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

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U.S. Department of Transportation
Federal Transit Administration

RAILTEC
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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

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

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 $4/m^2$ + AW1
- AW3 (Crush Load)
  - Standing passenger load at $6/m^2$ + AW1
- AW4 (Structural Design Load)
  - Standing passenger load at $8/m^2$ + 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 $4/m^2$ + AW1
- **AW3 = Maximum Passenger Capacity × Average Passenger Weight + AW0**
- AW4 (Structural Design Load)
  - Standing passenger load at $8/m^2$ + 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

$$Total\ Car\ Weight = 199\ lbs \times Seat\ Cap. + 106\ lbs \times ft^2\ stand\ space + Car\ Weight$$

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

*Parsons Brinckerhoff, Inc. 2012. Track Design Handbook for Light Rail Transit, TCRP Report 155. Transit Research Board, Washington, DC

Rail Transit Vehicle Weight

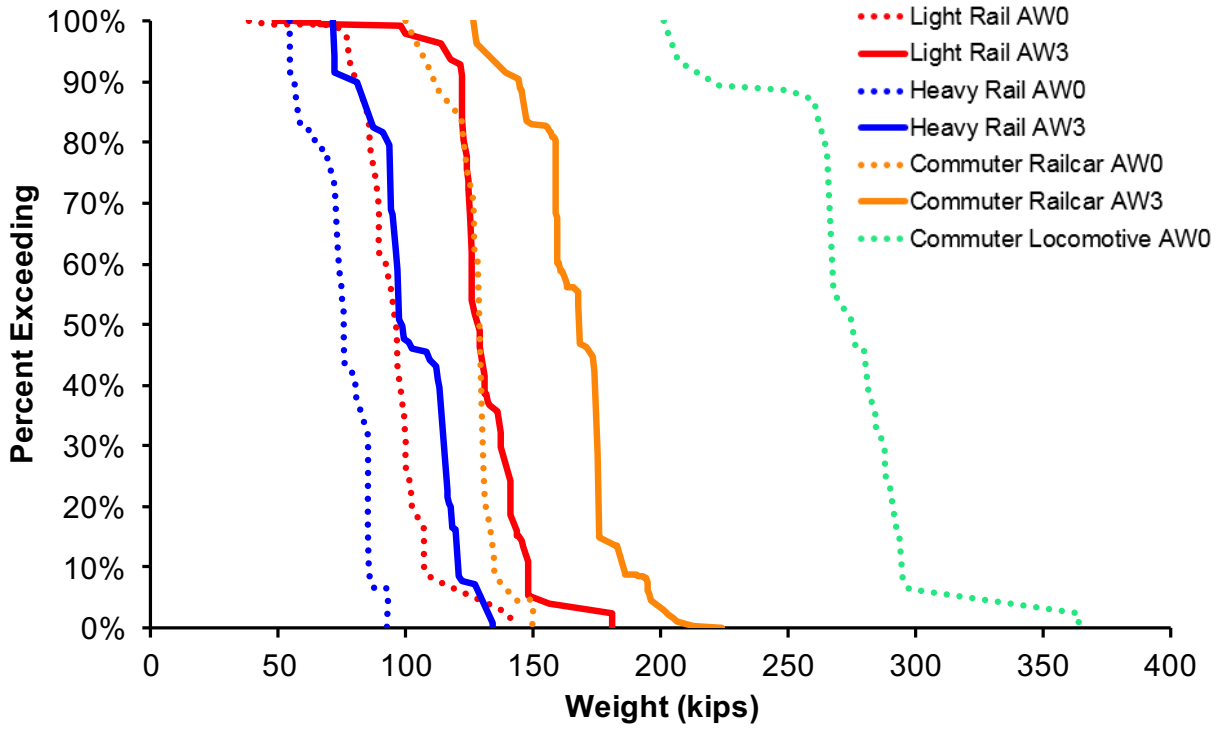
- Empty car weight data were collected for transit systems
  - 2,072 out of 2,072 light rail vehicles (100%)
  - 9,781 out of 11,474 heavy rail vehicles (85%)
  - 4,353 out of 6,047 commuter railcars (72%)
  - 674 out of 738 commuter locomotives (91%)

Vehicle Dimensions and Weight

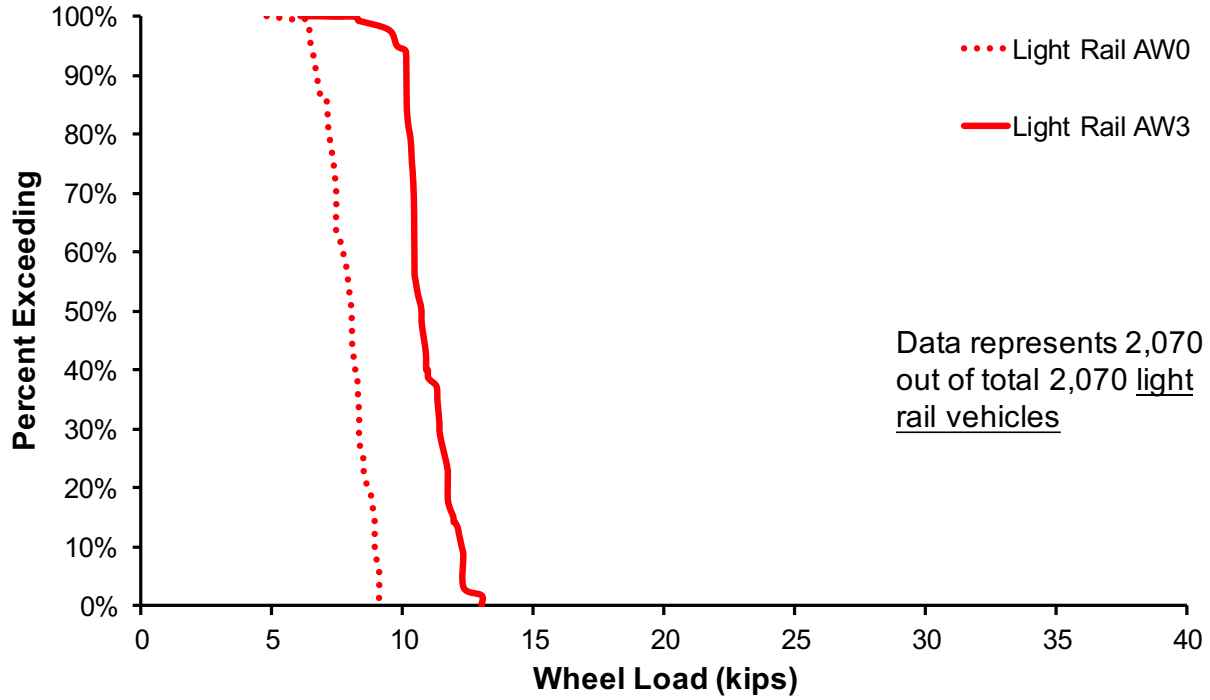
Length over couplers	81.4 ft	24820 mm
Width	8.7 ft	2654 mm
Height with pantograph (locked down)	12.4 ft	3786 mm
Maximum pantograph height	up to 23 ft	7010 mm
Vehicle empty weight	89500 lbs (AW0)	40600 kg
High-floor section above TOR	3.2 ft	985 mm
Low-floor section above TOR	n/a	n/a
Minimum turning radius	82 ft	25 m
Vertic		
Vertic		
Track		
Wheel		

Vehicle empty weight 89500 lbs (AW0) 40600 kg

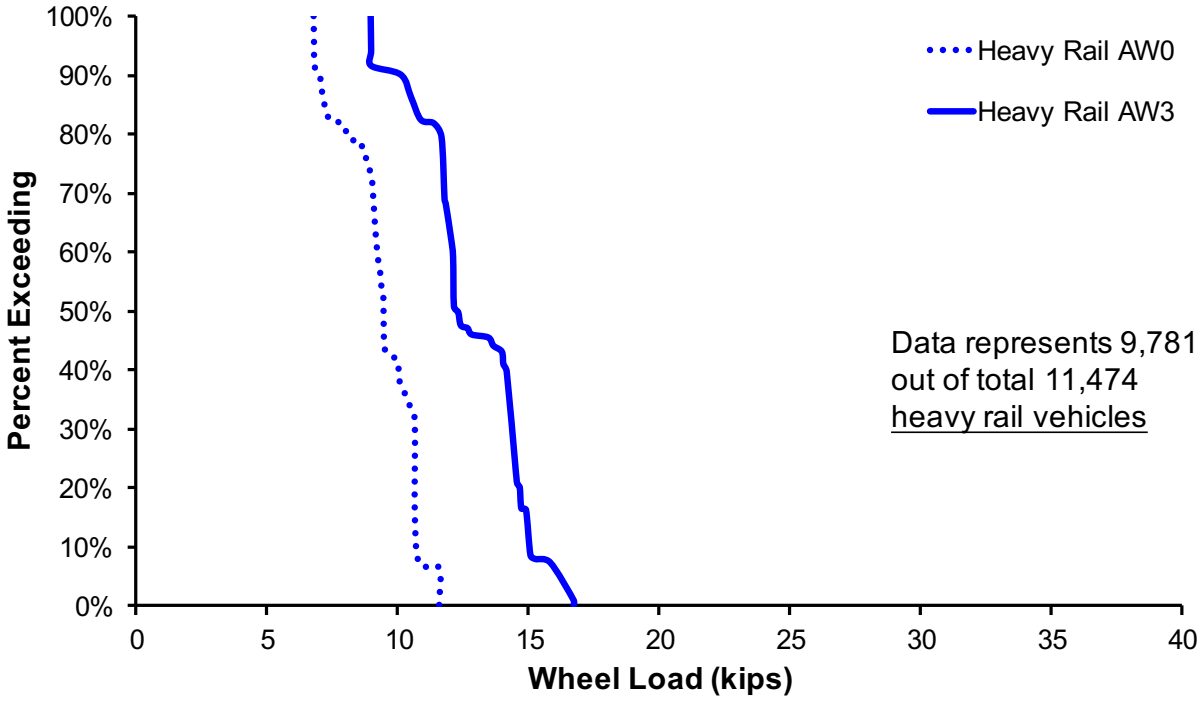
Light Rail, Heavy Rail, and Commuter Rail Vehicle Weight Distribution



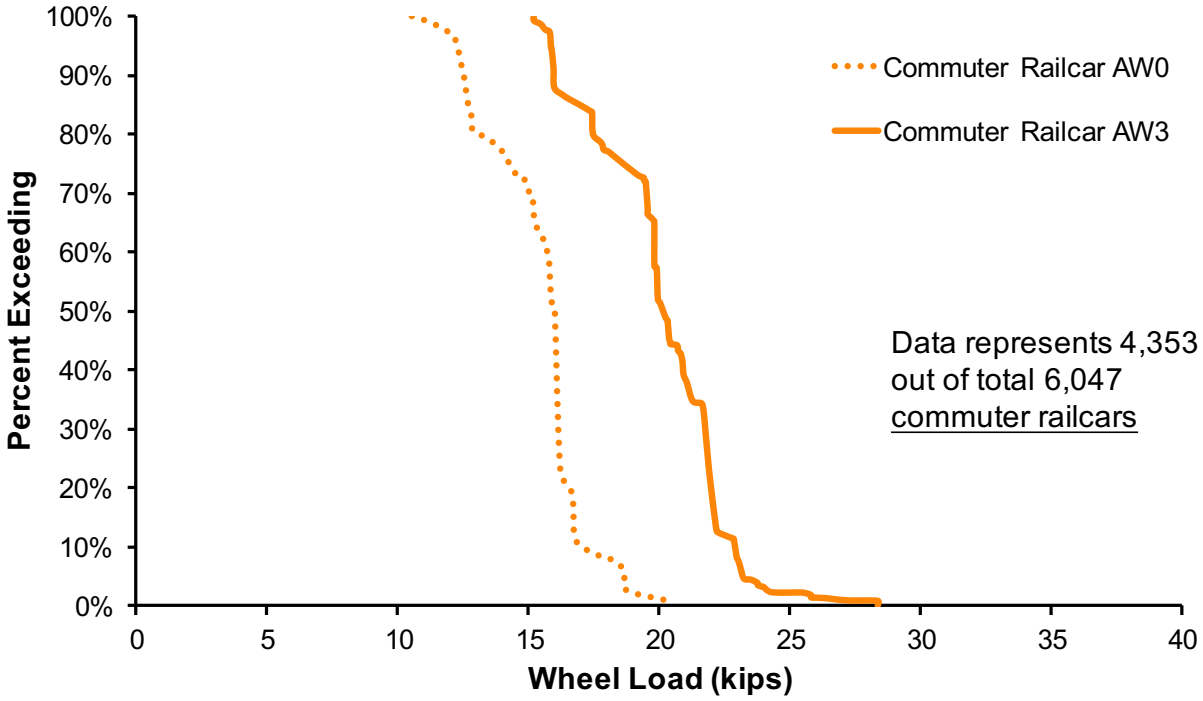
Light Rail Wheel Load Distribution



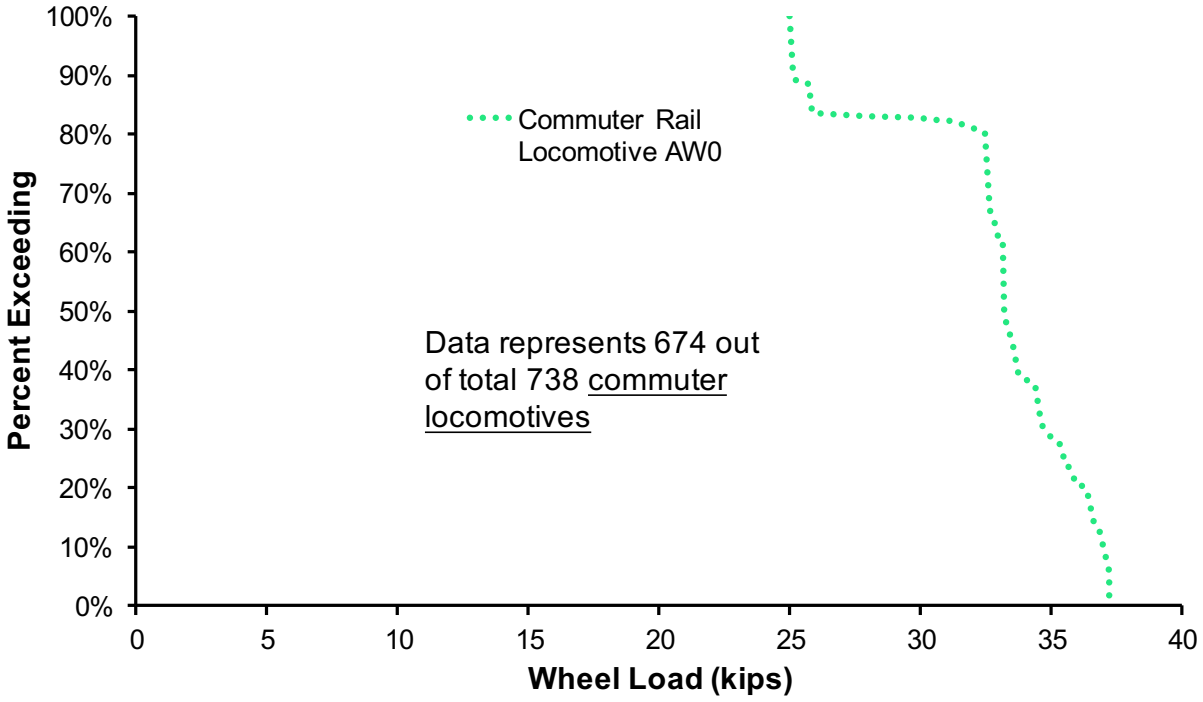
Heavy Rail Wheel Load Distribution



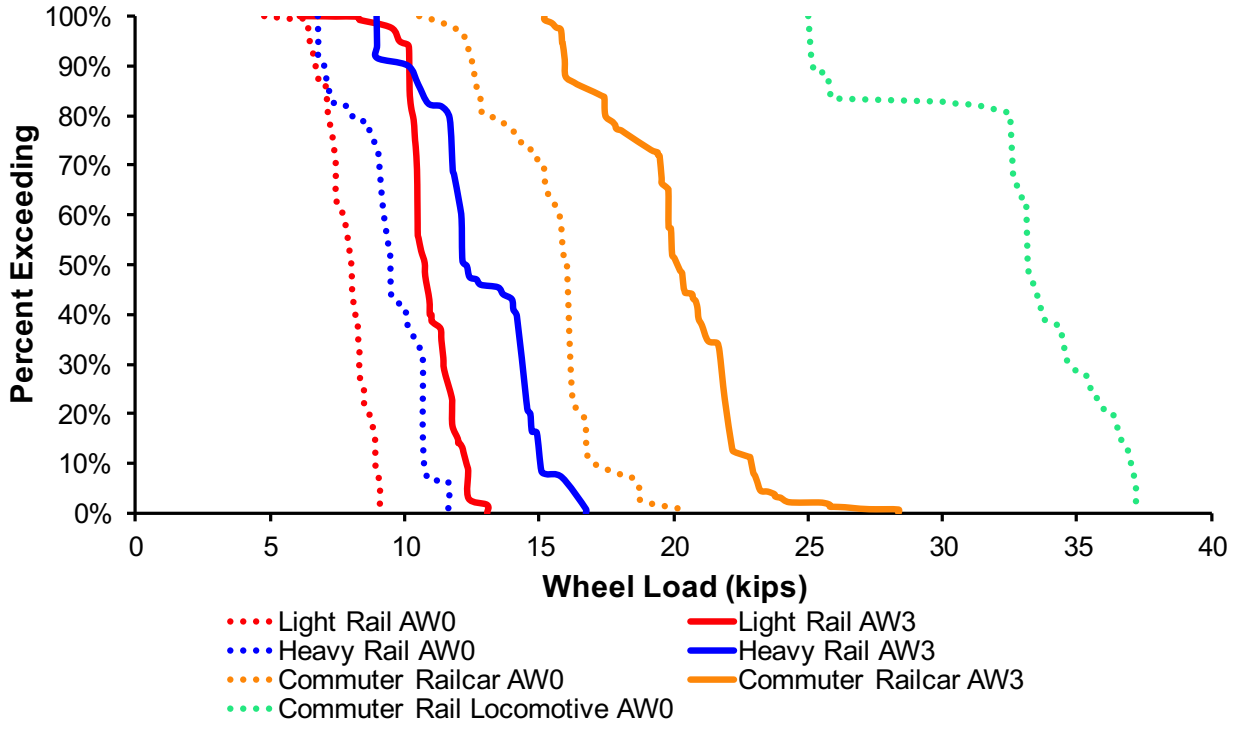
Commuter Railcar Wheel Load Distribution



Commuter Locomotive Wheel Load Distribution



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



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

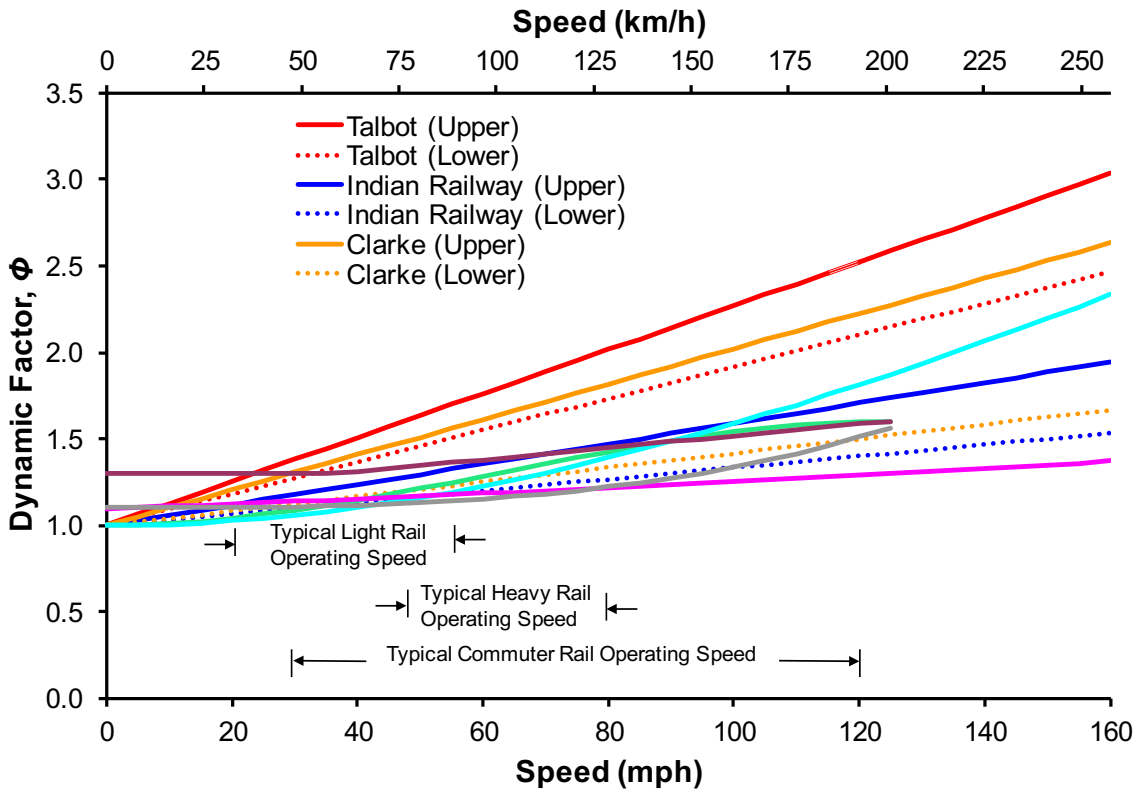
Imperial Units						
	AW0 Wheel Load (kips)			AW3 Wheel Load (kips)		
Vehicle Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Light Rail	4.8	9.1	7.9	6.1	13.0	10.9
Heavy Rail	6.8	11.6	9.4	8.1	16.8	12.8
Commuter Railcar	10.6	20.4	10.6	15.2	28.4	20.0
Commuter Rail Locomotive	25.0	37.2	32.7	N/A	N/A	N/A

Metric Units						
	AW0 Wheel Load (kN)			AW3 Wheel Load (kN)		
Vehicle Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Light Rail	21.4	40.5	35.2	27.1	57.9	48.5
Heavy Rail	30.3	51.6	41.8	36.0	74.8	57.0
Commuter Railcar	47.2	90.8	47.2	67.6	126.4	89.0
Commuter Rail Locomotive	111.3	165.5	145.5	N/A	N/A	N/A

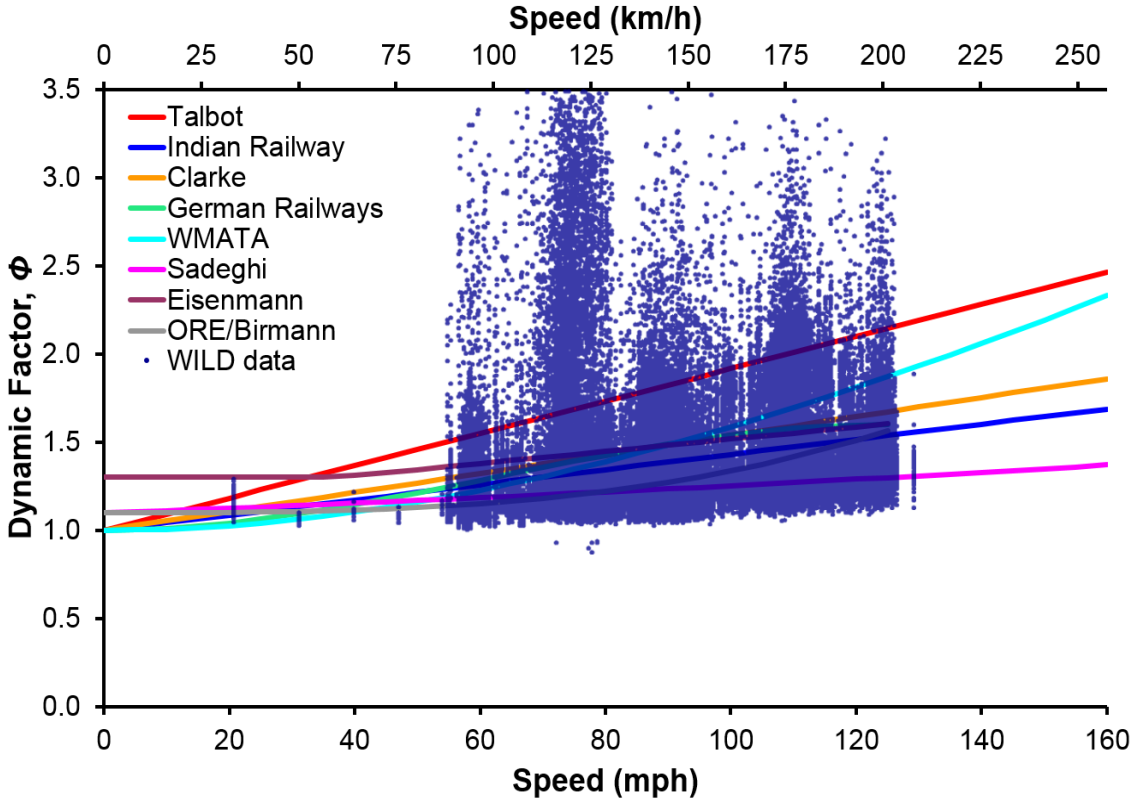
Methods for Estimating Rail Transit Vehicle Dynamic Loads

	Vehicle Parameters Included						Track Parameters Included					
Dynamic Factor	Train Speed	Wheel Diameter	Static Wheel Load	Unsprung Mass	Vehicle Center of Gravity	Locomotive Maintenance Condition	Track Modulus	Track Stiffness at Rail Joint	Track Joint Dip Angle	Cant Deficiency in Curves	Curve Radius	Track Maintenance Condition
Talbot	•	•										
Indian Railways	•						•					
Eisenmann	•											•
ORE/Birmann	•				•	•				•	•	•
German Railways	•											
British Railways	•		•	•				•	•			
South African Railways	•	•										
Clarke	•	•					•					
WMATA	•											
Sadeghi	•											
AREMA C30	•											

Rail Transit Vehicle Dynamic Factors



Rail Transit Vehicle Dynamic Factors



Evaluative Metric: Mean Signed Difference

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

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

Predicted dynamic factor, given wheel's speed

Ratio of peak to nominal vertical load

Number of wheels

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

Rail Transit Vehicle Dynamic Factors

	Dynamic Factors							
Evaluation Metric	Talbot	Indian Railways	Eisenmann	ORE/Birmann	German Railways	Clarke	WMATA	Sadeghi
Percent Exceeding	7%	35%	26%	68%	27%	26%	24%	79%
Mean Signed Difference $\sum \frac{(f(x_i)-y_i)}{n}$	0.47	-0.02	0.07	-0.15	0.08	0.09	0.14	-0.19
Mean Percentage Error $\frac{100\%}{n}\sum(f(x_i)-y_i)/y_i$	35.6	1.5	7.8	-7.9	8.1	9.1	12.7	-10.8
Root Mean Square Deviation $\sqrt{\sum(f(x_i)-y_i)^2/n}$	0.30	0.07	0.08	0.10	0.08	0.08	0.10	0.11
Speed-Weighted Signed Difference $\sum(x_i f(x_i) - x_i y_i)/\sum x_i$	0.48	-0.01	0.07	-0.16	0.08	0.10	0.16	-0.19
Load-Weighted Signed Difference $\sum(Q_i f(x_i) - Q_i y_i)/\sum Q_i$	0.48	0.00	0.09	-0.13	0.10	0.11	0.16	-0.17

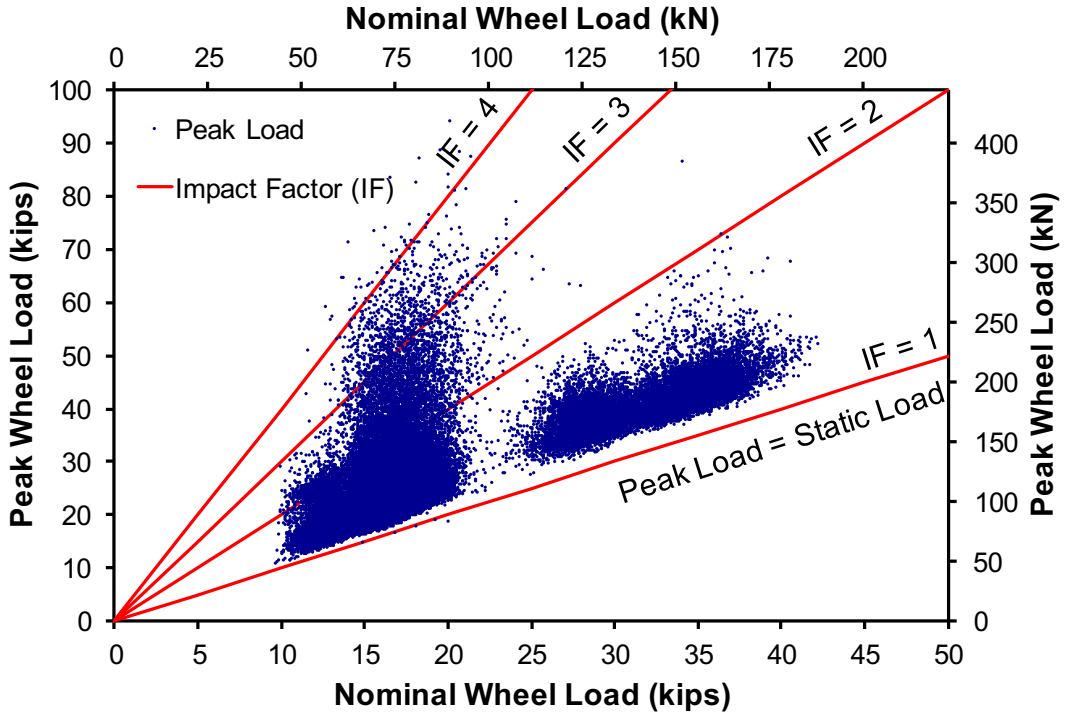
Dynamic Factor Evaluation Thoughts

- 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

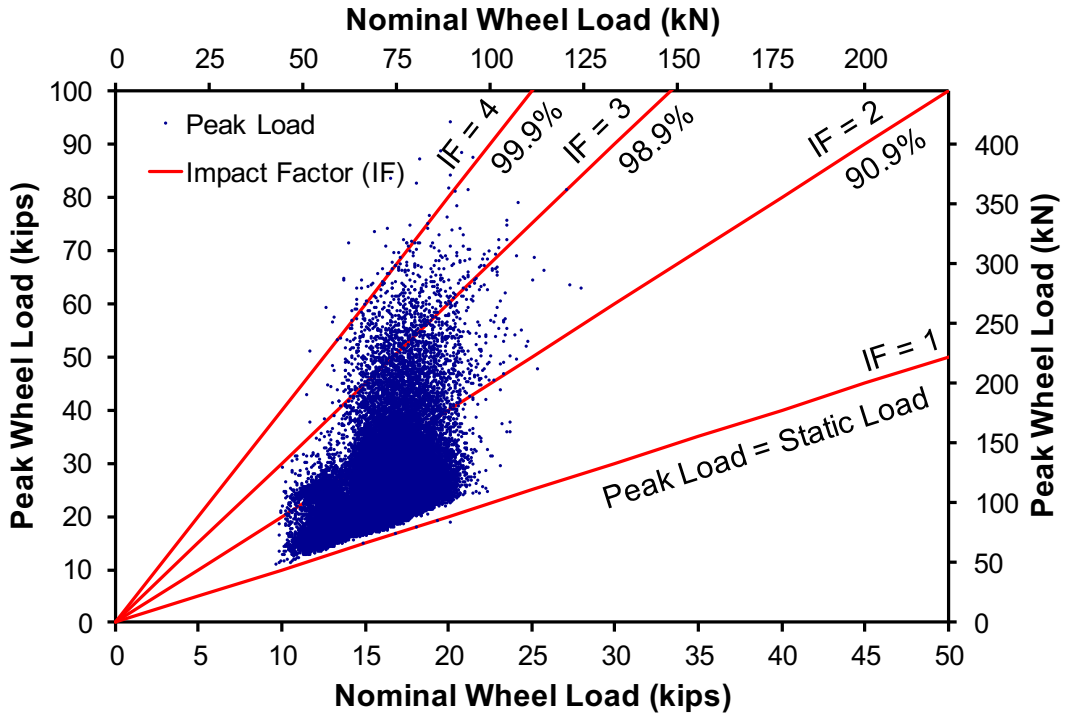
Rail Transit Vehicle Impact Factor

- 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

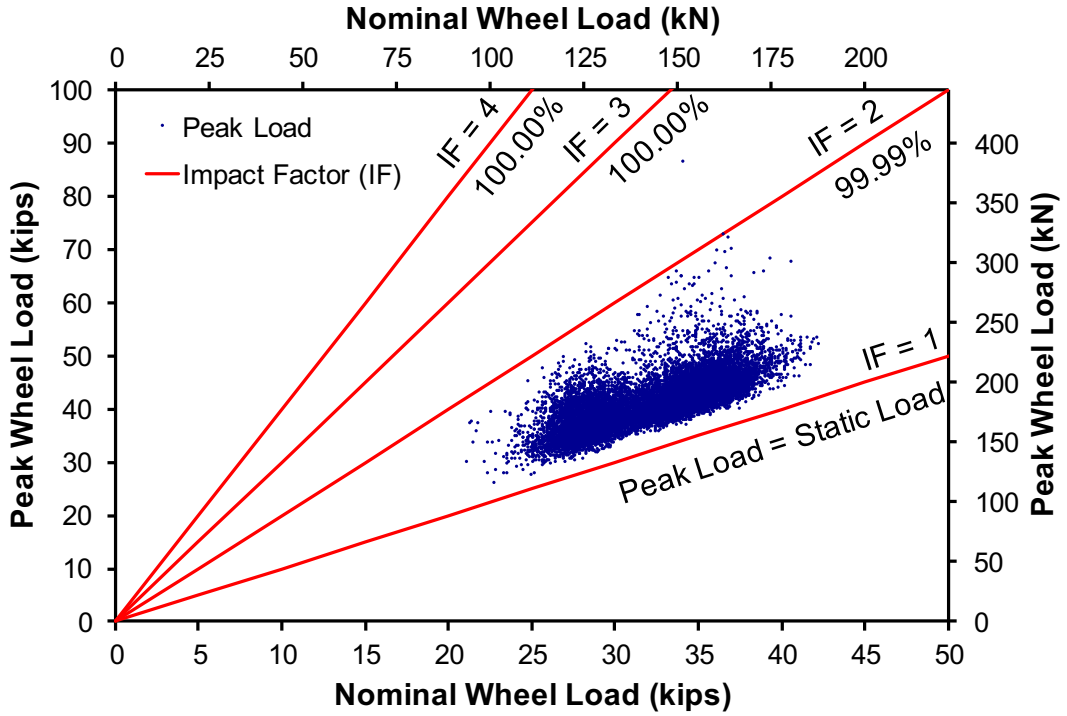
Peak Load vs. Nominal Wheel Load for Commuter Rail Vehicles



Peak Load vs. Nominal Wheel Load for Commuter Railcars



Peak Load vs. Nominal Wheel Load for Commuter Locomotives



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

Survey of Rail Transit Track Superstructure Design and Performance

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The Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) has been awarded a grant from the FTA titled ***"Resilient Concrete Crosstie and Fastening System Designs for Light Rail, Heavy Rail, and Commuter Rail Transit Infrastructure"***. The primary objective of this project will be to develop new concrete crosstie and fastening system designs used in light rail, heavy rail and commuter rail infrastructure that take into account their unique loading conditions.

The RailTEC team, along with its Industry Partners, is conducting a survey to help determine the most critical aspects of crossties and fastening systems that should be made resilient in the face of natural disasters or other events that place increased stress on infrastructure and its components. We invite you to participate in this survey at the following link:

https://goo.gl/QVJuyB

Survey results will be used to guide the field and laboratory experimental efforts as well as the analytical finite element (FE) modeling components of this project.

If you have any questions about this survey, please feel free to contact RailTEC Graduate Research Assistant Xiao (Sean) Lin at xiaolin4@illinois.edu.

FTA Project Industry Partners

- APTA
- NYCT (New York City, NY)
- Metra (Chicago, IL)
- MetroLink (St. Louis, MO)
- TriMet (Portland, OR)
- Pandrol USA
- GIC
- Rail Product Solutions (RPS), Inc.
- LBFoster, CXT Concrete Ties
- Hanson Professional Services, Inc.
- Amtrak

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

Acknowledgements

U.S. Department of Transportation
Federal Transit Administration

NURail Center

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  - **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 (NYCT)
  - Metra (Chicago, Ill.)
  - MetroLink (St. Louis, Mo.)
  - TriMet (Portland, Ore.)
  - Pandrol USA
  - Rail Product Solutions (RPS), Inc.
  - LBFoster, CXT Concrete Ties
  - GIC Inc.
  - Hanson Professional Services, Inc.
  - Amtrak

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The way to really fly.

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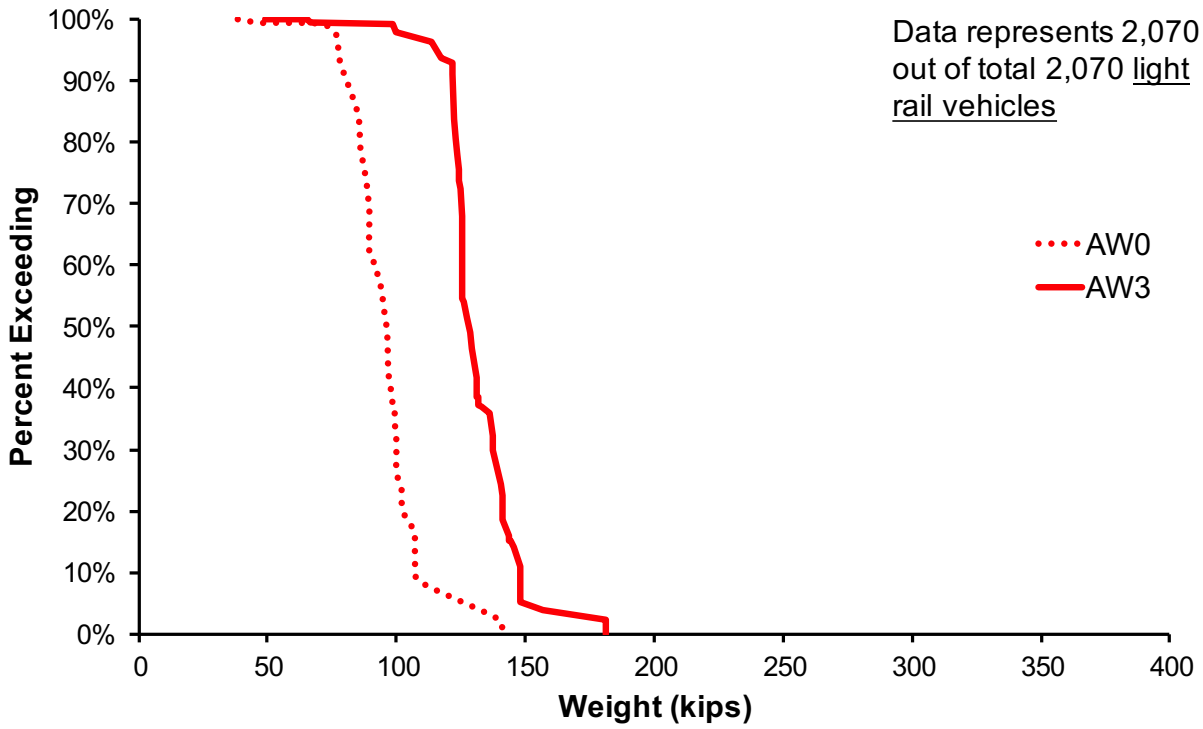
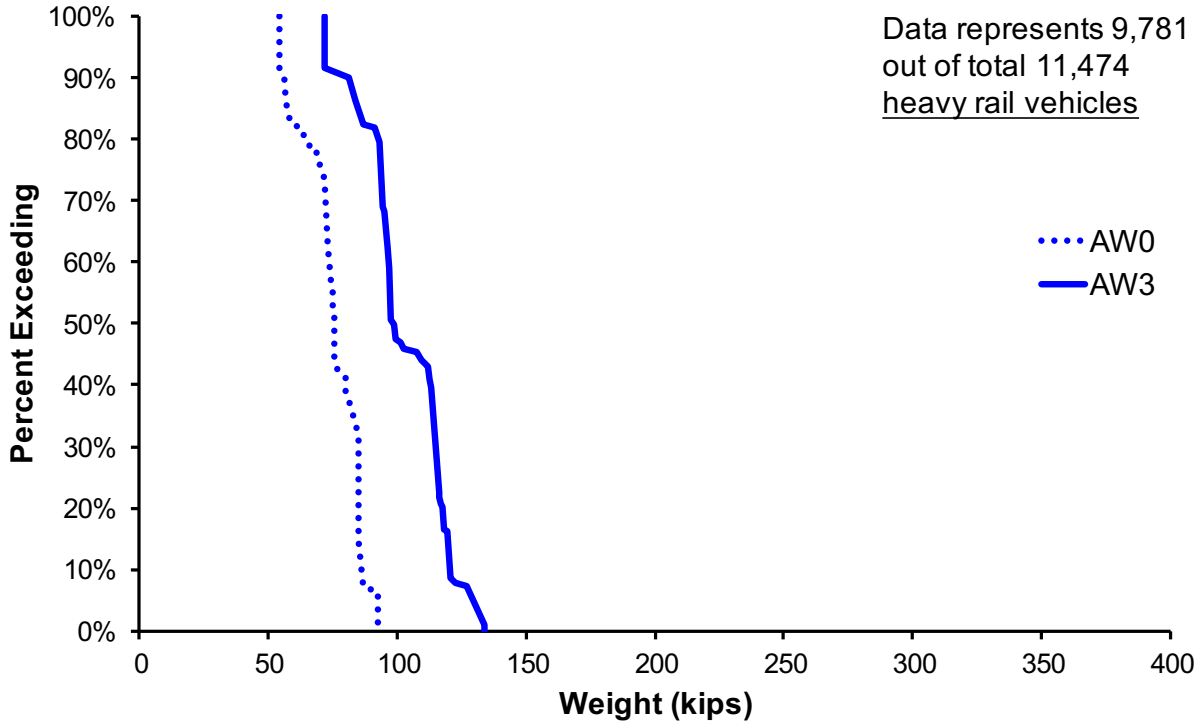
Appendix

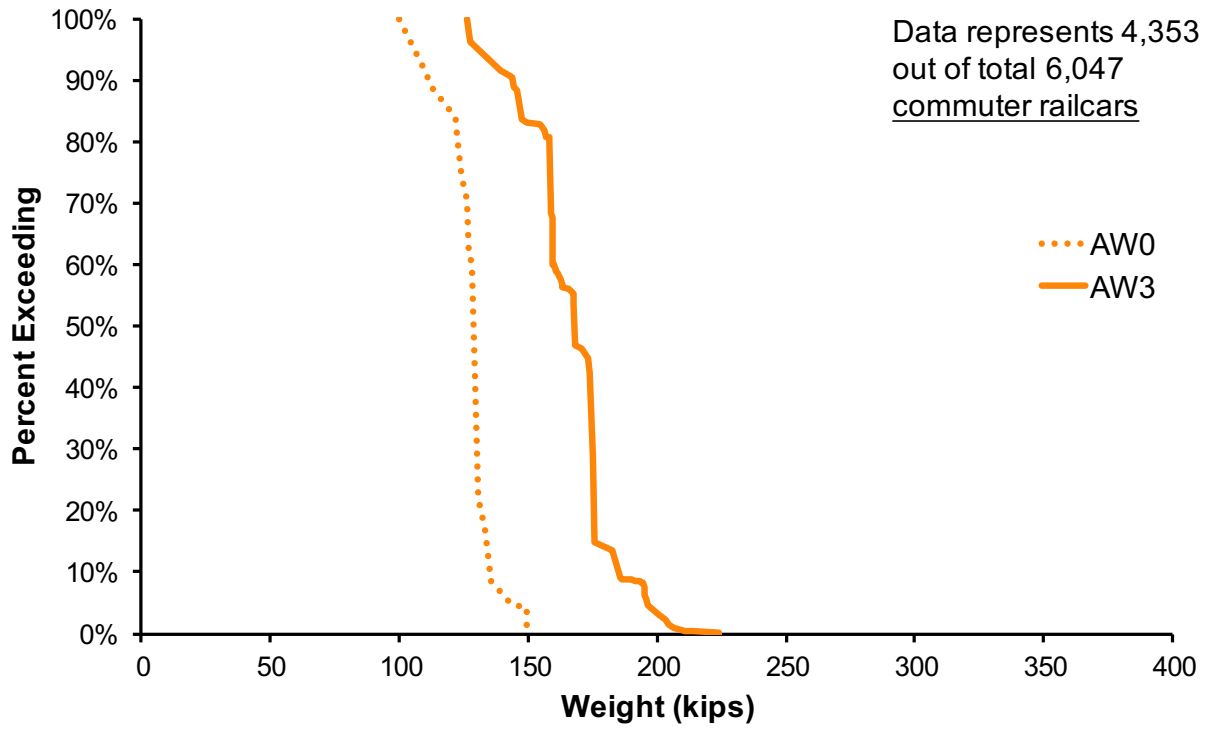
Light Rail Vehicle Weight Distribution



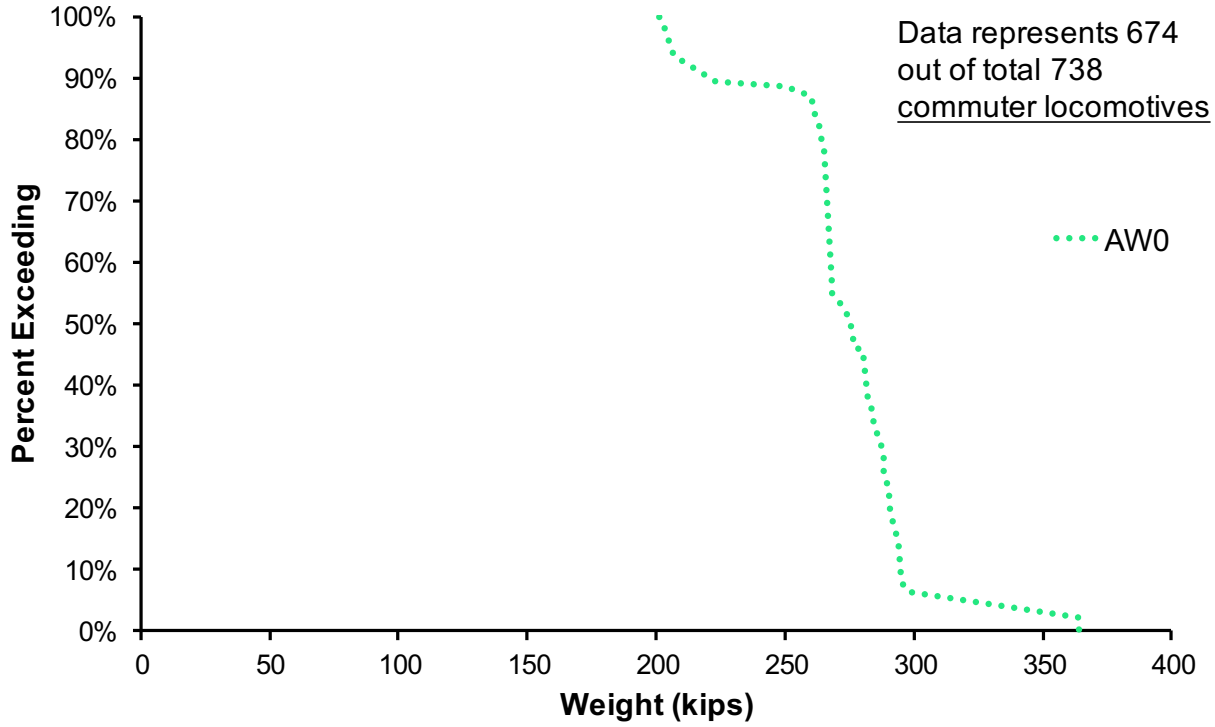
Heavy Rail Vehicle Weight Distribution



Commuter Railcar Weight Distribution



Commuter Locomotive Weight Distribution



Dynamic Factor Equations and Listing of Input Parameters

		Vehicle Parameters Included						Track Parameters Included					
Dynamic Factor	Expression for ϕ	Train Speed	Wheel Diameter	Static Wheel Load	Unsprung Mass	Vehicle Center of Gravity	Locomotive Maintenance Condition	Track Modulus	Track Stiffness at Rail Joint	Track Joint Dip Angle	Cant Deficiency in Curves	Curve Radius	Track Maintenance Condition
Talbot (Hay 1953)	$1+\frac{33V}{100D}$	•	•										
Indian Railways (Srinivasan 1969)	$1+\frac{V}{3\sqrt{U}}$	•						•					
Eisenmann (Esveld 2001)	$1+\delta\eta t$	•											•
ORE/Birmann (Birmann 1965)	$1+\alpha+\beta+\gamma$	•				•	•				•	•	•
German Railways (Schramm 1961)	$1+\frac{11.655V^2}{10^5}-\frac{6.252V^3}{10^7}$	•											
British Railways (Doyle 1980)	$1+14.136(\alpha_1+\alpha_2)V\sqrt{\frac{D_jP_u}{g}}$	•		•	•				•	•			
South African Railways (Doyle 1980)	$1+0.312\frac{V}{D}$	•	•										
Clarke (Doyle 1980)	$1+\frac{15V}{D\sqrt{U}}$	•	•					•					
WMATA (Prause et al. 1974)	$(1+0.0001V^2)^{\frac{2}{3}}$	•											
Sadeghi (Sadeghi & Barati 2010)	$1.098+0.00129V+2.59(10^{-6})V^2$	•											
AREMA C30	For $20<V<120$: $0.6+0.005V$	•											

Definitions of Dynamic Factor Variables

Variable	Definition
V	Train speed (mph)
D	Wheel diameter (in)
U	Track modulus (psi)
δ	0.1, 0.2, 0.3, depending on track conditions
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/s^2)

Definitions of dynamic factor evaluative metrics

Percent exceeding – percentage of wheels exceeding predicted dynamic factor

Mean percentage error – computed average of percentage errors by which predictions of a model differ from actual values of the quantity being predicted

$$\frac{100\%}{n}\sum_{i=1}^{n}\frac{f(x_i)-y_i}{y_i}$$

x_i is the speed of a single wheel
y_i is the ratio of peak vertical load to nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Root mean square deviation – measures differences between values predicted by estimator and actual recorded values (absolute value)

$$\sqrt{\frac{\sum_{i=1}^{n}(f(x_i)-y_i)^2}{n}}$$

x_i is the speed of a single wheel
y_i is the ratio of peak vertical load to nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Mean signed difference – summarizes how well an estimator matches the quantity that it is supposed to estimate

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

x_i is the speed of a single wheel
y_i is the ratio of peak vertical load to nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Speed-weighted signed difference – signed difference, with weight given for the speed of the wheel

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

x_i is the speed of a single wheel
y_i is the ratio of peak vertical load to nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels

Load-weighted signed difference – signed difference, with weight given for the nominal wheel load

$$\frac{\sum_{i=1}^{n}(Q_i f(x_i)-Q_i y_i)}{\sum Q_i}$$

Q_i is the nominal load of a single wheel
x_i is the speed of a single wheel
y_i is the ratio of peak vertical load to nominal vertical load of a single wheel
$f(x_i)$ is the predicted dynamic factor of a wheel given its speed
n is the total number of wheels