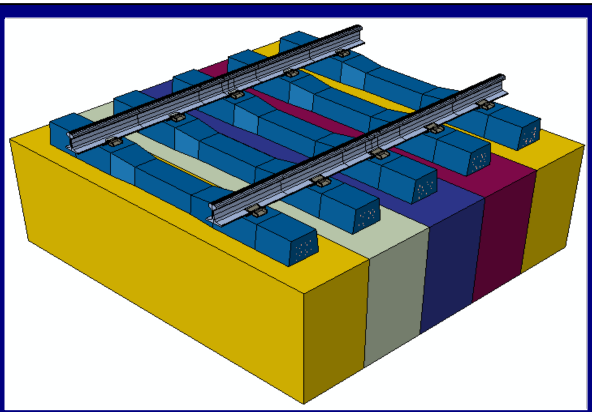
Summary on FE Analysis and Parametric Study



FRA Tie and Fastening System BAA - Industry Partners Meeting

Orlando, FL

15 October 2014

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U.S. Department of Transportation

Federal Railroad Administration

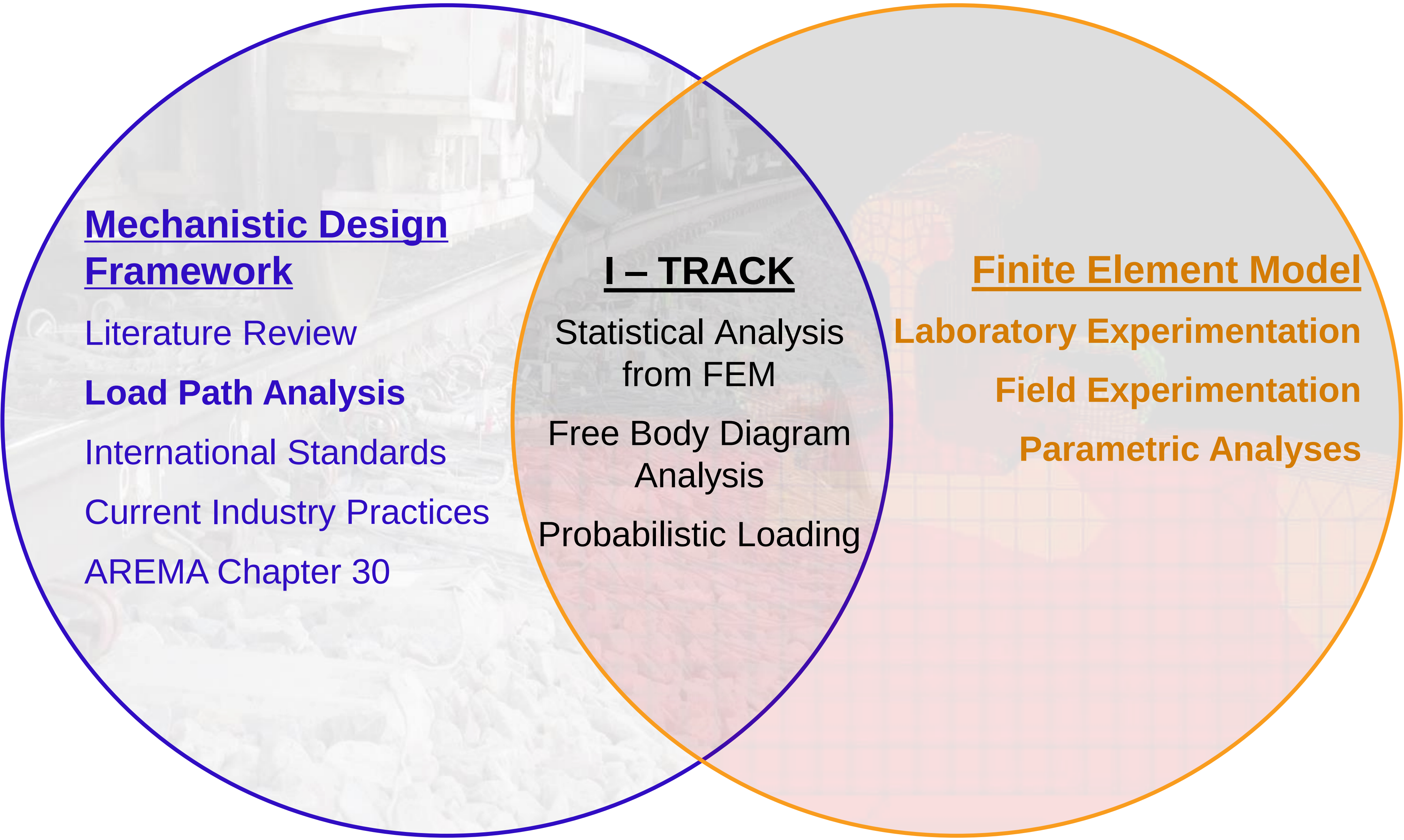
RAILTEC

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Outline

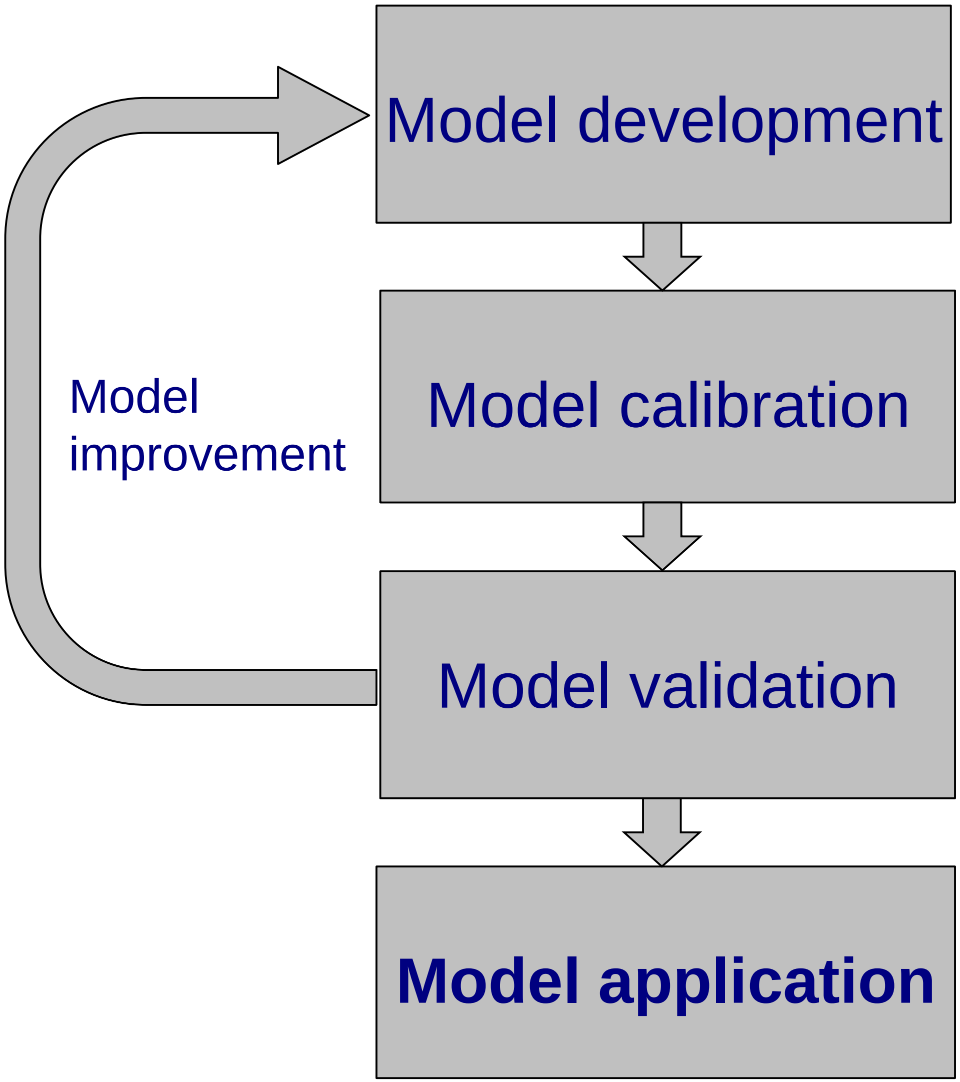
- Role of Finite Element (FE) analysis in mechanistic design
- Methodology and validation of the FE model
- Review of existing FE analysis
- Parametric studies about critical design parameters
- Conclusions based on parametric studies

Overall Project Deliverables



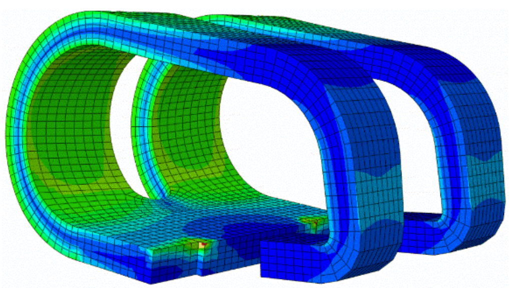
Methodology for FE Analysis

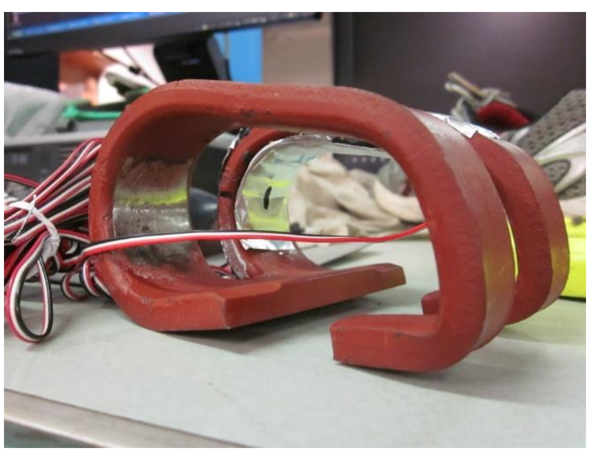
- Model development
  - Component model
  - Single-tie model
  - Multiple-tie model
- Model calibration
  - Displacement/strain measurement
- Model validation
  - Vertical/lateral load distribution
- **Model application**
  - **Parametric studies**
  - ITRACK



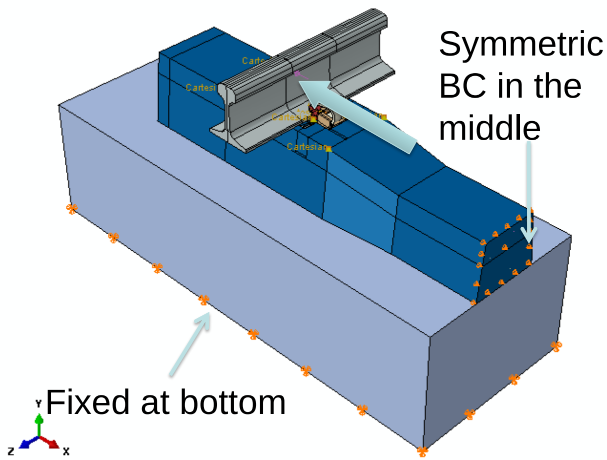
Review of Model Development: Previous FE Analysis

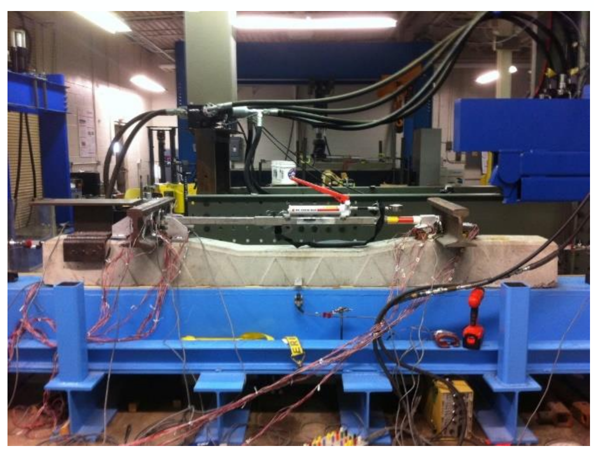
Component Validation



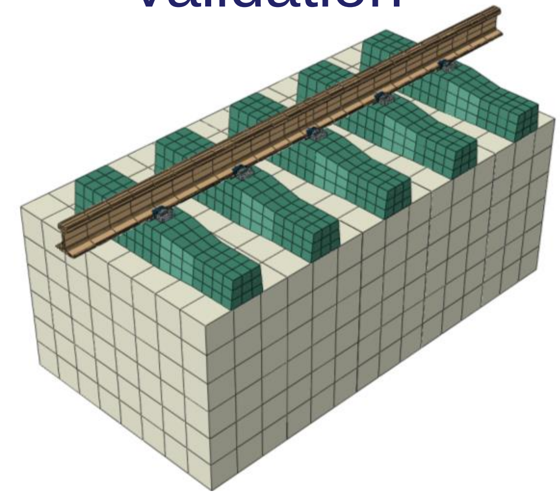


Laboratory Test Validation





Field Test Validation

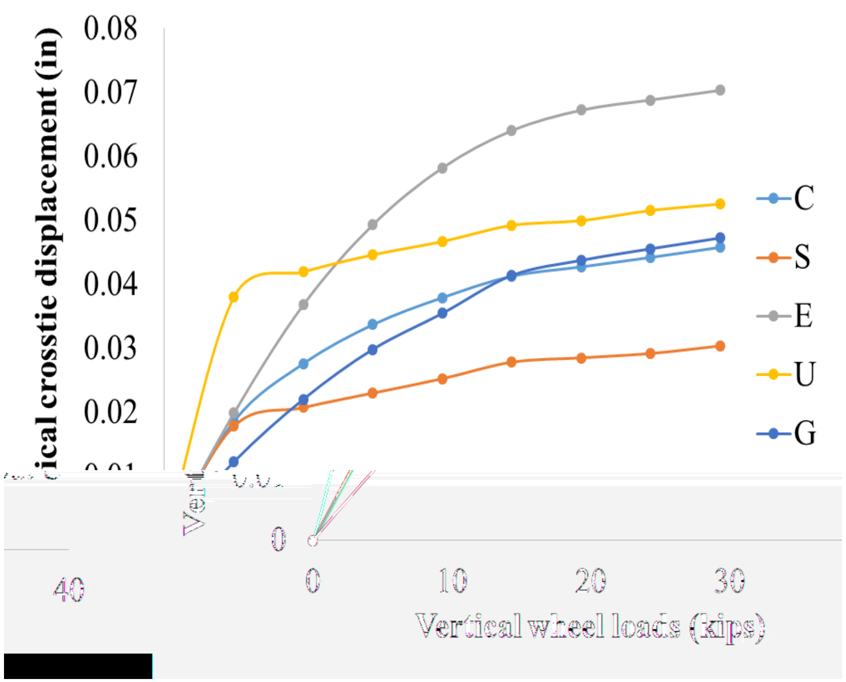


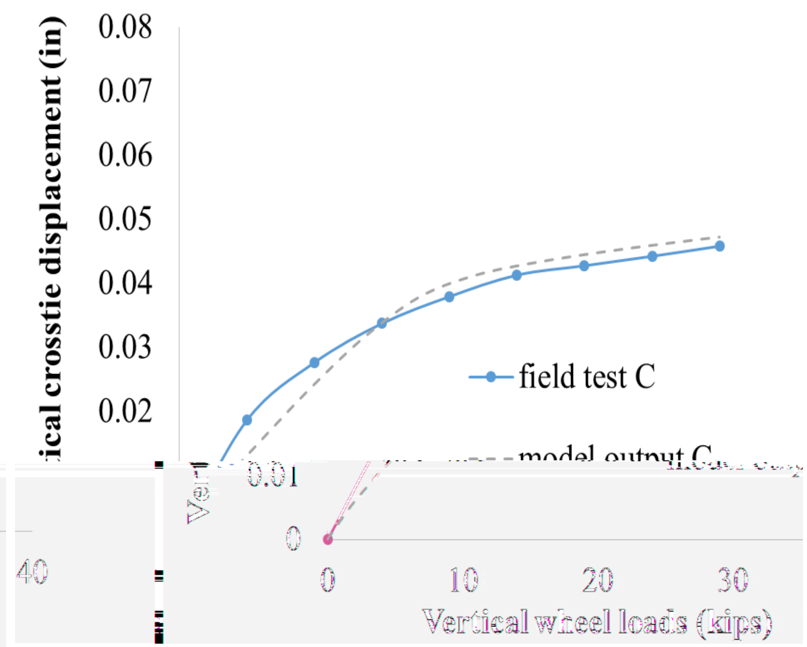
Review of Findings:
Vertical Track Stiffness

- In the field experimentation, linear potentiometers were installed to measure the vertical crosstie displacement

Review of Findings: Vertical Track Stiffness

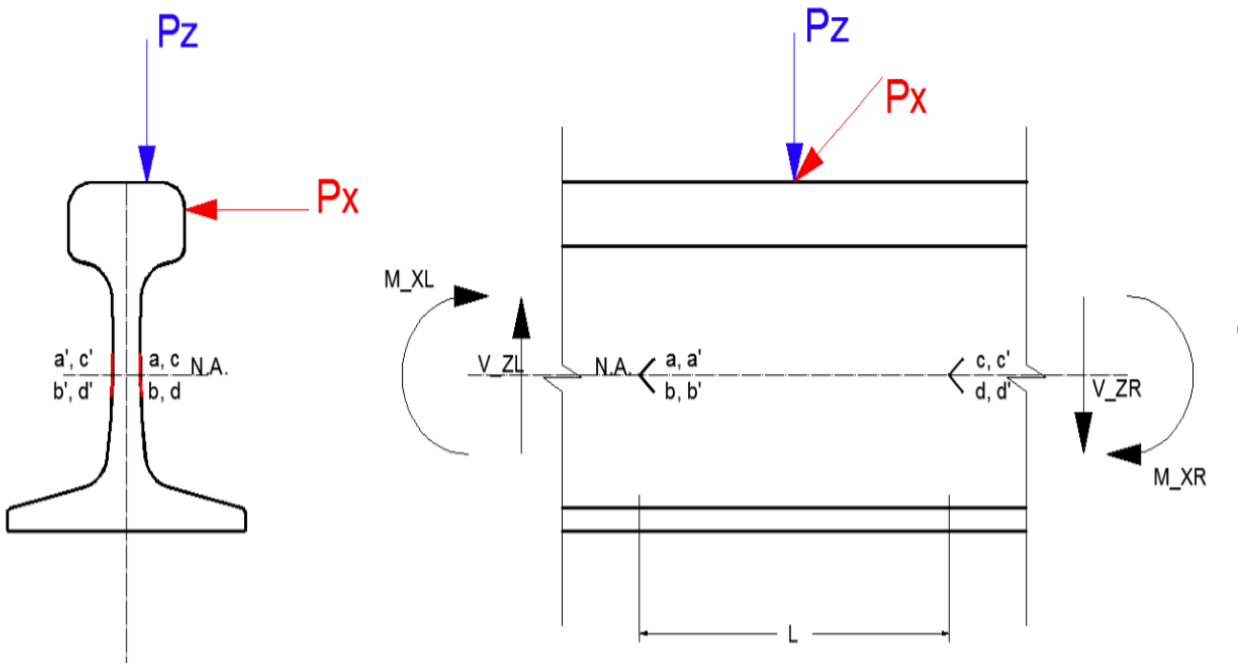
- the vertical track stiffness (incremental wheel load divided by incremental crosstie vertical displacement) gradually increase under higher vertical wheel load
- The track stiffness varied considerably among different crossties





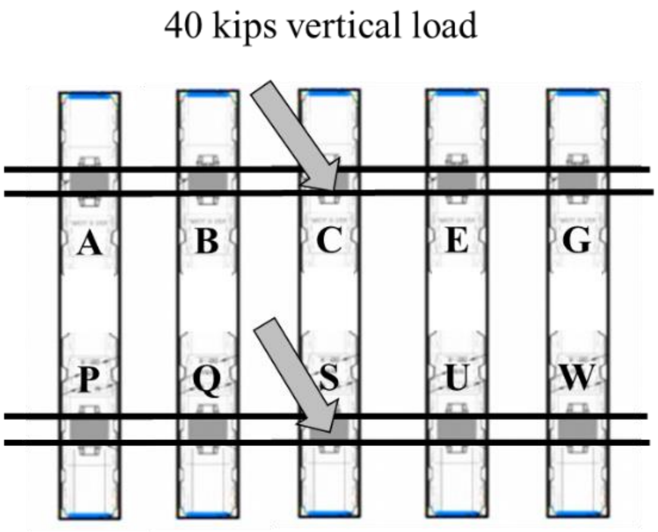
Review of Findings: Vertical Wheel Load Distribution

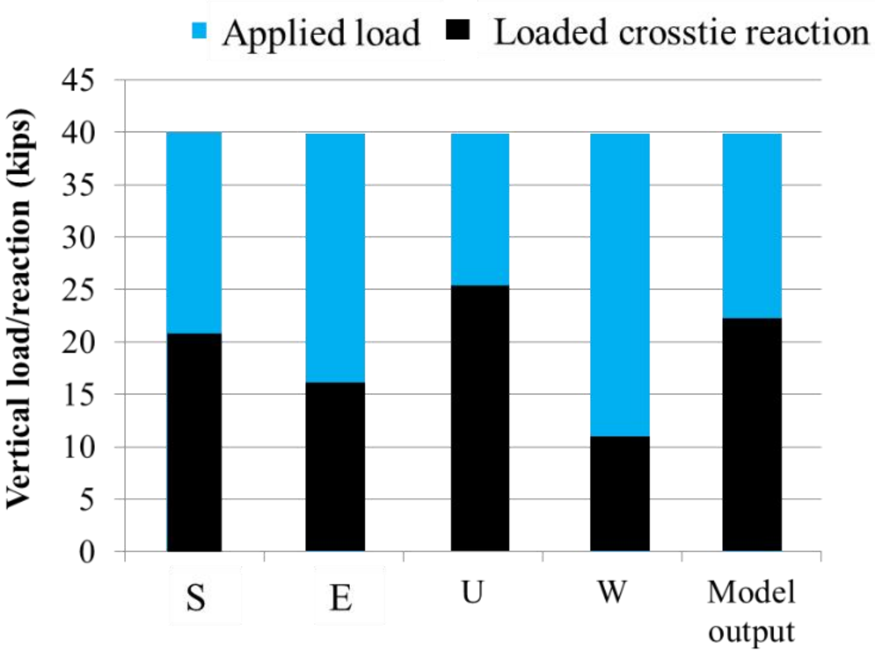
- In the field experimentation, strain gauges were attached to the rail web in Chevron patterns to determine the vertical rail seat load



Review of Findings: Vertical Wheel Load Distribution

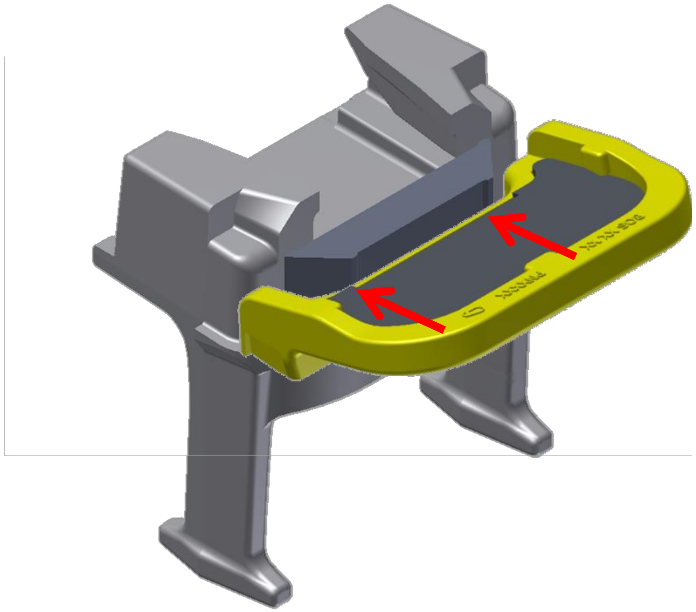
- Both field experimentation and FE analysis shows that vertical wheel load is primarily distributed among the five nearest concrete crossties
- Based on the varying support condition of different crossties, 28% to 63% of the applied vertical wheel load was resisted by the loaded rail seat

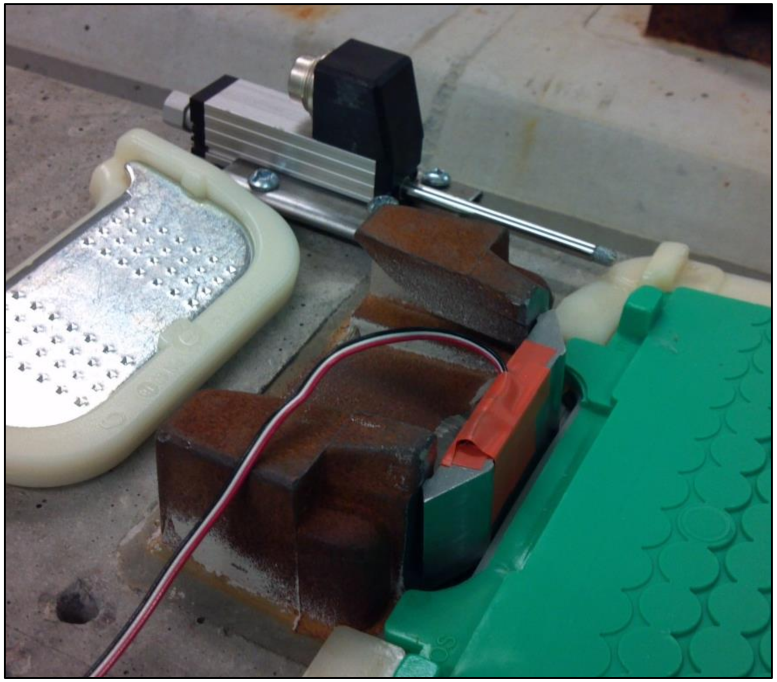




Review of Findings: Lateral Wheel Load Distribution

- instrumented steel beams were installed in place of the shoulder face to measure the interaction force between field-side shoulder and insulator

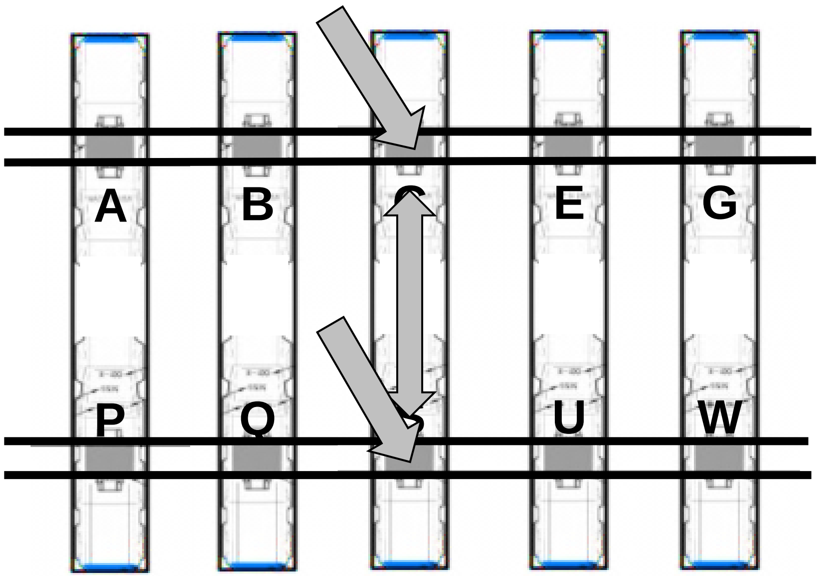


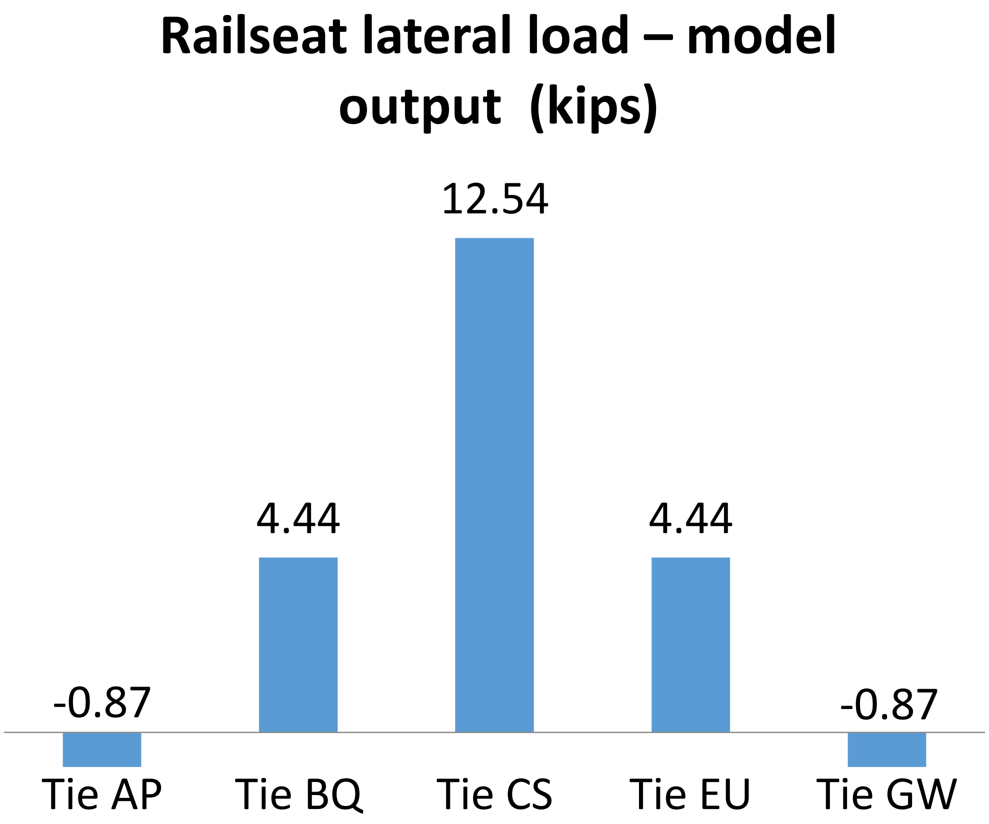


Review of Findings: Lateral Wheel Load Distribution

- The lateral wheel load is primarily distributed among the three concrete crossties that are closest to the point of loading
- At a specific rail seat, the lateral deflection of the rail is resisted by the frictional force at the bottom of the rail and the bearing force from field-side shoulder

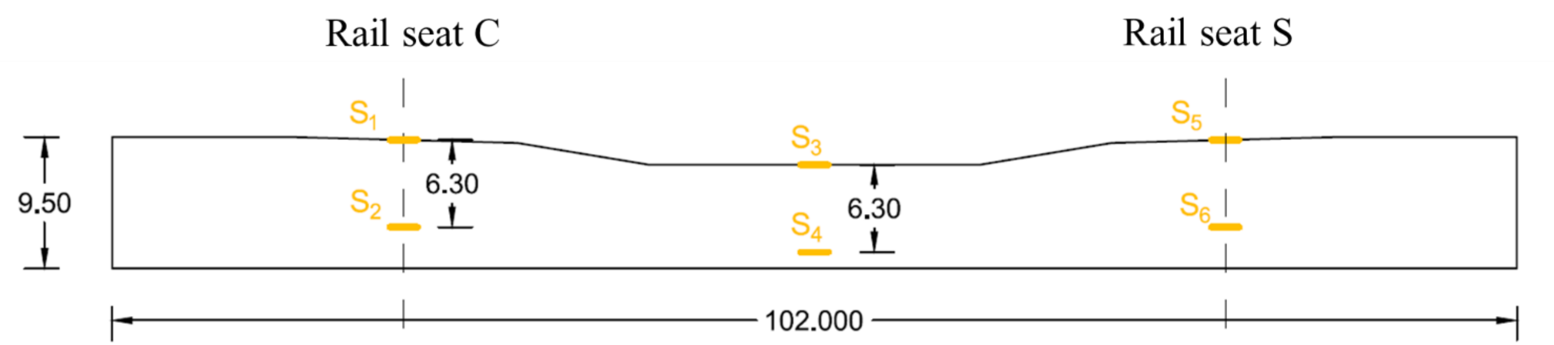
40 kips vertical load
20 kips lateral load





Review of Findings: Crosstie Support Condition

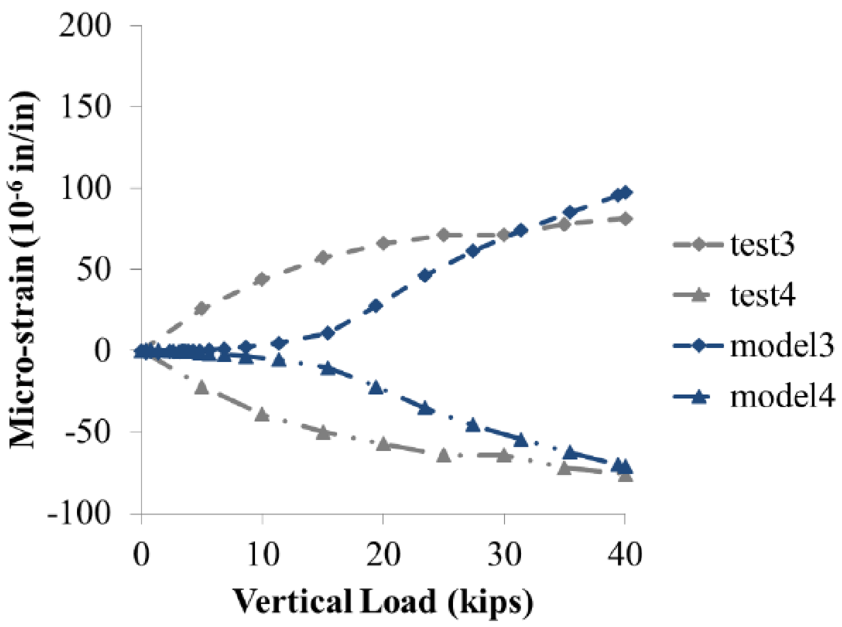
- As a part of field experimentation, concrete surface strain gauges were attached in the longitudinal direction on multiple crossties to measure the flexural strain of concrete under wheel load

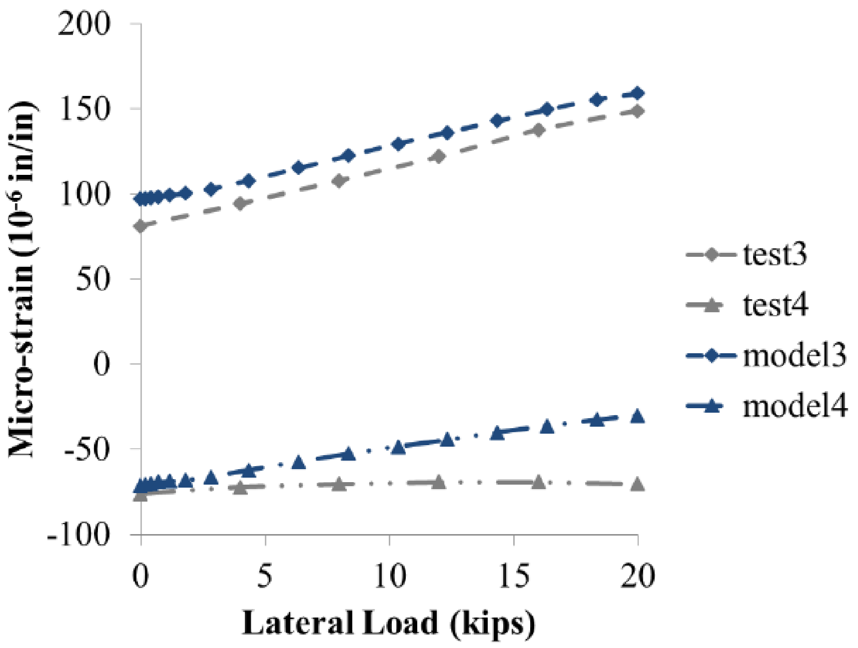


Locations of concrete surface strain gauges (Unit in inches)

Review of Findings: Crosstie Support Condition

- The support of ballast under instrumented concrete crossties are not uniform
- Gaps of different sizes exist between concrete crossties and the ballast, and could be closed under vertical wheel load





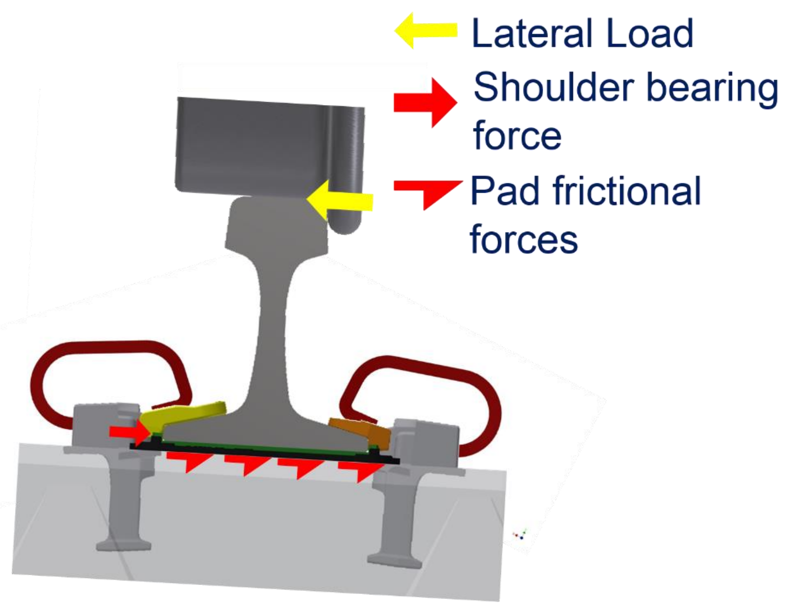
Parametric Study on Critical Design Parameters

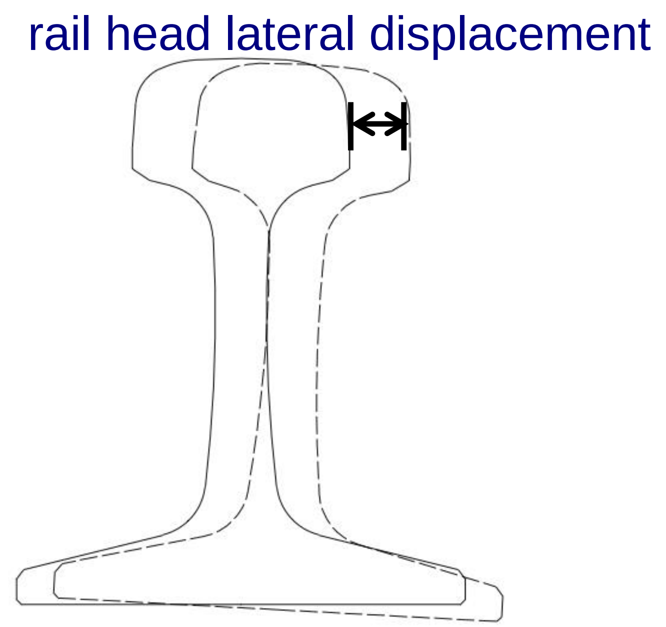
- The validated FE model was used to evaluate the effect of some critical design parameters on the performance of the track structure in different loading scenarios
- The range of design parameters were determined based on reference

		Range	Base value
Input	Crosstie spacing (in)	20~30	24
	Rail-pad and plate-concrete COF	0.12~1.0	0.3
	Pad elastic modulus (psi)	4,000~400,000	7,500
	Insulator elastic modulus (psi)	400,000~2,000,000	440,000
Output	Rail head lateral displacement		
	Shoulder bearing force at the loaded rail seat		
	Pad friction force at the loaded rail seat		
	Vertical rail seat load		
Loading scenarios	Loading scenario 1: V=40 kips, L=10 kips		
	Loading scenario 2: V=40 kips, L=20 kips		
	Loading scenario 3: V=40 kips, L=30 kips		
	Loading scenario 4: V=10 kips, L=5 kips		
	Loading scenario 5: V=20 kips, L=10 kips		
	Loading scenario 6: V=30 kips, L=15 kips		

Parametric Study on Critical Design Parameters

- The parametric study was divided into two phases for each loading scenario
- In the first phase, a full factorial design of cases was generated at the maximum and minimum values of the design space
- Based on the FE model output, an analysis of variance (ANOVA) was used to determine the interaction of design parameters that are statistically significant
- In the second phase, more cases were generated to further investigate significant input interactions

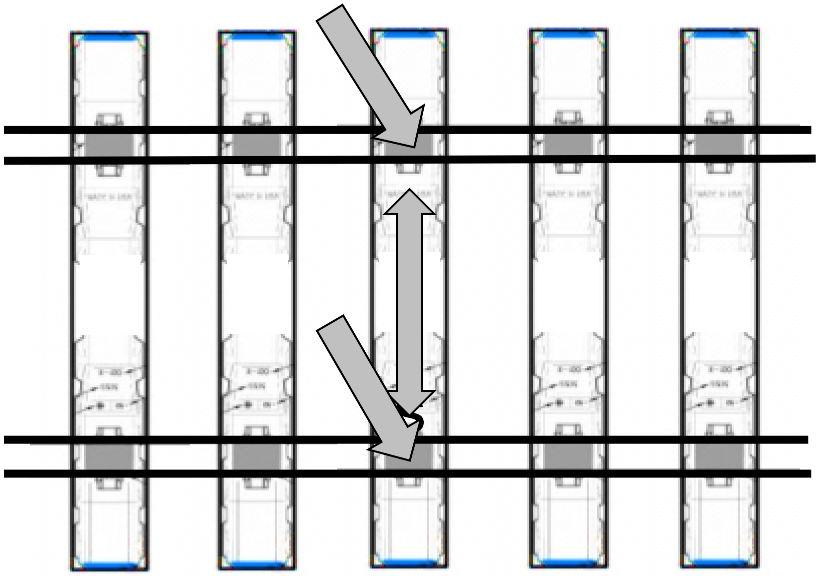




Parametric Study on Critical Design Parameters

- In the parametric study, symmetric loading condition is assumed as in the field experimentation
- Design parameters not included in the design of experiment remain the same as in the field experimentation in all the cases (substructure support stiffness, distribution of prestressing strands, etc.)
- In total 480 cases were generated for the 6 loading scenarios

Defined vertical and lateral wheel load



Parametric Study on Critical Design Parameters: Significant Interactions

- Input interactions with a p-value smaller than 0.05 are determined as significant
- The significant input interactions are similar in four loading scenarios
- The insulator elastic modulus is not significant to any of the output
- The second-order interactions of the other three input are significant to at least one output
- The third-order interaction is not significant to any of the output

Interaction	P-value			
	Rail head lateral deflection	Shoulder bearing force	Rail pad frictional force	Vertical rail seat load
Loading Scenario 1: Vertical load = 40 kips, Lateral load = 10 kips				
Spacing:COF			3.75E-02	4.01E-03
Spacing:Pad modulus	4.85E-04	4.55E-03	7.10E-04	
COF:Pad modulus	4.79E-06	6.71E-07	3.74E-10	2.02E-03
Loading Scenario 2: Vertical load = 40 kips, Lateral load = 20 kips				
Spacing:COF	1.27E-04			6.98E-05
Spacing:Pad modulus	1.61E-03			
COF:Pad modulus	5.09E-06	4.16E-06	6.68E-06	3.51E-09
Loading Scenario 3: Vertical load = 40 kips, Lateral load = 30 kips				
Spacing:COF	4.37E-08			3.60E-07
Spacing:Pad modulus	1.68E-04			
COF:Pad modulus	4.23E-06	2.20E-10	4.14E-06	1.18E-12

Parametric Study on Critical Design Parameters: Significant Interactions

- Input interactions with a p-value smaller than 0.05 are determined as significant
- The significant input interactions are similar in four loading scenarios
- The insulator elastic modulus is not significant to any of the output
- The second-order interactions of the other three input are significant to at least one output
- The third-order interaction is not significant to any of the output

Loading Scenario 4: Vertical load = 10 kips, Lateral load = 5 kips

Interaction	P-value			
	Rail head lateral deflection	Shoulder bearing force	Rail pad frictional force	Vertical rail seat load
Spacing:COF		9.2E-03		1.2E-02
Spacing:Pad modulus	9.9E-03	2.8E-02		
COF:Pad modulus	4.9E-07	2.1E-06	5.8E-04	4.0E-03

Loading Scenario 5: Vertical load = 20 kips, Lateral load = 10 kips

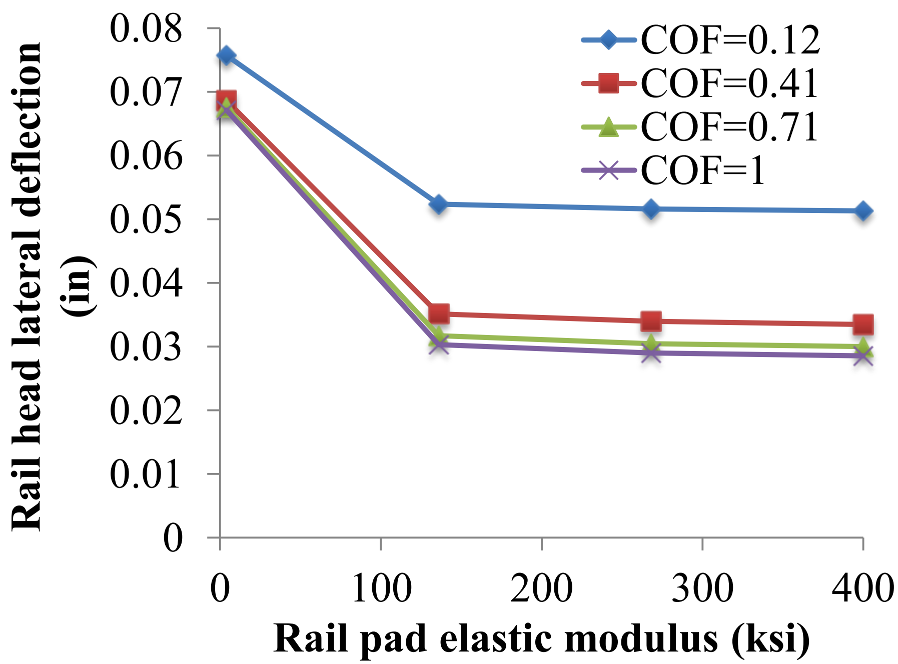
Interaction	P-value			
	Rail head lateral deflection	Shoulder bearing force	Rail pad frictional force	Vertical rail seat load
Spacing:COF	1.4E-02			4.6E-03
Spacing:Pad modulus	5.0E-03			
COF:Pad modulus	6.6E-06	2.4E-04	3.0E-05	1.0E-06

Loading Scenario 6: Vertical load = 30 kips, Lateral load = 15 kips

Interaction	P-value			
	Rail head lateral deflection	Shoulder bearing force	Rail pad frictional force	Vertical rail seat load
Spacing:COF	1.1E-03			2.0E-04
Spacing:Pad modulus	2.3E-03			
COF:Pad modulus	8.7E-06	2.0E-05	7.3E-06	2.1E-09

Example: V=30 kips, L=15 kips
Output: Rail head lateral deflection

- Rail head lateral deflection generally decreased with higher rail pad elastic modulus, higher COF, and closer crosstie spacing
- Compared to COF and rail pad elastic modulus, crosstie spacing had relatively little effect on the variation of rail head lateral deflection



Example: V=30 kips, L=15 kips
Output: Rail head lateral deflection

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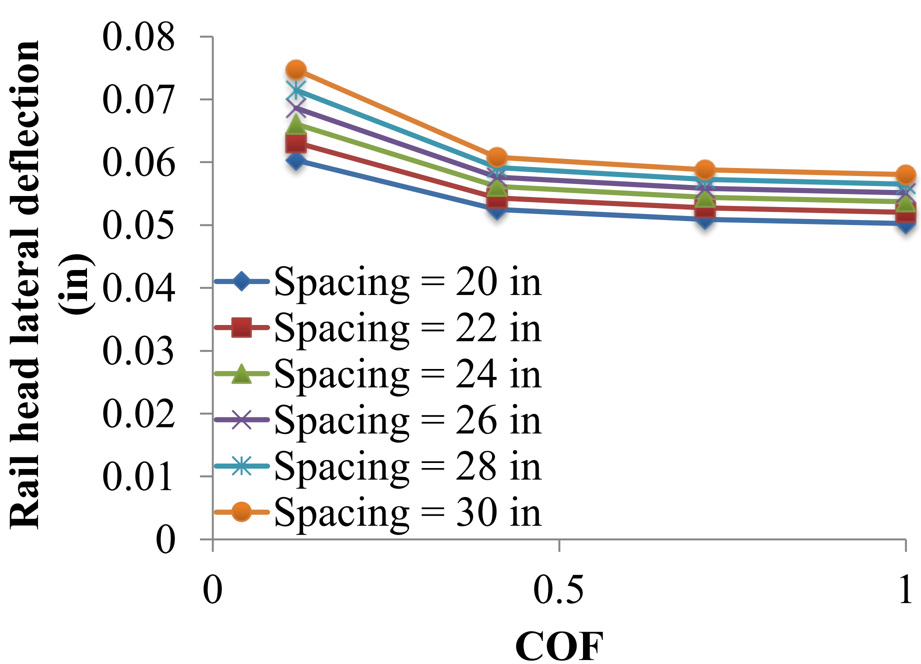
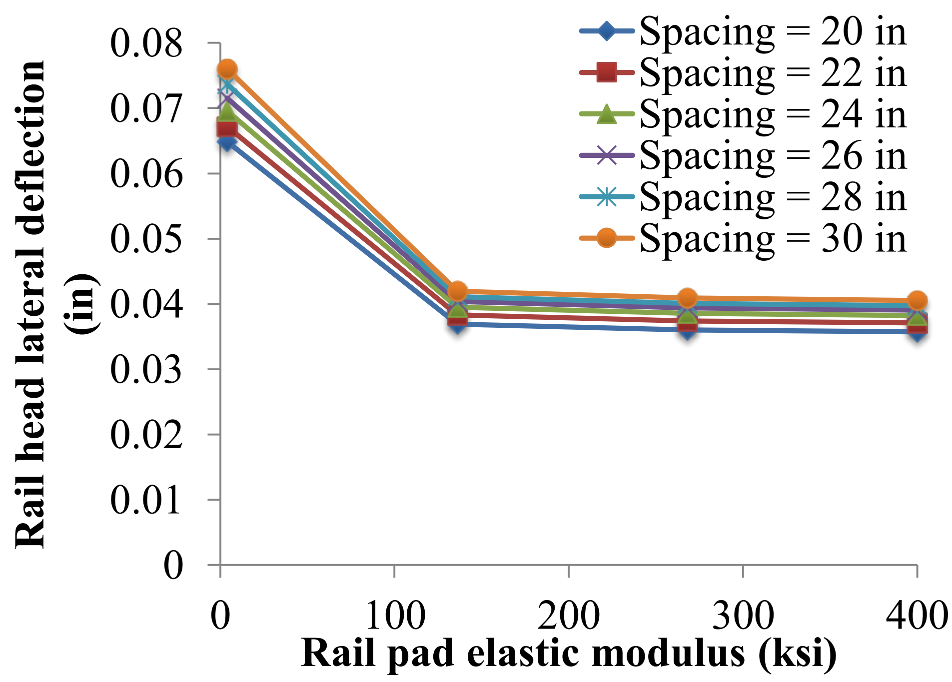
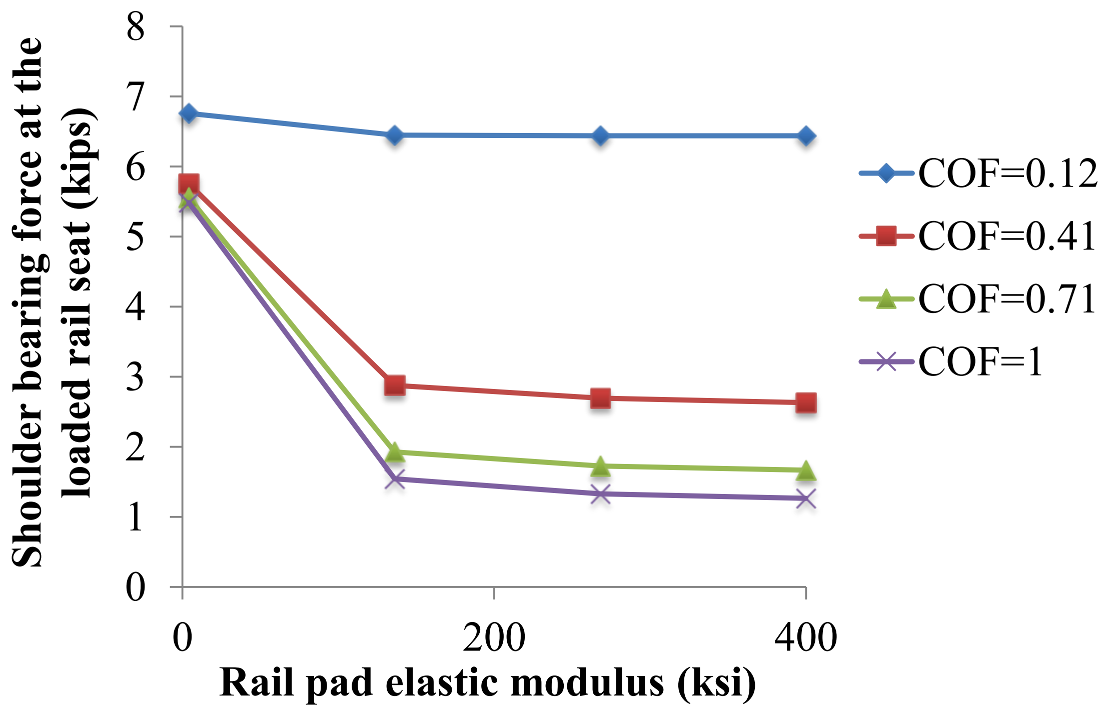




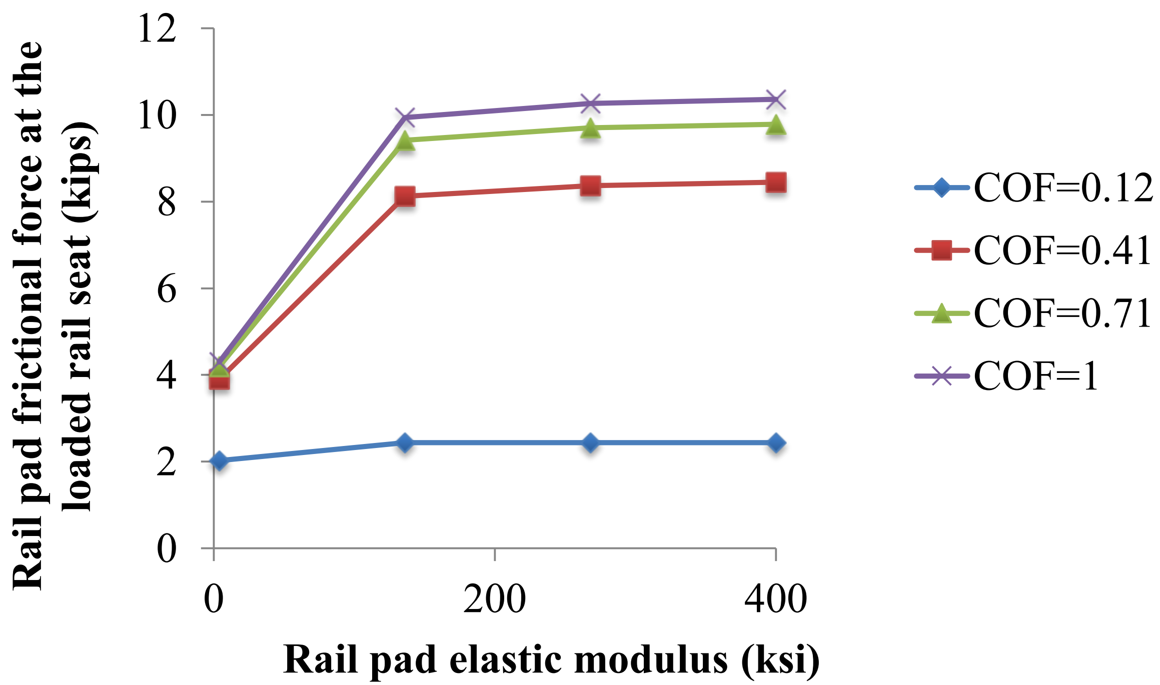
Example: V=30 kips, L=15 kips
Output: Shoulder Bearing Force

- The shoulder bearing force at the loaded rail seat gradually decreased with higher rail pad elastic moduli, and higher COF
- the shoulder bearing force at the loaded rail seat is affected by the design of the fastening system (COF and rail pad elastic modulus) more than the global system configuration (crosstie spacing)
- the shoulder bearing force gradually converged to a set value at high rail pad elastic moduli and high COF



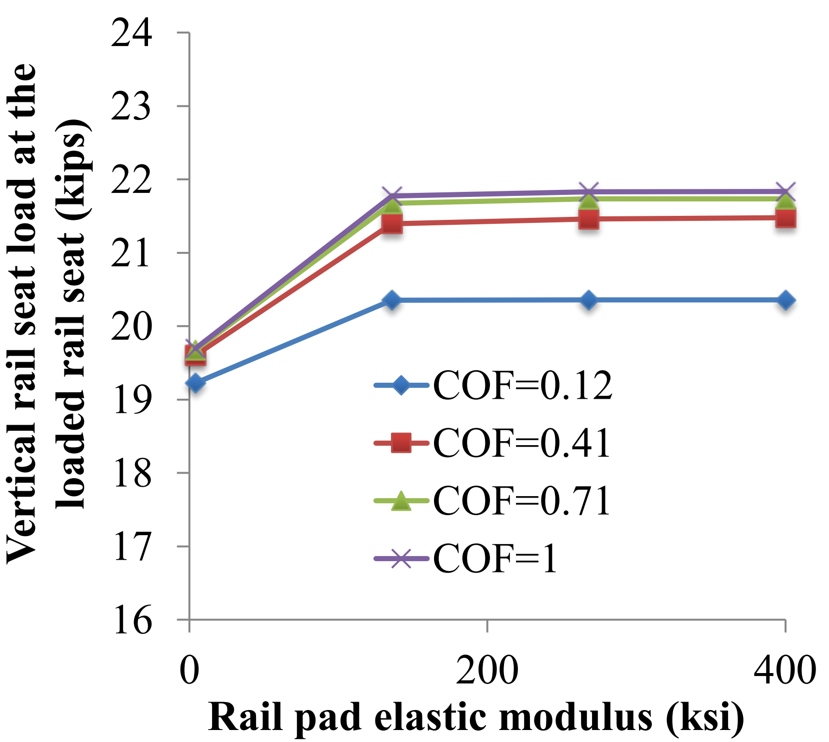
Example: V=30 kips, L=15 kips
Output: Rail Pad Friction Force

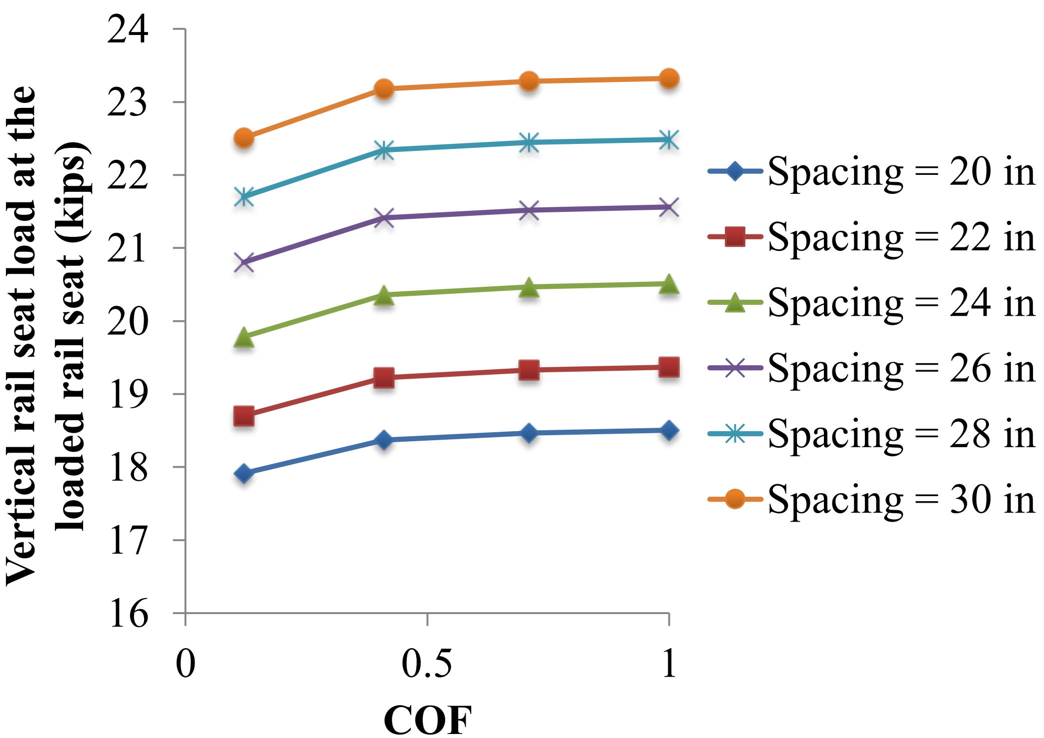
- The rail pad friction force gradually decreased with lower rail pad elastic modulus, and lower COF
- The rail pad elastic modulus had larger impact on the rail pad friction force at low load magnitudes (COF), and the impact gradually reduced at higher load magnitudes (COF)



Example: V=30 kips, L=15 kips
Output: Vertical Rail Seat Load

- The vertical rail seat load gradually decreased with smaller rail pad elastic modulus, lower COF, and closer crosstie spacing
- The relationship between crosstie spacing and vertical rail seat load was linear, and the crosstie spacing had a greater impact on the vertical rail seat load than the other two input variables





Conclusions Based on Parametric Studies

- The elastic modulus of the fastening system insulator has little effect on the lateral load path through the fastening system
- The COF at the rail-pad and the plate-concrete interfaces, and the elastic modulus of the rail pad significantly affect the performance of the fastening system under lateral wheel load
- Compared to the COF at the rail-pad and plate-concrete interfaces, and the elastic modulus of rail pad, crosstie spacing has a minimal impact on the performance of the fastening system under lateral wheel loads
- Crosstie spacing significantly affects the distribution of vertical wheel load among multiple rail seats, and the relationship between crosstie spacing and the vertical rail seat load under the point of load application is approximately linear

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FRA Tie and Fastener BAA Industry Partners:

Thank You

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