ABSTRACT
With increasing demands for rail passenger and freight operations, sharing a line or track is an economical solution if operation efficiency and track reliability challenges can be accommodated properly. Complex dynamic loading patterns that exist especially in shared rail lines demand adequate tie support conditions. A better basic understanding of ballast mechanistic behavior under different tie support conditions and loading patterns can improve track reliability and operation efficiency. As part of a major research effort that focused on the development of improved concrete tie designs for use on Amtrak’s Northeast Corridor (NEC), recent numerical modeling work at the University of Illinois has critically examined certain complex dynamic loading patterns associated with freight and passenger cars traveling
at different speeds, and tie support scenarios leading to track geometry deterioration. Freight car loadings at two low speeds (20 mph and 50 mph) and passenger car loadings at two higher speeds (110 mph and 150 mph) were studied. Four common tie support conditions (lack of rail seat support, full support, lack of center support, and high center binding) were developed to study particulate nature ballast behavior using the Discrete Element Method (DEM). A total of 16 scenarios utilizing DEM model simulations for these tie support conditions were created and analyzed. Ballast particle contact force networks were visualized and compared quantitatively using statistical methods. Based on the tie vibration velocities captured, statistical analyses were conducted to determine the differences among all the cases studied. Results reveal that for the same axle load, higher speeds will cause larger ballast particle movements. However, with higher load magnitudes, larger particle movements can be observed even at lower speeds. Generally, high center binding results in the smallest particle movement while lack of center support presents the largest particle movement. Dynamic load responses of the ballast layer simulations provide insights into evaluating and optimizing tracks to be shared by passenger and freight trains.

INTRODUCTION

Most of the U.S rail corridors are ballasted track. Ballast layer provides its functionality in distributing wheel load and draining moisture in the ballasted railway tracks. Ballasted track is quite economical with relatively lower cost in construction and maintenance compared to slab track. Ballast aggregate materials are easy to maintain and essential to controlling track geometry in accordance with Federal Railroad Administration (FRA) safety standards. However, after extended service use, ballast undergoes settlement due to particle degradation/breakdown and this may often result in non-uniform support conditions for crossties in different sections of the track.

Discrete Element Method (DEM) has been widely used in different industrial problems dealing with particulate nature granular material behavior, such as the ballast layer in track substructure, in the past several decades (1-6). DEM is accepted by engineering research community to be an effective numerical modeling method with its direct application to simulate behavior of large ballast particles, monitoring the inter-particle contact forces, particle displacements, and particle velocities. Most of the previous research studies on DEM modeling of ballast deformation behavior assumed uniform and full support at the interface between ballast and crosstie and assumed the crosstie to be uniformly supported. However, as recently observed from field instrumentation studies (7-8), repeated dynamic loading applied on ballasted track structures can lead to non-uniform support between the ballast layer and the crosstie. Such non-uniform support conditions were shown to have major adverse effects on the flexural bending behavior of crossties (9). Note that investigation into ballast layer under non-uniform support conditions is very limited.

In addition to the various support conditions, various dynamic loading patterns exist in railroad lines considering loading amplitude and frequency. Previous studies showed that effects of loading patterns on ballast layer performance were largely influenced by the loading frequency (linked to train speed), rest period (time difference between two adjacent axles and/or front and rear bogies), and magnitude of wheel loads (10-13). It is concluded that when analyzing the loading pattern effects, it is of vital importance to simulate realistic loading patterns (frequency, load amplitude, and rest period) as applied on track structures. Therefore, to better represent the in-track ballast behavior under various crosstie support conditions, it is necessary to consider multiple loading patterns of trains and the dynamic characteristics.

Understanding ballast mechanistic behavior under different crosstie support conditions and loading patterns can improve track reliability and operation efficiency. From a qualitative perspective, recent studies at the University of Illinois have considered both developing new concrete tie designs, which are primarily based on considering static loads, and investigating tie-ballast support conditions which should deal with both static and dynamic loading characteristics. The support conditions and loading patterns were found to have noticeable impact on the tie responses and the deformation behavior of the ballast materials (14-15). Amtrak’s Northeast Corridor (NEC) has been the focus with its shared corridor operation and critically examined for its certain complex dynamic loading patterns associated with freight and passenger cars traveling at different speeds, and tie support scenarios leading to track geometry
deterioration. Freight car loadings at two low speeds (20 mph and 50 mph) and passenger car loadings at two higher speeds (110 mph and 150 mph) are studied in this paper. Four common crosstie support conditions (lack of rail seat support, full support, lack of center support, and high center binding) are investigated to study the influence of dynamic loading patterns on these crosstie support conditions from a quantitative perspective using the DEM to gain a better understanding of the particulate nature ballast behavior and the associated track structure performance.

ANALYTICAL FRAMEWORK

DEM Model Setup
In this study, a polyhedral 3D DEM code, BLOKS3D (16-17), was utilized to simulate the behavior of ballast particles under dynamic loading scenarios. The dimensions of the established full-track model is shown in Figure 1. Full width of the track was modeled with 11.8 in. wide ballast shoulders and 2:1 shoulder slope. The length in the train moving direction was chosen as 24 in., which is approximately one crosstie spacing. The in-track gradation (meeting AREMA No. 3 and No. 4A) and shape properties of the ballast material were adequately simulated by polyhedron DEM elements. In total, 11,000 ballast particles were generated in the simulation in each case. Detailed ballast material properties can be found in a recent publication by the authors (14-15). Note that crosstie was a master block also used as a discrete element in the DEM simulations. The DEM model was successfully validated with laboratory testing results (14-15) and ready to use for simulating the dynamic loadings.

![FIGURE 1 Geometry under one crosstie established in the ballast DEM simulation (14).](image)

Different Support Conditions
To assess the effect of loading patterns on different tie support conditions, several likely to happen support conditions in track were selected. These typical support conditions include: a) **Lack of rail seat support** representing the in-track condition caused by high impact wheel loads and insufficient ballast support under rail seats; b) **Full support** representing an idealized track condition with uniform ballast support under crosstie; c) **Lack of center support** representing the idealized track condition possibly right after tamping, providing adequate support under the rail seats and decreased support in the center of the crosstie, and finally, d) **High center binding** representing the lack of track support towards the center of the crosstie. Figure 2 shows the four DEM models created using BLOKS3D, one model for each support condition.
FIGURE 2 Profile views of four different support conditions studied in DEM simulations

Different Field Loading Patterns
Besides the four different support conditions, four different loading patterns were applied in the DEM model. At this moment, it was of interest to investigate the effect of train speed, the train load magnitude, and the corresponding rest periods in loading. As a result, two train load magnitudes representing both freight and passenger trains were selected to study the effect of different loading patterns on dynamic responses of ballast particles. Two different speeds were also selected for each type of train. Note that locomotives were not included in the simulations for the sake of simplicity and easier comparison. Figure 3 shows the four loading patterns; freight train (286 kip gross rail load) operating at 20 mph and 50 mph, respectively, as well as passenger train (143 kip gross rail load) operating at 110 mph and 150 mph, respectively. The magnitude of load pulse reflects the magnitude of rail seat load. The rest period between load pulses is a reflection of axle/bogie spacing divided by train speed. Detailed computations of rail seat load values and axle/bogie spacing can be found in a recent publication (15).

It was assumed that the rail seat load under passage of the freight train (23 kips) was almost twice of that for the passenger train (11.5 kips). The two axles from the same bogie are represented as two haversine pulses with no rest period in between. Note that rest periods exist between the two adjacent axles from different bogies. In the numerical simulations, an eight-car train was adopted for both the passenger (similar to ACELA Express train having two locomotives and 6 passenger cars) and the freight trains to apply dynamic loading patterns in accordance to those shown in Figure 3 on top of the created ballast DEM models, consisting of 32 haversine load pulses in total. Finally, the dynamic behavior of discrete element particles in the models were analyzed, including inter-particle contact forces, particle displacements, and crosstie/particle velocities.

To summarize, four common tie support conditions (lack of rail seat support, full support, lack of center support, high center binding) were developed using the DEM modeling as indicated in Figure 2. Combining with four loading patterns, a total of 16 scenarios were created and analyzed in this paper using a statistical analysis framework for the computed ballast contact forces, crosstie vibration velocities, and ballast particle movements. Figure 4 illustrates the matrix of all simulated cases through the DEM modeling study.
FIGURE 3. Loading patterns applied in DEM model simulations (15).

FIGURE 4. DEM model study matrix for the various support and loading conditions.

STATISTICAL ANALYSES OF DEM RESULTS
The crosstie and ballast layer have various dynamic behavior trends under different support conditions and loading patterns. Towards the way of developing safe, reliable and readily sustainable railway
corridors for maintenance requirements, a better basic understanding of such dynamic behavior trends should be investigated. Four different support conditions and four different loading patterns were simulated in DEM models as discussed in the previous session. Accordingly, only one train pass (i.e. eight rail cars) was modelled for all sixteen cases. The ballast layers were prepared in a consistent manner with minimum compaction or packing by only considering gravity loading. Such loose ballast initial conditions were especially targeted in DEM model setup to potentially magnify any ballast deformation trends that could be observed under the application of only one train passage. The findings from the DEM simulations are presented in terms of ballast contact forces, crosstie vibration velocities, and ballast particle movements as the quantitative results and evaluated using a statistical analysis approach.

**Ballast Contact Forces**

Contact forces between individual ballast particles are established in response to particle self-weights and external dynamic train loads. Ballast layer under one crosstie contains thousands of such contact forces. Figure 5 is a plot of the ballast particle contact force network obtained for the full support condition presented by Feng et al. (15) when the wheel load is directly applied on the subject crosstie (see the peak point indicated as the corresponding time of the load pulse application). The darker and thicker the particle contact force chains are the higher are the magnitudes of the contact forces. Such plots provide important qualitative results for the ballast contact force distributions under different support conditions. However, even though complete contact force magnitude results are available for each individual ballast particle pair in contact, performing quantitative comparisons of force networks for the 16 cases studied are quite challenging based on such plots.

![Figure 5](image)

**FIGURE 5. Ballast layer particle contact force network for full support condition (15)**

Boxplot is a graphical method to depict numerical data through quartiles, which can achieve the goal of quantitatively comparing ballast contact force networks. Figure 6 is a comprehensive boxplot showing different support conditions and three loading stages, i.e., initial, middle and peak, of a load pulse (note that Figure 5 only showed the peak loading contact force network). Support conditions are labeled with abbreviations in the x axis: FS, HCB, LoCS, and LoRSS correspond to full support, high center binding, lack of center support, and lack of rail seat support, respectively. Three loading stages are also included in the boxplot with initial, middle, and peak, which again correspond to no external wheel load, external wheel load felt at half of it peak magnitude, and external wheel load reached at the maximum or peak magnitude, respectively.

According to Figure 6, at the initial loading stage, contact forces between ballast particles are minimal. For all four support conditions, their boxplots are similar with a range from 0 lbf to 50 lbf. At the middle loading stage, contact forces for the lack of center support condition have the largest variation among the four having a range from 50 lbf to 300 lbf. Contact forces for the lack of rail seat support condition have the lowest range and variation from 50 lbf to 200 lbf. At the peak loading stage, contact forces for the lack of center support condition still have the largest variation from 80 lbf to 380 lbf. Comparing the contact forces indicated in Figure 6 for the middle and peak stage loads, the boxplots for the high center binding
condition have only limited increase for the mean and median values while boxplots for the other three support conditions have more significant increases for the means and medians.

**FIGURE 6.** Boxplots for different support conditions and loading stages

**Crosstie Vibration Velocities**

Railroad crossties vibrate in response to external dynamic train loads. Severe crosstie vibrations can have negative effects on the ballast particle degradation and deformation behavior as well as other rail components to eventually reduce track serviceability and reliability. Investigating crosstie vibration velocity trends can provide a better insight into mechanics of track structure and potentially help to improve crosstie design.

Figure 7 shows rather large crosstie vibration velocities of a freight car traveling at 50 mph predicted by the DEM for the full support condition. Feng et al. (15) presented and qualitatively discussed results of all crosstie vibration velocities for the four support conditions and under the four dynamic loading patterns.

**FIGURE 7.** DEM model predicted large crosstie vibration velocities – freight car, 50 mph (15)
To quantitatively analyze the crosstie vibration velocity differences among all the sixteen cases, it is necessary to utilize statistical methodologies such as the hypothesis testing. Absolute values of the maximum and minimum crosstie vibration velocities (i.e. sixteen data points for each case) were used for the hypothesis analysis adopted in this study. Equation (1) is the effect model with null hypothesis as $H_0: \tau_t = 0$ and the alternative hypothesis as $H_a: \tau_t \neq 0$.

$$y_{tk} = \mu + \tau_t + \epsilon_{tk}$$  \hspace{1cm} (1)

where $y$ is the selected crosstie vibration velocity. If one compares the effect of different support conditions, $\mu$ is the average vibration velocity of all four support conditions; $\tau_t$ is the effect of different support condition; and $\epsilon$ is the error term. If one compares the effect of different loading patterns, $\mu$ is the average vibration velocity of all four loading patterns, $\tau_t$ is the effect of different loading pattern; and $\epsilon$ is still the error term.

Table 1 lists the hypothesis testing results for all the support conditions and loading patterns. The 20mph and 50mph correspond to speeds for the freight car travelling at 20mph and 50mph, respectively. The 110mph and 150 mph correspond to speeds for the passenger car traveling at 110mph and 150mph, respectively. Abbreviations of FS, HCB, LoCS and LoRSS have the same meaning as discussed in the previous ballast contact force section. Dots and stars in the third and sixth columns indicate testing significance level.

<table>
<thead>
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<th>Support Conditions</th>
<th>p value</th>
<th>Loading Patterns</th>
<th>p value</th>
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<td>8.710E-02</td>
<td>20mph_FS</td>
<td>2.640E-06</td>
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<td>20mph_LoRSS</td>
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<td>150mph_FS</td>
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<tr>
<td>50mph_FS</td>
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<tr>
<td>110mph_HCB</td>
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<td></td>
<td>150mph_LoRSS</td>
</tr>
</tbody>
</table>

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

For different support conditions, most $p$ values are above 0.05 and no $p$ value has a significance level below 0.001. Therefore, crosstie vibration velocity variation is limited between different support conditions which agrees with the observations made in the recent publication (15). For the full support condition, freight car travelling at 20mph and passenger car traveling at 150mph are significantly different with 20mph case being the lowest and 150mph case being the highest for the crosstie vibration velocities. For the other three support conditions, freight car travelling at 20mph and 50mph are significantly different with 20mph case being the lowest and 50mph case being the highest for the crosstie vibration velocities. Such analysis results also match well with observations noted in the recent publication (15).

**Ballast Particle Movements**

Ballast layer provides an important support for the whole track superstructure. Major particle movements will open up gaps in crosstie support conditions to potentially risk track serviceability and even endanger safety and reliability of a shared corridor track structure. Figure 8 provides a qualitative visualization of
particle movements after one train pass in the DEM simulation for the full support condition. Arrows in the figure indicate movement direction and colors indicate movement magnitudes. However, one may also be interested in a particle movement ratio, which is the movement in vertical direction divided by the movement in transverse (horizontal) direction. It is difficult to observe and compare such a ratio for all the different support conditions and loading patterns studied.

**FIGURE 8. Ballast particle movement trends under full support condition (15)**

To quantitatively compare ballast particle movement ratios boxplots are presented in Figure 9. The 20mph and 50mph data indicate speeds of freight car traveling at 20mph and 50mph, respectively. Whereas, the 110mph and 150mph data indicate speeds of passenger car traveling at 110mph and 150mph, respectively. FS, HCB, LoCS and LoRSS are the same abbreviations used for the four support conditions as given in the previous ballast contact force section.

**FIGURE 9. Boxplots of particle movement ratio (vertical/transverse) for different support conditions and loading patterns**

Comparing the effect of loading patterns, dynamic loads from passenger cars can cause higher particle movement ratios than those that resulted from freight cars; in other words, for the same amount of particle transverse movement, passenger cars can cause higher vertical movements. Note that the y-axis in Figure 9 is only the ratio between vertical movement and transverse movement, and accordingly, any interpretation of particle movement magnitude is not applicable. Comparing the effect of different support
conditions within one loading pattern, one can note that the lack of rail seat support condition always has the lowest movement ratios and highest data variations followed by the full support condition. High center binding always causes the highest particle movement ratios and highest data variations.

CONCLUSIONS
Four common crosstie support conditions for ballasted track were simulated based on the Discrete Element Method (DEM) simulations for four dynamic loading patterns (freight train at 20mph and 50mph, passenger train at 110mph and 150mph) in shared corridors such as Amtrak’s Northeast Corridor. Dynamic behavior trends of ballast layer and crosstie were simulated using DEM models and studied quantitatively using a statistical approach for the combined effects of all the sixteen different scenarios. Boxplots of ballast particle contact forces were presented with different support conditions and at different crosstie wheel loading stages. Hypothesis testing was conducted to quantitatively differentiate crosstie vibration velocity trends under different support conditions and different loading patterns. Individual ballast particle movements were studied using a particle movement ratio, defined as the movement in vertical direction divided by the movement in transverse (horizontal) direction, and compared for all the sixteen cases through comprehensive boxplots. Several conclusions can be made based on the study findings:

- At the initial wheel approaching crosstie loading stage, contact forces are minimal and quite similar for all the four support conditions; at middle and peak loading stages, contact forces have the largest magnitudes and data variations for the lack of center support condition.
- From the middle to peak loading (wheel directly on top of crosstie) stage, contact forces may only have limited increase for the high center binding support condition; whereas, they register large increases for the other three support conditions.
- For the four different support conditions studied, crosstie vibration velocities do not vary in a statistically significant manner. However, for different dynamic loading patterns, crosstie vibration velocities show significant differences. For example, the 20mph and 50mph cases are significantly different for the full support condition than the other three support conditions.
- Under different loading patterns, passenger cars (i.e. 110mph and 150mph cases) result in higher particle movement ratios than those obtained from freight cars (i.e. 20mph and 50mph cases). In general, the high center binding support condition had the highest particle movement ratios while the lack of rail seat support had the lowest ratios.

ACKNOWLEDGEMENTS
The Amtrak Concrete Tie and Track Structure Improvement project undertaken in the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) provided partial support for this research study. The authors thank Huseyin Boler, a graduate student at UIUC, for his help with the DEM simulations and Wei Li, a graduate student at Zhejiang University, for his help with the visualization of results.

REFERENCES

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Figure 8. Ballast particle movement trends under full support condition
Figure 9. Boxplots of particle movement ratio (vertical/transverse) for different support conditions and loading patterns
Field Loading and Tie Support Conditions Influencing Track Substructure – Modeling Ballast Behavior and Statistical Perspective

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Bin Feng¹ – Graduate Research Assistant
Wenting Hou¹ – Graduate Research Assistant
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¹University of Illinois at Urbana-Champaign
²Amtrak
• Amtrak passenger train speeds up to 150 mph
• Heavy Axle Load freight: 36–39 tons per axle
• Can we accommodate the requirements of both, while maintaining high efficiency and performance of each?
Background

- In shared corridors, under repeated train loading, track geometry deterioration is more likely to be encountered over short performance periods.
- Ballast layer may quickly undergo non-uniform settlement leading to excessive vibrations of the track system.
- Previous phase of this research (Hou et al., 2018) shows under severe lack of support condition (i.e., severe center binding) the maximum crosstie-ballast contact force will exceed the AREMA allowable value by over 30% (seat load 20 kips).

Reference: Hou et al. (2018)

Developing non-uniform support
Amtrak Concrete Tie and Track Structure Improvement Study at UIUC

Amtrak NEC NB
MP 75.12, Edgewood, MD
Track speed 125 mph

AREMA ballast pressure based on uniform support assumption

Reference: Gao et al. (2017)
Objective

Statistically evaluate the influence of support conditions and loading patterns

- Tie-ballast interaction
- Tie performance
- Ballast particle performance

Amtrak Concrete Tie and Track Structure Improvement Study at UIUC
Approach

**Discrete Element Method (DEM)**

- Calibrated with previous laboratory testing results
- Concrete tie dimensions: $10\ 3/8 \times 9\ 5/8 \times 102$ in.
- Ballast layer dimensions: 14 in. thick $\times$ 24 in. wide
- Total of $\sim11,000$ ballast particles

Reference: Gao et al. (2017)

Reference: Hou et al. (2018)
Ballast Properties & DEM Model Parameters

- Grain size distribution – meets AREMA No. 3 and No. 4A
- Particle shape – Enhanced UI Aggregate Image analyzer

<table>
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<th>Ballast Gradation / Sieve Size</th>
<th>Percent Passing (%)</th>
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<tbody>
<tr>
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<td>2” 50.8 mm</td>
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</tr>
<tr>
<td>1 ½” 38.1 mm</td>
<td>65</td>
</tr>
<tr>
<td>1” 25.4 mm</td>
<td>10</td>
</tr>
<tr>
<td>½” 12.7 mm</td>
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</tr>
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</table>

Parameters in DEM:
- Normal contact stiffness 20MN/m
- Shear contact stiffness 10MN/m
- Global damping ratio 0.00
- Contact damping ratio 0.40
- Aggregate surface friction angle 31°
### DEM Model Calibration

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<th>Discrete Element Method</th>
<th>Support Condition</th>
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<td><img src="image8.png" alt="Image" /></td>
<td>High Center Binding</td>
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</tbody>
</table>
DEM Model Calibration

Trends and magnitudes of force distributions along tie bottom match reasonably

Reference: Gao et al. (2017)
Shared Corridor Field Loading Patterns

- **Loading frequency** determined by the speed of trains:
  - freight car (1272-kN/286-kip gross rail load): **20 mph, 50 mph**
  - passenger car (636-kN/143-kip gross rail load): **110 mph, 150 mph**

- **Load magnitude** determined using the AREMA force distribution method: 
  \[ F = \frac{P}{2} \times a \times \frac{k}{\sqrt{4EI}} \] 
  by assuming
  - Modulus of track elasticity \( k = 422 \frac{kg}{cm^2} \) (6000 \( \frac{lb}{in^2} \)) for normal concrete crosstie
  - Rail type is 136 RE, moment of inertia \( I = 3970 \, cm^4 \) (95.4 \( in^4 \))
  - Crosstie spacing \( a = 61 \, cm \) (24 \( in \))
  - Modulus of elasticity of steel \( E = 2 \times 10^8 \, kPa \) (3 \( \times 10^7 \, psi \))
Freight Car

Rail Seat Load = 23 kips

Loading Patterns - Passenger Car

Passenger Car Rail Seat Load = 11.5 kips


Passenger 110 mph

Passenger 150 mph
‘Critical Paths’ experience higher contact forces and longer load durations
Results - Ballast Contact Force

Lack of Center Support

‘Critical Paths’ experience higher contact forces and longer load durations
Results - Ballast Contact Force

‘Critical Paths’ experience higher contact forces and longer load durations
Lack of Rail Seat Support

‘Critical Paths’ experience higher contact forces and longer load durations
Results - Ballast Contact Force

- FS - Full Support;
- HCB - High Center Binding;
- LoCS - Lack of Center Support;
- LoRSS - Lack of Rail Seat Support

Reference: Feng et al. (2019)
## Results - Crosstie Vibration Velocity

<table>
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<tr>
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<th>20 mph–freight car</th>
<th>50 mph – freight car</th>
<th>110 mph – passenger car</th>
<th>150 mph – passenger car</th>
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<td><strong>Full Support</strong></td>
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<td><img src="image7" alt="Graph" /></td>
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<tr>
<td><strong>High Center Binding</strong></td>
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</tbody>
</table>
Hypothesis:
- $H_0: \tau_t = 0$
- $H_a: \tau_t \neq 0$

If comparing effect of different loading patterns:
- $\mu$ is the average peak vibration of all four loading patterns
- $\tau$ is the effect of loading patterns, $t \in \{20\text{mph, 50\text{mph, 110\text{mph, 150\text{mph}}\}}$
- $\varepsilon$ is the errors $\sim N(0, \sigma^2)$, $k$ is the sample number

If comparing effect of different support conditions:
- $\mu$ is the average peak vibration of all four support conditions
- $\tau$ is the effect of support conditions, $t \in \{\text{FS, HCB, LoCS, LoRSS}\}$
- $\varepsilon$ is the errors $\sim N(0, \sigma^2)$, $k$ is the sample number

* FS - Full Support; HCB - High Center Binding; LoCS - Lack of Center Support; LoRSS - Lack of Rail Seat Support
## Results - Crosstie Vibration Velocity

<table>
<thead>
<tr>
<th>Support Conditions</th>
<th>p value</th>
<th>Loading Patterns</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20mph_FS</td>
<td>8.710E-02</td>
<td>20mph_FS</td>
<td>2.640E-06</td>
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<tr>
<td>20mph_HCB</td>
<td>7.582E-01</td>
<td>50mph_FS</td>
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<tr>
<td>20mph_LoCS</td>
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<td>110mph_FS</td>
<td>4.160E-01</td>
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<tr>
<td>20mph_LoRSS</td>
<td>2.570E-02</td>
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<td>50mph_FS</td>
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<td>20mph_HCB</td>
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<tr>
<td>50mph_HCB</td>
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<td>50mph_HCB</td>
<td>1.470E-07</td>
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<td>50mph_LoCS</td>
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<td>50mph_LoRSS</td>
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<td>110mph_FS</td>
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<td>150mph_LoRSS</td>
<td>9.520E-02</td>
<td>150mph_LoRSS</td>
<td>1.535E-02</td>
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</tbody>
</table>

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Results - Ballast Particle Movement

20 mph freight car

Reference: Feng et al. (2019)
Results - Ballast Particle Movement

50 mph freight car

Reference: Feng et al. (2019)
Results - Ballast Particle Movement

- Full Support
- Lack of Center Support
- High Center Binding
- Lack of Rail Seat Support

110 mph passenger car

Reference: Feng et al. (2019)
Results - Ballast Particle Movement

Reference: Feng et al. (2019)
Results - Ballast Particle Movement Ratio

<table>
<thead>
<tr>
<th>Support Condition &amp; Loading Pattern</th>
<th>20 mph</th>
<th>50 mph</th>
<th>110 mph</th>
<th>150 mph</th>
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<tbody>
<tr>
<td>FS - Full Support</td>
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</tr>
<tr>
<td>HCB - High Center Binding</td>
<td>HCB</td>
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</tr>
<tr>
<td>LoCS - Lack of Center Support</td>
<td>LoCS</td>
<td>LoCS</td>
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<td>LoCS</td>
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<tr>
<td>LoRSS - Lack of Rail Seat Support</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FS - Full Support;
HCB - High Center Binding;
LoCS - Lack of Center Support;
LoRSS - Lack of Rail Seat Support

Particle Movement Ratio: Vertical/Lateral

HCB lowest lateral movement followed by LoCS...

Reference: Feng et al. (2019)
Conclusions

- In ballasted track, most track settlement is often attributed to ballast layer deformation caused by degradation due to dynamic impact forces and non-uniform support.
- In DEM simulations, one or two connected ballast force networks as critical path(s) were always observed in all tie support conditions during a loading cycle.
- Ballast particles on the critical path experienced higher contact force and longer loading duration, which can eventually lead to earlier particle breakage and faster ballast degradation.
  - contact forces distribution only have limited increase for high center binding support condition.
Conclusions (cont’d)

- Among the different dynamic loading patterns, crosstie vibration velocities show significant differences
  - Freight car loads at 50 mph induced the highest magnitude of crosstie vibration velocities in three support conditions other than the full support condition
- Ballast particles had the largest movements under freight car loads at 20 mph. Higher load magnitudes had a more significant influence than the increased speed.
  - Large ballast particle movements indicate less stability for the ballast layer and may lead to more severe loss of support
Conclusions (cont’d)

- Under different loading patterns, lighter passenger cars result in higher particle movement ratios (vertical/transverse) than those obtained from freight cars
  - More vertical movement of ballast and less pushing to the sides
- High center binding support condition had the highest particle movement ratios (mainly vertical push and less lateral movements)
- Lack of rail seat support had the lowest particle movement ratios (much higher lateral spreading under wheel loading)
Ongoing Research

Simulate ballast layer performance under various mixed traffic conditions:

- freight → passenger → freight → passenger
- passenger → freight → passenger → freight
- ...

[Diagram of trains]
Acknowledgements

- Amtrak Concrete Tie and Track Structure Improvement Study
- Huseyin Boler & Wei Li, graduate students
- Dr. Yu Qian, Assistant Professor, University of South Carolina

Thank you! Questions?