Development of Traffic Live-Load Models for Bridge Rating

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Overview

Background | WIM Data Analysis | Reliability Analysis | Load Models

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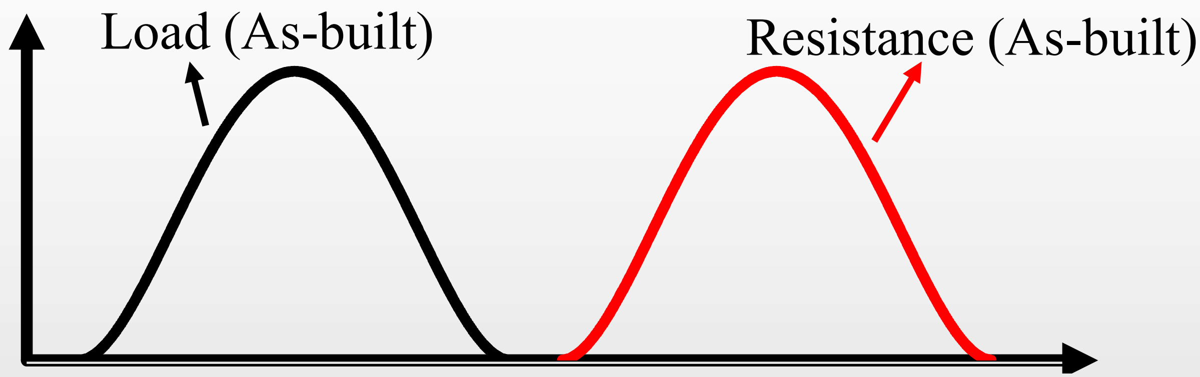
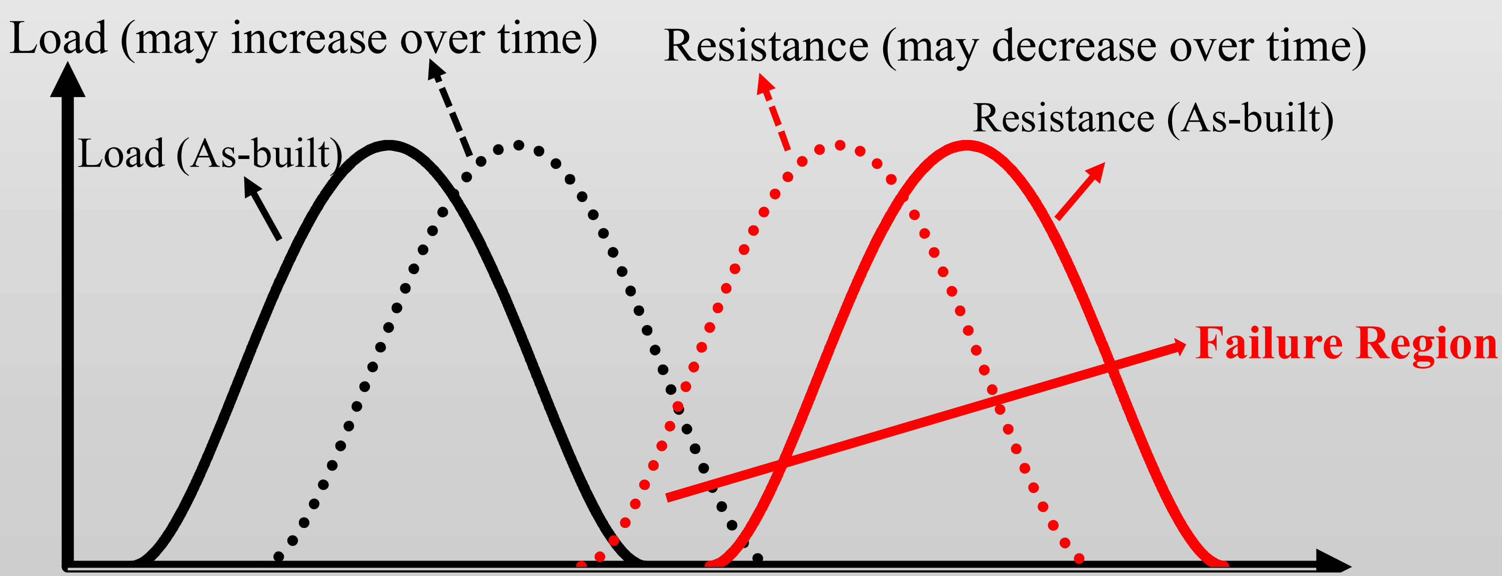
what loads should be used to rate bridges?





Background | WIM Data Analysis | Reliability Analysis | Load Models

- AASHTO LRFD and MBE load models were based on vehicles not representative of MI traffic.
- AASHTO LRFD: Load model developed from about 10,000 heavy truck weights recorded in Ontario, Canada in 1975.
- Bridges were rated based on the *Manual for Condition Evaluation of Bridges* based on Load Factor Rating (LFR) , which was not reliability-based.
- The *Manual of Bridge Evaluation* was later released in 2008 based on LRFR to develop appropriate load factors which produce a consistent level of reliability.
- These factors were later revised in 2011 (Sivakumar et al. 2011) using weigh-in-motion (WIM) data from truck traffic collected from six states including New York, Mississippi, Indiana, Florida, California, and Texas.

Background | WIM Data Analysis | Reliability Analysis | Load Models

- MDOT: MDOT load models were developed in 1970s.
- Will using current live-load models for bridge rating result in inappropriate levels of safety for MI bridges?
- Propose efficient and reliable approach to develop live-load models for state-specific reliability-based rating of bridges.
- Disclaimer: This research was partially sponsored by MDOT (report SPR-1640). MDOT has not reviewed or been involved with the presented approaches. The views, opinions, and conclusion reflected in this study are the responsibility of authors and do not represent the official policy or position of MDOT.

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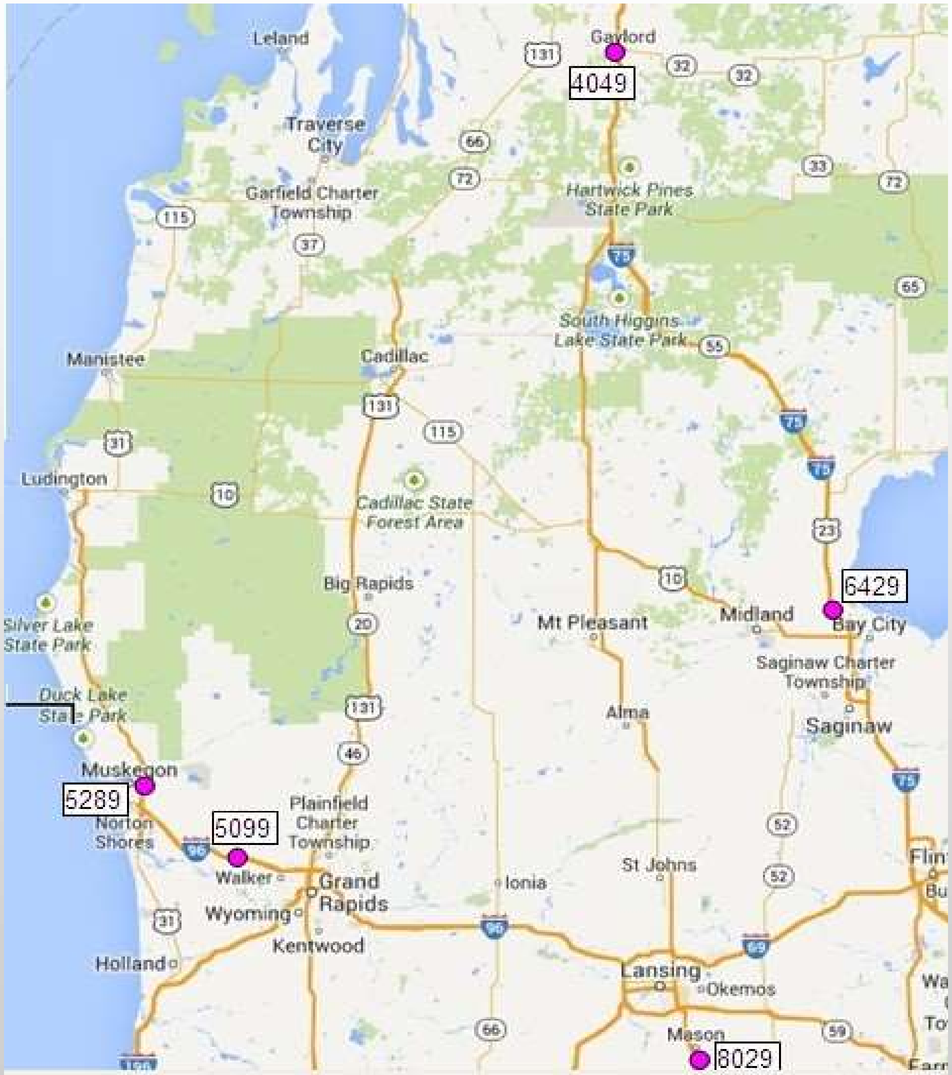
From the 41 available sites in Michigan, the data from 20 sites were used in this study. The data were collected for approximately three years (from May 2014 to Jan 2017, excluding April and May 2014).

Site	Location	ADTT
High ADTT (≥ 5000)		
9209	I-275	4850
7029	I-94	4930
8869	I-69	4980
9189	I-275	5120
7269	I-69	5290
8839	I-94	6340
7169	I-94	6480
7219	I-94	8440
7159	I-94	9900
9699	I-75	11100

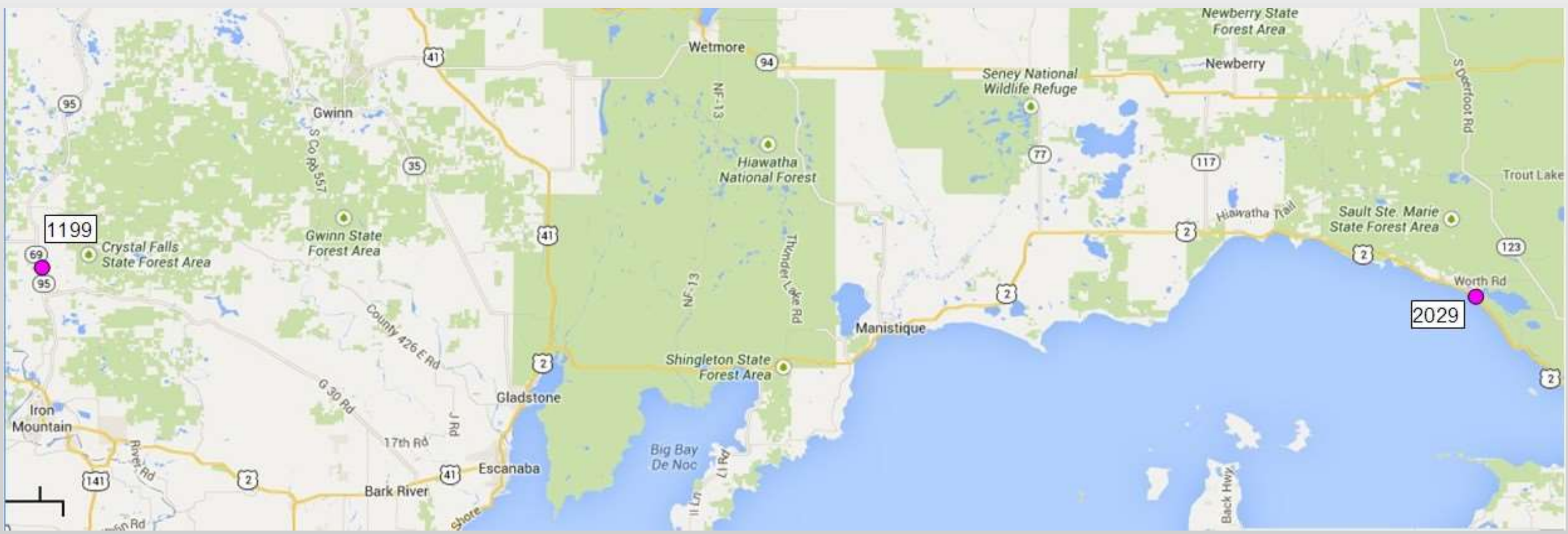
Site	Location	ADTT
Mid ADTT (~2500)		
5059	I-196	2520
6369	I-69	2650
6469	I-94	2640
Low ADTT (~1000)		
4049	I-75	850
5289	US-31	1050
6429	I-75	1340
5099	I-96	1350
8029	US-127	1560
Very Low ADTT (~400)		
1199	M-95 (UP)	400
2029	US-2 (UP)	420

WIM Sites With ADTT ≥5000.



WIM Sites With ADTT ~ 1500.

WIM Sites With ADTT ~3500.



WIM Sites With ADTT ~400

Data filtering criteria must be employed to eliminate lightweight or unrealistic vehicles from the database.

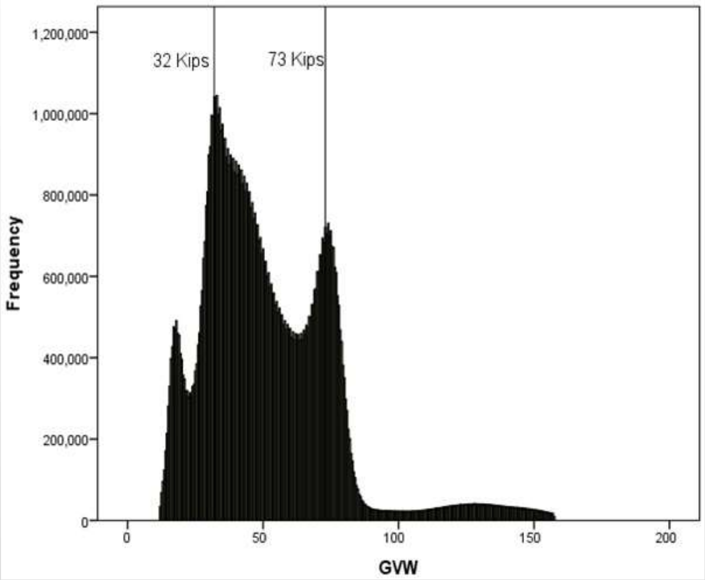
Criteria Type	Criteria for Elimination
Vehicle Class	Class 1-3 (automatic elimination)
Gross Vehicle Weight	GVW < 12 kips (No upper limit) GVW differs from axle weight sum by more than 10%.
Axle Weight	First axle > 25 kips or < 6 kips. Any axle > 40 kips or < 2 kips.
Vehicle Length	Length < 5 ft. Length > 200 ft.
Axle Spacing	First axle spacing < 5 ft. Any axle spacing < 3 ft.
Speed	Speed < 20 or > 100 MPH for GVW vehicles < 200 kips. Speed < 20 or > 85 MPH for GVW vehicles > 200 kips.
Number of Axles	Number of axles < 2 or > 13.

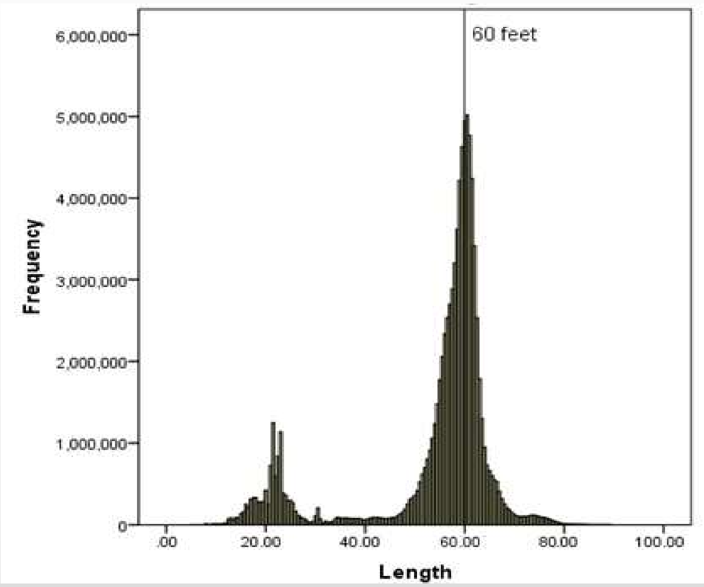
- Out of the ~159 million total vehicles represented by 41 high-speed WIM sites, the 20 sites selected contained ~101 million vehicles (63.6% of the total available).
- Overall, ~ 12 million (11.7%) of the results from the 20 selected sites were removed due to data filtering resulting in ~ 90 million vehicles remained.
- The data is further filtered to only capture Michigan Legal and Extended Permit (MI-LEP) vehicles for Legal Load rating.

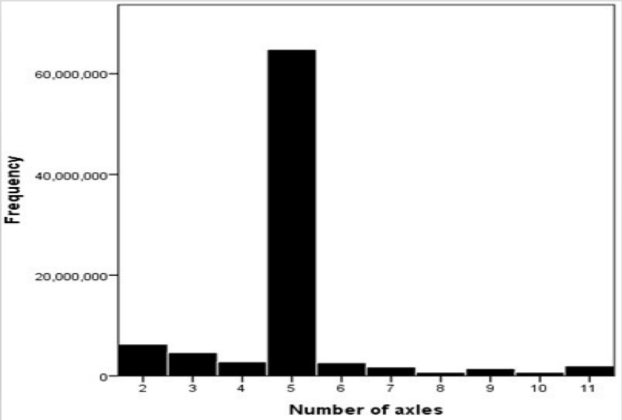
Vehicle Type	MI-LEP Criteria
Legal, GVW > 80 kips	For axles spaced ≥ 9 ft, axles ≤ 18 kips For axles spaced from 3.5 – 9 ft, axles ≤ 13 kips For axles spaced < 3.5 ft, axles ≤ 9 kips
Legal, GVW < 80 kips	Any individual axle ≤ 20 kips Sum of tandem axles ≤ 34 kips
Extended Permit (Construction)	Length ≤ 85 ft Any axle ≤ 24 kips GVW ≤ 150 kips

Background | **WIM Data Analysis** | Reliability Analysis | Load Models

From (~ 90 million vehicle records, ~ 89 millions (99.3%) fall into legal and extended permit category.







Background | **WIM Data Analysis** | Reliability Analysis | Load Models

- Vehicle load effects were calculated for span length of 20-200 ft. in increments of 20 ft..
- Considered effects were maximum simple span moments and shear.
- Both one-lane (single vehicle and following vehicles) and two-lane (side-by-side) load effects were considered.

One-Lane

Two-Lane

Single

Following

Side-by-Side

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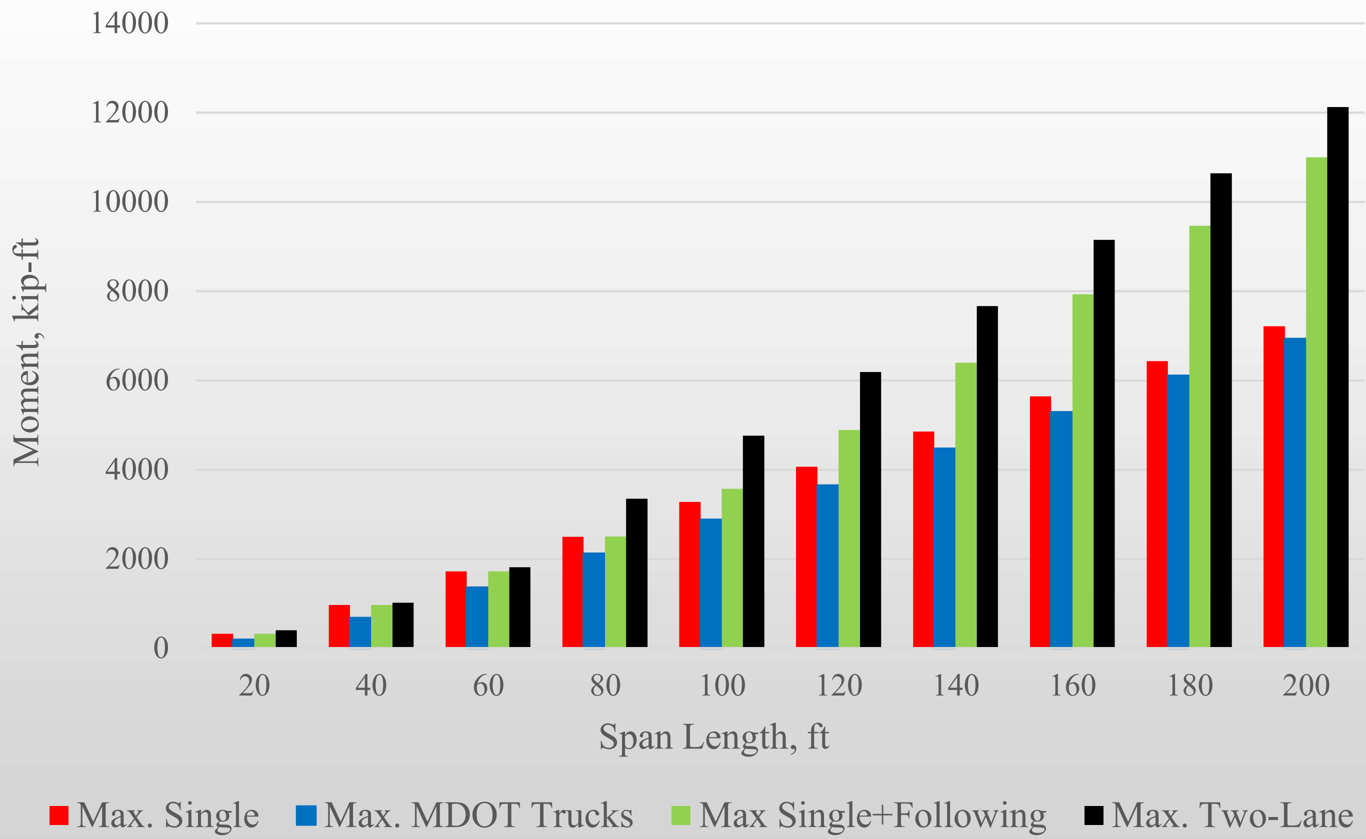
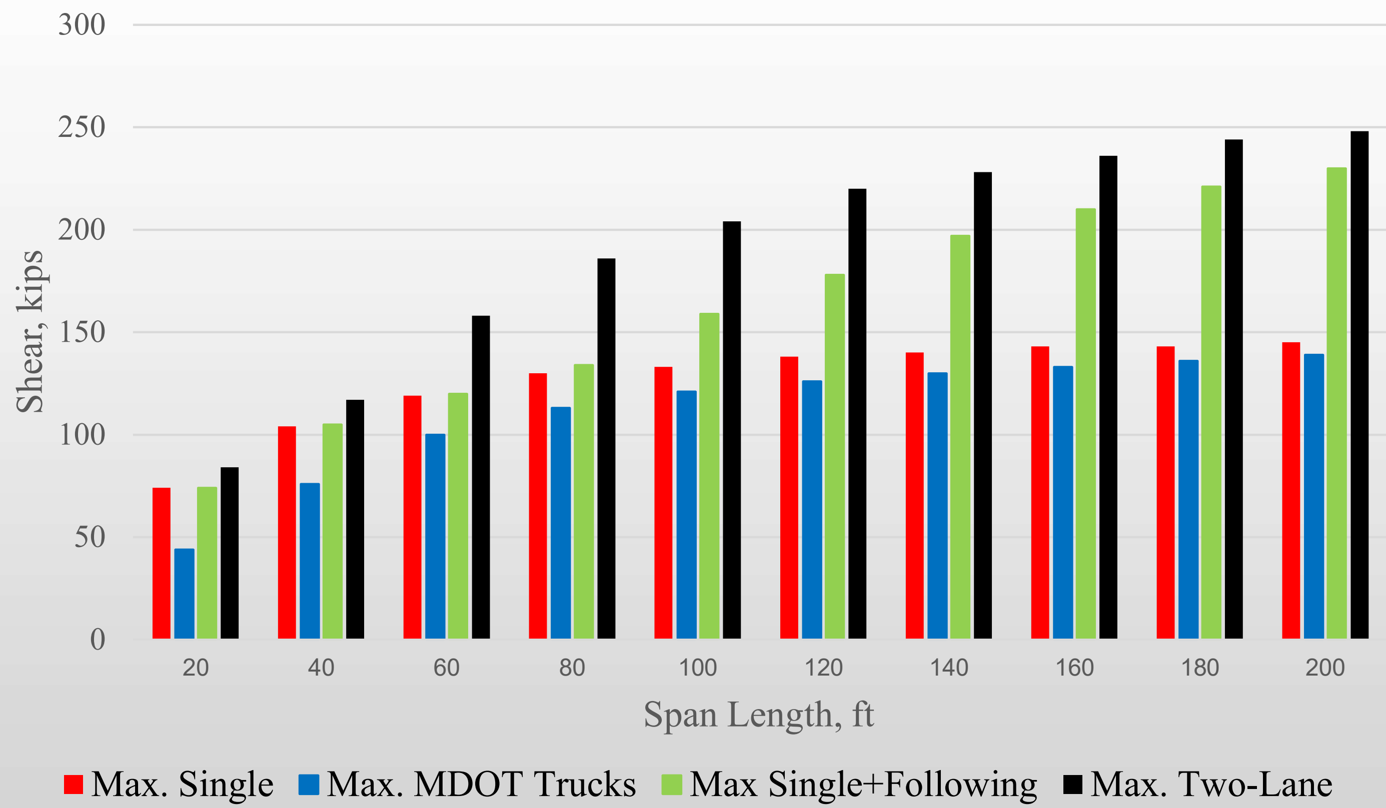
Background | **WIM Data Analysis** | Reliability Analysis | Load Models



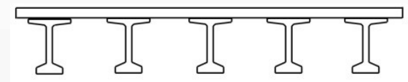
Maximum Single, Following, and Side-by-side Simple Span Moments.



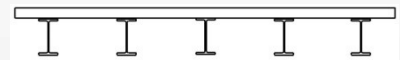
Maximum Single, Following, and Side-by-side Simple Span Shears.

Determine Bridge Types to Consider for Analysis :

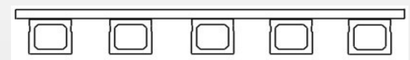
1. Girder Type:
   a. Prestressed concrete I-girders (PC).



   b. Steel girders (CS).



   c. Reinforced concrete girders (RC).
   d. Prestressed concrete box beams, spaced (BS).



   e. Prestressed concrete box beams, side-by-side (BT).

2. Span Type and Load Effects (both single lane and two lane):
   a. Simple Span, Moment.
   b. Simple Span, Shear

3. Span Lengths:

   20-200 ft at increments of 20 ft.

4. Girder Spacing (as applicable):
   a. 4-12 ft. at increments of 2 ft.
   b. For side-by-side box beams, two widths (36”, 48”) are used.

In total 195 bridge cases
780 combinations

- Live Load statistics: Rating - 5 years.
- Regression analysis to best-fit upper tail of load effects.
- Extreme Type I probability theory to estimate statistical parameters (mean and COV).

$$\bar{L}_{\max} = \mu_N + \frac{0.5772157}{\alpha_N}$$

$\bar{L}_{\max}$ = Mean maximum of load effect for the projected return period.

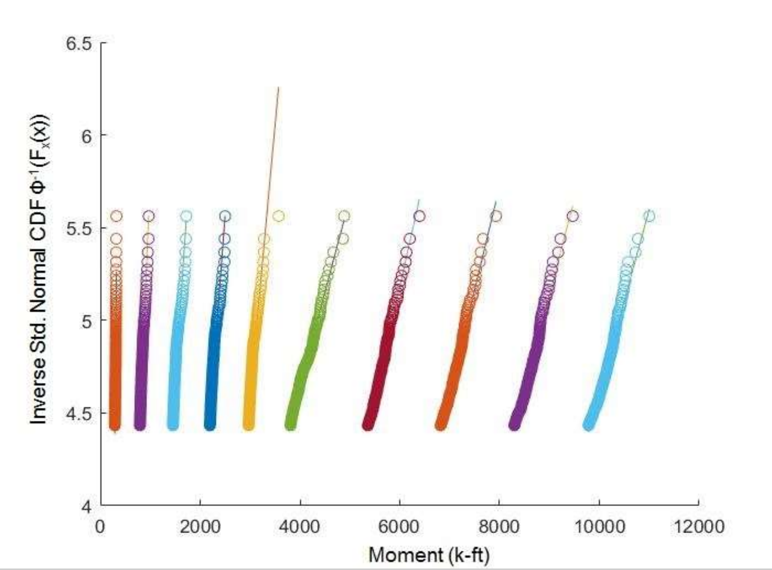
$$\sigma_{L\max} = \frac{\pi}{\sqrt{6}\alpha_N}$$

$\sigma_{L\max}$ = Standard deviation of load effect for the projected return period.

where

$$\mu_N = \bar{x} + \sigma\left(\sqrt{2\ln(N)} - \frac{\ln(\ln(N)) + \ln(4\pi)}{2\sqrt{2\ln(N)}}\right)$$

$$\alpha_N = \frac{\sqrt{2\ln(N)}}{\sigma}$$



- Live Load Uncertainties:

a) Data projection (V_{proj}).

b) Site-to-site variation (V_{site}).

c) Uncertainty in $\bar{L}_{max}$ based on the WIM data at a particular site (V_{data}).

d) Impact factor (V_{IM}). (based on available field tests)

e) Distribution of load to the girder (V_{DF}). (based on available field tests)

$$V_{\max L} = \sqrt{V_{projection}^2 + V_{site}^2 + V_{data}^2 + V_{IM}^2 + V_{DF}^2}$$

The general limit state function for a bridge girder in this study is:

$$g = R - (Dp+Ds+DW) - LL$$

where
R: Girder resistance
Dp : Dead load due to prefabricated components
Ds : Dead load due to site-cast components
Dw : Dead load due to wearing surface
LL: Vehicular live load

RVs from Nowak (1999) to be consistent with the AASHTO LRFD and MBE calibrations.

Also, girder resistance is taken as a lognormal random variable while the sum of load effects is assumed normal.

Random Variable	Bias Factor	COV
Resistance RVs (R)	**λ**	
Prestressed Concrete, Moment	1.05	0.075
Prestressed Concrete, Shear	1.15	0.14
Reinforced Concrete, Moment	1.14	0.13
Reinforced Concrete, Shear	1.20	0.155
Steel, Moment	1.12	0.10
Steel, Shear	1.14	0.105
Load RVs		
Vehicle Live Load (LL), Moment	1.07-2.08	0.16-0.27
Vehicle Live Load (LL), Shear	1.0-1.64	0.16-0.30
Live Load Impact Factor (IM)	1.13, 1.10	0.09, 0.055
Vehicle Load Distribution Factor (DF)	0.72-0.99	0.11-0.18
Dead Load, Prefabricated (D_p)	1.03	0.08
Dead Load, Site-Cast (D_s)	1.05	0.10
Dead Load, Wearing Surface (D_w)	mean 89 mm	0.25

Determine needed design and rating load models to meet required safety levels

- For rating: β min = 1.5, β min ave = 2.5

$\beta = 1.50 \longrightarrow P_f \approx 1{:}15$ $\beta = 2.50 \longrightarrow P_f \approx 1{:}160$

These reliability targets are notional values and corresponding failure probabilities should not be taken literally.

$$RF = \frac{\varphi R_n - 1.25DC - 1.5DW}{\gamma_{LL}(LL + IM)} \longrightarrow RF = \frac{R_n - 1.25DC - 1.5DW}{(RLE)(DF)}$$

$$RF = \frac{R_n - 1.25DC - 1.5DW}{(RLE)(DF)} \xrightarrow{RF=1} R_n = (1/\phi)(1.25DC + 1.5DW + \gamma_{LL}(LL + IM))$$

- Knowing the minimum (1.50) and average (2.50) target reliability index, minimum value of γ_{LL}(LL+IM) or Required Load Effect (RLE) can be determined.

- The possibilities to develop live-load models:

1- For each bridge type, apply the appropriate load factor such that the minimum reliability index is met. In this study, for 195 bridges, 195 load factors is required!

- Drawbacks:

Accurate but not practical!

2- Use the current load models (i.e. AASHTO and MDOT rating trucks) and increase/modify the load factor such that the minimum reliability index (level of safety) is met for all considered bridge types.

- Drawbacks:

May result in large inconsistencies in level of reliability, where many of the structures are greatly under-rated, producing overly conservative results and leads to unnecessarily traffic restriction (posting).

The degree of conservatism in rating costs much more money comparing to the design.

3- Determine a new, better set of rating trucks. A Reliability based design optimization can be used such that the best option(s) for the axle weight and spacing can be determined.

- Drawbacks:

1- May result in an unrealistic vehicle configuration.
2- Complexity and computational cost.
3- convergence to a local rather than global optimum.

4- Using a reliability-based design optimization (RBDO) to develop an expression for the load model.

- Drawbacks:

  Accurate but not practical (no actual rating vehicle)!
  Potentially high computational cost.

- A function is needed to directly describe the required load effect (RLE) caused by a rating vehicle.

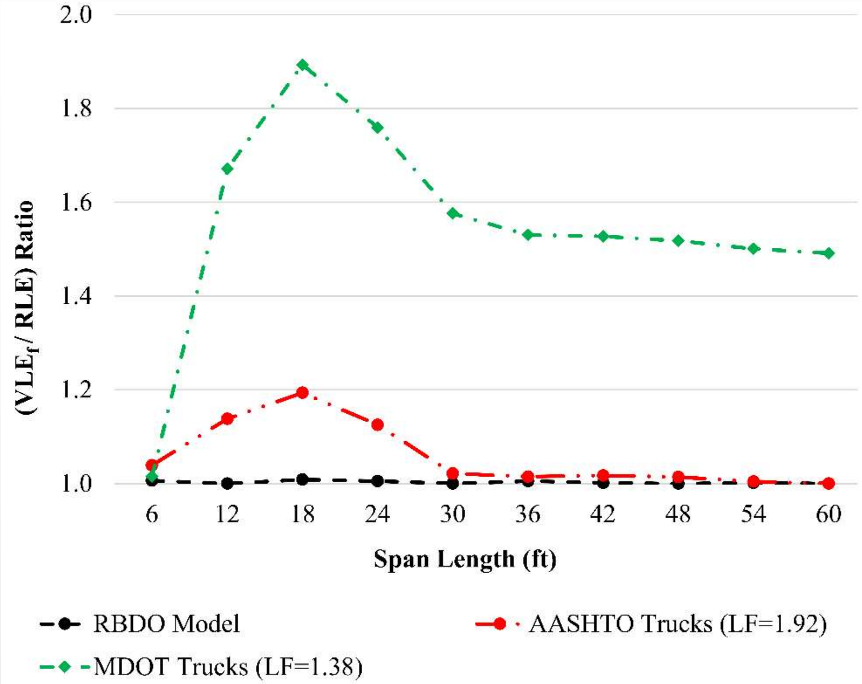
- Various curves including logarithmic, power, compound, logistic, growth, polynomial, and sum of sines functions were considered.

$$RLE = \sum_{i=1}^{n} a_i \, sin(b_i x + c_i)$$

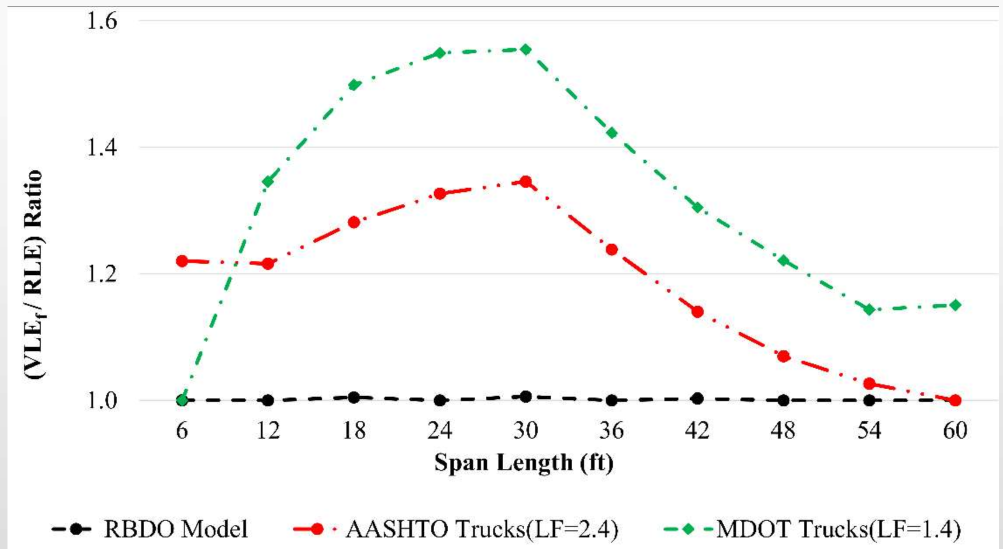
- Constants a_i, b_i, and c_i represent design variables to be determined in the optimization and x is bridge span length.

- A genetic algorithm (GA) is used for the solver.
- Objective function: minimize variability in structural reliability among the different bridge girders considered for rating.
- Constraint: The reliability index constraint for girder i (β_i) is greater than the minimum acceptable reliability index (β_{min}).

$$\min f(\boldsymbol{X}, \boldsymbol{Y})$$
$$\text{s.t. } \beta_i \geq \beta_{min} \text{ (here is 2.5)}; \; i = 1, N_p$$
$$Y_k^l \leq Y_k \leq Y_k^u; \; k = 1, NDV$$



MI-LEP Moment



MI-LEP Shear

Load Effect	Parameter								
	a_1	b_1	c_1	a_2	b_2	c_2	a_3	b_3	c_3
MI-LEP Moment	8556	0.015	-0.621	4879	0.022	2.07	295	0.053	1.91
MI-LEP Shear	244	0.002	.021	113	0.002	6.30	4.59	0.062	-1.67

5- "Modified Best Selection" approach

- The goal is to choose the best truck with the appropriate load factor from the WIM-data such that the minimum reliability index can meet while the variation from the target reliability index is minimized.

- The proposed model was found not only to be more simple but to have a substantial computational advantage over RBDO for load model development

Step by Step Procedure of Modified Best Selection Approach:

Step 1:

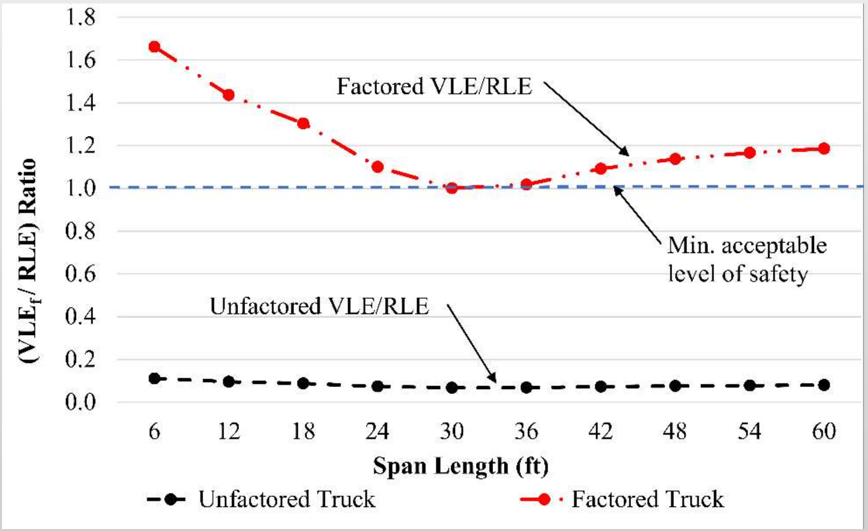
- Calculate the minimum load factor required for all span lengths and bridge types.

- The load factor is determined such that the value of VLE×LF/RLE across all bridge types and span lengths is not less than one (minimum acceptable level of safety is met for all bridge cases).

The minimum load factor (LF) $= \frac{1}{min(\frac{VLE}{RLE})_i}$

where

i is the considered span lengths
VLE is vehicle load effect
RLE is required load effect



Step 2:

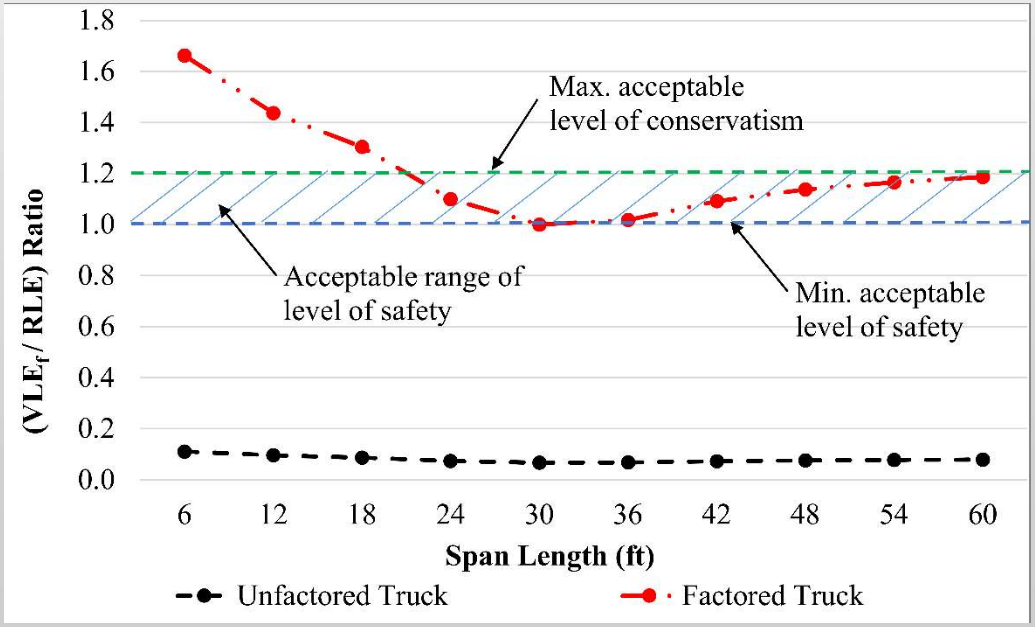
- Select a set of initial trucks for further consideration (i.e. remove the vehicles that do not have the potential to be selected as an optimal selection).
- WIM data contains 89 million MI-LEP. Full consideration for all vehicles is costly.
- In this step, only the vehicles that produce a range of provided to required load effect ratios within a specified limit are taken for further consideration. This selection limit can be expressed as:

$$\left(\frac{VLE \times LF}{RLE}\right)_{max} < 1 + k$$

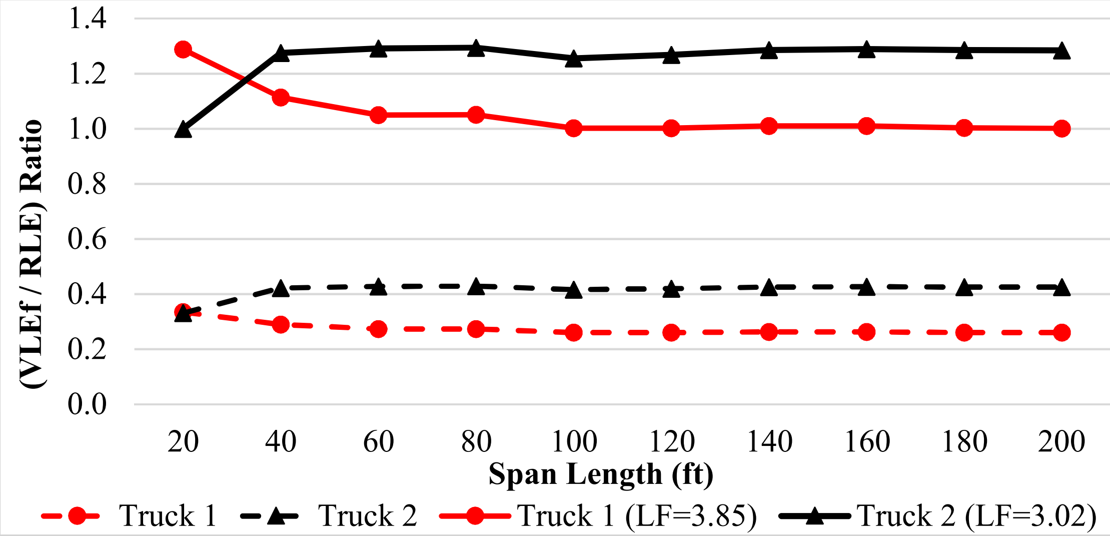
k is the fractional range limit imposed.

The higher k value increase the level of conservatism.

Here, the k is limited to 20%



- In the steps 1 and 2, $\left(\frac{VLE\times LF}{RLE}\right)$ ratio shifts above one and the maximum $\left(\frac{VLE\times LF}{RLE}\right)$ ratio is limited to 1.20.
- It may appear intuitive to do so, choosing the lowest $\left(\frac{VLE\times LF}{RLE}\right)_{max}$ does not simply select the best vehicle across all span lengths.
- Here both trucks have the same $\left(\frac{VLE\times LF}{RLE}\right)_{max}$ of 1.29 but truck 1 is a better option.



Step 3:

- In this study, the Demerit Points Classification suggested by Collins (2001) is modified and used for selecting the best truck(s).

Experimental over prediction ratio, λ	Classification	Penalty (PEN)
< 0.50	Extremely dangerous	10
0.50 – 0.65	Dangerous	5
0.65 – 0.85	Low safety	2
0.85 – 1.30	Appropriate safety	0
1.30 – 2.00	Conservative	1
> 2.00	Extremely conservative	2

Demerit Points Classification (Collins 2001)

$\lambda = \frac{VLE * LF}{RLE}$	Classification	Penalty (PEN)
$1.00 \leq \lambda \leq 1.03$	Best	0
$1.03 < \lambda \leq 1.05$	Ideal	1
$1.05 < \lambda \leq 1.10$	Very good	2
$1.10 < \lambda \leq 1.15$	good	5
$1.15 < \lambda \leq 1.20$	Conservative	10
$1.20 < \lambda$	Extremely conservative	20

Modified Demerit Points Classification (this study)

- In step 3, depending on the $\left(\frac{VLE \times LF}{RLE}\right)$ ratio for each span, a penalty point is assigned. The total penalty points for each vehicle are summed.

- The vehicle with the lowest penalty points can be selected as the best choice.

- vehicle live load factor γ_{LL} = max(VLE_f / $(VLE + IM)$)

- However, depending on the size of database, it is possible that multiple vehicles with the same penalty points can be determined.

- If multiple vehicles with the same penalty points are determined, as the final step, the vehicle with the minimum average $\left(\frac{VLE \times LF}{RLE}\right)$ across all bridge span lengths can be selected.

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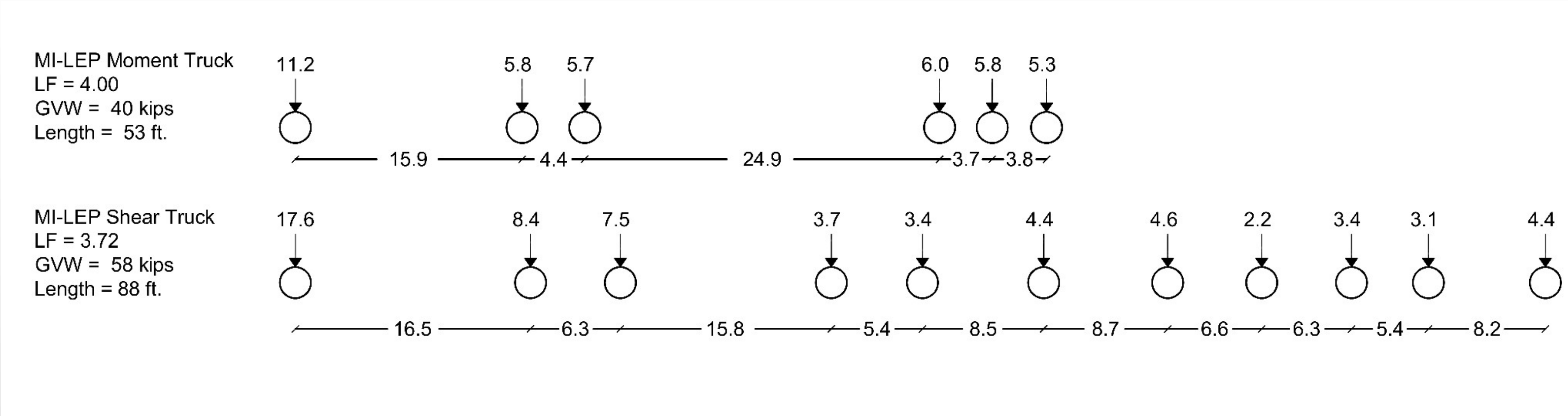

Modified Best Selection Approach Trucks (kips, ft.).

Database		RBDO	Mod. Best Selection	AASHTO	MDOT
MI-LEP Moment	PEN	1	0	21	180
	Mean	1.01	1.01	1.06	1.55
MI-LEP Shear	PEN	0	0	127	155
	Mean	1.00	1.01	1.19	1.32

Comparison of Total Penalty Points and average VLE × LF/RLE

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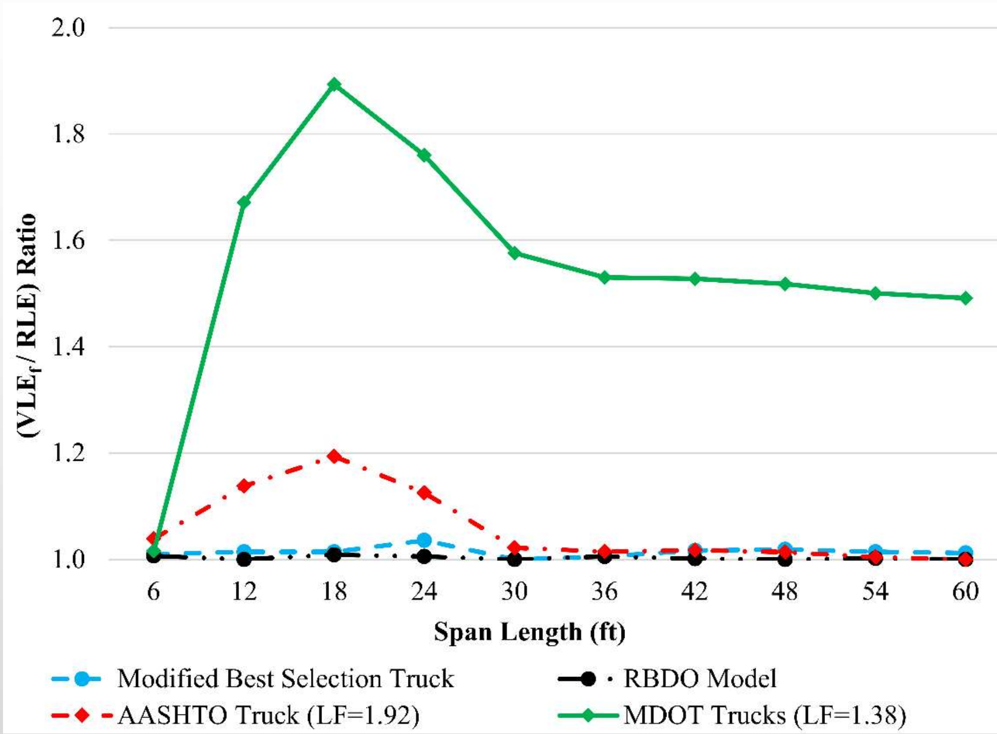
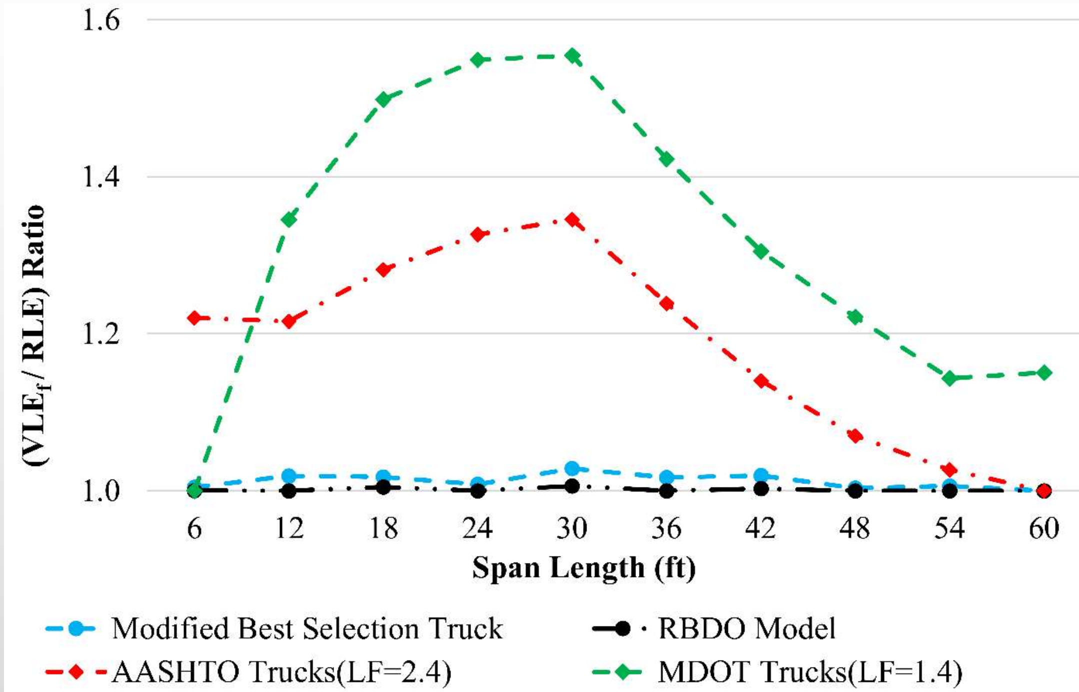
MI-LEP Moment



Design Load	Load Factor	β_{min}	β_{max}	$\beta_{average}$	COV
Exact (using RLE)	-	2.50	3.95	2.83	0.13
RBDO Load Model	-	2.50	3.95	2.84	0.13
Modified Best Selection Truck	4.00	2.50	3.95	2.87	0.13
MDOT Trucks (current LF)	varies[1]	2.13	5.52	3.74	0.20
MDOT Trucks (required LF)	1.35	2.50	5.74	4.09	0.18
AASHTO Trucks (required LF)	1.93	2.50	4.14	3.05	0.15

MI-LEP Shear



Design Load	Load Factor	β_{min}	β_{max}	$\beta_{average}$	COV
Exact (using RLE)	-	2.50	4.20	2.90	0.10
RBDO Load Model	-	2.50	4.25	2.91	0.10
Modified Best Selection Truck	3.72	2.50	4.26	2.93	0.11
MDOT Trucks (current LF)	varies[1]	2.10	4.67	3.22	0.14
MDOT Trucks (required LF)	1.40	2.50	5.05	3.55	0.14
AASHTO Legal Trucks (required LF)	2.40	2.50	4.97	3.33	0.14

- More complicated rating models are not necessarily most effective. Using Modified Best Selection approach, a single rating vehicle for moment effects and another vehicle for shear effects produced significantly more consistent results overall when compared to the multiple-vehicle AASHTO and MDOT alternative models.

- Modified Best Selection approach can be used to develop 1, 2, and 3-unit vehicles to meet bridge posting criteria.

- Modified Best Selection approach can be used to develop live load models for design.

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Thank you!

Questions?