Partners Update Meeting

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U.S. Department of Transportation
Federal Railroad Administration

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Acknowledgements

- Project Sponsor

U.S. Department of Transportation
Federal Railroad Administration

- Industry Partnership

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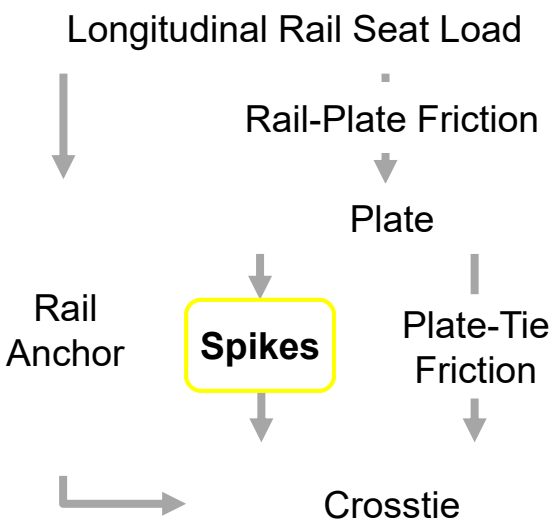
Outline

- Problem Overview
- Project Summary
  - Field, Lab, and Modelling
- Wheel and Rail Seat Loads – Field Results
  - Vertical
  - Lateral
  - Longitudinal
- Spike Stress Mitigation Methods - Modeling
  - Cross Sectional Area
  - Screw vs Cut
  - Load Location
  - Plate Clamping Force
  - Spike Engagement
- TTC Results
  - Test vs Control
- Preliminary Recommendations for Mitigating Spike Failures

Background on Spike Failures

- Spikes have been failing due to fatigue
  - Primarily on *premium fastening system*
  - Often *new ties*
  - Mainly on *curves*
  - Also in *special trackwork*
- Driven by overloading mechanism

Traditional System with Anchor



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- Leads to rapid gauge deterioration causing at least 10 derailments since 2000

Likely Driving Factors

- *Lack of anchor increases* longitudinal loads

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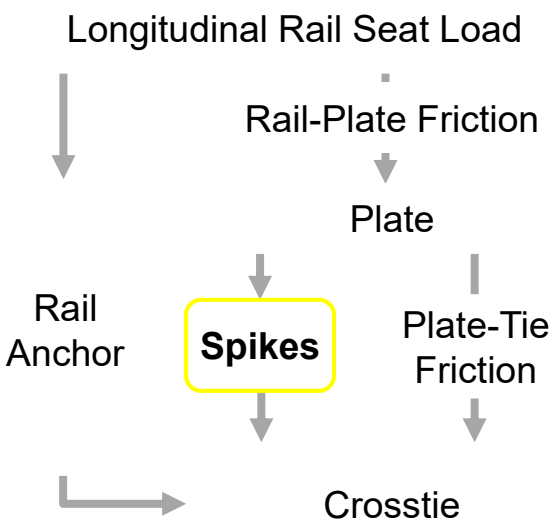

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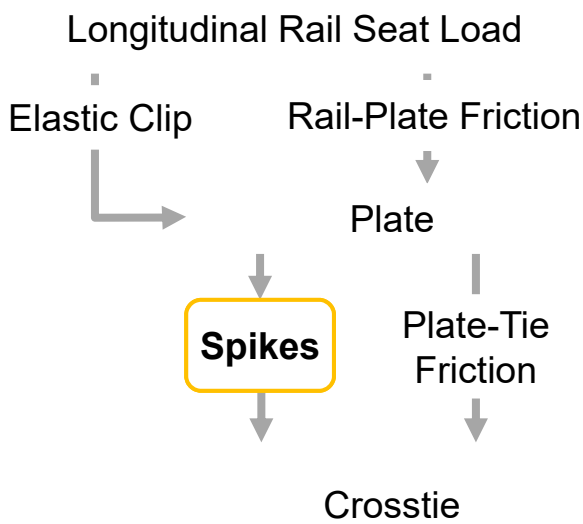
Premium System with Clip



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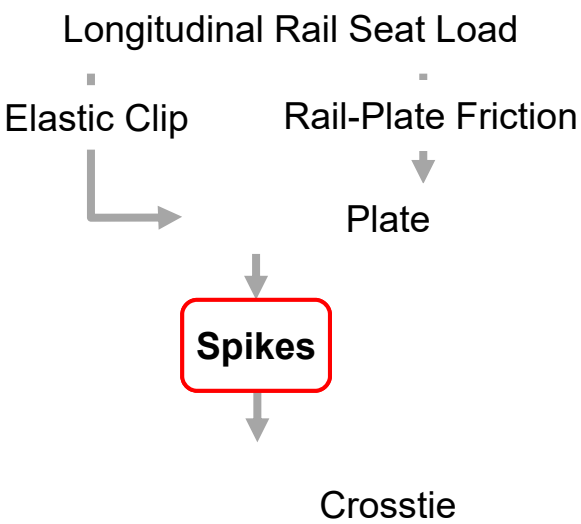
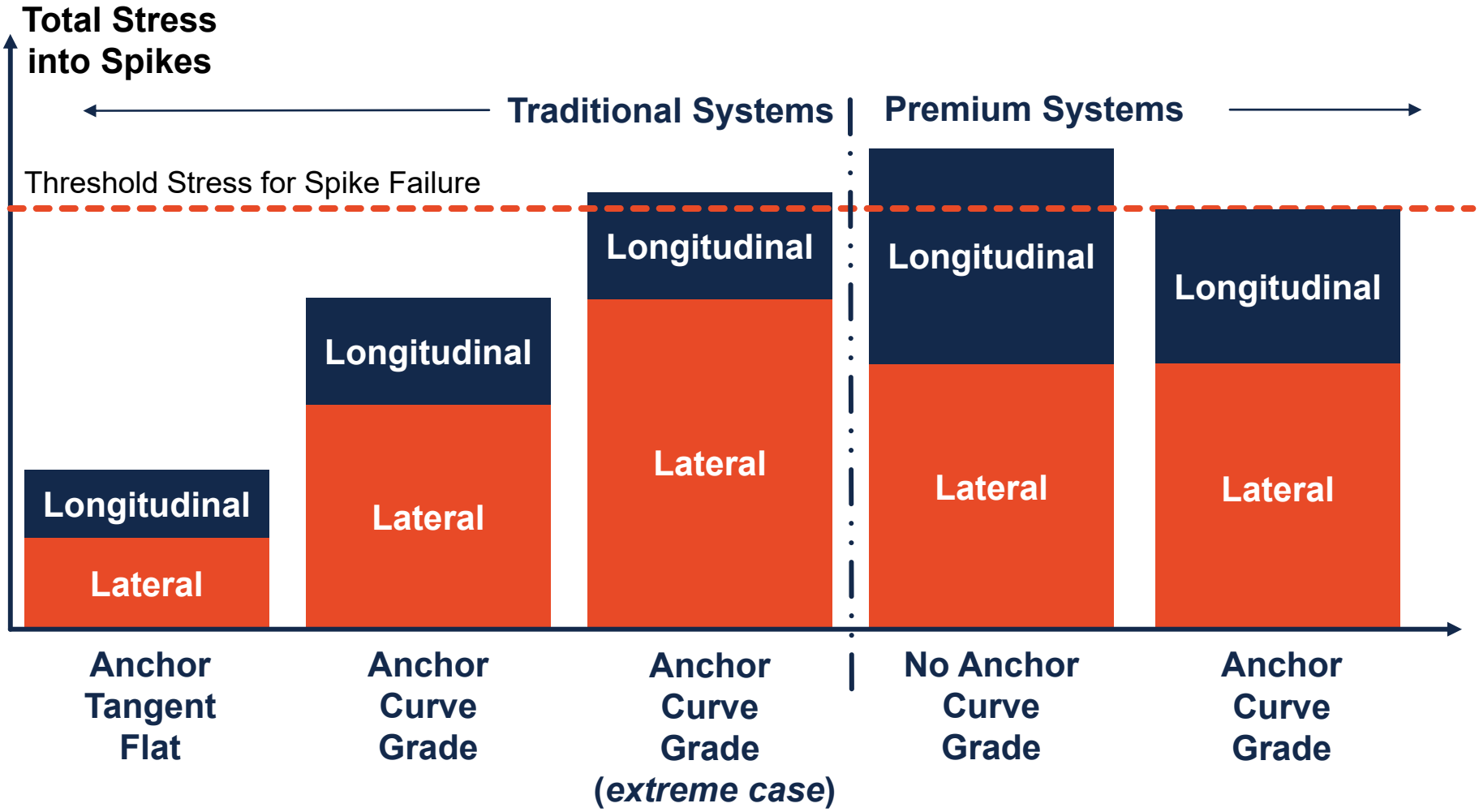


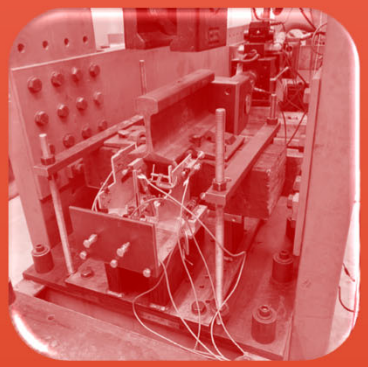
Likely Driving Factors

- *Lack of anchor increases* longitudinal loads
  - Wood is weaker in this direction
- *Plate uplift* further increases loads
- Stiffer fasteners reduce distribution of loads
- Crosstie age

Stress in Spikes – Hypothetical Graph



Project Thrust Areas



Laboratory

Controlled experiments to better characterize load transfer and rail displacement/slip of various fasteners

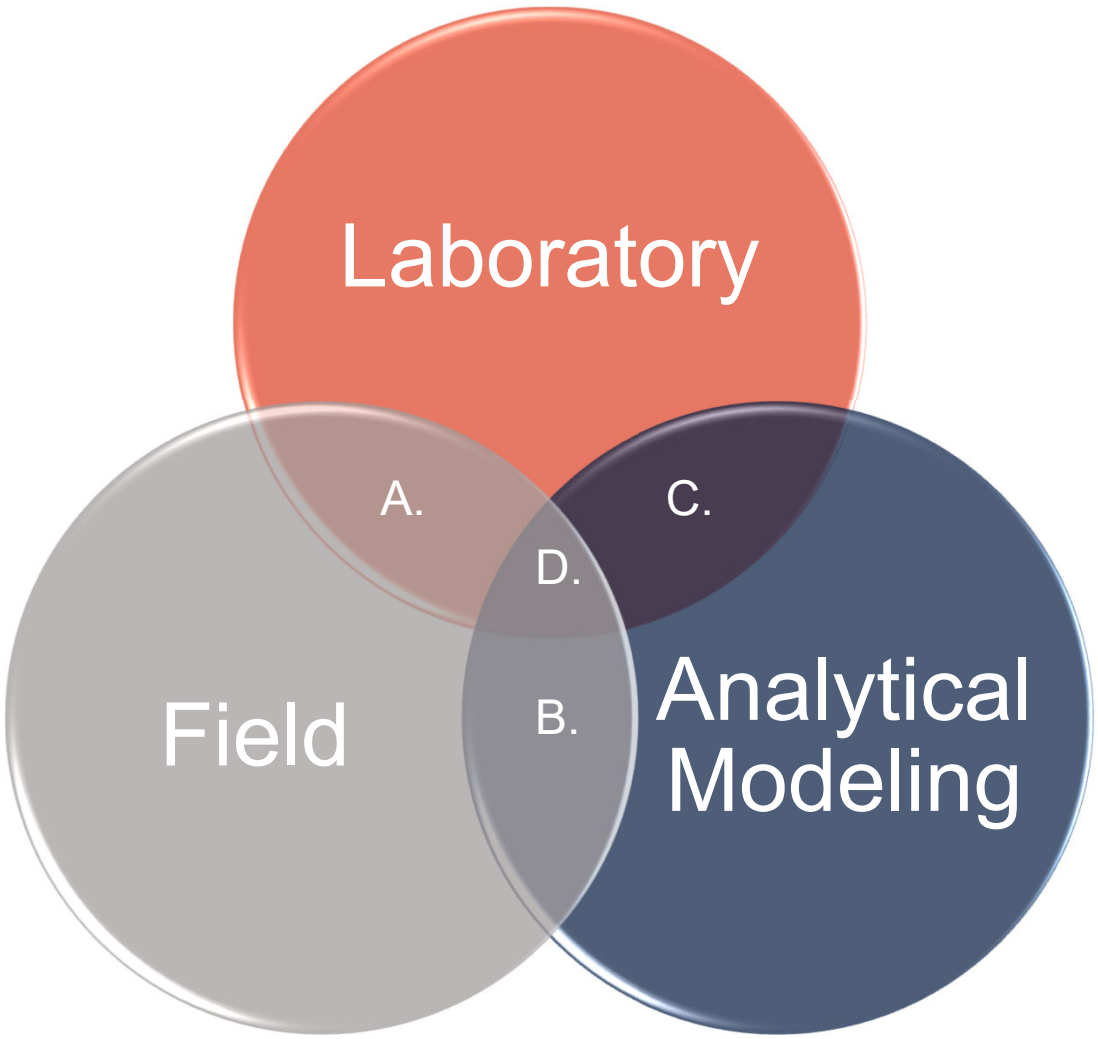
Analytical Modeling

Quantification of load distribution and spike stress while investigating key factors affecting load transfer

Field

Quantification of loading demands (vert., lateral, long.) and fastener response to service loading

Thrust Area Interaction



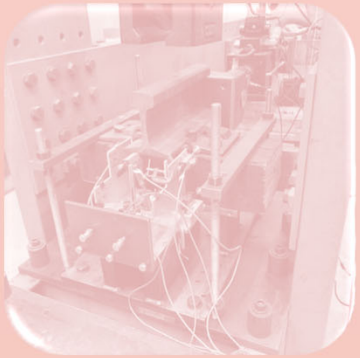
A. Lab ↔ Field:
   - Field data can inform lab loading magnitude
   - Controlled experiments can challenge/replicate field data and inform future field work

B. Field → Model:
   - Field provides load input for model

C. Lab ↔ Model:
   - Lab provides data for calibration of models
   - Model helps to focus lab experiments

D. Provides opportunity to make comprehensive recommendations

Project Thrust Areas



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Field Experimentation Motivation

High Level Outcomes

Data acquisition through field experimentation allows for

- **Quantification of Loading Environment**
  - Improve our understanding of the load demands placed on the fastening systems as a result of passing trains
- **Evaluation of Fastening System Response**
  - Improve our understanding of the characteristic stiffnesses, deformations, and displacements as demands/conditions (loading, weather, etc.)
- **Development of Analytical Model**
  - Validate a three dimensional (3D) finite element (FE) model
  - Compare data with laboratory results

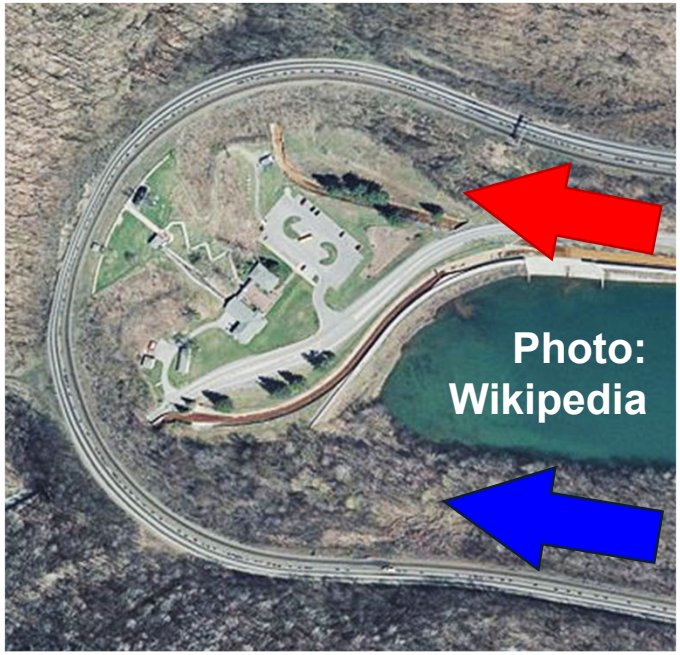
Field Experimentation Overview

Horseshoe Curve

- 3-track curve in Norfolk Southern's Pittsburgh line
- Westbound track has primarily **uphill empty** trains (45.6 MGT)
  - Tractive effort is distributed throughout *the locomotives*
- Eastbound track has primarily **downhill loaded** trains (50 MGT)
  - (Air)break forces are distributed throughout *the entire train*

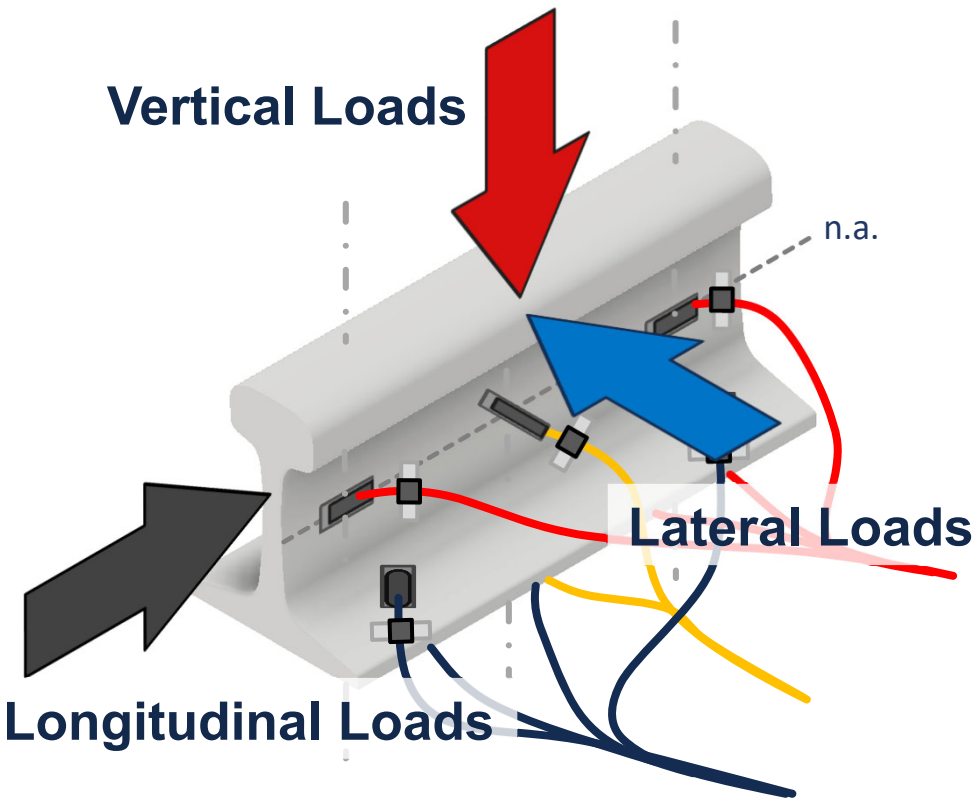
Key feature: Tracks have the *same curvature, grade and climate*, allowing the comparison of the effects of the following on loading demand and fastener response

- Anchor
- Temperature
- Load
- Speed
- Direction of traffic
- Braking vs. traction forces
- High vs. low rail

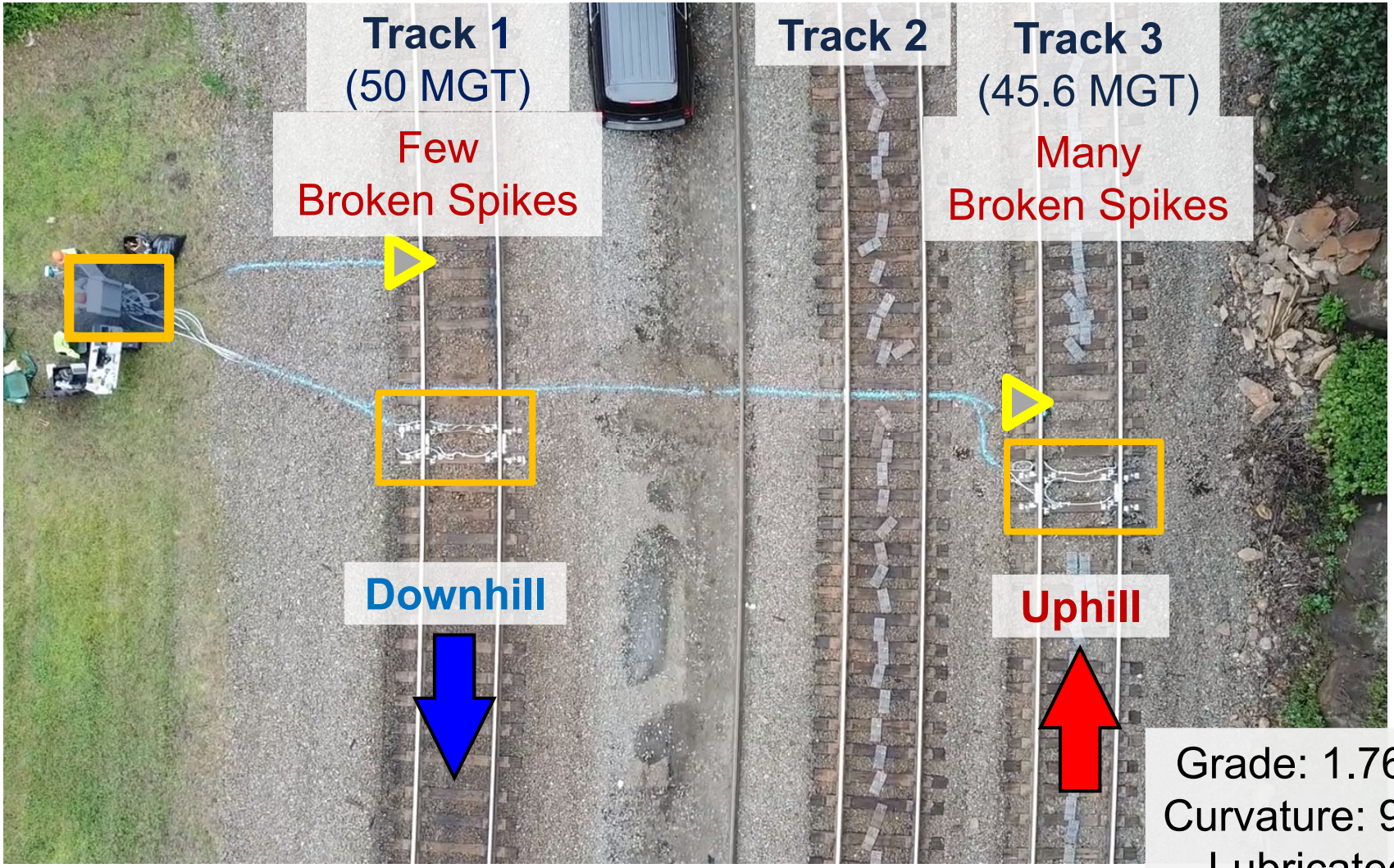


Quantification of Loading Environment

- Vertical, lateral and longitudinal loads collected with industry standard load circuits installed in the center of the crib on both high and low rails



Field Experimentation Review



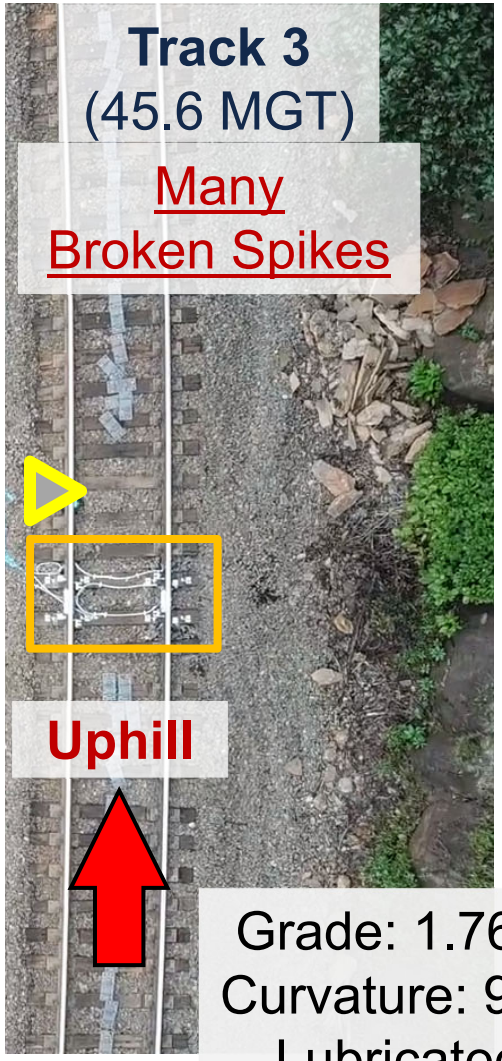
Grade: 1.76%
Curvature: 9.2°
Lubricated
Airbrake grade

Instrumentation Area

Data Collection Box

Wheel Counter

Track Overview



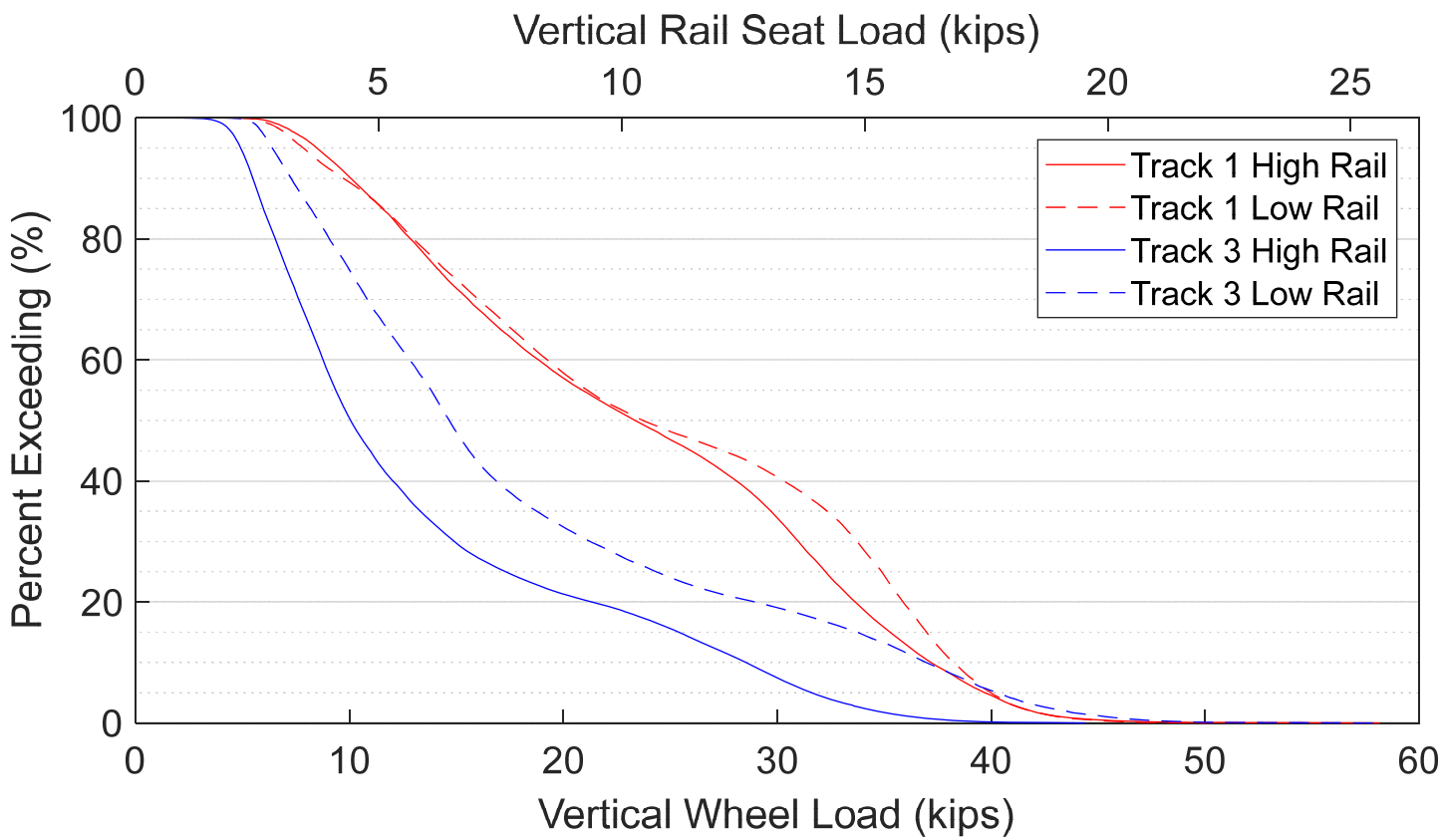
Grade: 1.76%
Curvature: 9.2°
Lubricated
Airbrake grade

- Two ties and one crib instrumented in each track

Percent Exceeding Vertical Wheel Loads

(July 2019)

(43% of Wheel Load)



- Vertical wheel loading is generally greater in Track 1
  - Expected, since operations of loaded trains are biased on that track
- Track 3 operations are seen to be underbalanced
  - In average, low rail vertical loads are more than 30% greater than in high rail

Percent Exceeding Vertical Wheel Loads

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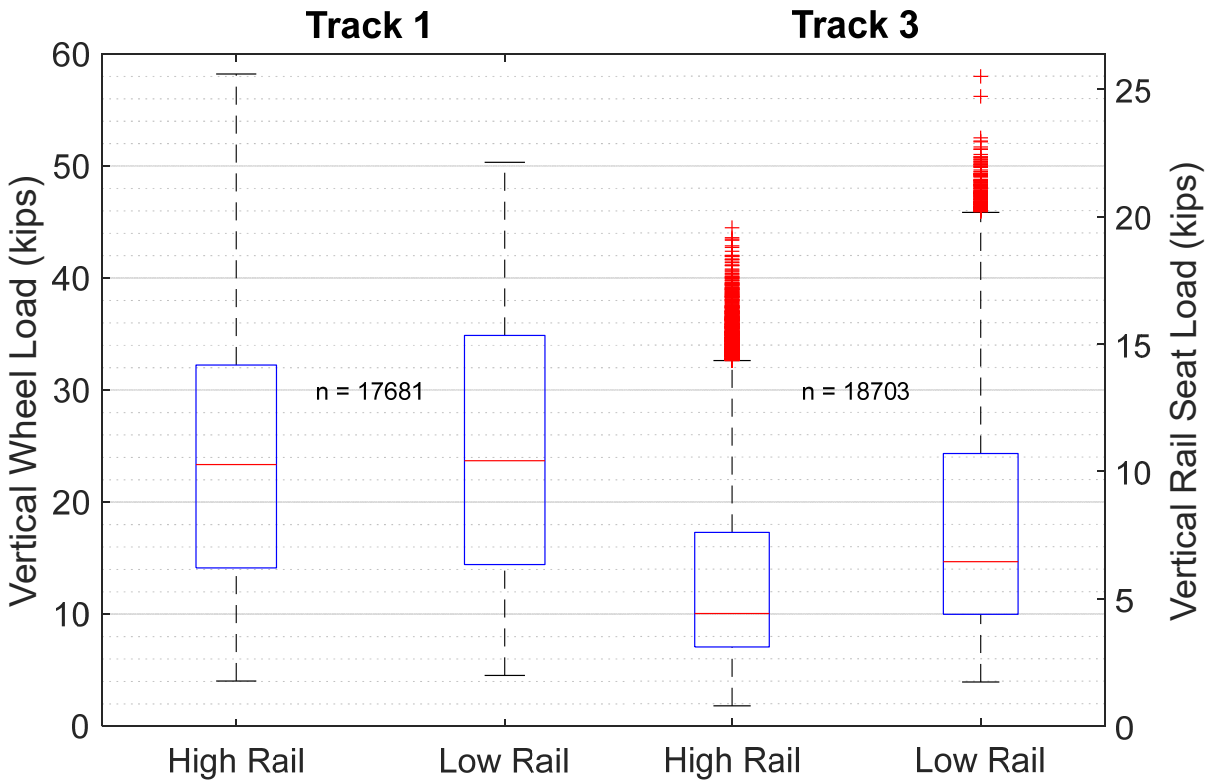

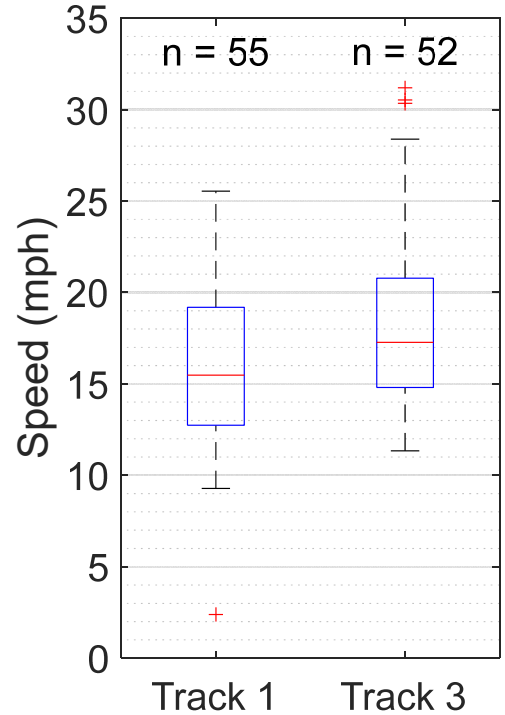

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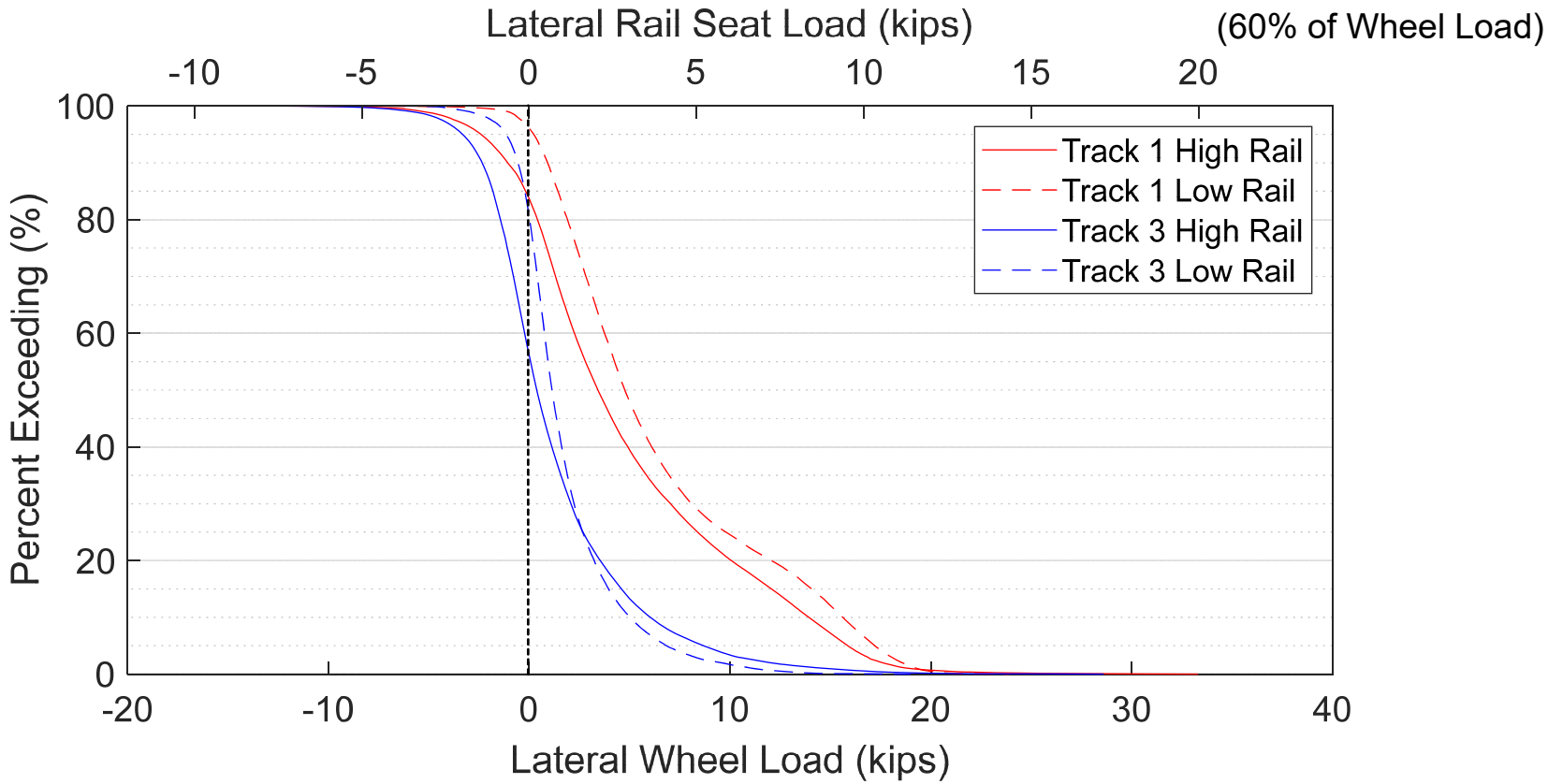

- Track 1 field-facing lateral wheel loads are measured to be, on average, 130% higher than in Track 3
- 10% of lateral loads are gauge-facing in Track 1 and 30% in Track 3

Percent Exceeding Lateral Wheel Loads

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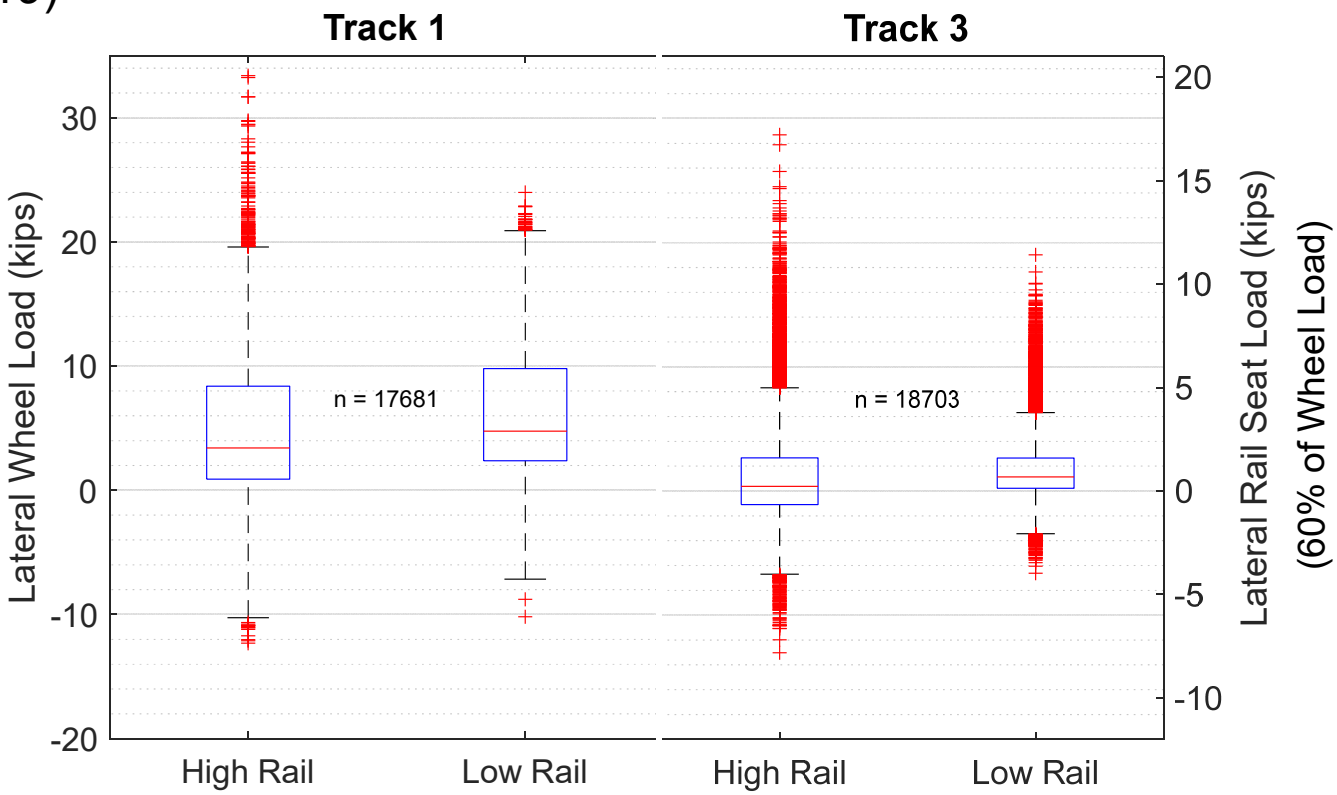

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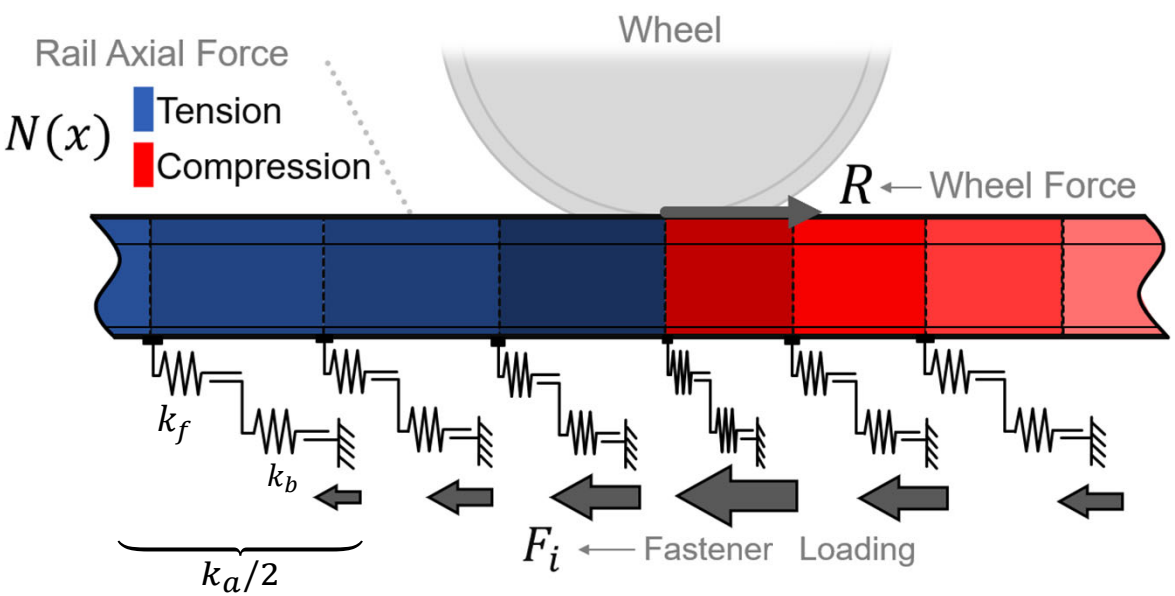
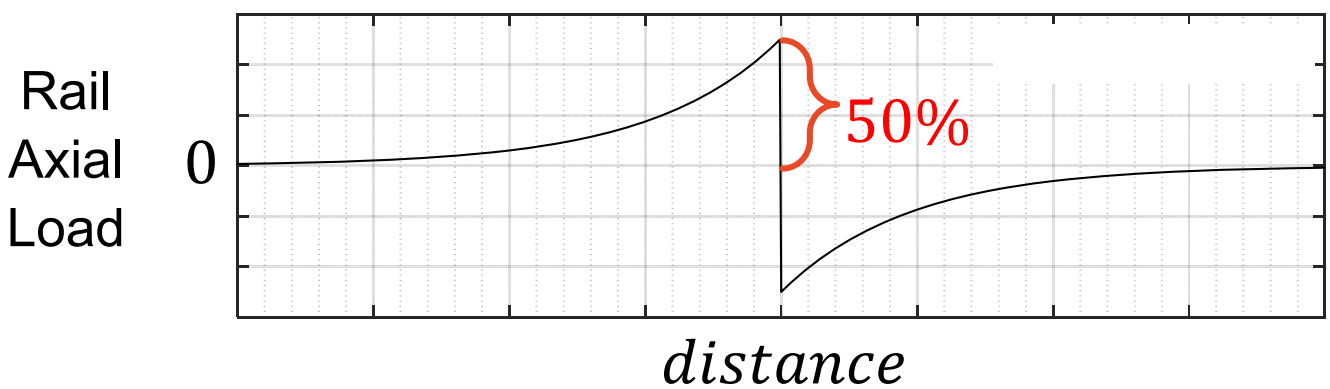
Longitudinal Loading

Wheel, rail axial, and fastener





Following elastic track model by Kerr(2003)

Longitudinal Loading

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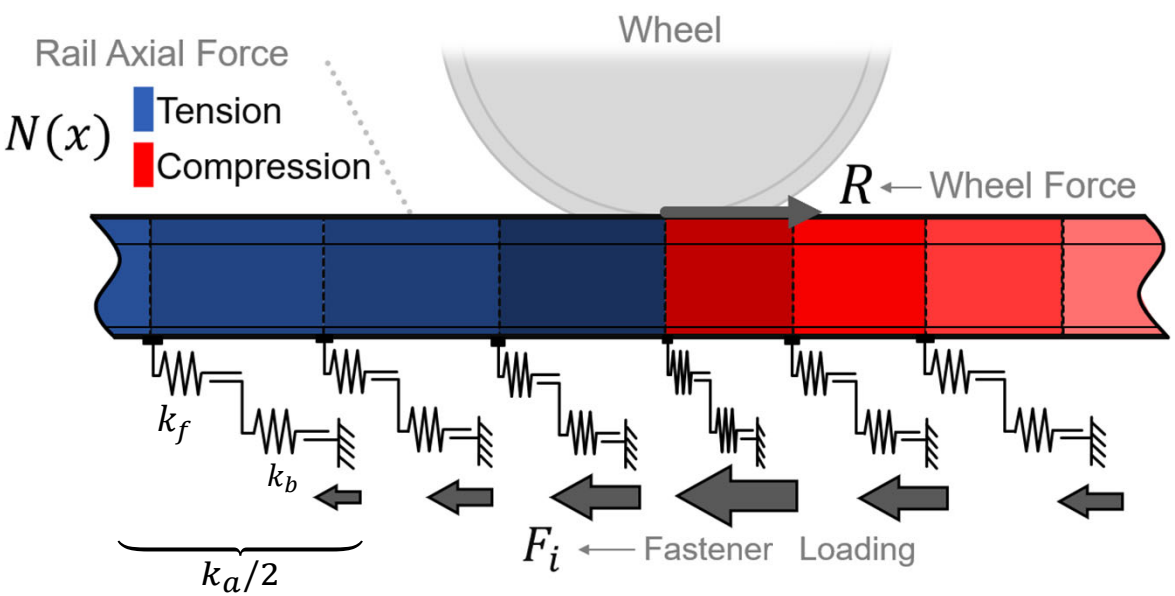
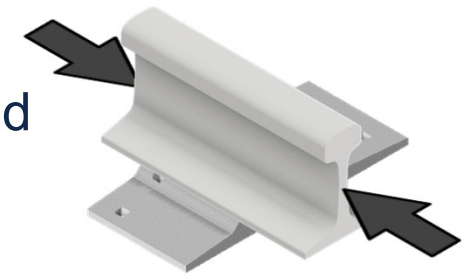
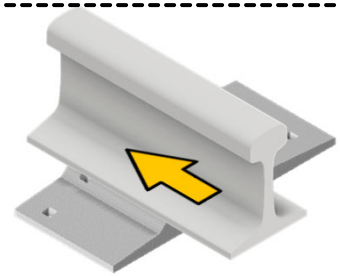
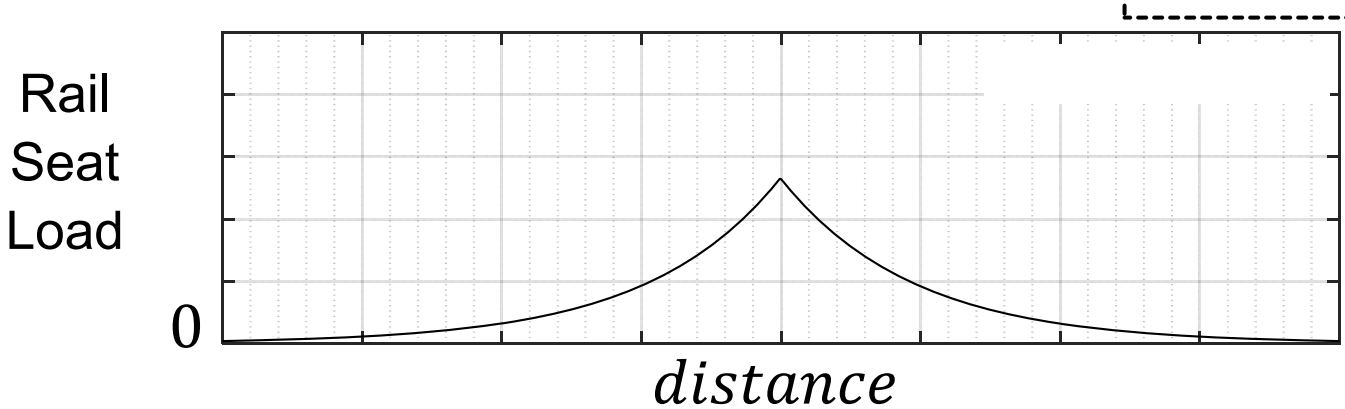


Axial Load



Longitudinal Fastener Load





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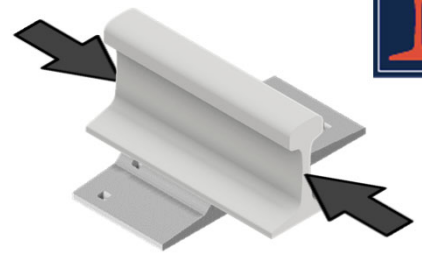
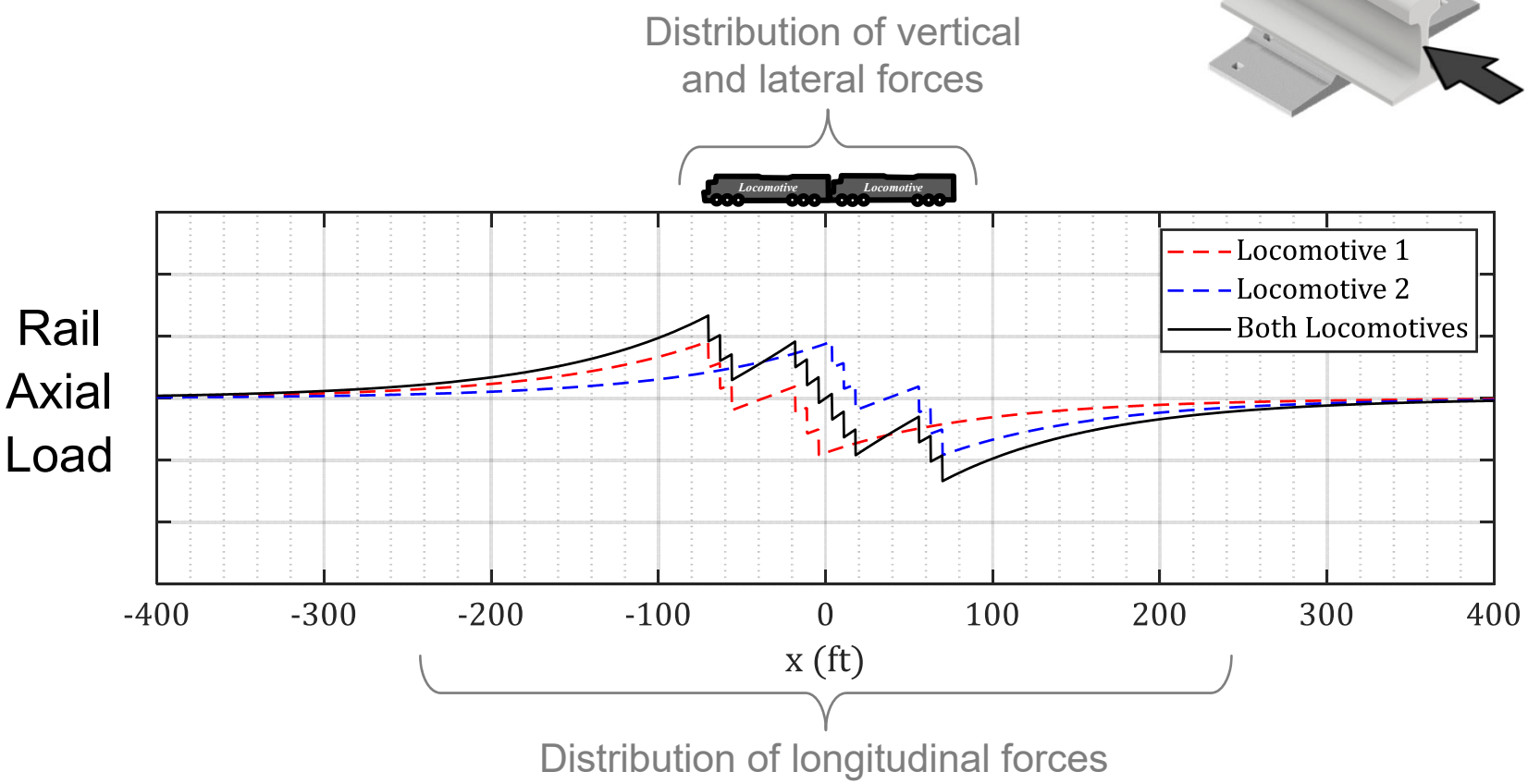
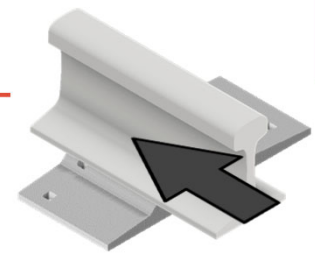
Superposition of Axial Loads

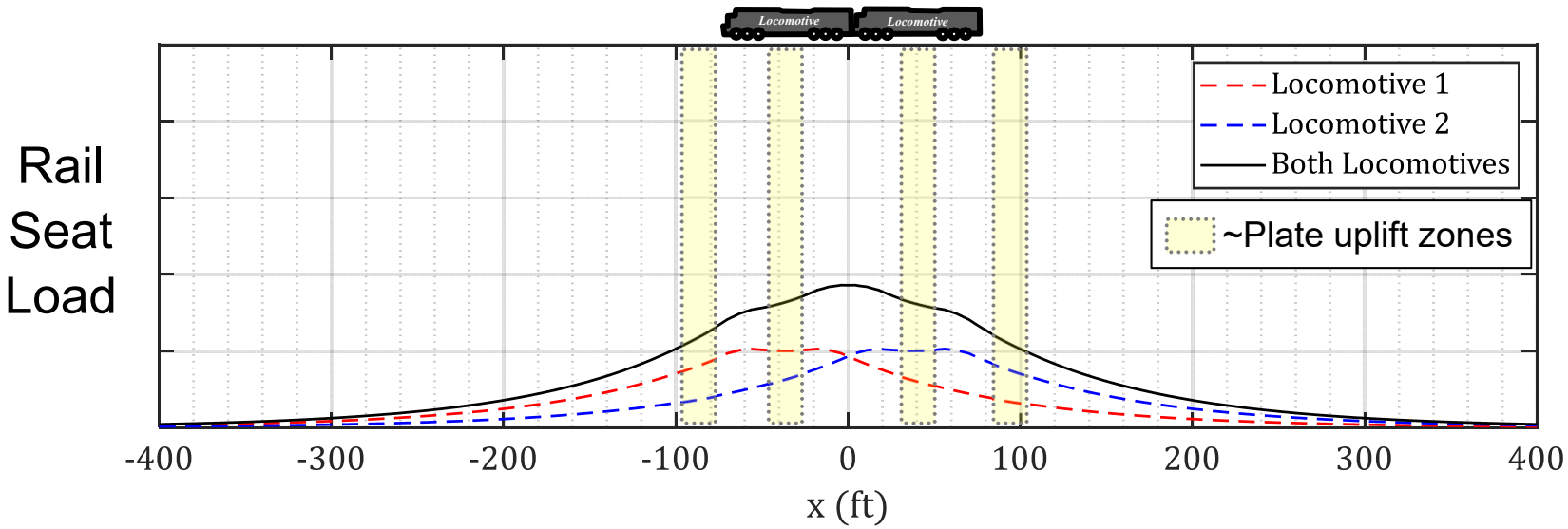




- Cancellation of rail axial forces occur between locomotives

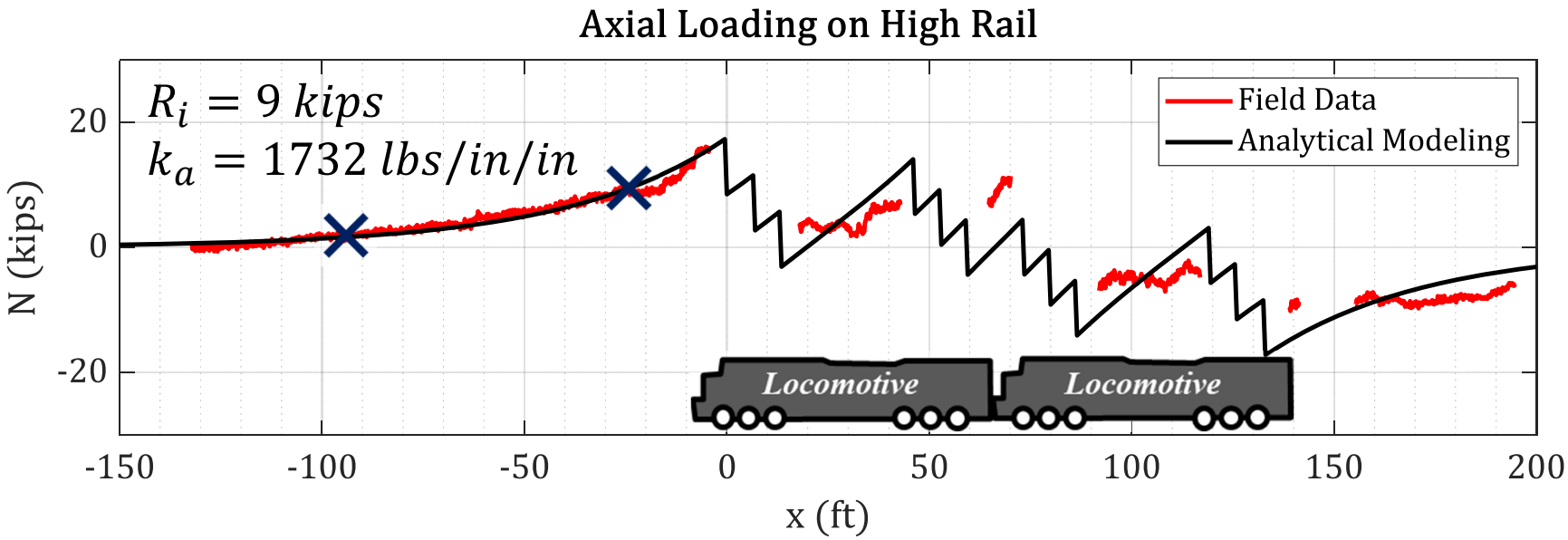
Superposition of Fastener Loads





- Fastener loading is greatest **between** locomotives
- Plate uplift can occur during application of longitudinal loading
- Load superposition studied:
  - Draft paper: “Analytical Elastic Modelling of Railroad Track Response”
  - Initial feedback collected from reviewers

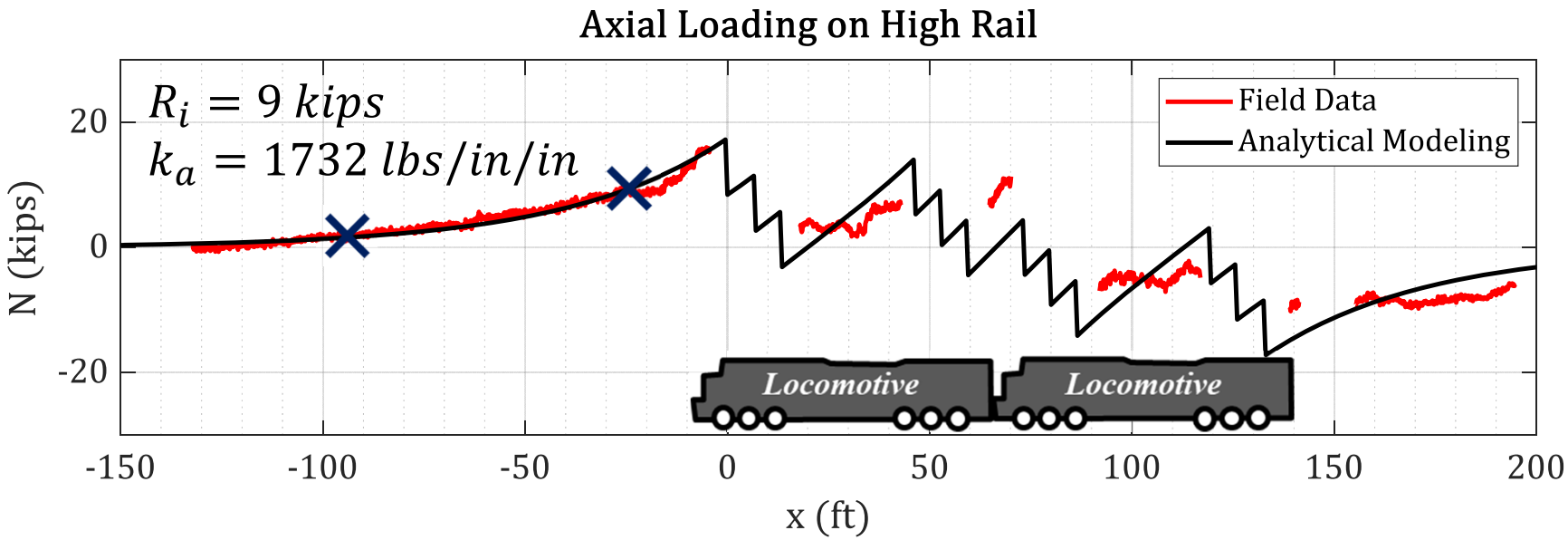
Rail Seat Load Example Calculation

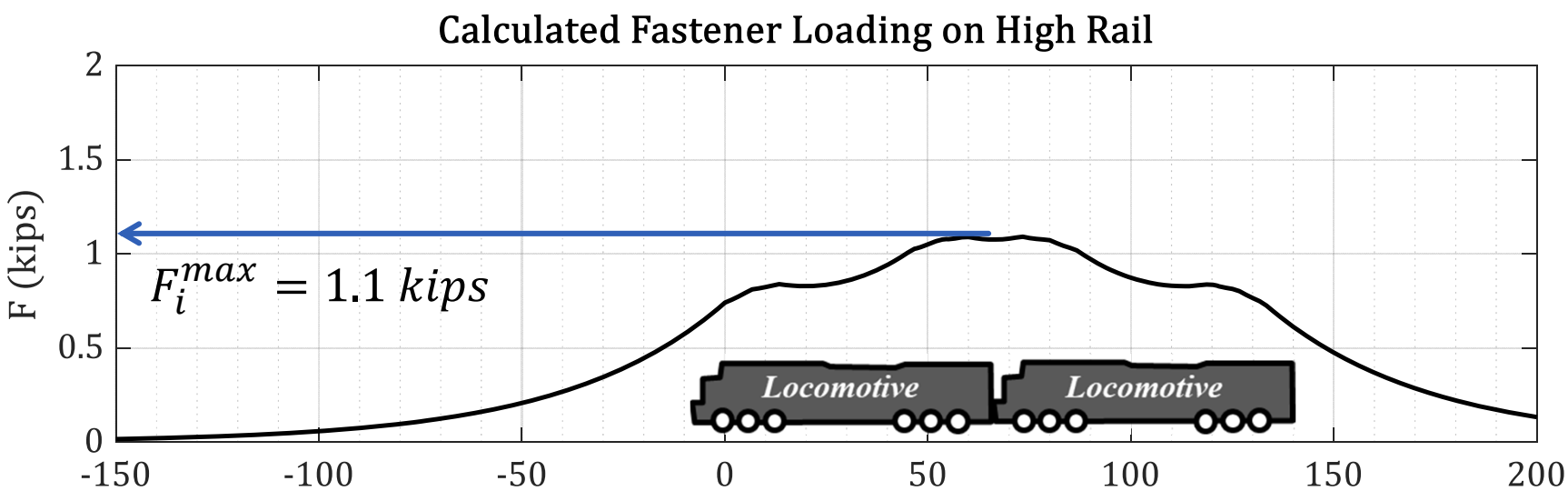


Rail seat force estimation example:

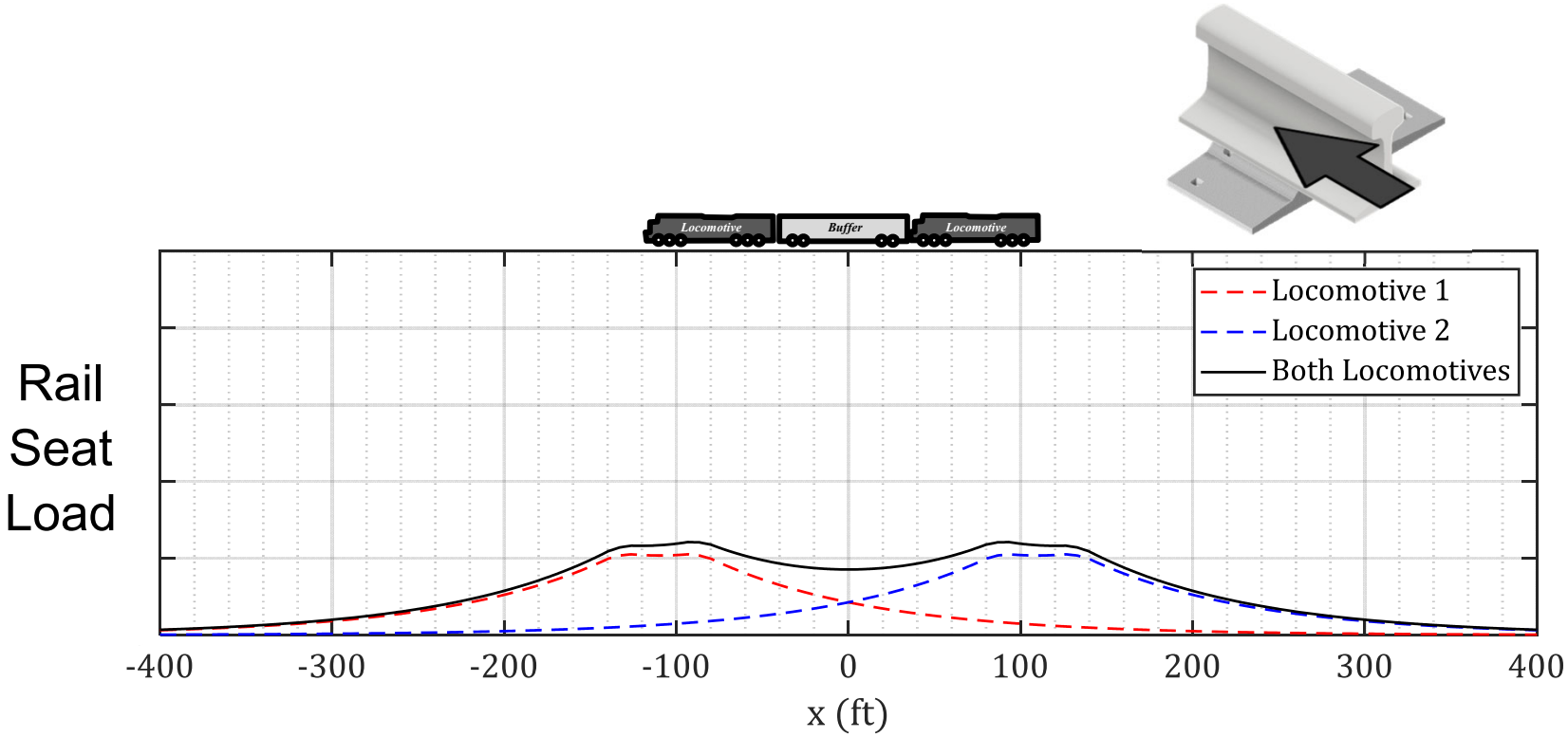
- Choose datapoints (two in this example)
- Create a generic function for axial loads based on number of locomotives
- Solve for longitudinal wheel loads and track stiffness
- Generate function for rail seat forces for the same number of locomotives and find maximum

Rail Seat Load Example Calculation



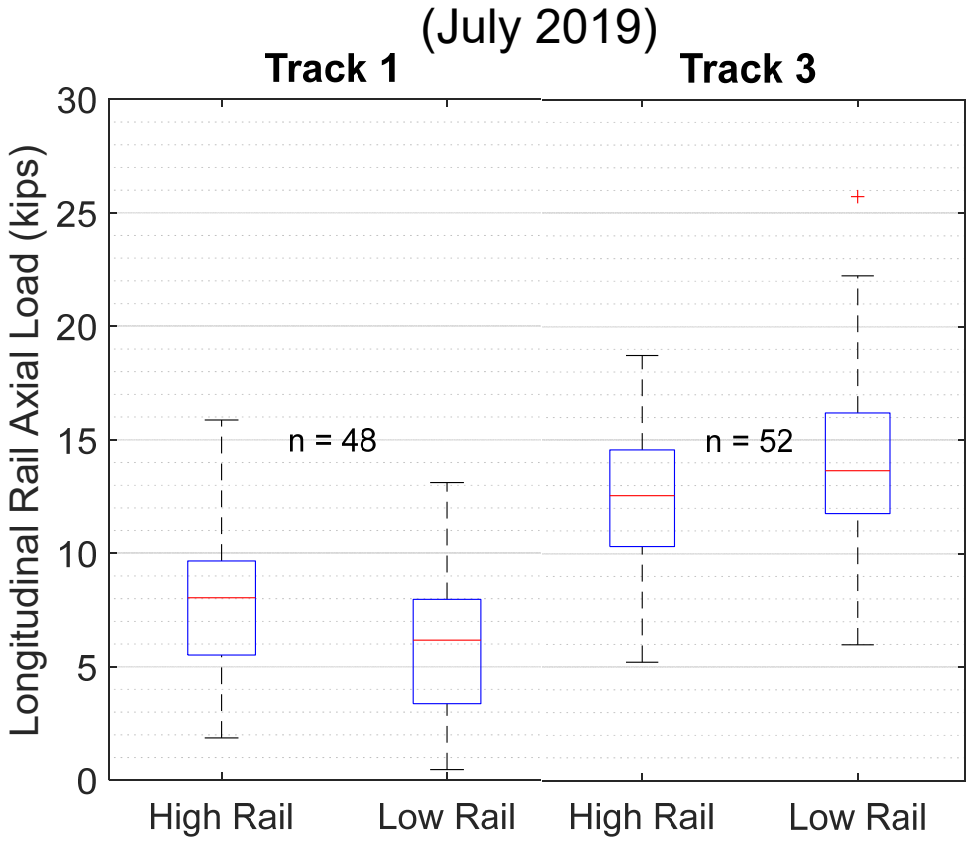


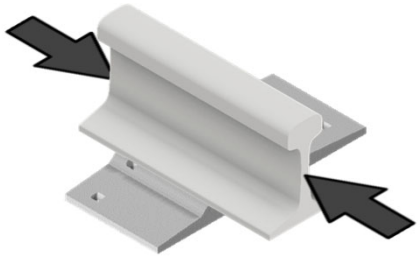
Effect of Distributed Power on Fastener Loads



- Increased distance between trucks reduce superposition effects
- This example shows a 40% reduction of fastener demand by having two locomotives just 1 car apart

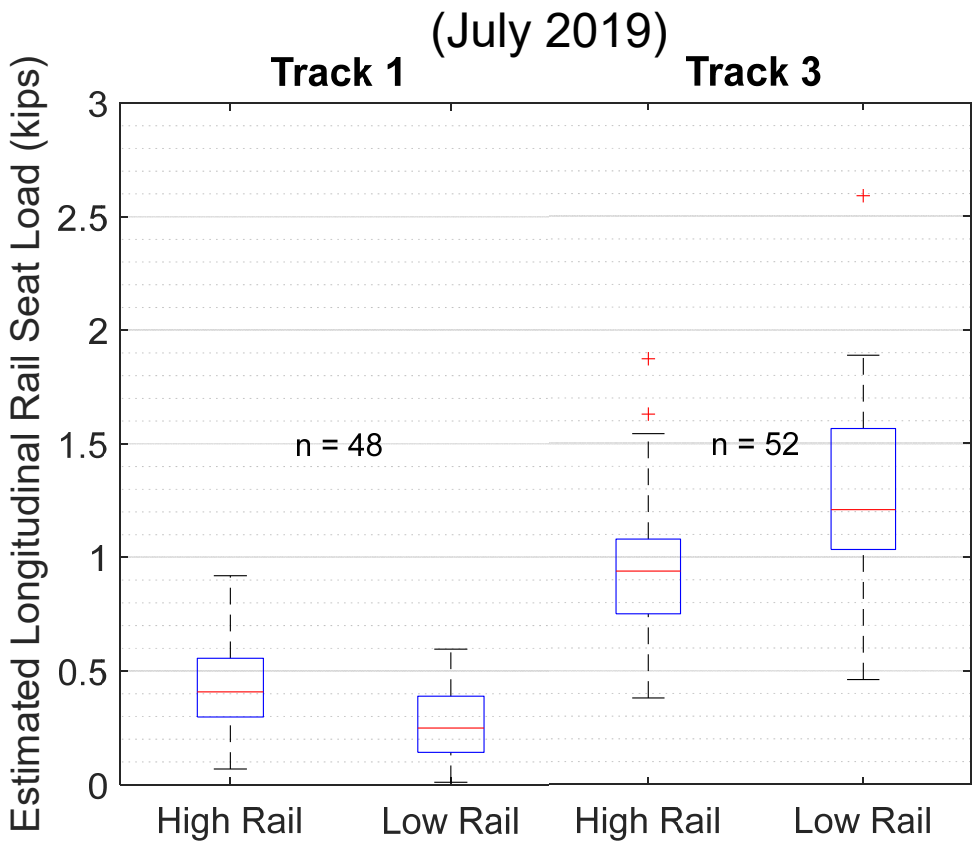
Measured Rail Axial Forces

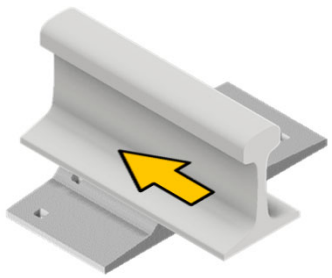




- The average magnitude of measured rail axial forces are 50-100% higher on Track 3
- An analysis of load distribution was necessary to understand if longitudinal rail seat loading is greater on Track 3

Estimated Longitudinal Fastener Forces



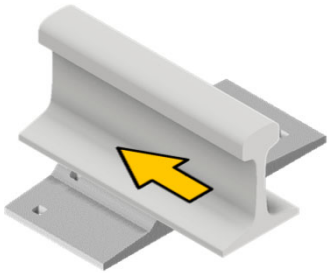


Track stiffness and longitudinal wheel forces estimated and used for calculation of rail seat forces

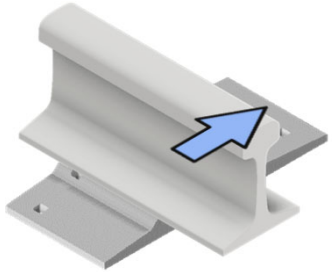
- Maximum longitudinal rail seat loads are estimated to be 10-20x lower than rail axial forces
- Longitudinal fastener loading on Track 3 predicted to be 2-5x higher than Track 1 (in average)
  - Reasonable considering differences between traction and braking

Estimated Longitudinal Fastener Forces

	Estimated Longitudinal Fastener Loads (kips)			
	Track 1		Track 3	
Percentile	High Rail	Low Rail	High Rail	Low Rail
99	0.92	0.60	1.87	2.59
95	**0.87**	**0.54**	**1.55**	**1.79**
90	0.78	0.50	1.42	1.72
50	0.41	0.25	0.94	1.21



	Lateral Fastener Loads (60% of rail load) (kips)			
	Track 1		Track 3	
Percentile	High Rail	Low Rail	High Rail	Low Rail
99	11.38	11.59	8.88	6.70
95	**9.51**	**10.32**	**5.21**	**4.10**
90	8.36	9.37	3.62	3.01
50	2.05	2.86	0.22	0.68



- 95th percentile longitudinal loads are 2-3x greater on Track 3 compared to Track 1
- 95th percentile lateral loads are 2-2.5x greater on Track 1 compared to Track 3
- If these loads were transferred to spikes, fatigue failures would occur in all rails

Field Conclusions and Path Forward

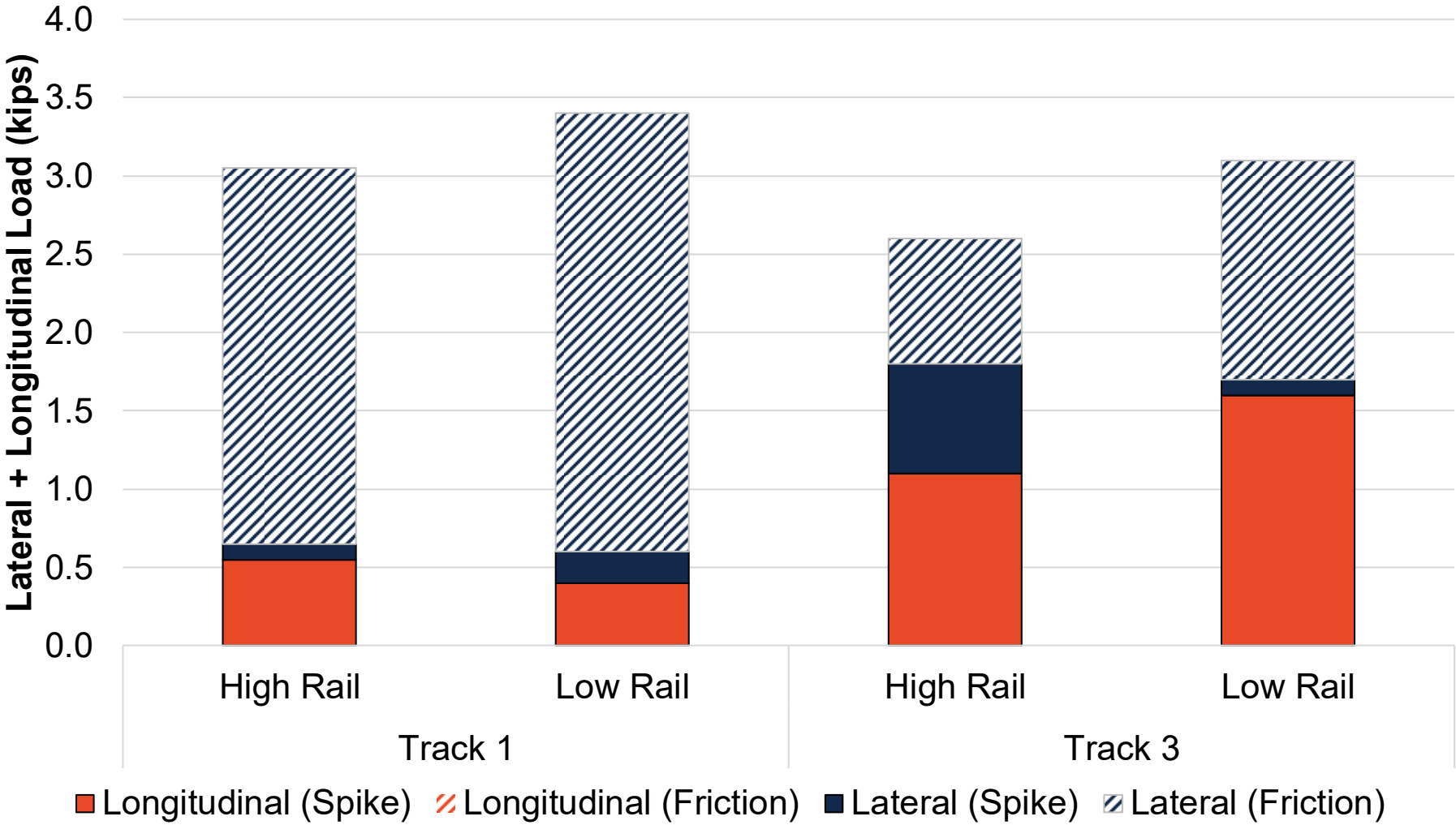
- Longitudinal rail seat loads (up to ~2,600 lbs.) are one order of magnitude lower than rail axial load (up to ~25,000 lbs.)
- Underbalanced speed operations on Track 3 lead to 30% greater vertical loads on low rail compared to high rail
- Load demand itself does not explain why failure is predominant on the high rail of Track 3

Future Work:

- Investigate the effect of operational characteristics and friction on rail seat load transfer to crossties
  - Longitudinal
    - Loads are applied before uplift occurs
    - Uplift likely mitigates the effect of friction on longitudinal load transfer
  - Lateral
    - Loads applied roughly with vertical loads
    - Friction should help transfer lateral loads

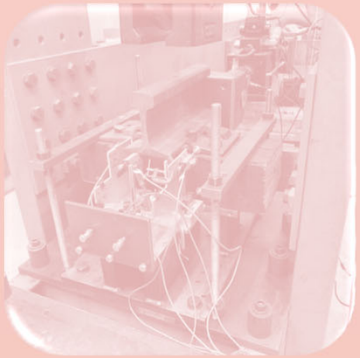
Hypothetical: Rail Seat Load Components

Lateral (Spike), Lateral Friction, and Longitudinal (Spike)



Coefficient of friction assumed to be 0.20 between plate and crosstie

Project Thrust Areas



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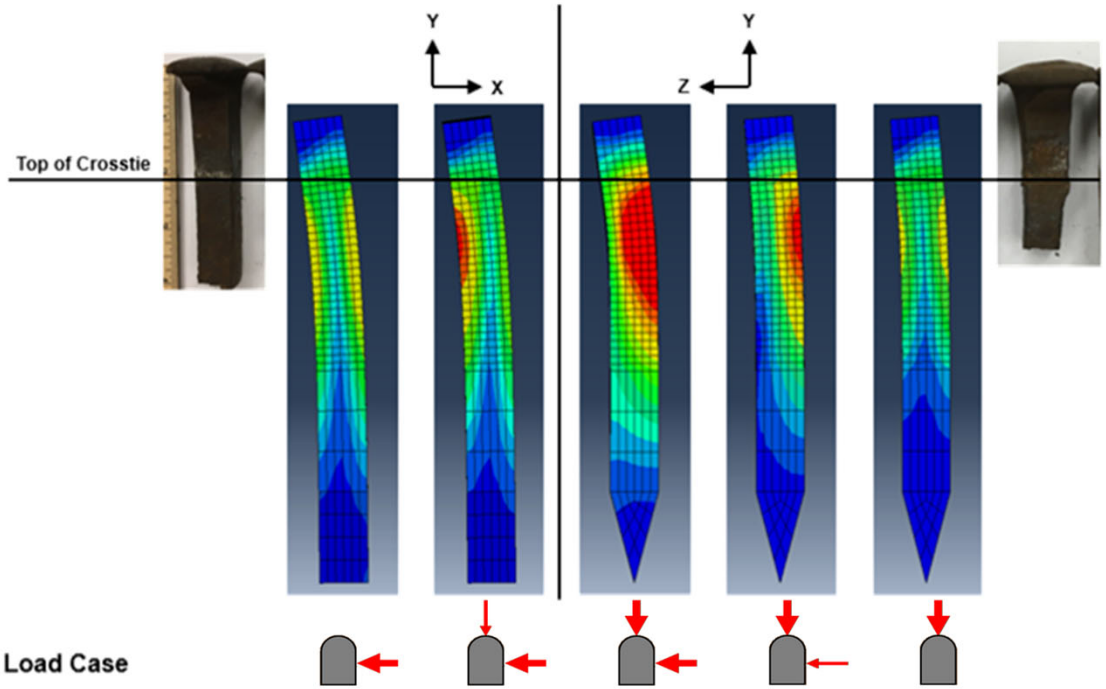
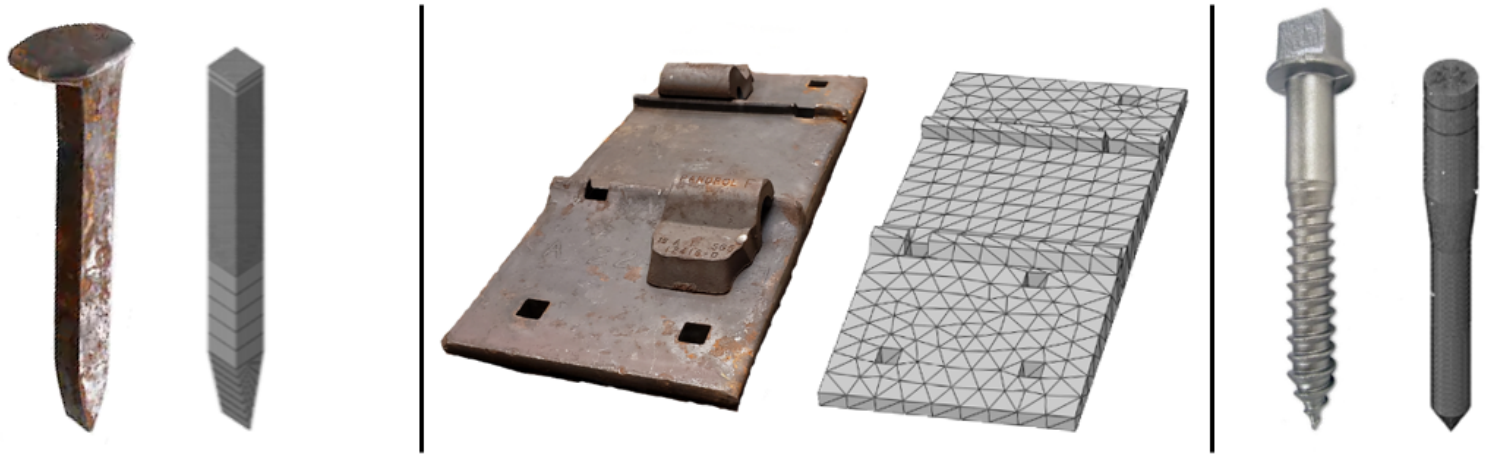
Single Spike FEM Summary



- Longitudinal load is more detrimental than an equivalent lateral load
  - This is due to the timber being less resistant in that direction
  - This finding supports the theory that spike failures in premium fastening systems are primarily related to longitudinal loads
- Stress can exceed the fatigue limit of spike steel at regular service loads
- Max. stress depth varies with the magnitude and direction of applied load
- Species of timber significantly effects the depth/load of failure

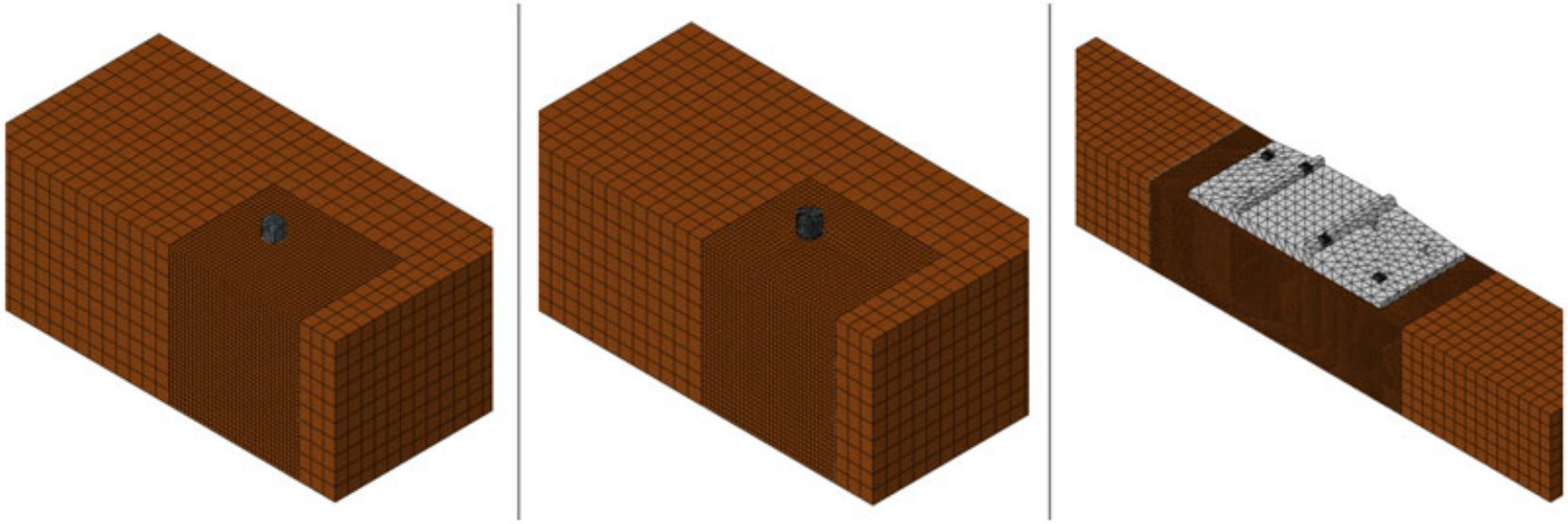
Recent FEA Investigation Focus: Spike Stress Mitigation Methods

- Spike cross-sectional area
- Spike type (cut vs screw)
- Spike loading location
- Plate engagement with tie (vertical clamping force)
- Spike engagement with plate
- Quantity of spikes within a given fastening system



Modeling Overview

- Three basic models were developed for this study:
  - Single cut spike-timber block model
    - Quantify effect of cross-sectional area and loading location
  - Single screw spike-timber block model
    - Quantify effect of spike type
  - Single rail seat model with multiple spikes, plate, and timber block
    - Quantify effect of spike/plate/tie engagement and quantity of spikes used



Cross-Sectional Area: Background

- At least one manufacturer has discussed using larger spikes with larger cross-sectional area

- Stress (σ) is a function of the moment (M), area moment of inertia (I) and distance from the neutral axis (y)

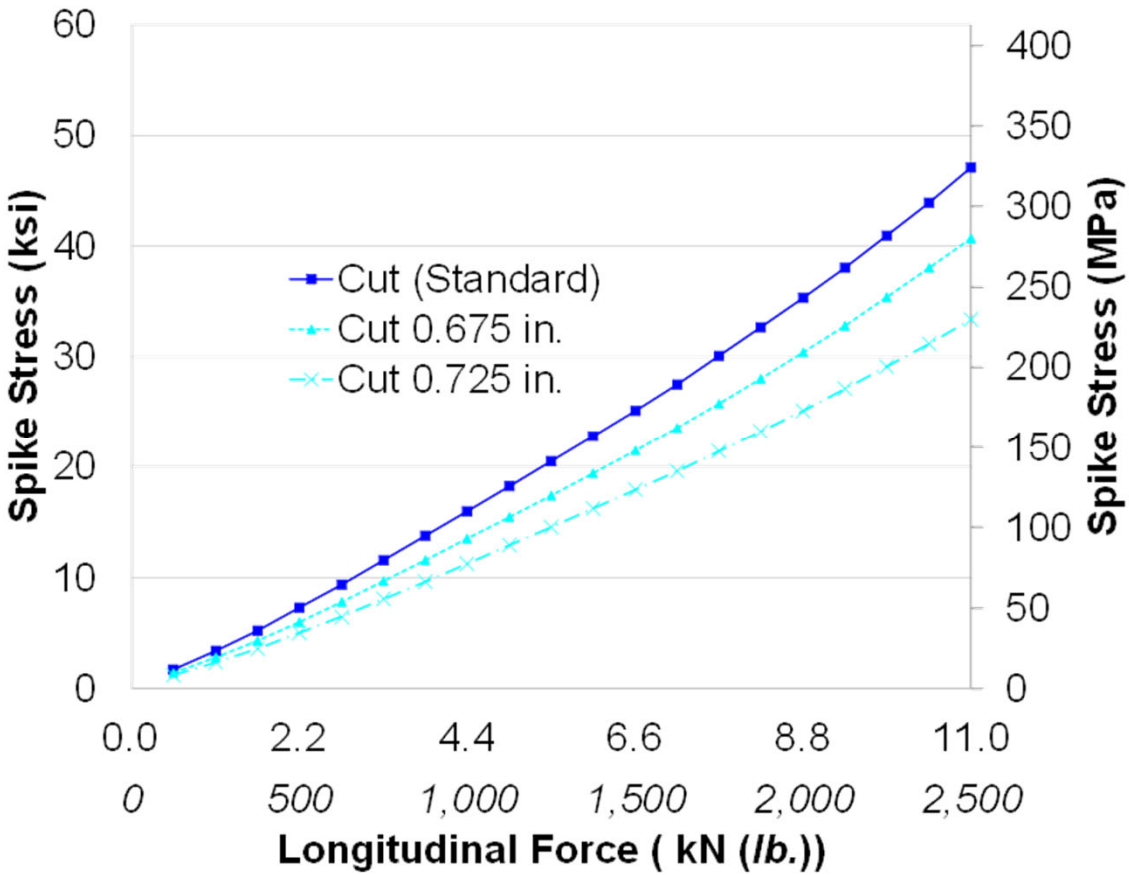
$$\sigma = \frac{My}{I} \quad \text{where,} \quad I = \frac{bh^3}{12} \quad \text{and,} \quad y = \frac{b}{2}$$

- Increasing cross-sectional area would increase I at a greater rate than y

- Stress would be lower for a given moment (i.e. applied load)

Effect of Cross-Sectional Area

- Each spike subjected to 2,500 lb. longitudinal load



- Inverse linear relationship between cross-sectional area and stress
- For each 1% increase in standard spike width there is ~ 2% reduction in stress
- Increasing spike width by 0.1” resulted in 29% reduction in stress

Cut vs Screw Spikes: Background

- Multiple railroads are moving from cut spikes to screw spikes for premium fasteners
  - At least one railroad has moved from screw spikes to cut spikes
- Perceived advantages of screw spikes *(relative to cut spikes):*
  - Increased bending strength
  - Increased plate hold-down strength

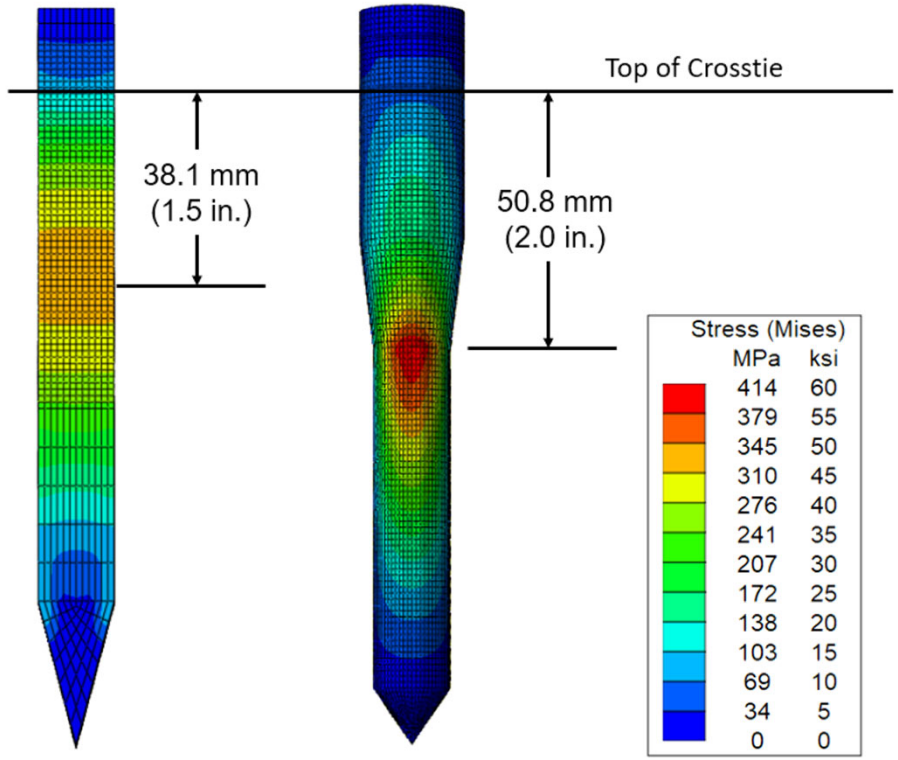
Spike (type/location)	Cut	Screw (Upper Shaft)	Screw (Threads)
Cross Section			
Area Moment of Intertia Formula	$bh^3/12$	$\pi r^4/4$	$\pi r^4/4$
I (in⁴)	0.0127	0.0380	0.0110
y (in.)	0.3125	0.4690	0.3438
Stress (force/in²)	24.6 × M*	12.3 × M*	31.3 × M*

**where M represents the internal moment in force-in.*

- Expectations based on geometry *(relative to cut spikes):*
  - Increased bending strength at the upper shaft
  - Decreased bending strength at threads
  - Increased stresses in the threads at equivalent loads

Cut vs Screw Spike: Visualization

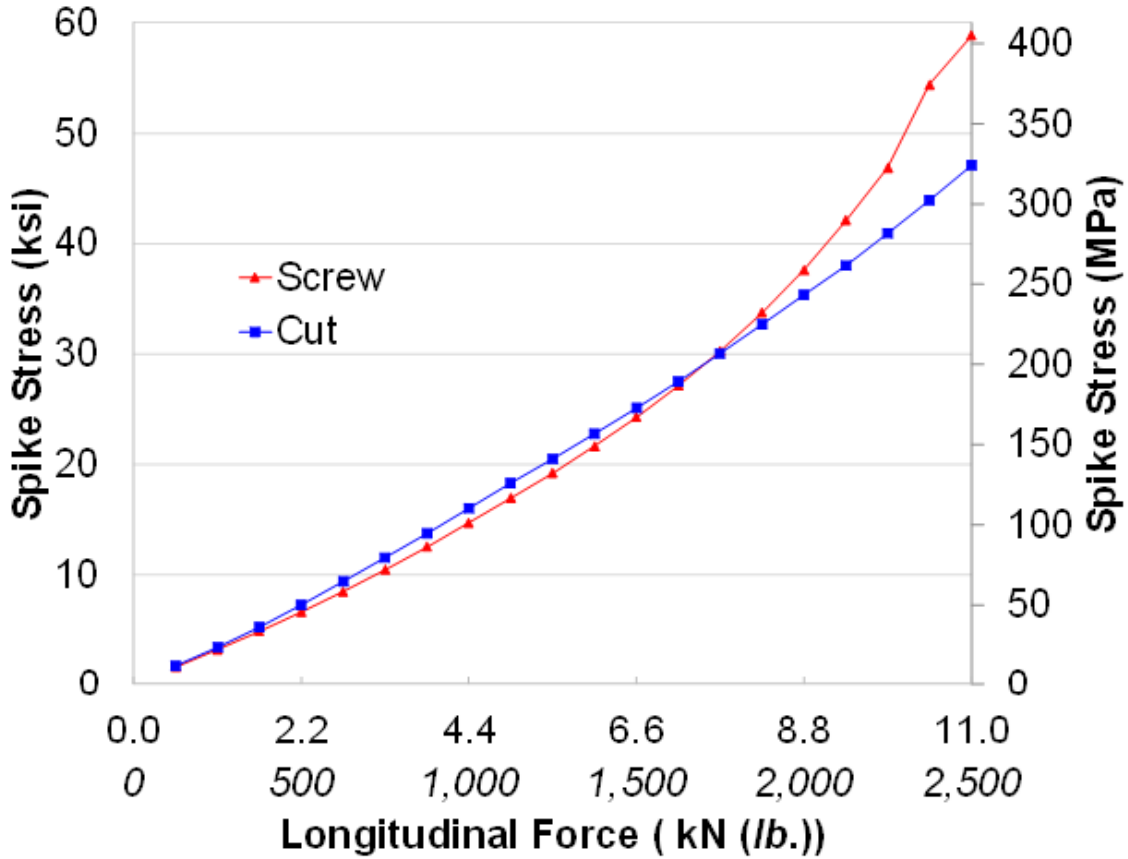
- Each spike subjected to 2,500 lb. longitudinal load



- Maximum spike stress depth:
  - Cut spike: 1.5”
  - Screw spike: 2.0”

Cut vs Screw Spike: Quantification

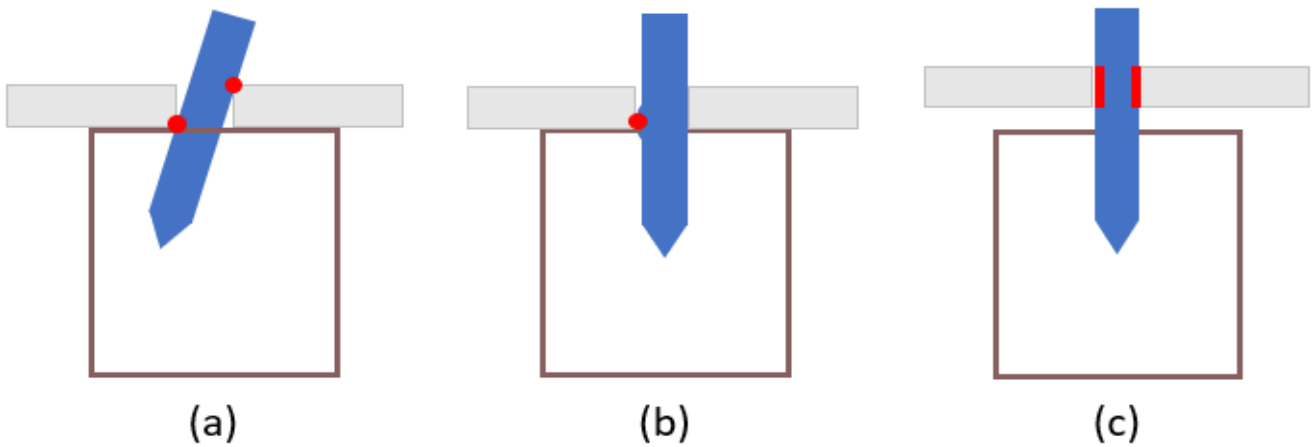
- Each spike subjected to 2,500 lb. longitudinal load



- Longitudinal loads < 2000 lb. there is < 10% difference in max stress
- Beyond 2000 lb. stress in screw spikes increase rapidly

Loading Location: Background

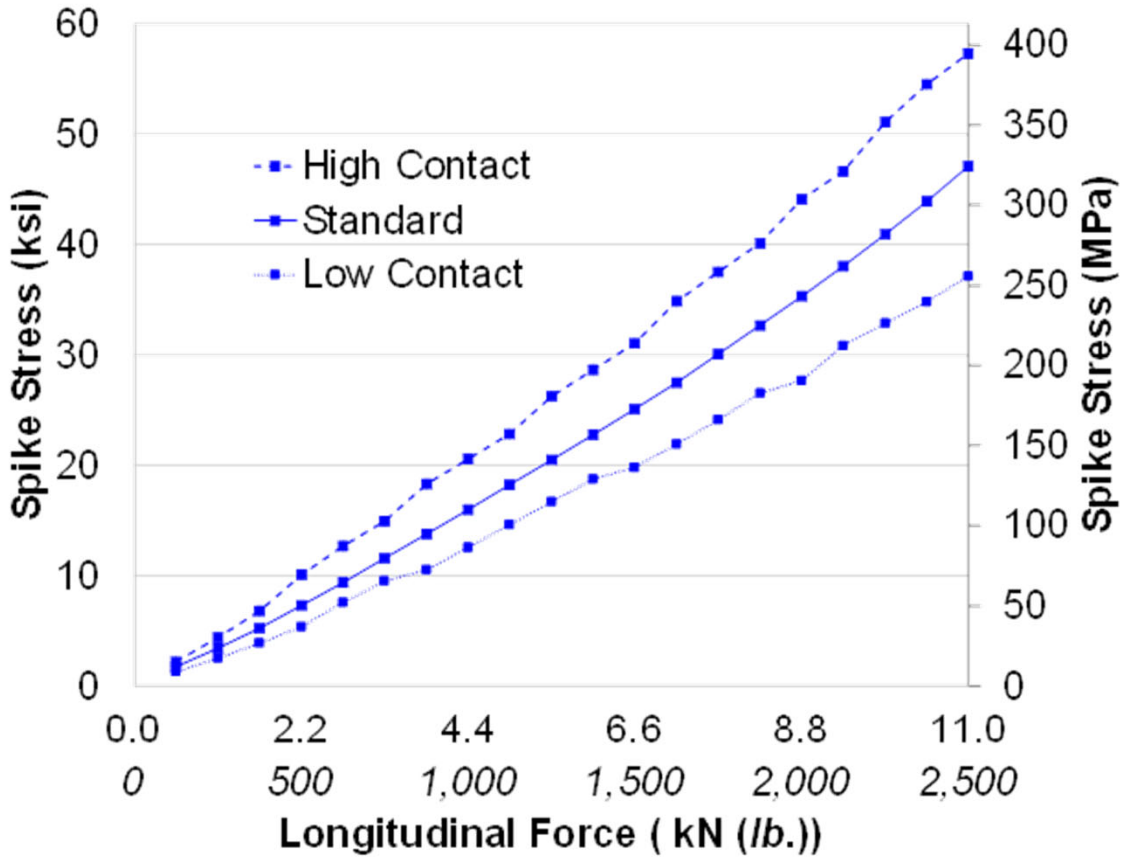
- Currently it is assumed that the load transfer into the spikes is uniform
- Reasons for non-uniform are as follows:
  - (a) the angle of spike being driven into the tie
  - (b) the non-planar finished surface of the spike or plate
  - (c) plate uplift



- To quantify the effect of plate uplift, the location of applied load will be varied

Effects of Loading Location

- Each spike subjected to 2,500 lb. longitudinal load



- Direct linear relationship between change in load location and max stress
- +/- 20% change from control case when load moves up/down, relatively

Normal Clamping Force: Background

Goal:

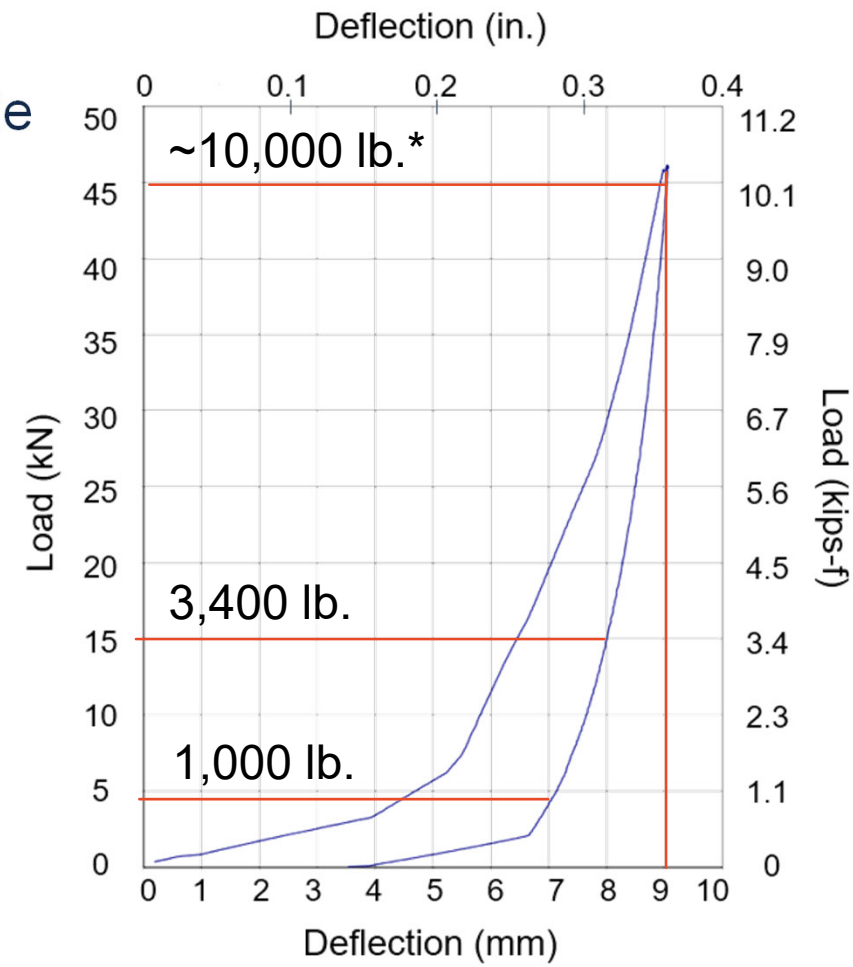
- Ensure load is transferred through spike and friction when plate is engaged with tie

Challenge:

- Wave action of the rail leads to uplift of the plate, eliminating friction

Proposed Solution:

- Develop friction force through preloading of plate:
  - Screw spikes do this upon first installation, but can loosen over time
  - Spring washers could be utilized (*and are utilized internationally*)
- Spring washer applied load studied:
  - 3,400 lb. ea. after initial "settling"
  - 1,000 lb. ea. after minimal cutting/loosening

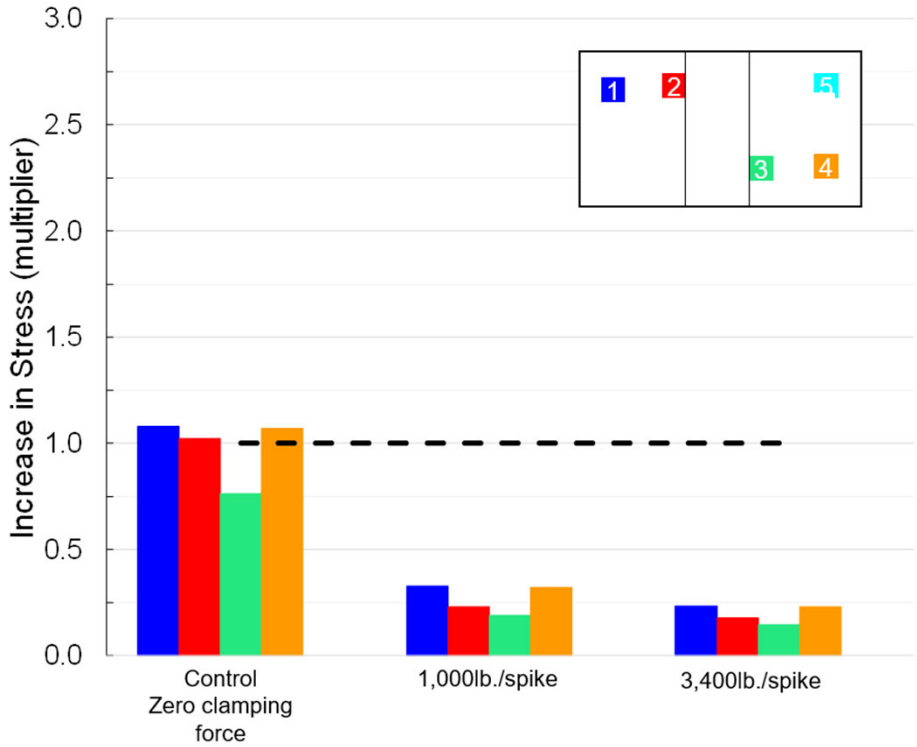


Load vs deflection of spring washer

** Example of load vs disp. for this spring washer, not an indication of load at installation.*

Effect of Normal Clamping Force

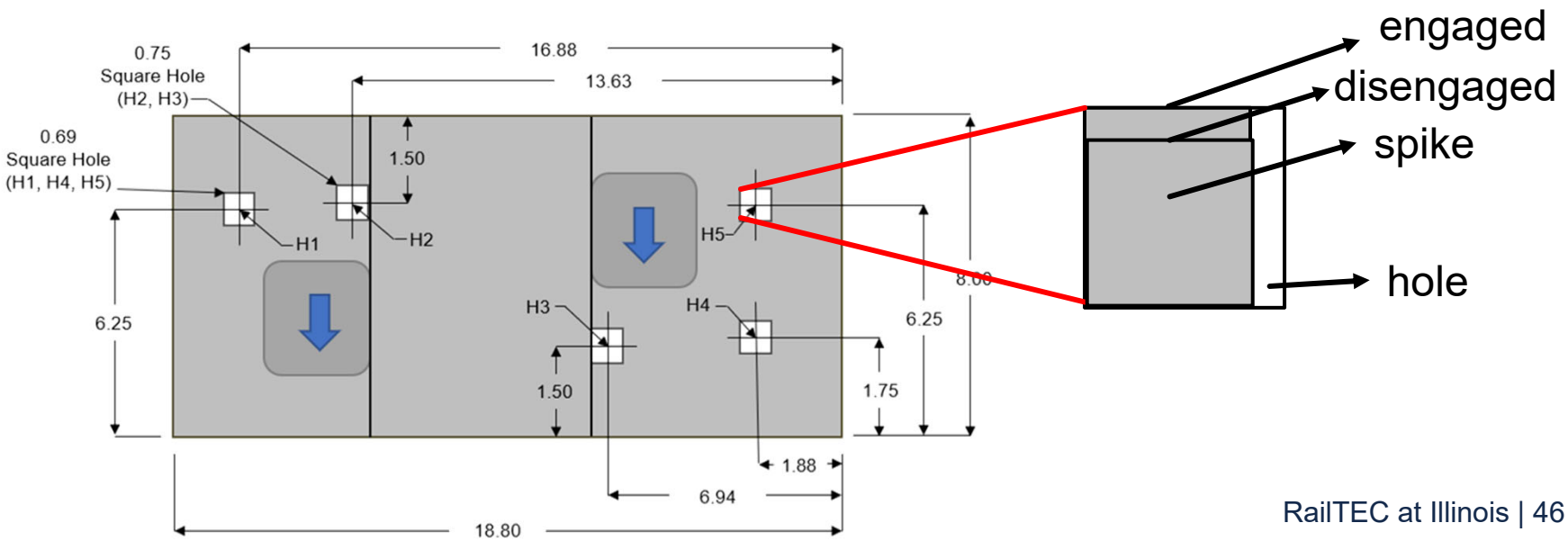
- Fastening system subjected to 2,500 lb. longitudinal load
- Normal clamping force of 1,000lb./spike and 3,400lb./spike investigated



- 3,370lb./spike resulted in an 80% reduction in spike stress (on average)
- 1,000lb./spike resulted in a 70% reduction in spike stress (on average)
- Thus, most of longitudinal force taken by friction

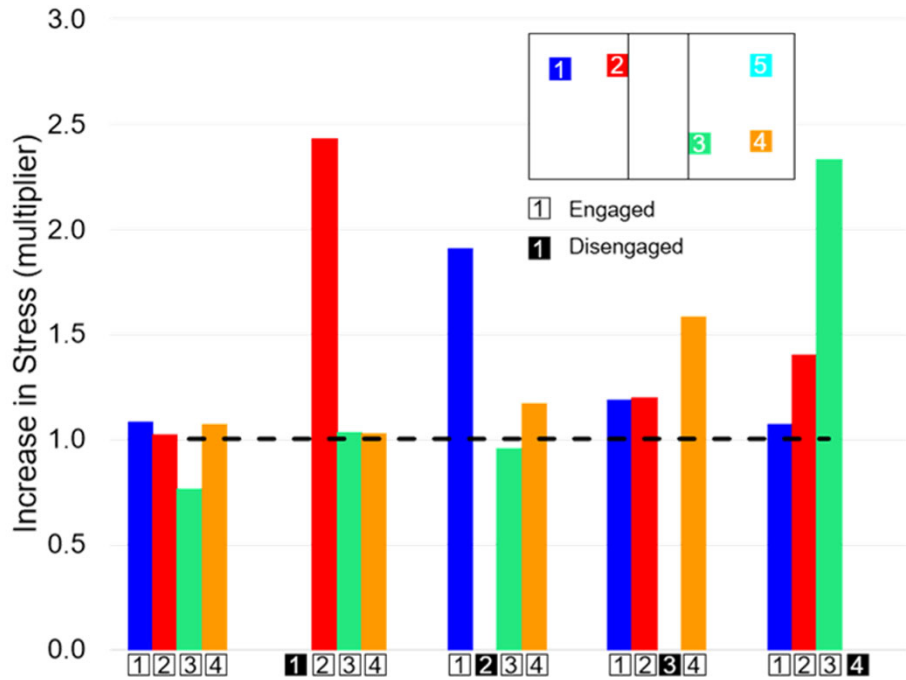
Spike Engagement and Quantity of Spikes: Background

- Plate hole tolerances are larger than potential displacement
  - Hold down and line spike holes are 0.065 in. and 0.125 in. larger than the 0.625 in. standard cut spike
  - Displacement of spike subjected to load not expected to exceed 0.04 in.
- Not all spikes will be in contact at one time
- Many railroads use 4 spikes within premium fasteners
  - Some use 5 in most demanding locations/after maintenance



Effect of Spike Engagement with Plate

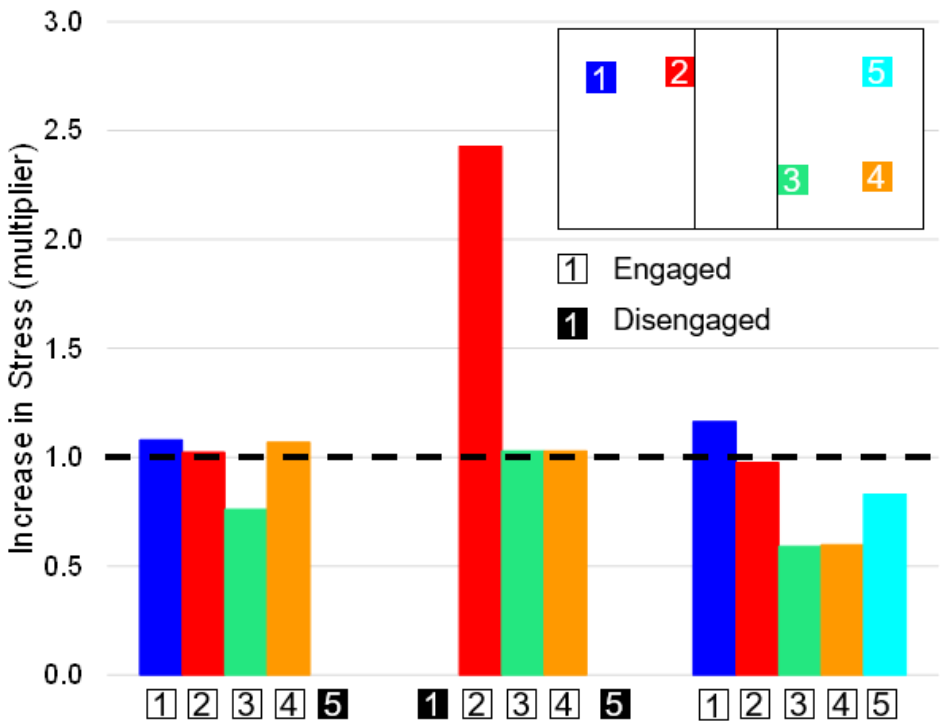
- Fastening system with 4 spikes subjected to 2,500 lb. longitudinal load with one spike moved to other side of spike hole (extreme tolerance)



- Disengaged spike acts as though it has been removed from system
- Load is not evenly redistributed among engaged spikes
- Disengagement of a single spike resulted in up to a 140% (2.4 times) increase in spike stress

Effect of Quantity of Spikes

- Fastening system with 3 - 5 spikes subjected to 2,500 lb. longitudinal load



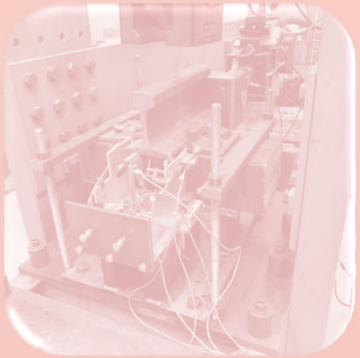
- Increasing spike quantity will not ensure max stress reduction for all spikes
- Addition of fifth spike reduced stress of spikes 3 and 4, not 1 and 2

Modelling Conclusions

1. The disengagement of a single can lead to a 140% (2.4 times) increase in a remaining spike's stress
2. There is an inverse relationship between plate-sleeper normal clamping force and spikes stress
   - Clamping force of 1,000 lb./spike can reduce spike stress by 70%
3. There is little difference in cut and screw spike strength (capacity) at longitudinal loads below 2,000 lbs. (8.90 kN)
4. There is an inverse linear relationship between spike cross-section and resulting stress
   - For each 1% increase in spike width there is ~ 2% reduction in stress
   - Increasing spike width by 0.1" resulted in 29% reduction in stress
5. There is direct linear relationship between spike contact location and resulting stress
   - A +/- 0.245" change in load location can lead to -/+ 20% change in maximum stress

► Draft journal paper submitted to JRRT
   - *"Methods to Mitigate Railway Premium Fastening System Spike Fatigue Failures using Finite Element Analysis"*

Project Thrust Areas



Laboratory

Controlled experiments to better characterize load transfer and rail displacement/slip of various fasteners

Analytical Modeling

Quantification of load distribution and spike stress while investigating key factors affecting load transfer

Field

Quantification of loading demands (vert., lateral, long.) and fastener response to service loading

TTC Field Work Overview

- Control zone:
  - Victor Plates with e-clips and cut spikes
  - 20 crossties
- Test zone:
  - Vossloh fastener with screw spike, spiral washer, tension clamp
  - 30 crossties
- Installed: Fall 2019
- Tonnage Accumulated: 170 MGT
- Visual Inspections:
  performed every few months
- Track Geometry and Loaded Gage: measured after fall and spring seasons

TTC Visual Inspection Results

	Control	Test
Plate Cutting	minimal	none visible
Broken Components	6 broken spikes	none visible
Loosened Components	spike uplift	3 (1.3%) screw spikes (at 60 MGT)
Plate Movement	some evident	none visible
Skewed Crossties	several ties (reset multiple times)	two ties, minimal (after 140 MGT)

- Details of "loose screw spikes" within Test zone (after 60 MGT)
  - 3 of 240 exhibited 30 – 45 degrees of rotation (1 – 1.5 mm of uplift)
  - Spring washers estimated to still apply between 2 – 3 kips of clamping force
- Indications of additional "loose screw spikes" after 170 MGT on 5 rail seats

Tie skewing example

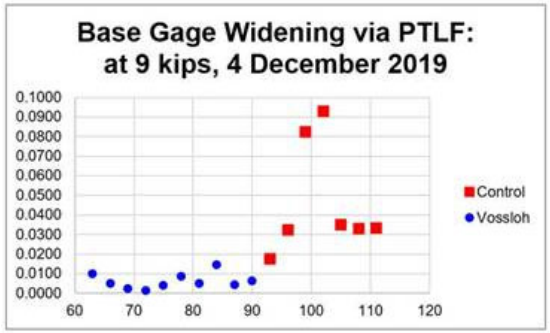
Potential spike uplift

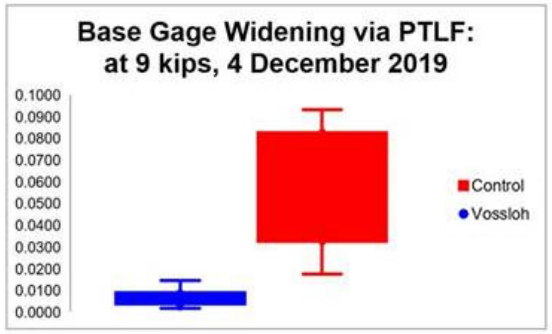
Broken spike

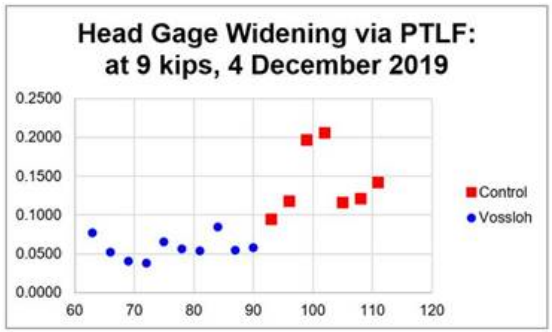
TTC Field Gage Results and Discussion

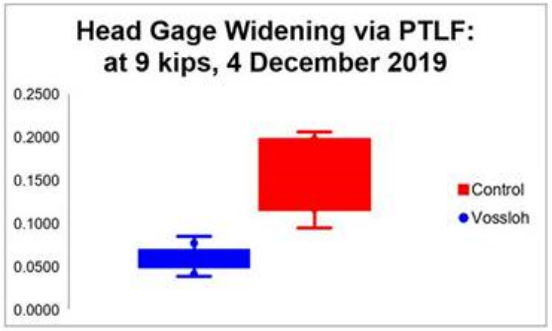
Potential factors leading to improved performance of Test Zone

- Spring washers encourage plate to crosstie contact
  - Increases friction between plate and crosstie
  - Finite element analysis indicates a benefit
  - Indicated in reduced base gage widening
- Tension clamps provide improved/consistent clamping force compared to e-clip
  - More consistent toe-load
  - Increased lateral/rotational strength/stiffness
  - Indicated in reduced head gage widening









Preliminary Recommendations for Mitigating Spike Failures

- Through Operations:
  - Reduce longitudinal demands by:
    - Distributing power where possible/feasible
    - Evenly distributing tractive effort among multiple units
  - Reduce lateral forces when possible by:
    - Proper gauging (wide gauge),
    - TOR lubrication,
    - etc.
  - Operating near balanced speed to encourage equal vertical loading on high and low rail
  - Building trains limiting unloading of vertical rail (string line condition, etc.)

- Through Fastening System Design:
  - Encourage engagement (clamping/contact) between plate and crosstie
  - Encourage engagement of all spikes with plate
  - Increase strength of spike(s) to account for additional loading

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- Project Sponsor:

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CSX

BNSF RAILWAY

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vossloh North America

Progress Rail A Caterpillar Company

PANDROL

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U.S. Department of Transportation
Federal Railroad Administration

NURail Center
U.S. Department of Transportation

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APPENDIX

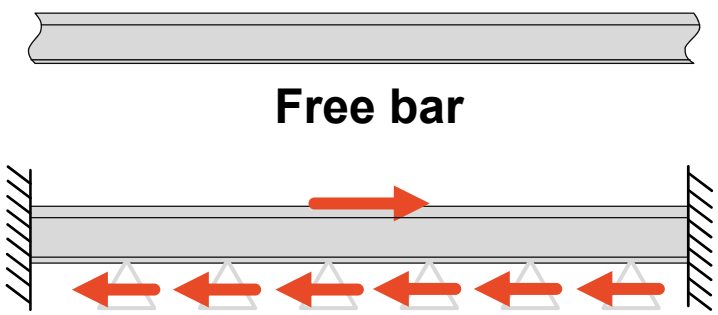
Vertical Wheel Loads (July 2019)

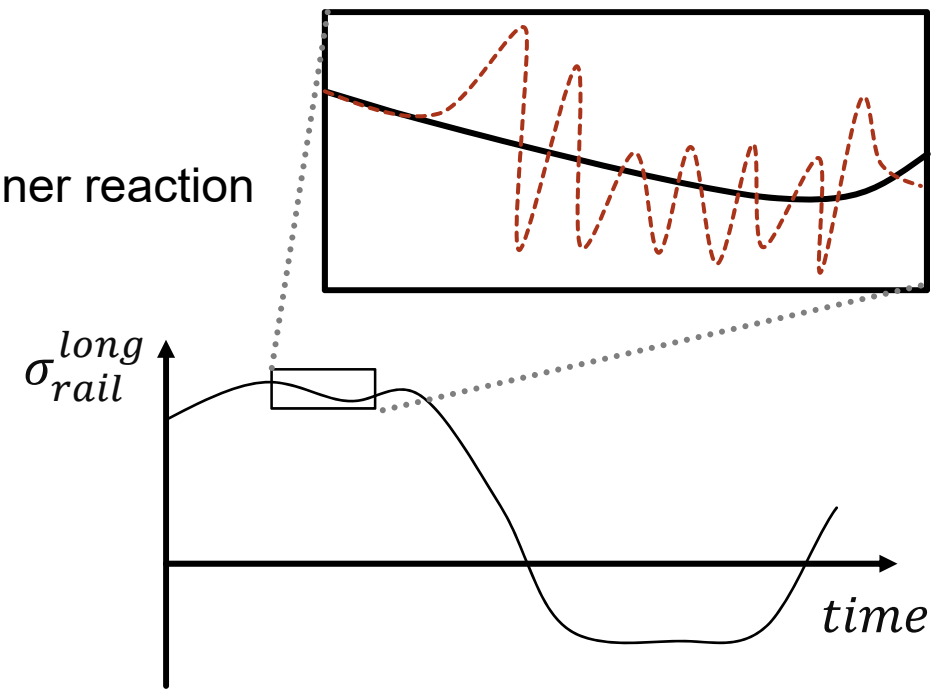
	Vertical Wheel Loads (kips)			
	Track 1		**Track 3**	
Percentile	High Rail	Low Rail	High Rail	Low Rail
99	43.4	43.2	36.3	45.5
95	39.7	40.0	31.6	40.3
90	37.2	38.2	28.5	37.0
50	23.4	23.7	10.0	14.7

Rail Axial Loads (Constrained Rail)

Axial Loading Mechanisms

- Uniform temperature changes
  - Rail tries to expand in the heat – **Compressive Loads**
  - Rail tries to contract in the cold – **Tensile Loads**
    - No relative rail movement → no fastener loading
- Temperature gradient
- Train **tractive**/ breaking efforts
  - Produce directional movement
    - Therefore introducing fastener reaction
  - Today's focus

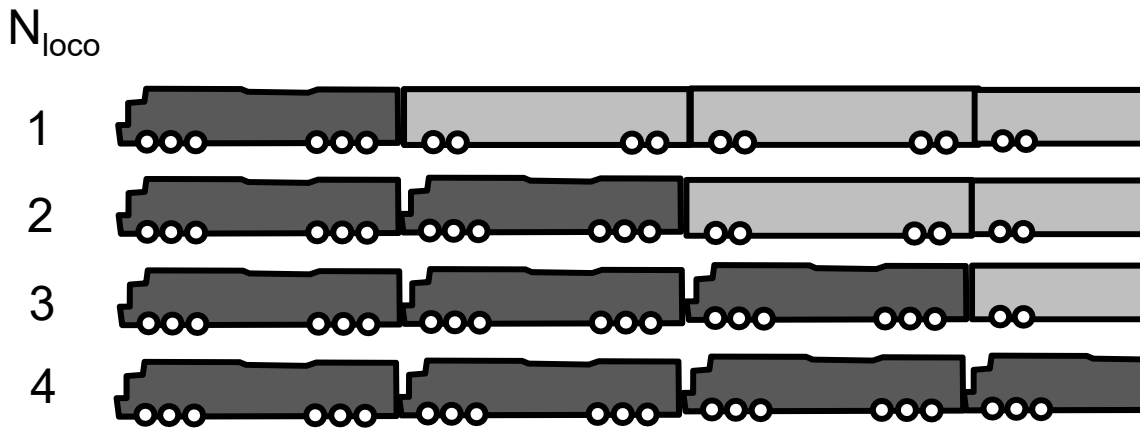




Axial Loading Profile

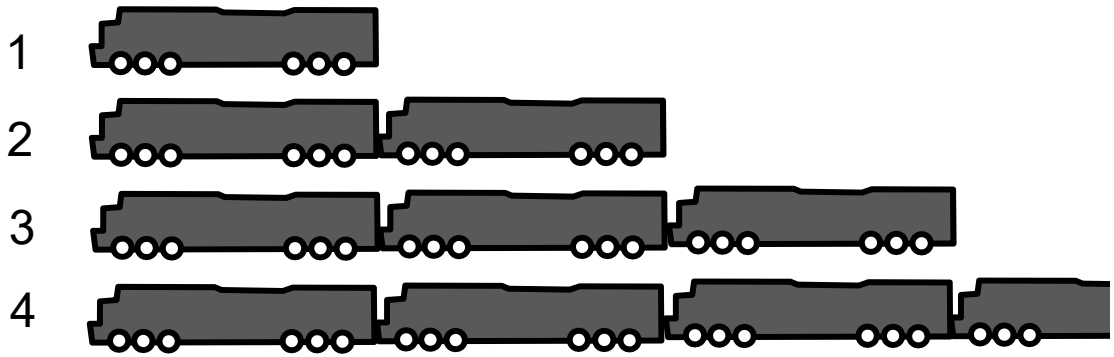
Track 1: Downhill Trains

- Every axle is contributing to braking
- Uniform forces considered



Track 3: Uphill Trains

- Only locomotives are introducing tractive effort
- Uniform forces considered



Axial Loading Profile

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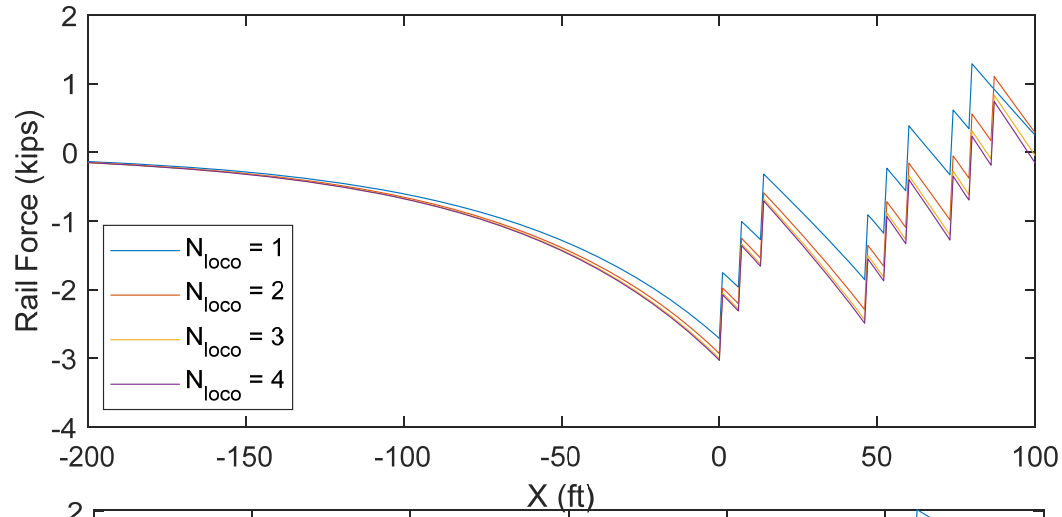
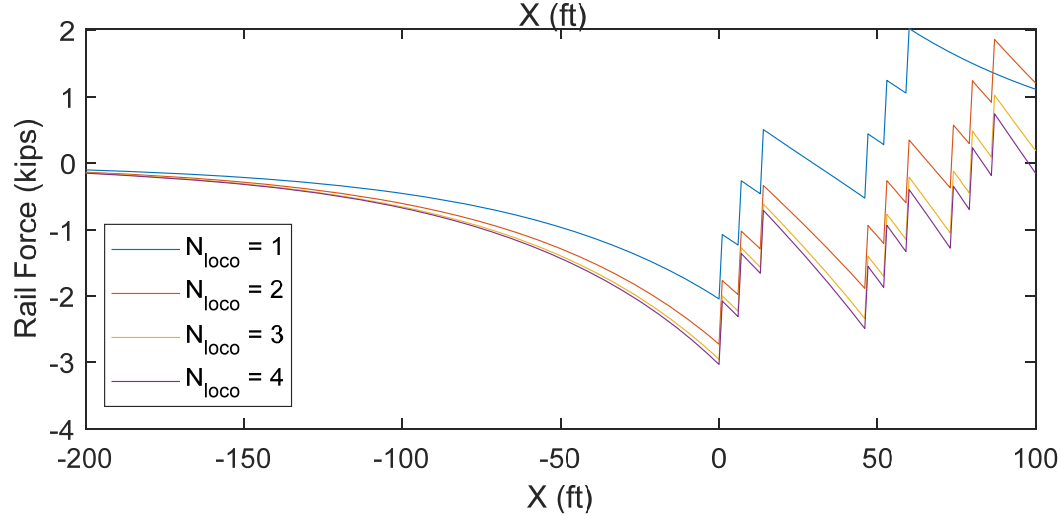
- Uniform forces considered



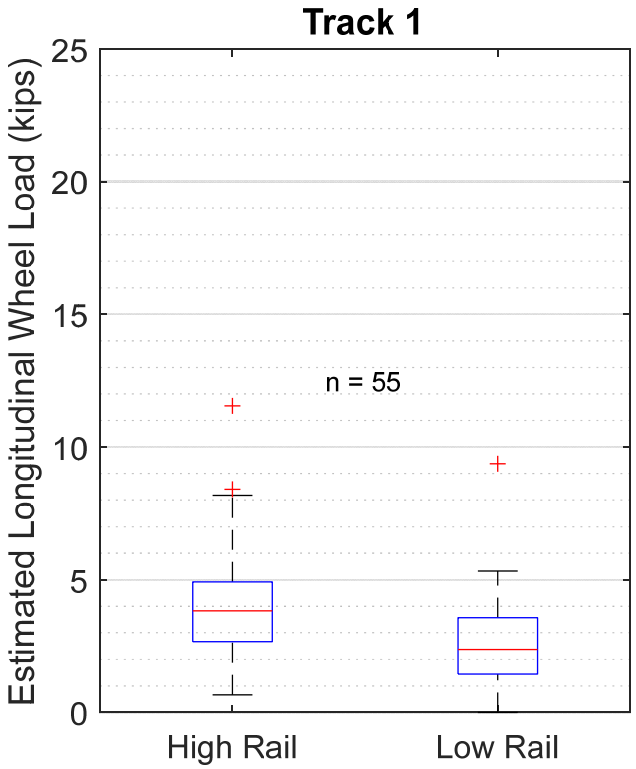
Track 3: Uphill Trains

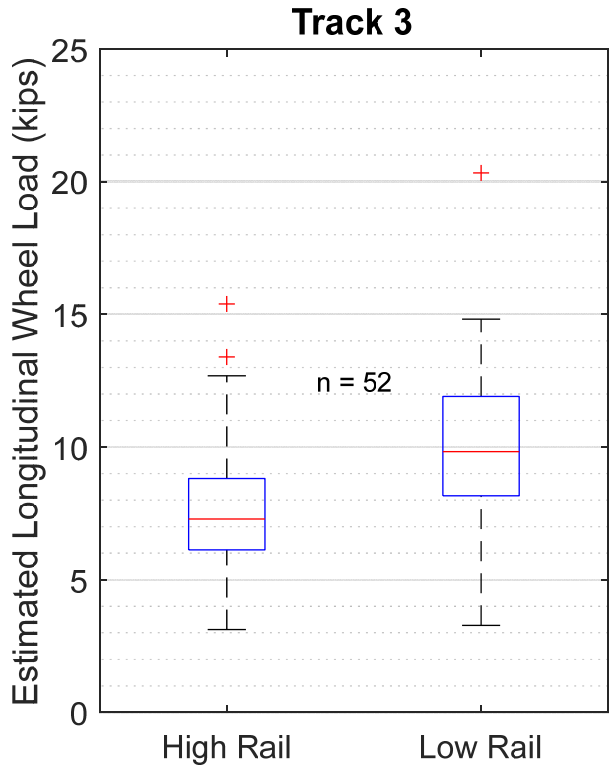
- Only locomotives are introducing tractive effort
- Uniform forces considered

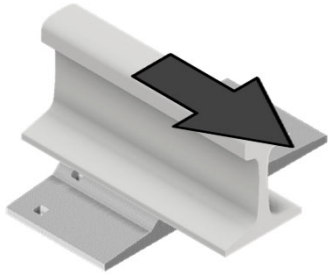


Signature axial loads differ

Estimated Average Long. Wheel Load (R)

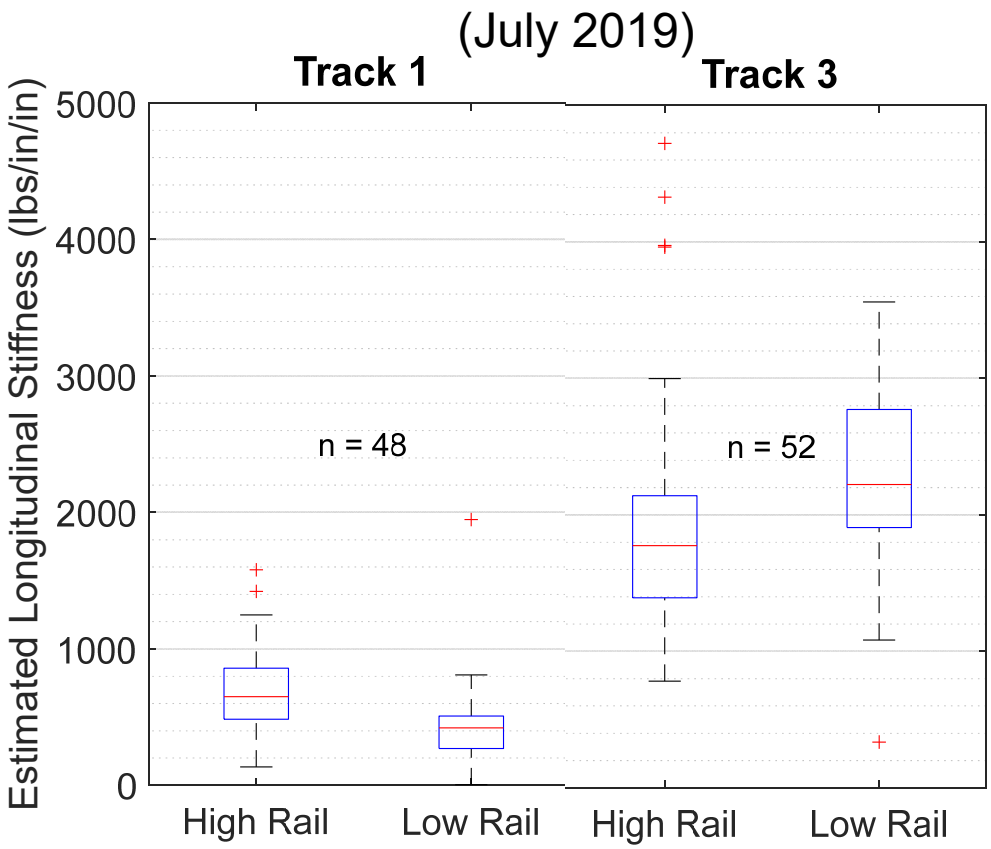


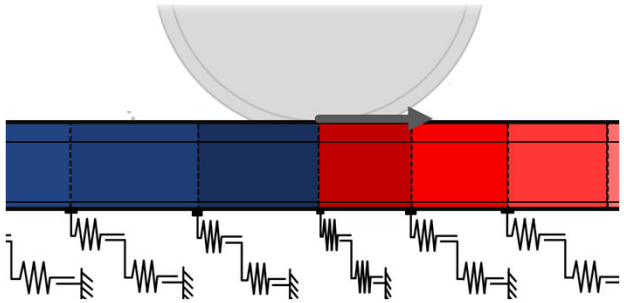




- Calculated wheel loads indicate that tractive effort in track 3 is, in average, +80% higher than breaking effort in track 1
- However, longitudinal loading in track 1 occurs in a longer section, and an increased number of wheels should be considered in the superposition of fastener forces

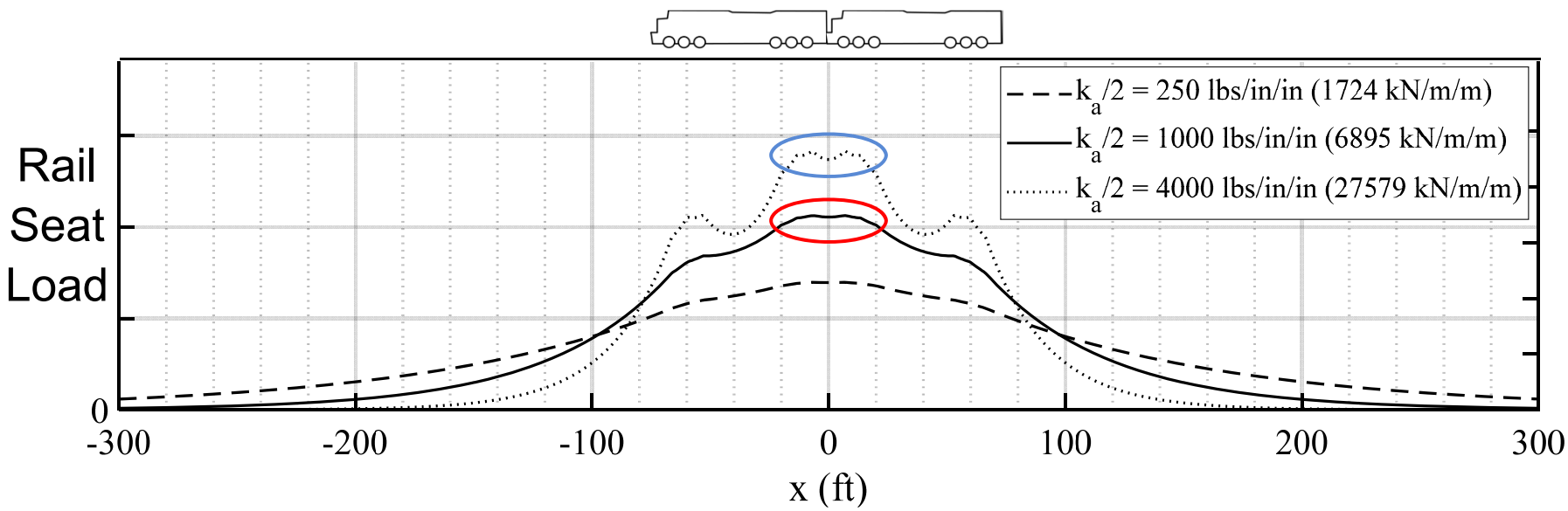
Estimated Longitudinal Track Stiffness (k)



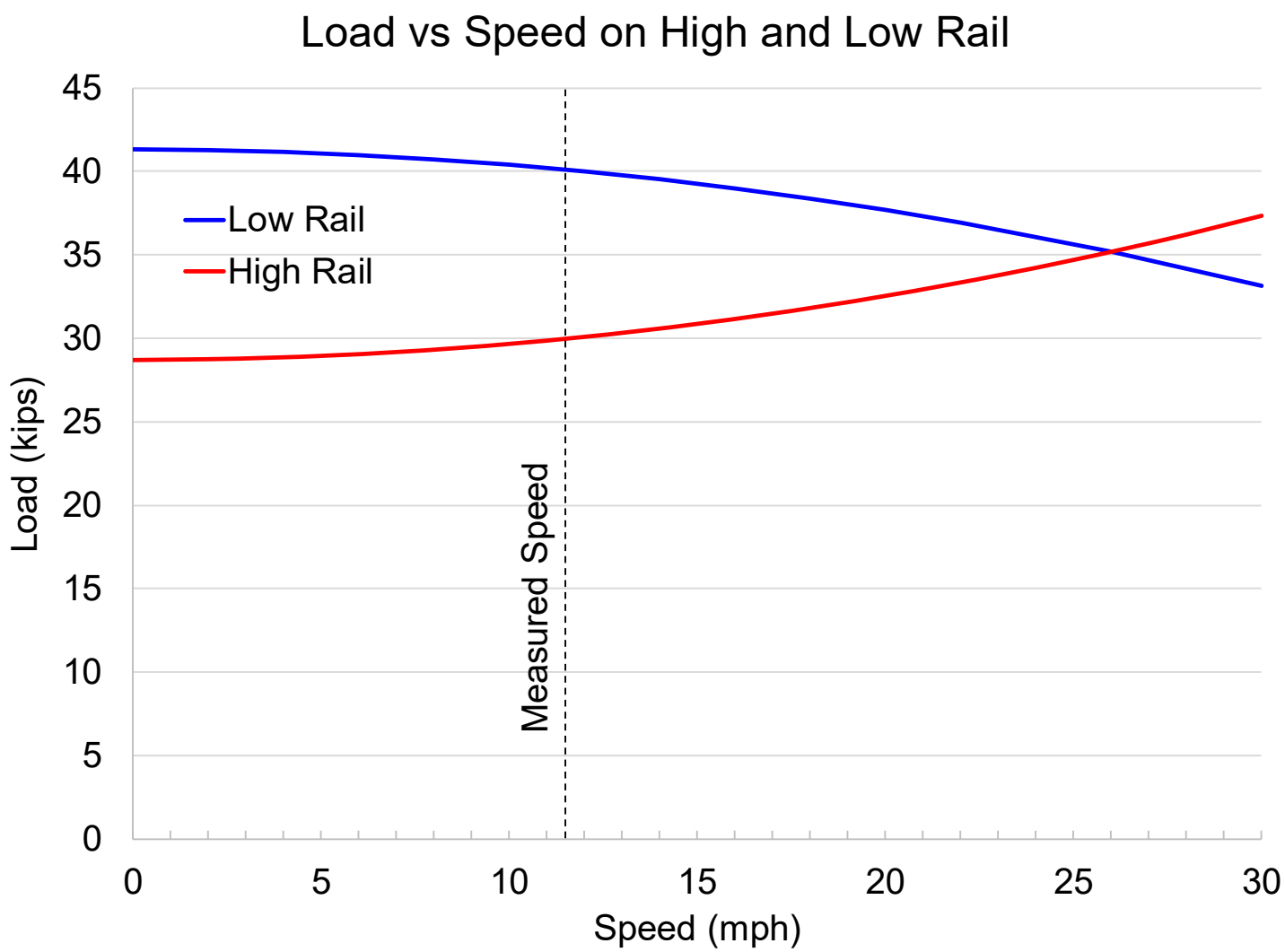


- Stiffness ranges are in the order of magnitude of shakedown laboratory tests
- The methodology estimates Track 3 to be 2-4x stiffer than Track 1 *

Track Response: Change in Stiffness



- Higher stiffness leads to increased fastener forces, but also reduces load superposition
- * Longitudinal track stiffness are not the greatest factor that affects rail seat loads
  - Reducing the longitudinal stiffness to a quarter (from 4000 to 1000 lbs/in/in) reduced maximum fastener loads by 25%


Load vs Speed on High and Low Rail
Low Rail
High Rail
Measured Speed
Load (kips)
Speed (mph)
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30

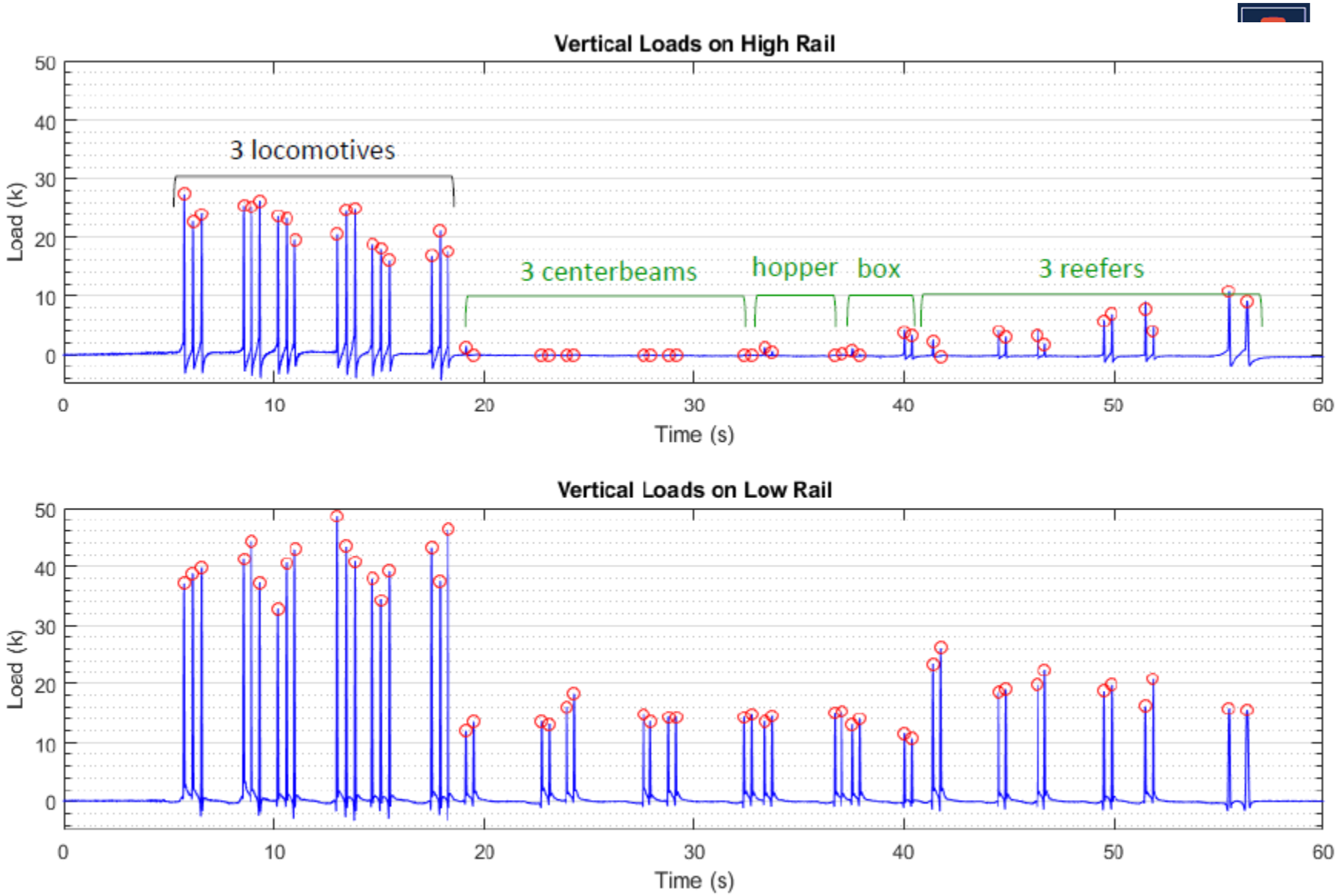


Figure 7: Vertical wheel loads on high and low rails under the three locomotives and the eight head cars of train 35A.

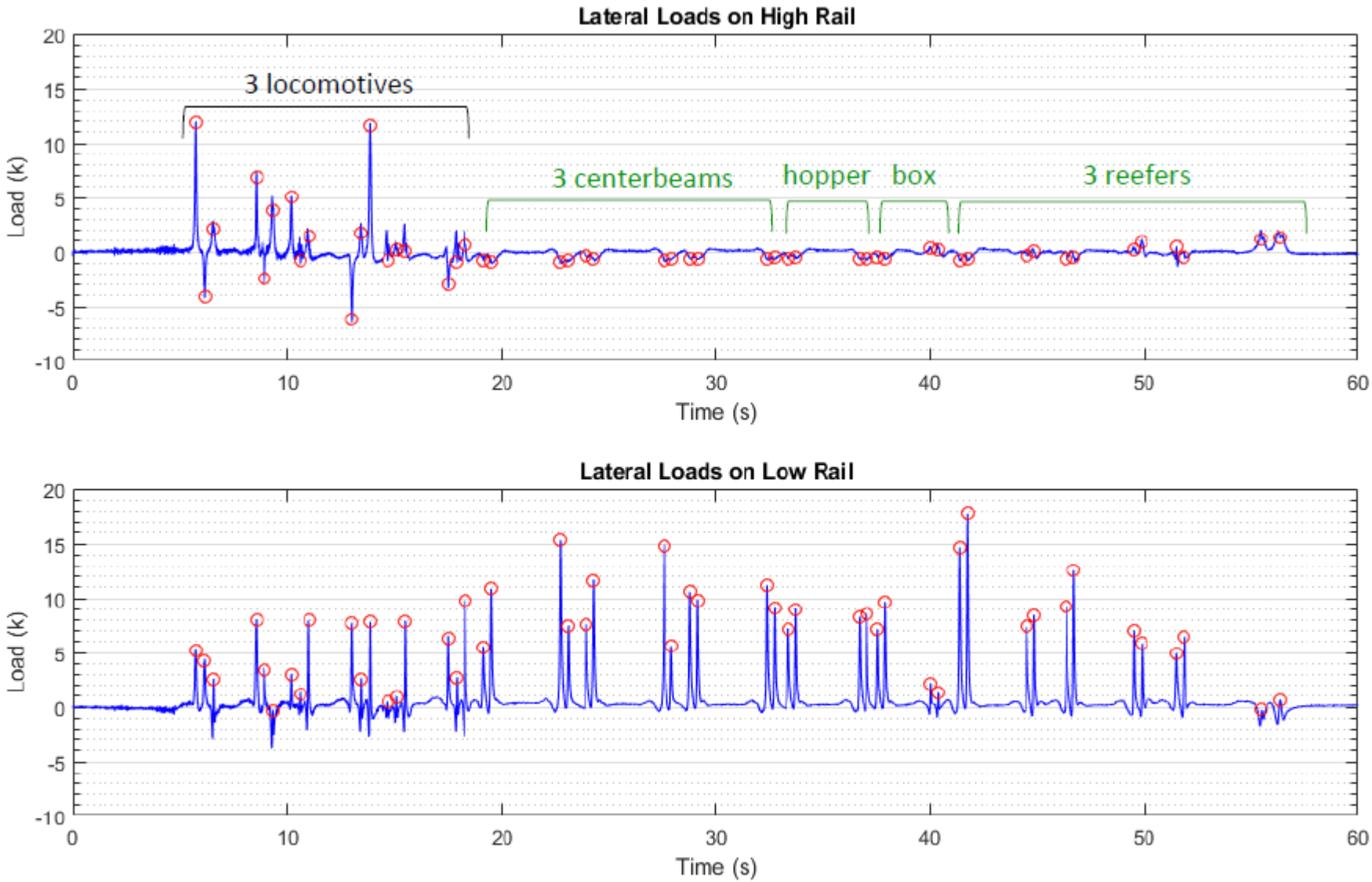
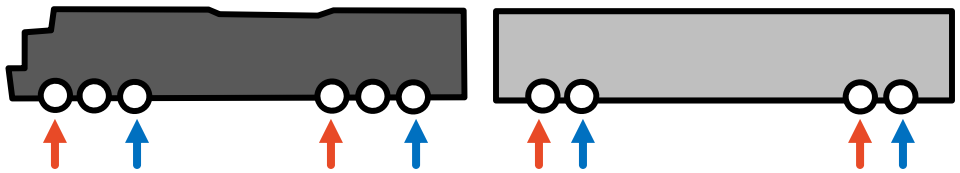


Figure 8: Lateral wheel loads on high and low rails under the three locomotives and head eight cars of train 35A.

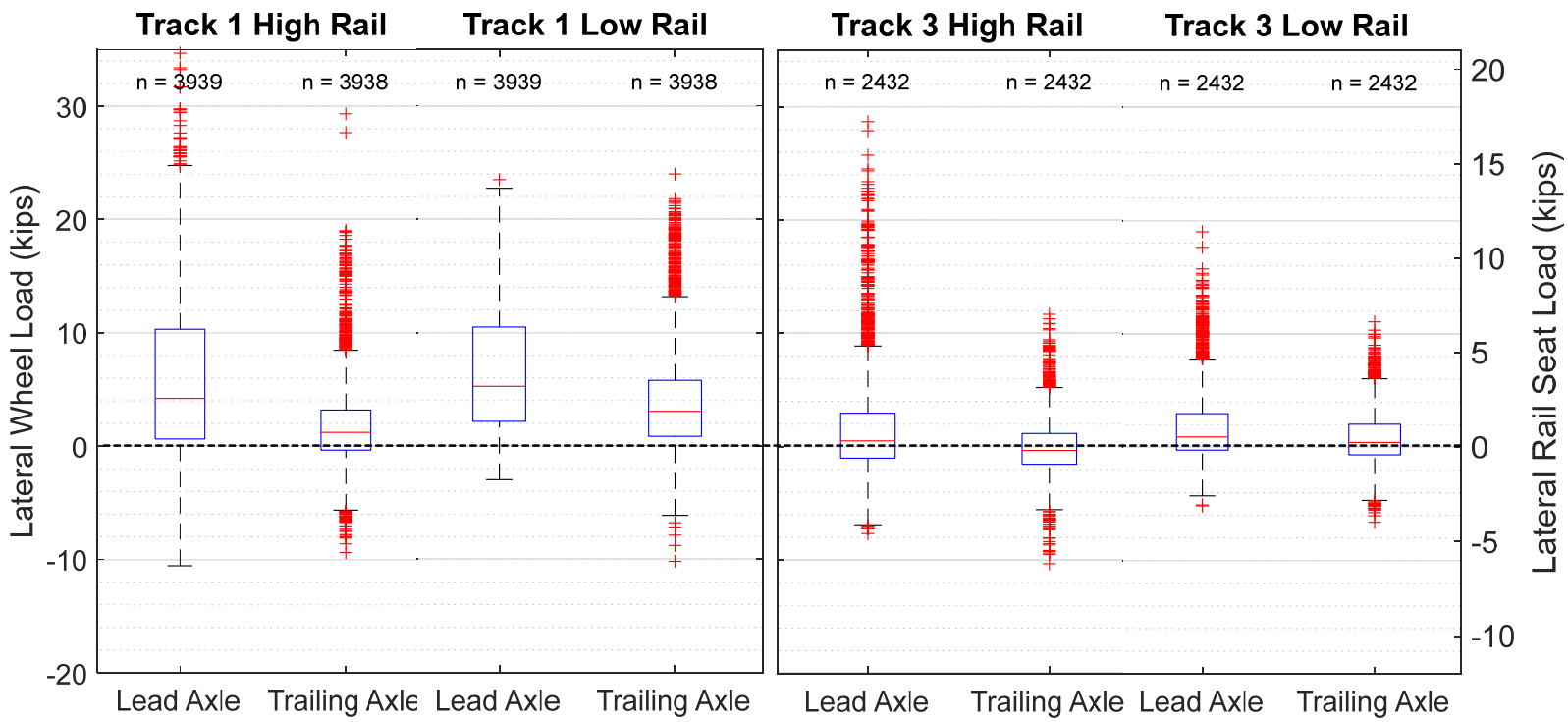
Lateral Wheel Loads By Axle Position

(July 2019)



Lead axle

Trailing axle



- Lateral wheel loads in lead axles observed to be 30-100% higher than in trailing axles

Model Details

- **Cut spikes:**
  - Geometry simplification**:** removed head
  - Key geometry details: 6” long by 0.625in. Square
  - Material properties: validated via lab tensile testing of actual spike
- **Screw spikes:**
  - Geometry simplification**:** Removed threads and head,
  - Key geometry details: 11/16” diameter threaded shaft
  - Material properties: same as cut spike (confirmed by manufacturer’s lab testing)
- **Single spike timber block:**
  - Key geometry details: 7” by 9” by 18”
  - Material properties: validated UMAT utilized in previous studies; hourglass control
- **Single rail seat model:**
  - Representative system for North American heavy axle load (HAL) Class I railroad
  - Components: cut spikes, timber block,
  - Block geometry details: 7” by 9” by 51”
  - Quantity of spikes: four or five (dependent on study)
- **Elements:** 8-node linear brick, reduced integration used for all parts except the plate