The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Design Guidelines for Bridges Subjected to Light Rail Transit Loads

Tuesday, April 24, 2018
1:00-2:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss NCHRP Report 851.

Learning Objectives

At the end of this webinar, you will be able to:

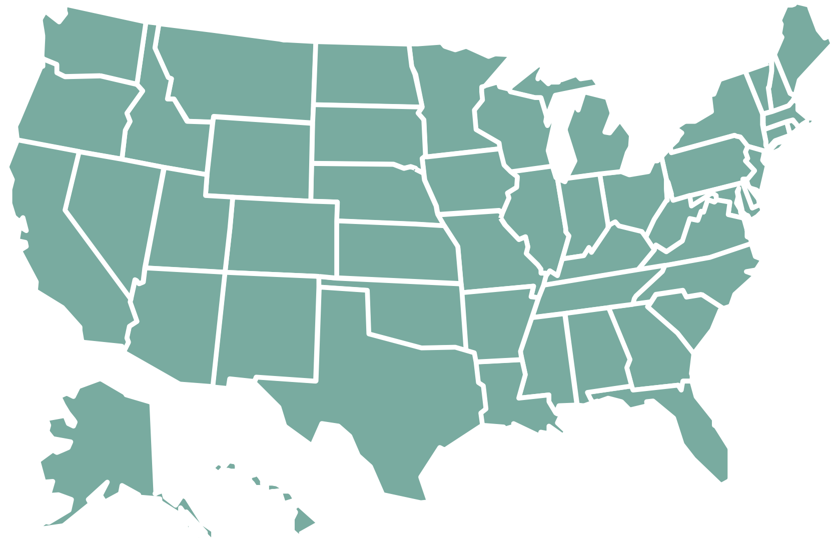
- Discuss the current state of light rail bridge design
- Describe the behavior of bridges subjected to light rail loadings along with various forces
- Identify the effort to establish a new design approach for light rail loadings
- Describe how to design light rail bridges pursuant to the AASHTO Guide Specifications for Light Rail Bridges

NCHRP Research Report 851: Proposed AASHTO LRFD Bridge Design Specifications for Light Rail Transit Loads

NCHRP Project 12-92

NCHRP is a State-Driven Program

- Sponsored by individual state DOTs who
  - Suggest research of national interest
  - Serve on oversight panels that guide the research.



- Administered by TRB in cooperation with the Federal Highway Administration.

Practical, ready-to-use results

- Applied research aimed at state DOT practitioners
- Often become AASHTO standards, specifications, guides, syntheses
- Can be applied in planning, design, construction, operations, maintenance, safety, environment

Today's Speakers

- *Dr. Yail Jimmy Kim, Design Guidelines for Bridges Subjected to Light Rail Transit Loads*
- *Bill DuVall, Moderator*

Design Guidelines for Bridges Subjected to Light Rail Transit Loads

Yail Jimmy Kim, Ph.D., P.Eng., F.ACI

Professor, Department of Civil Engineering

University of Colorado Denver

President, ***Bridge Engineering Institute***

Contents

Introduction

Introduction

Problem Statement

- Live load effects of light rail trains (e.g., load distribution, multiple presence, and dynamic load allowance) are limitedly known. AASHTO LRFD BDS and AREMA are frequently referenced even though their live load characteristics are different from those of light rail trains.
- The absence of a standard live load (e.g., HL-93 of AASHTO LRFD and E80 of AREMA) results in various design outcomes depending upon transit agencies. A standard load model should be proposed.
- There is a practical need for light rail bridges to carry both light rail train and regular highway traffic loads. Such a requirement is currently not implemented in design of light rail structures. A unified design approach is necessary.

Introduction

Problem Statement (cont'd)

- Load factors used for light rail structures are directly obtained from AASHTO LRFD BDS (Art. 3.4.1) or from modified sources. Given that the load characteristics of light rail trains are different from those of highway traffic, adequate evaluation is required and alternative factors need to be proposed.

- The ambiguous article of AASHTO LRFD BDS should be updated: Art. 3.6.1.5 (*where a bridge also carries rail-transit vehicles, the owner shall specify the transit load characteristics and the expected interaction between transit and highway traffic*) and C.3.6.1.5 (*If the rail transit is supposed to mix with regular highway traffic, the owner should specify or approve an appropriate combination of transit and highway loads for the design*).

Introduction

The objectives of the research are:

- To characterize light rail transit load effects on the behavior of bridge superstructure (e.g., standard train load, dynamic load allowance, load distribution, and design factors for LRFD)

- To examine the interaction between the light rail load and supporting structures, which can generate various forces to consider in design and practice

- To propose a unified design approach for light rail transit and highway traffic, and corresponding design articles and commentaries for AASHTO LRFD Specifications, including design examples for practitioners

Introduction

Overview of Research

Phase I
(Planning)

- Literature review (155 papers)
- Research methodologies
- Outline of specifications

Phase II
(Implementation)

- Site work and FE modeling
- Standard light rail load model
- Load effects and forces/load factors

Phase III
(Specifications)

- Specification articles proposed
- Design examples

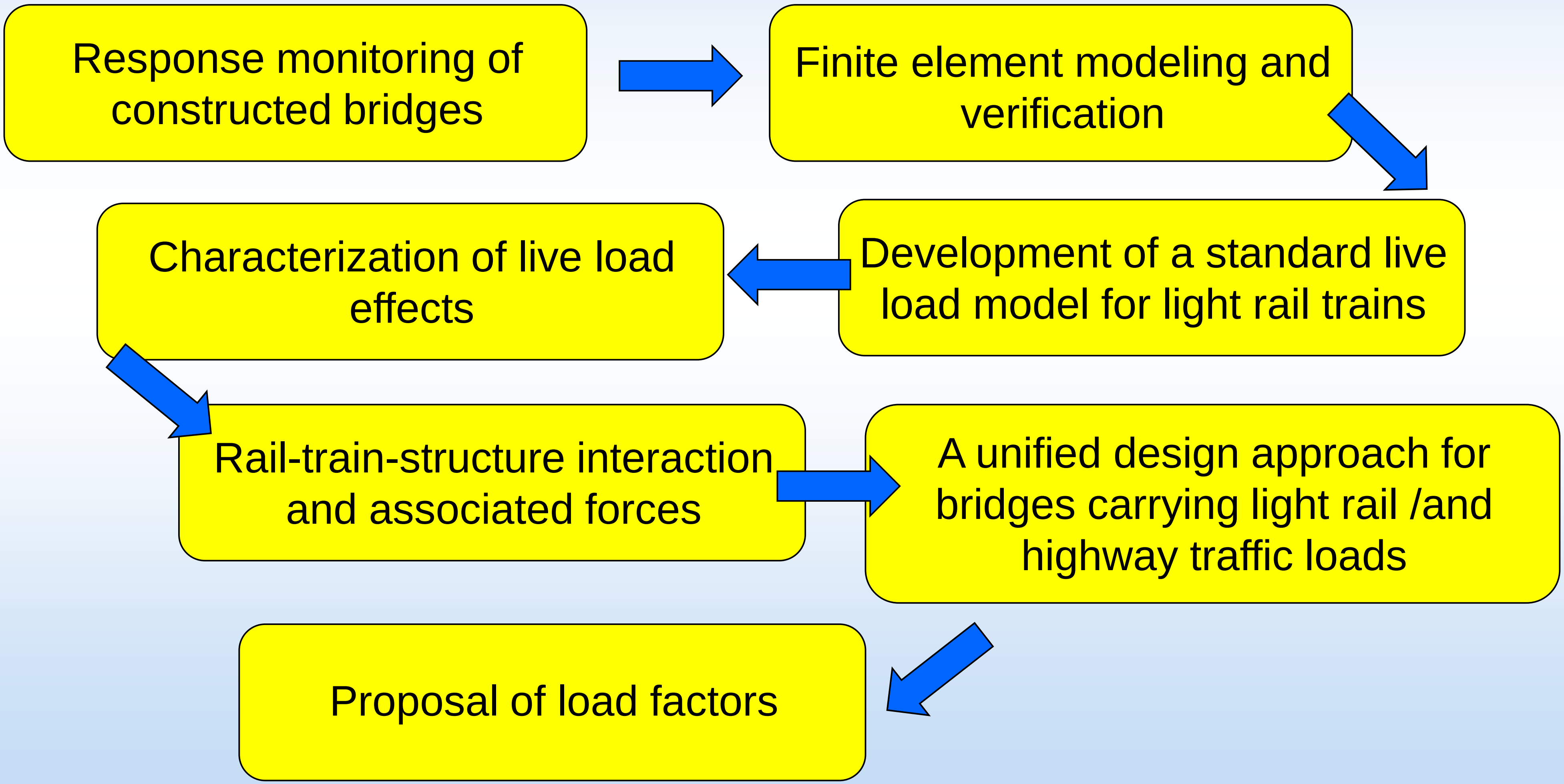
Phase IV
(Final product)

- Update of specifications
- Ballot items for AASHTO

Research Program

Research Program

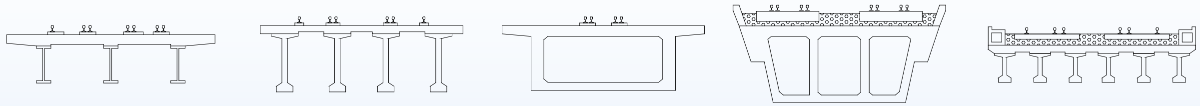
Overview of Technical Tasks

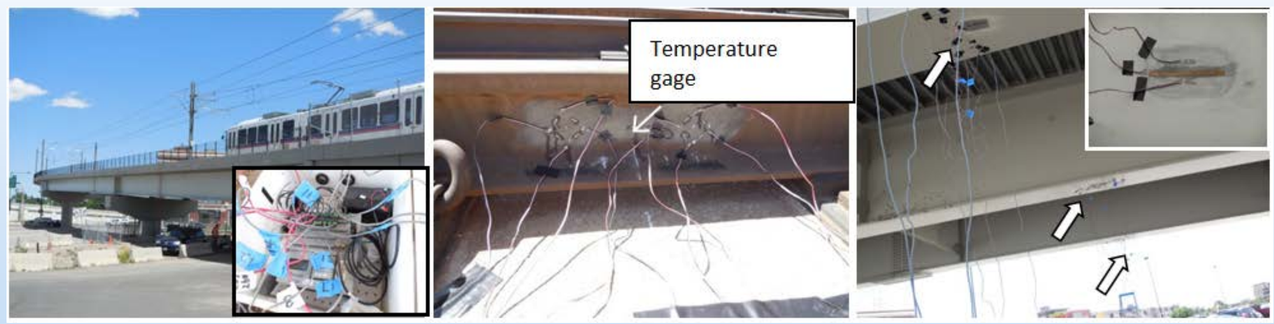


Research Program

Task 1: Response monitoring of constructed bridges

- Objectives of this task are:
  - to collect field data with regard to bridge behavior and track responses subjected to light rail train load
  - to provide necessary information on validating finite element models and conducting statistical investigations

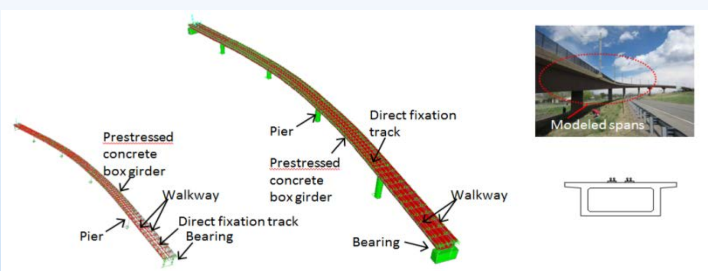


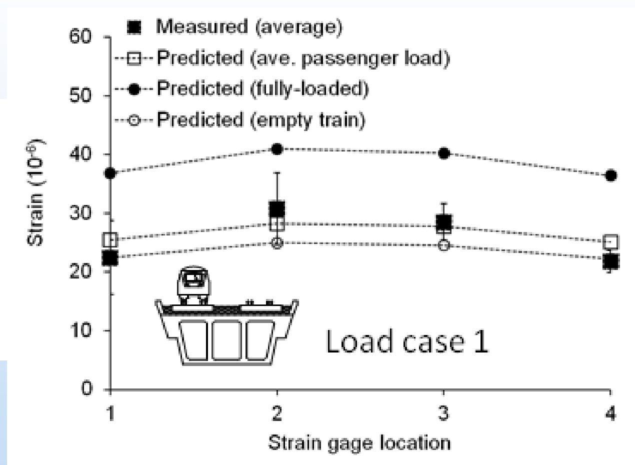


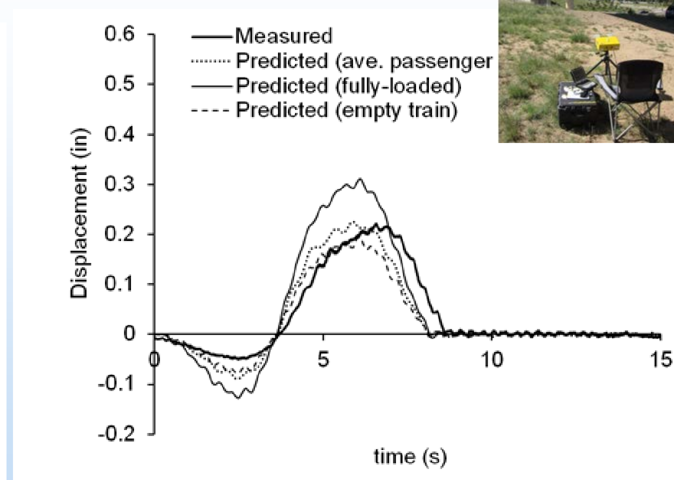
Research Program

Task 2: Finite element modeling

- Objectives of this task are:
  - to propose a bridge-model matrix for conducting technical analysis
  - to develop a reliable predictive method for examining bridge responses associated with various light rail train loads



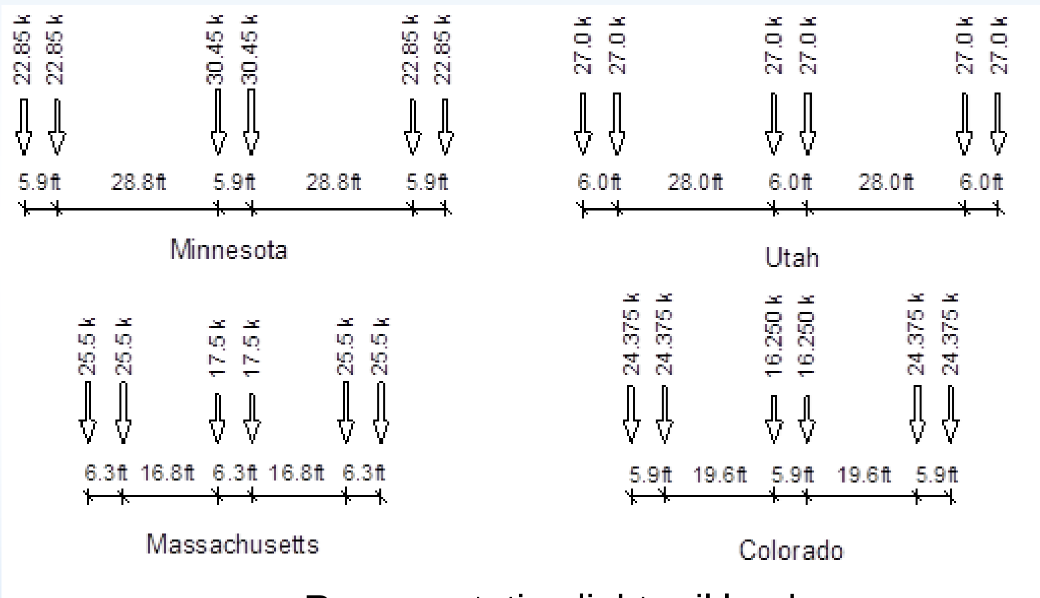




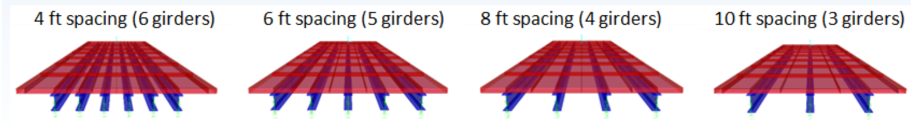
Research Program

Task 2: Finite element modeling

- Benchmark bridges (representative live loads/ FE models)



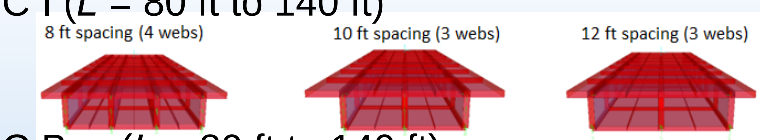
Representative light rail loads



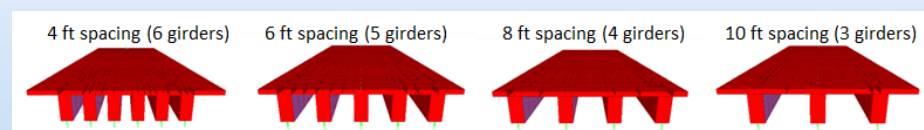
Steel Plate (*L* = 80 ft to 160 ft)

Steel Box (*L* = 80 ft to 14o ft)

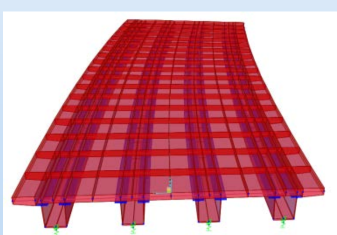
PC I (*L* = 80 ft to 140 ft)



PC Box (*L* = 80 ft to 140 ft)

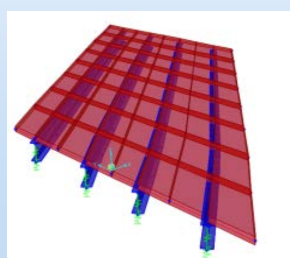


RC (*L* = 30 ft to 70 ft)



Curved

(*R* = 500 ft to 1500 ft)



Skewed (0º to 60º)

Research Program

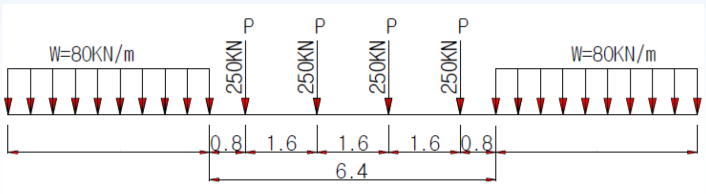
Task 3: Development of a standard live load model for light rail transit

- Objectives of this task are:
  - to propose a standard live load model for design of bridges carrying light rail transit gravity loadings
  - to establish a foundation for developing reliability-based load factors dedicated to bridges carrying light rail trains or carrying light rail trains and highway gravity loadings

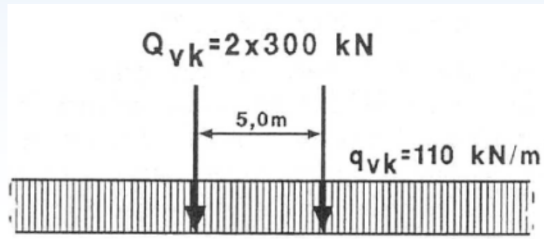
Research Program

Task 3: Development of a standard live load model

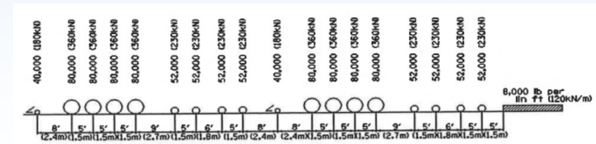
- Reference load models (European standard train loading)



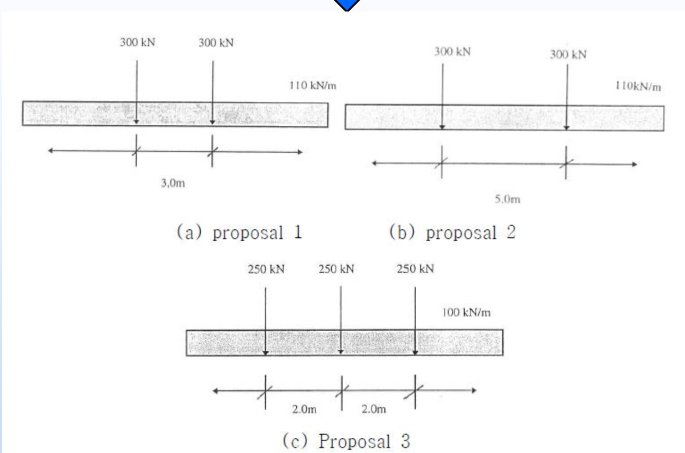
LM71 (existing)



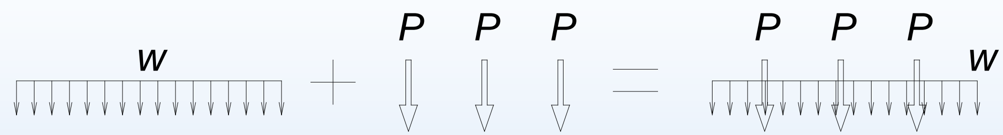
LM2000 (new)



Cooper E80 (AREMA)



Candidate models



Uniformly distributed load (Magnitude to be determined)

Concentrated loads (Magnitude, spacing, and number of concentrated loads to be determined)

Proposed live load model

Proposed format
(convenience and familiarity: AASHTO-oriented model)

Research Program

Task 3: Development of a standard live load model

- Procedure

Deterministic analysis → **Probabilistic analysis** → **Integration**

Deterministic analysis
- Selection and modeling of representative load models
- Numerical parametric study
- Determination of equivalent live load models (lane and concentrated loads)

Probabilistic analysis
- Simulation of bridge responses with various live load effects at multiple risk levels
- Identifying possible response ranges in bending and shear

Integration
- Integration of deterministic and probabilistic analysis results
- Proposal of standard live load for light rail transit
- Comparative assessment with existing load models (load-enveloping)

Research Program

Task 3: Development of a standard live load model

- Probability-based load inference to better address uncertainty

  - *75-year anticipated load*: AASHTO LRFD BDS requires a 75 year design life; HL93 was developed based on this probability level

  - *99.9% anticipated load*: potential occurrences of 99.9%, 95%, and 90% are conventionally used in probability-based design

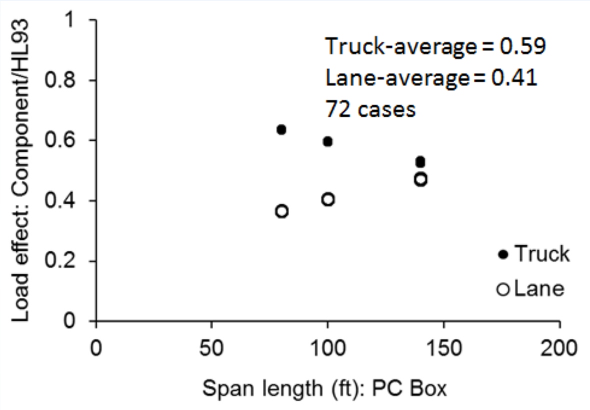
  - *Upper 20% anticipated load*: a typical bias of 20% exists between design load and corresponding responses. This calibration category can address potential risk induced by overloading

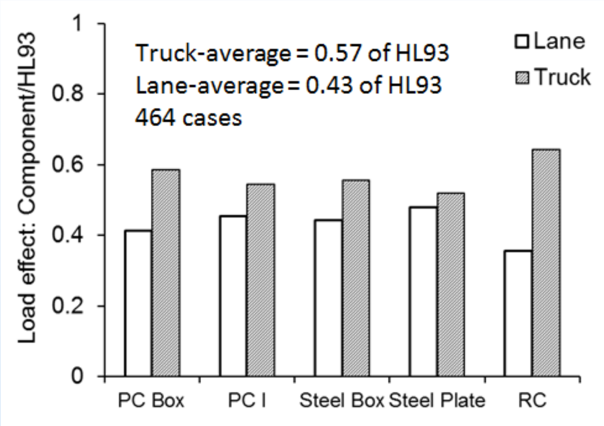
  - *Average anticipated load*: this load level characterizes average load effects of the representative light rail trains

Research Program

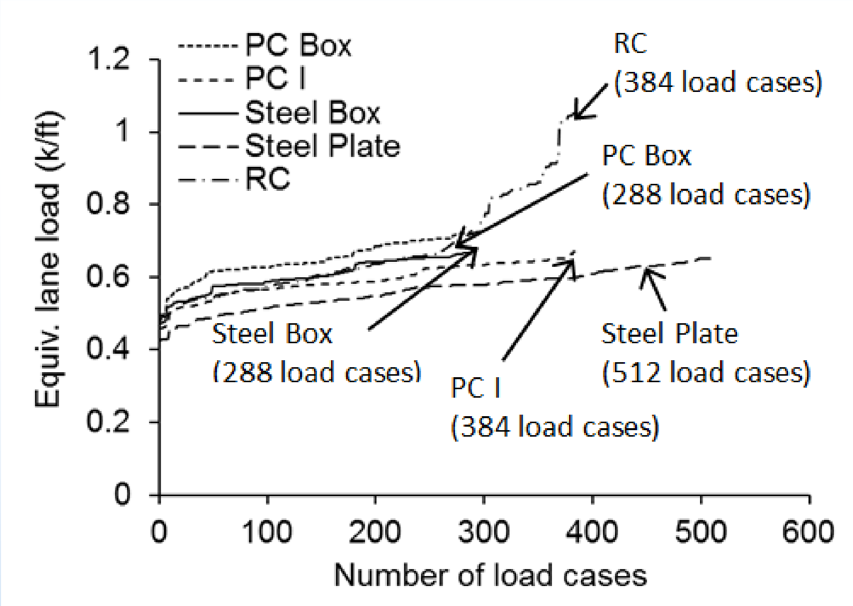
Task 3: Development of a standard live load model

- Decomposition of HL93 (concentrated load and lane load)





464 load cases with HL93

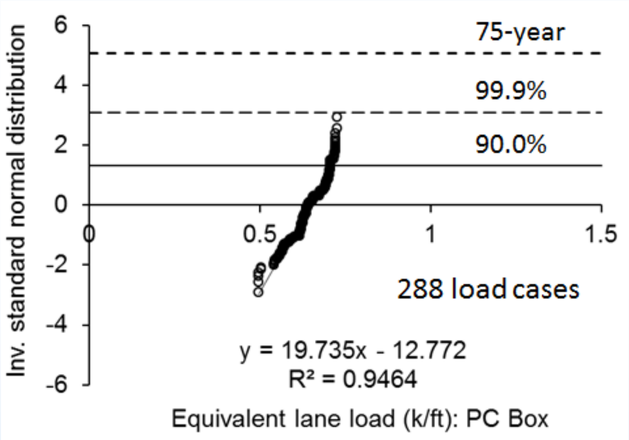


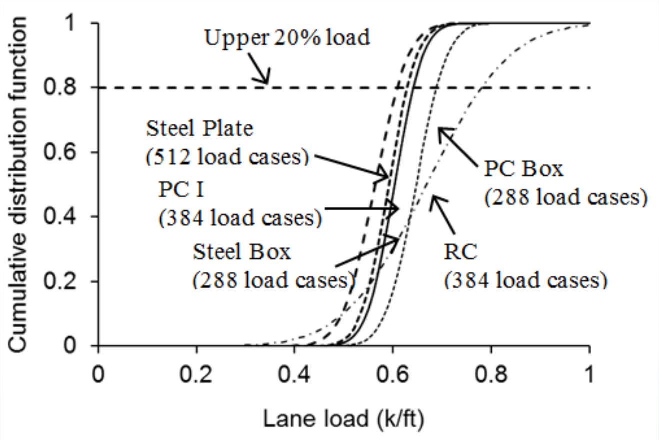
1,856 load cases with representative light rail trains

Research Program

Task 3: Development of a standard live load model

- Probability-based inference (equivalent lane load)

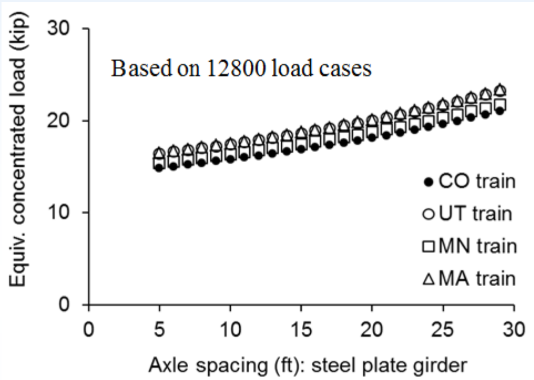


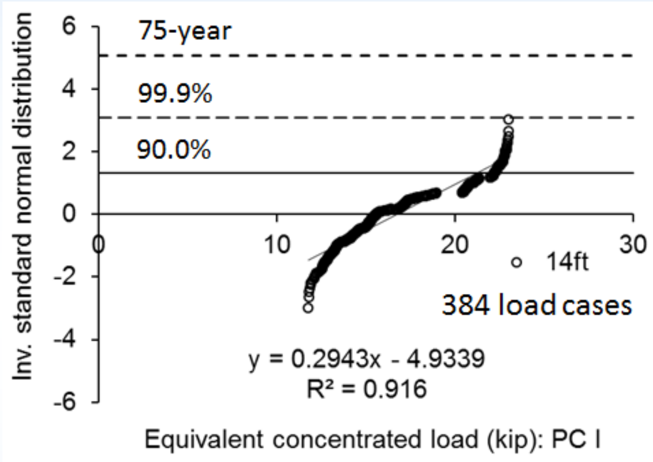


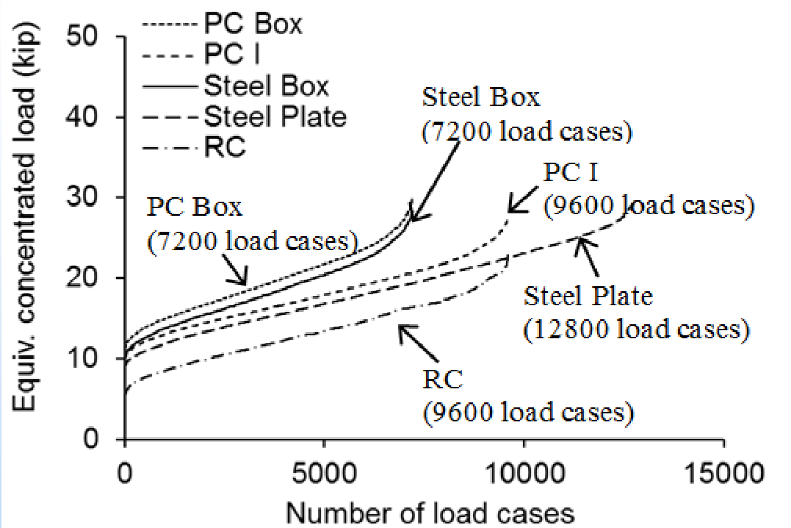
Research Program

Task 3: Development of a standard live load model

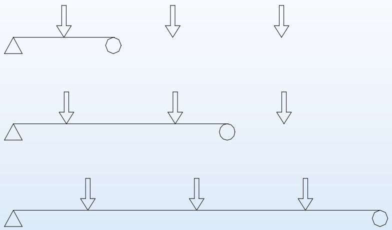
- Probability-based inference (equiv. concentrated load, single axle *P*)

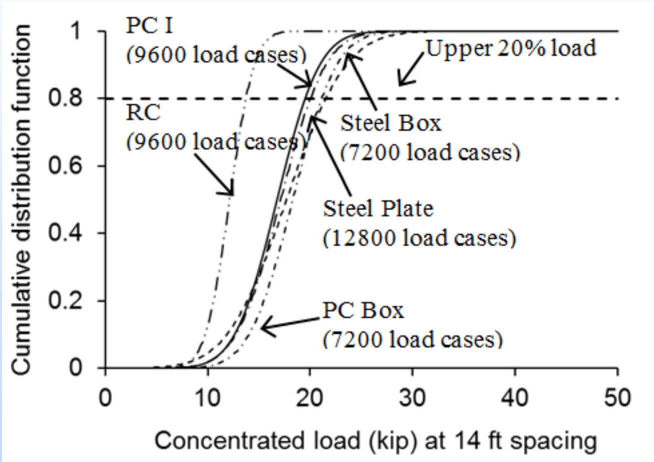






46,400 load cases

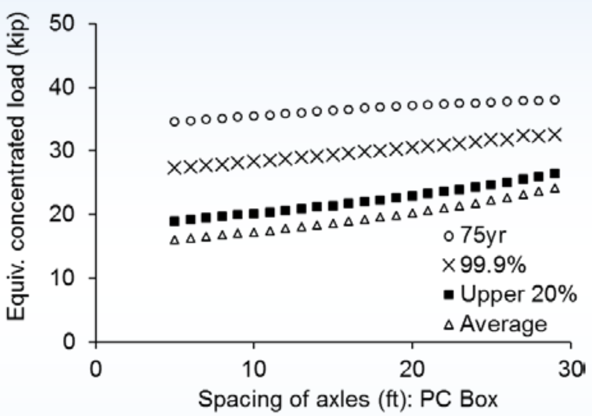


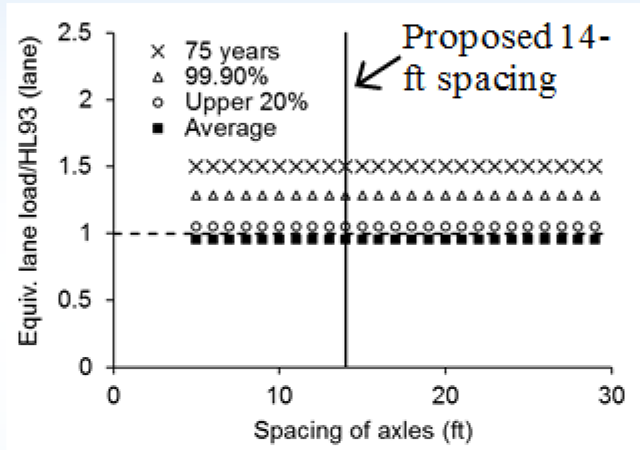


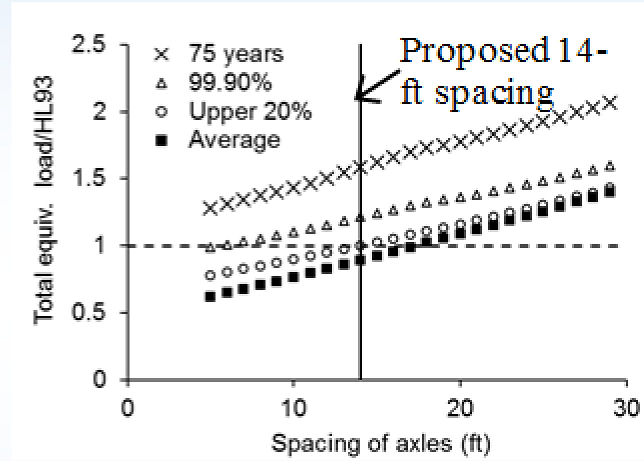
Research Program

Task 3: Development of a standard live load model

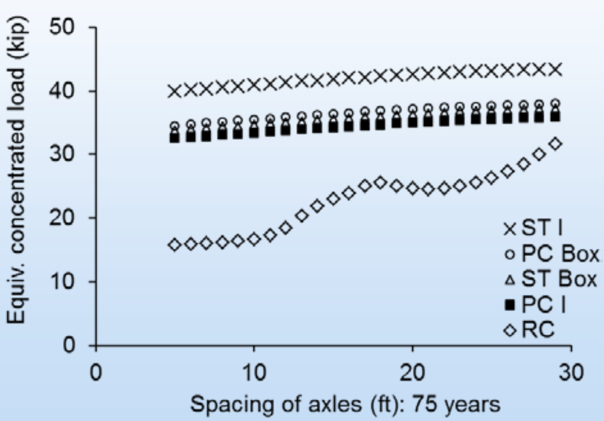
- Probability-based inference (equiv. concentrated load, single axle *P*)

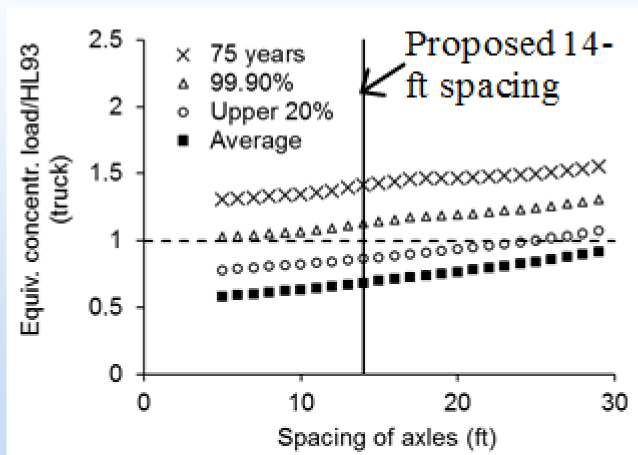


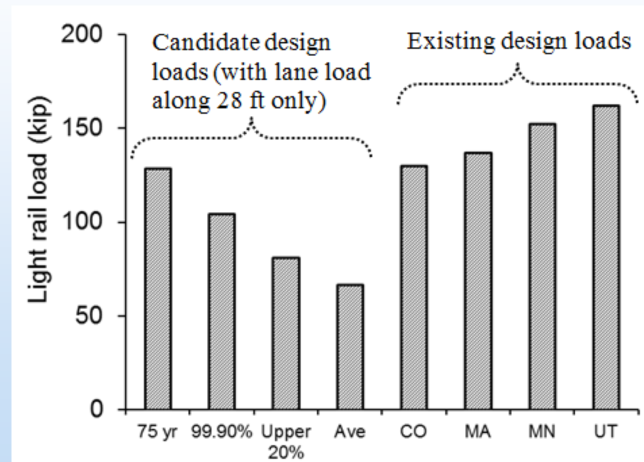




Effect of probably level







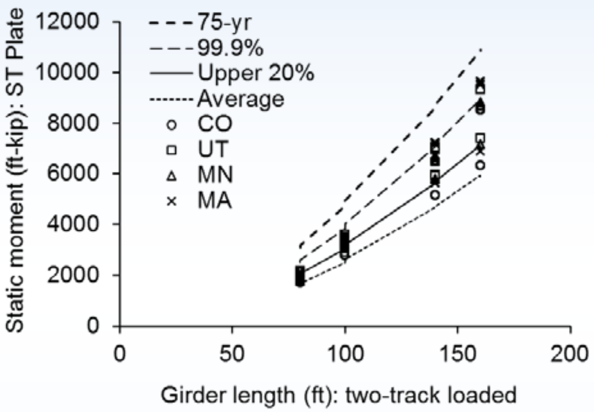
Effect of bridge type

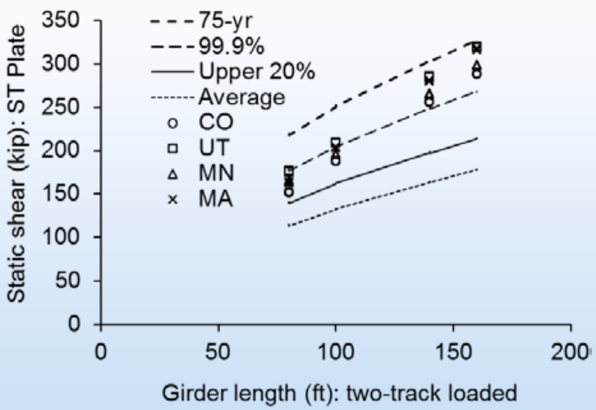
Not overly conservative

Research Program

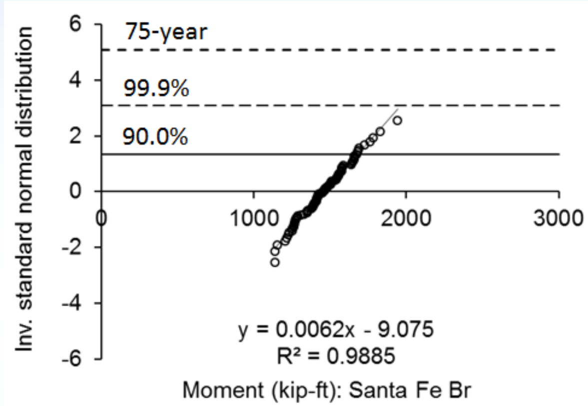
Task 3: Development of a standard live load model

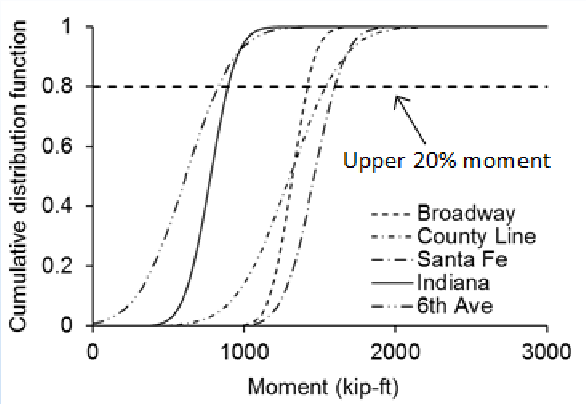
- Assessment based on i) load-enveloping and ii) site-based inference



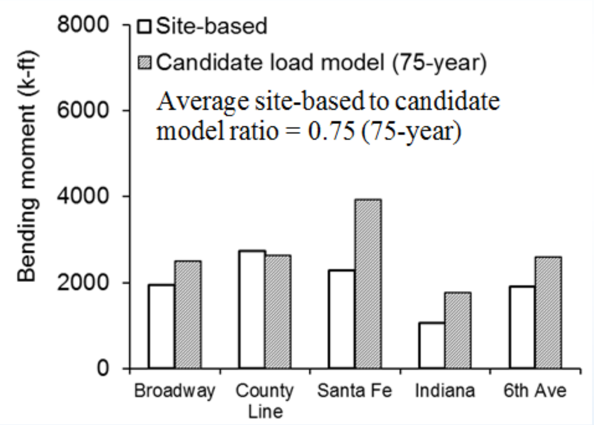


FE-based load-enveloping (deterministic)





Site-based (probabilistic)

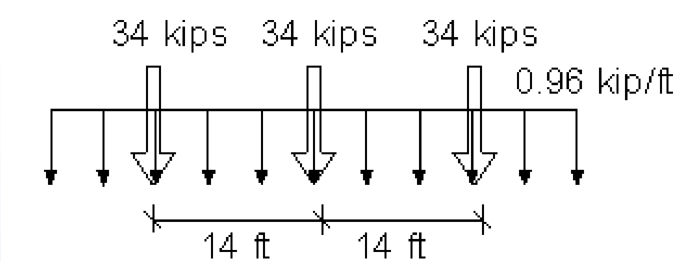


Service/ultimate = 0.75

Research Program

Task 3: Development of a standard live load model

- Proposed live load model
  - 0.96 k/ft + three axles of 34 kips at a spacing of 14 ft (Standard live load model)
  - Alternative site-specific load models are allowed based on the discretion of individual transit agencies



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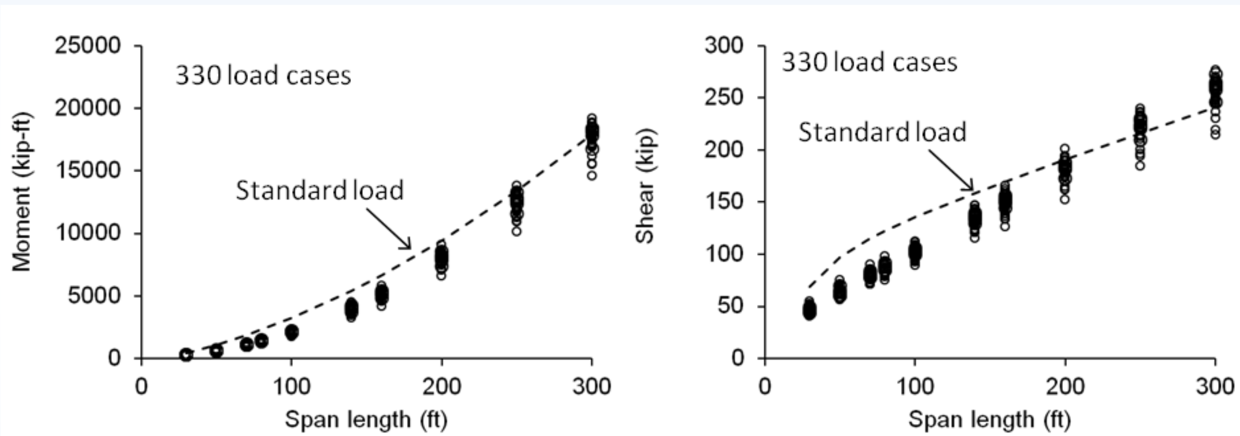
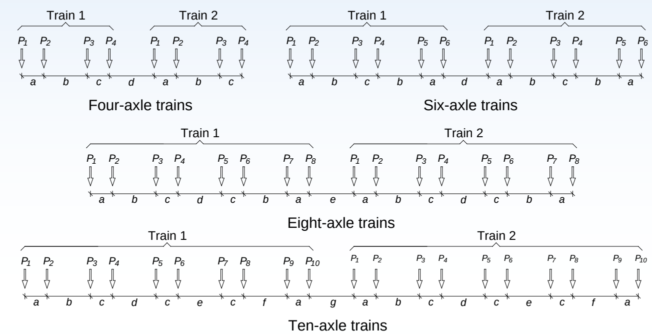
Research Program

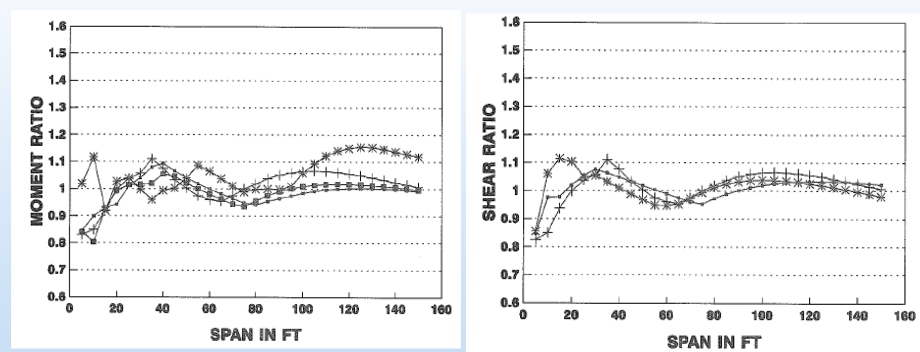
Task 3: Development of a standard live load model

- Load-enveloping with 33 trains operated in nation (4 Canadian trains)





Empty train weight: 51 k to 156 k/train
Number of axles: 4-10 axles/train
Number of seats: 29 to 120/train



HL-93 load-enveloping
(AASHTO LRFD BDS Art. 3.6.1.2)

Research Program

Task 4: Characterization of live load effects

- Objectives of this task are:
  - To examine the behavior of bridge superstructures with an emphasis on deflection, live load distribution, dynamic load allowance, and multiple presence
  - To evaluate the existing design provisions of AASHTO LRFD BDS and the AREMA manual for light rail train load
  - To propose design information about live load effects for bridges carrying light rail trains or carrying light rail trains and highway vehicles

Research Program

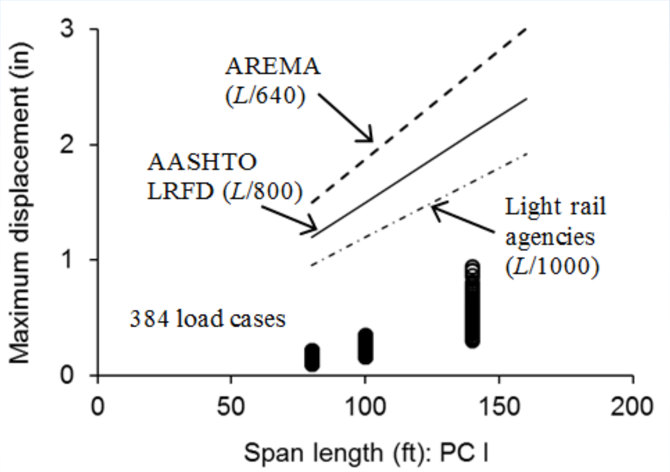
Task 4: Characterization of live load effects

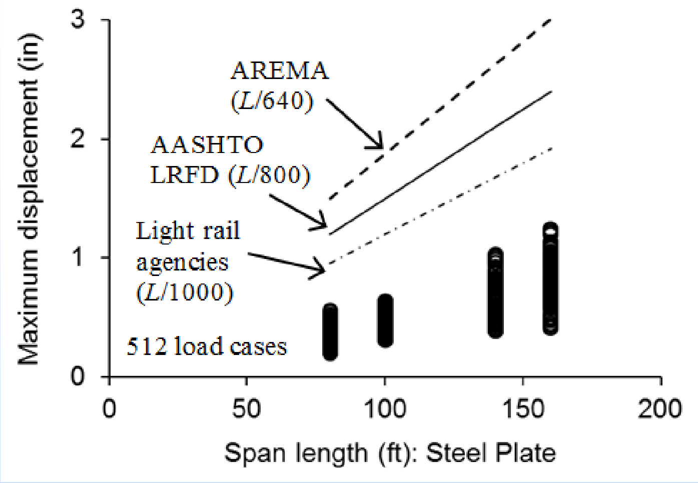
- Deflection

Constructed light rail bridges

Bridge	Type	Monitored span	Test		Model			
			Service load		Empty train		Fully-loaded train	
			$\delta_{max\text{-}average}$	$\delta_{control}$	δ_{max}	$\delta_{control}$	δ_{max}	$\delta_{control}$
Broadway	Steel plate girder	119 ft	0.365 in	L/3910	0.252 in	L/5670	0.412 in	L/3470
Indiana Bridge	PC box girder	95 ft	0.040 in	L/28500	0.038 in	L/30000	0.062 in	L/18390
Santa Fe Bridge	PC box girder	155 ft	0.224 in	L/8300	0.194 in	L/9590	0.311 in	L/5980
County Line Bridge	PC I girder	160 ft	0.250 in	L/7680	0.156 in	L/12310	0.274 in	L/7010
6th Avenue Bridge	PC I girder	80 ft	0.066 in	L/14550	0.054 in	L/17780	0.089 in	L/10790

Art. 2.5.2.6.1 of AASHTO LRFD BDS (deflection limitations are optional for bridges) is valid for light rail bridges and the subsequent user comfort criteria described next can be added



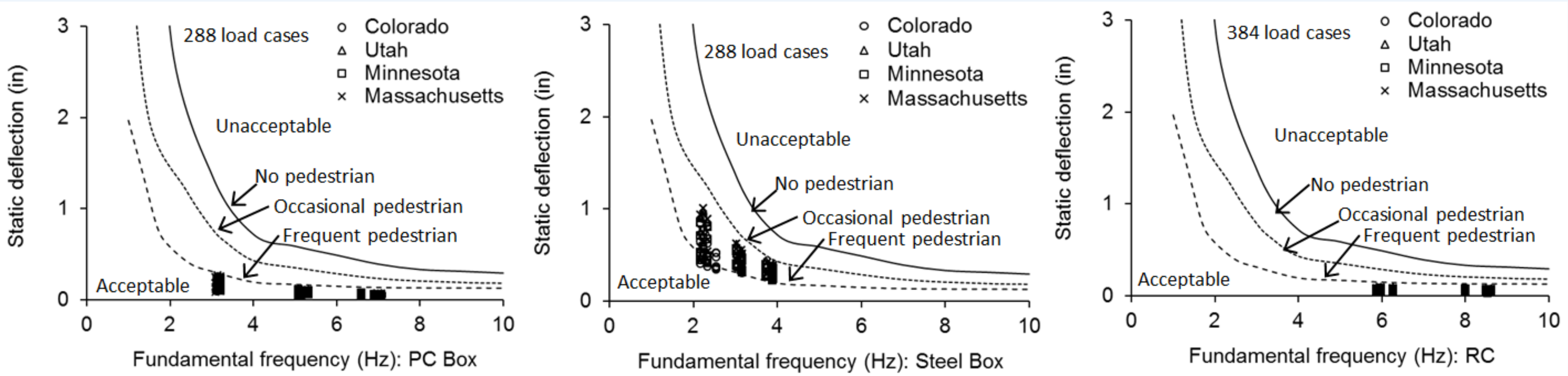


Benchmark bridge models

Research Program

Task 4: Characterization of live load effects

- User comfort (Canadian Highway Bridge Design Code)



Function of mass, stiffness (flexural rigidity), and span length

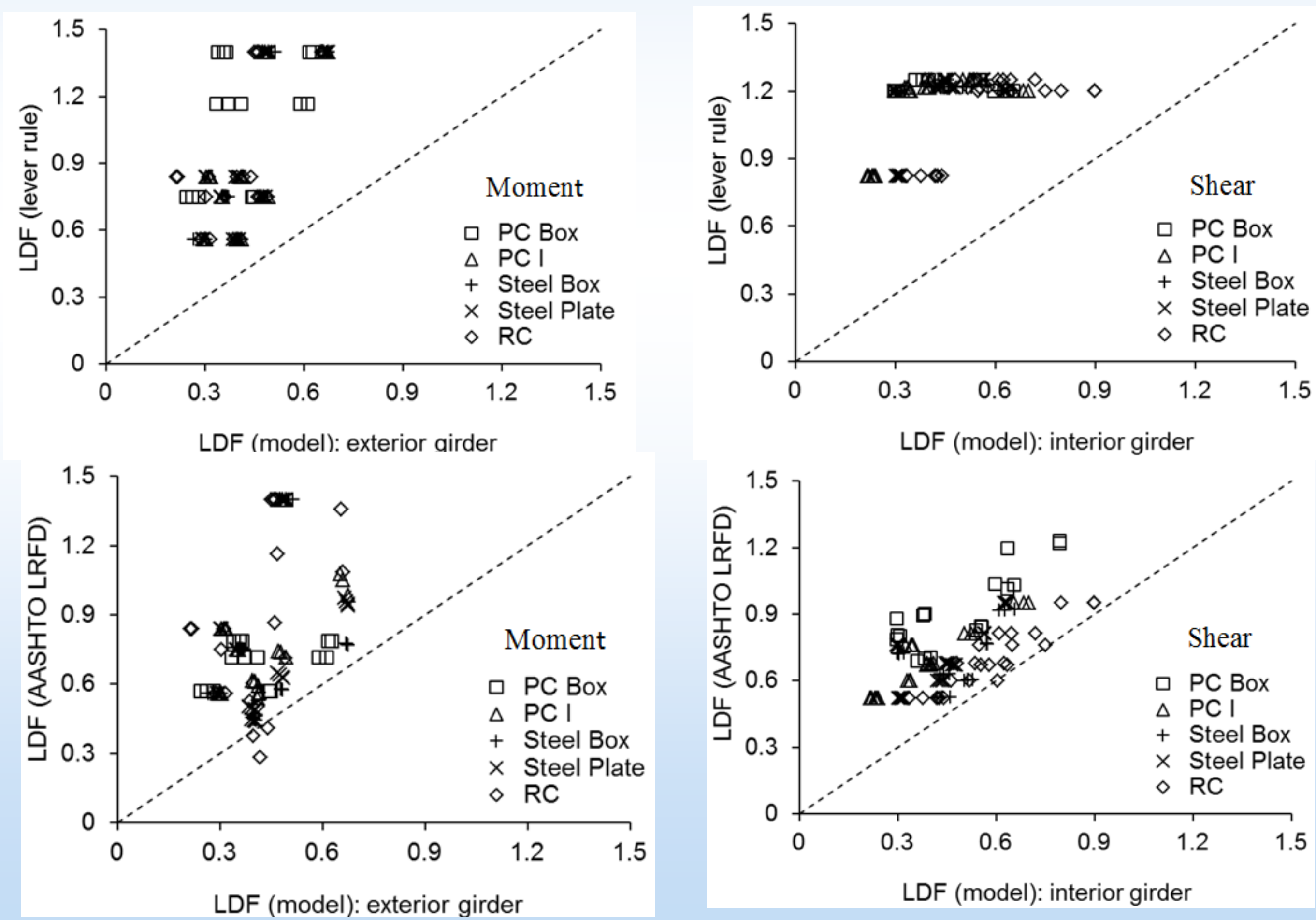
User comfort may not be a critical issue for light rail bridges when primarily subjected to train loading, whereas care should be exercised to check user comfort requirements if a light rail bridge is intended for frequent pedestrian use, as part of serviceability limit states

Passenger comfort is satisfactory according to UIC Code 776-2 (International Union of Railways)

Research Program

Task 4: Characterization of live load effects

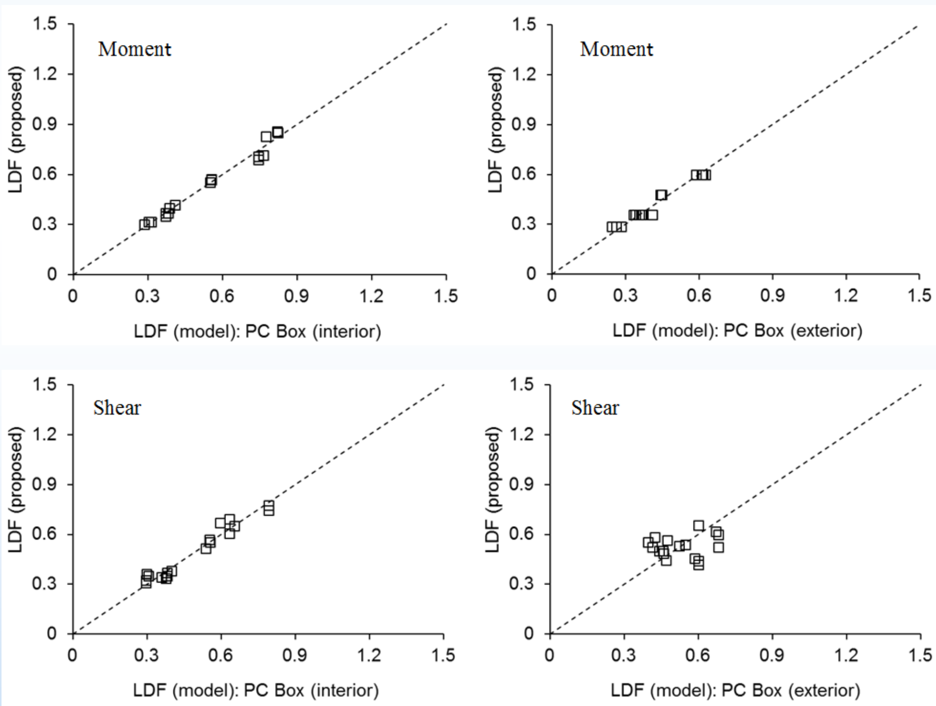
- Live load distribution (assessment of existing methods)

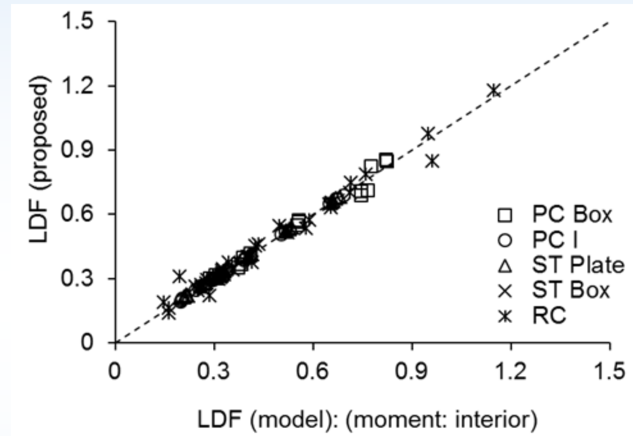


Research Program

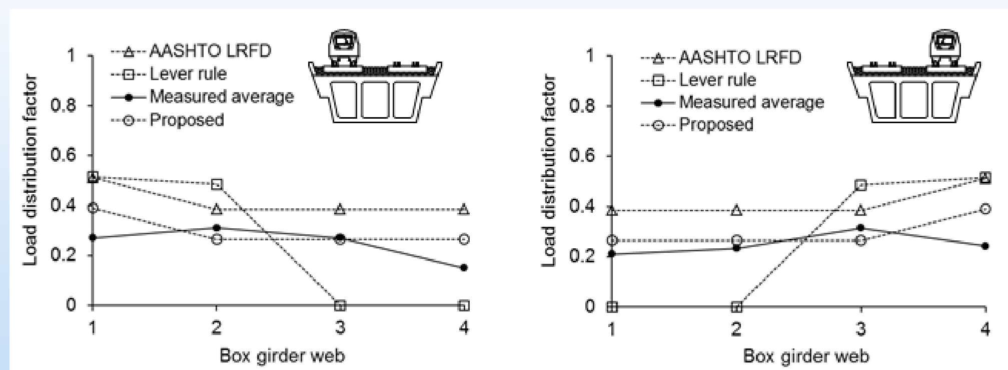
Task 4: Characterization of live load effects

- Live load distribution (calibration and proposal)





Comparison b/w proposed eqs and FE results

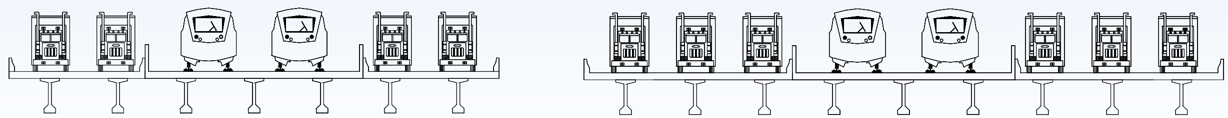


Evaluation using site data

Research Program

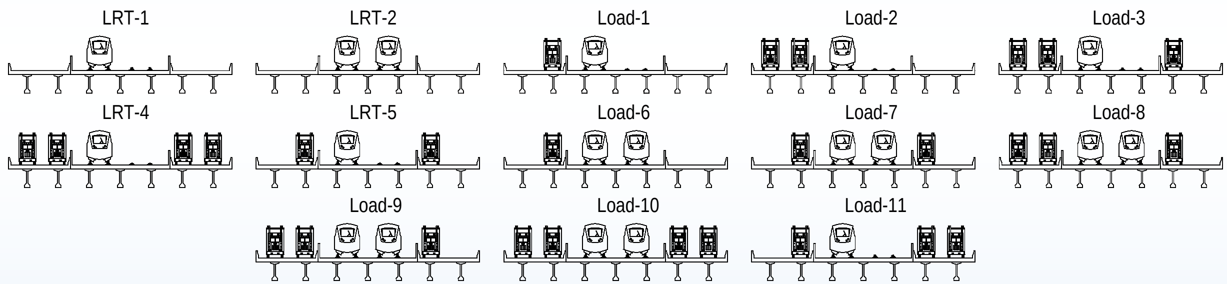
Task 4: Characterization of live load effects

- Light rail transit combined with highway loadings

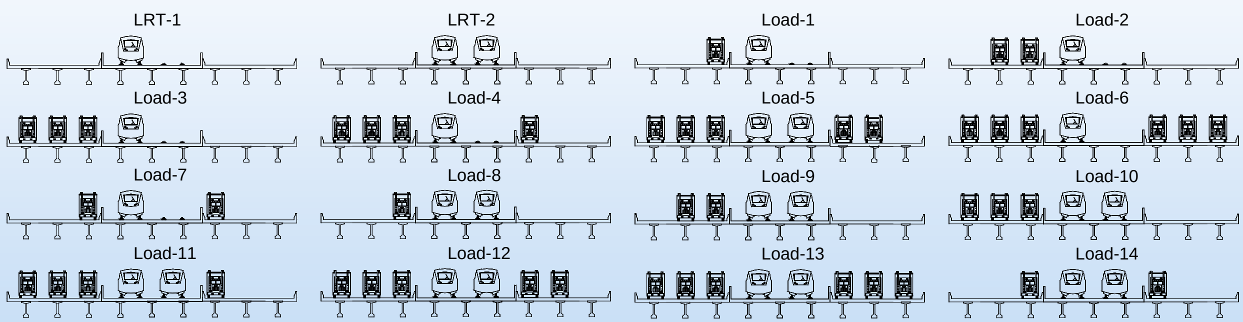


2+2+2 loading

3+2+3 loading



13 cases

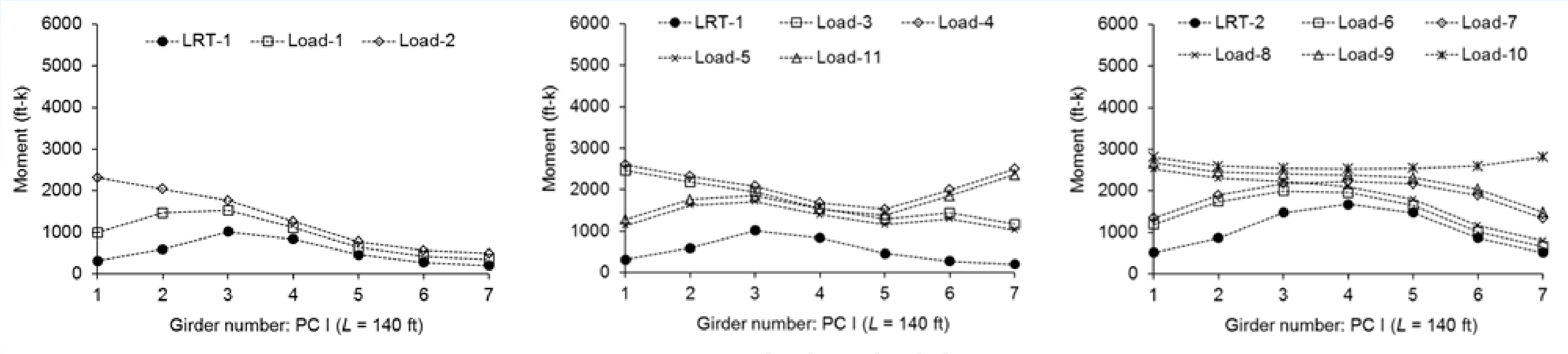


16 cases

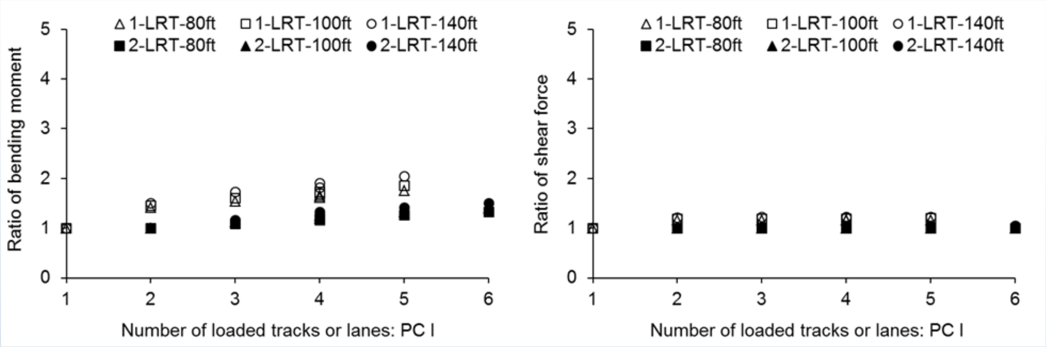
Research Program

Task 4: Characterization of live load effects

- Light rail transit and highway loadings combined



PC I girder bridge



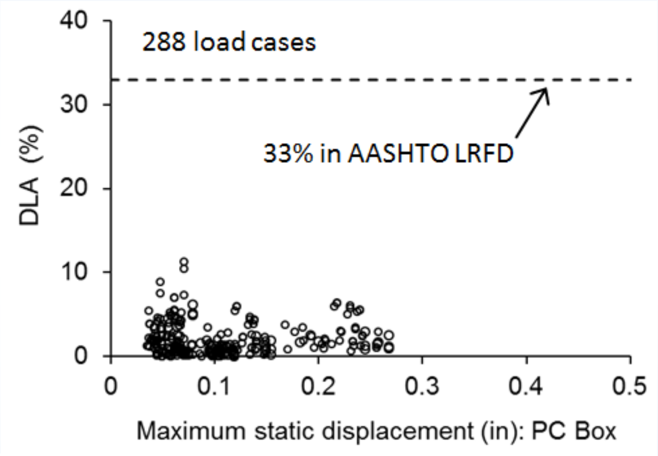
- Distribution factors for interior girders were reduced with an increase in span length
- Distribution factors for exterior girders were influenced by location of loaded lanes

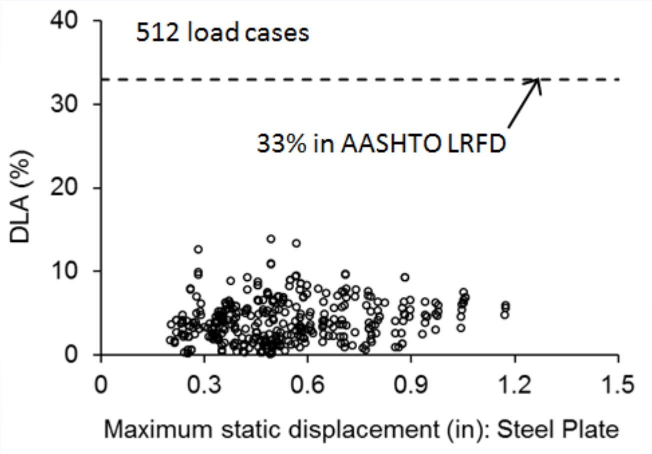
Research Program

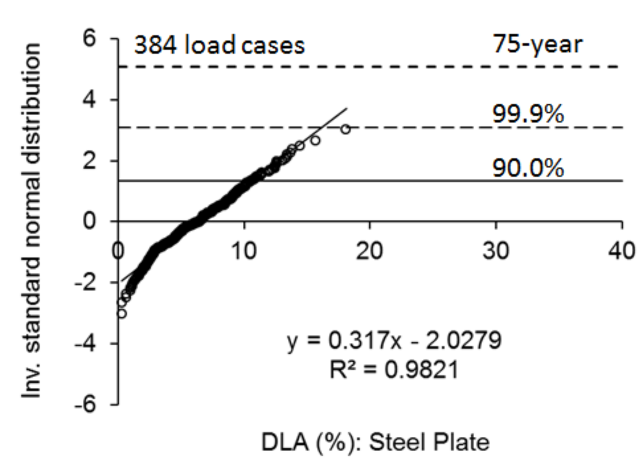
Task 4: Characterization of live load effects

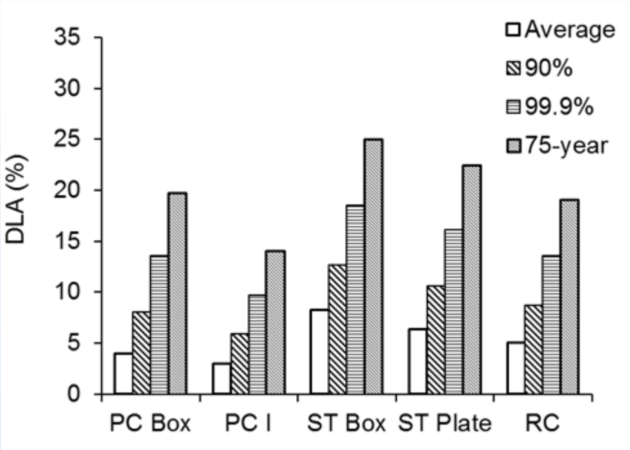
- Dynamic load allowance (IM): 2,960 load cases

$$DLA = \frac{\delta_{dynamic} - \delta_{static}}{\delta_{static}} \times 100(\%)$$









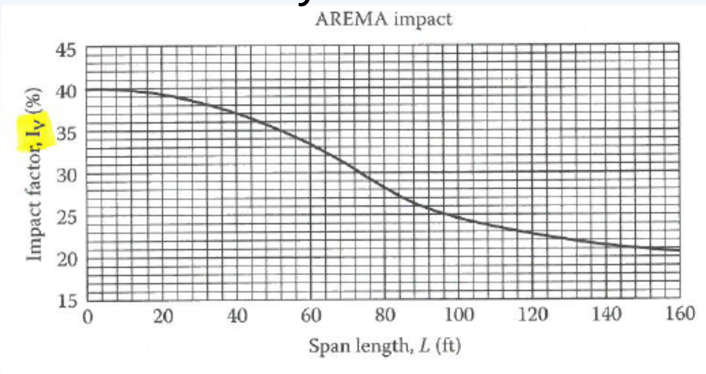
Proposed DLA = 30%
(25% plus 5% margin)

Research Program

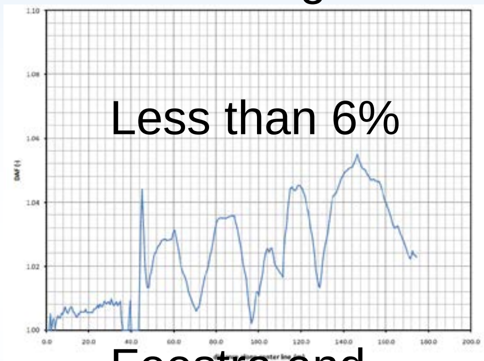
Task 4: Characterization of live load effects

- Dynamic load allowance (IM): assessment

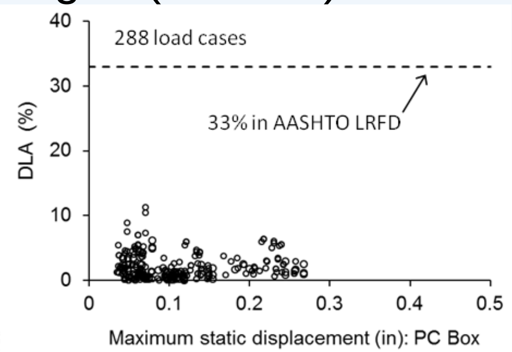
Heavy-haul trains



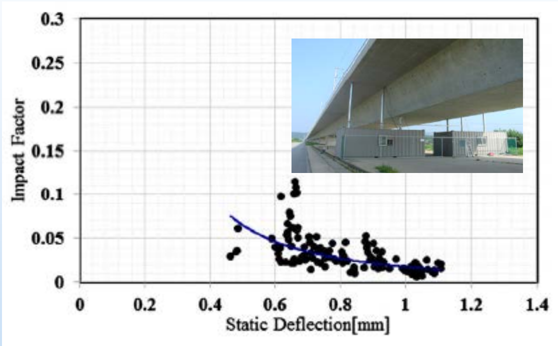
Light rail bridges (PC Box)



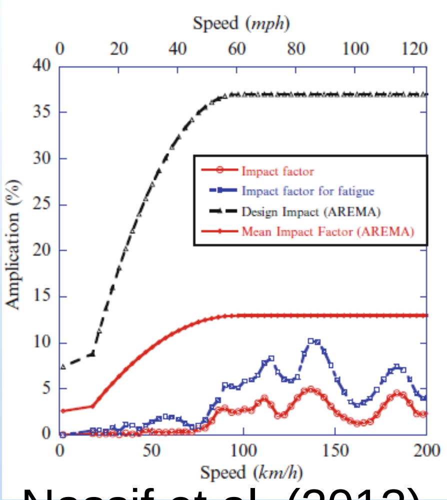
Feestra and Isenberg (2012)



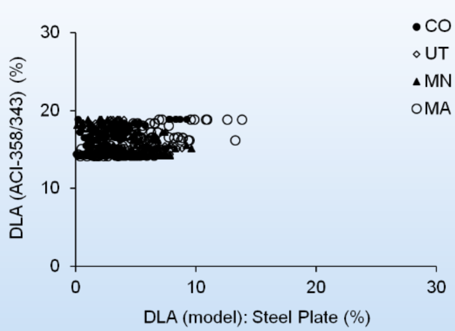
NCHRP 12-92

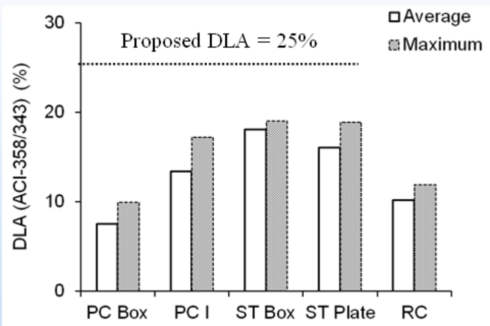


Yoon et al. (2013)



Nassif et al. (2013)





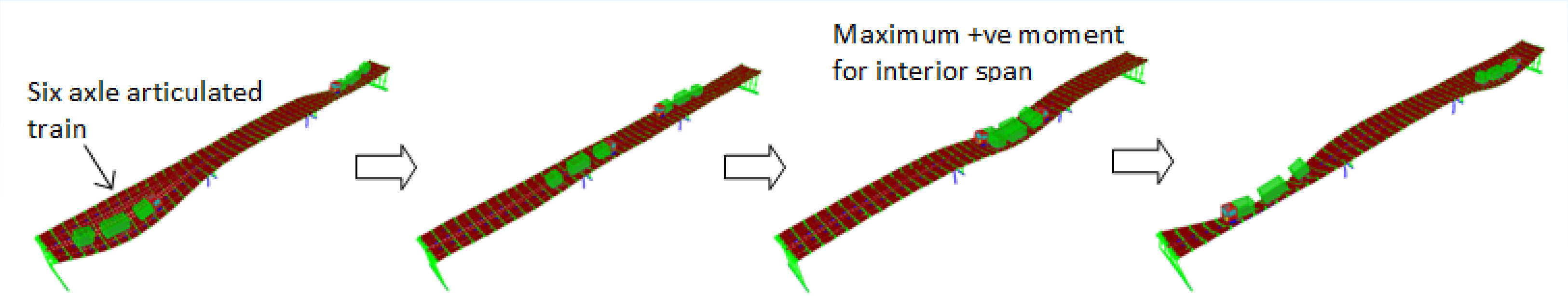
ACI 358/343

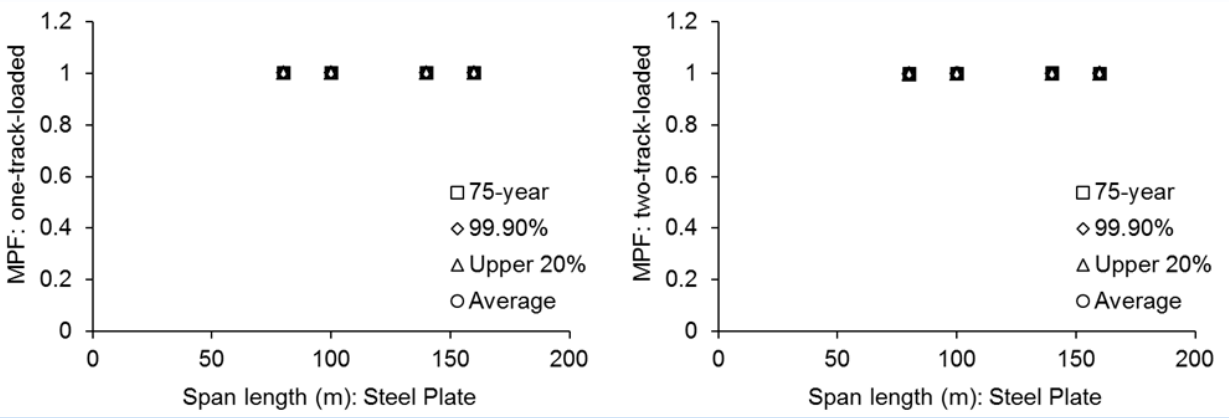
Research Program

Task 4: Characterization of live load effects

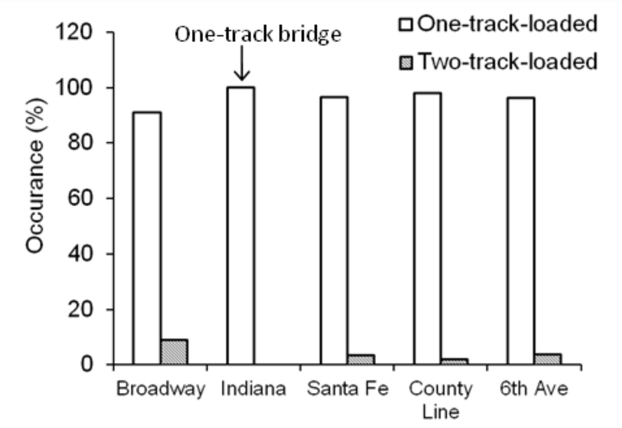
- Multiple presence factor

$$MPF = \frac{E_N}{E_1}\frac{1}{N}$$





Proposed MPF = 1.0 (same as AREMA)

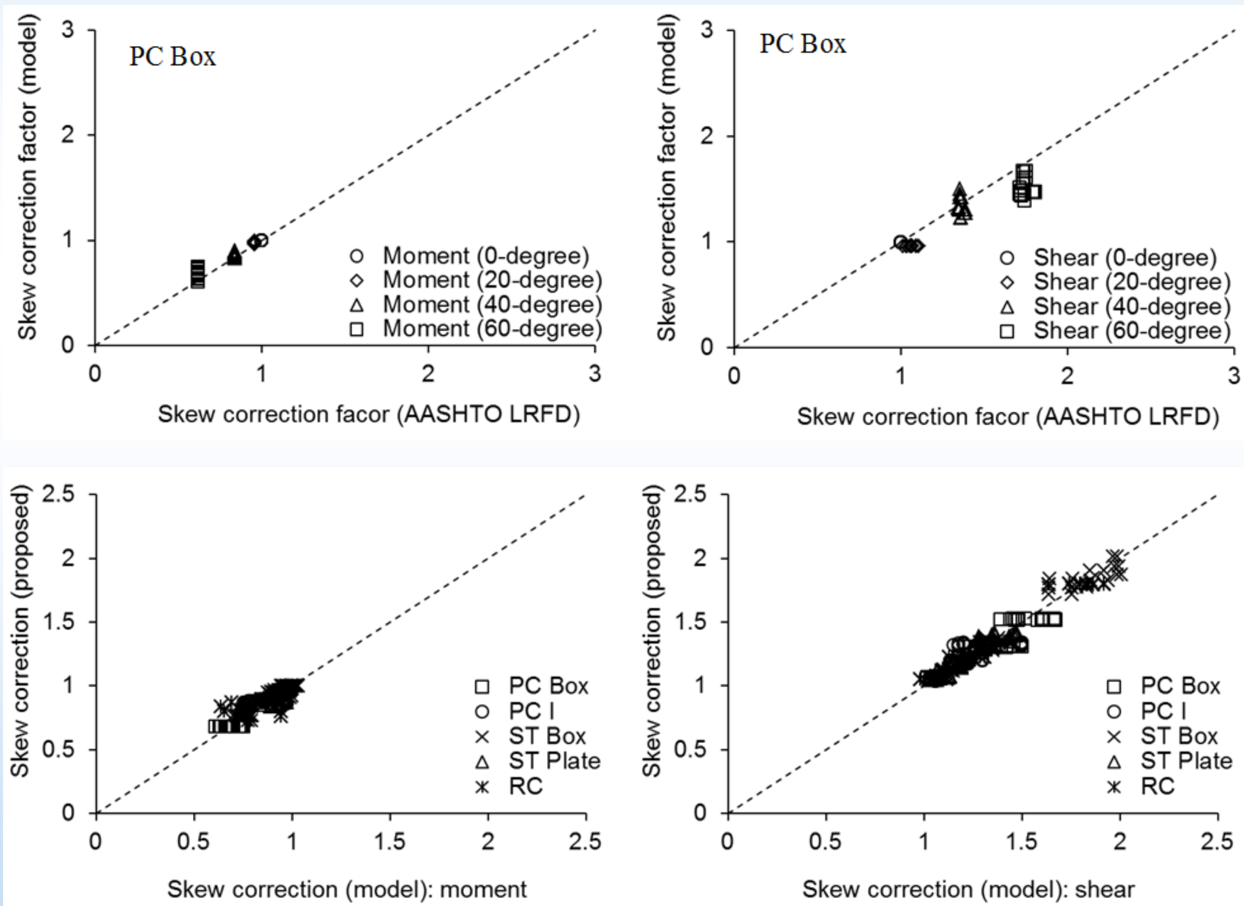


Frequency of multiple presence observed on site (2014 and 2015)

Research Program

Task 4: Characterization of live load effects

- Skew correction factor (assessment and proposal)



Research Program

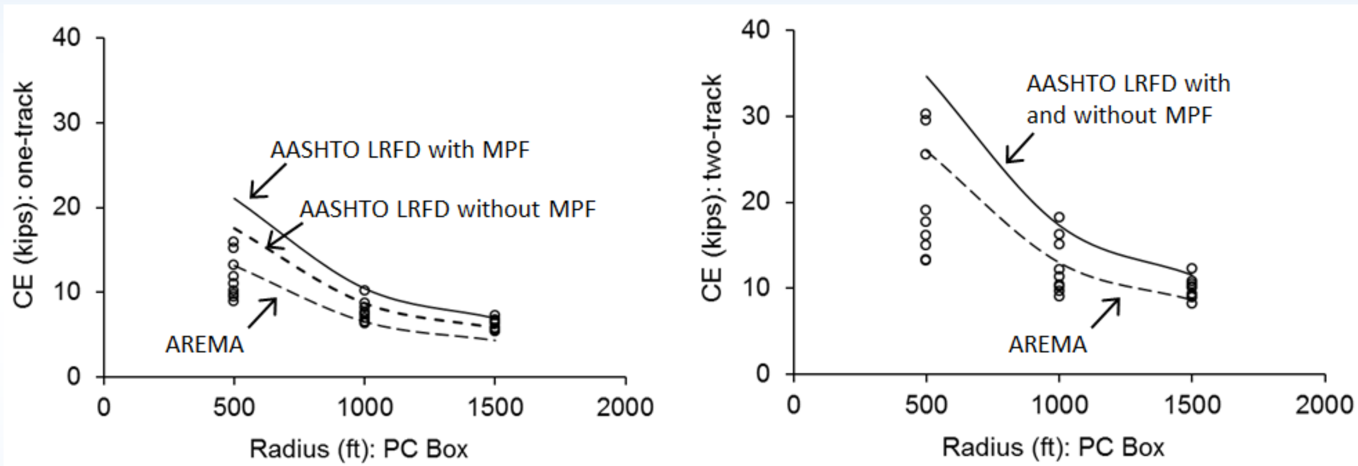
Task 5: Rail-train-structure interaction and associated forces

- Objectives of this task are:
  - To better understand and to provide clearer insights into wheel-rail interaction and associated forces with light rail trains
  - To establish reasonable yet conservative design criteria for light rail bridges

Research Program

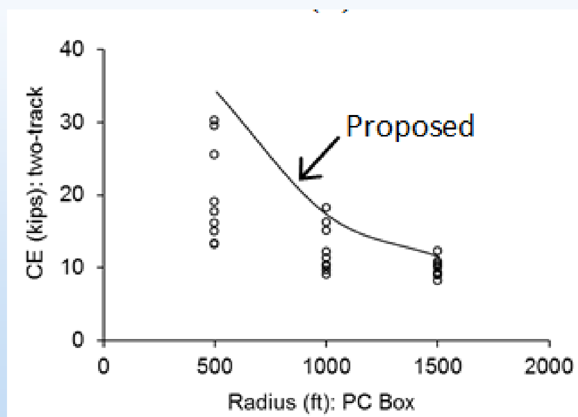
Task 5: Rail-train-structure interaction and associated forces

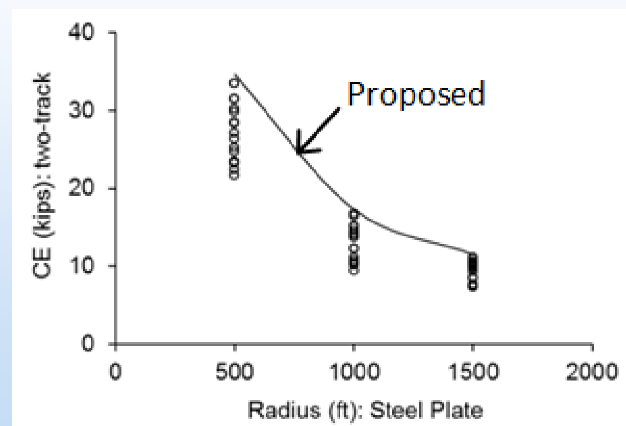
- Centrifugal force (CE)



Proposed CE multiplier

$$C = \frac{4}{3}\frac{v^2}{gR}\left(-0.2n + 1.4\right)$$





Research Program

Task 5: Rail-train-structure interaction and associated forces

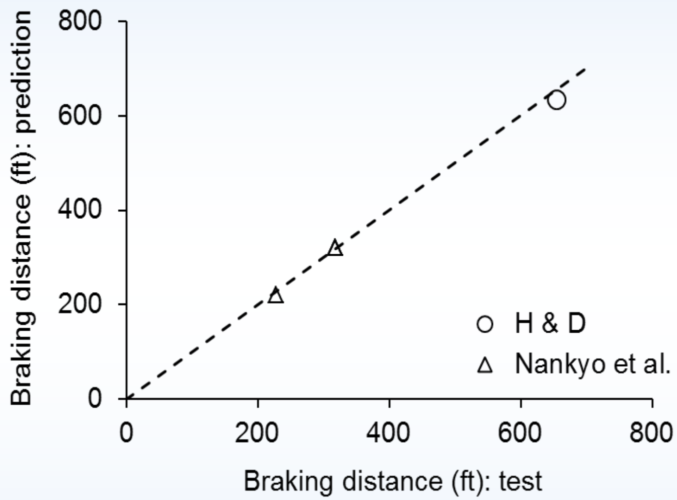
- Longitudinal force (BR)

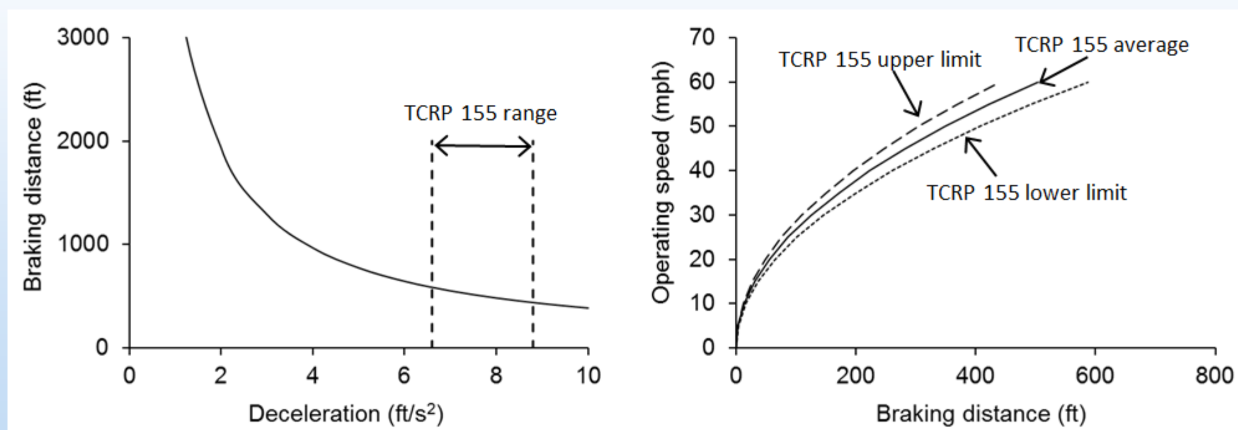
$$s = \left(\frac{1}{2} V^2 + g \Delta h \right) / a$$

Braking distance (s)

$$F_b = \frac{1}{2} \left(\frac{V^2}{gs} \right) W = \alpha W$$

Longitudinal force multiplier



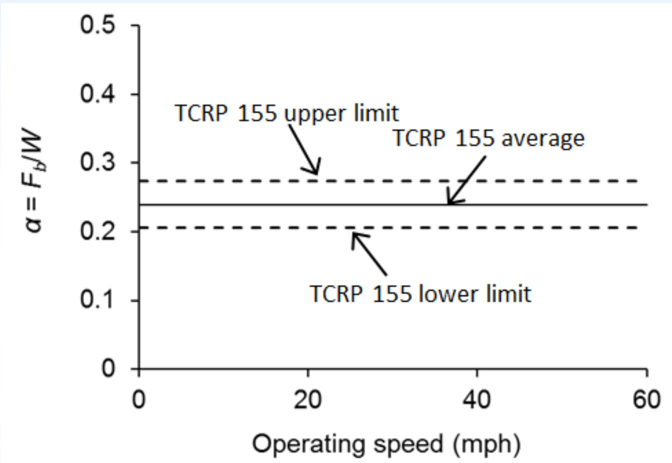


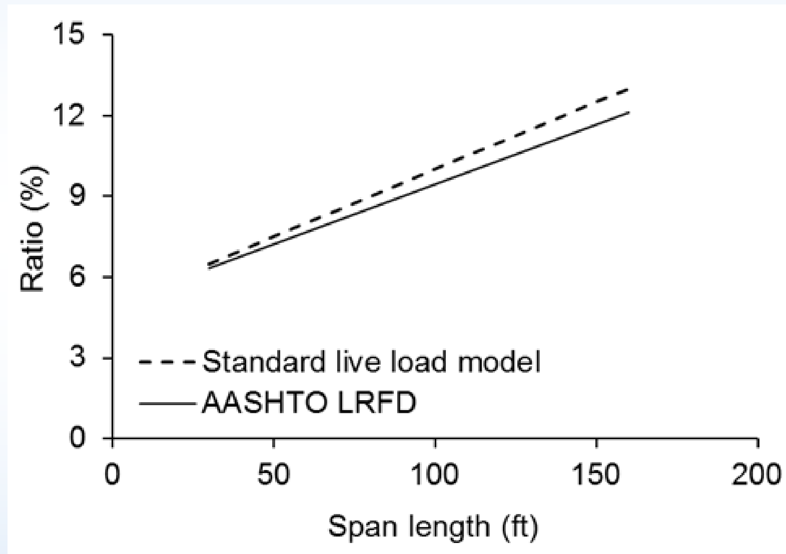
Research Program

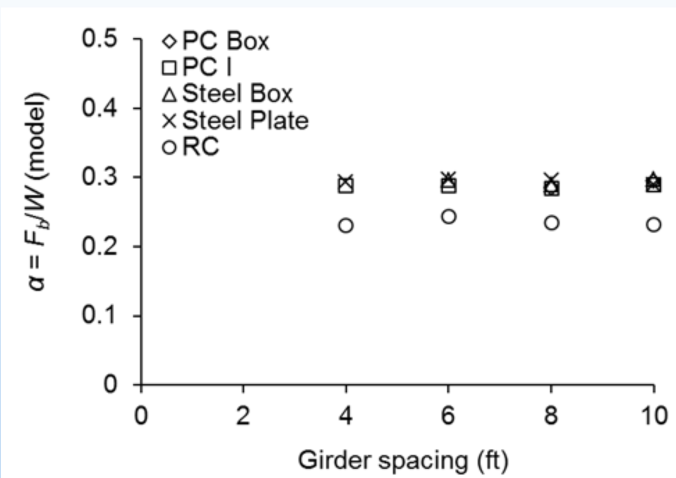
Task 5: Rail-train-structure interaction and associated forces

- Longitudinal force (BR)

$$Ratio = \frac{F_{b-lane}}{F_{b-concentrated}} \times 100(\%)$$







Proposed BR

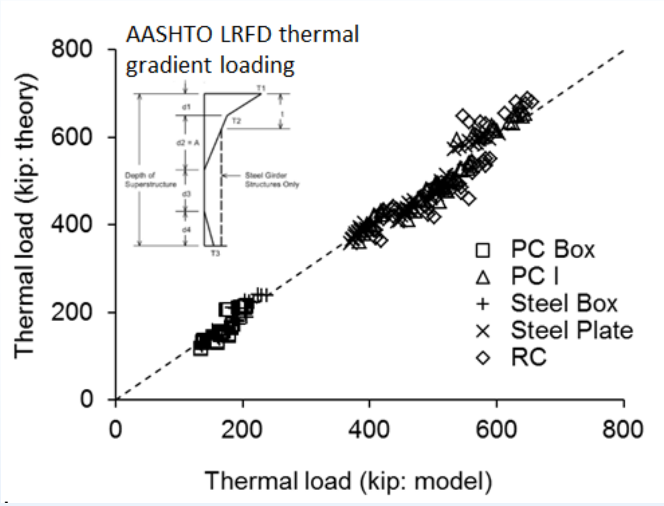
- 28 percent of the axle weights of light rail train or
- 5 percent of the axle weights plus lane load

Note: AASHTO LRFD BDS, α = 25%

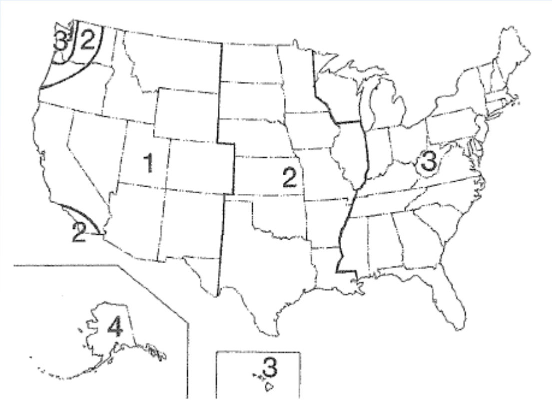
Research Program

Task 5: Rail-train-structure interaction and associated forces

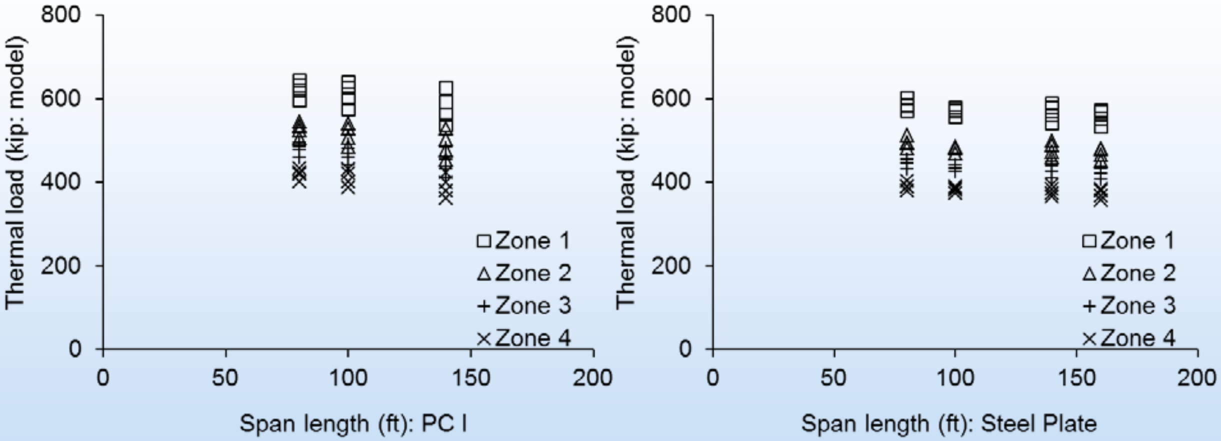
- Thermal force



Thermal gradient loading



Art. 3.12.3 *Temperature gradient*



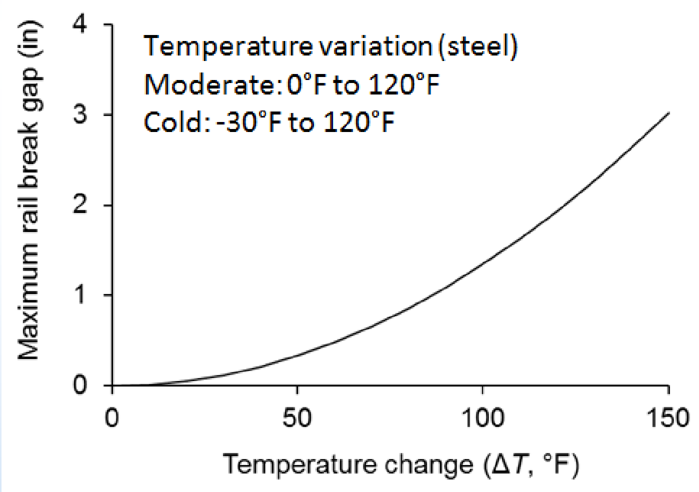
Thermal response

Research Program

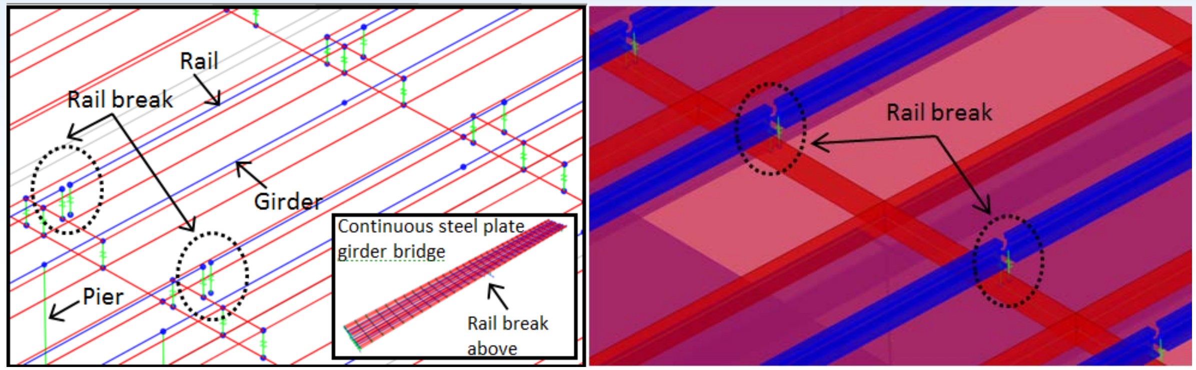
Task 5: Rail-train-structure interaction and associated forces

- Rail break

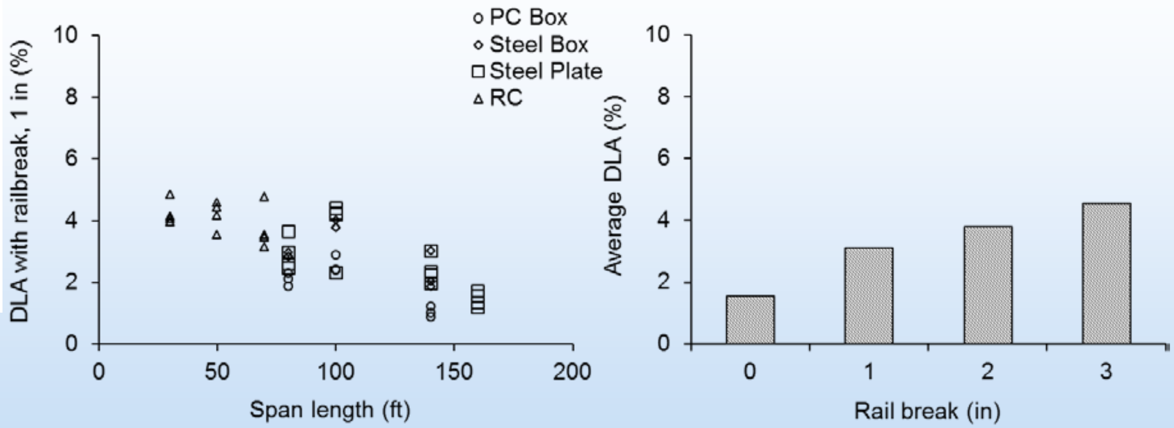
$$Gap_{\max} = 2\frac{EA(\alpha \Delta T)^2}{N_{clip}\mu P_{TL}}S$$



Based on Art. 3.12.2.1 of AASHTO LRFD BDS



Rail break at expansion joints

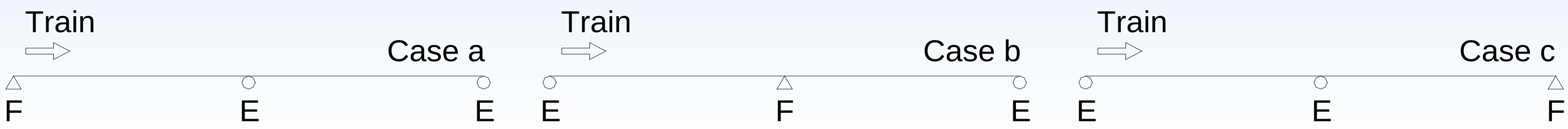


Proposed 30% DLA is sufficient in the event of rail break at expansion joints up to 3 in.

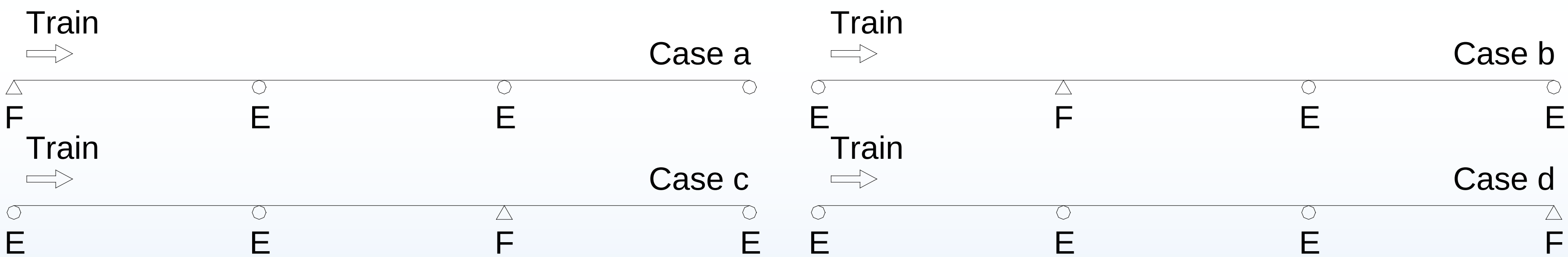
Research Program

Task 5: Rail-train-structure interaction and associated forces

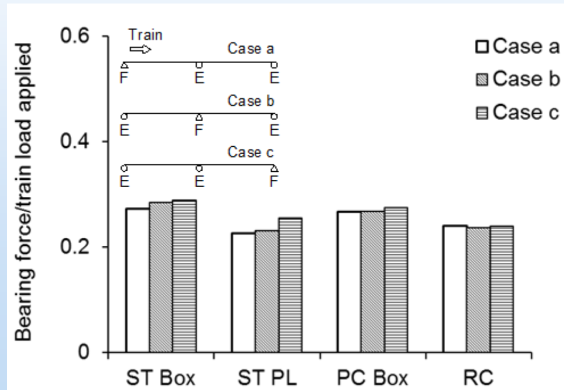
- Effect of bearing arrangement

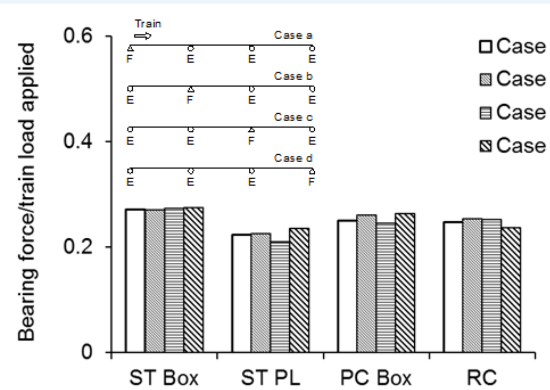


Two-span continuous



Three-span continuous

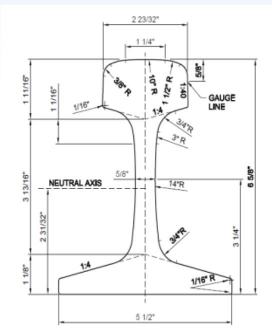




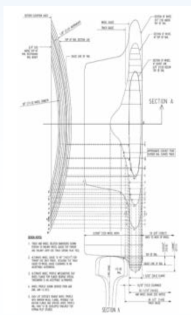
Research Program

Task 5: Rail-train-structure interaction and associated forces

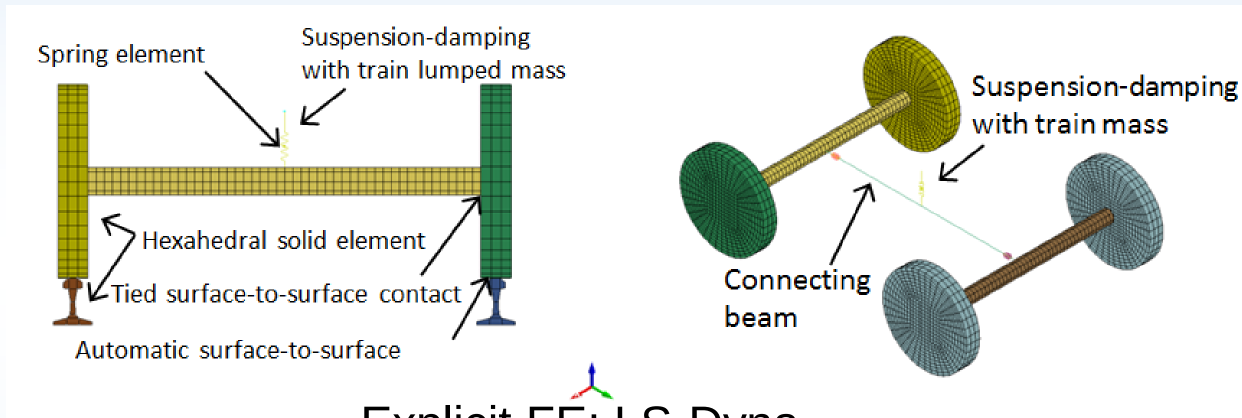
- DLA based on wheel-rail interaction



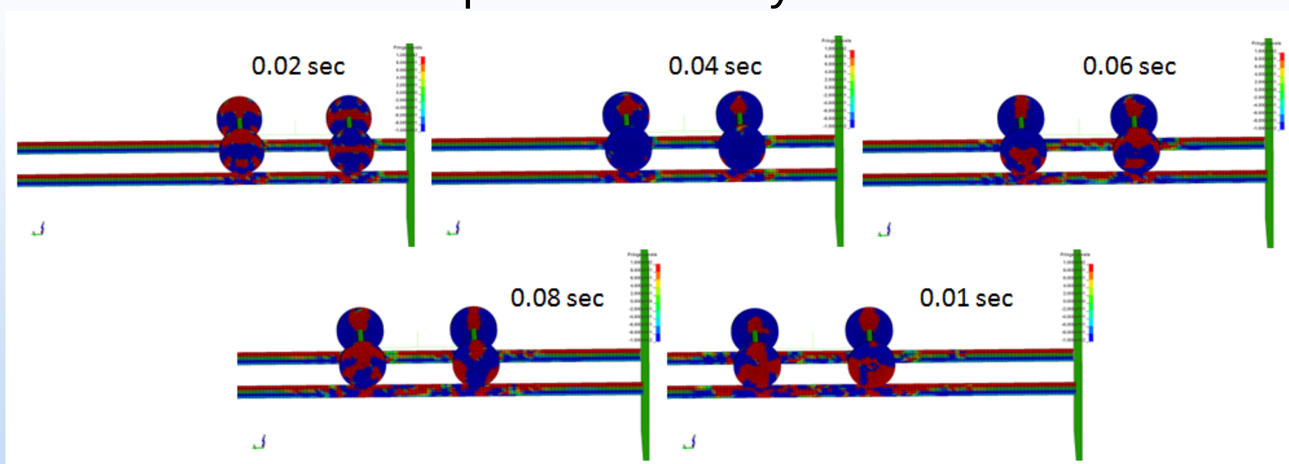
115RE



AAR-1B wheel



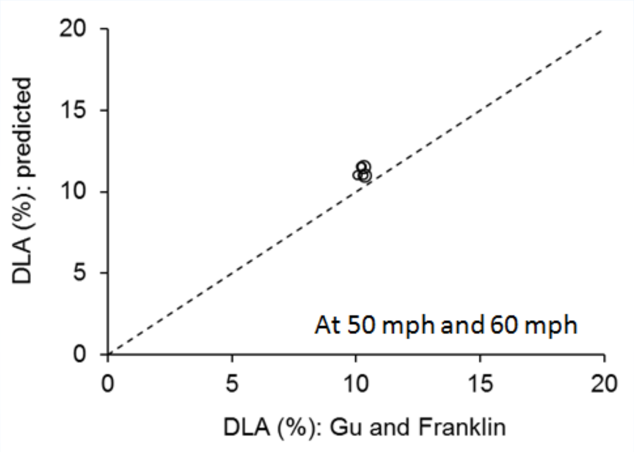
Explicit FE: LS-Dyna



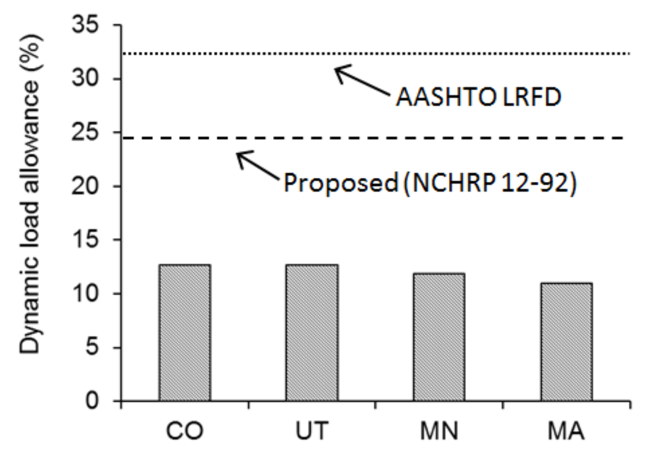
Research Program

Task 5: Rail-train-structure interaction and associated forces

- DLA based on wheel-rail interaction

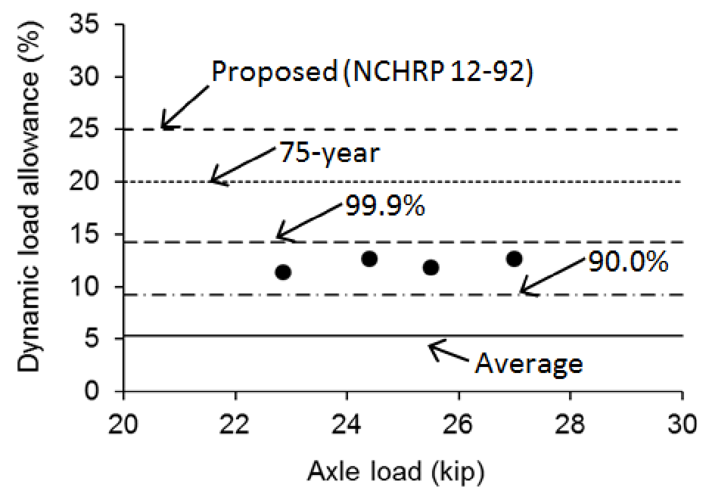


Validation against literature



Assessment of DLA at local level (without 5% margin)

Comparison between local and global level responses



Research Program

Task 6: A unified approach for designing bridges carrying light rail and highway traffic loads

- Objectives of this task are:
  - To statistically examine the behavior of bridges subjected to light rail train and highway loadings
  - To propose a unified design approach for bridges carrying light rail train and highway vehicle loadings

Research Program

Task 6: A unified approach for designing bridges carrying light rail and highway traffic loads

- Statistical approaches

  - *Analysis of Variance* (ANOVA): to characterize the behavior of light rail bridges when specific design parameters are considered (95% confidence interval)

$$F = \frac{ms_{\bar{x}}^2}{\left(\sum_{i=1}^{k} s_i^2\right)/k}$$

  - *t-test*: to check whether the behavior is in compliance with AASHTO LRFD BDS or the proposed design information (95% confidence interval)

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

Research Program

Task 6: A unified approach for designing bridges carrying light rail and highway traffic loads

- Effects of design parameters on behavior of light rail bridges
  - Bearing arrangement did not affect, regardless of span numbers
  - Curvature-radius affected centrifugal force that was not influenced by other geometric parameters (girder spacing and span length)
  - Dynamic load allowance was not affected by single- and multiple-spans, justifying use of a single DLA
  - Multiple presence factors were independent of bridge types
  - Rail break influenced DLA, still lower than the proposed 30% DLA
  - Skewed bridges were affected by span length, but not by girder spacing

Research Program

Task 6: A unified approach for designing bridges carrying light rail and highway traffic loads

- Assessment of design expression (No = not usable; Yes = usable)
  - Braking force (BR): AASHTO LRFD (No); Proposed (Yes)
  - Centrifugal force (CE): AASHTO LRFD (Yes); Proposed (Yes)
  - Dynamic load allowance (IM): both conservative
  - Multiple presence factor: AASHTO LRFD (No); Proposed (Yes)
  - Skew correction factor: AASHTO LRFD (No); Proposed (Yes)
  - Live load distribution: Lever rule (No); Proposed (Yes)

For design of bridges:

- carrying highway traffic: recommend AASHTO LRFD BDS
- carrying light rail loading: recommend Proposed
- potentially carrying both highway traffic and light rail loadings: recommend conservative provisions to be taken between AASHTO LRFD and Proposed

Research Program

Task 7: Proposal of load factors

- Objectives of this subtask are:
  - To calibrate load factors for light rail bridges against a safety index of $\beta = 3.5$
  - To propose load factors for bridges carrying light rail train /and highway vehicle loadings

Research Program

Task 7: Proposal of load factors

- Calibration methodologies

  - Strength I: i) refined iterative and ii) approximate direct calculation
  - Service I: direct load effect
  - Fatigue I (infinite fatigue): occurrence probability of 1/10,000 (NCHRP 12-83)
  - Fatigue II: (finite fatigue) ratio between service live load and design load (AASHTO LRFD BDS)

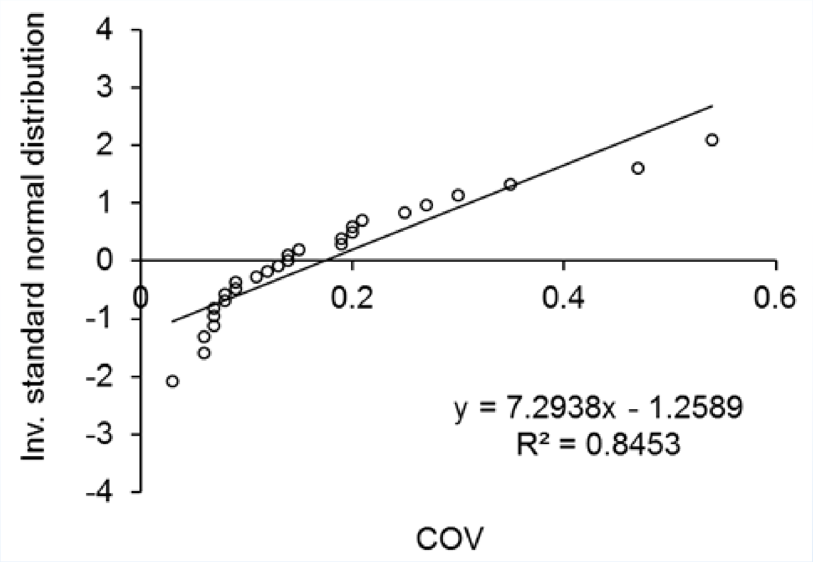
Note:

- Strength I and II limit states can be combined for light rail bridges

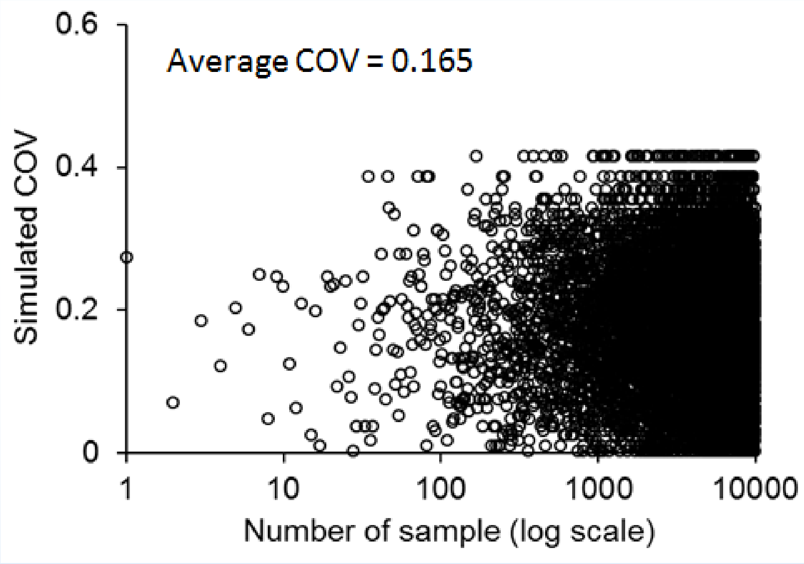
Research Program

Task 7: Proposal of load factors

- Probability distribution and simulation of light rail loading



In-situ loading: Gaussian distribution (in agreement with general bridge literature: load response- normal and structural resistance- lognormal)

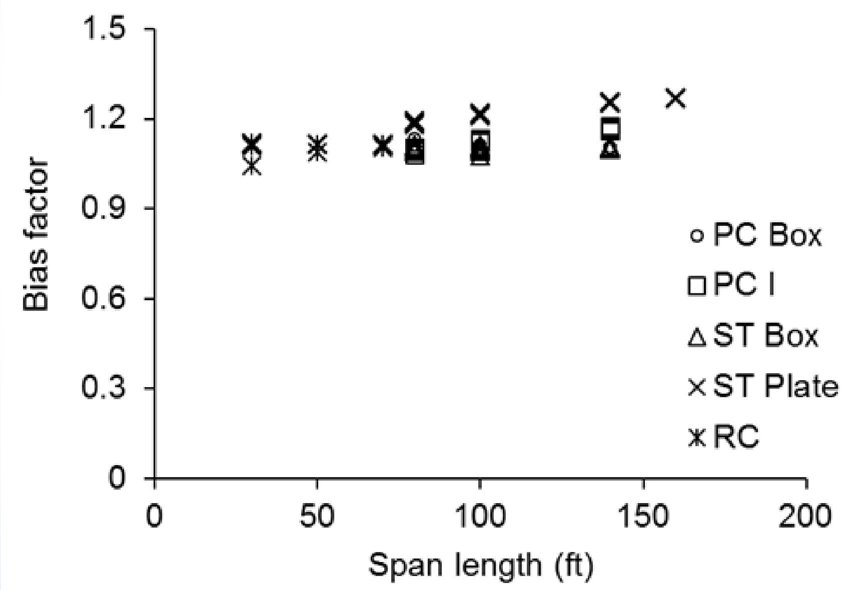


In-situ loading: 0.161

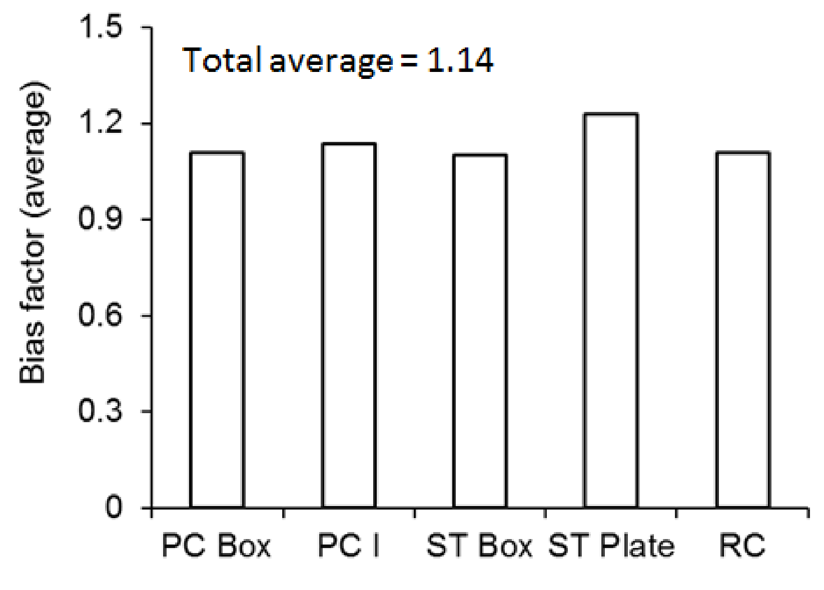
Research Program

Task 7: Proposal of load factors

- Calibration of load factor for Strength I



Bias factor = maximum 75-year load effect / nominal design load effect (NCHRP 12-33)

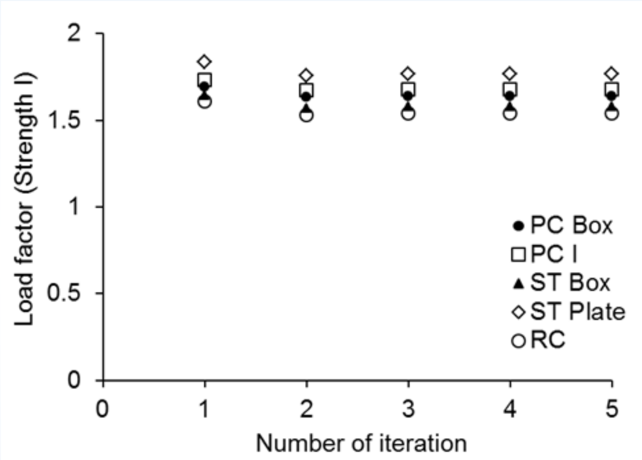


Similar to the bias of highway bridges ranging from 1.05 to 1.14 (Barker and Puckett 1997)

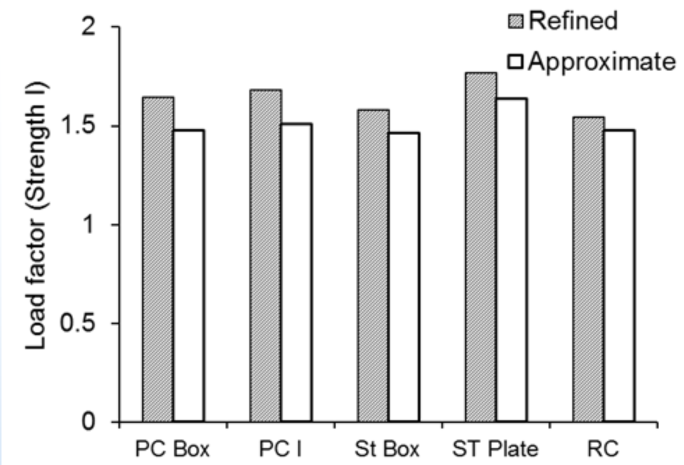
Research Program

Task 7: Proposal of load factors

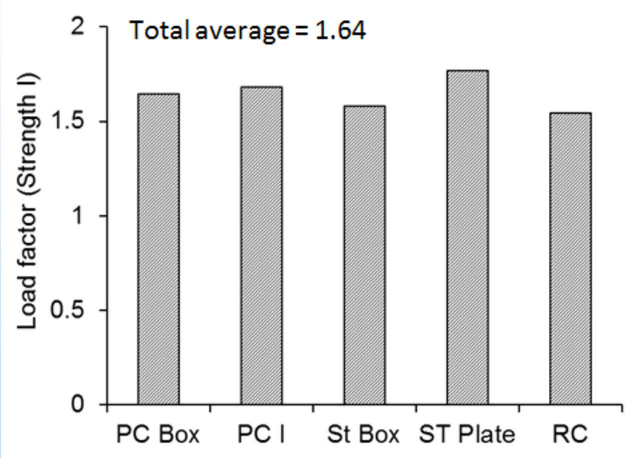
- Calibration of load factor for Strength I



Refined iterative method



Independent calibration and evaluation of Direct calibration method

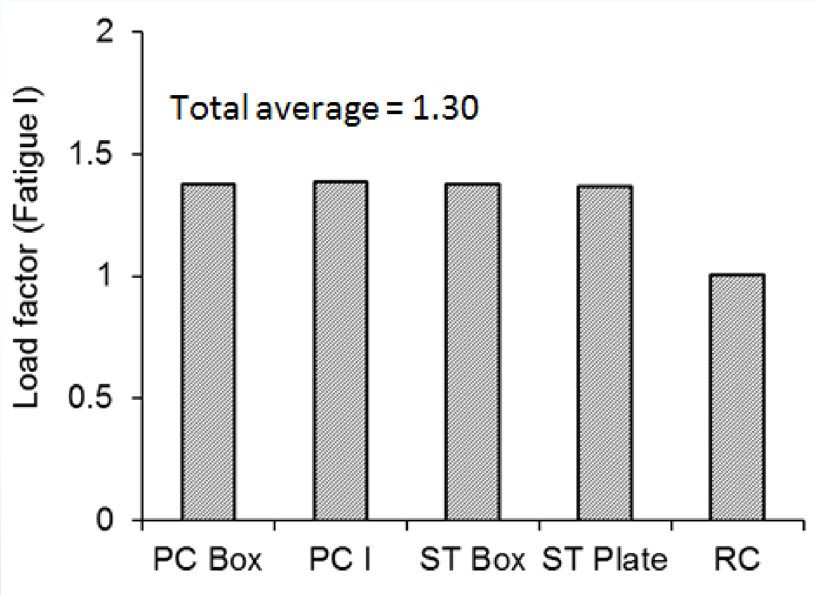


Proposed = 1.65 (uncertainty of light rail loading less than that of highway traffic)

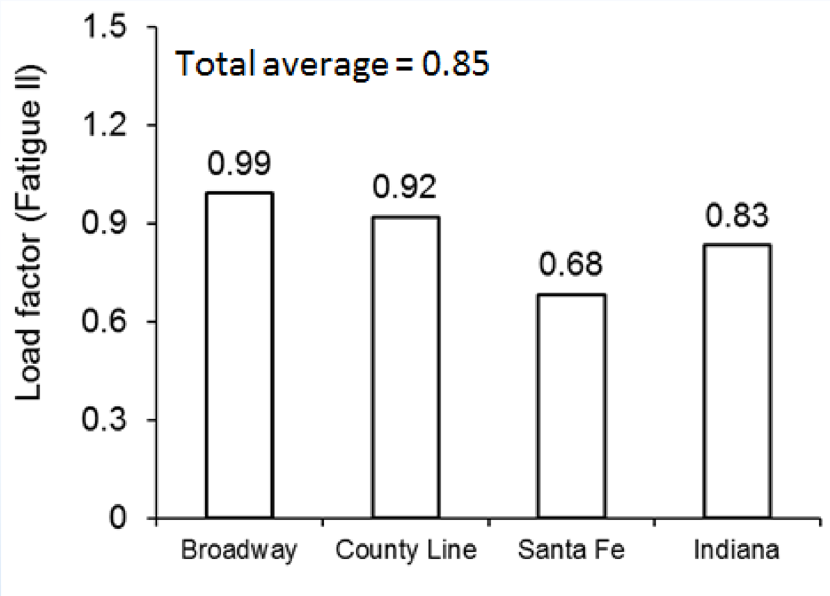
Research Program

Task 7: Proposal of load factors

- Calibration of load factor for Fatigue I and II



Fatigue I = load effect of 1/10,000 occurrence probability / load effect of average design load (NCHRP 12-83)

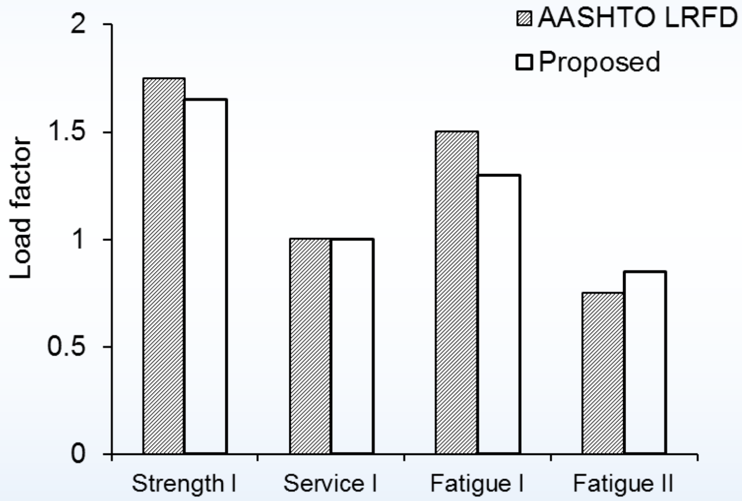


Fatigue II = service live load effect/ design load effect (AASHTO LRFD BDS)

Research Program

Task 7: Proposal of load factors

- Comprehensive comparison of load factors



For design of bridges:

- carrying highway traffic:
  recommend AASHTO LRFD BDS
- carrying light rail loading
  recommend Proposed
- potentially carrying both highway traffic and light rail loadings: below

	Strength I	Service I	Fatigue I	Fatigue II
Load factor	1.75	1.00	1.50	0.85

AASHTO Guide Specifications

I II III IV V VI

Guide Specifications

AASHTO LRFD design specifications and commentary

- Contents

1. General
2. Design Philosophy
3. Loads
4. Structural Analysis
5. References

Guide Specifications

AASHTO LRFD design specifications and commentary

1. General
   - Scope

   These guide specifications (LRT Guide Specifications) are a supplement to AASHTO LRFD BDS, which address the design of bridges subjected to light rail transit (LRT) loadings or LRT and conventional highway traffic loadings.

   - Notations: AASHTO LRFD BDS

   - Definitions: AASHTO LRFD BDS

Guide Specifications

AASHTO LRFD design specifications and commentary

2. Design Philosophy
   - General (in conformance with Art. 2.5 of BDS)
   - Limit States
     - Service I, II, III, and IV (2016 interim used)
     - Strength I, III, IV, and V (2016 interim used)
     - Extreme Event I (earthquake), II (derailment), and III (rail break)
     - Fatigue I (infinite) and II (finite)

Guide Specifications

AASHTO LRFD design specifications and commentary

2. Design Philosophy
   - Load factors and combinations (light rail only; light rail/highway)

Table 2.3-1. Load combinations and load factors for bridges carrying light rail transit loading

										Use of One of These at a Time						
Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU*	*TG*	*SE*	*EQ*	*BL*	*IC*	*CT*	*CV*	*RB*	*DE*
Strength I (unless noted)	γ_p	1.65	1.0	—	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength II	γ_p	—	1.0	—	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength III	γ_p	—	1.0	1.0	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength IV	γ_p	—	1.0	—	—	1.0	0.5/1.2	—	—	—	—	—	—	—	—	—
Strength V	γ_p	1.35	1.0	1.0	1.0	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Extreme Event I	1.0	γ_{EQ}	1.0	—	—	1.0	—	—	—	1.0	—	—	—	—	—	—
Extreme Event II	γ_p	0.5	1.0	—	—	1.0	—	—	—	—	1.0	1.0	1.0	1.0	—	1.0
Extreme Event III	γ_p	1.00	1.0	—	—	1.0	0.5/1.2	—	—	—	—	—	—	—	1.0	—
Service I	1.0	1.0	1.0	1.0	1.0	1.0	1.0/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Service II	1.0	1.3	1.0	—	—	1.0	1.0/1.2	—	—	—	—	—	—	—	—	—
Service III	1.0	γ_{LL}	1.0	—	—	1.0	1.0/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Service IV	1.0	—	1.0	1.0	—	1.0	1.0/1.2	—	1.0	—	—	—	—	—	—	—
Fatigue I—LL,IM, & CE Only	—	1.40	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fatigue II—LL,IM, & CE Only	—	0.85	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 2.3-2. Load combinations and load factors for bridges carrying both light rail transit and highway traffic loadings

										Use of One of These at a Time						
Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU*	*TG*	*SE*	*EQ*	*BL*	*IC*	*CT*	*CV*	*RB*	*DE*
Strength I (unless noted)	γ_p	1.75	1.0	—	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength II	γ_p	1.35	1.0	—	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength III	γ_p	—	1.0	1.0	—	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Strength IV	γ_p	—	1.0	—	—	1.0	0.5/1.2	—	—	—	—	—	—	—	—	—
Strength V	γ_p	1.35	1.0	1.0	1.0	1.0	0.5/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Extreme Event I	1.0	γ_{EQ}	1.0	—	—	1.0	—	—	—	1.0	—	—	—	—	—	—
Extreme Event II	γ_p	0.5	1.0	—	—	1.0	—	—	—	—	1.0	1.0	1.0	1.0	—	1.0
Extreme Event III	γ_p	1.0	1.0	—	—	1.0	0.5/1.2	—	—	—	—	—	—	—	1.0	—
Service I	1.0	1.0	1.0	1.0	1.0	1.0	1.0/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Service II	1.0	1.3	1.0	—	—	1.0	1.0/1.2	—	—	—	—	—	—	—	—	—
Service III	1.0	γ_{LL}	1.0	—	—	1.0	1.0/1.2	γ_{TG}	γ_{SE}	—	—	—	—	—	—	—
Service IV	1.0	—	1.0	1.0	—	1.0	1.0/1.2	—	1.0	—	—	—	—	—	—	—
Fatigue I—LL,IM, & CE Only	—	1.75/ 1.40[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fatigue II—LL,IM, & CE Only	—	0.85	—	—	—	—	—	—	—	—	—	—	—	—	—	—

[a]: light rail loading

Guide Specifications

AASHTO LRFD design specifications and commentary

2. Design Philosophy
   - User comfort criteria
     - General: deflection vs frequency (CHBDC)
     - Passengers: equivalent def. = *L*/600 (UIC- Int. Union of Railways)

CHBDC (Art. 3.4.4)

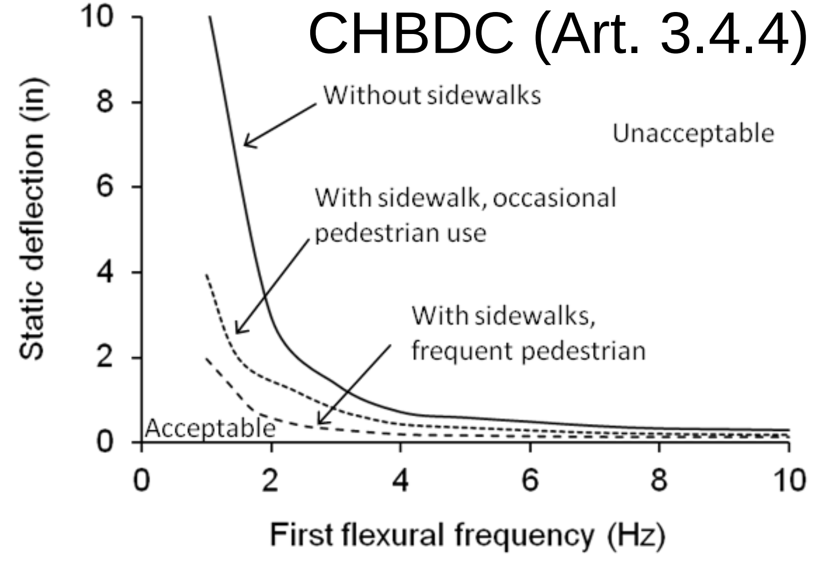


Table 2 : Indicative levels of comfort

Level of comfort	**Vertical acceleration b_v (m/s^2)**
Very good	1,0
Good	1,3
Acceptable	2,0

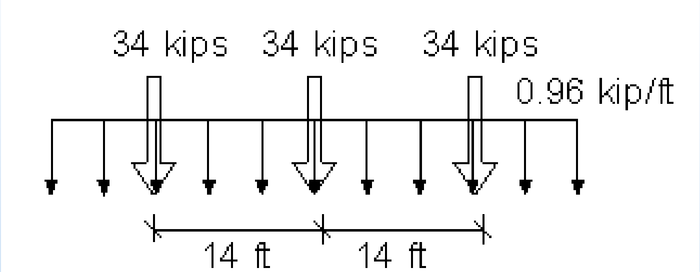
UIC Code 776-2 (Art. 5.2)

Guide Specifications

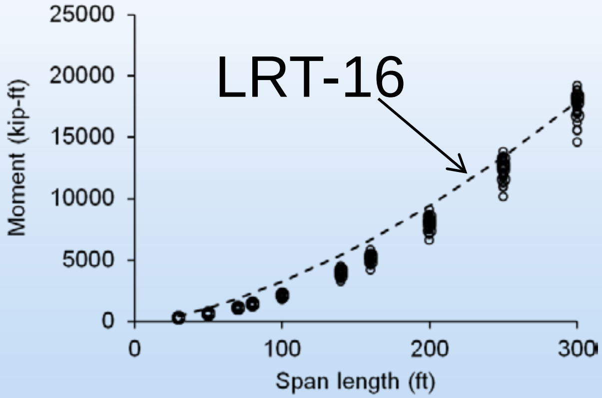
AASHTO LRFD design specifications and commentary

3. Loads
- Permanent loads (*DC*, *DW*, and *EV* based on BDS)
- Earth loads (*EH*, *ES*, and *DD* based on BDS)
- Live loads (*LL* and *PL*)
  - Number of design tracks
  - Multiple presence of live load
  - Design light rail transit load (LRT-16):

- 48,256 models
- 4 probability levels
- 660 load enveloping cases with 33 trains operated in the nation



LRT-16



30 ft to 160 ft (initial)
HL-93 up to 150 ft
30 ft to 300 ft (T-5)

Guide Specifications

AASHTO LRFD design specifications and commentary

3. Loads

- Dynamic load allowance (*IM*): 30% (25% plus a 5% margin)
- Derailment load (*DE*): 100% vertical and 40% horizontal
- Centrifugal force (*CE*):

$$C = \frac{4}{3}\frac{v^2}{gR}\left(-0.2n + 1.4\right)$$

- Braking force (*BR*)

  28 percent of the axle weights of light rail design train or
  5 percent of the axle weights plus lane load
- Wind loads: *WS* (on structure) and *WL* (on trains)
- Earthquake effects (*EQ*): Art. 3.10 of BDS

Guide Specifications

AASHTO LRFD design specifications and commentary

4. Structural Analysis
    - Acceptable method of structural analysis (Arts. 4.4/4.5 of BDS)
    - Structural material behavior (Arts. 4.5.2.2/4.5.2.3 of BDS)
    - Modeling geometry and boundary conditions (Art. 4.5.3 of BDS)
    - Influence of plan geometry (Art. 4.6.1 of BDS)
    - Distribution factor methods for moment and shear
        - PC box, PC I, Steel box, Steel plate, and RC
    - Skewed bridges

Table 4.4.2-1. Distribution of Light Rail Live Loads for Moment in Interior Beams

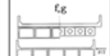
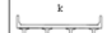
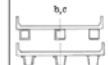
Type of Superstructure	Applicable Cross Section in AASHTO LRFD BDS	Distribution Factor	Range of Applicability
PC Box	f,g 	One-track-loaded $(0.22+\frac{S}{19.0})(\frac{1}{L})^{[illegible]}(\frac{1}{N})^{[illegible]}$ Two-track-loaded $(\frac{13}{N})^{[illegible]}(\frac{S}{10.3})(\frac{1}{L})^{[illegible]}$	$8.0 \le S \le 12.0$ $80 \le L \le 140$ $N_b \ge 3$
PC I	k 	One-track-loaded $-0.2+(\frac{S}{67.5})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$ Two-track-loaded $0.2+(\frac{S}{12.7})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$	$4 \le S \le 10$ $t_s = 10$ $80 \le L \le 140$ $N_b \ge 3$ $500{,}000 \le K_g \le 2{,}500{,}000$
Steel Box	b,c 	One-track-loaded $(\frac{S}{68.0})^{[illegible]}(\frac{Sd}{12.0L})^{[illegible]}$ Two-track-loaded $(\frac{S}{14.2})^{[illegible]}(\frac{Sd}{12.0L})^{[illegible]}$	$6 \le S \le 10$ $80 \le L \le 140$ $33 \le d \le 65$ $3 \le N_c \le 5$
Steel Plate	a 	One-track-loaded $-0.15+(\frac{S}{87.5})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$ Two-track-loaded $0.2+(\frac{S}{16.0})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$	$4 \le S \le 10$ $t_s = 10$ $80 \le L \le 160$ $N_b \ge 3$ $400{,}000 \le K_g \le 5{,}000{,}000$
RC	e 	One-track-loaded $0.04+(\frac{S}{14.2})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$ Two-track-loaded $0.07+(\frac{S}{11.1})^{[illegible]}(\frac{S}{L})^{[illegible]}(\frac{K_g}{12.0Lt^3})^{[illegible]}$	$4 \le S \le 10$ $t_s = 10$ $30 \le L \le 70$ $N_b \ge 3$ $50{,}000 \le K_g \le 2{,}000{,}000$

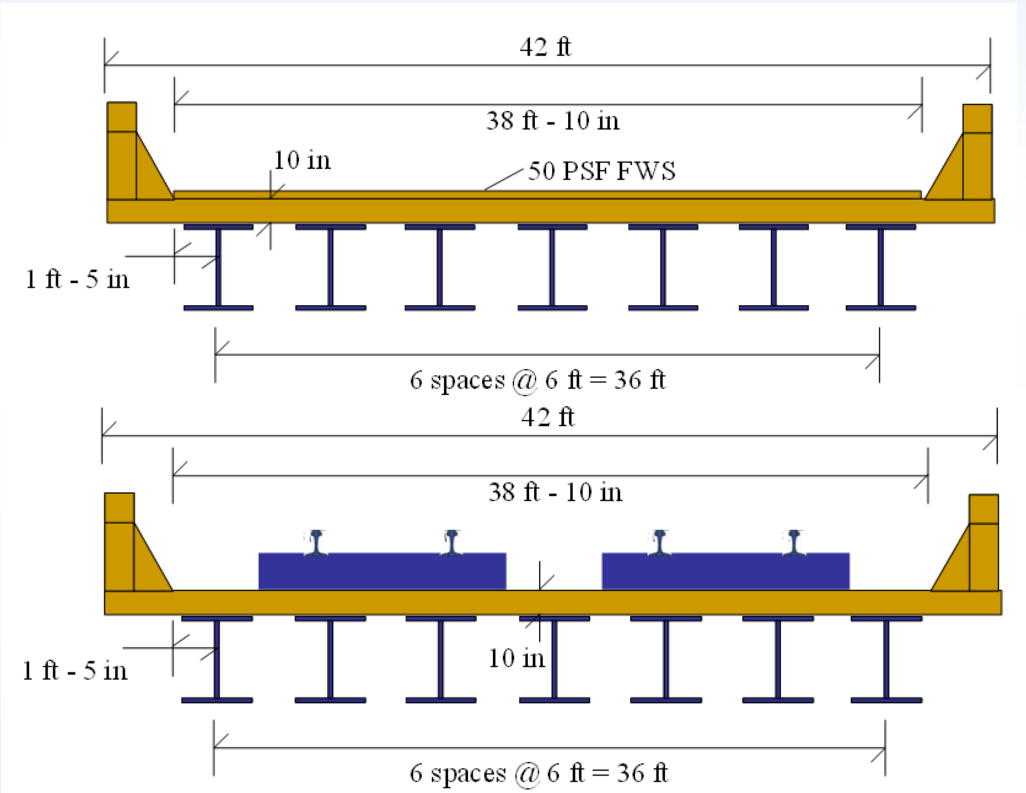
Table 4.4.3-1. Skew Correction Factors for Light Rail Bridges

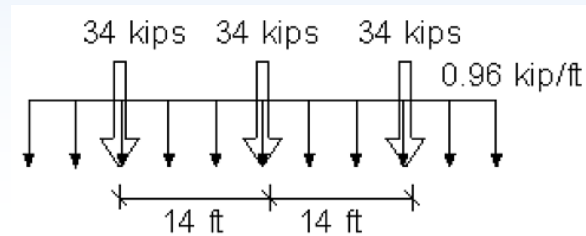
Type of Superstructure	Correction Factor	
	Moment	Shear
PC Box	$1.05-0.21\tan\theta$	$-17.7+\left(19.0+\frac{12L}{70dS}\right)(\tan\theta)^{0.02}$
PC I	$1-c_1(\tan\theta)^{1.6}$ $c_1=0.32\left(\frac{K_g}{9.6Lt_s^3}\right)^{-0.45}\left(\frac{S}{L}\right)^{-0.13}$	$0.15+1.1\left(\frac{12.0Lt_s^3}{K_g}\right)^{-0.04}(\tan\theta)^{0.17}$
ST Box	$1.02-0.15\tan\theta$	$1.04+\left(\frac{\sqrt{\frac{Ld}{86}}}{15.2S}\right)^{0.36}(\tan\theta)^{1.5}$
ST Plate	$1-c_1(\tan\theta)^{2.5}$ $c_1=0.1\left(\frac{K_g}{0.77Lt_s^3}\right)^{-0.31}\left(\frac{S}{L}\right)^{0.12}$	$1+0.3\left(\frac{12.0Lt_s^3}{K_g}\right)^{0.16}(\tan\theta)^{0.7}$
RC	$1-c_1(\tan\theta)^{1.5}$ $c_1=0.25\left(\frac{K_g}{12.0Lt_s^3}\right)^{0.25}\left(\frac{S}{L}\right)^{0.5}$	$1+0.3\left(\frac{1995Lt_s^3}{K_g}\right)^{0.004}(\tan\theta)^{1.7}$

Design Examples

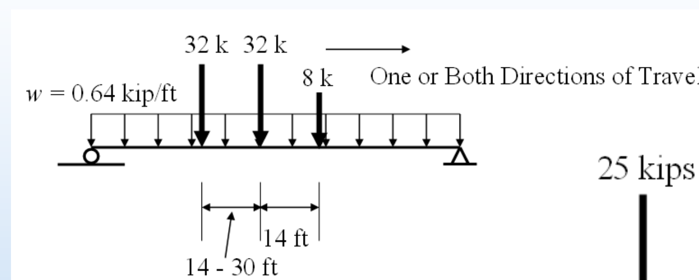
Design Example

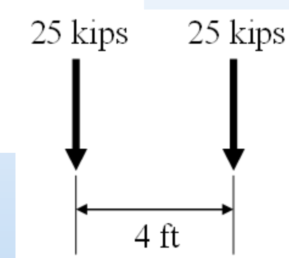
Example No. 1: Simple Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)





L = 125 ft

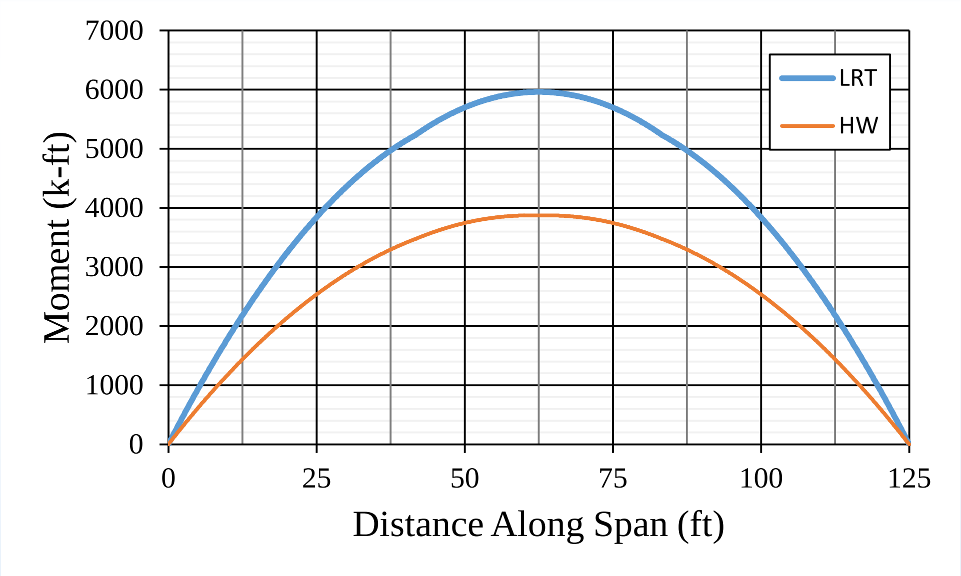




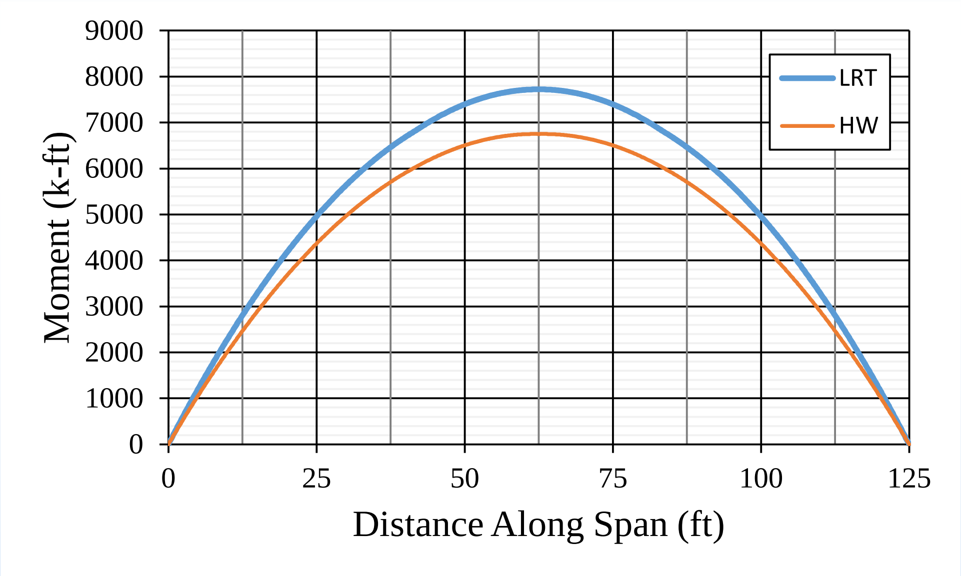
Design Example

Example No. 1: Simple Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)

Live load distribution factors from the LRFD BDS (HWY) and LRT specs



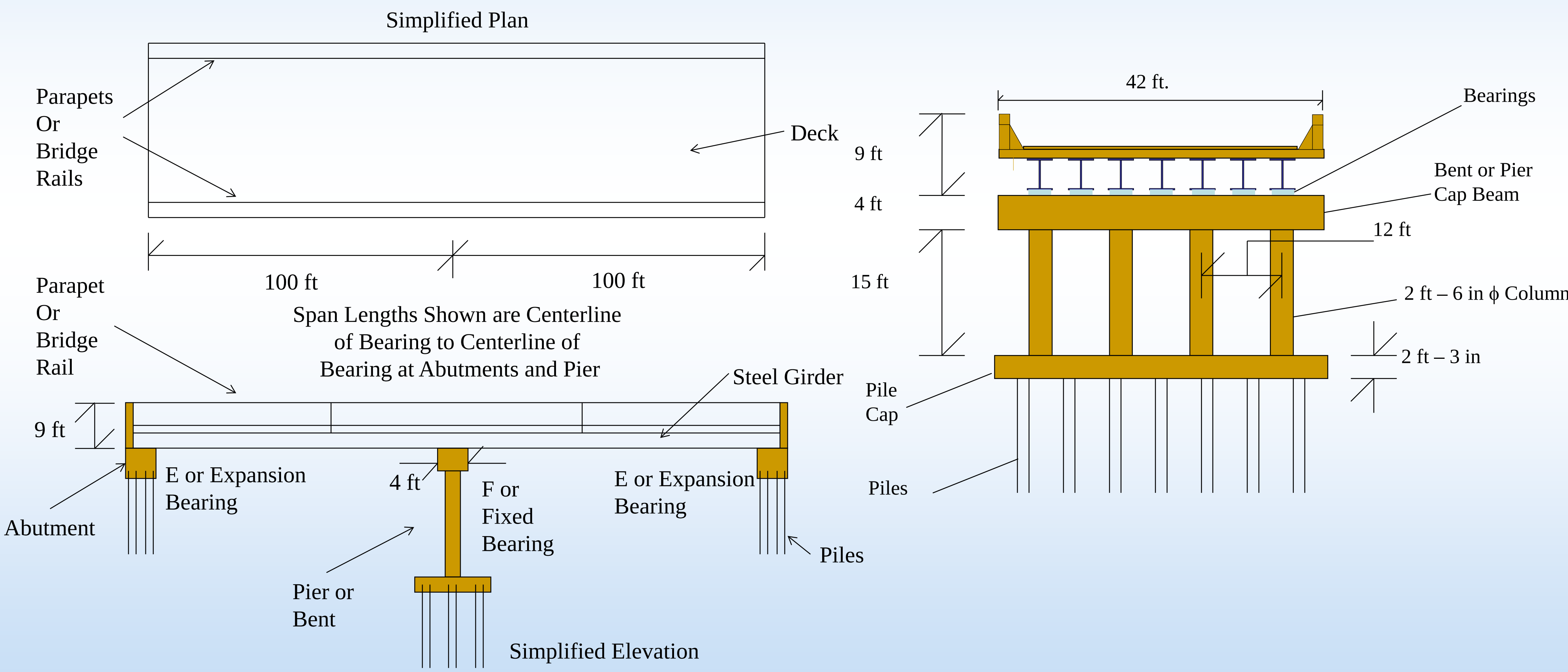
Unfactored undistributed live load moment



Strength I factored design moment (1.25 DL and 1.75 HWY / 1.65 LRT)

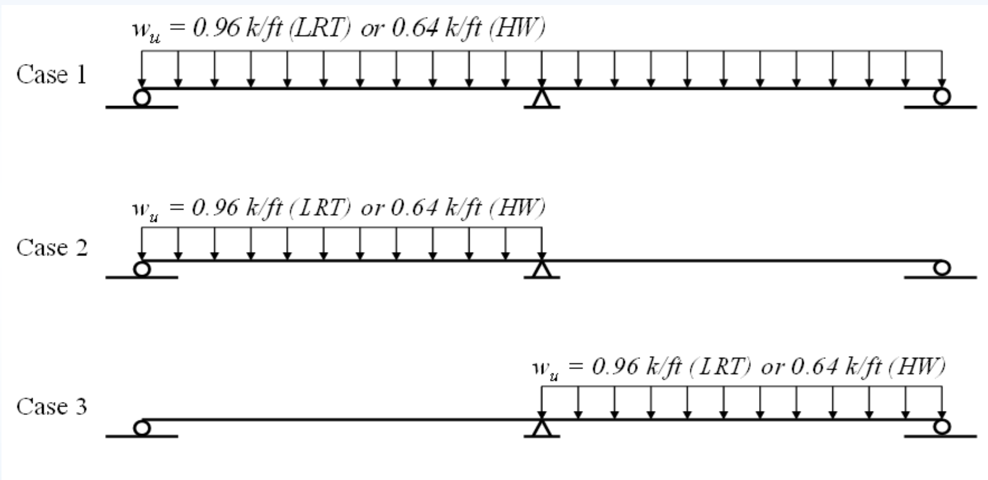
Design Example

Example No. 2: Continuous Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)



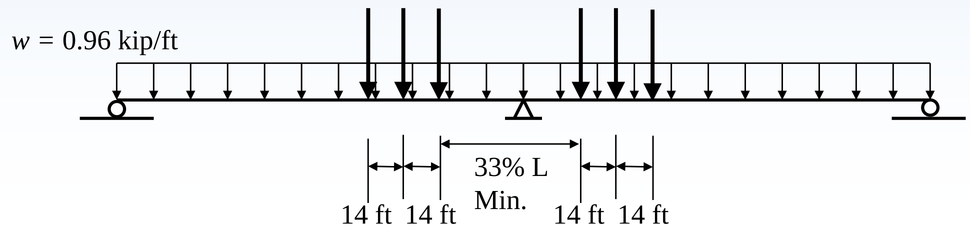
Design Example

Example No. 2: Continuous Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)

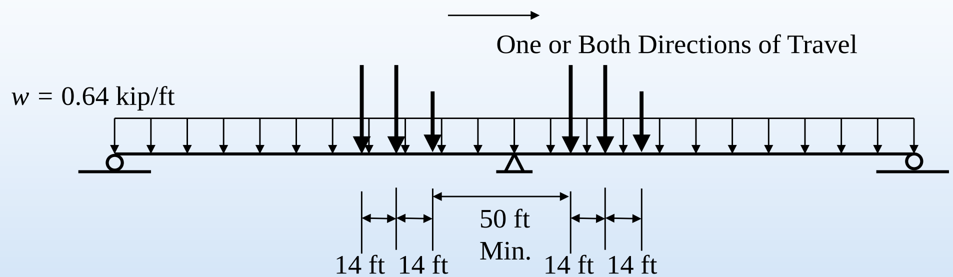


Uniform patch loads for +ve moment

-ve moment near pier



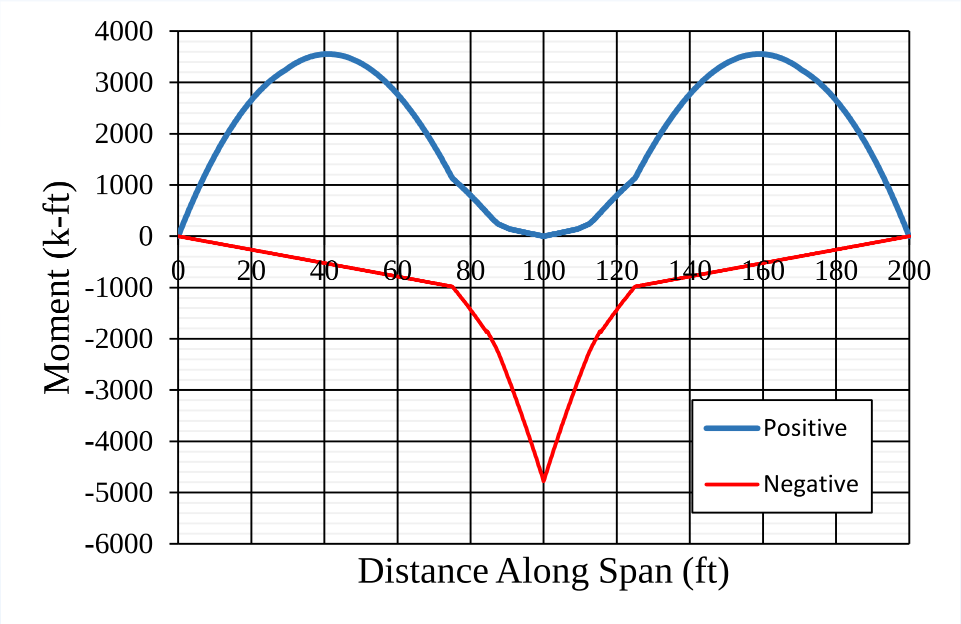
LRT: 90% of 2 LRT trains + 90% of UDL

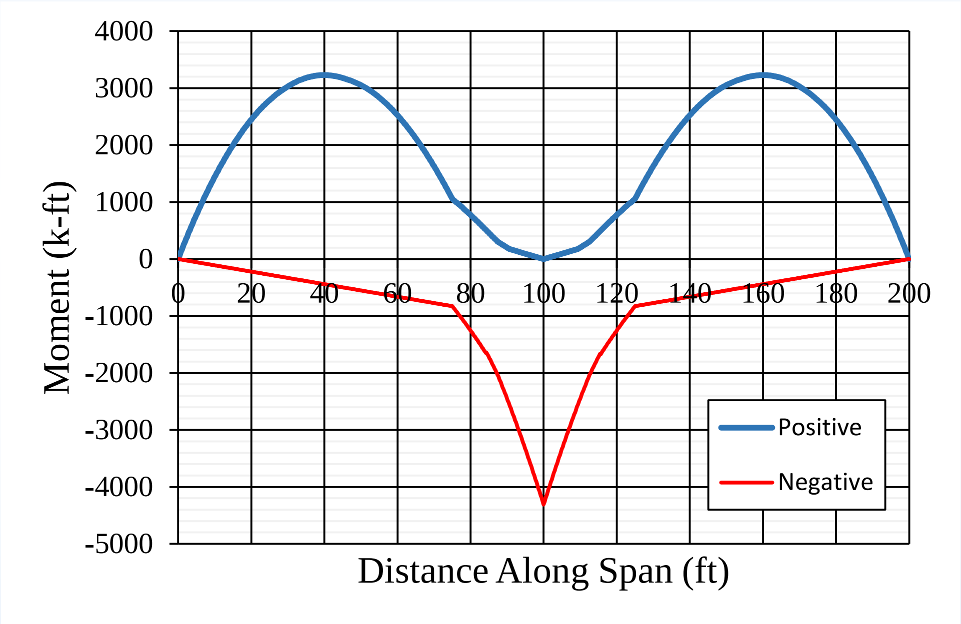


HWY: 90% of 2 HS-20 trucks + 90% of UDL

Design Example

Example No. 2: Continuous Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)



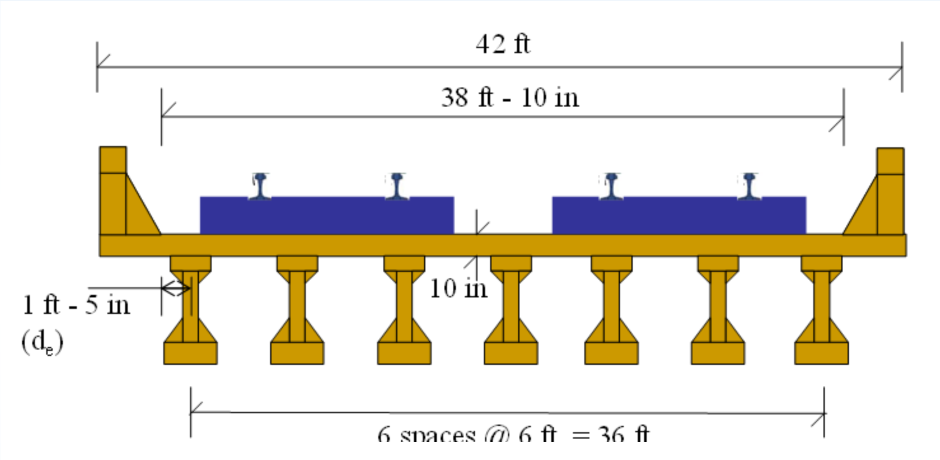


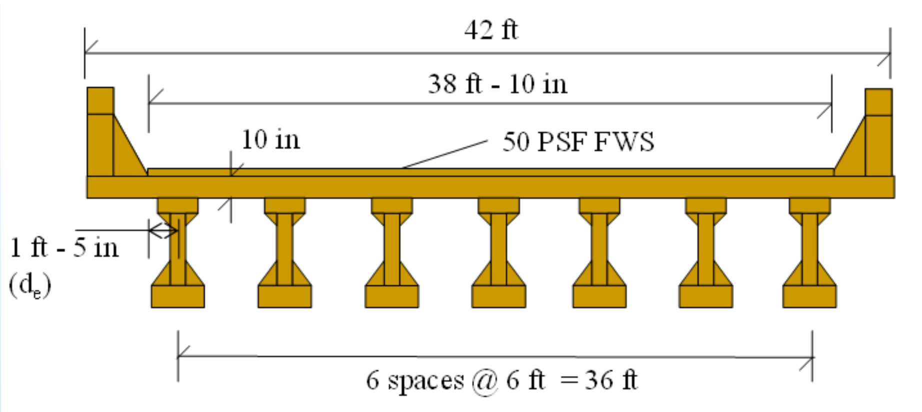
Strength I factored design moment (LRT)

Strength I factored design moment (HWY)

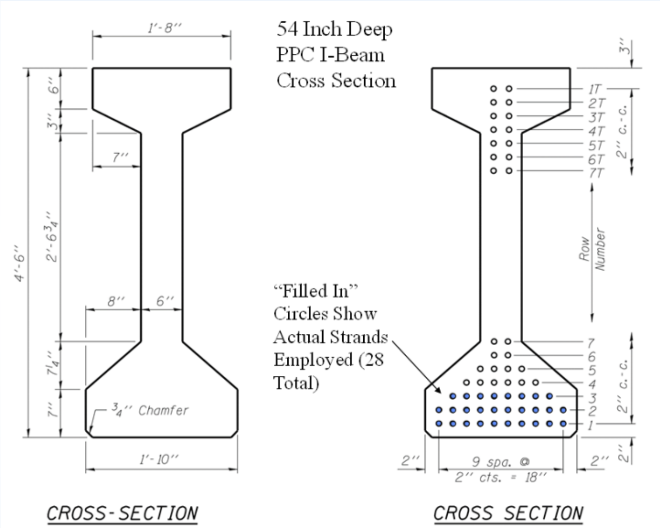
Design Example

Example No. 3: Simple Span Composite Precast Prestressed Girder – Service Stress Checks (LRT-16 and HL-93)





L = 80 ft



Design Example

Example No. 3: Simple Span Composite Precast Prestressed Girder – Service Stress Checks (LRT-16 and HL-93)

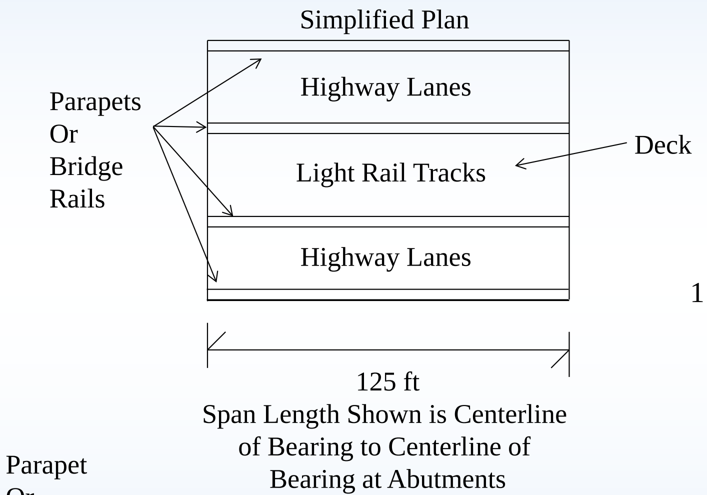
Stress Check w/o Live Loads (Check LRT Case): BDS Art. 5.9.4.2.1 (compression service stresses)
f_{top} = 1.15 ksi < 0.45 f'_c (2.7 ksi): OK

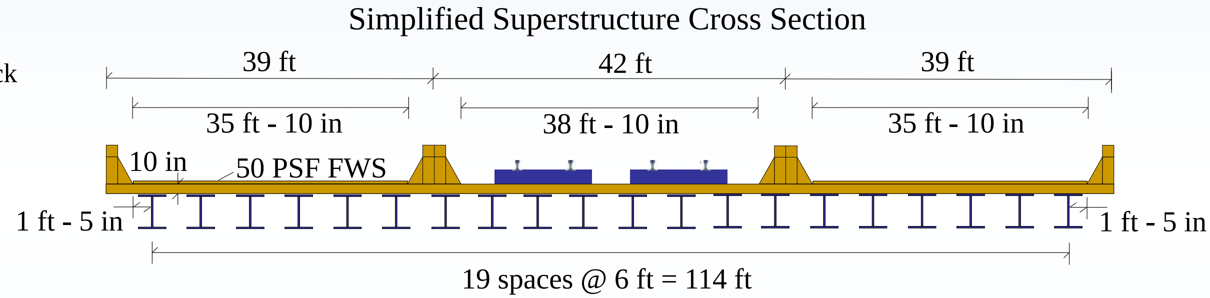
Stress Check w/ Live Loads (Check LRT Case): BDS Art. 5.9.4.2.1 (compression service stresses)
f_{top} = 1.46 ksi < 0.6ϕ_w f'_c (3.6 ksi): OK

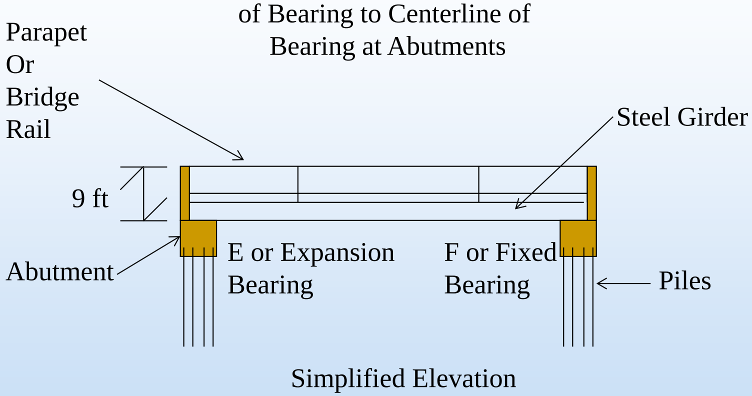
Stress Check w/ Live Loads (Check LRT Case): BDS Art. 5.9.4.2.2 (tensile service stresses)
f_{bot}= 0.047 ksi < 0.19 SQRT (f'_c) (0.465 ksi): OK

Design Example

Example No. 4: Simple Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)



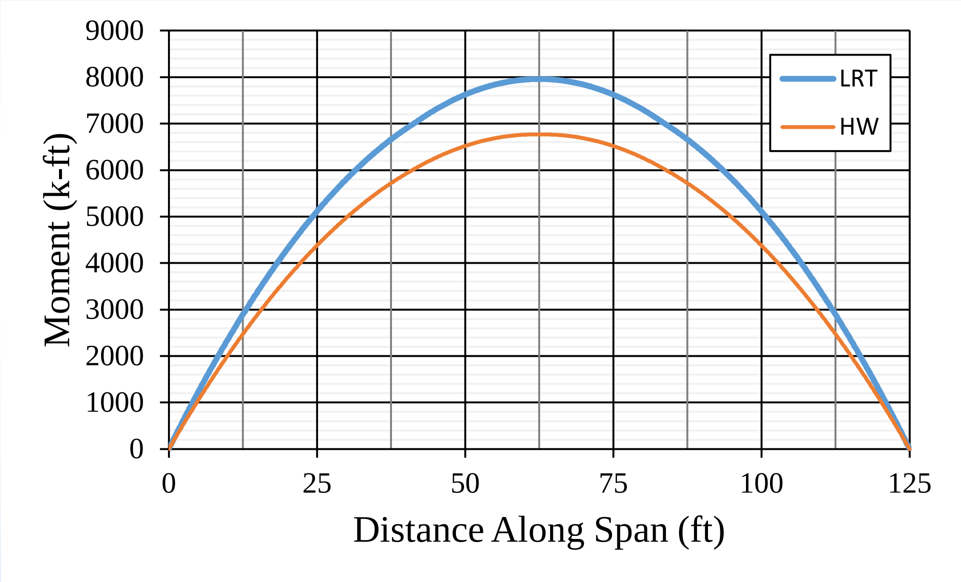




If the bridge is expected to carry both light rail and highway traffic loadings, the foregoing train loadings and HL-93 design truck or tandem and lane load specified in Article 3.6.1.2 of AASHTO LRFD BDS shall both be considered independently. The maximum load effects from these two cases should be used for design.

Design Example

Example No. 4: Simple Span Composite Steel Plate Girder – Strength I Moment (LRT-16 and HL-93)



Strength I factored design moment

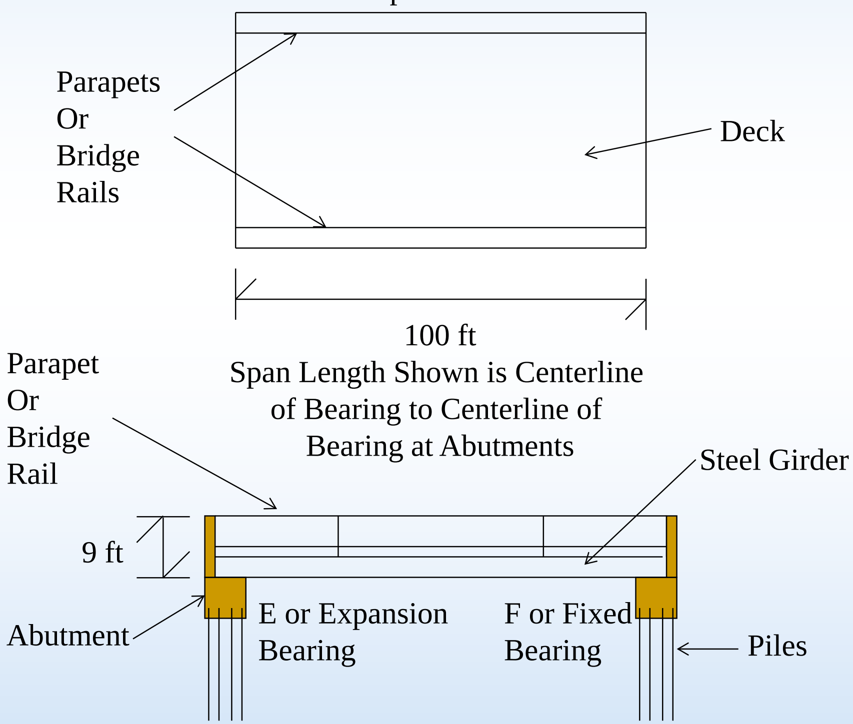
BDS Article 6.10.6.2.2 – Composite Sections in Positive Flexure

BDS Article 6.10.7.3 Ductility Requirement

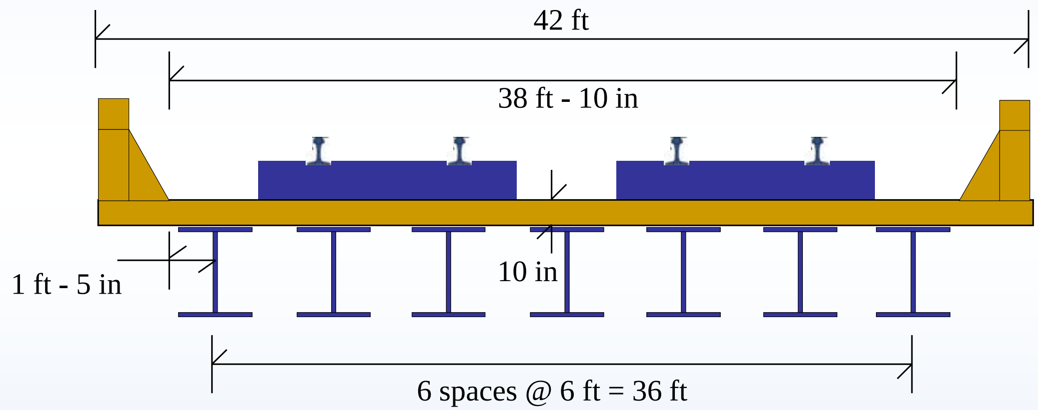
Design Example

Example No. 5: Simple Span Composite Steel Plate Girder – Other Considerations (LRT-16)

Simplified Plan



Simplified Elevation

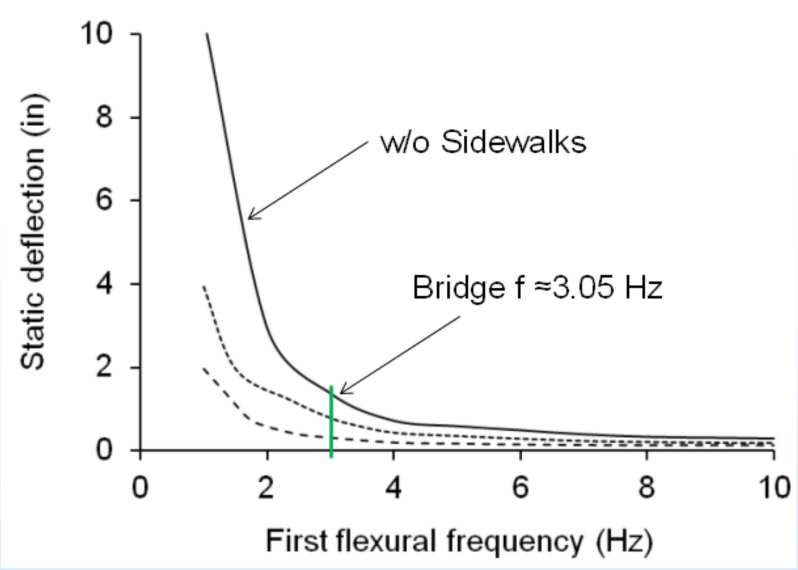


Full LRT-16 loading

Design Example

Example No. 5: Simple Span Composite Steel Plate Girder – Other Considerations (LRT-16)

Deflection and Pedestrian Comfort (passenger comfort = *L*/600)



Rail break

$$Gap_{max} = 2\frac{EA(\alpha \Delta T)^2}{N_{clip}\mu P_{TL}} S$$

Assuming :

$E = 29000\ ksi$ (*Modulus of Elasticity of Steel*)

$A = 11.25\ in^2$ (*Area of 115RE Rail*)

$\alpha = 6.5 \times 10^{-6} / {}^{\circ}F$ (*Coefficie nt of Thermal Expansion*)

$\Delta T = 120^{\circ}F$

$N_{clip} = 2$ (*No. of Rail Clips on the Fastener*)

$\mu = 0.5$ (*Coefficien t of Friction Between Rail and Rail Clip from TCRP 71*)

$P_{TL} = 6153\ {}^{lb}/_{fastener}$ (*Individual Clip Toe Load from TCRP 71*)

$S = 30\ in$ (*Spacing of Fastener*)

Then :

$$Gap_{max} = 2\frac{29000 \times 11.25(6.5 \times 10^{-6} \times 120)^2}{2 \times 0.5 \times 6153} 30 = 1.94\ in < 3.0\ in\ max,\ OK$$

Summary

Summary

- In-situ bridge monitoring and statistical data acquisition
- Benchmark bridges designed and FE models calibrated
- Standard live load model proposed (deterministic + probabilistic)
- Load effects characterized (deflection, user comfort, load distribution, dynamic load allowance, multiple presence, and skew correction)
- Associated forces/effects proposed (centrifugal, longitudinal, thermal and rail break, and bearing arrangement)
- Unified design approaches proposed (light rail only and light rail/highway traffic loadings)
- Load factors proposed (Strength I, Service I, and Fatigue I and II)
- Design examples presented

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- National Academy of Sciences

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