Load Quantification for Light Rail, Heavy Rail, and Commuter Rail Transit Infrastructure

FRA and FTA Crosstie and Fastening System Research Program
Industry Partners (IP) Meeting
Tucson, AZ
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Xiao (Sean) Lin, Riley Edwards, Marcus Dersch, and Conrad Ruppert Jr.

Outline

• Background and Problem Statement
• Purpose and Scope of Work
• Rail Transit Vehicle, Infrastructure, and System Characteristics
• Accomplished Work
  – Rail Transit Vehicle Weight and Wheel Load
  – Rail Transit Vehicle Dynamic Factors
  – Rail Transit Vehicle Impact Factor
  – Survey of Rail Transit Track Superstructure Design and Performance
• Future Work
Background and Problem Statement

- Rail transit systems have unique loading conditions
- Limited research has been conducted to understand the type and magnitude of loads in rail transit systems
- Transit design standards need to be updated to account for current loading conditions
- Aging rail transit infrastructure assets need to be well maintained or replaced to maintain the system in a “state of good repair”

Purpose and Scope of Work

- Quantify current rail transit loading environment
- Characterize the desired requirements for concrete crosstie and fastening systems
- Characterize the critical factors affecting the performance of concrete crossties and fastening systems in transit environment
- Develop more effective design practices for systems in use on light rail, heavy rail, and commuter rail in the US
- Improve safety, performance, and life cycle of track components and increase the effectiveness of transit agencies’ capital spending
**Rail Transit Vehicle, Infrastructure, and System Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Light Rail</th>
<th>Heavy Rail</th>
<th>Commuter Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (prs/h)</td>
<td>6,000 – 20,000</td>
<td>10,000 – 60,000</td>
<td>8,000 – 45,000</td>
</tr>
<tr>
<td>Exclusive ROW</td>
<td>40% – 90%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Power Supply</td>
<td>Overhead/diesel</td>
<td>Third rail/overhead</td>
<td>Overhead/third rail/diesel</td>
</tr>
<tr>
<td>Area coverage</td>
<td>Central business district</td>
<td>Mostly central business district</td>
<td>Limited CBD, mostly suburban coverage</td>
</tr>
<tr>
<td>Station Spacing</td>
<td>0.25 – 1 miles</td>
<td>0.5 – 2 miles</td>
<td>2 – 5 miles</td>
</tr>
<tr>
<td>Frequency</td>
<td>5 – 20 minutes</td>
<td>5 – 20 minutes</td>
<td>0.5 – 3 hours</td>
</tr>
<tr>
<td>Speed</td>
<td>20 – 55 mph</td>
<td>50 – 80 mph</td>
<td>30 – 125 mph</td>
</tr>
</tbody>
</table>

**Example**

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**Rail Transit Vehicle Weight Definitions**

- **AW0**: Empty vehicle operating weight
- **AW1** (Seated Load)
  - Fully seated passenger load + AW0
- **AW2** (Design Load)
  - Standing passenger load at 4/m² + AW1
- **AW3** (Crush Load)
  - Standing passenger load at 6/m² + AW1
- **AW4** (Structural Design Load)
  - Standing passenger load at 8/m² + AW1
Rail Transit Vehicle Weight Definitions

- AW0: Empty vehicle operating weight
- AW1 (Seated Load)
  - Fully seated passenger load + AW0
- AW2 (Design Load)
  - Standing passenger load at 4/m² + AW1
- AW3 = Maximum Passenger Capacity × Average Passenger Weight + AW0
- AW4 (Structural Design Load)
  - Standing passenger load at 8/m² + AW1

Rail Transit Vehicle Weight Definitions

- Rail Transit Vehicle Capacity
  - National Transit Database (NTD) Revenue Vehicle Inventory
    - Seating and standing capacity
    - Number of active vehicles
    - Manufacturer, manufacture year, and model number

NTD
National Transit Database
Federal Transit Administration
Rail Transit Vehicle Weight Definitions

• Average Passenger Weight
  – 155 lbs per passenger is currently used in the Light Rail Design Handbook*
  – Smith and Schroeder (2013) took quantitative and statistical approach to the best way to account for the growth in rider size and weight over the last 30-40 years

\[ \text{Total Car Weight} = 199 \text{ lbs} \times \text{Seat Cap.} + 106 \text{ lbs} \times \text{ft}^2 \text{ stand space} + \text{Car Weight} \]

  – 195 lbs is used as average passenger weight to simplify calculation


Rail Transit Vehicle Weight

• Empty car weight data were collected for transit systems
  – 2,072 out of 2,072 light rail vehicles (100%)
  – 9,781 out of 11,474 heavy rail vehicles (85%)
  – 4,353 out of 6,047 commuter railcars (72%)
  – 674 out of 738 commuter locomotives (91%)

<table>
<thead>
<tr>
<th>Vehicle Dimensions and Weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over couplers</td>
<td>81.4 ft</td>
</tr>
<tr>
<td>Width</td>
<td>8.7 ft</td>
</tr>
<tr>
<td>Weight with passenger (floor)</td>
<td>32.8 lbs</td>
</tr>
<tr>
<td>Minimum passenger height</td>
<td>54.6 in</td>
</tr>
<tr>
<td>Empty vehicle weight</td>
<td>89,500 lbs (AW0)</td>
</tr>
</tbody>
</table>
**Light Rail, Heavy Rail, and Commuter Rail Vehicle Weight Distribution**

The graph shows the weight distribution for different types of rail vehicles:
- **Light Rail AW0**
- **Light Rail AW3**
- **Heavy Rail AW0**
- **Heavy Rail AW3**
- **Commuter Railcar AW0**
- **Commuter Railcar AW3**
- **Commuter Locomotive AW0**

**Light Rail Wheel Load Distribution**

The data represents 2,070 out of total 2,070 light rail vehicles.
**Heavy Rail Wheel Load Distribution**

Data represents 9,781 out of total 11,474 heavy rail vehicles.

**Commuter Railcar Wheel Load Distribution**

Data represents 4,353 out of total 6,047 commuter railcars.
Commuter Locomotive Wheel Load Distribution

Data represents 674 out of total 738 commuter locomotives.

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

Percent Exceeding Wheel Load (kips)

- Light Rail AW0
- Heavy Rail AW0
- Commuter Railcar AW0
- Commuter Rail Locomotive AW0
- Light Rail AW3
- Heavy Rail AW3
- Commuter Railcar AW3
Light Rail, Heavy Rail, and Commuter Rail Vehicle Wheel Load Distribution

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Imperial Units</th>
<th>Metric Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AW0 Wheel Load (kips)</td>
<td>AW3 Wheel Load (kips)</td>
</tr>
<tr>
<td>Light Rail</td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>4.8</td>
<td>9.1</td>
<td>7.9</td>
</tr>
<tr>
<td>Heavy Rail</td>
<td>6.8</td>
<td>11.6</td>
</tr>
<tr>
<td>Commuter Railcar</td>
<td>10.6</td>
<td>20.4</td>
</tr>
<tr>
<td>Commuter Rail Locomotive</td>
<td>25.0</td>
<td>37.2</td>
</tr>
</tbody>
</table>

Methods for Estimating Rail Transit Vehicle Dynamic Loads

<table>
<thead>
<tr>
<th>Dynamic Factor</th>
<th>Vehicle Parameters Included</th>
<th>Track Parameters Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Speed</td>
<td>Wheel Diameter</td>
<td>Stiffness at Rail Joint</td>
</tr>
<tr>
<td>Static Wheel Load</td>
<td>Unsprung Mass</td>
<td>Track Joint Dip Angle</td>
</tr>
<tr>
<td>Unloaded Load</td>
<td>Vehicle Center of Gravity</td>
<td>Centrifugal Stiffness in Curves</td>
</tr>
<tr>
<td>Loaded Load</td>
<td>Locomotive Motion Condition</td>
<td>Track Modulus</td>
</tr>
<tr>
<td></td>
<td>Track Stiffness of Locomotive</td>
<td>Track Maintenance Condition</td>
</tr>
</tbody>
</table>
Rail Transit Vehicle Dynamic Factors

- **Speed (km/h)**
- Dynamic Factor, \( \Phi \)
- Typical Light Rail Operating Speed
- Typical Heavy Rail Operating Speed
- Typical Commuter Rail Operating Speed

**Graphs:**
- Various railway types and operating speeds, including Talbot, Indian Railway, Clarke, and others, shown across different speeds in 
  - km/h and mph.

**Data Points:**
- Dynamic Factors for different speeds, illustrating the impact on rail transit infrastructure.
Evaluative Metric: Mean Signed Difference

- Summarizes how well an estimator matches the quantity that it is supposed to estimate

\[ \sum_{i=1}^{n} \frac{f(x_i) - y_i}{n} \]

- Additional “signed difference” metrics were developed, with weight given each for vehicle speed and nominal wheel load

<table>
<thead>
<tr>
<th>Evaluation Metric</th>
<th>Dynamic Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Exceeding</td>
<td>Talbot</td>
</tr>
<tr>
<td></td>
<td>7%</td>
</tr>
<tr>
<td>Mean Signed Difference</td>
<td>0.47</td>
</tr>
<tr>
<td>Mean Percentage Error</td>
<td>35.6</td>
</tr>
<tr>
<td>Root Mean Square Deviation</td>
<td>0.30</td>
</tr>
<tr>
<td>Speed-Weighted Signed Difference</td>
<td>0.48</td>
</tr>
<tr>
<td>Load-Weighted Signed Difference</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Dynamic Factor Evaluation Thoughts

- The Talbot dynamic factor was generally more conservative when compared to actual loading data.
- The WMATA dynamic factor becomes conservative when evaluated using the speed-weighted signed difference (factor increases exponentially with speed).
- Using several evaluative metrics, the Eisenmann dynamic factor generally estimated the actual loading data well.
- Multiple evaluative metrics can be used to evaluate and compare dynamic factors in determining which may be appropriate for design.

Rail Transit Vehicle Impact Factor

- Impact factor is defined as a percentage increase over static vertical loads intended to estimate the dynamic effect of wheel and rail irregularities.
- AREMA specifies an impact factor of 200%, which indicates the design load is three times the static load, equivalent to an impact load factor of three.
- The same impact factor of three applies to both freight railroads and rail transit systems.
Peak Load vs. Nominal Wheel Load for Commuter Rail Vehicles

**Nominal Wheel Load (kN)**

- Peak Load
- Impact Factor (IF)

**Peak Wheel Load (kips)**

- Peak Load = Static Load

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Peak Load vs. Nominal Wheel Load for Commuter Railcars

**Nominal Wheel Load (kN)**

- Peak Load
- Impact Factor (IF)

**Peak Wheel Load (kips)**

- Peak Load = Static Load

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Slide 27

Peak Load vs. Nominal Wheel Load for Commuter Locomotives

Slide 28

Survey of Rail Transit Track Superstructure Design and Performance

- Develop an understanding of the current state-of-practice regarding the design and performance of concrete crosstie and fastening system in rail transit systems
- Characterize the critical factors affecting the performance of concrete crossties and fastening systems in transit environment
- Assess the resilience of rail transit infrastructure to natural disasters and identify the most vulnerable components
- Provide information needed to guide many aspects of the FTA project including finite element modeling, laboratory instrumentation, and field testing
Survey of Rail Transit Track Superstructure Design and Performance

• Responses were received from Metro St. Louis, MTA New York City Transit, TriMet, Regional Transportation District, Utah Transit Authority, and Chicago Transit Authority

• Focused surveys aimed at concrete crosstie and fastening system manufacturers

Future Work

• Further expand the understanding of vehicle and infrastructure characteristics for rail transit systems

• Incorporate field data to evaluate the effectiveness of dynamic factor models and rail seat load models for light rail and heavy rail systems

• Collect survey responses from rail transit industry, as well as focused surveys aimed at concrete crosstie and fastening system manufacturers
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  - TriMet (Portland, Ore.)
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  - GIC Inc.
  - Hanson Professional Services, Inc.
  - Amtrak

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Appendix
Light Rail Vehicle Weight Distribution

Data represents 2,070 out of total 2,070 light rail vehicles

Heavy Rail Vehicle Weight Distribution

Data represents 9,781 out of total 11,474 heavy rail vehicles
Commuter Railcar Weight Distribution

Data represents 4,353 out of total 6,047 commuter railcars

Commuter Locomotive Weight Distribution

Data represents 674 out of total 738 commuter locomotives
Dynamic Factor Equations and Listing of Input Parameters

<table>
<thead>
<tr>
<th>Dynamic Factor</th>
<th>Expression for φ</th>
<th>Vehicle Parameters Included</th>
<th>Track Parameters Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talbot (Hay 1955)</td>
<td>$1 + \frac{33V}{10D}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Indian Railways (Srinivasan 1969)</td>
<td>$1 + \frac{V}{\sqrt{D\mu}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Eisenmann (Esveld 2001)</td>
<td>$1 + 0.5\mu$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>ORE/Binnunm (Binnunm 1965)</td>
<td>$1 + \alpha + \beta + \gamma$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>German Railways (Schramm 1961)</td>
<td>$1 + \frac{11.65V^2 - 6.252V^2}{10^2}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>British Railways (Doyle 1980)</td>
<td>$1 + 14.136(\alpha_1 + \alpha_2)V\sqrt{\frac{P_a}{g}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>South African Railways (Doyle 1980)</td>
<td>$1 + 0.312\frac{V}{D}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Clarke (Doyle 1980)</td>
<td>$1 + 15V \delta$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>WMATA (Prance et al. 1974)</td>
<td>$(1 + 0.0001V^2)^{\frac{3}{2}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Sadeghi (Sadeghi &amp; Barati 2010)</td>
<td>$1.098 + 0.00129V + 2.59(10^{-4})V^2$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>AREMA C30</td>
<td>For $20 &lt; V &lt; 120; 0.6 + 0.005V$</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

Definitions of Dynamic Factor Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Train speed (mph)</td>
</tr>
<tr>
<td>D</td>
<td>Wheel diameter (in)</td>
</tr>
<tr>
<td>U</td>
<td>Track modulus (psi)</td>
</tr>
<tr>
<td>δ</td>
<td>0.1, 0.2, 0.3, depending on track conditions</td>
</tr>
</tbody>
</table>
| η        | 1 for vehicle speeds up to 37 mph  
            $1 + \frac{V-37}{87}$ for vehicle speeds between 37 and 125 mph |
| t        | 0, 1, 2, 3, depending on chosen upper confidence limits defining probability of exceedance |
| α        | Coefficient dependent on level of track, vehicle suspension, and vehicle speed, estimated to be $0.167\left(\frac{V}{100}\right)^3$ in most unfavorable case |
| β        | Coefficient dependent on wheel load shift in curves (0 in tangent track) |
| γ        | Coefficient dependent on vehicle speed, track age, possibility of hanging crossties, vehicle design, and locomotive maintenance conditions, estimated to be $0.10 + 0.071\left(\frac{V}{100}\right)^3$ in most unfavorable case |
| $\alpha_1 + \alpha_2$ | Total rail joint dip angle (radians) |
| $D_j$    | Track stiffness at the joints (kN/mm) |
| $P_u$    | Unsprung weight at one wheel (kN) |
| g        | Acceleration due to gravity (m/s²) |
### Definitions of dynamic factor evaluative metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent exceeding</td>
<td>Percentage of wheels exceeding predicted dynamic factor</td>
</tr>
<tr>
<td>Mean percentage error</td>
<td>Computed average of percentage errors by which predictions differ from actual values of the quantity being predicted</td>
</tr>
<tr>
<td>Root mean square deviation</td>
<td>Measures differences between values predicted by estimator and actual recorded values (absolute value)</td>
</tr>
<tr>
<td>Mean signed difference</td>
<td>Summarizes how well an estimator matches the quantity that it is supposed to estimate</td>
</tr>
<tr>
<td>Speed weighted signed difference</td>
<td>Signed difference, with weight given for the speed of the wheel</td>
</tr>
<tr>
<td>Load weighted signed difference</td>
<td>Signed difference, with weight given for the nominal load wheel</td>
</tr>
</tbody>
</table>