Wheel-Rail Force Analysis under Rail Transit Loading Conditions

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Outline

• Project Background
• Estimation of Static Loads
• Field Quantification of Wheel-Rail Loads
  • Light Rail
  • Heavy Rail
  • Commuter Rail
• Summary of Rail Transit Loading Conditions
• Future Research
• Questions and Comments
Background and Problem Statement

• Rail transit systems have unique loading conditions due to the variety of vehicles used from system to system

• Limited research has been conducted to understand the type and **magnitude of loads** in rail transit systems

• Aging rail transit infrastructure assets need to be well maintained or replaced to keep the system in a “state of good repair” – a USDOT Strategic Goal
FTA Project Mission

Charaterize the desired performance and resiliency requirements for concrete crossties and fastening systems, quantify their behavior under load, and develop resilient infrastructure component design solutions for concrete crossties and fastening systems for rail transit operators.
FTA Project Acknowledgements

- Funding for this research has been provided by:
  - Federal Transit Administration (FTA)
  - National University Rail Center (NURail Center)
- Industry partnership and support has been provided by:
  - American Public Transportation Association (APTA)
  - New York City Transit (NYCTA)
  - Metra (Chicago, Ill.)
  - MetroLink (St. Louis, Mo.)
  - TriMet (Portland, Ore.)
  - Pandrol USA
  - Progress Rail Services
  - LBFoster, CXT Concrete Ties
  - GIC Inc.
  - Hanson Professional Services, Inc.
  - Amtrak
- Special thanks to MetroLink, NYCTA, and Union Pacific for providing access to their infrastructure for instrumentation
FTA Project Approach

Paper Study

Industry Surveys

Field Data Collection

Laboratory Experimentation

Finite Element Modelling

Environmental Factors and Special Circumstances

Resilient Concrete Crosstie and Fastening System for Rail Transit
Rail Transit Vehicle Weight Definitions

- **AW0 (Empty Load)**
  - Empty vehicle weight, ready to operate

- **AW1 (Seated Load)**
  - Crew and fully seated passenger load + AW0

- **AW2 (Design Load)**
  - Standing passenger load at 4/m² + AW1

- **AW3 (Crush Load)**
  - Maximum passenger capacity × average passenger weight + AW0

- **AW4 (Structural Design Load)**
  - Standing passenger load at 8/m² + AW1
Wheel-Rail Interface Load Quantification

Rail Transit Vehicle Weight Quantification

- AW0 and AW3 weights were calculated for rail transit vehicles operating within the United States as of August 2015
  - National Transit Database (NTD) Revenue Vehicle Inventory
  - Vehicle datasheets
- Data obtained and analyzed for:
  - 100% of light rail vehicles (2,072 of 2,072)
  - 85% of heavy rail vehicles (9,781 of 11,474)
  - 72% of commuter railcars (4,353 of 6,047)
  - 91% of commuter locomotives (674 of 738)
- 195 lbs. (88.5 kg) per person was used as average passenger weight for AW3 calculations based on multiple sources, including Federal Aviation Administration (FAA) standards
- Data tabulated and balloted for inclusion in the AREMA Manual for Railway Engineering (2018 Version)
Wheel-Rail Interface Load Quantification

Light Rail, Heavy Rail, and Commuter Rail Vehicle Wheel Load Distribution

Wheel Load (kN)

Percent Exceeding

Wheel Load (kips)

- Light Rail AW0
- Light Rail AW3
- Heavy Rail AW0
- Heavy Rail AW3
- Commuter Railcar AW0
- Commuter Railcar AW3
- Commuter Rail Locomotive AW0

*Data as of August 2015
Wheel-Rail Interface Load Quantification

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Resilient Concrete Crosstie and Fastening System for Rail Transit
Typical Field Instrumentation Map

- Metrics to quantify:
  - Crosstie bending strain (crosstie moment design)
  - Rail displacements (fastening system design)
  - **Vertical and lateral input loads** (crosstie and fastening system design, and load environment characterization)
  - Crosstie temperature gradient

**Crosstie Bending Strain**

**Vertical and Lateral Load (Wheel Loads)**

**Rail Displacement (Base Vertical, Base Lateral)**

**Thermocouple**

**Rail Displacement (Base Vertical)**

**Laser Trigger**

(Ambient Temperature)
Instrumentation Overview

**Vertical** and Lateral Wheel Loads

- **Desired data:**
  - Vertical and lateral loads at the wheel-rail interface and rail seat

- **Instrumentation description and methodology:**
  - Industry standard strain gauge bridges applied to rail web and flange, similar to a wheel impact load detector (WILD) site
  - Based on previous UIUC field instrumentation, one instrumented crib per rail to approximate wheel loads throughout whole test section
Partner Agencies

- Metra
- MTA New York City Transit
- RAILTEC

(Two Sites; Curve & Tangent)
Light Rail Tangent Data

Trains in Dataset: 2,245
From 18 March 2016
to 26 April 2016

(Tangent Location)
MetroLink Tangent Location

- East St. Louis, IL
- Track speed: 55 MPH
- ~154 trains/day (Red & Blue lines)
- 0.9 miles west of Fairview Heights Station

MetroLink Tangent Location Map:
- Washington Park Station: 2 miles
- Fairview Heights Station: 0.9 miles
- St. Clair Avenue (IL-161)
- IL-157
- [Google Earth]
Vertical Rail Loads
St. Louis MetroLink (Tangent)
Vertical Rail Loads
St. Louis MetroLink (Tangent)
Box Plot Background

- Box plots are great to:
  - Visualize outliers
  - Compare variability of different cases
  - Check for symmetry
  - Check for normality
- 50% of Data are within the box

**Box Plot Diagram**

- **Median**
- **IQR**
- **Q1 (25th Percentile)**
- **Q3 (75th Percentile)**
- **Upper inner fence (Q3+1.5×IQR)**
- **Lower inner fence (Q1-1.5×IQR)**
- **Max (within fences)**
- **Min (within fences)**
- **Outliers**

**Bar Chart**

- **Bending Moment**
- **Percentage**
Vertical Wheel Loads
St. Louis MetroLink (Tangent)

- **Static Load Near Rail**
- **Static Load Far Rail**
- **Dynamic Load Near Rail**
- **Dynamic Load Far Rail**

Graph showing vertical load in kips against axle number.
Vertical Wheel Loads
St. Louis MetroLink (Tangent)
Vertical Wheel Loads
St. Louis MetroLink (Tangent)
Comparative Data
Modal Comparison: Vertical Wheel Loads

- Commuter Rail
- Heavy Rail
- Light Rail
- Commuter Locomotive
## Vertical Load Percentiles for Each Mode

<table>
<thead>
<tr>
<th>Percentile Vertical Load</th>
<th>Light Rail (Tangent) kips (kN)</th>
<th>Heavy Rail (Curve) kips (kN)</th>
<th>Commuter Rail (Tangent) kips (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>2.7 (12.2)</td>
<td>6.4 (28.5)</td>
<td>11.2 (49.9)</td>
</tr>
<tr>
<td>50%</td>
<td>8.1 (36.0)</td>
<td>13.8 (61.4)</td>
<td>15.8 (70.1)</td>
</tr>
<tr>
<td>90%</td>
<td>9.4 (42.0)</td>
<td>16.4 (72.9)</td>
<td>18.3 (81.3)</td>
</tr>
<tr>
<td>95%</td>
<td>9.8 (43.8)</td>
<td>17.5 (77.8)</td>
<td>32.6 (145.2)</td>
</tr>
<tr>
<td>99%</td>
<td>10.7 (47.5)</td>
<td>21.1 (93.8)</td>
<td>37.1 (165.0)</td>
</tr>
<tr>
<td>Maximum</td>
<td>18.6 (82.6)</td>
<td>59.3 (263.9)</td>
<td>44.9 (199.7)</td>
</tr>
</tbody>
</table>

| Sample Size (Wheel Passes) | 53,880 | 143,680 | 372 |
| Max. AW0                  | 9.59 (42.6) | 11.4 (50.6) | 18.7 (83.5) |
| Max. AW3                  | 12.5 (55.5) | 16.6 (74.0) | 23.1 (103.0) |
### Impact Factor Percentiles for Each Mode

<table>
<thead>
<tr>
<th>Percentile Impact Factor</th>
<th>Light Rail (Curve)</th>
<th>Light Rail (Tangent)</th>
<th>Heavy Rail (Curve)</th>
<th>Commuter Rail (Tangent, Coaches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.47 – 0.91</td>
<td>0.22 - 0.42</td>
<td>0.39 - 0.56</td>
<td>0.49 - 0.88</td>
</tr>
<tr>
<td>50%</td>
<td>0.70 – 1.35</td>
<td>0.65 - 1.25</td>
<td>0.83 - 1.21</td>
<td>0.68 - 1.23</td>
</tr>
<tr>
<td>90%</td>
<td>0.90 – 1.72</td>
<td>0.76 - 1.46</td>
<td>0.99 - 1.44</td>
<td>0.73 - 1.33</td>
</tr>
<tr>
<td>95%</td>
<td>0.94 – 1.82</td>
<td>0.79 - 1.52</td>
<td>1.05 - 1.54</td>
<td>0.76 - 1.37</td>
</tr>
<tr>
<td>99%</td>
<td>1.02 – 1.97</td>
<td>0.86 - 1.65</td>
<td>1.27 - 1.85</td>
<td>0.79 - 1.44</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.14 – 2.19</td>
<td>1.49 - 2.86</td>
<td>3.57 - 5.21</td>
<td>0.96 - 1.74</td>
</tr>
</tbody>
</table>

**Impact Factor** = \( \frac{\text{Dynamic Load}}{\text{Static Load}} \)

*Static load is bounded by Min. AW0 and Max. AW3*
Impact Factor Comparison

- MetroLink Curve Low Estimate
- MetroLink Tangent Low Estimate
- NYCTA Curve Low Estimate
- Metra Tangent Coaches Low Estimate
- MetroLink Curve High Estimate
- MetroLink Tangent High Estimate
- NYCTA Curve High Estimate
- Metra Tangent Coaches High Estimate
- AREMA Recommended Impact Factor

Percent Exceeding

Impact Factor
Impact Factor Comparison Chart

- MetroLink Curve Low Estimate
- MetroLink Tangent Low Estimate
- NYCTA Curve Low Estimate
- Metra Tangent Coaches Low Estimate
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Impact Factor
Impact Factor Comparison Chart

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- MetroLink Tangent High Estimate
- NYCTA Curve High Estimate
- Metra Tangent Coaches High Estimate
- AREMA Recommended Impact Factor

0.046%
Modal Comparison: Lateral Loads Curve Locations

Graph showing the percent exceeding of lateral loads for Heavy Rail and Light Rail. The x-axis represents the lateral load in kN (kilonewtons) and kips, while the y-axis represents the percent exceeding.
Modal Comparison: L/V Ratios

Curve Locations

Percent Exceeding

L/V Ratio

Heavy Rail

Light Rail

(-) (+)
Center Negative Bending Comparison

Bending Moment (kNm)

Percent Exceeding

0% 20% 40% 60% 80% 100%

Bending Moment (kip-inches)

- Light Rail (St. Louis MetroLink)
- Heavy Rail (NYCTA)
- MetroLink Specification
- NYCTA Specification
- CXT 100 Design Capacity
- CXT 495-20 D
Center Negative Bending Comparison

Bending Moment (kNm)

Percent Exceeding

Bending Moment (kip-inches)

- Light Rail (St. Louis MetroLink)
- Heavy Rail (NYCTA)
- MetroLink Specification
- NYCTA Specification
- CXT 100 Design Capacity
- CXT 495-20 Design Capacity
Vertical Rail Load Data Conclusions

• Instrumentation was deployed and has successfully captured wheel-rail loading data from 3 rail transit modes at 4 field sites

• Impact Factors differ between modes; for example, between heavy and light rail the impact factor is:
  – 2.7 times greater at maximum load for heavy rail
  – 1.7 times greater at 99th percentile load for heavy rail

• The currently-accepted impact factor of 3 (e.g. 200% per AREMA) should be re-considered on a modal basis, and possibly on a system-by-system basis
Future Research & Path Forward

• Analyze extreme cases to understand better the environment leading to high wheel loads
  – Compare to other metrics (e.g. tie bending moments)
• Study the influence of speed on vertical & lateral loads
• Use field data to evaluate the effectiveness of dynamic factor models and rail seat load models for light, heavy, and commuter rail systems
• Perform analysis of seasonal variation
• *Further investigation of maintenance-of-way equipment loading conditions and their influence on design*
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