Safe Platooning Headways on Girder Bridges

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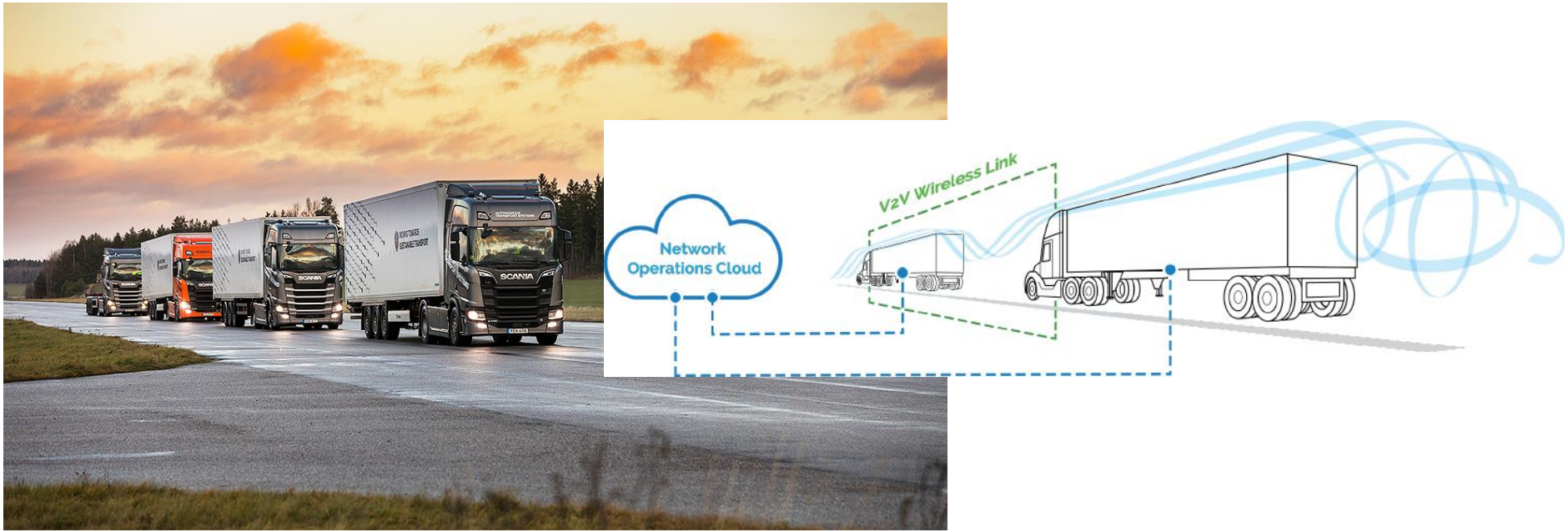
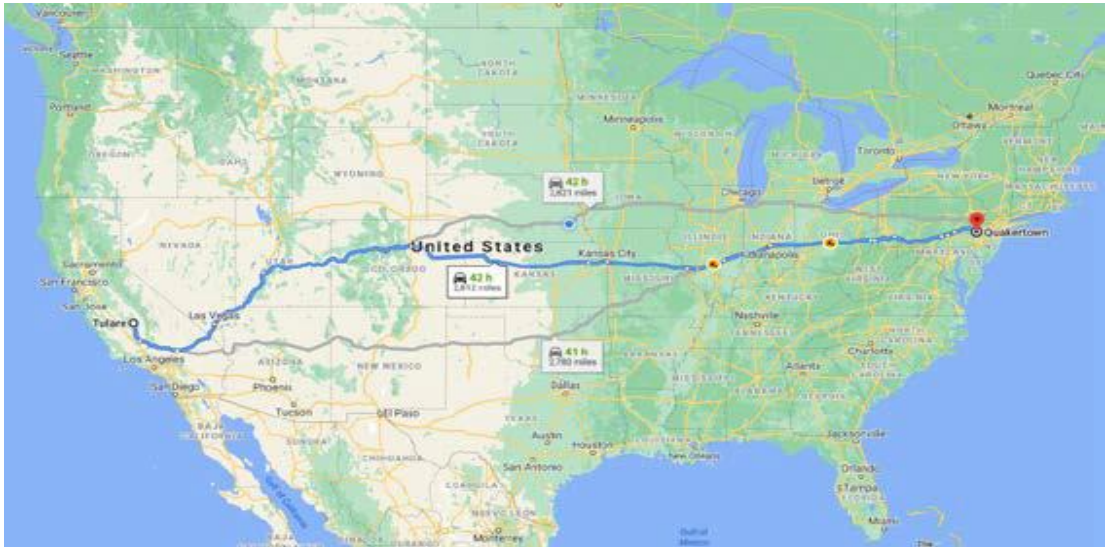
Background

- What is Truck Platooning?



Background

- Numerous companies (e.g., Plus.ai) are entering the autonomous truck market



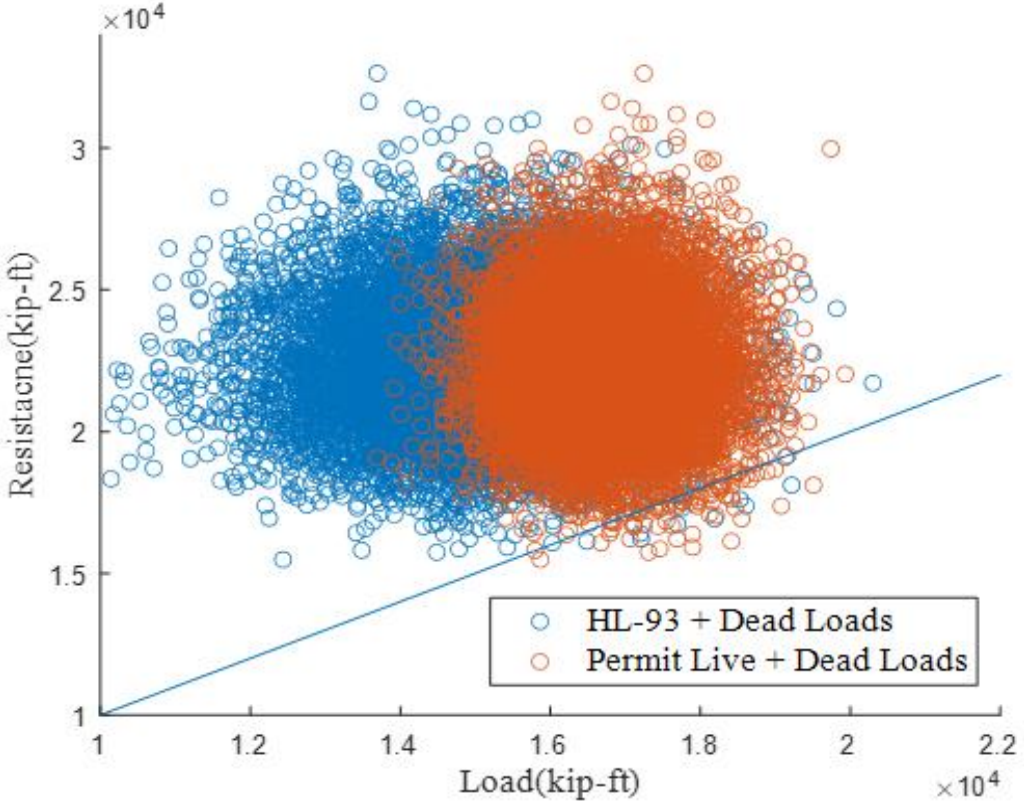
Background

- What are the benefits of truck platooning?
  - Reduce fuel use
  - Reduce carbon footprint
  - Reduce labor costs

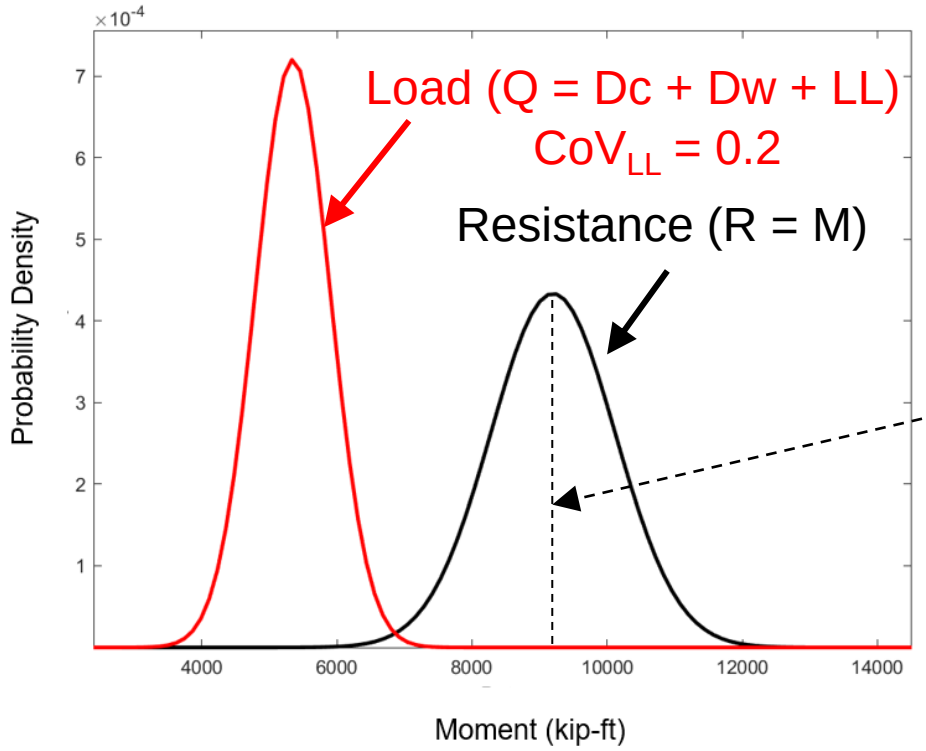
- Leverage benefits from *reduced uncertainties* with platoon operations

Background

- Heavy loads are acceptable without compromising safety



Background



M_n = 8213 k-ft

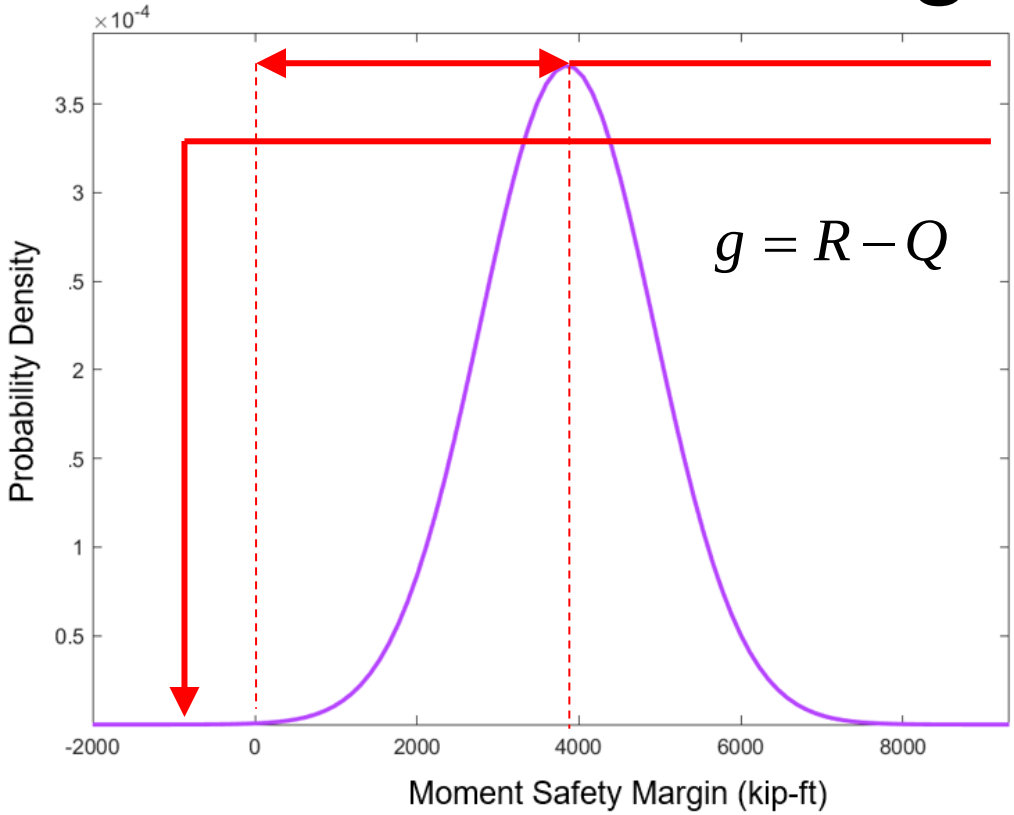
λ_R = 1.12

$\overline{M_n} = \lambda_R M_n$
= 9200 k-ft

CoV_R = 0.1

$\sigma_R = CoV_R \ \overline{M_n}$

Background



Reliability Index, β = 3.59

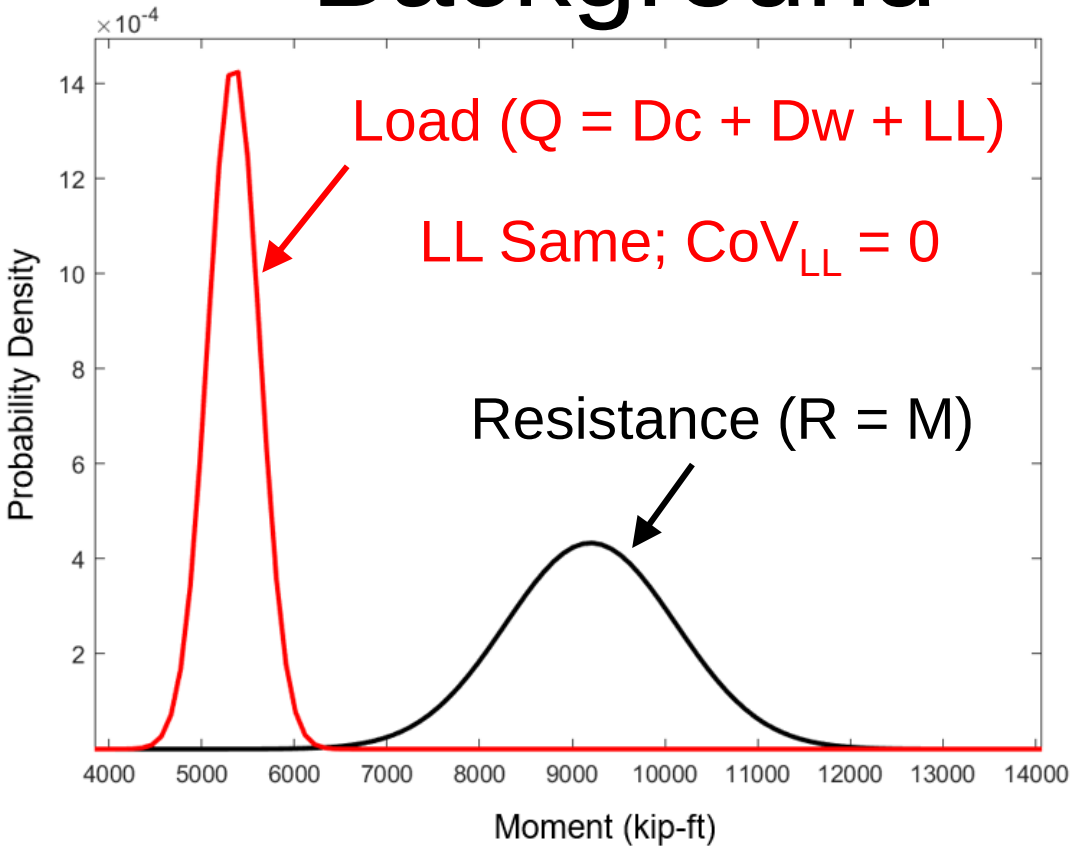
Probability of failure = 0.0165 %

“Failure” occurs when g < 0

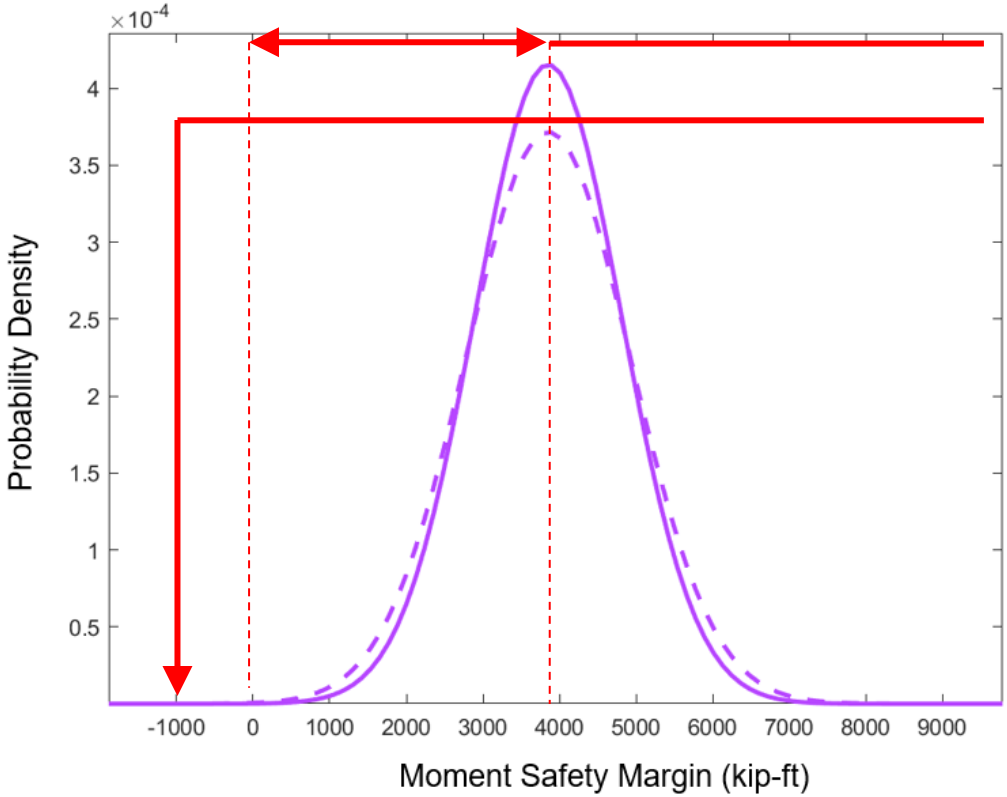
Reliability index:
(simplified & approximate)

$$\beta = \frac{\overline{R} - \overline{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

Background


×10^-4
14
12
10
8
6
4
2
Probability Density
Load (Q = Dc + Dw + LL)
LL Same; CoV_LL = 0
Resistance (R = M)
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
Moment (kip-ft)

Background

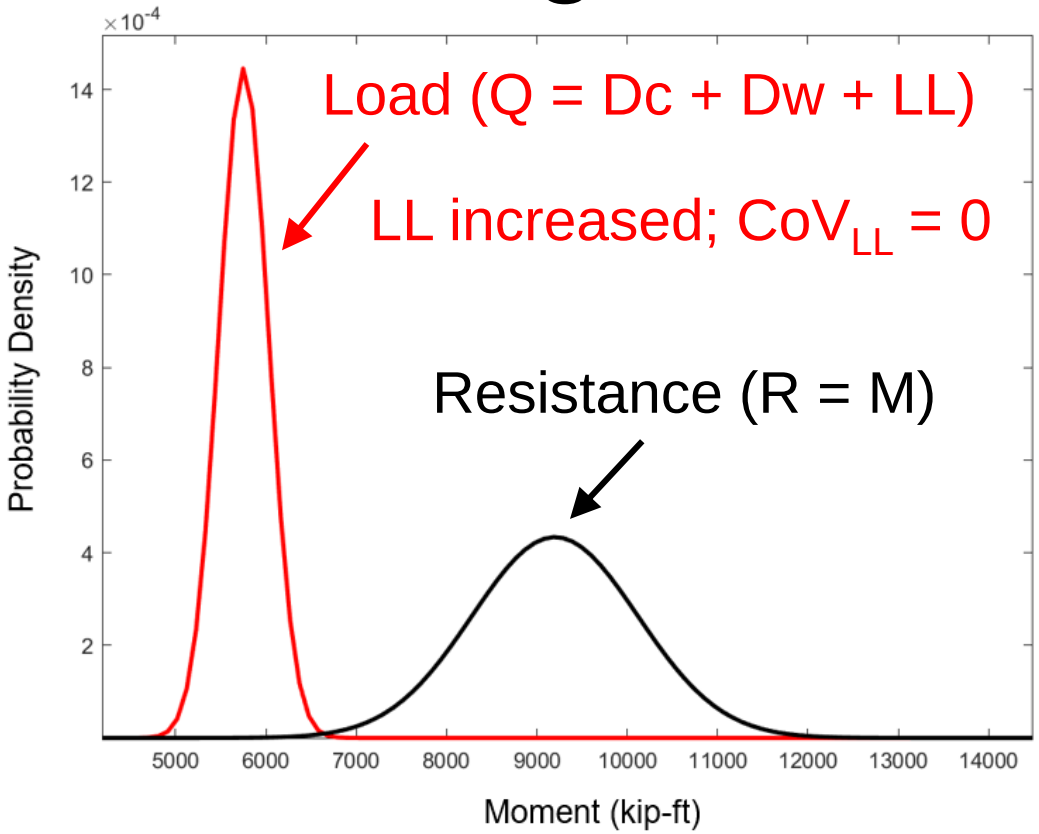


Reliability Index, β = 4.01

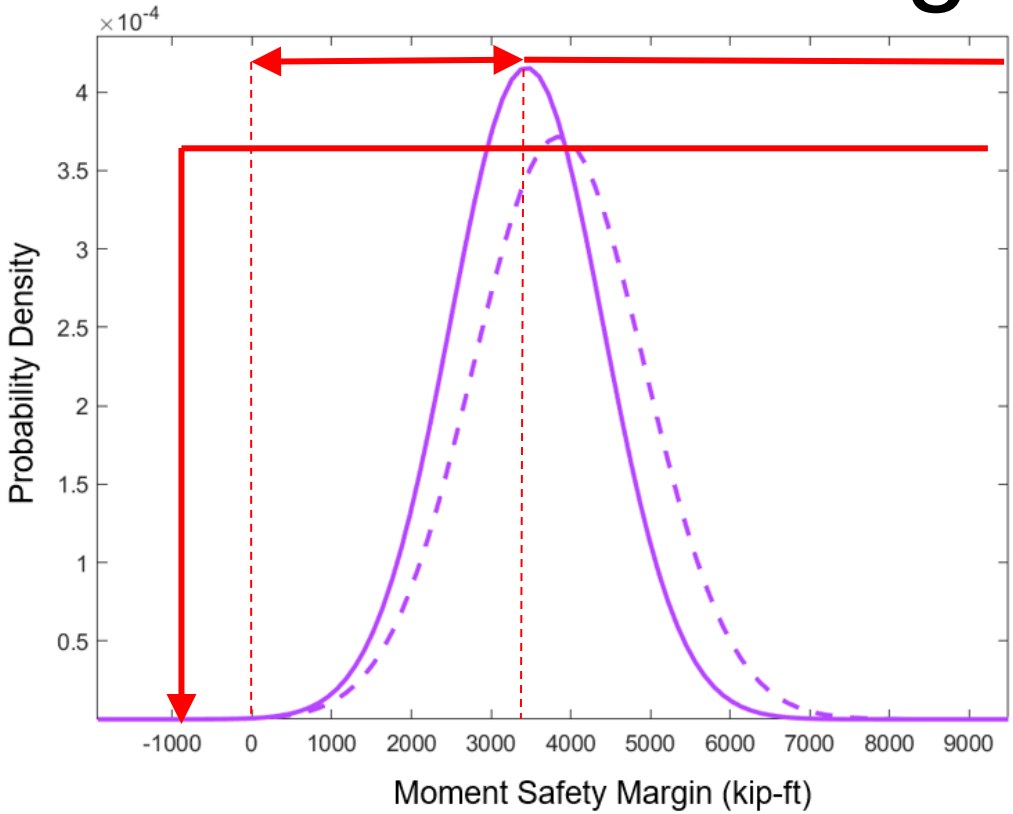
Probability of failure = 0.0032 %

$$\beta \uparrow = \frac{\overline{R} - \overline{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \downarrow$$

Background


×10^-4
14
12
10
8
6
4
2
Probability Density
Load (Q = Dc + Dw + LL)
LL increased; CoV_LL = 0
Resistance (R = M)
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
Moment (kip-ft)

Background



Reliability Index, β = 3.59

Probability of failure = 0.0165 %

$$\beta = \frac{\bar{R} - \bar{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

Objectives

- Provide a framework for determining how much load could potentially increase above legal limits, accounting for varying:
  - Live load uncertainties
  - Headways
- Establish platoon operation limitations and guidelines based on Strength I limit state

Scope

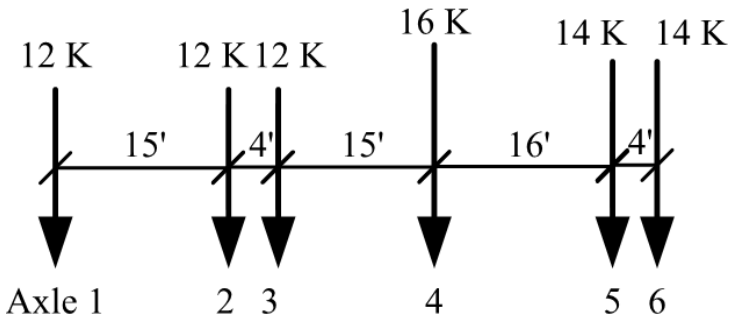
- Bridge parameters and ranges
  - Bridge types
    - Steel girder
    - Prestressed concrete girder
  - Bridge spans
    - Simple span
    - Two equal continuous spans

Scope

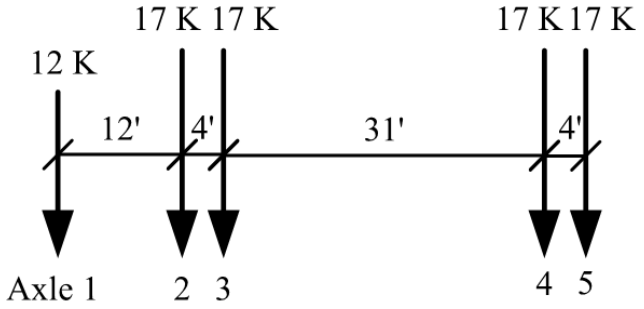
- Bridge parameters and ranges
  - Bridge span lengths
    - Steel : 30 ft – 150 ft @ 30 ft increments, 200 ft
    - P/S: 30 ft – 150 ft @ 30 ft increments
    - PCI Bridge Design Manual : Design charts for 30 ft – 150 ft
  - Girder spacings
    - 8, 10, and 12 ft
  - Design lanes
    - 2 lanes

Scope

- Vehicle types (GVW = 80 kips)



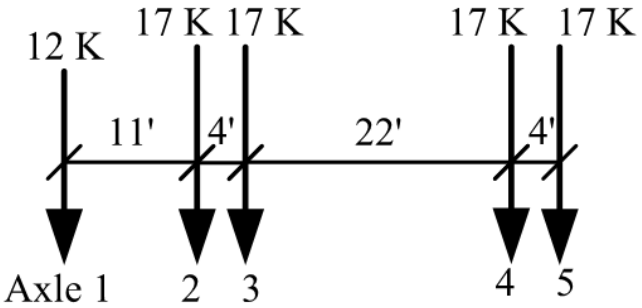
AASHTO Type 3-3 (80 kips GVW)



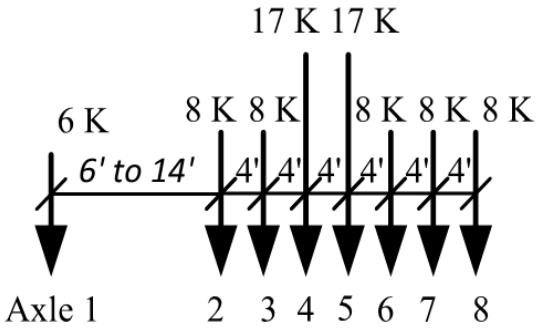
FHWA Class 9 (80 kips GVW)

Scope

- Vehicle types (GVW = 80 kips)



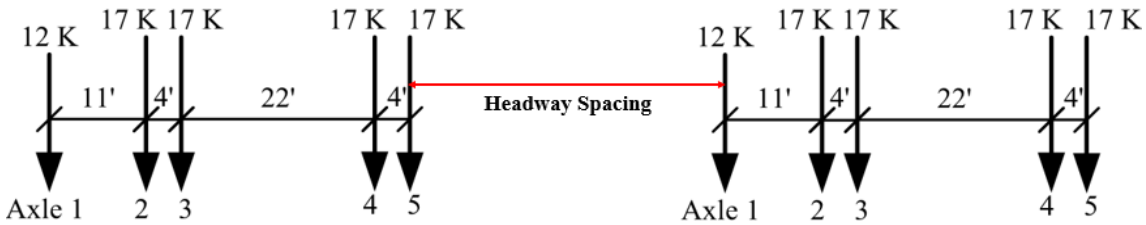
NJTA Type 3S2 (80 kips GVW)



AASHTO NRL (80 kips GVW)

Scope

- Vehicles
  - Number of trucks
    - 2, 3, or 4
  - Headways
    - 5 to 50 ft (typ.)
  - Lanes
    - Single-lane w/ adjacent traffic (heavy truck next to platoon)
    - Single-lane w/o adjacent traffic (only platoon on bridge)



Methodology

$$R_n = \frac{1.25DC + 1.5DW + 1.75L_n(1+IM)(GDF_m)}{\phi}$$

- DC, DW for steel bridges → prelim design @ Strength I & Service II
- DC, DW for P/S bridges → PCI design charts
- Interior girder
- LL: HL-93 Loading with AASHTO LRFD IM
- GDF_m: AASHTO approximate multi-lane loaded GDF

Methodology

- Dead load statistical parameters:
  - Consistent with NCHRP 20-07/186
  - Normal distribution

Component	λ_D	CoV_D
DC	1.05	0.10
DW	1.00	0.25

Methodology

- Resistance statistical parameters:
  - Consistent with NCHRP 20-07/186
  - Lognormal distribution

Type of structures	λ_R	CoV_R
Composite steel girders		
Moment	1.12	0.10
Shear	1.14	0.105
Prestressed Concrete		
Moment	1.05	0.075
Shear	1.15	0.140

Methodology

- Live load effects:
  - Dynamic Amplification (IM)
  - Girder distribution factors (GDFs)
  - Multiple presence

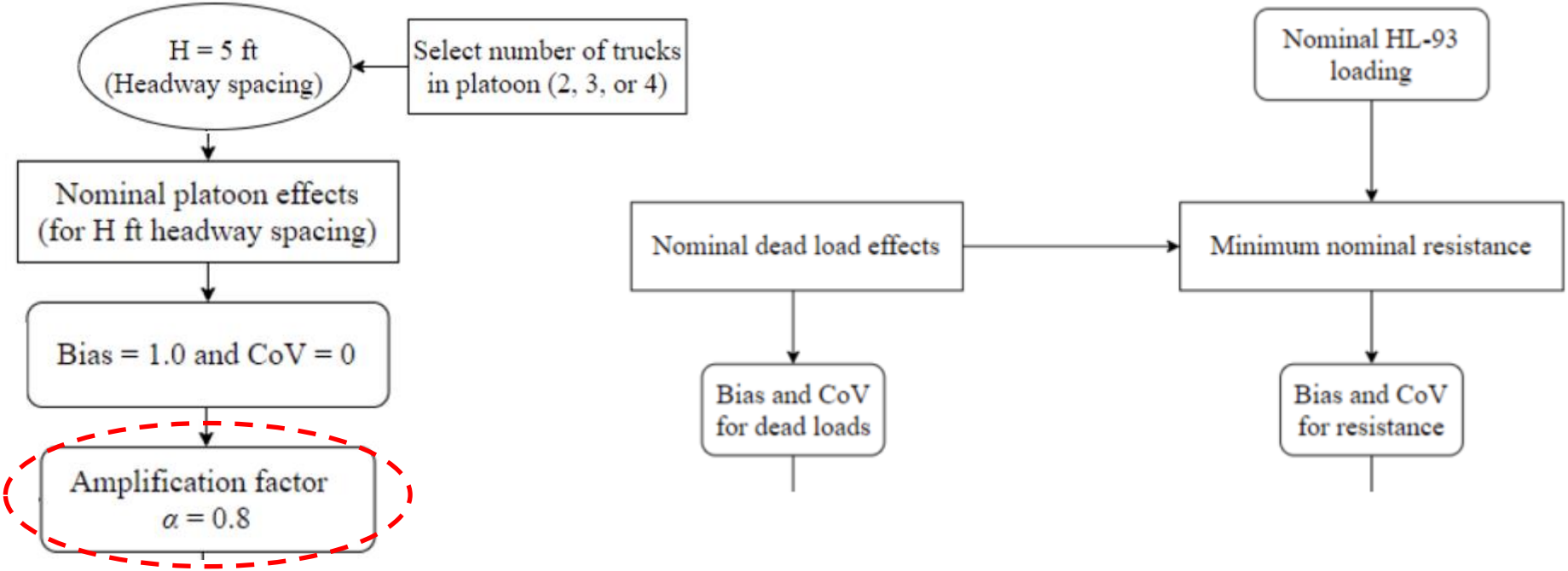
$$LL = L(GDF)(1+IM) = L(GDF) + L(GDF)IM$$

Methodology

- Live load statistical parameters:
  - Consistent with NCHRP 20-07/186
  - Bias = 1.0 for IM and GDFs

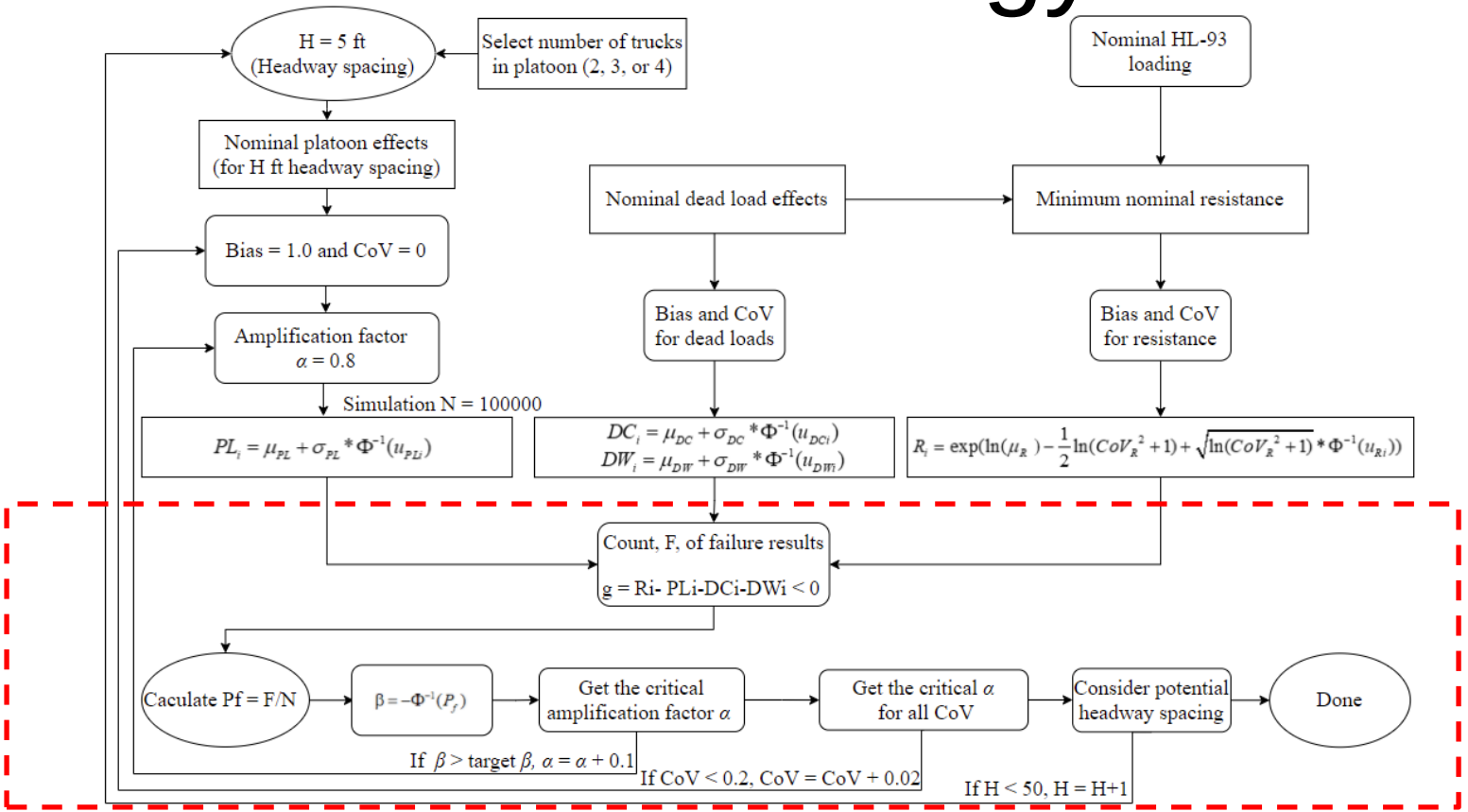
    $CoV_{GDF} = 0.12$ $CoV_{IM} = 0.80$ $\mu_{IM} = 0.10$
  - Bias = 1.0 and CoV = 0 to 0.2 for platoons
  - Platoon: Normal distribution
  - Adjacent loads: Extreme type I distribution

Methodology

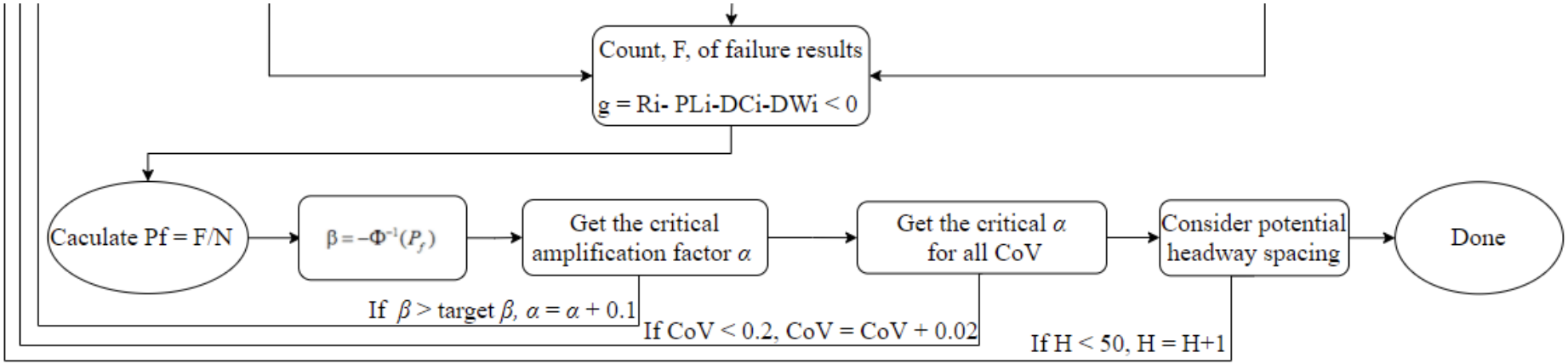


- α scales platoon vehicle weights relative to legal load limits
- α = 1 for an 80 kip platoon vehicle

Methodology



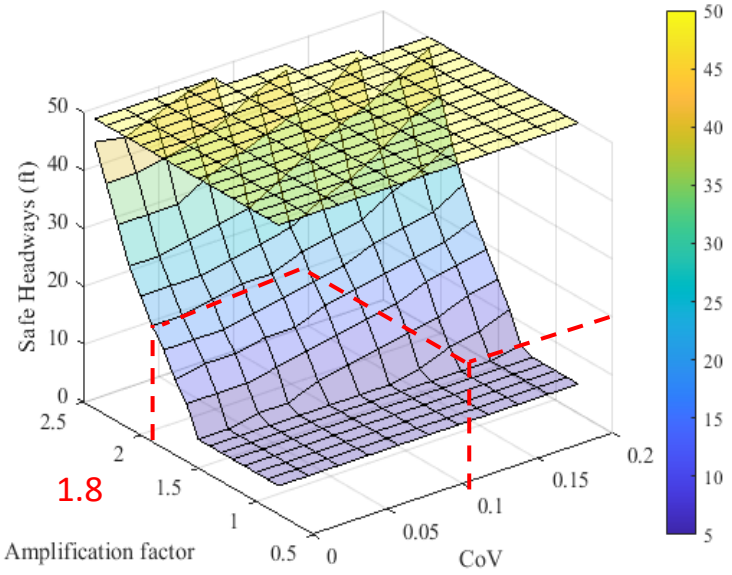
Methodology

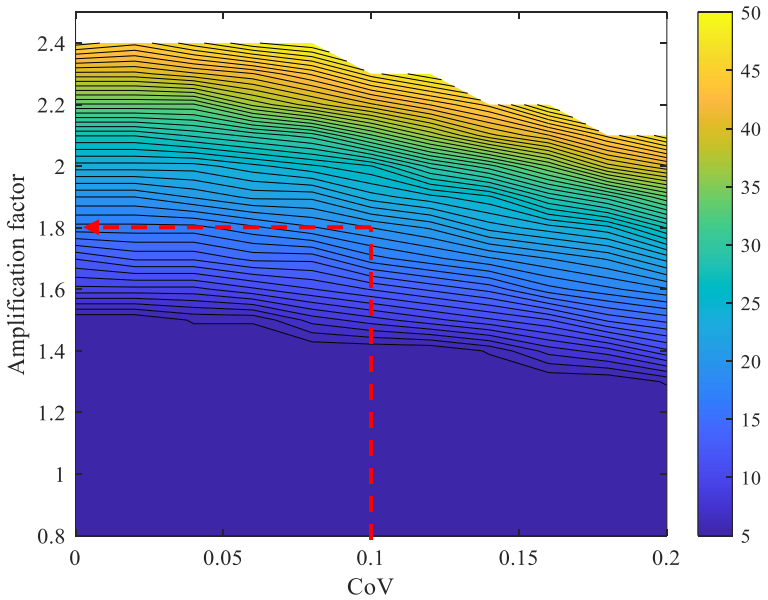


Results

- Example safe headways for a simple span bridge

➢ Target β = 2.5 ➢ Steel, 120 ft long ➢ Platoon w/ adjacent loads ➢ 3 Trucks





Results

- Example safe headways for a simple span bridge

Max w/ Headway & CoV Control

Max w/ Headway Control

Unrestricted

α \ CoV	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2
0.8	5	5	5	5	5	5	5	5	5	5	5
0.9	5	5	5	5	5	5	5	5	5	5	5
1	5	5	5	5	5	5	5	5	5	5	5
1.1	5	5	5	5	5	5	5	5	5	5	5
1.2	5	5	5	5	5	5	5	5	5	5	5
1.3	5	5	5	5	5	5	5	5	5	5	6
1.4	5	5	5	5	5	5	5	6	8	9	11
1.5	5	5	6	6	8	9	10	11	12	14	15
1.6	10	10	10	11	12	13	14	15	17	18	19
1.7	13	14	14	15	15	17	18	19	20	21	23
1.8	17	17	17	18	19	20	21	23	24	25	28
1.9	20	20	21	22	22	24	25	26	29	31	34
2	24	24	24	25	26	27	30	32	35	39	41
2.1	28	28	29	30	31	34	37	40	42	45	48
2.2	34	34	34	37	39	41	43	45	49	Fail	Fail
2.3	40	40	41	42	44	47	49	Fail	Fail	Fail	Fail
2.4	46	45	47	49	50	Fail	Fail	Fail	Fail	Fail	Fail
2.5	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Results

- Example safe headways for simple span bridges

Max w/ Headway & Selected Spans

Max w/ Headway Control

Unrestricted

α \ L	30 ft	60 ft	90 ft	120 ft	150 ft	200 ft
0.8	5	5	5	5	5	5
0.9	5	5	5	5	5	5
1	5	5	5	5	5	5
1.1	5	5	5	5	5	5
1.2	5	5	5	5	5	5
1.3	5	5	5	5	6	5
1.4	5	5	5	9	14	13
1.5	5	5	7	14	20	23
1.6	5	5	10	18	25	32
1.7	5	5	12	21	31	39
1.8	5	7	17	25	34	46
1.9	5	10	23	31	39	Fail
2	5	13	27	39	47	Fail
2.1	Fail	15	32	45	Fail	Fail
2.2	Fail	18	36	Fail	Fail	Fail
2.3	Fail	Fail	40	Fail	Fail	Fail
2.4	Fail	Fail	45	Fail	Fail	Fail
2.5	Fail	Fail	Fail	Fail	Fail	Fail

- Target $\beta = 2.5$
- $CoV = 0.18$
- Platoon w/ adjacent
- 3 Trucks

- At an $\alpha = 2.0$, the headway must increase to…
  - 13 ft for a 60-ft span
  - 27 ft for a 90-ft span
  - 39 ft for a 120-ft span, and
  - 47 ft for a 150-ft span.

Results

- What if a platooning operator wants to send a 3-truck platoon with α = 2.7 over a 120 ft simple span bridge?
  - Is tightening uncertainty and spacing out trucks enough?

Results

- Example safe headways for a simple span bridge

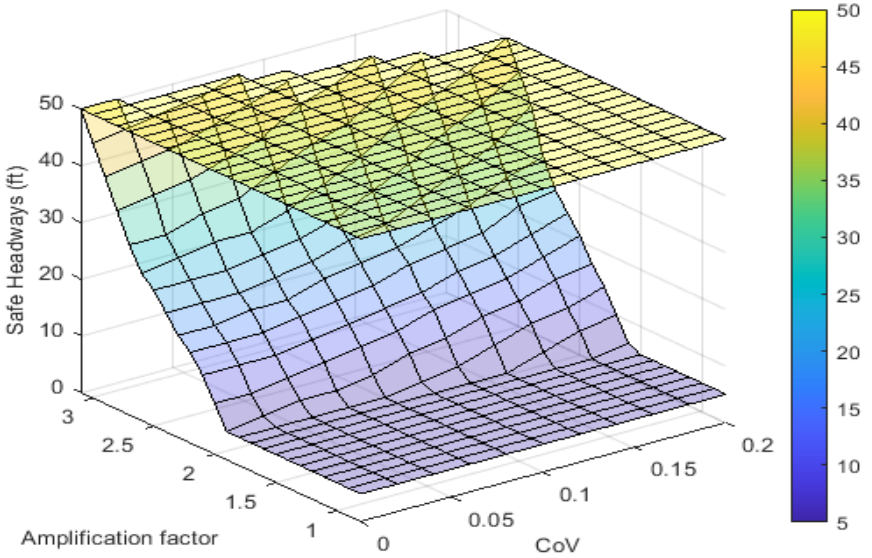
α \ CoV	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2
0.8	5	5	5	5	5	5	5	5	5	5	5
0.9	5	5	5	5	5	5	5	5	5	5	5
1	5	5	5	5	5	5	5	5	5	5	5
1.1	5	5	5	5	5	5	5	5	5	5	5
1.2	5	5	5	5	5	5	5	5	5	5	5
1.3	5	5	5	5	5	5	5				
1.4	5	5	5	5	5	5	5				
1.5	5	5	6	6	8	9	10				
1.6	10	10	10	11	12	13	14				
1.7	13	14	14	15	15	17	18				
1.8	17	17	17	18	19	20	21				
1.9	20	20	21	22	22	24	25				
2	24	24	24	25	26	27	30				
2.1	28	28	29	30	31	34	37				
2.2	34	34	34	37	39	41	43				
2.3	40	40	41	42	44	47	49	Fail	Fail	Fail	Fail
2.4	46	45	47	49	50	Fail	Fail	Fail	Fail	Fail	Fail
2.5	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

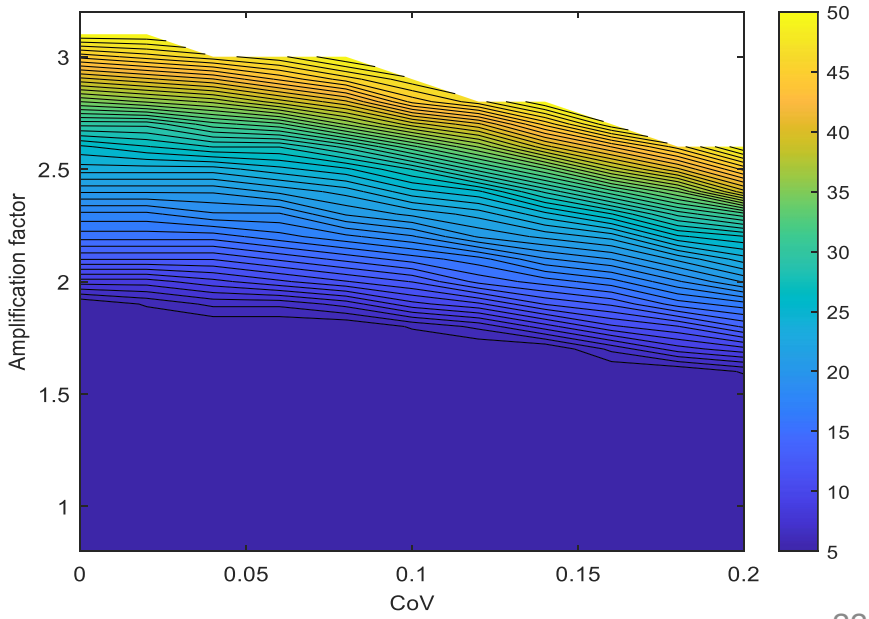
Results

- Looking forward – further optimization can be achieved with smart vehicles and networked infrastructure
  - If tightening uncertainty and spacing out trucks is not adequate then **optimize with traffic flow**
  - Use smart corridors and/or on-board sensors to *avoid multiple presence* with routine traffic

Results

- Example safe headways for a simple span bridge
  - ➢ Target β = 2.5
  - ➢ Steel, 120 ft long
  - ➢ *Single-lane loaded*
  - ➢ 3 Trucks





Results

- Example safe headways for a simple span bridge

Unrestricted

Max w/ Headway Control

Max w/ Headway & CoV Control

α \ CoV	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2
0.8	5	5	5	5	5	5	5	5	5	5	5
0.9	5	5	5	5	5	5	5	5	5	5	5
1	5	5	5	5	5	5	5	5	5	5	5
1.1	5	5	5	5	5	5	5	5	5	5	5
1.2	5	5	5	5	5	5	5	5	5	5	5
1.3	5	5	5	5	5	5	5	5	5	5	5
1.4	5	5	5	5	5	5	5	5	5	5	5
1.5	5	5	5	5	5	5	5	5	5	5	5
1.6	5	5	5	5	5	5	5	5	5	5	6
1.7	5	5	5	5	5	5	5	5	7	9	10
1.8	5	5	5	5	5	6	7	9	11	12	14
1.9	5	6	7	7	8	10	11	13	14	16	17
2	9	9	10	11	12	13	15	16	17	19	21
2.1	13	13	13	14	15	16	17	19	20	22	24
2.2	16	16	16	17	18	19	21	22	23	26	27
2.3	18	18	19	19	21	22	23	25	27	30	32
2.4	21	21	21	22	23	25	26	29	32	35	40
2.5	24	24	24	25	26	28	31	34	38	41	45
2.6	26	27	28	28	30	33	36	40	43	46	50
2.7	30	30	32	33	36	39	41	45	49	Fail	Fail
2.8	35	36	37	39	41	45	47	50	Fail	Fail	Fail
2.9	40	41	42	44	46	48	Fail	Fail	Fail	Fail	Fail
3	45	46	47	48	50	Fail	Fail	Fail	Fail	Fail	Fail
3.1	50	50	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail
3.2	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

- Increases from 1.2 (+17%)
- Increases from 2.1 (+24%)
- Increases from 2.4 (+25%)

Results

- Example safe headways for simple span bridges

Max w/ Span Length Control

Max w/ Headway Control

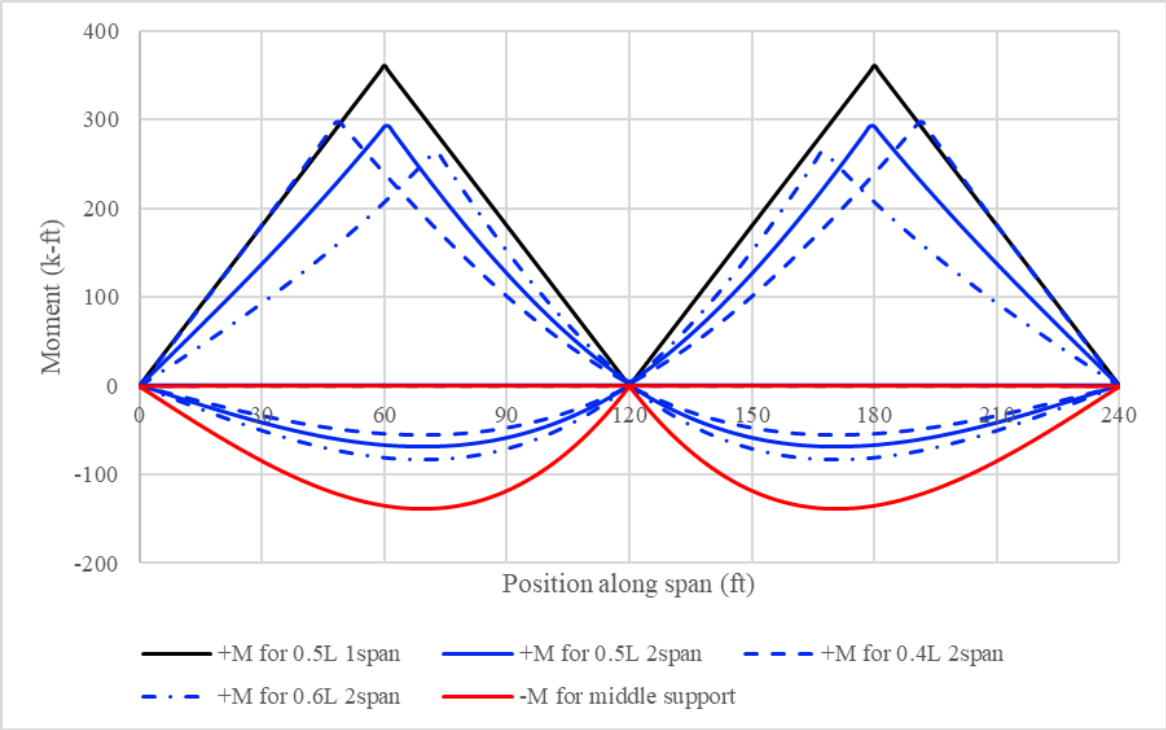
Unrestricted

α \ L	30 ft	60 ft	90 ft	120 ft	150 ft	200 ft
0.8	5	5	5	5	5	5
0.9	5	5	5	5	5	5
1	5	5	5	5	5	5
1.1	5	5	5	5	5	5
1.2	5	5	5	5	5	5
1.3	5	5	5	5	5	5
1.4	5	5	5	5	5	5
1.5	5	5	5	5	5	5
1.6	5	5	5	5	7	5
1.7	5	5	5	9	13	13
1.8	5	5	6	12	18	21
1.9	5	5	9	16	22	28
2	5	5	10	19	26	34
2.1	5	5	13	22	31	40
2.2	5	6	17	26	34	44
2.3	5	9	21	30	37	50
2.4	5	11	25	35	41	Fail
2.5	5	13	29	41	49	Fail
2.6	5	16	32	46	Fail	Fail
2.7	5	18	36	Fail	Fail	Fail
2.8	Fail	20	39	Fail	Fail	Fail
2.9	Fail	25	43	Fail	Fail	Fail
3	Fail	Fail	47	Fail	Fail	Fail
3.1	Fail	Fail	Fail	Fail	Fail	Fail

- Target $\beta = 2.5$
- *Only platoon live load*
- 3 Trucks
- $CoV = 0.18$

Results

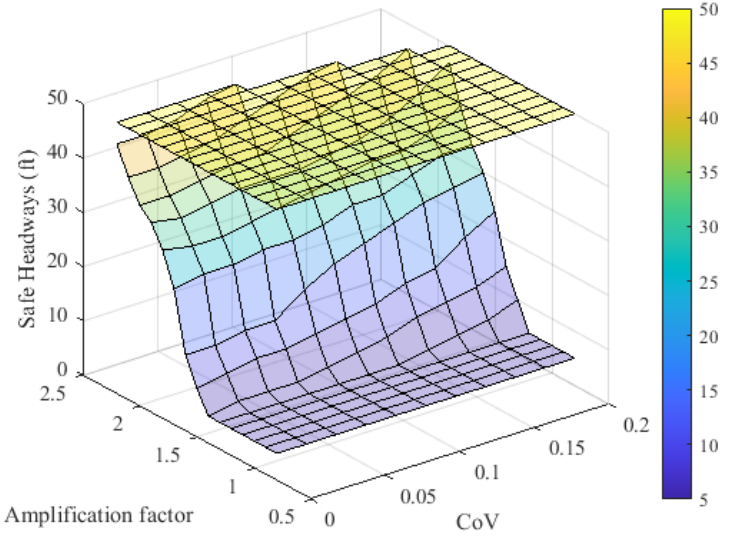
- Moment influence lines for *two equal span continuous* bridges

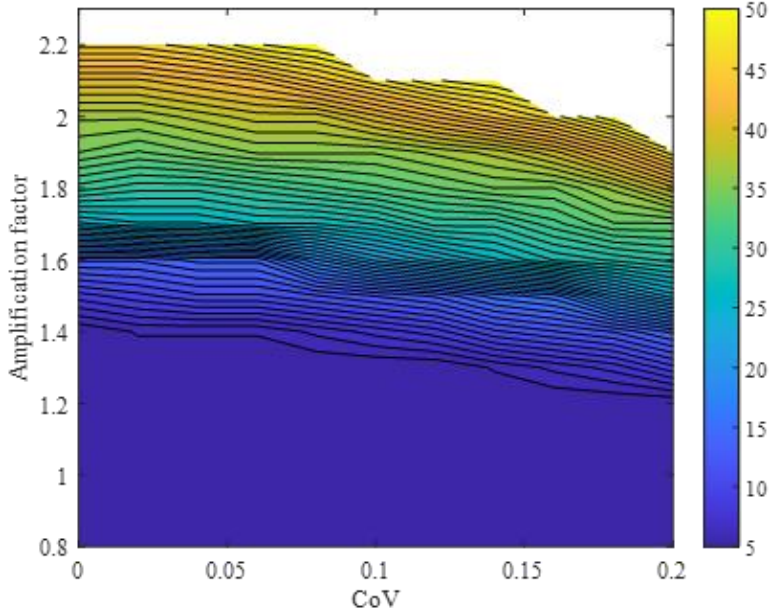


Results

- Example safe headways for a *two-span continuous* bridge

➢ Target β = 2.5 ➢ Steel, 120 ft long ➢ Platoon w/ adjacent loads ➢ 4 Trucks





Results

- Example safe headways for a *two-span continuous bridge*

Unrestricted

Max w/ Headway Control

Max w/ Headway & CoV Control

α \ CoV	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2
0.8	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50
0.9	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50
1	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50
1.1	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50
1.2	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50	5|50
1.3	5|50	5|50	5|50	5|50	5|50	5|50	5|50	6|50	7|50	8|50	10|50
1.4	5|50	6|50	6|50	6|50	7|50	8|50	9|50	11|50	12|50	13|50	15|50
1.5	9|50	10|50	11|50	11|50	12|50	13|50	14|50	16|50	17|50	21|50	24|50
1.6	14|50	14|50	15|50	15|50	19|50	21|50	24|50	26|50	27|50	28|50	30|50
1.7	26|50	26|50	26|50	26|50	27|50	29|50	30|50	31|50	31|50	33|50	34|50
1.8	30|50	30|50	31|50	32|50	32|50	33|50	34|50	35|50	36|50	37|50	40|50
1.9	34|50	35|50	35|50	35|50	36|50	36|50	37|50	38|50	40|50	43|50	47|50
2	37|50	37|50	38|50	38|50	38|50	41|50	43|50	45|50	47|50	50|50	Fail
2.1	40|50	41|50	42|50	43|50	45|50	47|50	49|50	50|50	Fail	Fail	Fail
2.2	46|50	46|50	47|50	49|50	50|50	Fail	Fail	Fail	Fail	Fail	Fail
2.3	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Results

- Example safe headways for *two-span continuous bridges*

Max w/ Headway & Span Control

Max w/ Headway Control

Unrestricted

α \ L	30 ft	60 ft	90 ft	120 ft	150 ft	200 ft
0.8	5|50	5|50	5|50	5|50	5|50	5|50
0.9	5|50	5|50	5|50	5|50	5|50	5|50
1	5|50	5|50	5|50	5|50	5|50	5|50
1.1	5|50	5|50	5|50	5|50	5|50	6|50
1.2	5|50	5|50	5|50	5|50	9|50	14|50
1.3	5|50	5|50	10|50	8|50	13|50	19|50
1.4	8|50	5|50	15|50	13|50	20|50	25|50
1.5	11|50	6|50	19|50	21|50	26|50	30|50
1.6	14|50	9|50	22|50	28|50	31|10	40|50
1.7	16|50	11|50	24|50	33|50	41|50	47|50
1.8	17|50	15|50	27|50	37|50	47|50	Fail
1.9	19|50	33|50	30|50	43|50	Fail	Fail
2	20|50	39|50	34|50	50|50	Fail	Fail
2.1	Fail	43|50	Fail	Fail	Fail	Fail
2.2	Fail	47|50	Fail	Fail	Fail	Fail
2.3	Fail	49|50	Fail	Fail	Fail	Fail
2.4	Fail	Fail	Fail	Fail	Fail	Fail

- Target $\beta = 2.5$
- $CoV = 0.18$
- Platoon w/ adjacent lane loaded
- 4 Trucks

Conclusions

Simple & two span bridges	$(CoV \& Headways)_a$ % of Legal load limit	$(CoV \& Headways)_b$ % of Legal load limit
With adjacent routine traffic		
Without adjacent routine traffic		

$(CoV \& Headways)_a$: W/o any reduction in uncertainty and restrictions of headways

$(CoV \& Headways)_b$: W/ restrictions of headways and w/ reduction in uncertainty

Future Research

- Policy for Platooning
  - Service performance
  - Fatigue life
  - Braking loads
  - Multiple presence calibration
- Disaster recovery

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