Effects of Evolving Vehicle Loading on the Serviceability of Concrete Bridges

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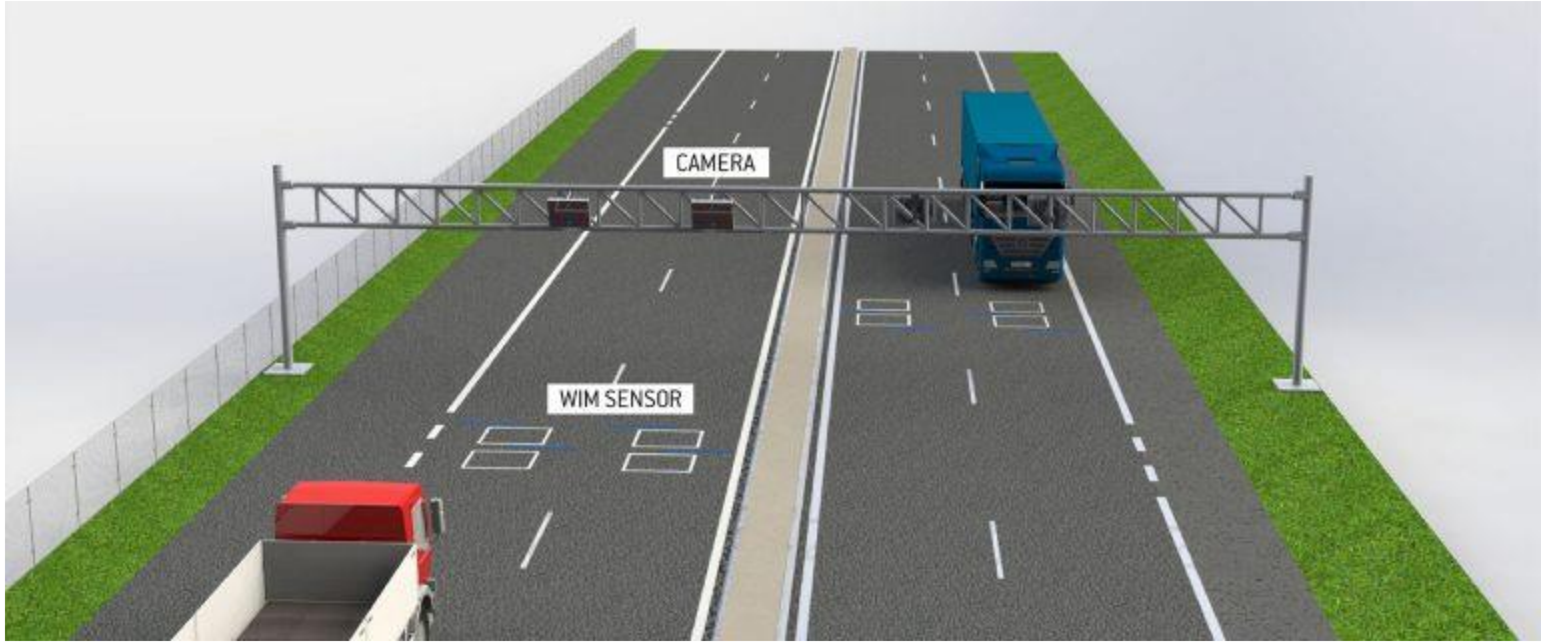
HNTB

Outline

- AASHTO Loading
- Loading Based in WIM Data
  - Methodology
  - Results
- Impacts on Serviceability
- Conclusions



What loading does the AASHTO LRFD use?

AASHTO LRFD HL-93 Live Load Model

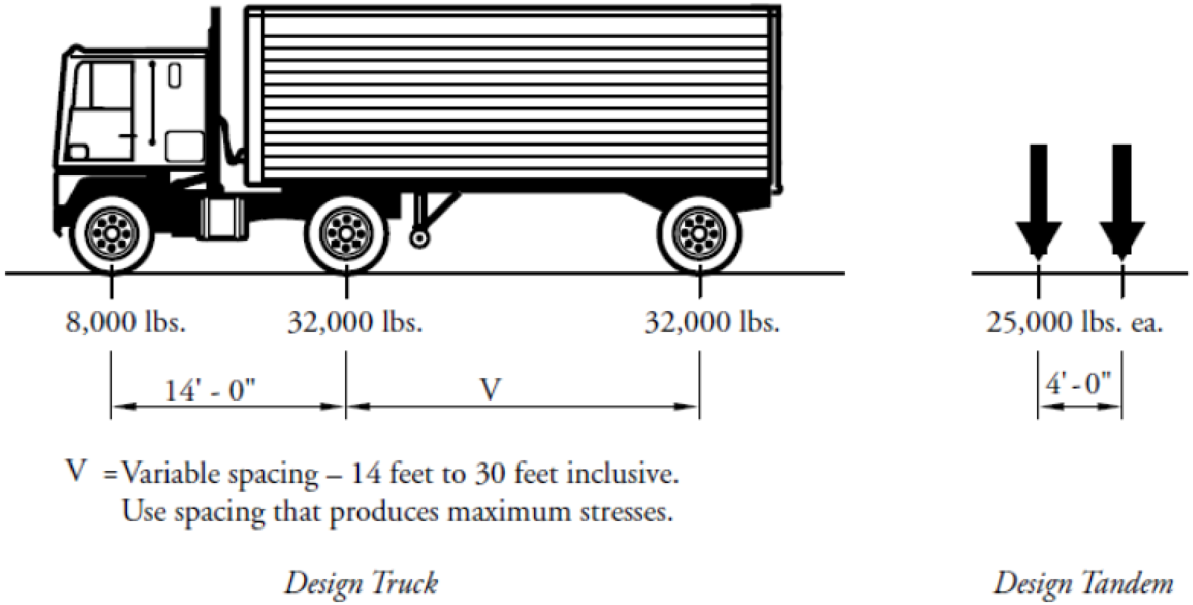
- Design truck
  - Front axle = 8 kip
  - Rear axles = 32 kip (each)

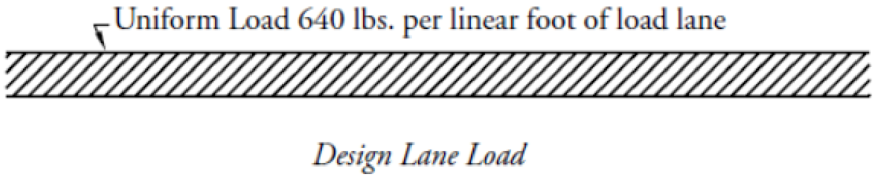
OR

- Design tandem
  - Two 25-kip axles with 4 ft spacing

PLUS

- Design lane
  - Equal to 640 lb/ft





How was the HL-93 loading developed?

AASHTO LRFD HL-93 Live Load Model

- Developed using 1975 truck data from the Ontario Ministry of Transportation
- Database consists of 9250 trucks
- Intended to generate the 75-year return period load effect
- Calibrated for 2 lanes, multiple presence factors are specified with 2+ lane bridges
- Calibration for span lengths up to 200 ft

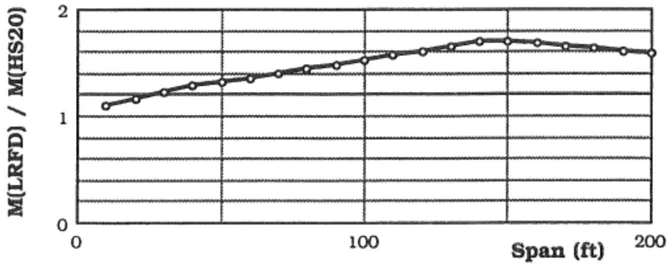


Fig. B-23. Ratio of the New Live Load Simple Span Moment, M(LRFD), and HS20 Moment, M(HS20).

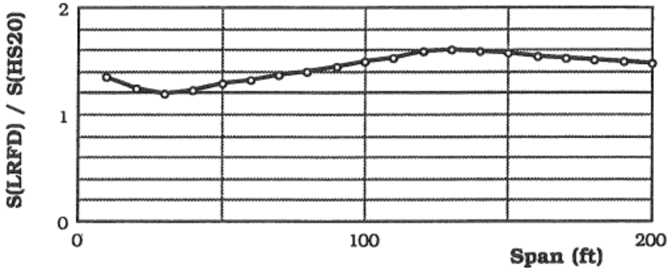


Fig. B-24. Ratio of the New Live Load Shear, S(LRFD), and HS20 Shear, S(HS20).

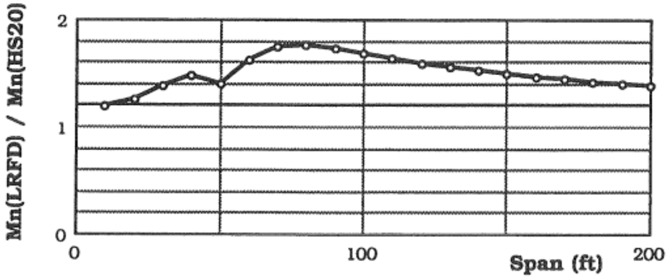


Fig. B-25. Ratio of the New Live Load Negative Moment, Mn(LRFD), and HS20 Negative Moment, Mn(HS20).

NCHRP Report 368 (Nowak, 1999)

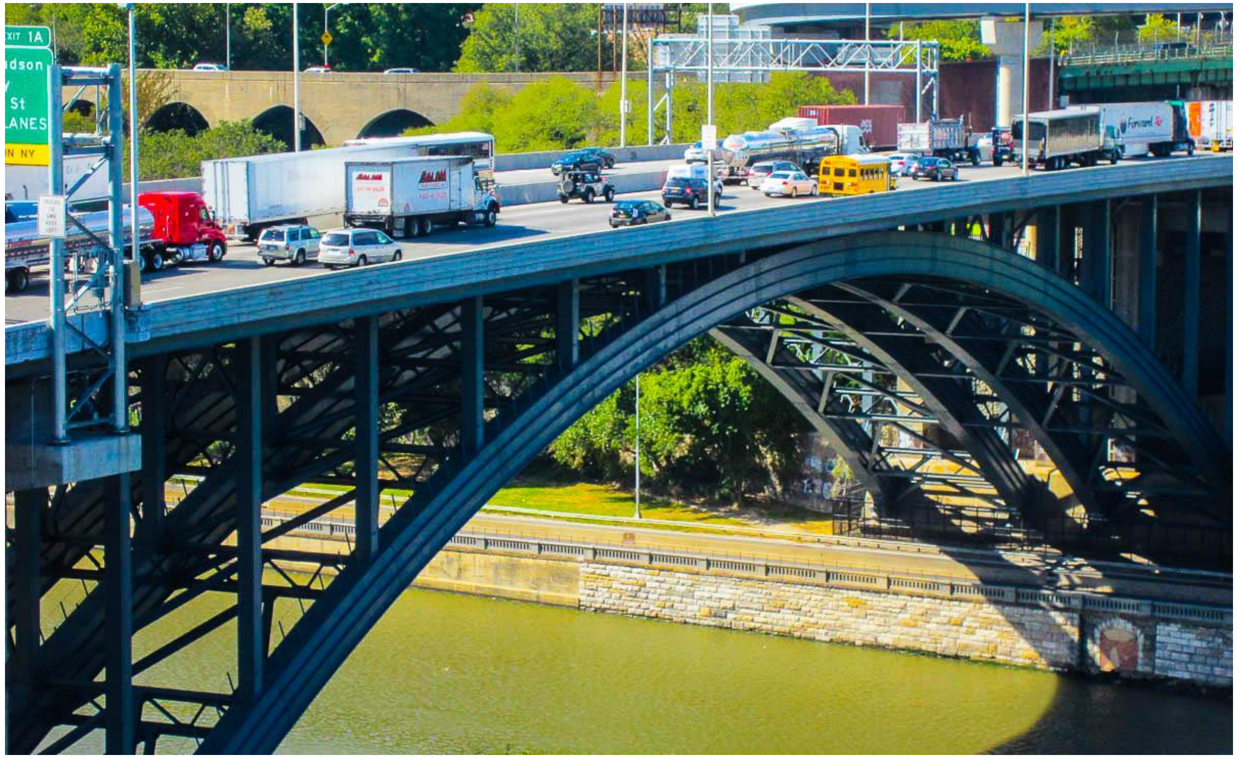
Can we improve our designs using WIM Data?

Image Credit: Josiah Farrow

Alexander Hamilton Bridge

Alexander Hamilton Bridge Location

What loading does the bridge actually see?

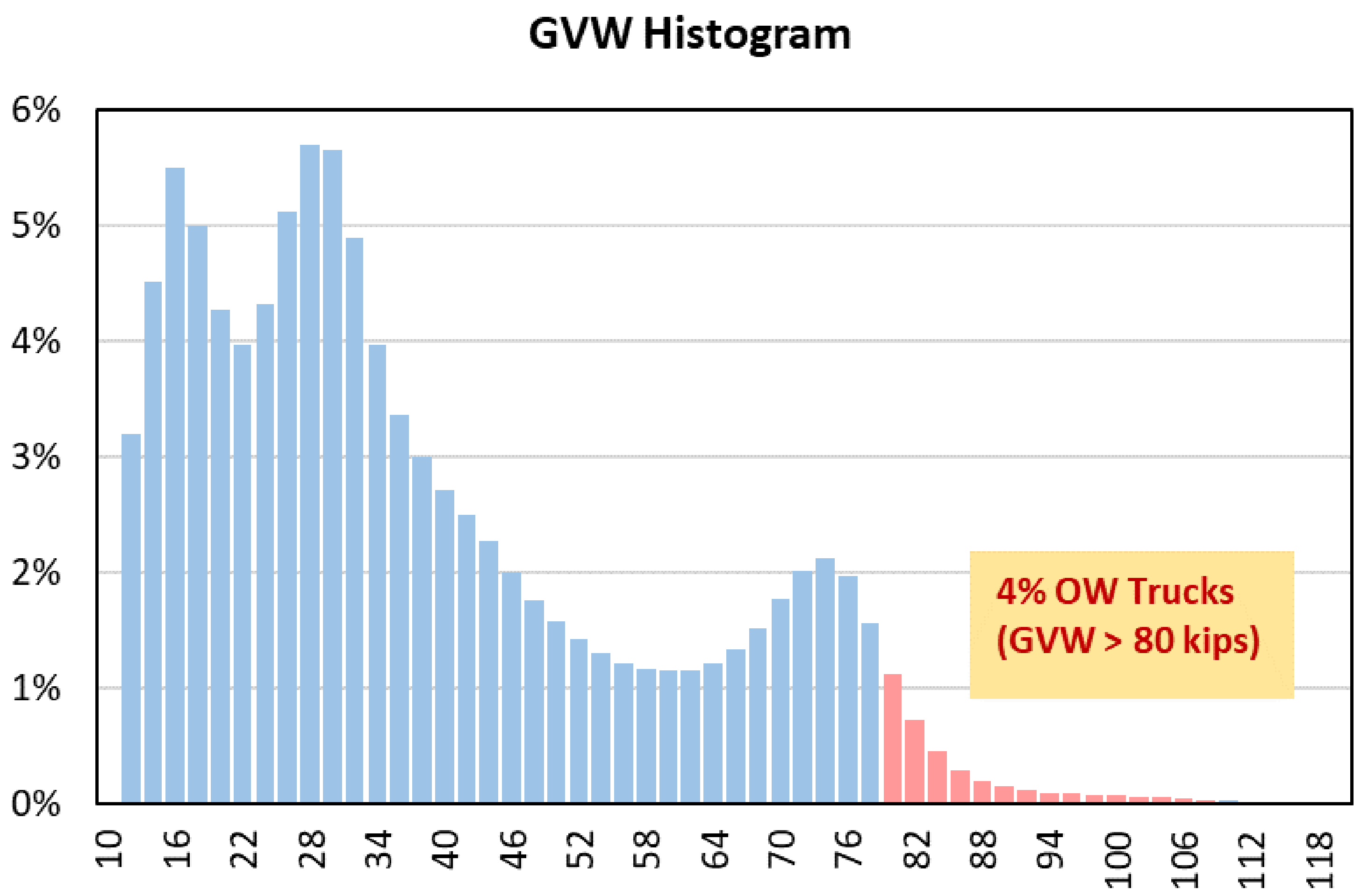


- Year: **2016**
- Number of days with truck records: **366**
- Total qualified truck record: **7,076,773**
- Average daily truck traffic (ADTT): **19,336**

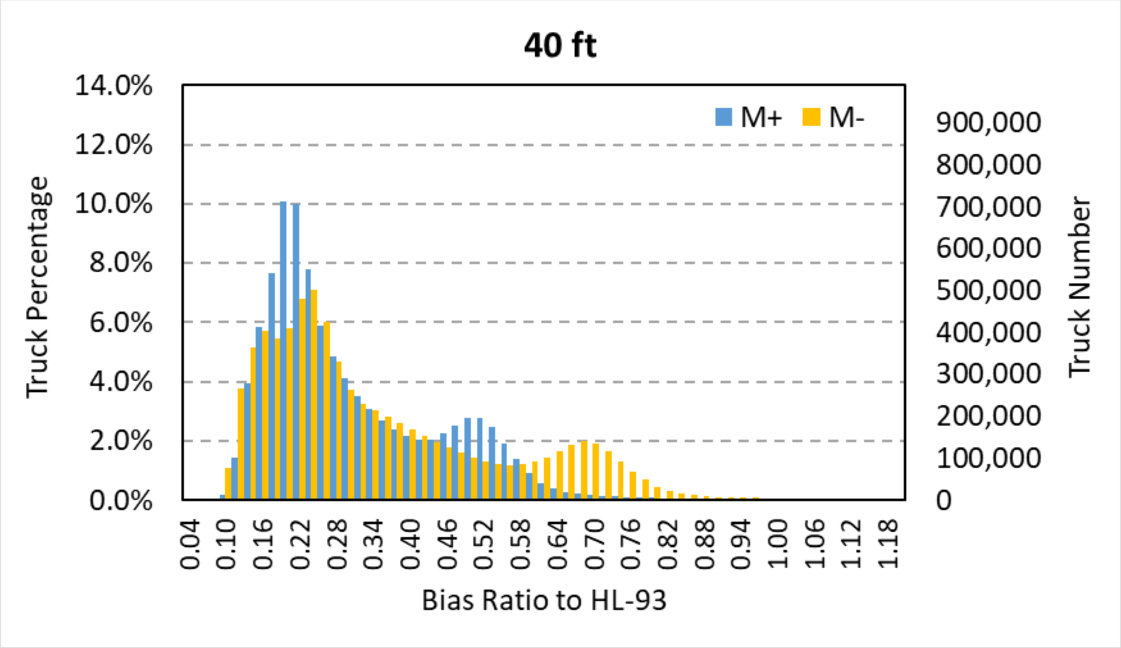
What loading does the bridge actually see?

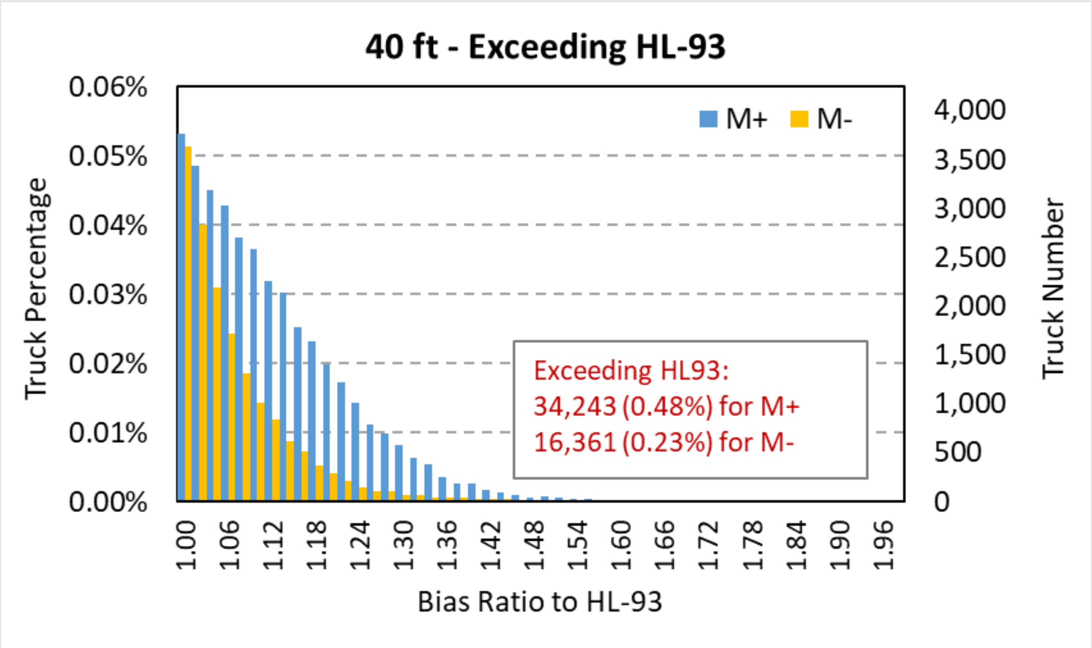
- Methodology
  - Line Girder Model
  - WIM Positive Moment and Negative Moment Load Effect: WIM Truck * IM
  - HL-93 Positive Moment in both Simple Spans and Continuous Spans: MAX(Truck*IM + LANE, Tandem*IM + LANE)
  - HL-93 Negative Moment in Continuous Spans: MAX(Truck*IM + LANE, Tandem*IM + LANE, (0.9*Double Truck*IM + 0.9*LANE))
- BIAS = WIM Load Effect / HL-93 Load Effect (BIAS > 1.0 is bad)
  - IM taken as 1.33 when computing BIAS values.

What loading does the bridge actually see?



How does that loading translate to typical bridges?





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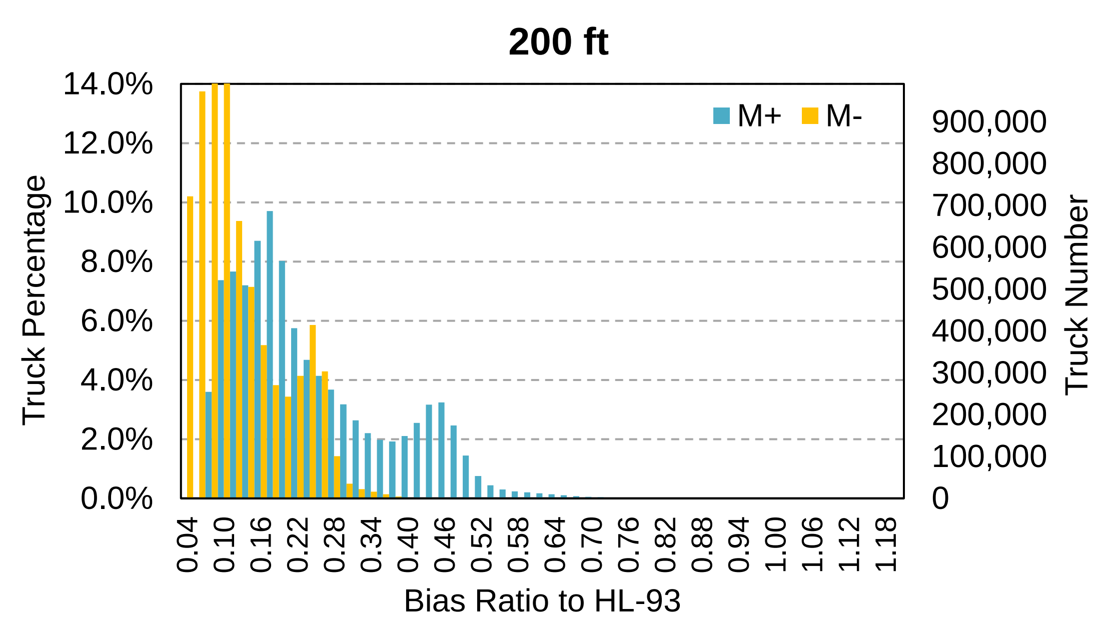

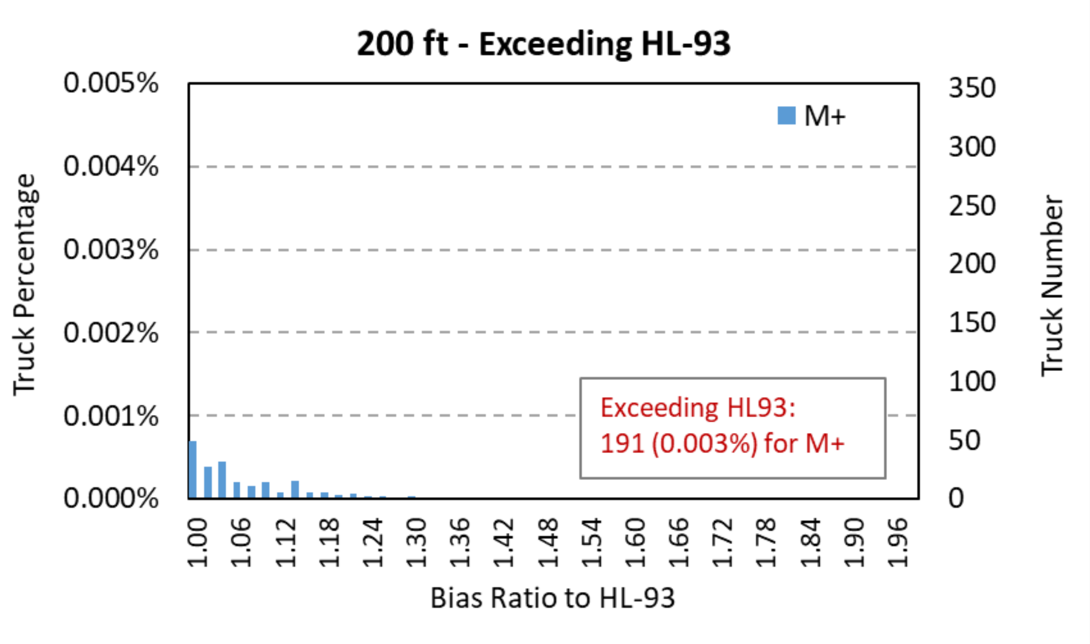

How does that translate to typical bridges?

Positive Moment	40 ft	60 ft	80 ft	100 ft	120 ft	140 ft	160 ft	180 ft	200 ft
Max	2.109	1.890	1.784	1.704	1.625	1.550	1.480	1.414	1.354
Min	0.078	0.070	0.064	0.061	0.061	0.057	0.059	0.059	0.059
Average	0.323	0.297	0.290	0.292	0.288	0.281	0.272	0.263	0.254
Std. Dev.	0.154	0.134	0.135	0.139	0.139	0.137	0.135	0.131	0.127
Exceedance of HL-93	34244	17056	7981	3577	1736	930	542	321	191
% exceedance of HL-93	0.48%	0.24%	0.11%	0.05%	0.02%	0.01%	0%	0%	0%

Negative Moment	40 ft	60 ft	80 ft	100 ft	120 ft	140 ft	160 ft	180 ft	200 ft
Max	1.828	1.461	1.117	0.946	0.872	0.820	0.773	0.745	0.719
Min	0.062	0.053	0.053	0.047	0.044	0.042	0.039	0.037	0.036
Average	0.361	0.254	0.191	0.168	0.162	0.155	0.148	0.142	0.135
Std. Dev.	0.195	0.137	0.096	0.082	0.081	0.079	0.076	0.073	0.070
Exceedance of HL-93	16361	134	6	0	0	0	0	0	0
% exceedance of HL-93	0.23%	0%	0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Why is serviceability important?

Serviceability design of concrete focuses on ensuring that a structure performs satisfactorily under normal service conditions without excessive deformation, cracking, or vibration.

- **Control of Deflections and Vibrations**
  - Excessive deflections and vibrations in concrete can cause service problems like misalignment of joints, cracking in non-structural elements, or discomfort to drivers and/or pedestrians.
  - The allowable deflection is usually limited to a fraction of the span (e.g., L/800 or L/1000) based on structural codes and specific usage requirements.
- **Crack Control**
  - Concrete can develop cracks due to shrinkage, temperature changes, and applied loads, which might impact the appearance and durability of the structure.
  - Codes specify limits for crack width to ensure concrete structures can withstand environmental exposure and maintain functionality over time.

What does ACI 343 say?

ACI 343R-95Analysis and Design of Reinforced Concrete Bridge Structures

8.7.1 Flexure—Non-prestressed members may be designed using service loads and allowable stresses. The stresses in concrete and reinforcement in flexure should not exceed the Following:

Table 8.7.1—Allowable stresses

Description		Basic value	
For normal weight concrete		psi	MPa
Flexure			
Extreme fiber stress in compression	f_c	$0.4 f_c'$	$0.4 f_c'$
Extreme fiber stress in tension (plain concrete)*	f_t	$1.6 \sqrt{f_c'}$	$0.13 \sqrt{f_c'}$
Modulus of rupture*	f_r	$7.5 \sqrt{f_c'}$	$0.62 \sqrt{f_c'}$
Shear			
Beams:			
Shear carried by concrete*	v_c	$0.95 \sqrt{f_c'}$	$0.08 \sqrt{f_c'}$
Maximum shear carried by concrete plus shear reinforcement	v	$5 \sqrt{f_c'}$	$0.42 \sqrt{f_c'}$
Slabs and footings:			
Shear carried by concrete*	v_c	$1.8 \sqrt{f_c'}$	$0.15 \sqrt{f_c'}$
Maximum shear carried by concrete plus shear reinforcement	v	$3 \sqrt{f_c'}$	$0.25 \sqrt{f_c'}$
Bearing on loaded area	f_b	$0.3 f_c'$	$0.3 f_c'$
Bearing on loaded area subjected to high edge stresses due to deflection or eccentric loading	f_b	$0.225 f_c'$	$0.225 f_c'$

*When lightweight aggregate concretes are used, the allowable stresses should be multiplied by 0.75 for "all-lightweight" concrete, and 0.85 for "sand-lightweight" concrete. Linear interpolation may be used when partial sand replacement is used.

What does ACI 343 say?

ACI 343R-95Analysis and Design of Reinforced Concrete Bridge Structures

8.6.2 Service load stresses—Flexural stresses in concrete at service load, after allowance for all prestress losses, should not exceed the following:

- Compression — 0.40 f_c'
- Tension in pre-compressed tension zone:
  - With bonded auxiliary reinforcement to control cracking - 6 f_c'
  - With bonded auxiliary reinforcement to control cracking but exposed to corrosive environment or severe exposure conditions - 3 f_c'
  - Without bonded auxiliary reinforcement - 0

What does AASHTO say?

AASHTO LRFD Bridge Design Specifications

- **Service I**—Load combination relating to the normal operational use of the bridge with a 70-mph wind and all loads taken at their nominal values. Also related to deflection control in buried metal structures, tunnel liner plate, and thermoplastic pipe, *to control crack width in reinforced concrete structures*, and for transverse analysis relating to tension in concrete segmental girders. This load combination should also be used for the investigation of slope stability.

- **Service III**—Load combination for longitudinal analysis relating to tension in prestressed concrete superstructures *with the objective of crack control* and to principal tension in the webs of segmental concrete girders.

What does AASHTO say?

AASHTO LRFD Bridge Design Specifications

5.5.2—Service Limit State

Actions to be considered at the service limit state shall be cracking, deformations, and concrete stresses, as specified in Articles 5.6.7, 5.6.3.5, and 5.9.2.3, respectively.

The cracking stress shall be taken as the modulus of rupture specified in Article 5.4.2.6..

5.6.7—Control of Cracking by Distribution of Reinforcement

Except for deck slabs designed in accordance with Article 9.7.2, the provisions specified herein shall apply to the reinforcement of all concrete components in which tension in the cross-section exceeds 80 percent of the modulus of rupture, specified in Article 5.4.2.6, at applicable service limit state load combination specified in Table 3.4.1-1.

The spacing, *s*, of non-prestressed reinforcement in the layer closest to the tension face shall satisfy the following:

$$s \leq \frac{700\gamma_e}{\beta_s f_{ss}} - 2d_c \qquad (5.6.7\text{-}1)$$

What does AASHTO say?

AASHTO LRFD Bridge Design Specifications

5.9.1.4—Crack Control

Where cracking is permitted under service loads, crack width, fatigue of reinforcement, and corrosion considerations shall be investigated in accordance with the provisions of Articles 5.5 and 5.6.

5.9.2.3.2a—Compressive Stresses

Compression shall be investigated using the Service Limit State Load Combination I specified in Table 3.4.1-1. The limits in Table 5.9.2.3.2a-1 shall apply. These limits may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.

Table 5.9.2.3.2a-1—Compressive Stress Limits in Prestressed Concrete at Service Limit State after Losses

Location	Stress Limit
• Due to the sum of effective prestress and permanent loads	$0.45f'_c$ (ksi)
• Due to the sum of effective prestress, permanent loads, and transient loads as well as during shipping and handling	$0.60\phi_w f'_c$ (ksi)

What does AASHTO say?

AASHTO LRFD Bridge Design Specifications

5.9.2.3.2b—Tensile Stresses

For longitudinal service load combinations that involve traffic loading tension stresses in members with bonded or unbonded prestressing tendons should be investigated using load combination Service III specified in Table 3.4.1-1. Load combination Service I should be investigated for load combinations that involve traffic loadings in transverse analyses of box girder bridges.

- The limits in Table 5.9.2.3.2b-1 shall apply.

Table 5.9.2.3.2b-1—Tensile Stress Limits in Prestressed Concrete at Service Limit State after Losses

Bridge Type	Location	Stress Limit
Other Than Segmentally Constructed Bridges These limits may be used for normal weight concrete with concrete compressive strengths for use in design up to 15.0 ksi and lightweight concrete up to 10.0 ksi.	Tension in the Precompressed Tensile Zone, Assuming Uncracked Sections • For components with bonded prestressing tendons or reinforcement that are subjected to not worse than moderate corrosion conditions • For components with bonded prestressing tendons or reinforcement that are subjected to severe corrosive conditions • For components with unbonded prestressing tendons	 $0.19\lambda\sqrt{f'_c} \leq 0.6$ (ksi) $0.0948\lambda\sqrt{f'_c} \leq 0.3$ (ksi) No tension

Why Does all this matter?

- There has been a movement to utilize WIM data in a wide range of research projects and practical applications to better understand live loads such as:
  - NCHRP 20-07/Task 285 “Recalibration of LRFR Live Load Factors in the AASHTO Manual for Bridge Evaluation” (TRB)
  - NCHRP 20-07/Task 410 “Load Rating for the Fast Act Emergency Vehicles EV2 and EV3” (TRB)
  - Site-specific Design Live Load Factor Calibration (Goethals Bridge, PANYNJ)
  - Site-specific Load Rating Live Load Factor Calibration & Truck Traffic Statistics (LADOTD, NJTA, OKDOT, UDOT)
  - ESAL Based Pavement Damage Studies (NYCDOT)

What are your conclusions?

- Overweight trucks with short wheelbases are likely to create problems in short span bridges for the SERVICE limit states
- When actual loads exceed the design load the performance of the structure can be compromised:
  - Excessive deflections and vibrations can:
    - Cause discomfort to drivers and/or pedestrians
    - Compromise joints and bearings
  - Excessive crack widths can:
    - Compromise durability
    - Impact the appearance of the bridge
- Using WIM to categorize actual loading will lead to improved structural performance