LRFD Fatigue Design of Steel Bridges in California

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Sept. 22, 2009

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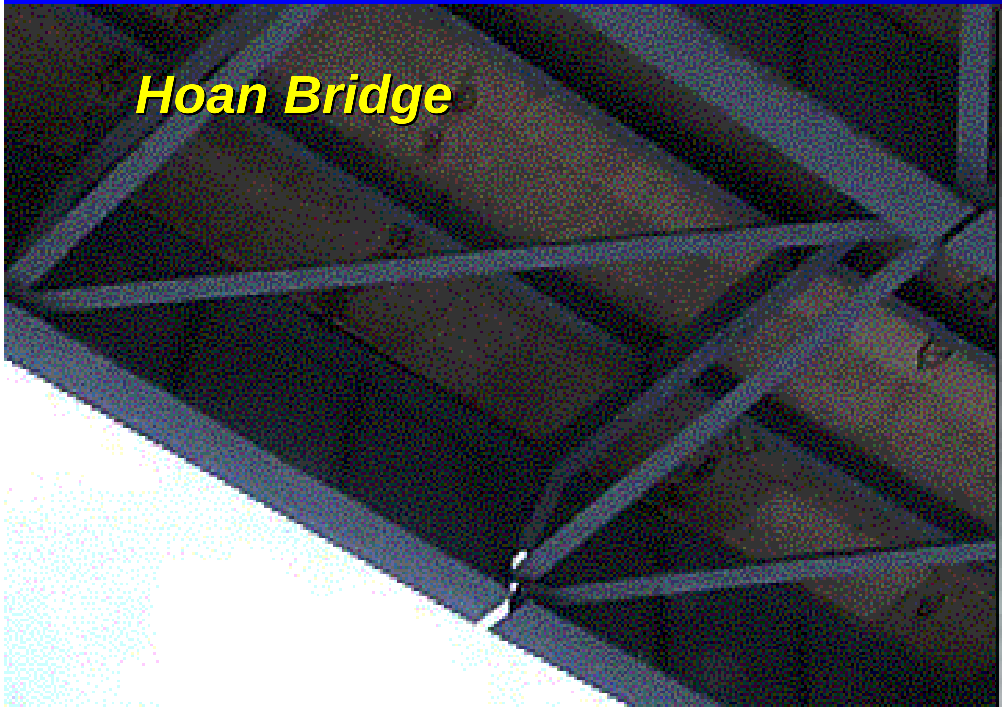
- Caltrans Bridge Design Specifications – Fatigue Design
- AASHTO-LRFD Fatigue Design
- AASHTO LRFD Vs. Standard
- California 2008 Amendments – Fatigue Design

Introduction

Fatigue Phenomena - Initiation and/or growth of cracks when cyclic stresses are applied



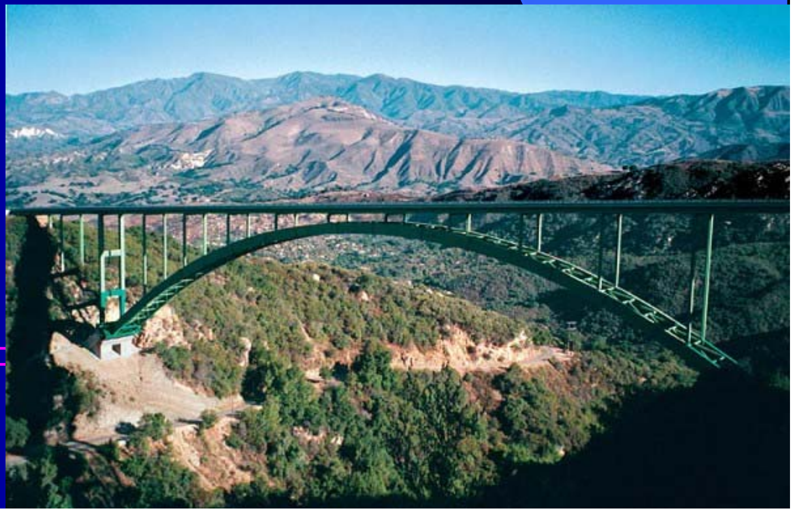
Introduction

Fatigue Design Approaches

- **Fracture-Mechanics – Widely used in automotive, airspace and machine industry**
- **Hot Spot - Widely used in offshore tubular structures**
- **S-N (Stress-life Detail-categories) Generally used in bridge and building structures**

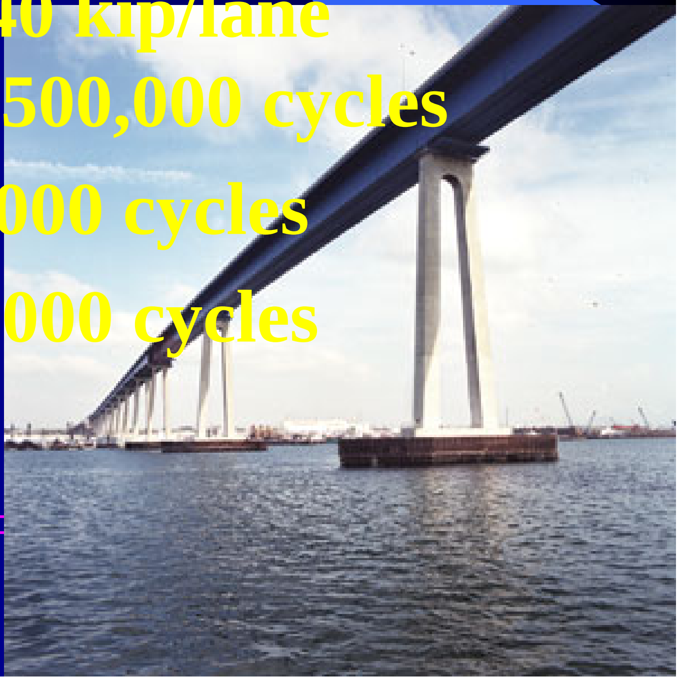
Caltrans BDS – Fatigue Design

- Used Prior to 2007
- Based on AASHTO Standard Specifications (17th Edition, 2002)
- Applied Stress Ranges - 4 Load Cases
- Allowable Stress Ranges
  - Redundancy
  - Number of Cycles
  - Type of Detail



Caltrans BDS – Fatigue Design

- Applied Stress Ranges - Service Load
  - Permit Truck (with adjacent HS20 Truck) - 100,000 cycles
  - HS20 Multiple Lane Load (0.640 kip/lane with shear or moment rider) - 500,000 cycles
  - HS20 Multiple Trucks - 2,000,000 cycles
  - HS20 Single Truck - >2,000,000 cycles



Caltrans BDS – Fatigue Design

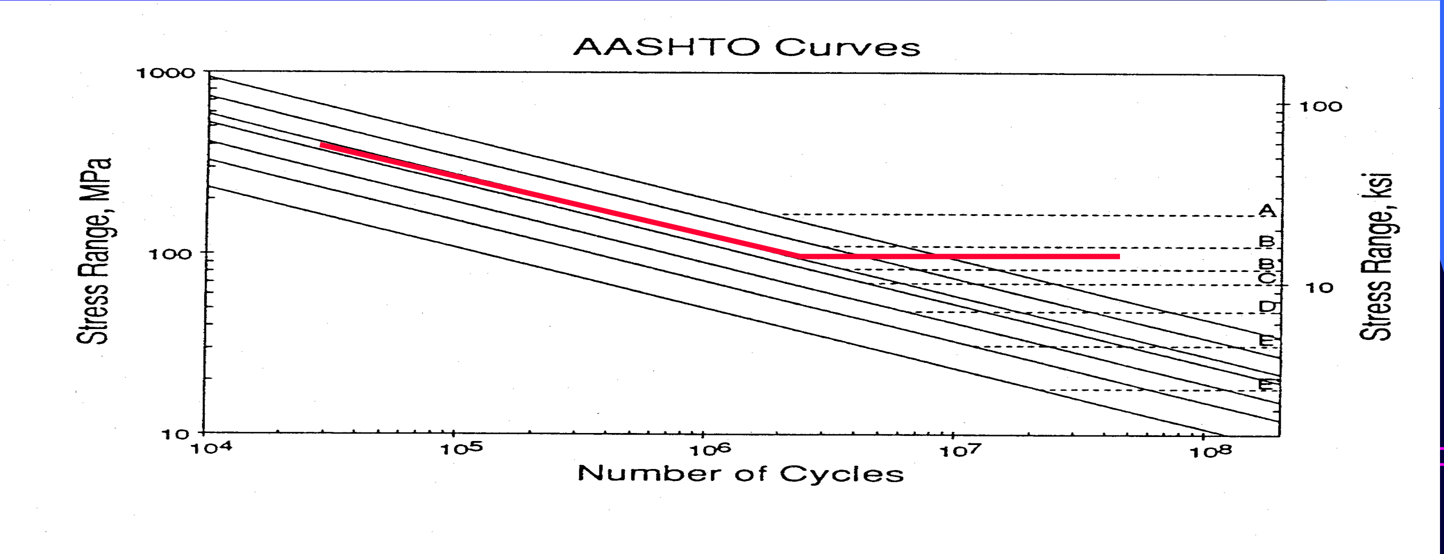
Allowable Fatigue Stress Ranges BDS Table 10.3.1A

REDUNDANT LOAD PATH STRUCTURES				
Category	Allowable Range of Stress, F_{sr} (ksi)			
(See Table	For 100,000	For 500,000	For 2,000,000	For > 2,000,000
10.3.1B)	Cycles	Cycles	Cycles	Cycles
Loading	Permit	HS20 Multilane	HS20 Multitruck	HS20 Single Truck
A	63	37	24	24
A (Weathering Steel)	49	29	18	16
B	49	29	18	16
B'	39	23	14.5	12
C	35.5	21	13	10
C (Trans Stiffener)	35.5	21	13	12
D	28	16	10	7
E	22	13	8	4.5
E'	16	9.2	5.8	2.6
F	15	12	9	8

AASHTO LRFD - Fatigue Design

Two Categories

- **Infinite Life -** Maximum applied stress range = (2x Effective stress Range) < Constant-amplitude fatigue threshold = $(\Delta F)_n$
- **Finite Life -** Effective stress range < $(A/N)^{1/3}$



AASHTO LRFD 4th Ed. 2007

Fatigue Design

Design Criteria

$$\gamma(\Delta f) \le (\Delta F)_n$$

γ = load factor (0.75) – (Means HS15)

(Δf) = live load stress range

$(\Delta F)_n$ = nominal fatigue resistance

$$(\Delta F)_n = \left(\frac{A}{N}\right)^{\frac{1}{3}} \ge \frac{1}{2}(\Delta F)_{TH}$$

in which

$$N = (365)(75)n(ADTT)_{SL}$$

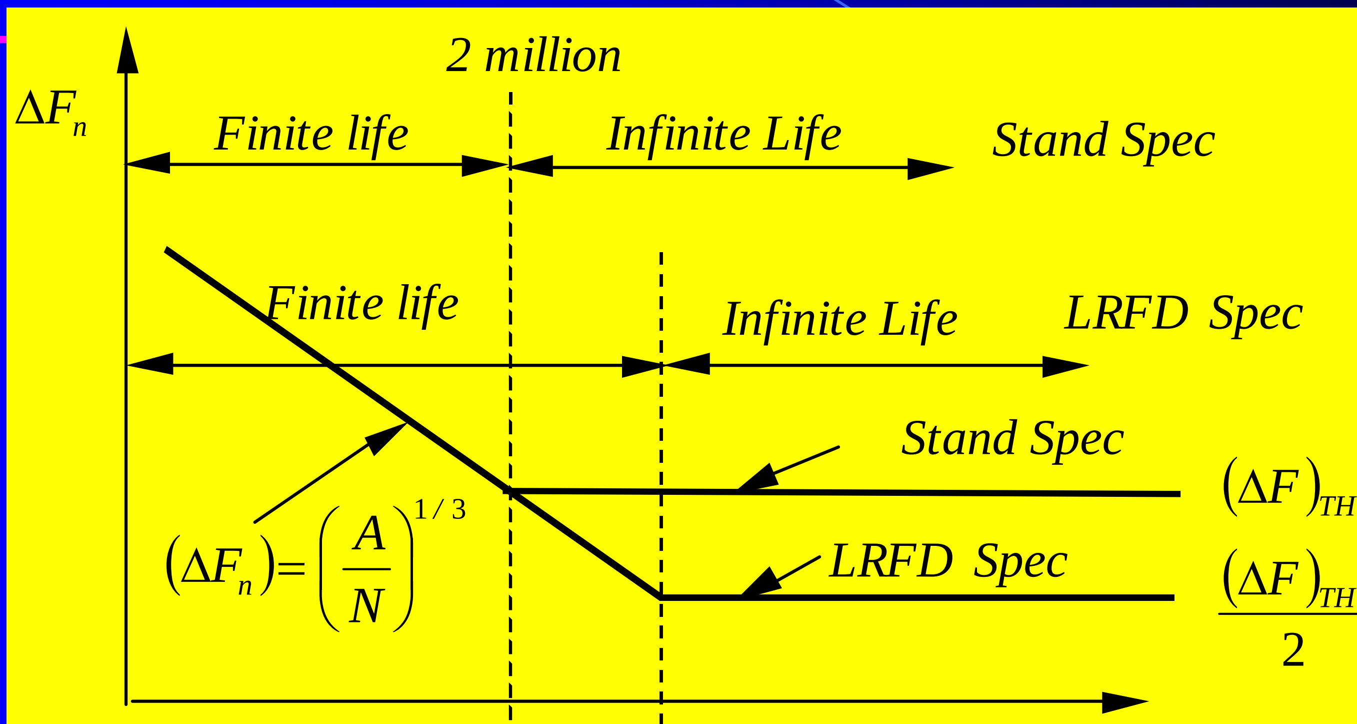
AASHTO LRFD Vs. Standard

Design Specifications	*AASHTO Standard Specifications* (17th Edition, 2002)	*AASHTO LRFD Bridge Design Specifications* (4th Edition, 2007)
Fatigue Load and Stress Cycles	***For finite life:*** N = 2,000,000, HS20 Truck Loading N = 500,000, HS20 Lane Loading ***For infinite life:*** N > 2,000,000 One HS20 Truck with a variable spacing of 14 ft. to 30 ft. between 32.0-kip axles	0.75 × (One HL93 Truck with a constant spacing of 30 ft. between the 32.0-kip axles) $N = 365(75)n(ADTT)_{SL}$
Live Load Distribution Factor	***For finite life*** (multiple lanes): $DF_{S\tan d} = \begin{cases} \frac{S}{11} & \text{For } S \le 14 \text{ ft} \\ \text{Lever Rule} & \text{For } S > 14 \text{ ft} \end{cases}$ (1a) ***For infinite life*** (one lane): $DF_{S\tan d} = \begin{cases} \frac{S}{14} & \text{For } S \le 10 \text{ ft} \\ \text{Lever Rule} & \text{For } S > 10 \text{ ft} \end{cases}$ (1b)	$DF_{LRFD} = \left[0.06 + \left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12Lt_s^3}\right)^{0.1}\right]/1.2$ (6) $\frac{K_g}{12\,Lt_s^3} = 1$ is used for this study
Multiple Presence Factor	Loaded Lanes — m 1 or 2 — 1.00 3 — 0.90 ≥ 4 — 0.75	***m* = 1.0**

AASHTO LRFD Vs. Standard

Design Specifications	***AASHTO Standard Specifications*** **(17th Edition, 2002)**	***AASHTO LRFD Bridge Design Specifications*** **(4th Edition, 2007)**
Allowable Fatigue Stress Ranges or Fatigue Resistance	For finite life (Less than 2 million cycles) $(\Delta F_n) = \left(\frac{A}{N}\right)^{1/3}$ (3) For infinite life (Over 2 million cycles) $(\Delta F_n) = (\Delta F)_{TH}$ (4)	For finite life $(\Delta F_n) = \left(\frac{A}{N}\right)^{1/3}$ (8) For infinite life $(\Delta F_n) = \frac{1}{2}(\Delta F)_{TH}$ (9)
Fatigue Moment Effects on Interior Girder	$M_{\mathrm{Stand}} = mDF_{\mathrm{Stand}} \times M_{HS20} \times (1+I)$ (5) where M_{HS20} is moment induced by the ***Standard*** fatigue loading, i.e., HS20 trucks, lane loading or single HS20 truck loading	$M_{\mathrm{Stand}} = \gamma_{LRFD} DF_{LRFD} \times M_{HL93} \times (1+IM)$ (10) where M_{HL93} is moment induced by the ***LRFD*** fatigue truck, one HL93 Truck with a constant spacing of 30 ft. between 32.0-kip axles; γ_{LL+IM} is a load factor of 0.75 for the fatigue limit state

AASHTO LRFD Vs. Standard



$$(\Delta F)_n = \left(\frac{A}{N}\right)^{\frac{1}{3}} \geq \frac{1}{2}(\Delta F)_{TH}$$

Fatigue Resistance vs. Number of Cycles

AASHTO LRFD Vs. Standard

Parameters in Comparison Study

Span length: 30 – 240 ft.

Girder spacing: 5 – 14 ft.

Bridge spans: Simple span
Two-equal span continuous

Structures: Redundant Load Path,
Case I Road, $ADTT \geq 2500$

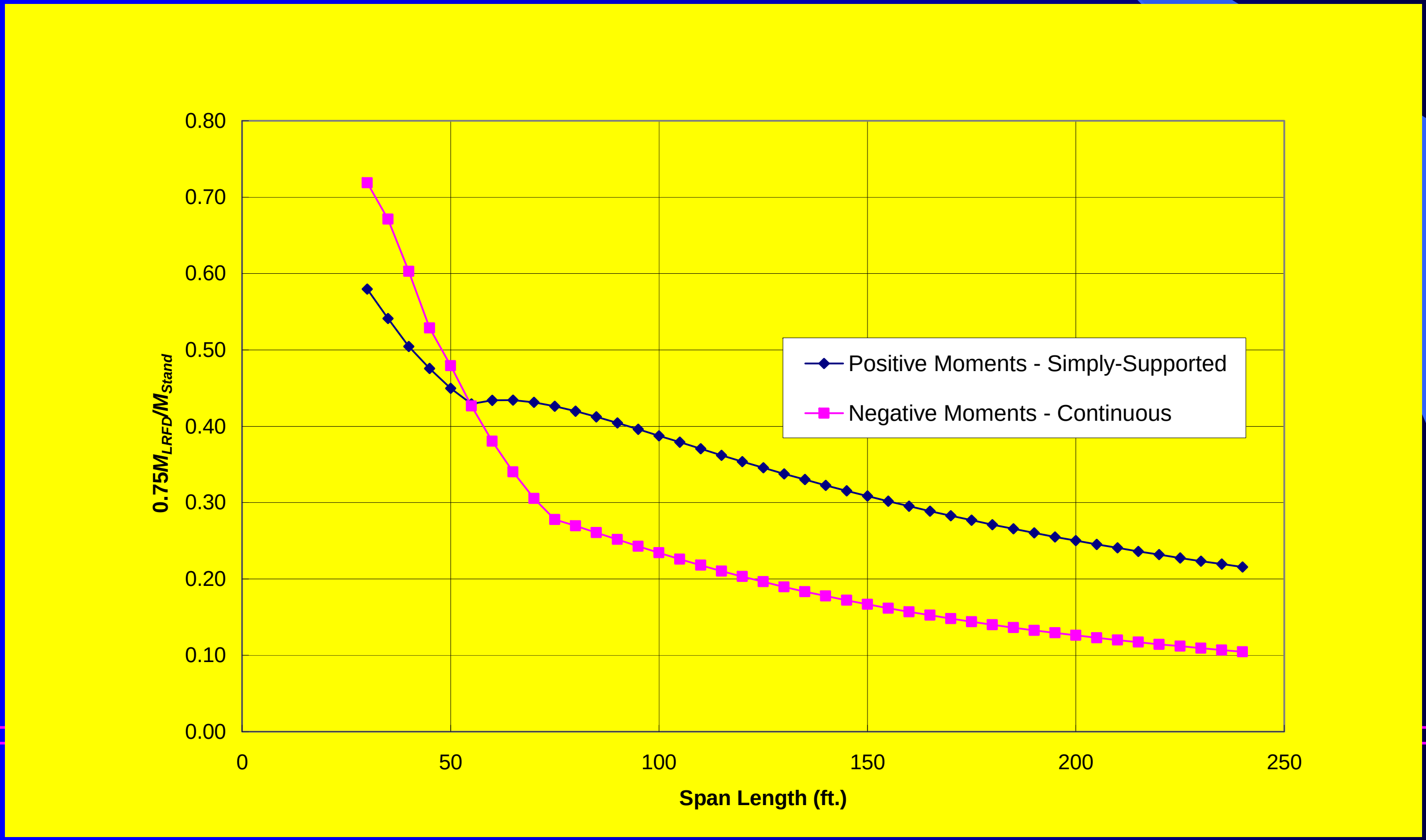
Girder: Interior girder

Moments: Max. Positive moments for simple span
Max. Negative moments at middle support of continuous spans

AASHTO LRFD Vs. Standard

Finite Life – 500,000 Cycles

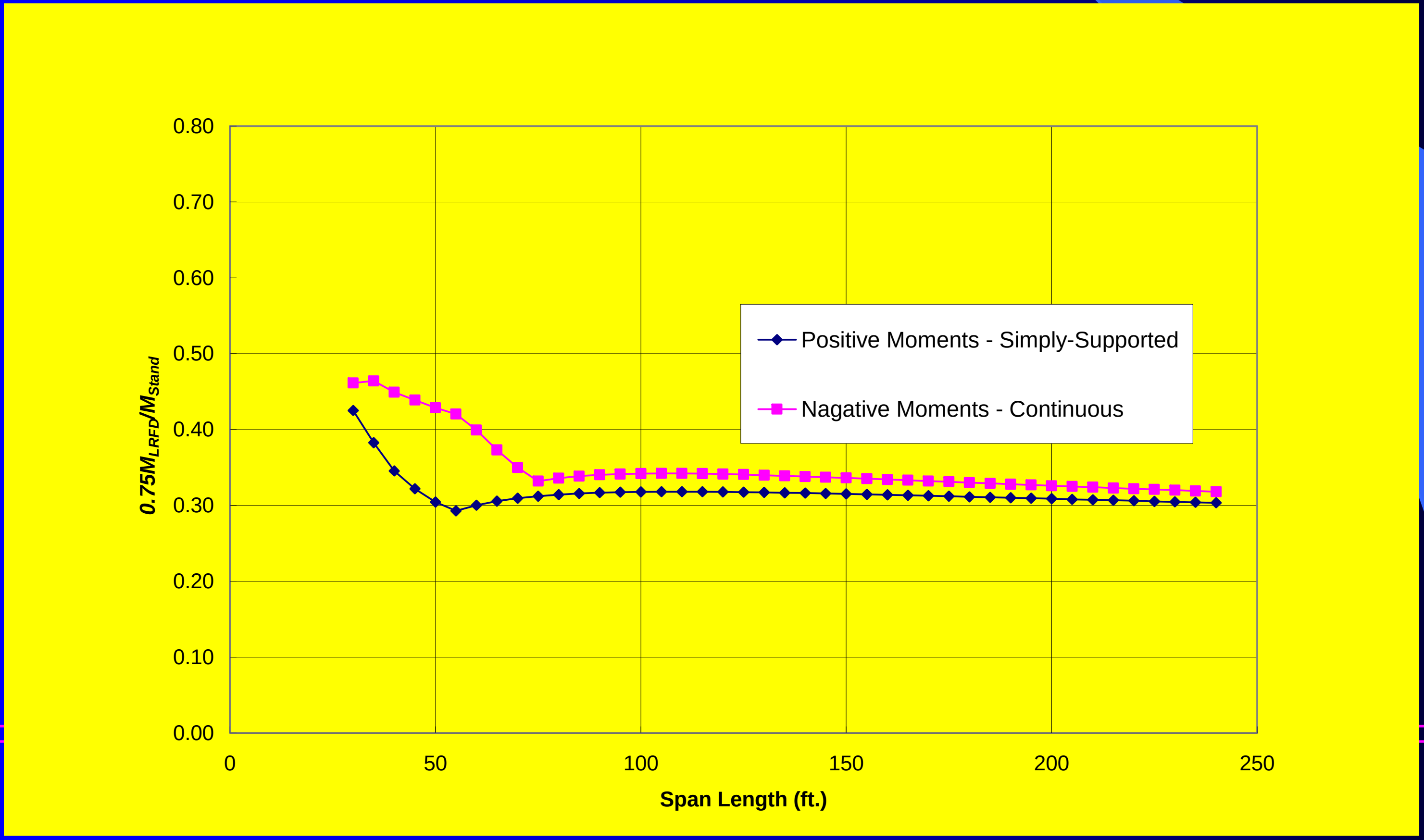
Mean M_{LRFD}/M_{Stand} = 0.23 -0.34 (SD = 0.10 – 0.16)



AASHTO LRFD Vs. Standard

Finite Life – 2 M Cycles

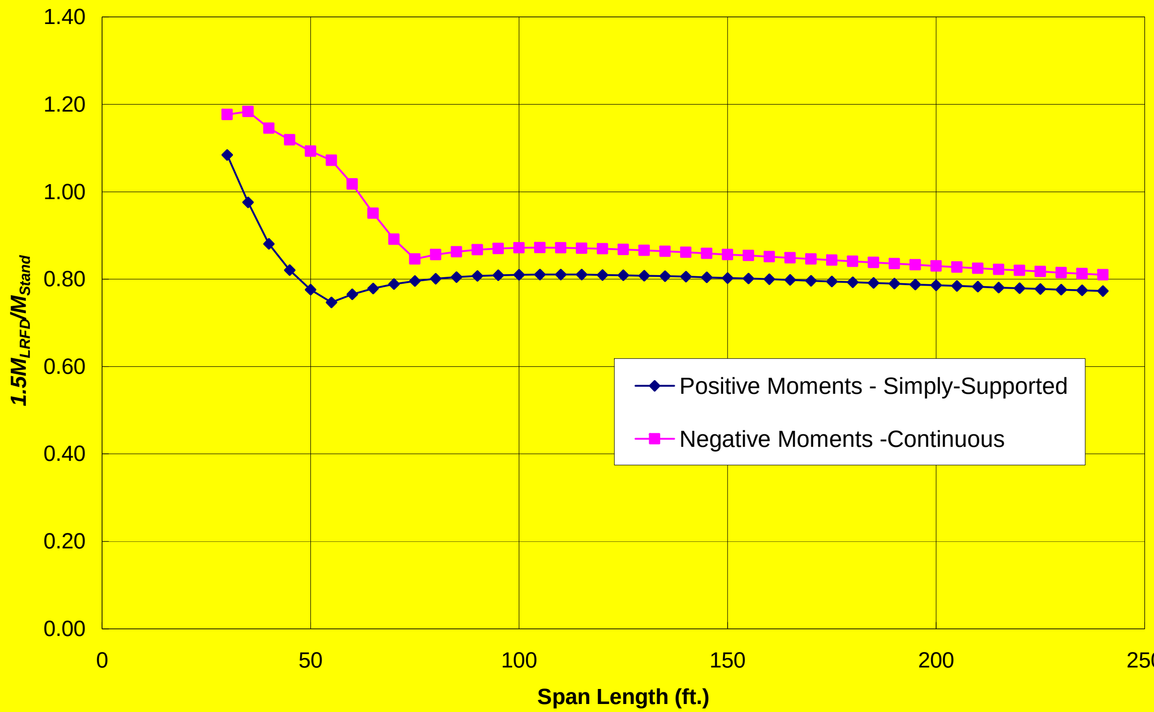
Mean M_{LRFD}/M_{Stand} = 0.31 -0.35 (SD = 0.05 – 0.06)



AASHTO LRFD Vs. Standard

Infinite Life – > 2 M Cycles

Mean M_{LRFD}/M_{Stand} = 0.81 -0.84 (SD = 0.07 – 0.15)



AASHTO LRFD Vs. Standard

For an interior girder

- **Finite Life :**

  $M_{LFRD}/M_{Stand} = 23\text{-}35\ \%$

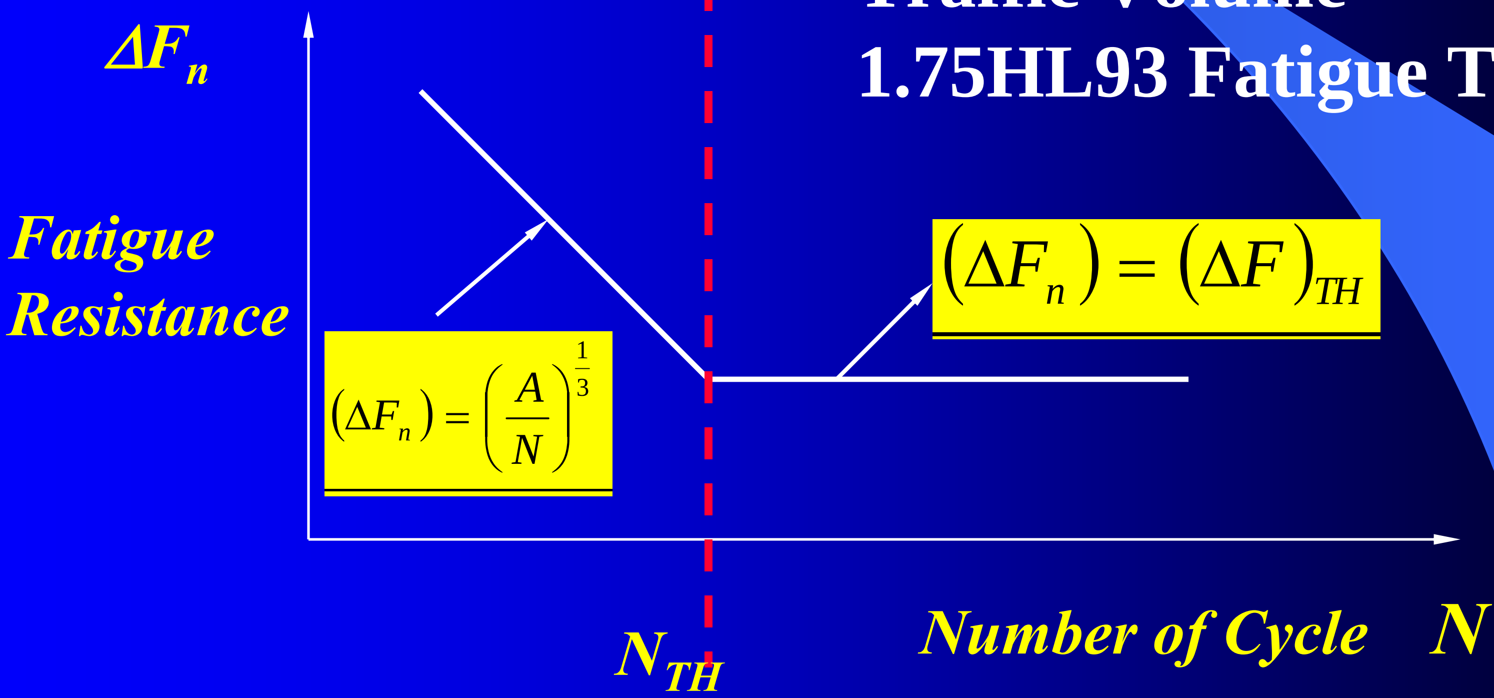
- **Infinite Life :**

  $M_{LFRD}/M_{Stand} = 81 - 84\ \%$

California 2008 Amendments Fatigue Design

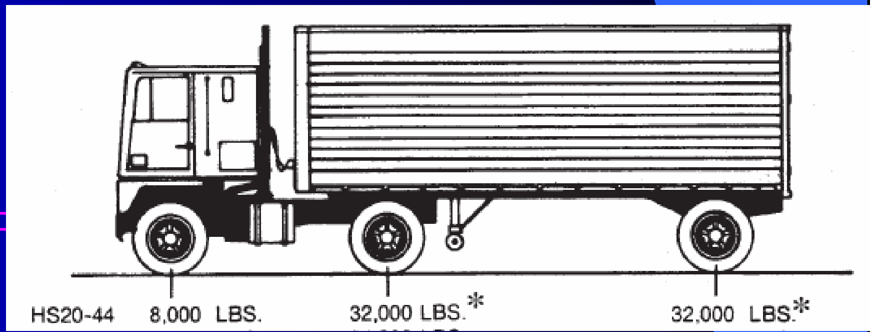
Finite Life – Lower Traffic Volume – P9

Infinite Life – Higher Traffic Volume – 1.75HL93 Fatigue Truck



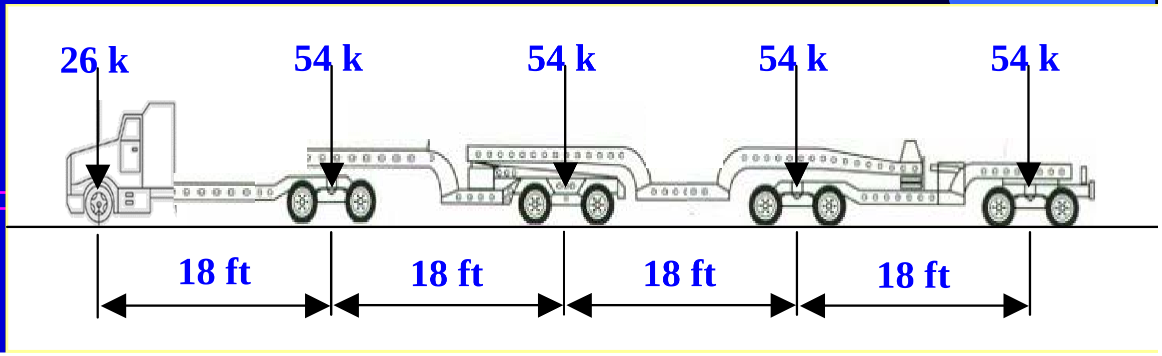
California 2008 Amendments Fatigue I – Infinite Life

- **One HL-93 Fatigue Design Truck with Fixed Axle Spacing and $\gamma = 1.75$ (AASHTO LRFD 2009 Interim $\gamma = 1.5$)**
- **To equate to past Caltrans' infinite fatigue life design practice**



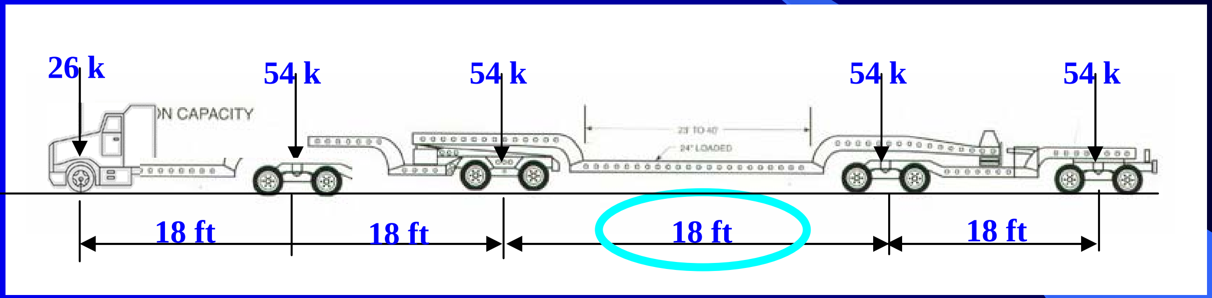
California 2008 Amendments Fatigue II – Finite Life

- Fatigue II – Finite Life – Permit 9-Axle Truck with $\gamma = 1.0$ and Average Daily Permit Truck (ADPT) = 20
- Based on Caltrans' Permit Truck Traffic by calibrating the Actual Permit Truck Traffic to Equivalent P-9 ADPT



California 2008 Amendments Fatigue II – Finite Life

1. **Fatigue Permit Truck 9-Axle**

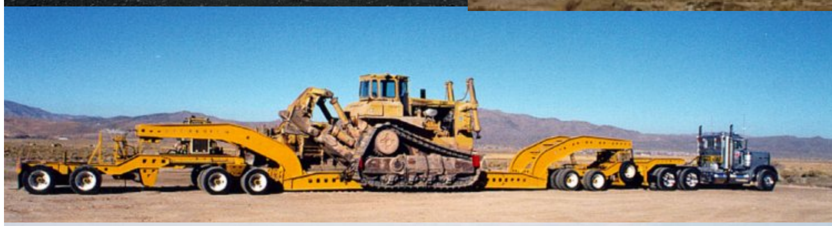


2. **Number of stress range cycles per fatigue permit truck passage (n)**

3. **Average Daily Permit Truck (ADPT) of Fatigue Design Permit Truck = 20**

Cycles Per Fatigue Permit Truck Passage			
		Span Length (ft)	
		>40	<=40
Simple Span		1.00	2.00
Continuous Spans			
	Near Support	1.20	2.00
	Elsewhere	1.00	2.00
Cantilever		5.00	5.00
Trusses		1.00	1.00
Transverse Members		1.00	2.00

California 2008 Amendments Permit Fatigue Truck



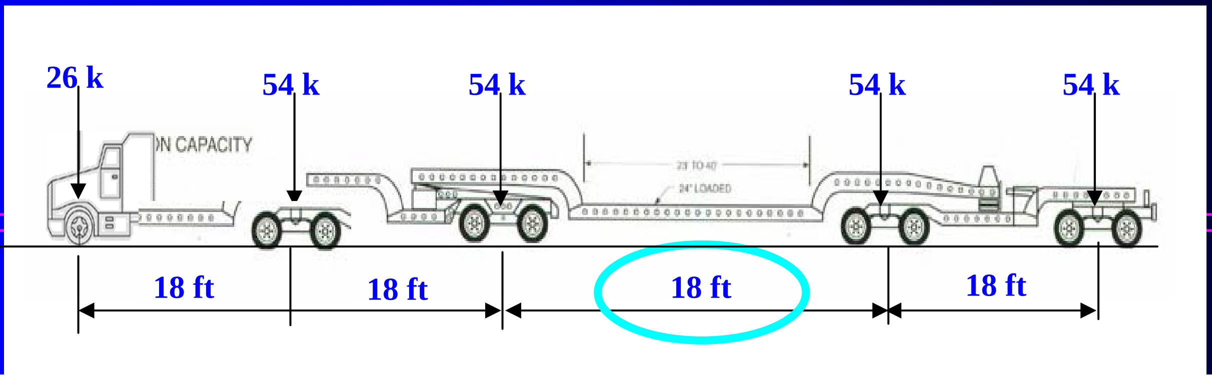
Number or Permit Trucks per year on HEAVILY used routes

Truck Name	Annual Count (Year 2004)	Growth Rate	Average per year (for 75 years life)	Average Daily Truck
P5	3000	1%	3563	10
P7	2000	1%	2375	7
P9	1500	1%	1781	5
P11	200	1%	238	1
P13	300	1%	356	1
P13 and Longer	10	1%	12	1
Total	7010		8325	25

Approximate numbers are given by HQ Permit Office

California 2008 Amendments
Finite II – Permit Fatigue Truck

- Most commonly used permit trucks are P5, P7 & P9
  - All of them have axle spread in the middle
  - Larger spread of axles creates larger negative moments
  - Creates increased number of cycles in shorter span bridges
  - However, it was decided to keep the 18 feet spacing and adjust the Average Daily Permit Truck (ADPT) volume
- P11, P13 and P15 trucks are less frequent
  - Decided to include effects of these vehicles by adjusting the ADPT



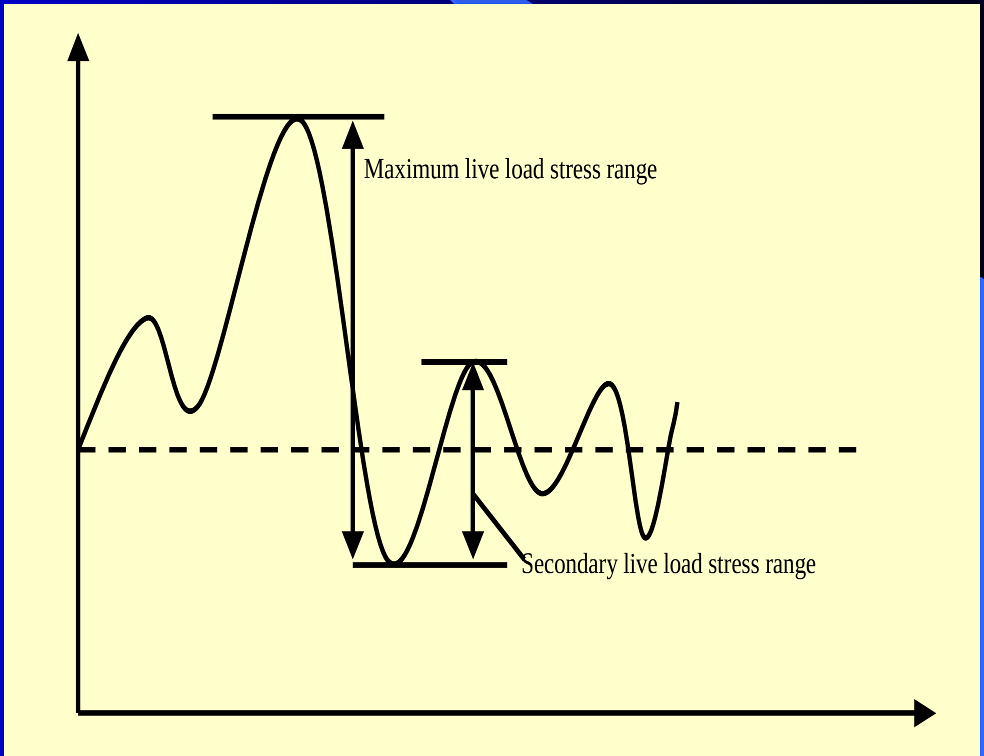
Equivalent Fatigue Truck Stress Cycles

Equivalent Fatigue Truck Cycles - using actual truck configurations and frequency

- **Tandem axles**
- **Variable axle spacing**
- **Number of permit trucks per day**
- **Number of stress cycles created by various truck configurations**
- **Probable axle load**

Stress Cycles per Truck Passage

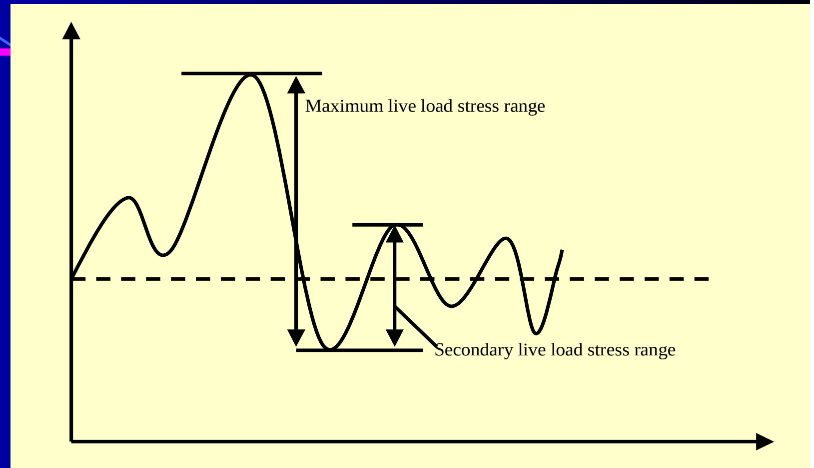
- **ASTM E-1049 - Rainflow Method**
- **Standard Practices for Cycle Counting in Fatigue Analysis**

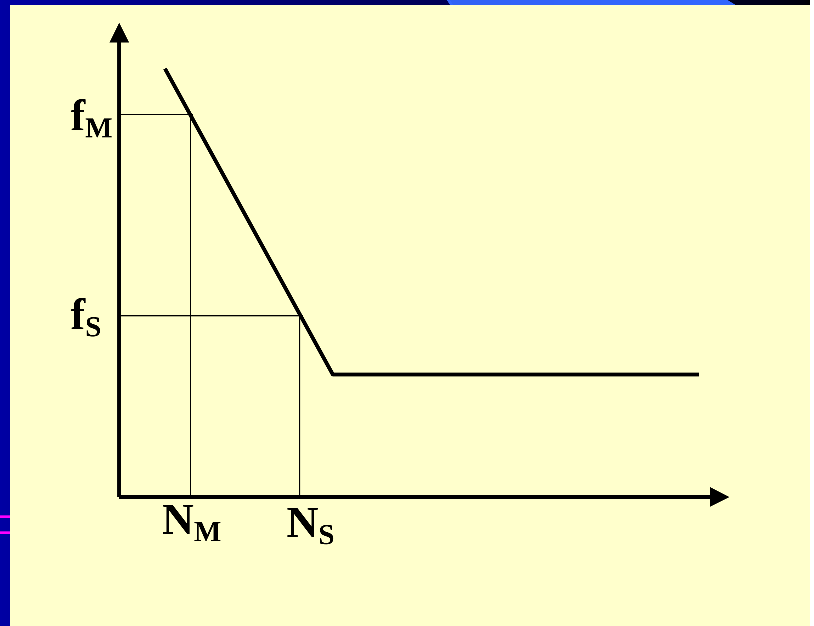


Equivalent Maximum Stress Range Cycles

- Obtain number of stress cycles
- Obtain the maximum stress range
- Based on Equal Fatigue Damage Principle to convert all stress range cycles to equivalent # of maximum stress range cycles

$$n_M = \sum_{i=1}^{p} \left(\frac{f_{Si}}{f_M} \right)^3 \times n_{Si}$$

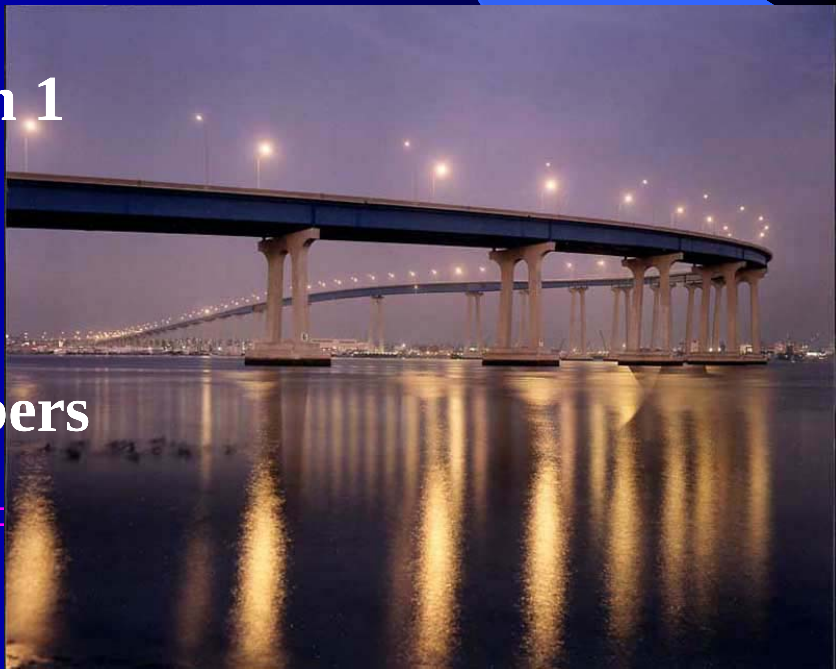




Stress Cycles per Truck Passage

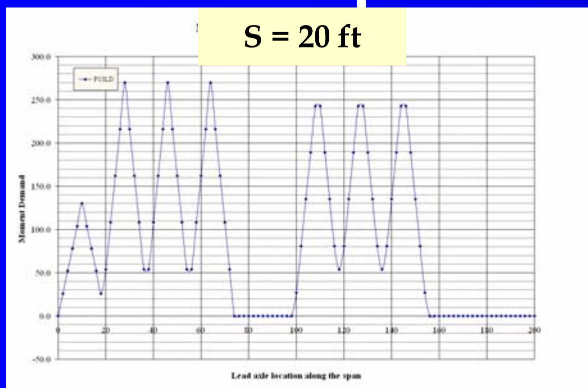
Stress Cycles are derived for the following cases:

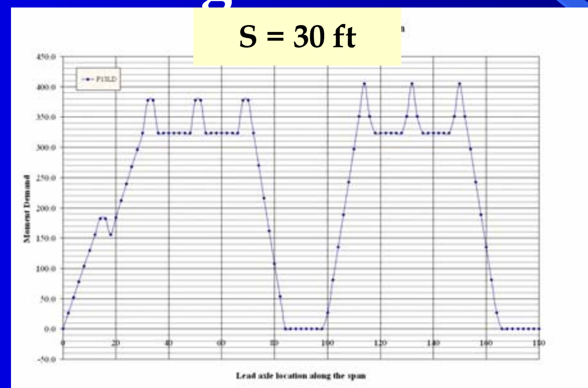
1. **Simple span mid span moment**
2. **Two Span Continuous Span**
   - **Moment over the support**
   - **Moment @0.9th pt of Span 1**
   - **Moment at 0.4th point**
   - **Moment at 0.8th point**
   - **Load on transverse members**

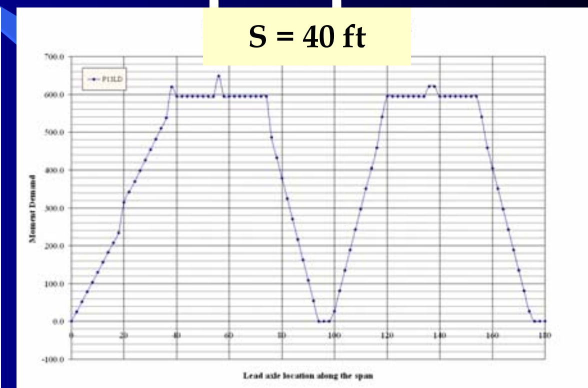


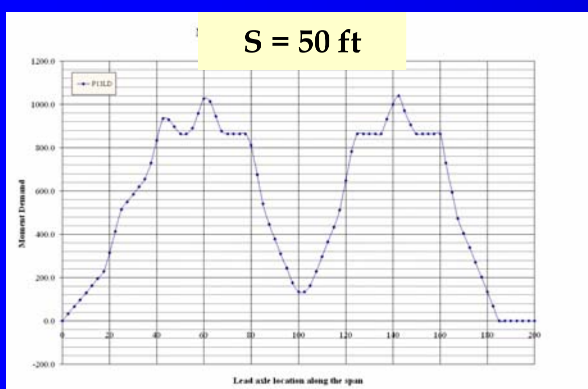
P13 Long Deck Truck Cycles

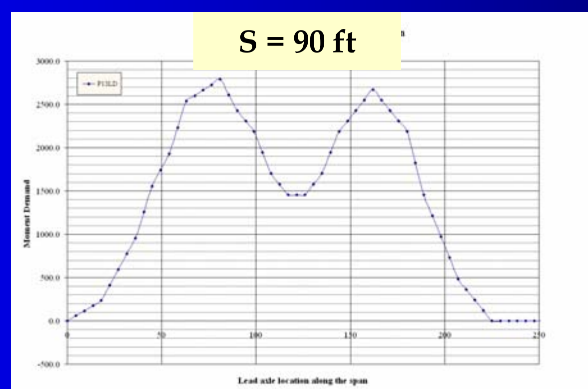
Mid span moment diagrams for various simple span

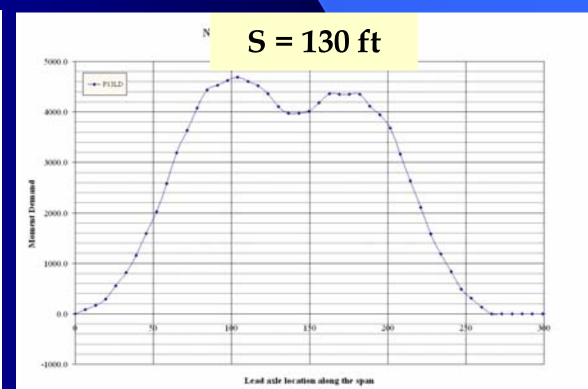












X-axis – distance of the Front axle of the Truck from start of the girder

Stress Cycle - P9 Fatigue Truck Simple Span

- **Span length 20-40 ft. Cycles varies between 1.00 and 2.59**
- **Span length larger than 40 ft. cycles varies from 1.0**
- **Recommend**
  Span > 40 ft. – Use 1.0
  Span < 40 ft. – Use 2.0

Span Length (ft)	Cycles
20	2.59
40	1.0
80	1.0
160	1.0
200	1.0
280	1.0

Stress Cycles -P9 Fatigue Truck Continuous Span at Support

- Span length 20-40 ft. Cycles varies between 1.00 and 1.96
- Span length larger than 40 ft. cycles varies from 1.0 – 1.21
- Recommend
  Span > 40 ft. – Use 1.2
  Span < 40 ft. – Use 2.0

Span Length (ft)	Cycles
20	1.96
40	1.0
80	1.0
160	1.04
200	1.10
240	1.16
280	1.21

Stress Cycles per Truck Passage

Cycles Per HS20 Fatigue Truck Passage			
	Span Length (ft)		
	>40	<=40	
Simple Span	1.00	2.00	
Continuous Spans			
Near Support	1.50	2.00	
Elsewhere	1.00	2.00	
Cantilever	5.00	5.00	
Trusses	1.00	1.00	
Transverse Mer	1.00	2.00	

Cycles Per Fatigue Permit Truck Passag			
		Span Length (ft)	
		>40	<=40
Simple Span		1.00	2.00
Continuous Spans			
	Near Support	1.20	2.00
	Elsewhere	1.00	2.00
Cantilever		5.00	5.00
Trusses		1.00	1.00
Transverse Members		1.00	2.00

Equivalent P9 Stress Cycles

Equivalent P9 Fatigue Truck Stress Cycles of a Specified Truck is given by:

M_{truck} = Moment range created by the specified Truck
N_{truck} = Number of truck volume per year
ns_{truck} = number of cycles per passage of the truck

M_{P9} = Moment range created by P9 Fatigue Truck
ESC_{P9F} = Equivalent P9 Fatigue Truck Stress Cycles per year

$$ESC_{P9F} = \left(\frac{M_{truck}}{M_{P9F}} \right)^3 \times N_{truck} \times ns_{truck}$$

Equivalent P9 ADPT

Equivalent P9 Fatigue Stress Cycles is Converted from all the permit trucks P5-P15:

$$ESC_{P9F} = \sum_{i=5,2}^{15} \left(\frac{M_{Pi}}{M_{P9F}} \right)^3 \times N_{Pi} \times ns_{Pi}$$

And, Equivalent Number of Fatigue Permit Truck Volume can be established as shown below :

$$N_{P9F} = \frac{ESC_{P9F}}{ns_{P9F}}$$

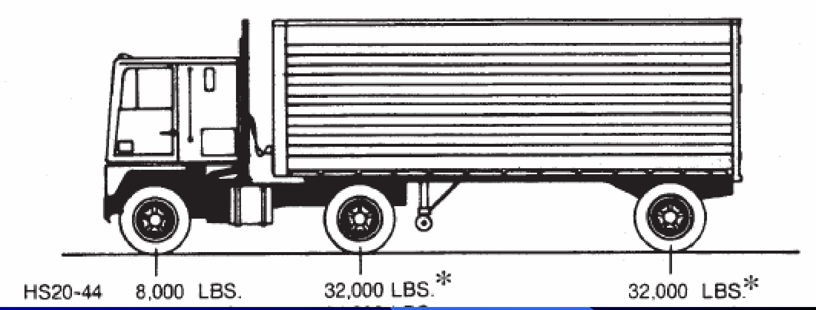
Maximum Equivalent P9 ADPT

Moment at Mid span of Simple Span	19
Moment at Support of Continuous Span	15
Moment at 0.9th point of Continuous Span	18
Moment at 0.4th point of Continuous Span	21
Moment at 0.8th point of Continuous Span	19
Reaction @ Midsupport of Continuous Span	15

California Amendment:

USE 20 as the ADPT of P9 Fatigue Trucks for design

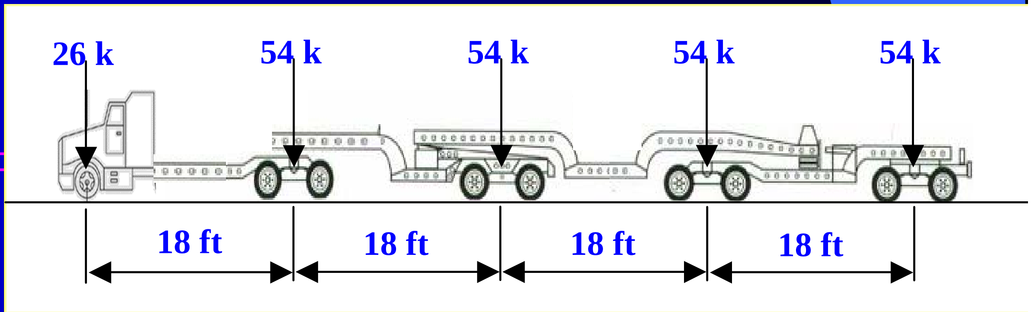
California 2008 Amendments
Fatigue Design Summary



- **Fatigue I – Infinite Life**

  One Design Truck with Fixed Axle Spacing and $\gamma = 1.75$ (AASHTO LRFD 2009 Interim $\gamma = 1.5$)

- **Fatigue II – Finite Life – Permit 9-Axle Truck with $\gamma = 1.0$ and ADPT = 20**



Summary

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Thanks!