William W. Hay Railroad Engineering Seminar

“Measuring and Modeling Differential Movement at Railroad Track Transitions”

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Date: Friday, January 30, 2015
Time: Seminar Begins 12:20
Location: Newmark Lab, Yeh Center, Room 2311

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[Images of railway and logo]
Measuring and Modeling Differential Movement at Railroad Track Transitions

Timothy D. Stark
Stephen T. Wilk
Jerry G. Rose
Yang Jiang
Congyue Fang
1. Identify problematic factors
2. Develop non-invasive measuring system
3. Evaluate design & repair measures
4. Dynamic numerical modeling
5. Substructure modulus
6. Summary
Identify Problematic Factors

- Open deck
- Wing walls
- Turn
- Fill height
- Soil type
- Fouling
- Poor drainage
- Grade crossing
- Rail joints
- Gaps

Stark et al. (2015)
Tie-Ballast Gap

- Six instrumented Amtrak sites
  - Wheel loads and vertical displacements with depth
- Upland Street
  - Upland (60 ft.) – Open track
  - Upland (15 ft.) – Transition zone

Stark et al. (2015)
Transient Vertical Displacements

**Upland (60 ft.)**
- Same Acela Power Car
- Upland (60 ft.) – good support
- Greater LVDT #1 transient vertical displacement (note different y-axis)
- LDVTs #2 to 5 delayed
- Erratic vertical displacements
- Rail rebound
- Identified tie-ballast gap

**Upland (15 ft.)**
- Upland (15 ft.) – poor support
Good Tie Support

- Loaded freight train, 25 mph

Stark et al. (2015)
Poor Tie Support

Stark et al. (2015)
Tie-Ballast Gap

**Tie-Ballast Gap Model**

- **Tie-ballast gap**
  - 0.25 mm v. 1.4 mm
- **Gap can increase with time**
  - Upland (15 ft.): 1.4 mm (January 2013)
  - Upland (15 ft.): 6.7 mm (July 2014)

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Stark et al. (2015)

[Diagram and graph showing load-displacement behavior]
- Tie-ballast gap
  - <0.5 mm v. ~2.5 mm
- Norfolk Southern:
  - Loaded and unloaded cars
  - Model load-displacement curve

Stark et al. (2015)
Load Redistribution

- Limited knowledge from one tie-ballast gap (Tie 5):
  - Gaps at surrounding ties affect load distribution (numerical modeling)
  - Need gap heights of adjacent ties (accelerometers)
Outline

1. Identify problematic factors
2. Develop non-invasive measuring system
3. Evaluate design & repair measures
4. Dynamic numerical modeling
5. Substructure modulus
6. Summary
Non-Invasive Instrumentation

- Non-invasive instrumentation
  - Accelerometers ➔ Tie accelerations & loads (heartbeat)
  - High-speed video cameras ➔ Rail and tie displacements
- 10 field sites
  - Good and poor support

Stark et al. (2015)
Accelerometers

- Indicators of poor tie support
- Greater tie acceleration
  - 30g v. 5g
  - < 5g is good support
  - $F = m \cdot a$

Stark et al. (2015)
High Speed Video Cameras

- 8 accelerometers & 2 video cameras
- Reoccurring track geometry problems
- **Rail-tie (#2) & Tie-ballast gap (#3)**
  - Rail and tie displacements
  - Tie accelerations
  - Double integration
  - Centerbound tie
  - Effect of air tamping

Stark et al. (2015)
C#2 (14 ft.): Rail-Tie Gap

- Large rail displacement (~0.4 inches; 7 mm)
  - Matches unloaded gap height
- Small tie displacement

Stark et al. (2015)
C#2 (14 ft.): Rail-Tie Gap

- Large rail displacement (≈0.4 inches; 10 mm)
- Some rail rebound (≈-0.1 – 0.2 inches; 3 – 5 mm)
- Small tie displacement

Stark et al. (2015)
C#3 (20 ft.): Rail & Ballast Gap

- Full time history
- Both rail and tie displacement
  - Rail: ~0.2 in (~5 mm)
  - Tie: ~0.25 in (~6 mm)
- Less rail movement than C#2

Stark et al. (2015)
Both rail and tie displacing
Greater tie displacements b/c tie bending
Centerbound tie?
Summarize C#2 (14 ft.) v. C#3 (20 ft.)

- Greater rail displacement near bridge (C#2)
  - Greater substructure settlement - cantilevered

Stark et al. (2015)
Accelerometers

Accel #2 (14 ft.)

Accel #3 (20 ft.)

~10g

~20g

Tank Cars

All responses >5g!

Stark et al. (2015)
Accelerometers v. Video Cameras

- Target and accelerometer on tie
- Camera v. double integration
- Similar vertical displacements

Stark et al. (2015)
• Compare Accel #3 & #4
• Similar tie accelerations (~20g)
  – More wheel flats at #4

Stark et al. (2015)
• 1st axle after tamping at Tie #2 (14 ft.)
  – 0.25” – rail and permanent tie $\Delta V$
Pre- & Post-Tamping – C#2 (14 ft.)

- Pre-tamping v. 6th train after tamping
- Smaller rail-tie gap (0.4” v. 0.3”)
  - Rail cantilevering again
- Similar tie-ballast behavior

Stark et al. (2015)
Two Transitions

66 ft.

Stark et al. (2015)
Effect of Train Direction

- T5 southbound v. T7 northbound
- Train direction large effect on Accel #7 & #8
  - Bouncing from crossing and bridge
  - Not observed at Accel #1 to #6

Accel #8 (51 ft.)

Accel #7 (36 ft.)

Train T5 (Loaded, 40 mph)
Train T7 (Mixed, 52 mph)

Stark et al. (2015)
Future Non-Invasive Work

- Permanent installation
- Environmental and seasonal changes
1. Dip/gap development
2. Develop non-invasive measuring system
3. Evaluate design & repair measures
4. Dynamic numerical modeling
5. Substructure modulus
6. Summary
• Hastings, MN
Transition Zone Scorecard

- Minimize differential transient and permanent displacements

- Questions:
  - Which components need to be addressed?
  - How to address them in most cost-effective manner?

- Measure performance:
  - Accelerometers
  - High-speed video cameras

<table>
<thead>
<tr>
<th>Transition and Bridge Displacement Component</th>
<th>Noticeable Transient</th>
<th>Noticeable Permanent</th>
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<tbody>
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<td>Rail compression</td>
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<td>Rail-tie gap</td>
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<td><strong>Total</strong></td>
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Stark et al. (2015)
Open Bridge Deck

- Timber tie open bridge deck
  - Tie-ballast gaps
  - Ballast, subballast, and subgrade displacement
  - Lateral displacement

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Stark et al. (2015)
Well-Performing Design

- Design attributes
  - Ballasted bridge deck
  - HMA underlayment
  - Consolidated fill
  - Concrete wing walls

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Rail

- Tie 4
- Tie 3
- Tie 2
- Tie 1
- Tie A
- Tie B

Ballast

- HMA layer
- Subballast
- Subgrade

Stark et al. (2015)
1. Dip/gap development
2. Identify problematic factors
3. Develop non-invasive measuring systems
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7. Summary
Gap Model

\begin{verbatim}
LS-DYNA keyword deck by LS-PrePost
Time = 0
\end{verbatim}

Stark et al. (2015)
Open Track – Load Redistribution

Stark et al. (2015)
Magnitude of Tie-Ballast Gap = ?

- Tie-ballast gaps > 1 mm → Increase applied loads

**Field Measurements**

- Tie-ballast gaps > 1 mm → Increase applied loads

**Laboratory Box Tests**

- Tie-ballast gap → Permanent vertical displacements
- Load redistribution – numerical modeling
- Impact loads - accelerometers

(Selig and Waters, 1994)
Bridge Approach Model

Stark et al. (2015)
• Time history v. distance from abutment (decouple front and back wheels)

• Load amplification
  – 30% increase about 10 feet (5 ties) from abutment

• **Tie-ballast gap** load amplification
  – 200% increase of tie-ballast load

Stark et al. (2015)
Outline

1. Dip/gap development
2. Develop non-invasive measuring system
3. Evaluate design & repair measures
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5. Substructure modulus
6. Summary
• **Ballast Seismic Property Analyzer (BSPA)**
  • Measure modulus using seismic waves
    – Impact hammer and accelerometers
    – Raleigh wave velocity ($V_r$)
• Non-invasive, portable
• BSPA orientations
  – Across tie (center)
  – Across tie (ends)
  – Parallel to tie
Substructure Modulus

- Track geometry problems
  - Substructure settlement due to low modulus
- Optimal ballast density
  - Loose ballast state after placement and tamping
  - Relate to modulus
  - Achieve desired modulus
- Subballast/subgrade modulus
- Effect of fouling
### Ballast Modulus – Fouling

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Seismic Testing</th>
<th>Young’s Modulus (ksi)</th>
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<tbody>
<tr>
<td>Dry &amp; Wet Clean Ballast</td>
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<td>30 – 40</td>
</tr>
<tr>
<td><strong>Dry</strong> Fouled Ballast</td>
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<td>50 – 55</td>
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<tr>
<td><strong>Wet</strong> Fouled Ballast</td>
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<td>20 - 25</td>
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- **Upland (60 ft.)**
  - January 2015 (Rain) ~29 ksi
  - June 2015 ~55 ksi
  - 47% reduction

Stark et al. (2015)
Additional Applications

- **Tie integrity**
  - Relate to tie modulus
  - Both concrete and timber ties

Stark et al. (2015)
Summary

• Differential transient and permanent displacements lead to dip
• Account for all displacements in bridge repair & design
• Poor track support
  – Higher tie accelerations (>5g) – Impact loads
  – Higher rail and/or tie displacements
  – Load redistribution
  – Impact loads at bridge approach
• Permanent site
• BSPA
  – Measure field ballast modulus
  – Effect of fouling
  – Tie integrity
1. New or freshly tamped track

2. Loading causes transient vertical displacements and ballast rearrangement.

3. Rail pulls tie up creating tie-ballast gap and other gap(s).
4. Rail can cantilever

5. Increased ballast loads from tie-ballast gap – $F = ma$ & accelerometers

6. TOR developing permanent vertical displacements/“Dip” in transition zone
Acknowledgments

- Federal Rail Administration
  - Hugh Thompson, Ted Sussumann, & Cam Stuart
- Amtrak – Dave Staplin, Steve Chrismer (LTK), and Mike Tomas
- CSX - Ed Sparks and Chris Garrett
- P&L - Tom Garrett and Gerald Gupton
- TTI – Russ Rogers
- UP – Caleb Douglas
- University of Kentucky
  - Drs. Jerry Rose & Reginald Souleyrette
  - Macy Purcell & John Magner
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- University of Illinois at Urbana-Champaign
  - Yang Jiang & Arthur Tseng
  - Congyue Fang
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