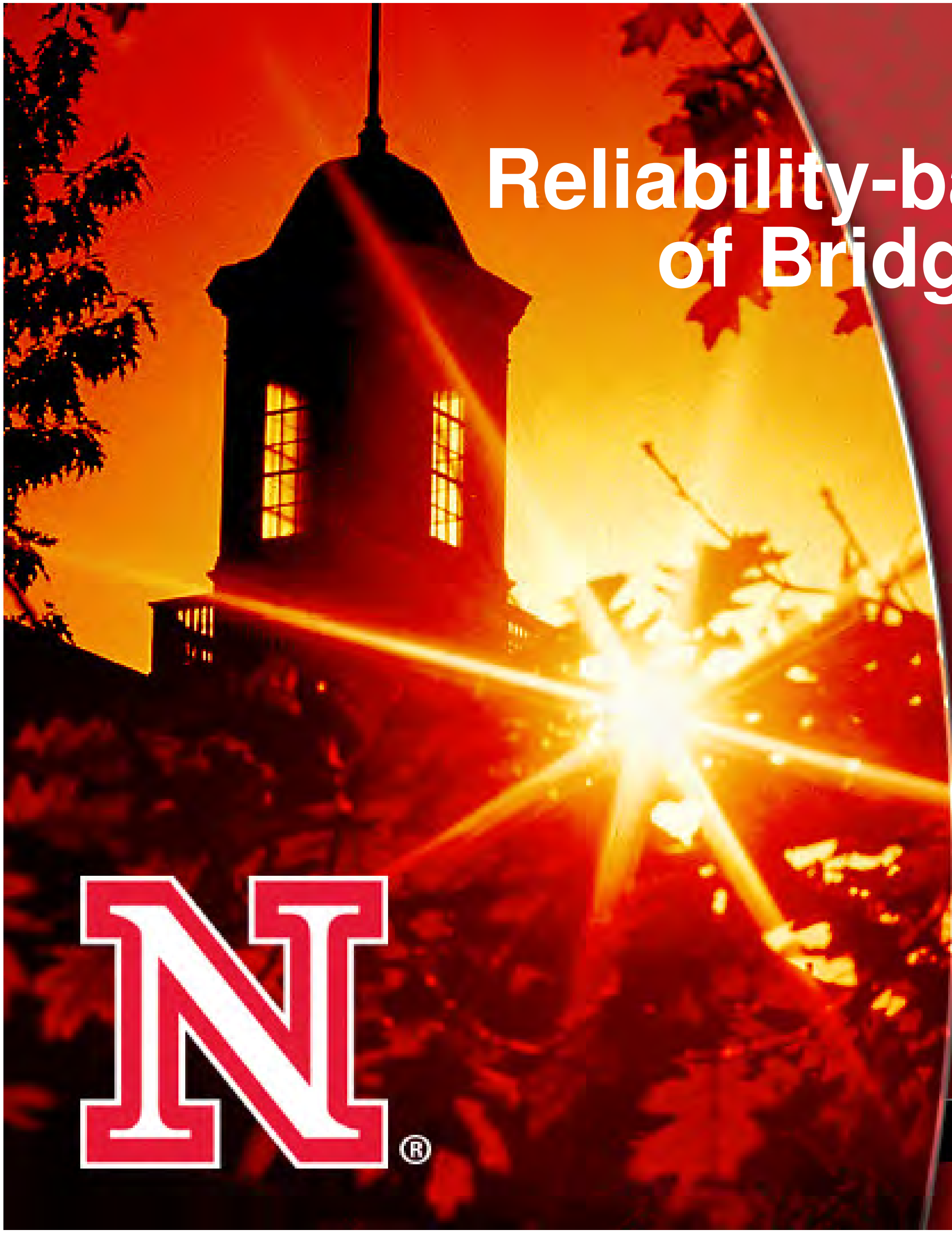


Reliability-based Calibration of Bridge Design Codes

Andrzej S. Nowak

UNIVERSITY OF NEBRASKA–LINCOLN

Outline

- Problem Statement
- Calibration procedure
- Load Models
- Resistance Models
- Reliability Analysis Procedure
- Target Reliability
- Load and Resistance Factors

Natural and Man-Made Threats

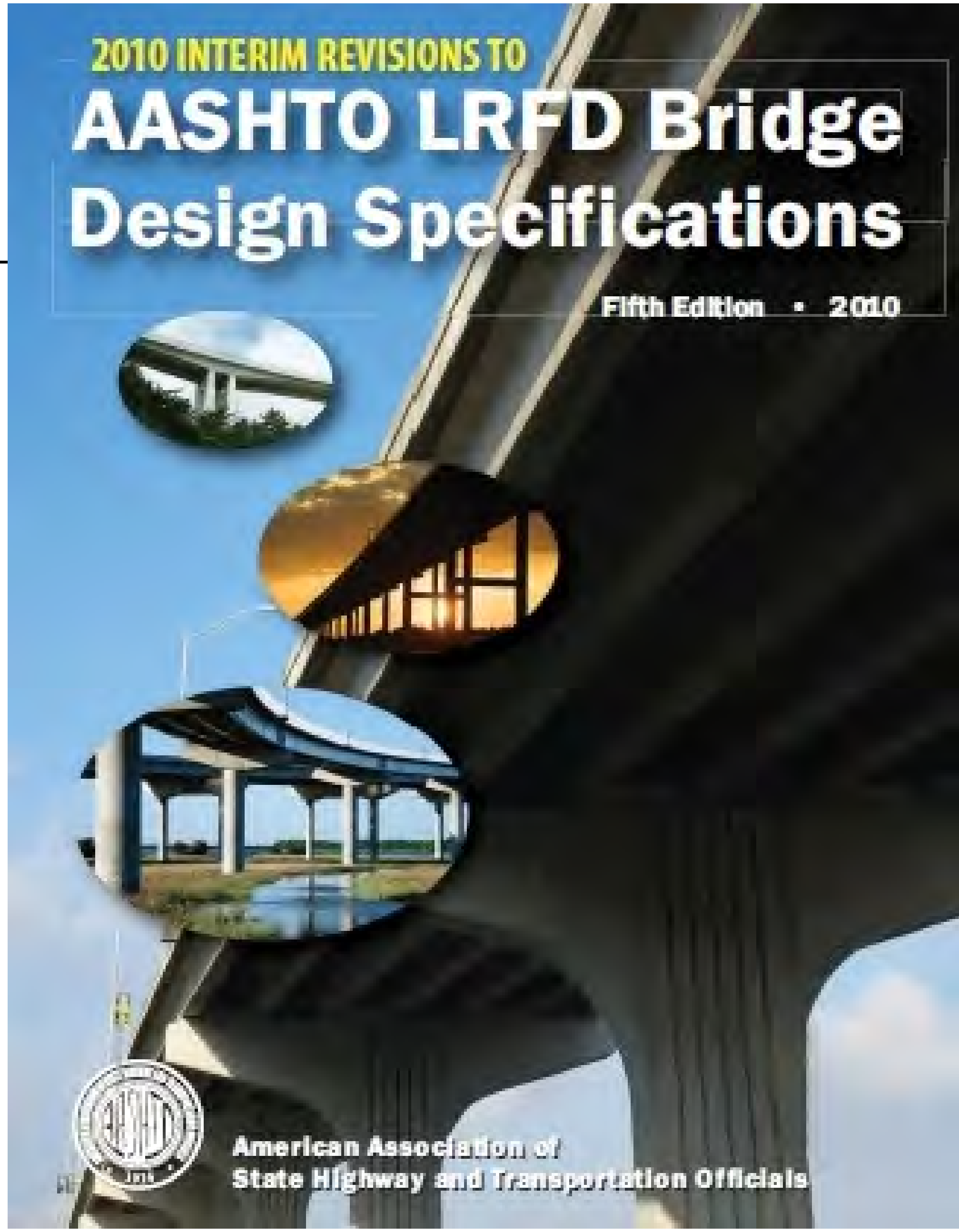
- Natural – hurricanes, floods, tornados, earthquakes
- Aging – degradation of materials
- Inadequate maintenance (corrosion, cracking)
- Collisions – vehicles and vessels
- Acts o vandalism, intentional damage
- Terrorist attacks, explosions, fires

Consequences of Uncertainties

- Deterministic analysis and design is insufficient
- Probability of failure is never zero
- Design codes must include a rational safety reserve
- Reliability is an efficient measure of the structural performance

Problem Statement

- New generation of design codes based on limit states (AASHTO LRFD)
- Load and resistance are random variables
- Reliability index as a measure of performance
- How to determine load and resistance factors?



University of Nebraska Lincoln
Department of Civil Engineering

Basic questions:

- How can we measure safety of a structure?
- How safe is safe enough? What is the target reliability?
- How to implement the optimum safety level?

Calibration Procedure

- Select representative structures
- Develop statistical models for loads
- Develop statistical models for resistance
- Develop/select reliability analysis procedure
- Determine the target reliability index
- Determine load and resistance factors

Representative Structures

- Structural types (slab, I-beam, T-beam, box-beam, truss)
- Materials (non-composite and composite steel, reinforced concrete, prestressed concrete, wood)
- Span length (short, medium, long)

Load Models

- Dead load
- Live load (static and dynamic)
- Environmental loads (wind, snow, earthquake, temperature, ice)
- Special loads (vehicle and vessel collision, fire, explosion)

Bridge Live Load

- Strongly site-specific
- Traffic volume (ADTT)
- Multiple presence
- Extreme expected live load (75 year maximum)
- Fatigue live load (magnitude and frequency)
- Service live load

Vehicles

Statistical Data Base

- Load surveys, e.g. weigh-in-motion (WIM) truck measurement
- Load distribution (load effect per component)
- Simulations (e.g. Monte Carlo)
- Finite element analysis
- Boundary conditions (field tests)


H-63


MISTER
RUBBISH
CAUTION
BLUE
LEACH

Weigh-in-Motion System

Quartz strip

WIM system built in a highway pavement

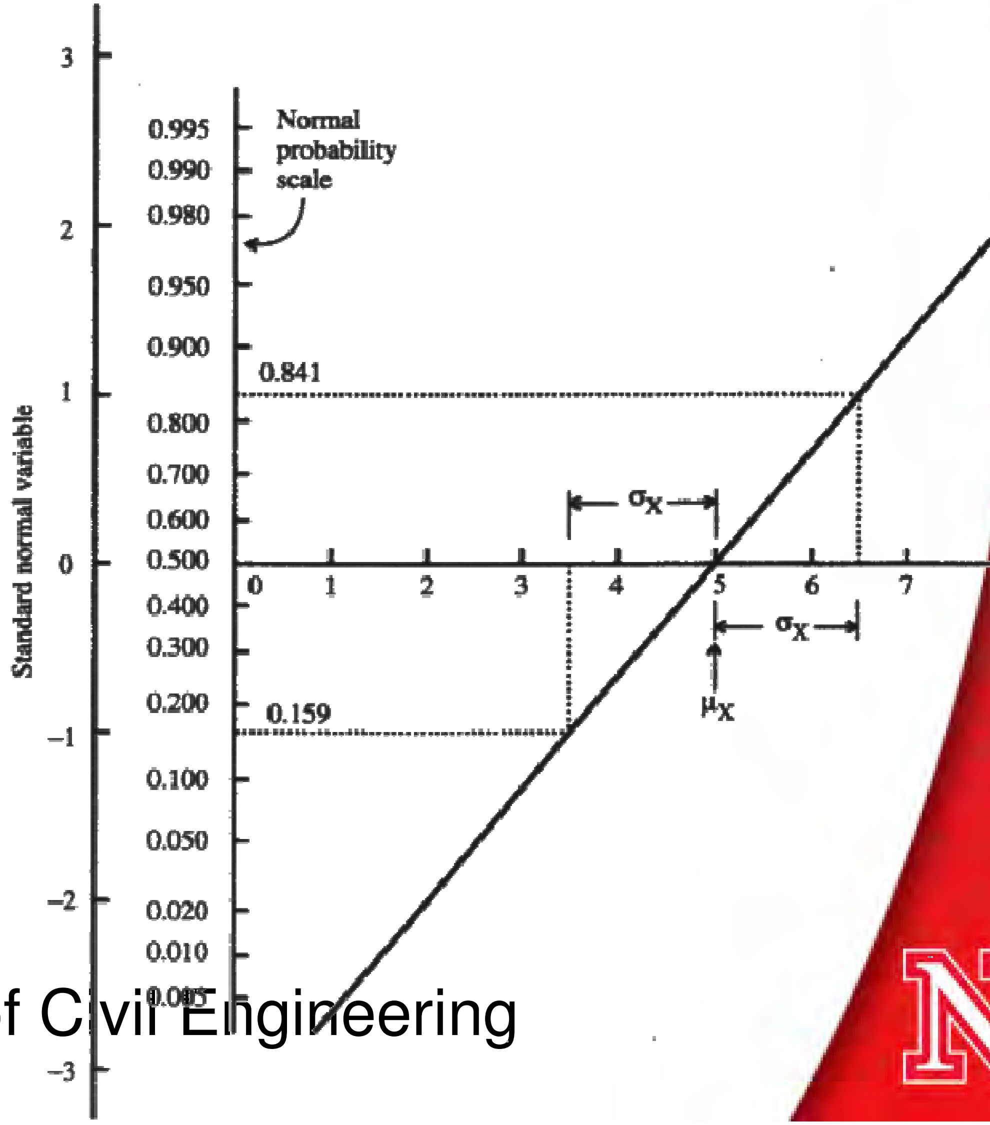
Highway Route 23 at Nagoya, Japan

Weigh-in-Motion Data

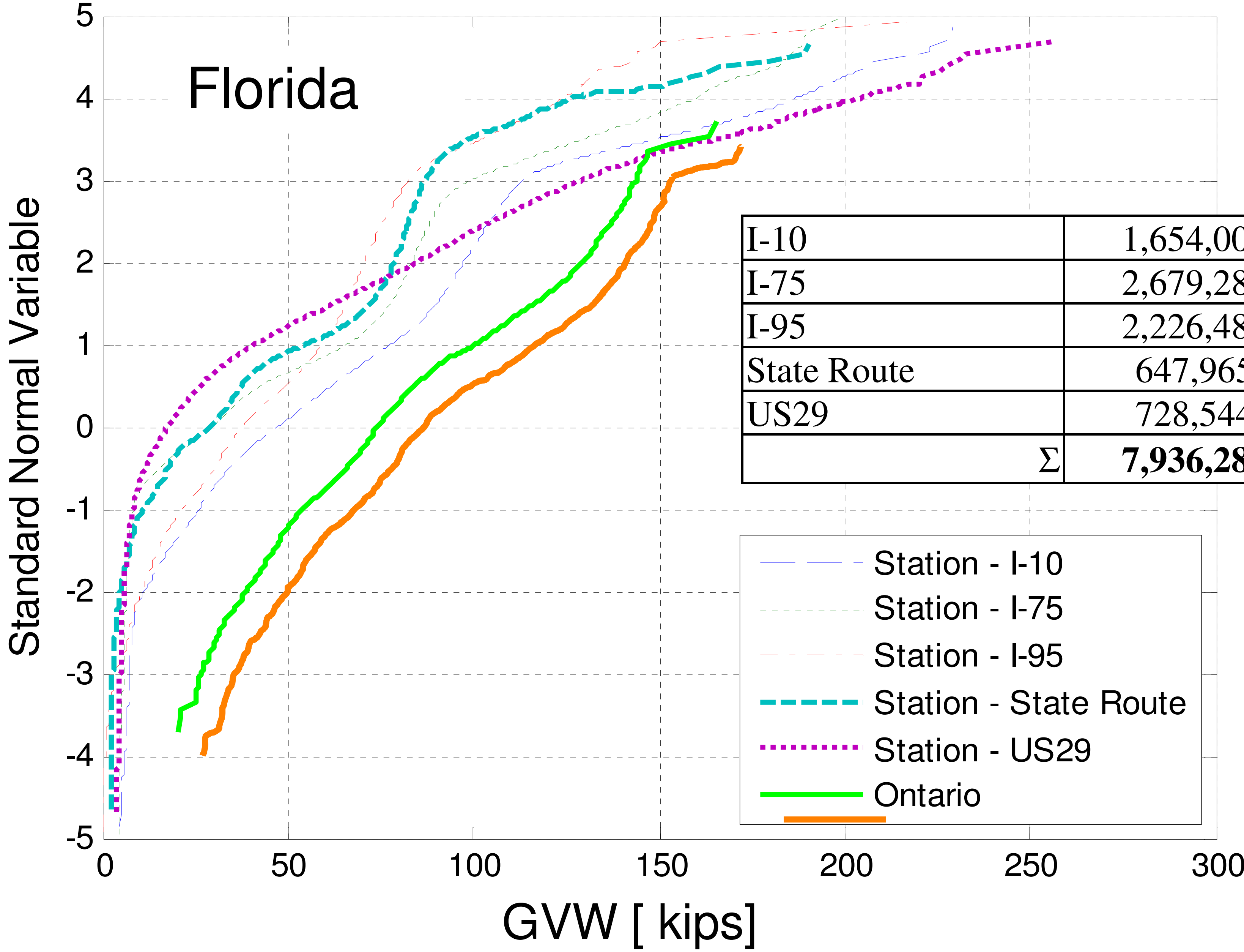
- Truck WIM data was obtained from the Federal Highway Administration and NCHRP Project 12-76
- Total number of records exceeds **70 million**

Probability Paper

Data is plotted on the normal probability paper.
A normal distribution function is represented by a straight line.

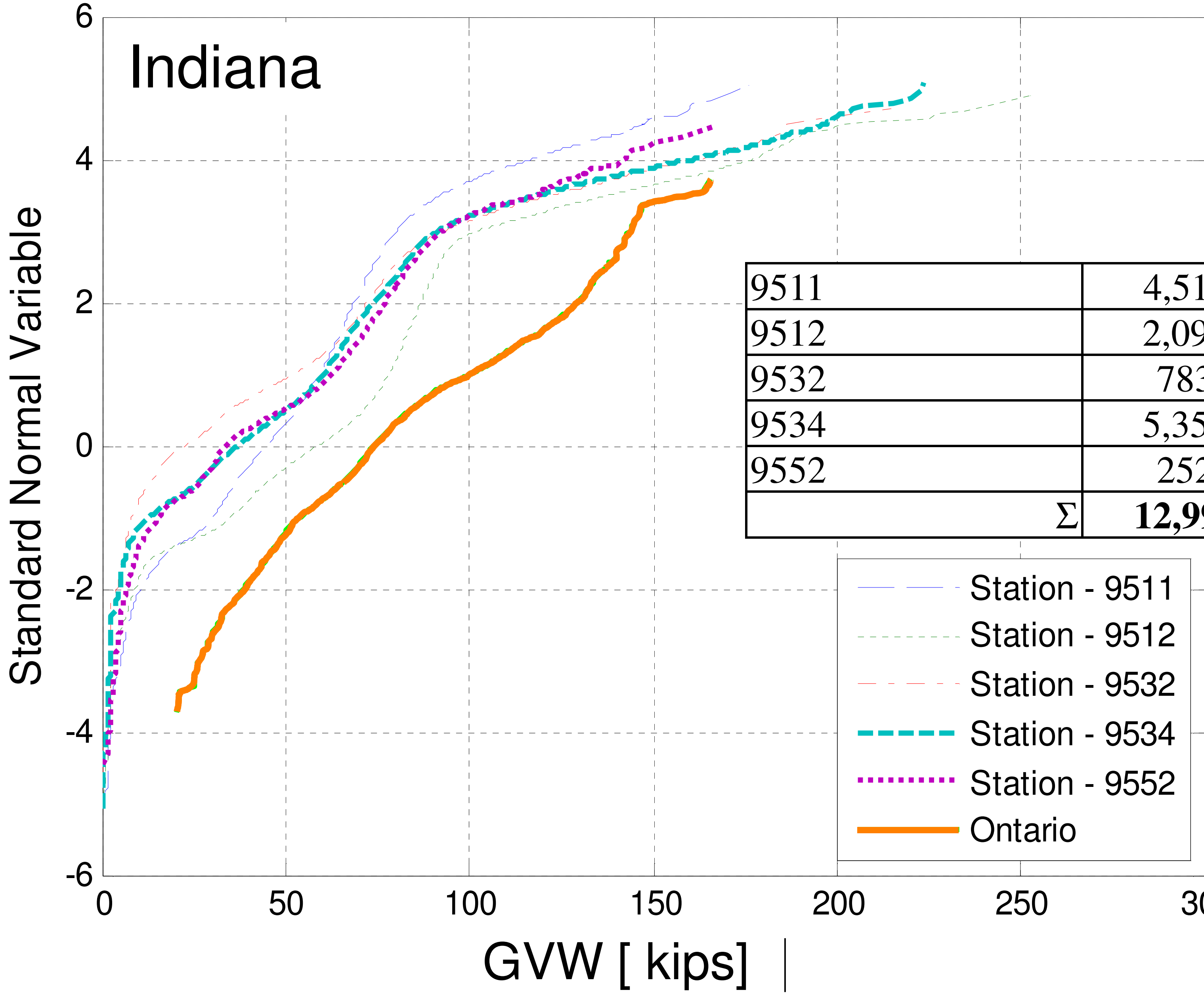


Gross Vehicle Weight



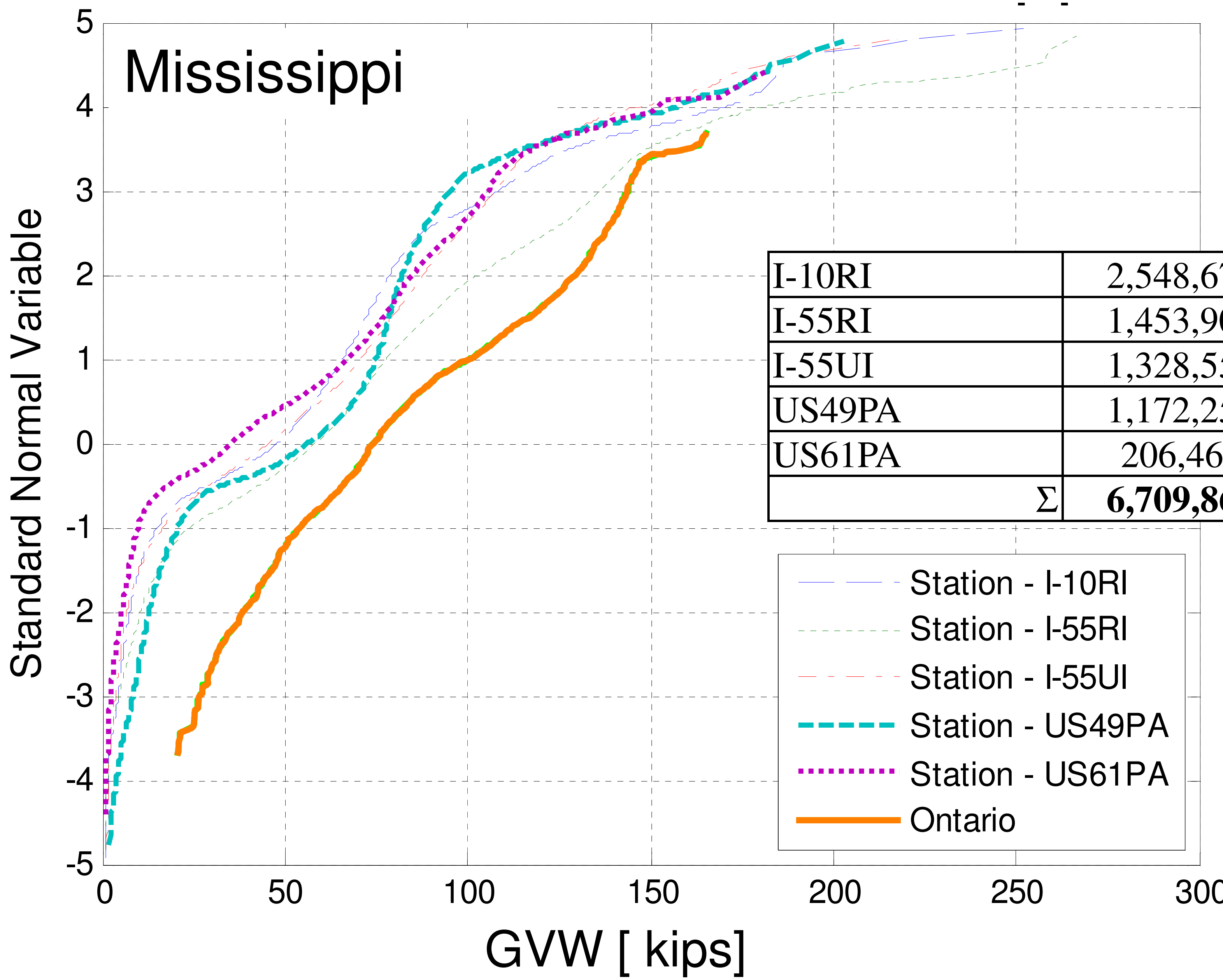
I-10	1,654,006
I-75	2,679,288
I-95	2,226,480
State Route	647,965
US29	728,544
Σ	**7,936,283**

Gross Vehicle Weight



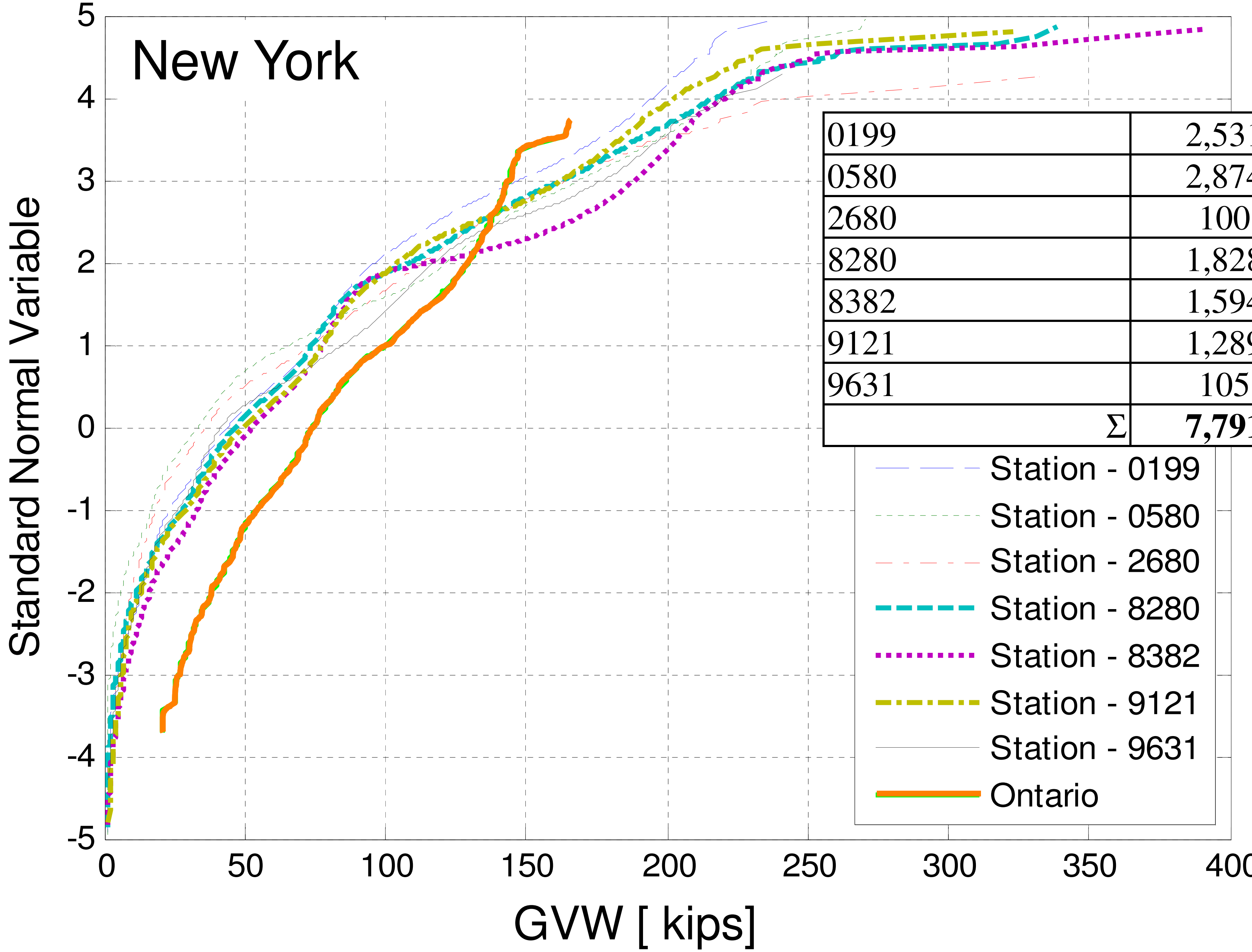
9511	4,511,842
9512	2,092,181
9532	783,352
9534	5,351,423
9552	252,315
Σ	**12,991,113**

Gross Vehicle Weight



I-10RI	2,548,678
I-55RI	1,453,909
I-55UI	1,328,555
US49PA	1,172,254
US61PA	206,467
Σ	**6,709,863**

Gross Vehicle Weight



0199	2,531,866
0580	2,874,124
2680	100,488
8280	1,828,020
8382	1,594,674
9121	1,289,295
9631	105,035
Σ	**7,791,636**

Development of Numerical Procedure

- For each cross-section the maximum moment and shear was determined
- For each truck maximum value of live load effect was stored

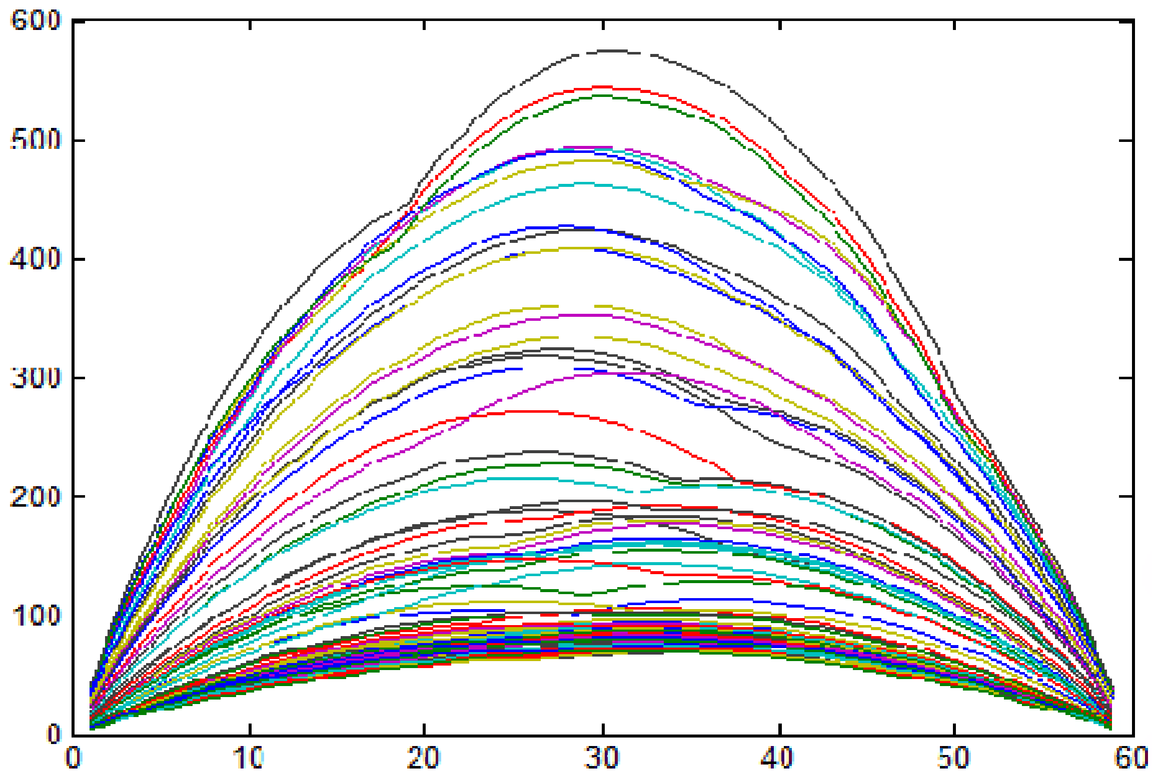
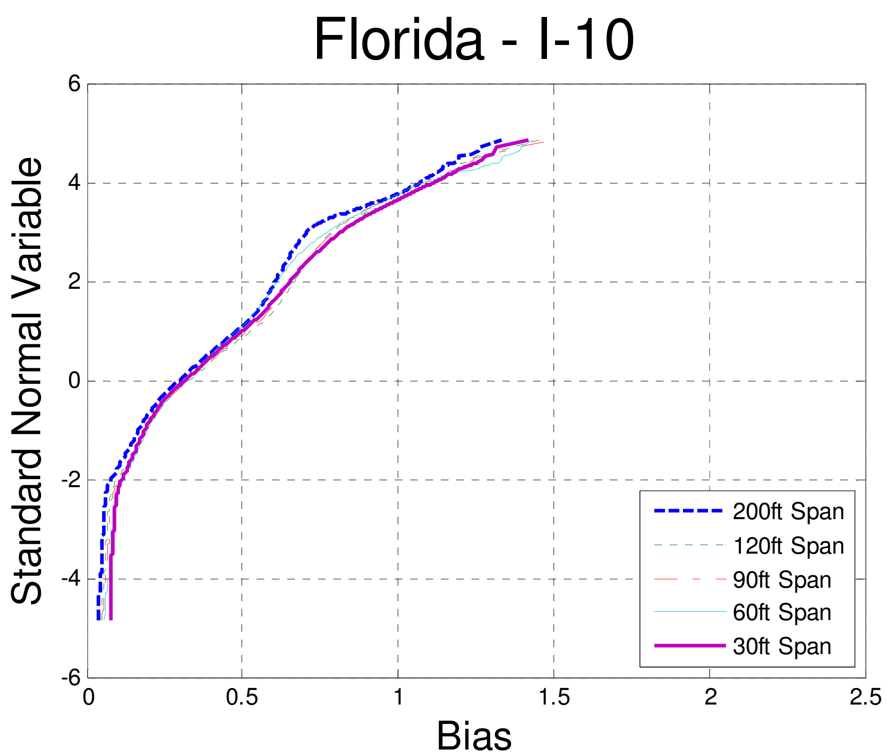
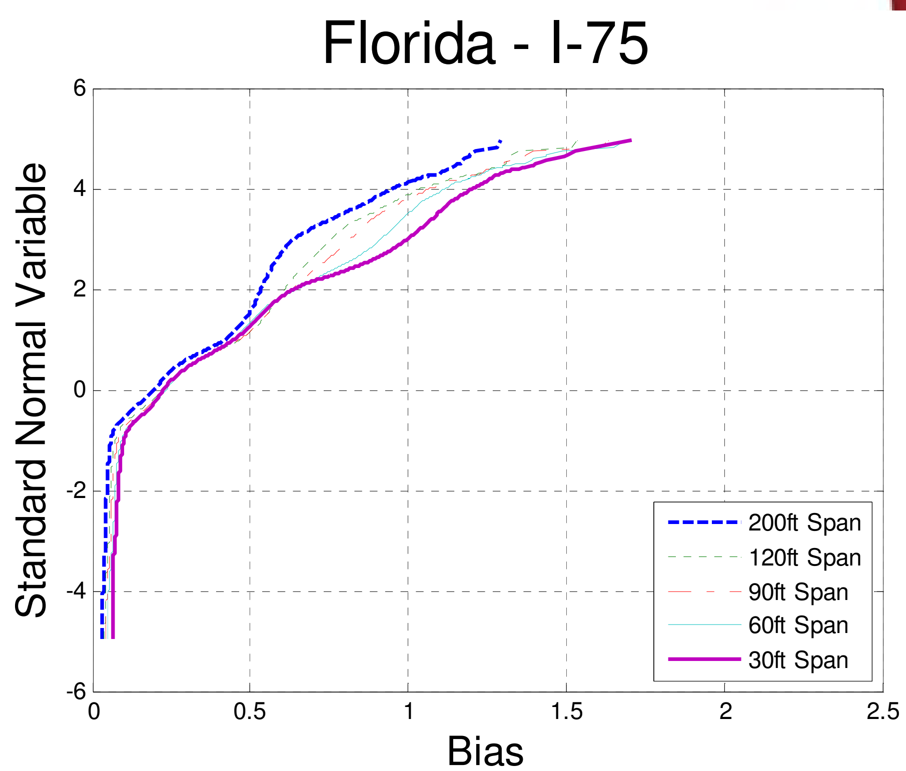


Figure 1 - Bending Moment Envelopes - First 100 Trucks – 60ft Span

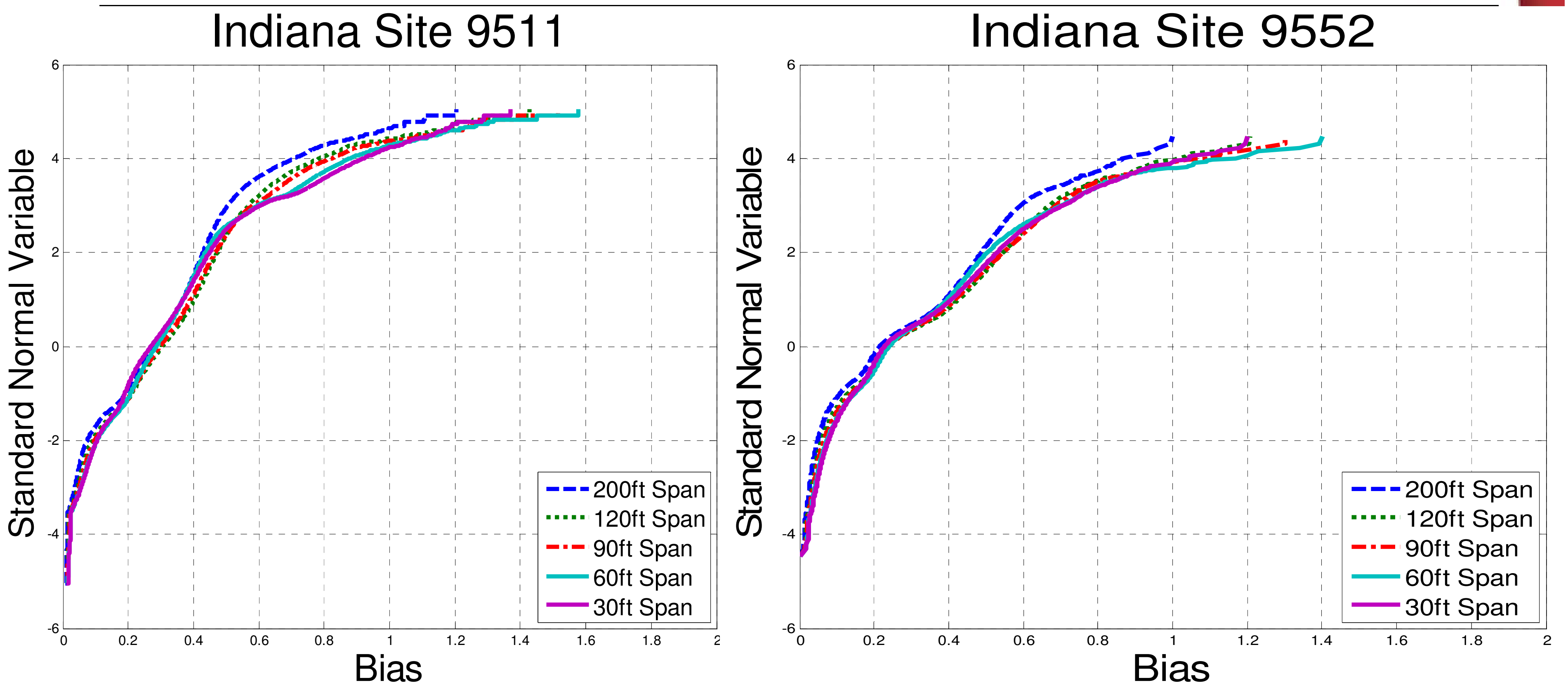
Florida – Load Effect – Moments





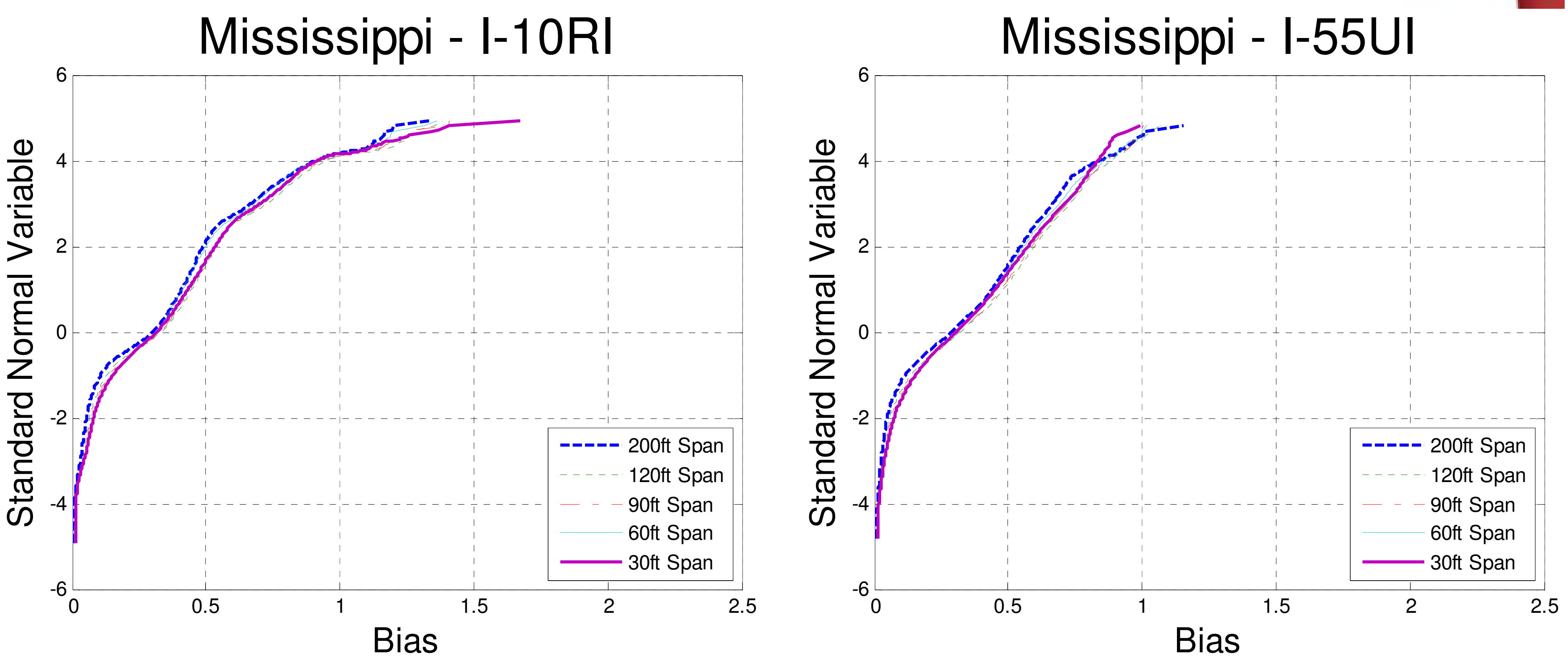
Cumulative Distribution Functions of Ratio of Truck Moment/ HL93 Moment - Simple Span Moment – Florida

Indiana – Load Effect – Moments



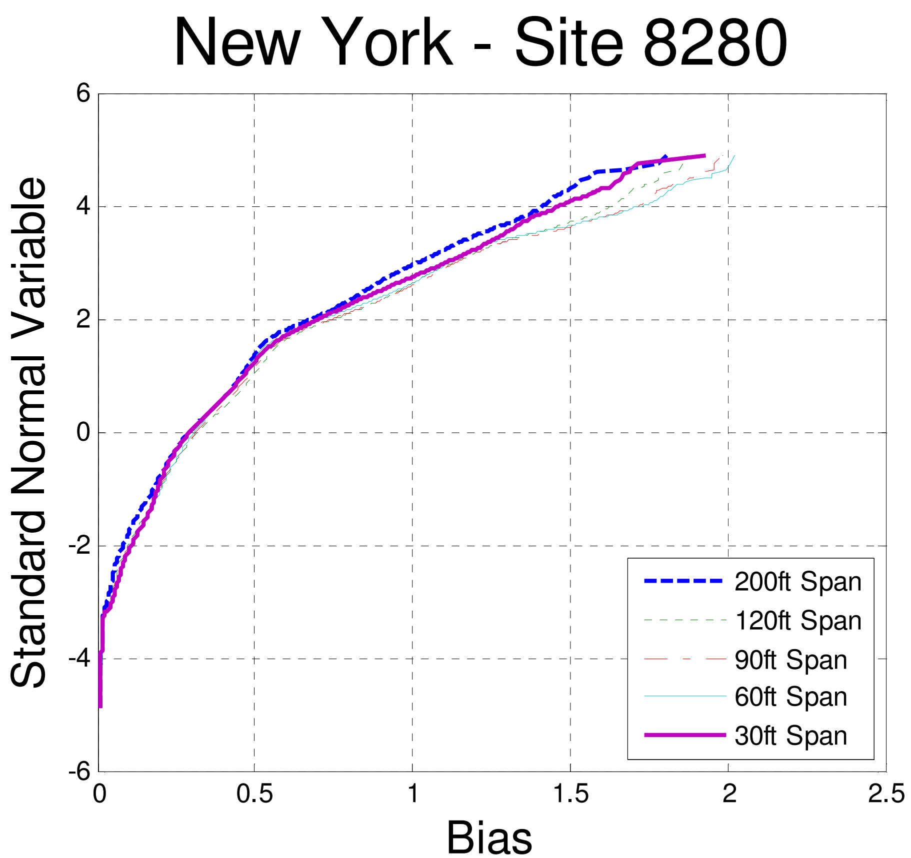
Cumulative Distribution Functions of Ratio of Truck Moment/ HL93 Moment - Simple Span Moment – Indiana

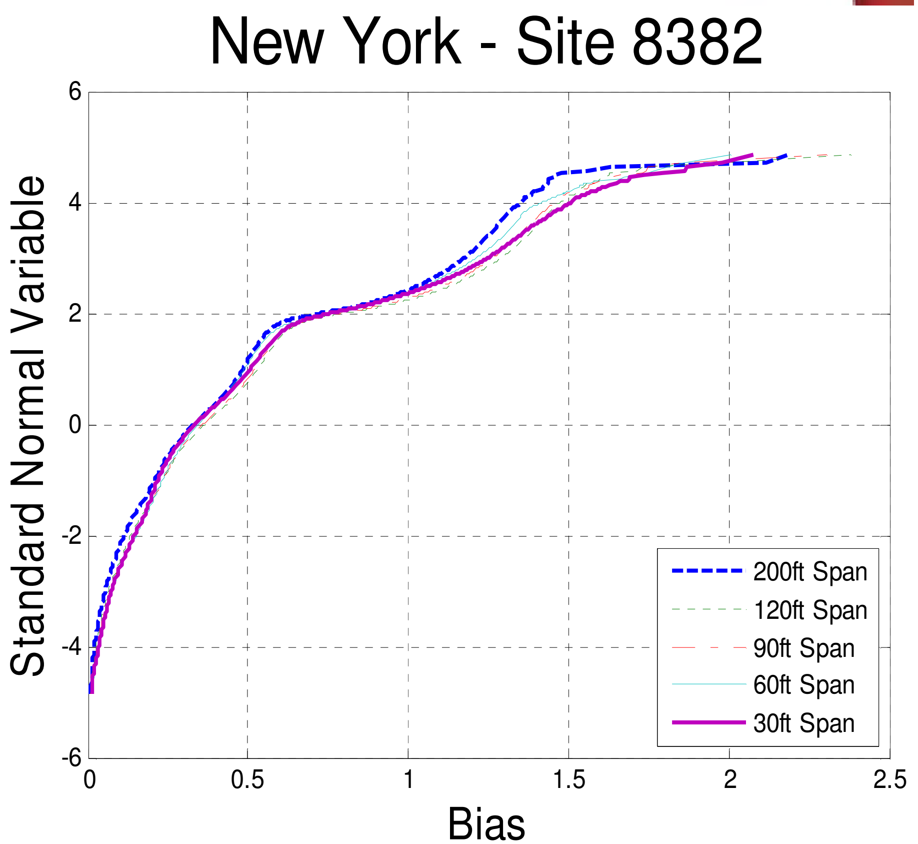
Mississippi – Load Effect – Moments



Cumulative Distribution Functions of Ratio of Truck Moment/ HL93 Moment - Simple Span Moment – Mississippi

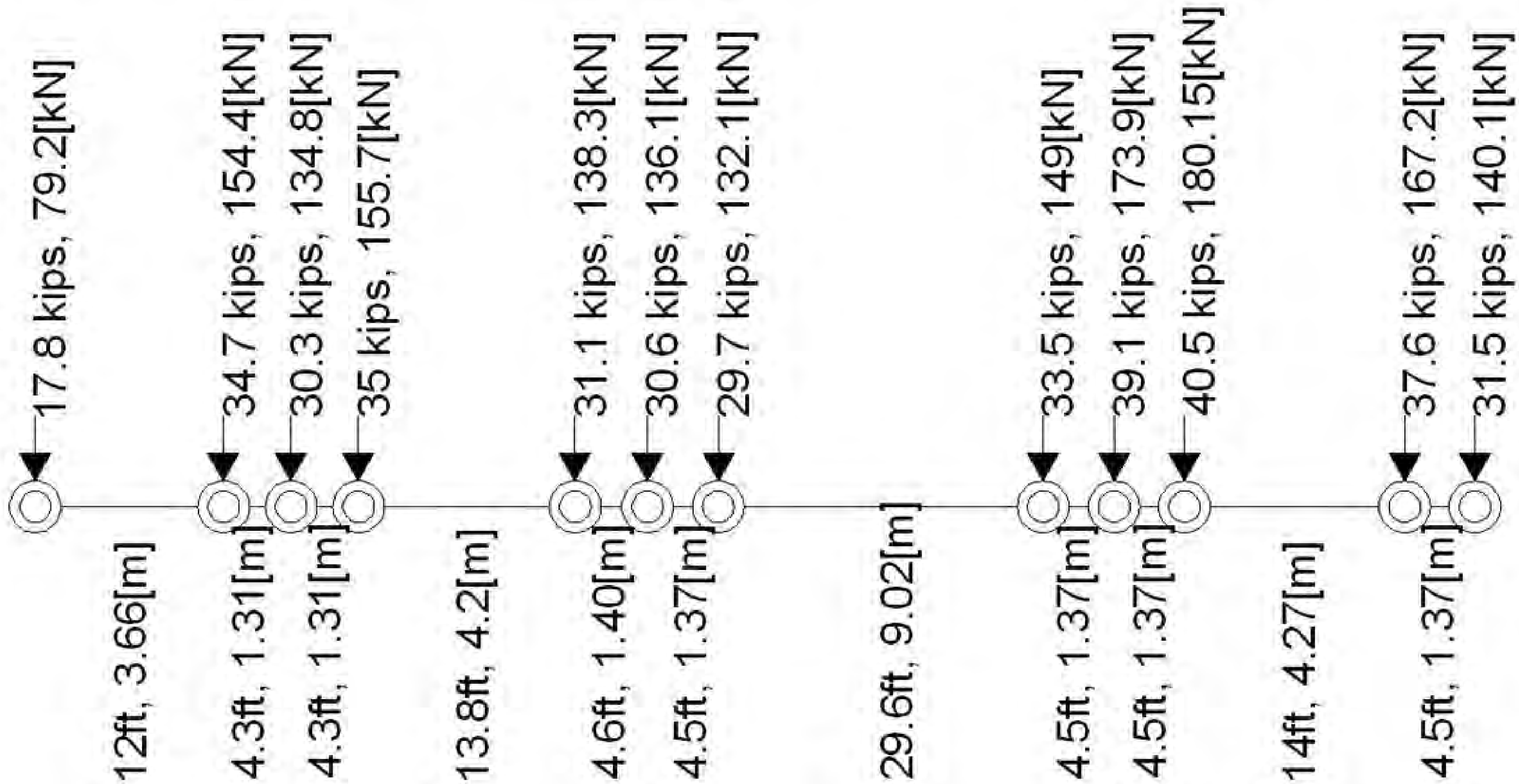
New York – Load Effect – Moments





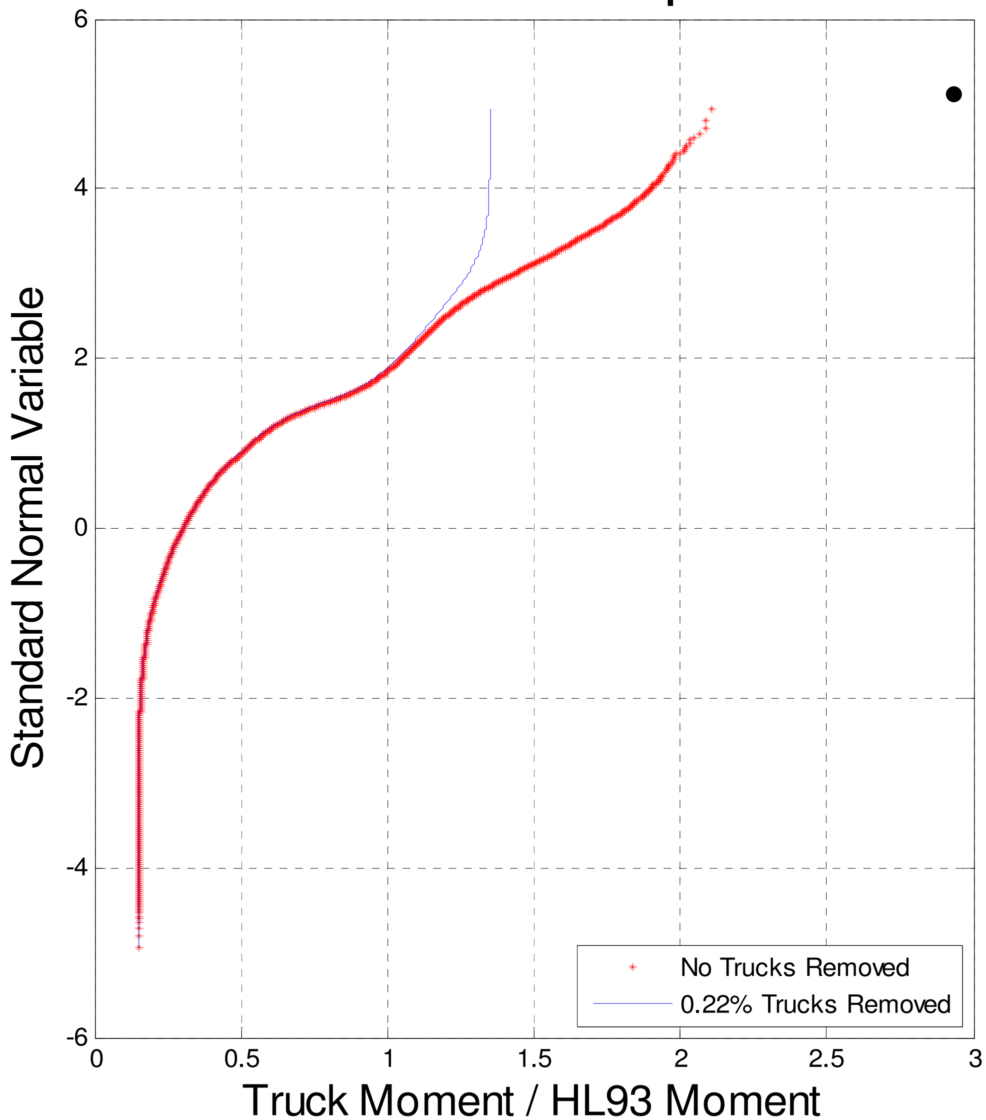
Cumulative Distribution Functions of Ratio of Truck Moment/ HL93 Moment - Simple Span Moment – New York

Configuration of the Heaviest Truck – New York 8382



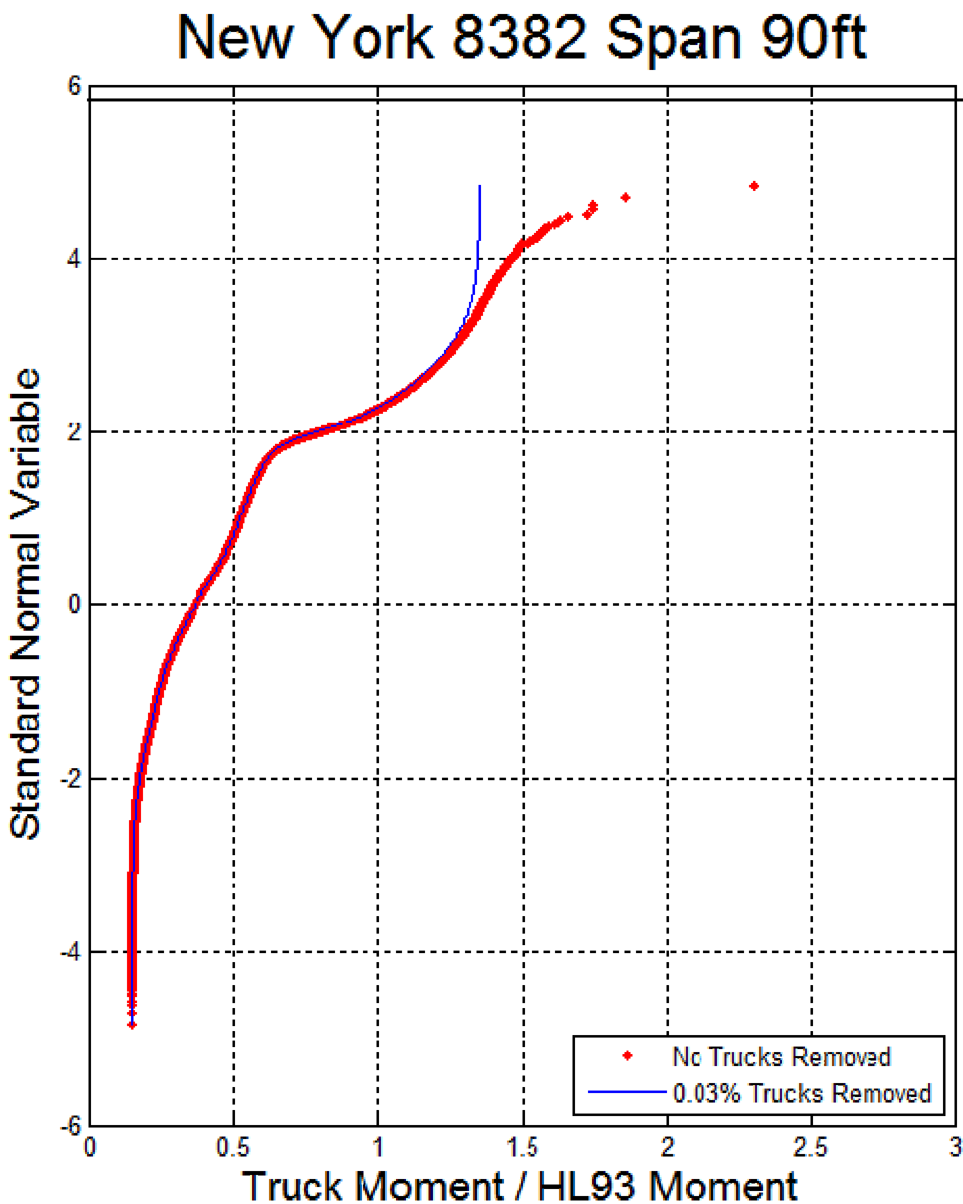
New York Extremely Heavy Trucks

New York 0580 Span 90ft



- Number of trucks: 2,474,407
  - Additional filter:
  - $M_{truck}/M_{HL93}>1.35$
    - 5,455 trucks removed
    - or 0.2%

New York Extremely Heavy Trucks



- Number of trucks: 1,594,674
  - Additional filter:
  - $M_{truck}/M_{HL93}>1.35$
    - 540 trucks removed
    - or 0.03%

Extreme Value Analysis

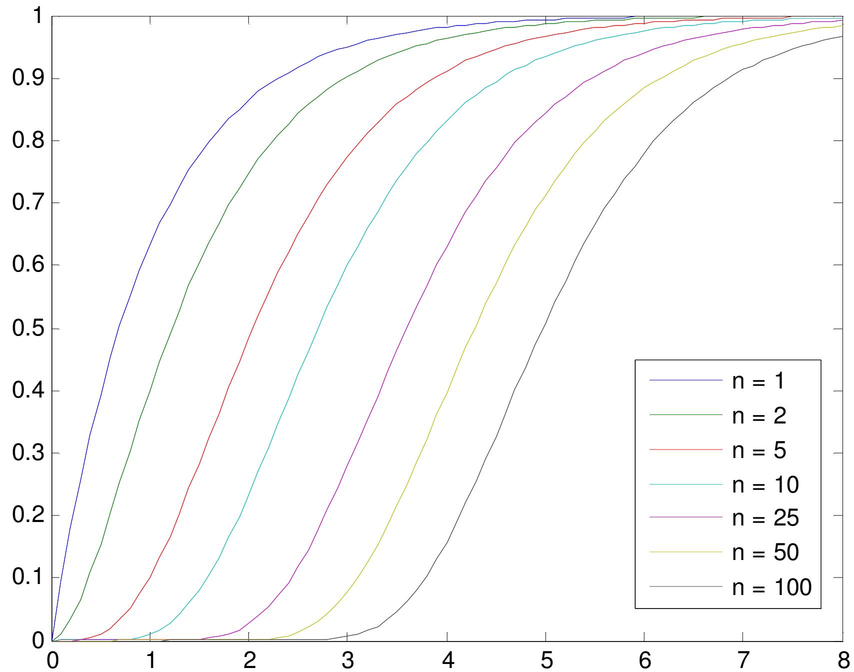
- The cumulative distribution function of X_n can be represented as:

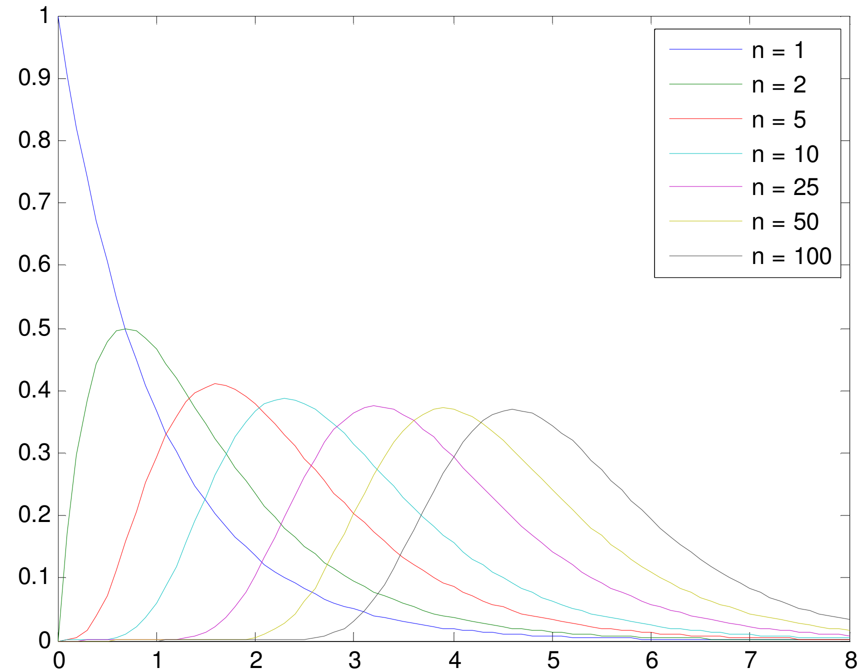
$$F_{M_n}(m) = F_X(m)^n$$

- and the probability density function $f_{Mn}(m)$:

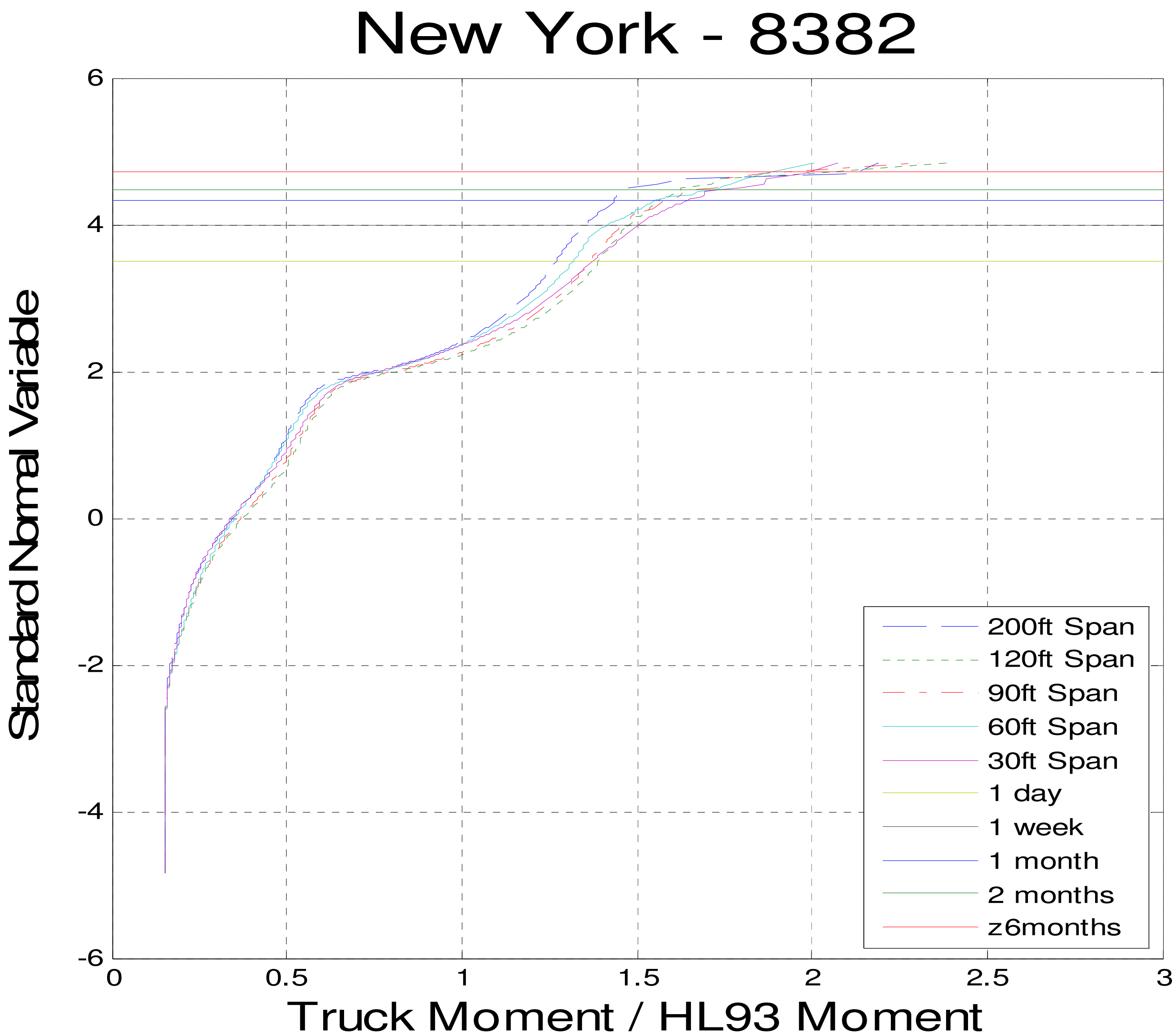
$$f_n(m) = nF(m)^{n-1} f(m)$$

Graphical representation of CDF and PDF





Moment and Return Periods

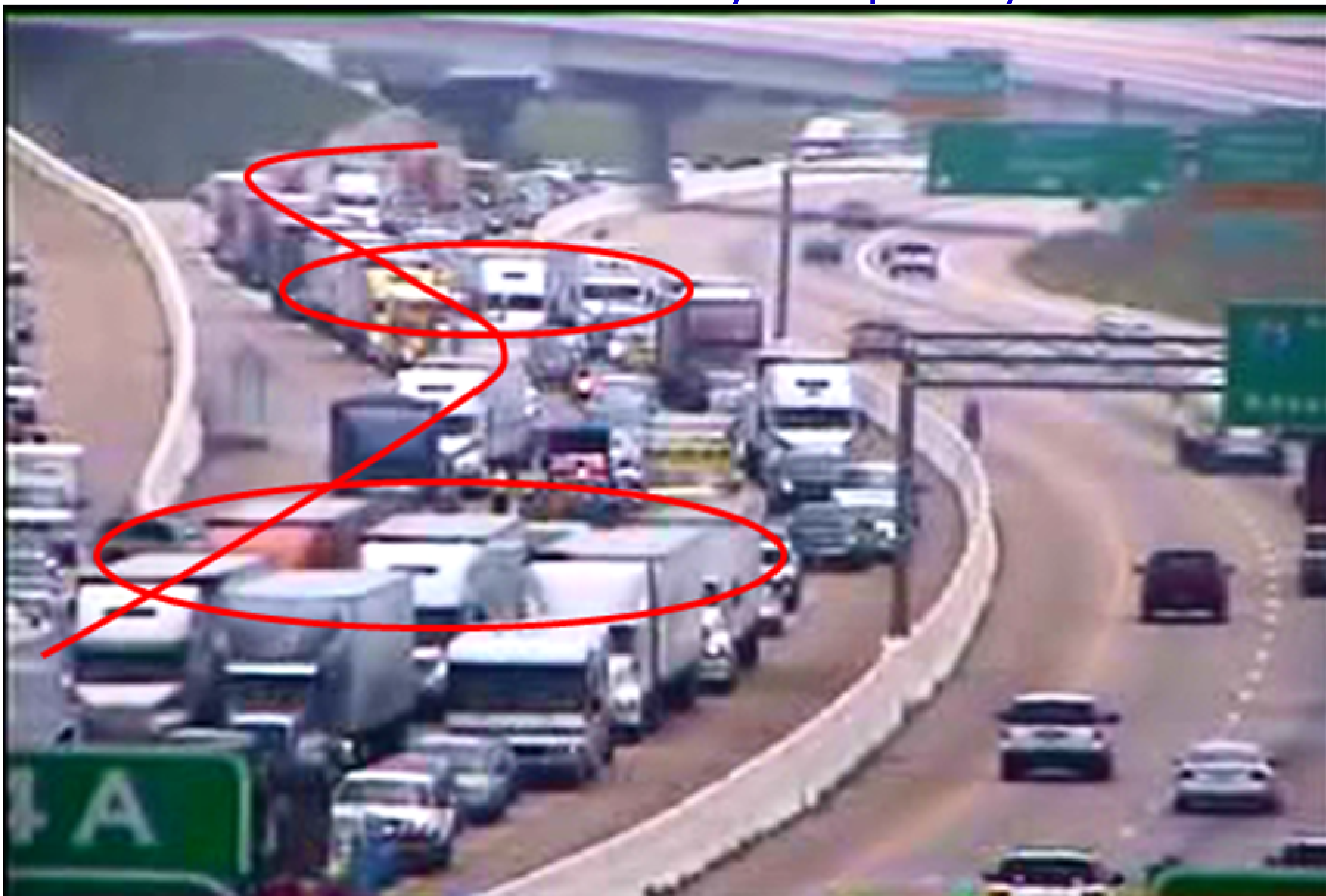


D

Two trucks side-by-side

Video Recordings of Traffic Jam Situations FHWA Data

- Multiple-presence of trucks occupying three lanes
- One lane is almost exclusively occupied by trucks



Dynamic Load

- Roughness of the road surface (pavement)
- Bridge as a dynamic system (natural frequency of vibration)
- Dynamic parameters of the vehicle (suspension system, shock absorbers)

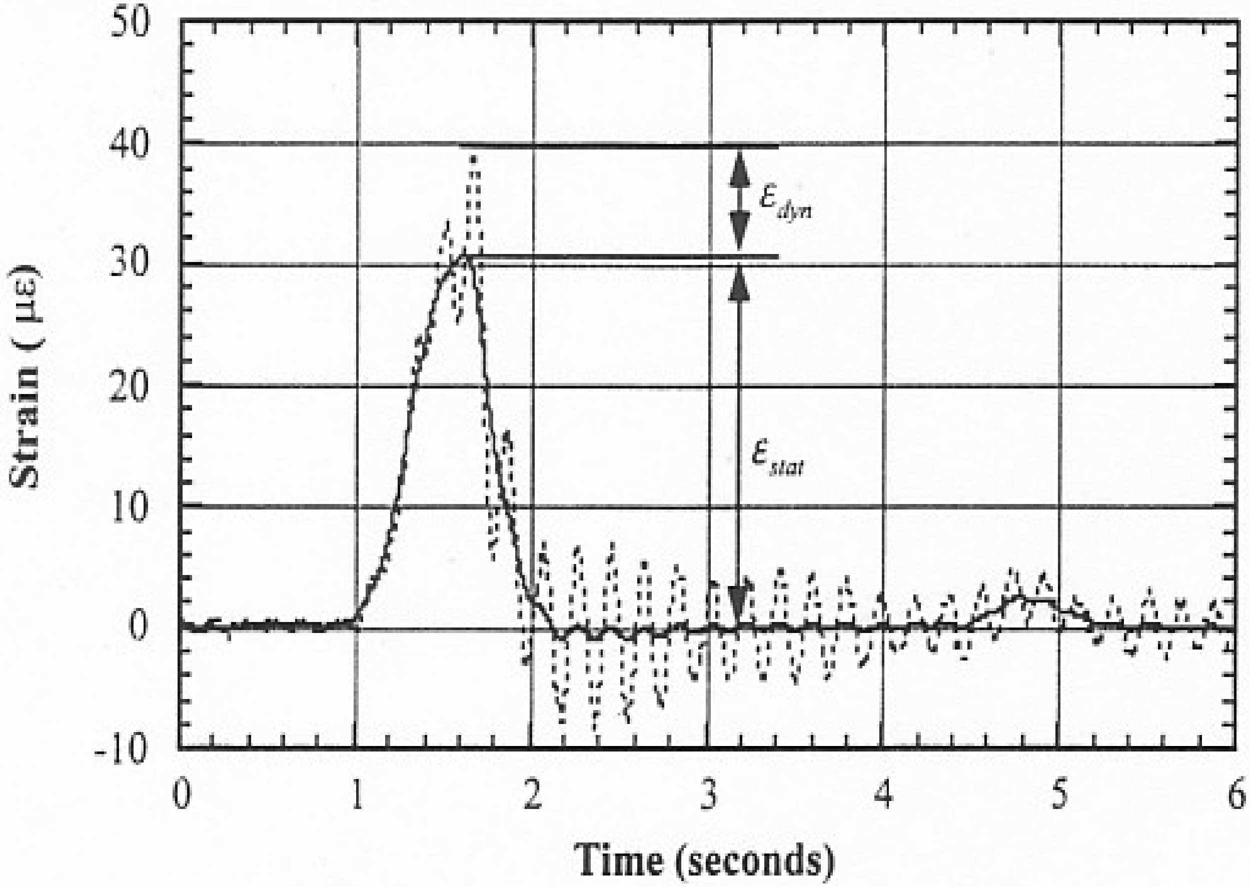


Figure 3.3. Dynamic and Static Strain under a Truck at Highway Speed.

Dynamic Load Factor (DLF)

- Static strain or deflection (at crawling speed)
- Maximum strain or deflection (normal speed)
- Dynamic strain or deflection =

  maximum - static
- DLF = dynamic / static

Code Specified Dynamic Load Factor

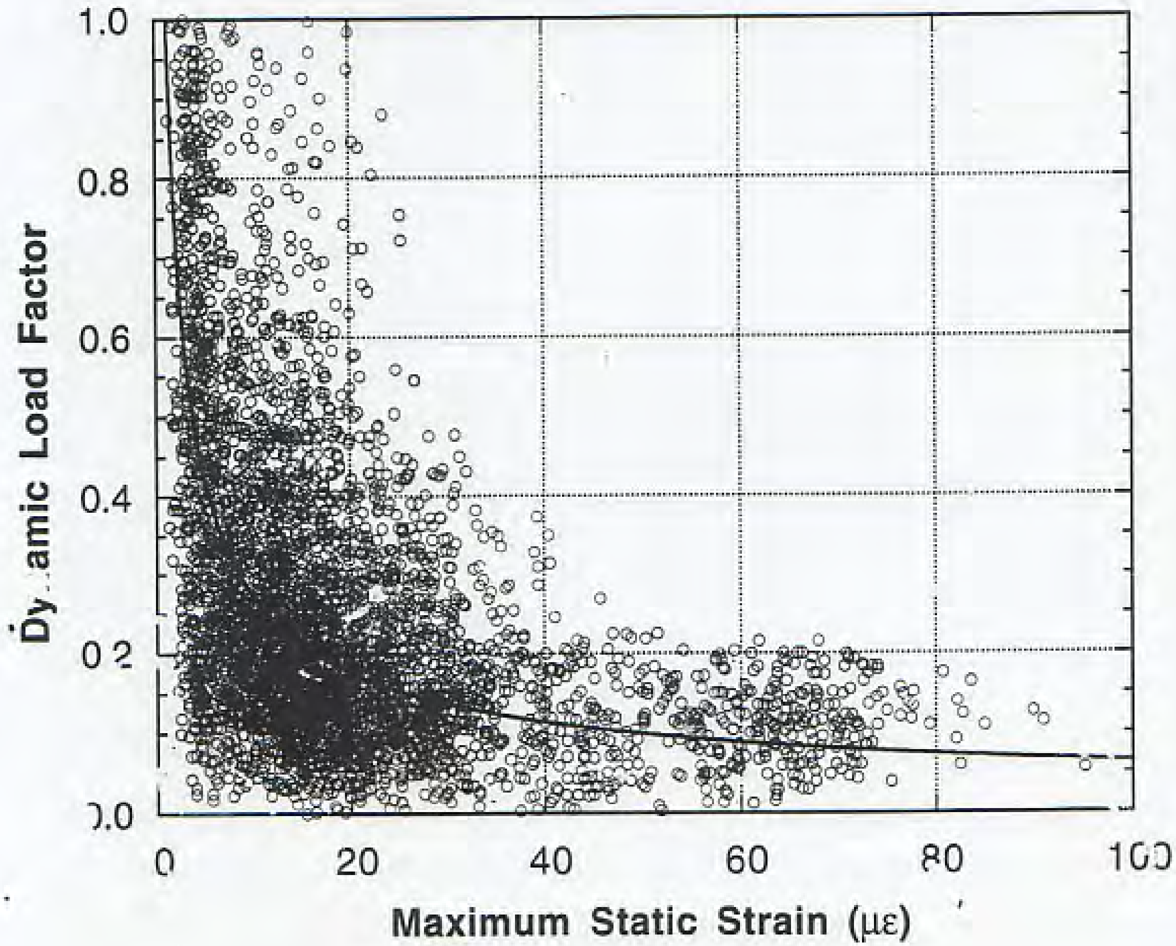
AASHTO Standard (2002)

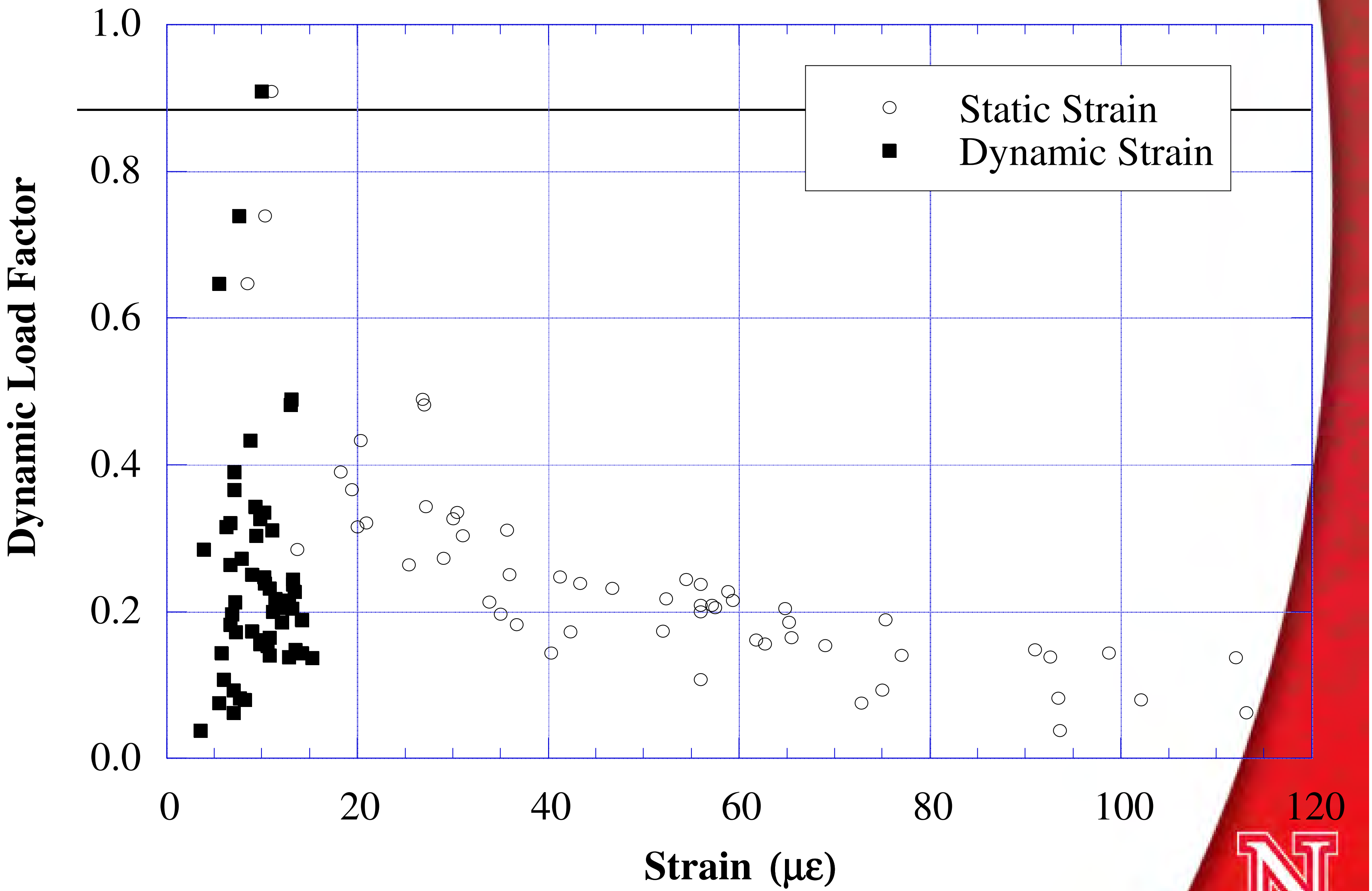
$$I = \frac{50}{3.28L + 125} \leq 0.3$$

AASHTO LRFD (2011)

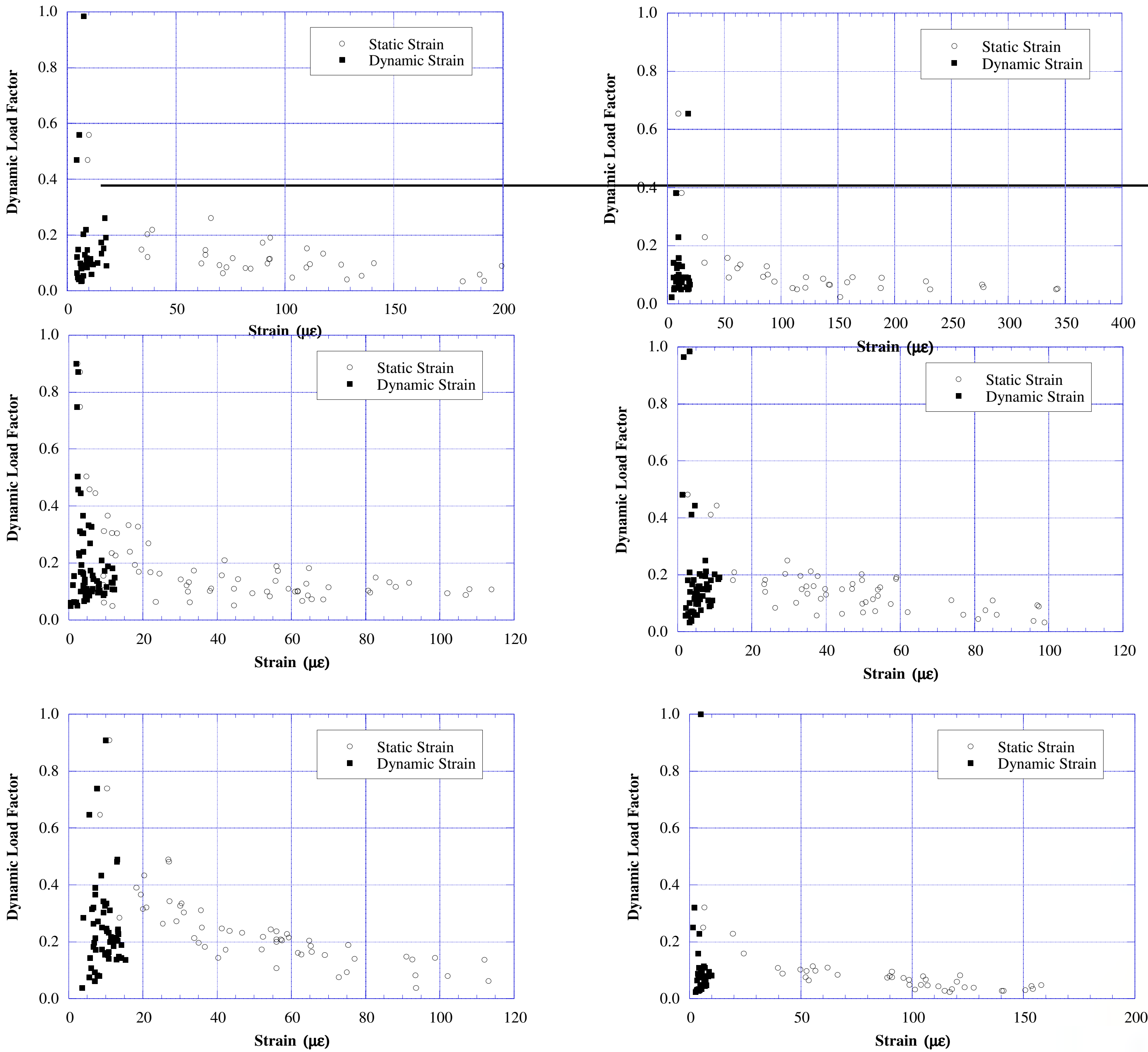
0.33 of truck effect, no dynamic load for the uniform loading

Dynamic Load Factor





1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
Dynamic Load Factor
Strain (με)
Static Strain
Dynamic Strain



Dynamic Load Factor
Strain (με)
Static Strain
Dynamic Strain

Dynamic Load - Conclusions

- Dynamic strain and deflection do not depend on truck weight
- Dynamic load factor (DLF) decreases for increased truck weight
- For a single truck DLF < 20%
- For two trucks side-by-side DLF < 10%

Parameters of Resistance

$$R = R_n \, M \, F \, P$$

where :

R_n = nominal value of resistance

M = material factor

F = fabrication factor

P = professional factor

Parameters of Resistance

- The mean value of R is

$$\mu_R = R_n \mu_M \mu_F \mu_P$$

- Coefficient of variation

$$V_R = \sqrt{(V_M)^2 + (V_F)^2 + (V_P)^2}$$

- Bias factor

$$\lambda_R = \lambda_M \lambda_F \lambda_P$$

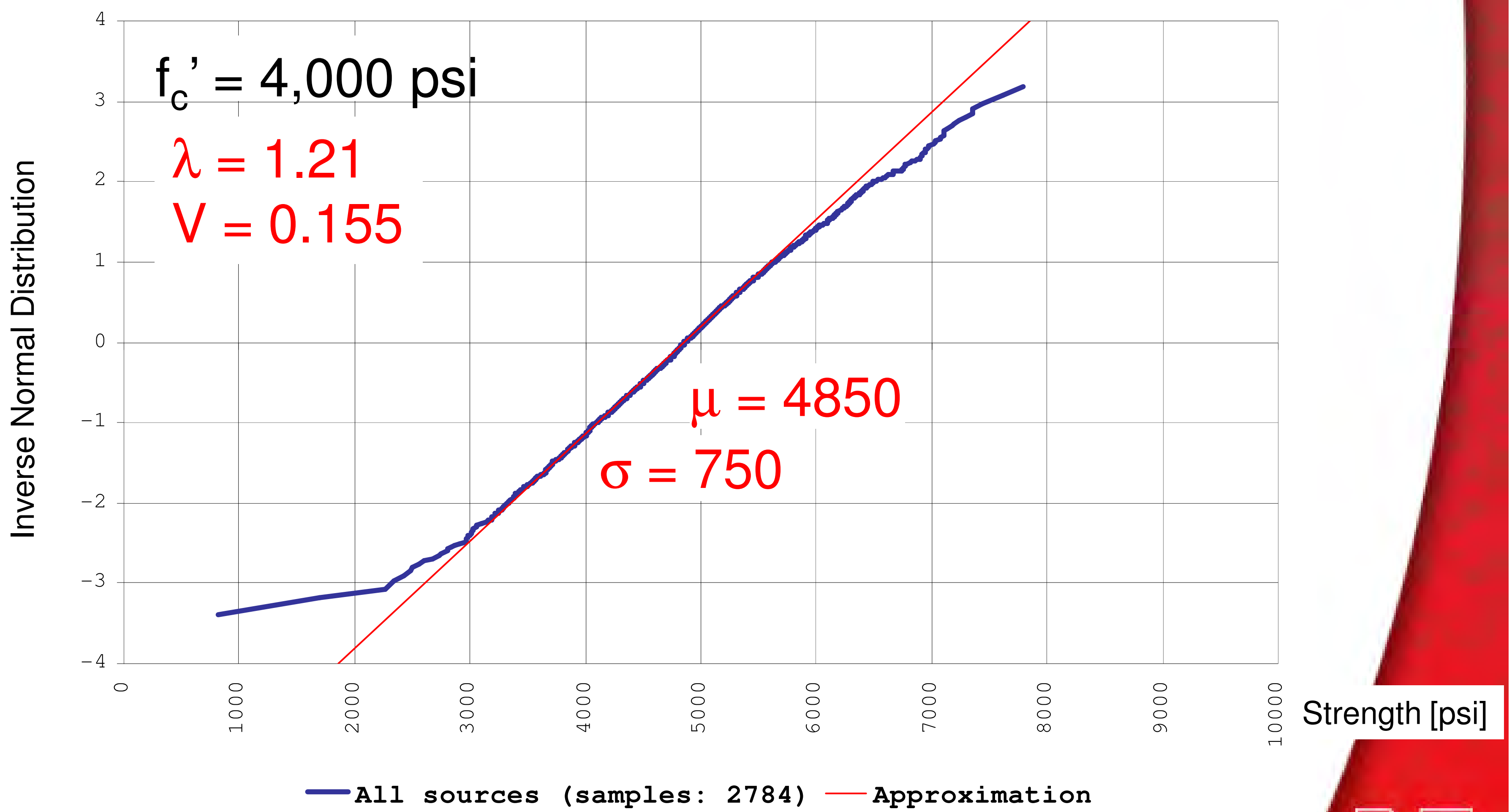
New Materials Data

- Compressive Strength of Ordinary Concrete, Ready mixed, fc': 3,000 3,500 4,000 4,500 5,000 and 6,000 psi
- Yield Stress of Reinforcing Steel Bars, Grade 60 Bar Sizes: #3, #4, #5, #6, #7, #8, #9, #10, #11 and #14
- Breaking Stress of Prestressing Steel (7-wire strands), Grade 270, Nominal Diameters: 0.5 in and 0.6 in

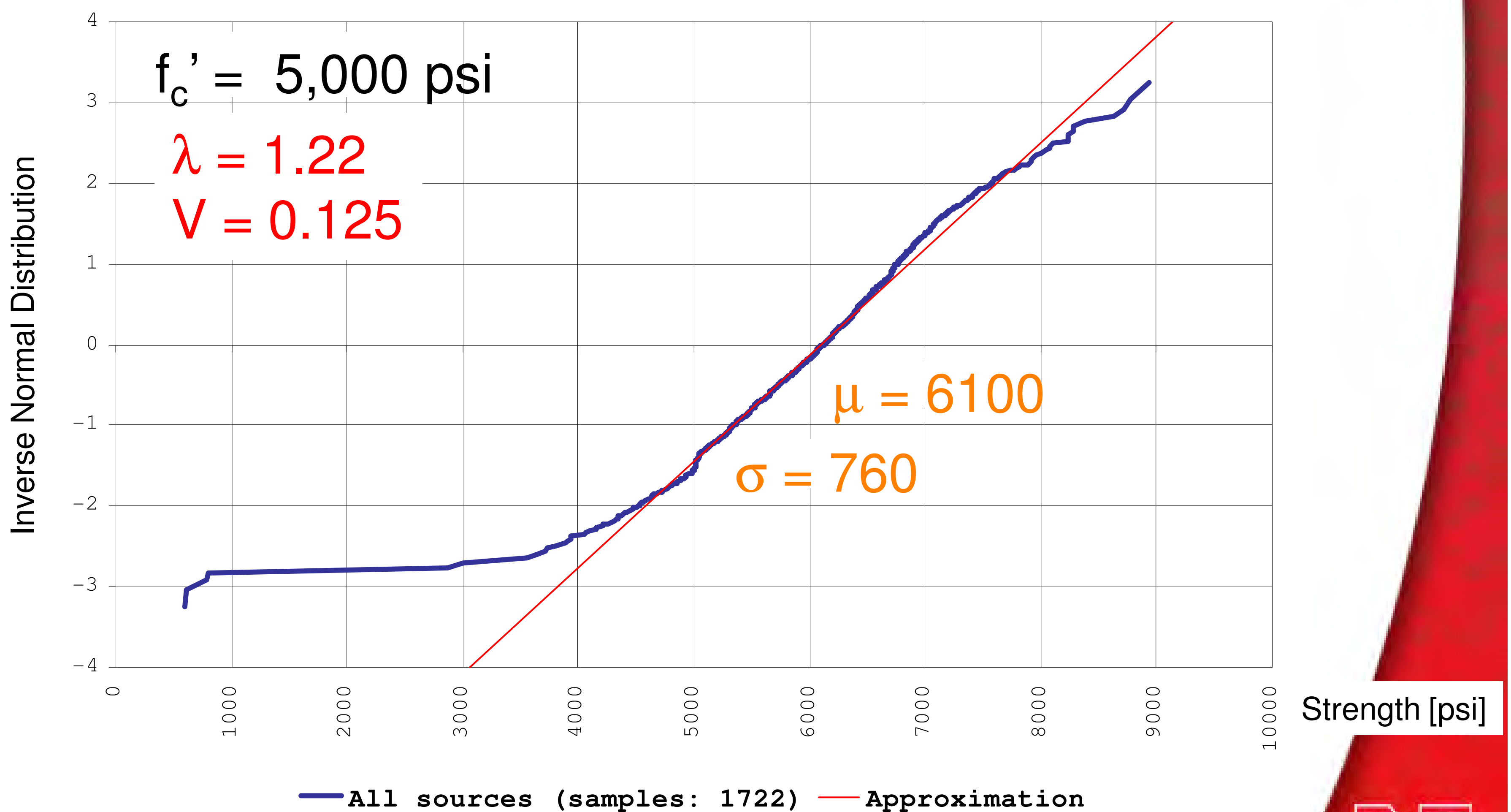

Holcim
3/15
1/7 +10
2/13 +10
2/8
5/30


34
MAX PLATEN

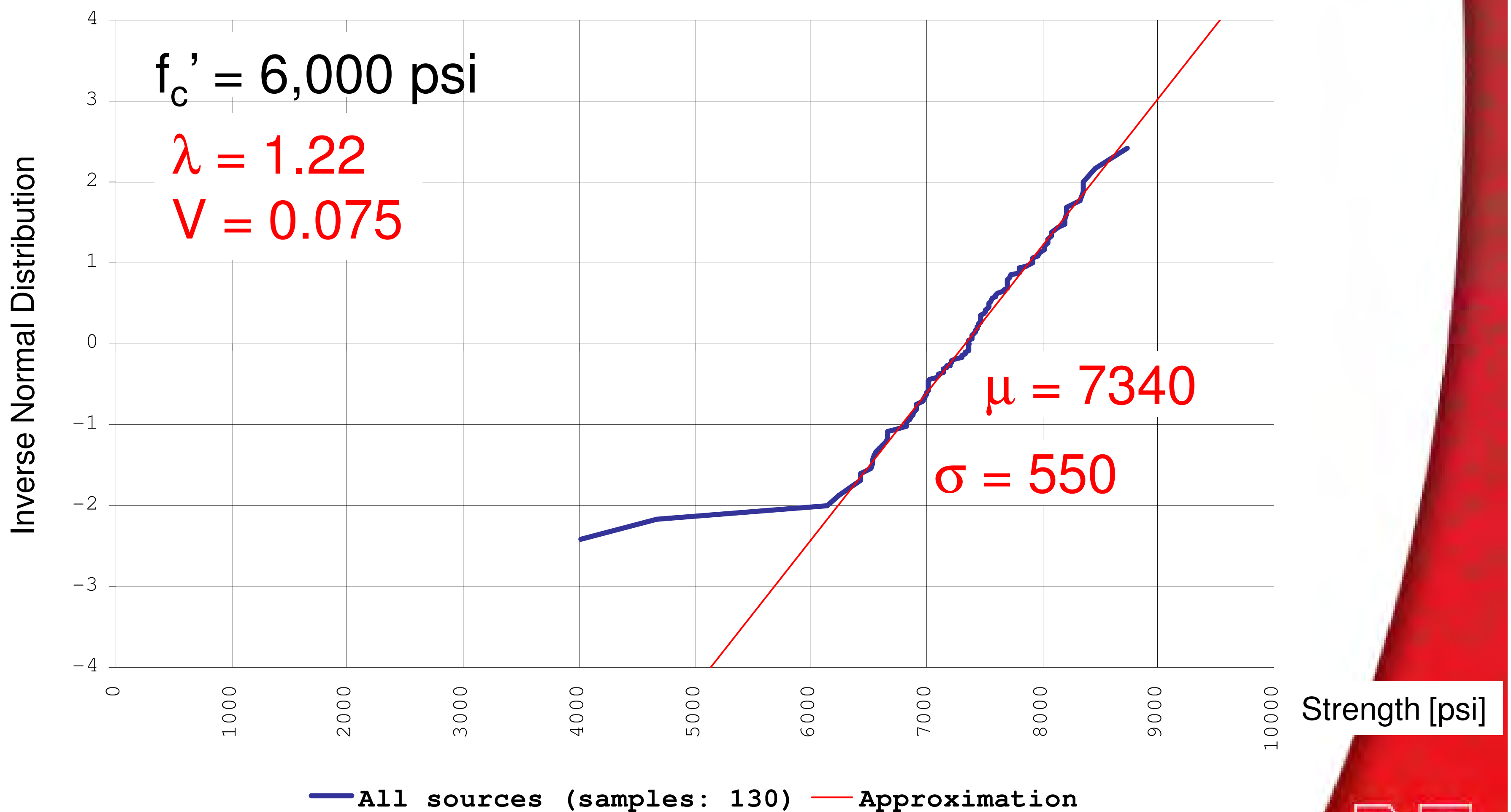
Ordinary Concrete – CDF of Strength



Ordinary Concrete – CDF of Strength

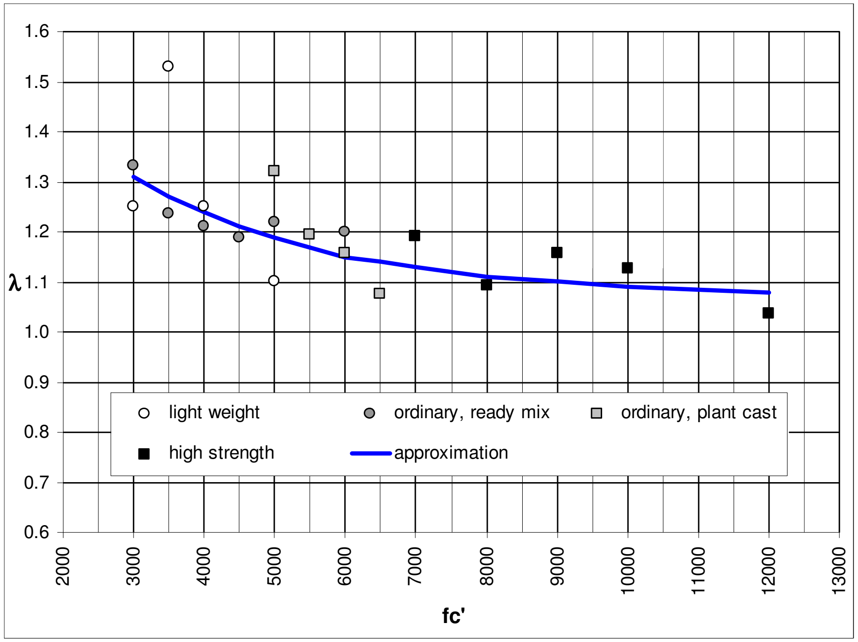


Ordinary Concrete – CDF of Strength

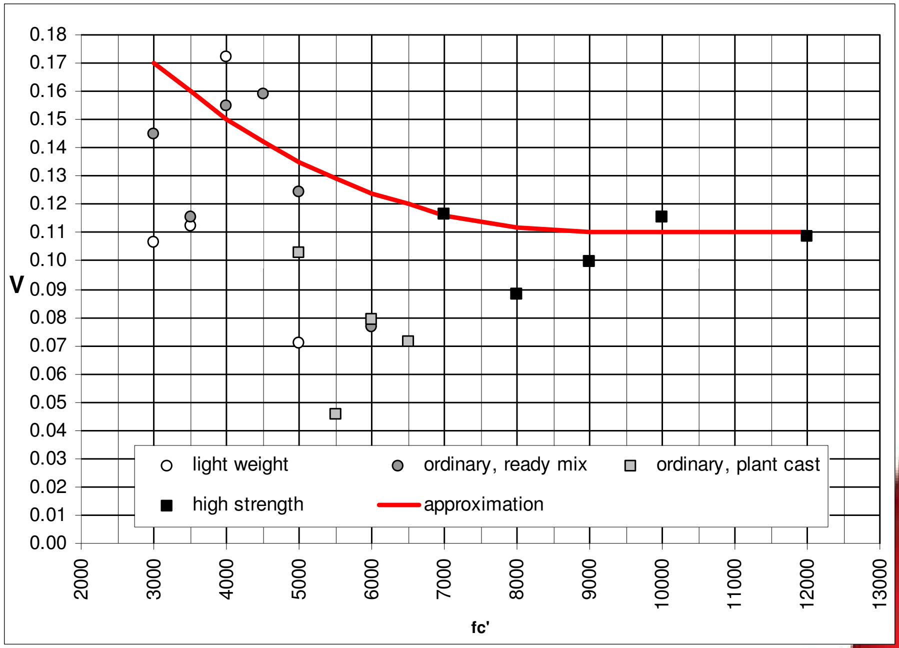


Summary of the Statistical Parameters for Concrete

λ



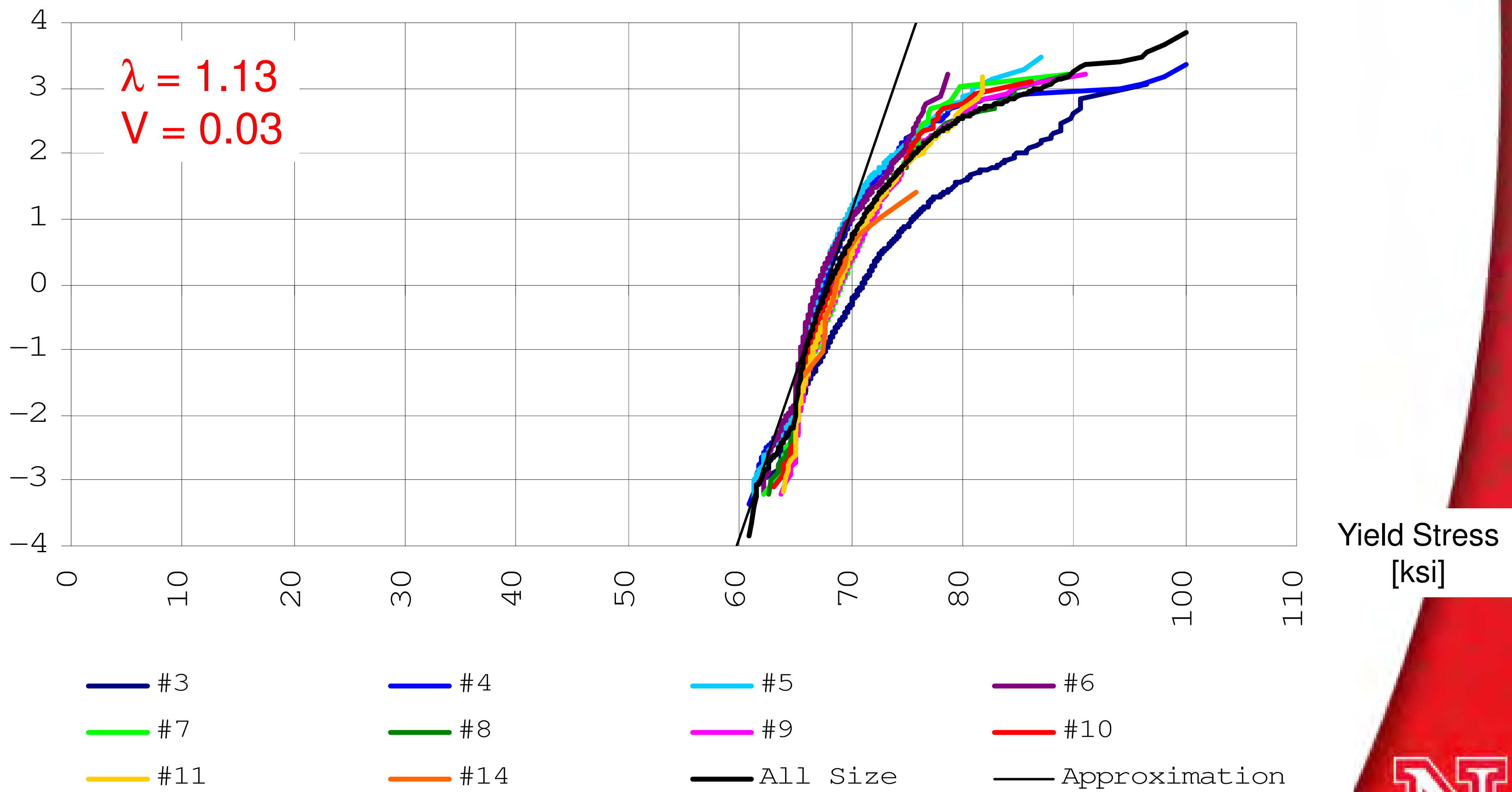
V



f_c' [psi]

f_c' [psi]

Statistical Parameters assumed for Monte Carlo Simulations - Reinforcing Steel Bars, Grade 60

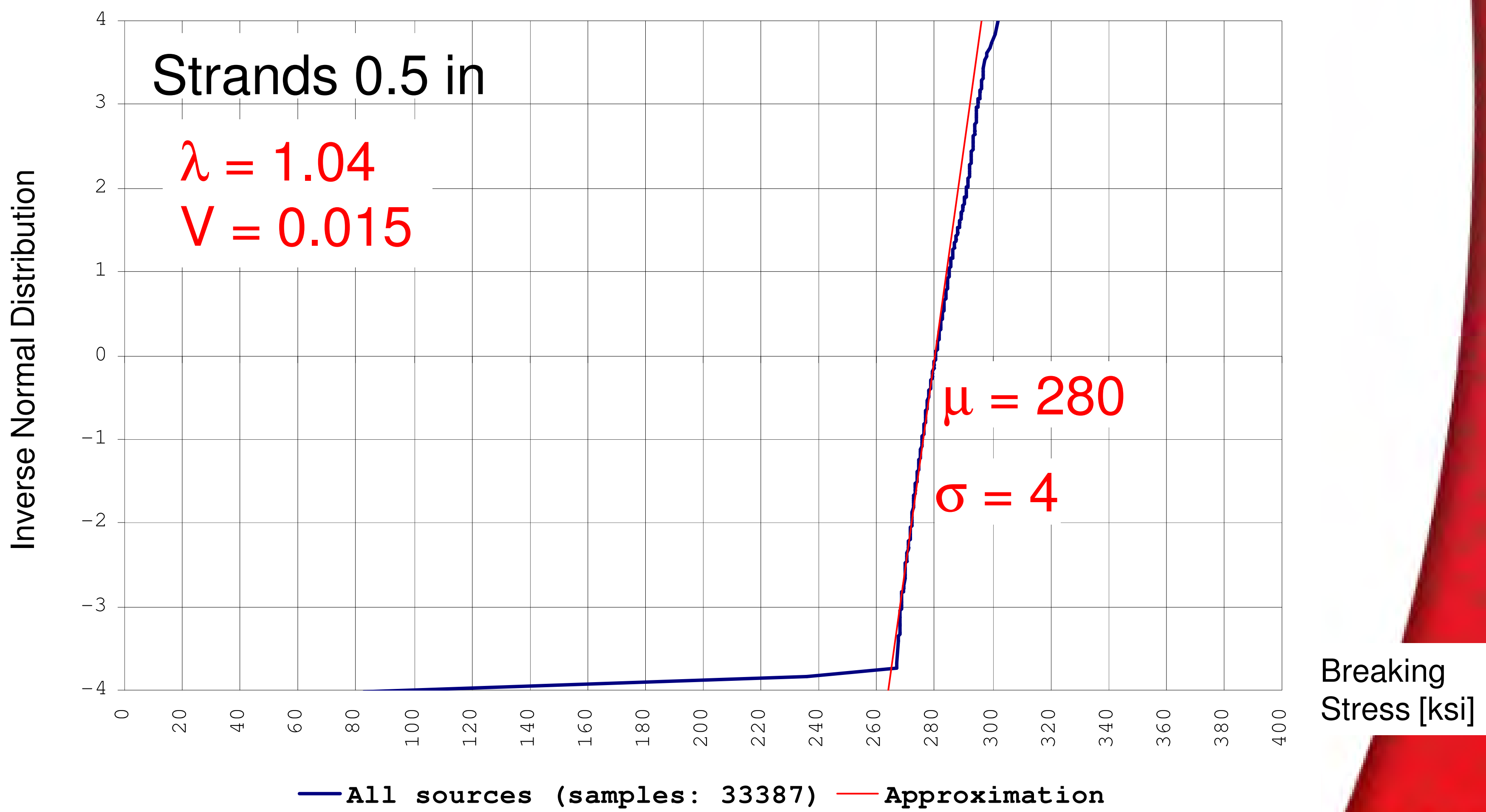


Reinforcing Steel Bars, Grade 60 – Statistical Parameters

Bar Size	λ	V
# 3	1.18	0.04
# 4	1.13	0.03
# 5	1.12	0.02
# 6	1.12	0.02
# 7	1.14	0.03
# 8	1.13	0.025
# 9	1.14	0.02
#10	1.13	0.02
#11	1.13	0.02
#14	1.14	0.02

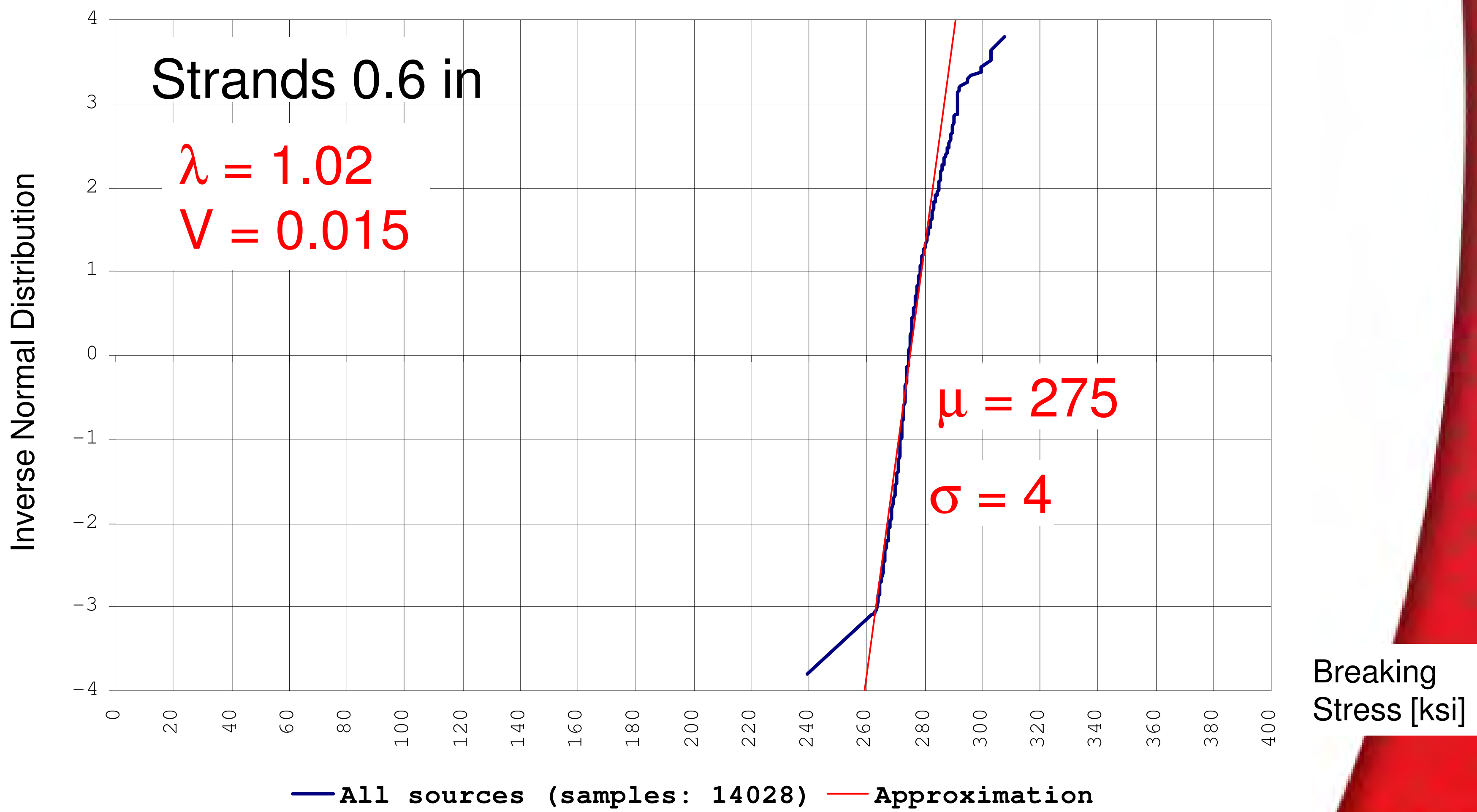
Prestressing Steel (7-wire strands), Grade 270

CDF of Breaking Stress



Prestressing Steel (7-wire strands), Grade 270

CDF of Breaking Stress



Prestressing Steel – Statistical Parameters

Grade	Size	Number of samples	Bias Factor	V
250 ksi	1/4 (6.25 mm) 3/8 (9.5 mm) 7/16(11 mm) 1/2 (12.5 mm)	22 83 114 66	1.07 1.11 1.11 1.12	0.01 0.025 0.01 0.02
270 ksi	3/8 (9.5 mm) 7/16 (11 mm) 1/2 (12.5 mm) 0.6 (15 mm)	54 16 33570 14028	1.04 1.07 1.04 1.02	0.02 0.02 0.015 0.015

Resistance Parameters

- Strength of material obtained from test data
- Load carrying capacity of components by Monte Carlo simulations
- Statistical parameters – mean value, bias factor (ratio of mean to nominal), coefficient of variation

Composite Steel Girders

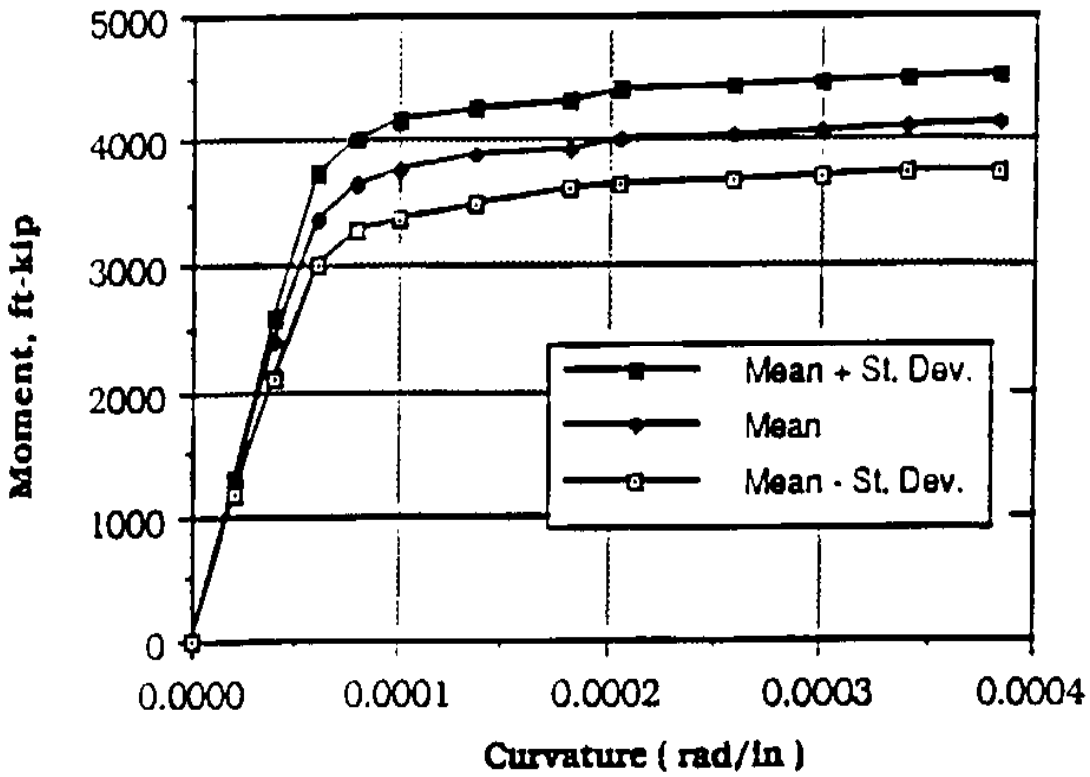


Fig. 8-8. Moment-Curvature Curves for a Composite W36x210 Steel Section.

Reliability Index, β

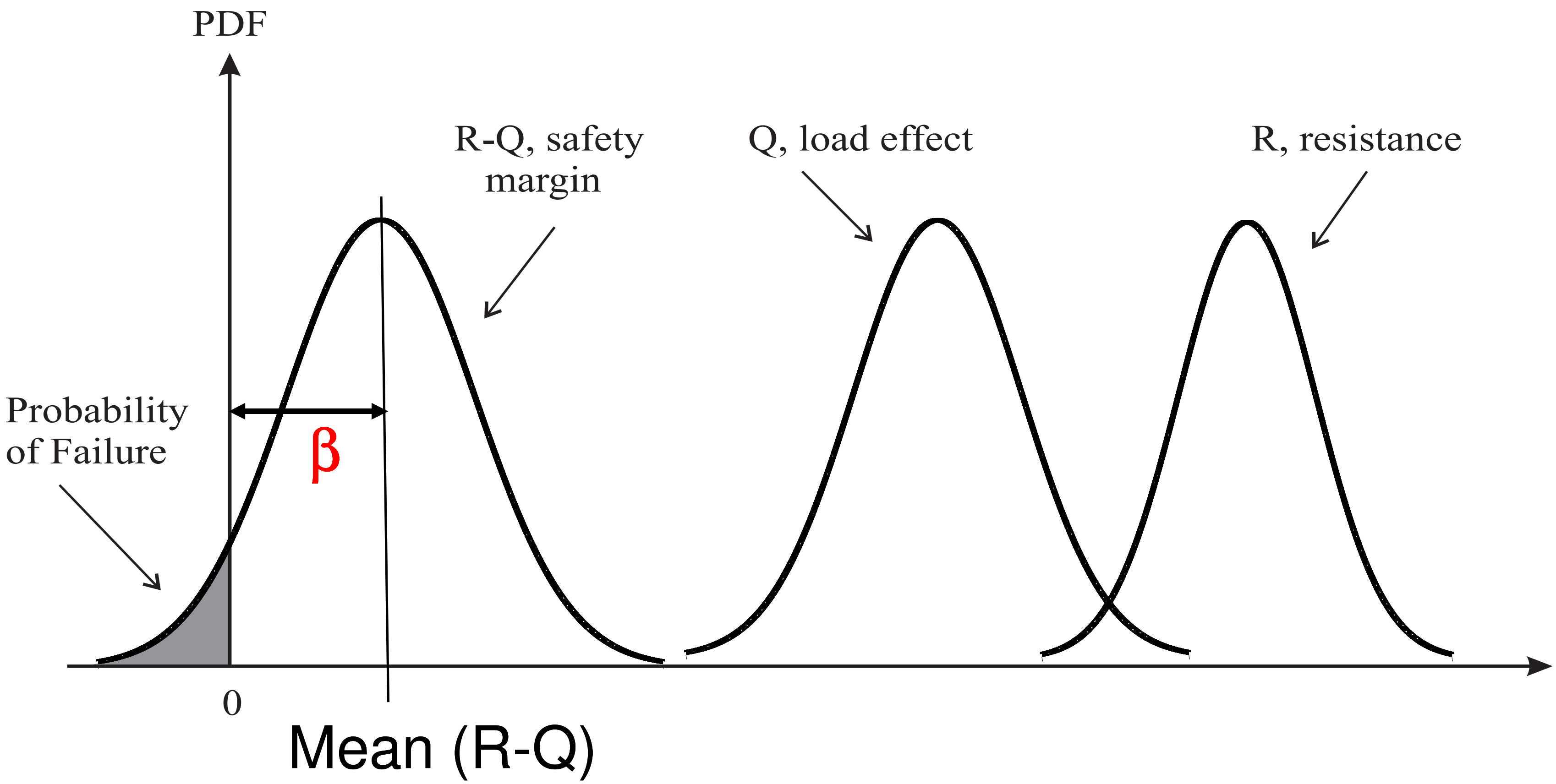


Figure 5-8 PDFs of load, resistance, and safety margin.

Reliability Index, β

For a linear limit state function, $g = R - Q = 0$, and R and Q both being normal random variables

$$\beta = \frac{(\mu_R - \mu_Q)}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

μ_R = mean resistance
μ_Q = mean load
σ_R = standard deviation of resistance
σ_Q = standard deviation of load

Reliability index and probability of failure

P_F	β
10^{-1}	1.28
10^{-2}	2.33
10^{-3}	3.09
10^{-4}	3.71
10^{-5}	4.26
10^{-6}	4.75
10^{-7}	5.19
10^{-8}	5.62
10^{-9}	5.99

Reliability Analysis Procedures

- Closed-form equations – accurate results only for special cases
- First Order Reliability Methods (FORM), reliability index is calculated by iterations
- Second Order Reliability Methods (SORM), and other advanced procedures
- Monte Carlo method - values of random variables are simulated (generated by computer), accuracy depends on the number of computer simulations

What is Optimum Reliability?

- If reliability index is too small – there are problems, even structural failures
- If reliability index is too large – the structures are too expensive

Target Reliability

- Consequences of failure
- Economic analysis
- Past practice
- Human perception
- Social/political decisions

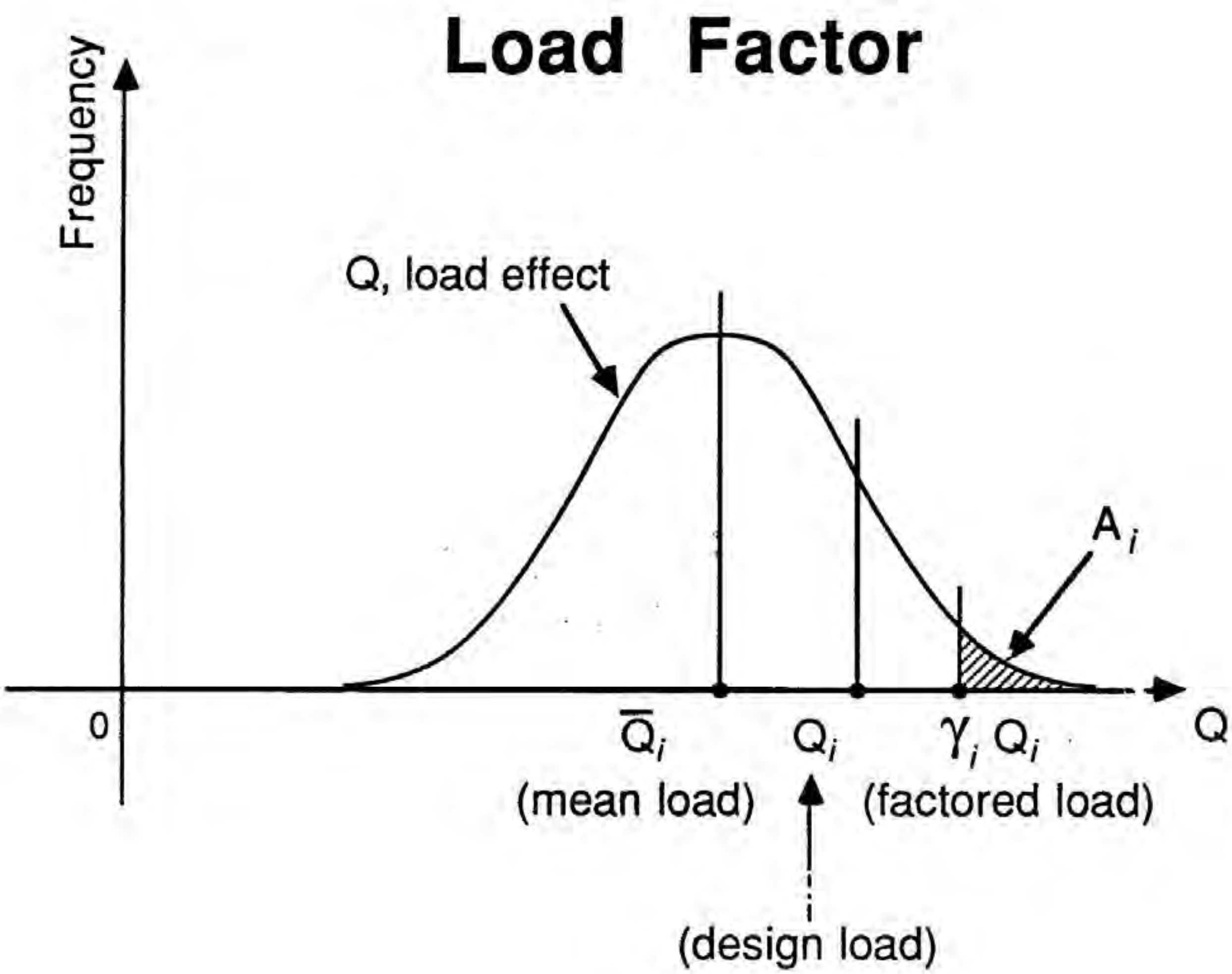
Recommended β_T

TIME PERIOD	PRIMARY COMPONENTS		SECONDARY COMPONENTS
	Single Path	Multiple Path	
5 years	3.50	3.00	2.25
10 years	3.75	3.25	2.50
50 years	4.00	3.50	2.75

Recommended β_T

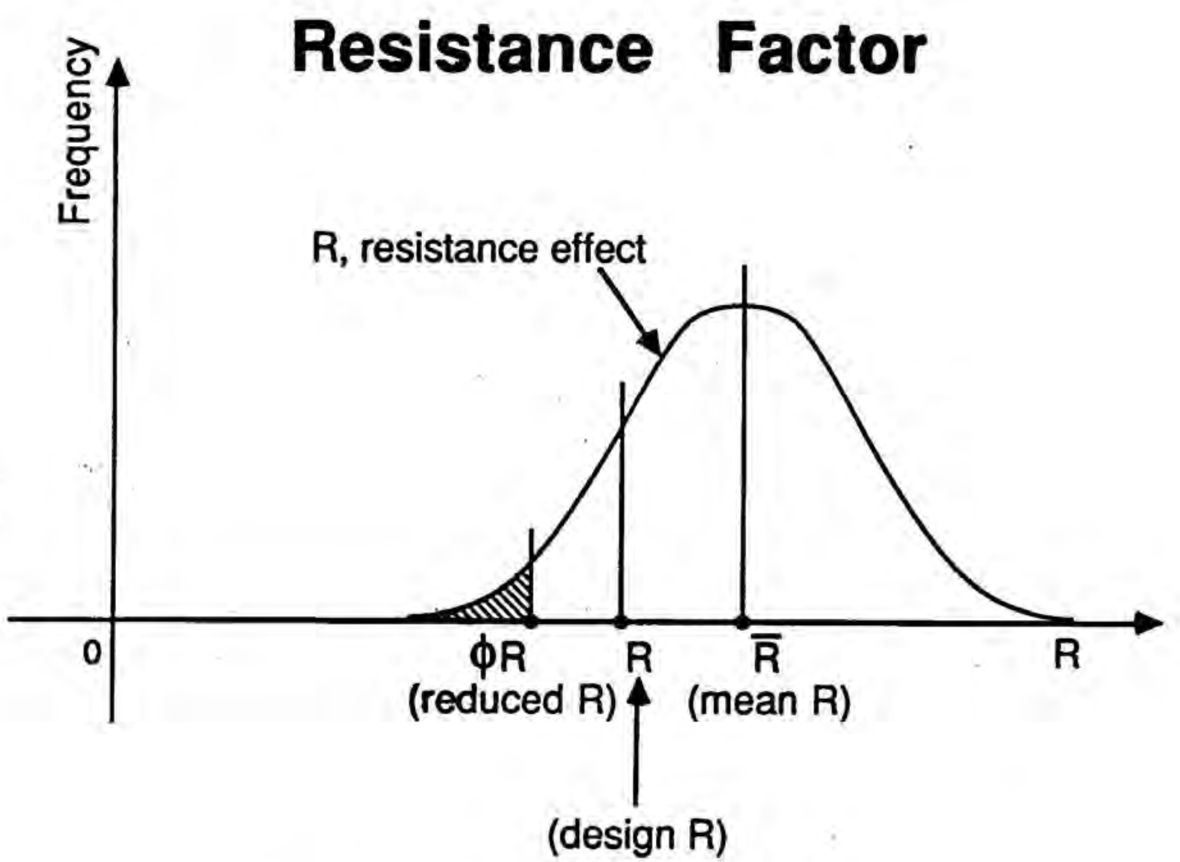
IMPORTANCE	NEW DESIGN	EXISTING	HISTORICAL
Low priority	3.0 – 3.5	2.0 -2.5	3.25 – 3.5
Medium priority	3.5 – 4.0	2.5 – 3.0	3.5 – 4.5
High priority	3.75 – 4.5	2.75 – 3.5	3.75 – 4.75

Load Factor



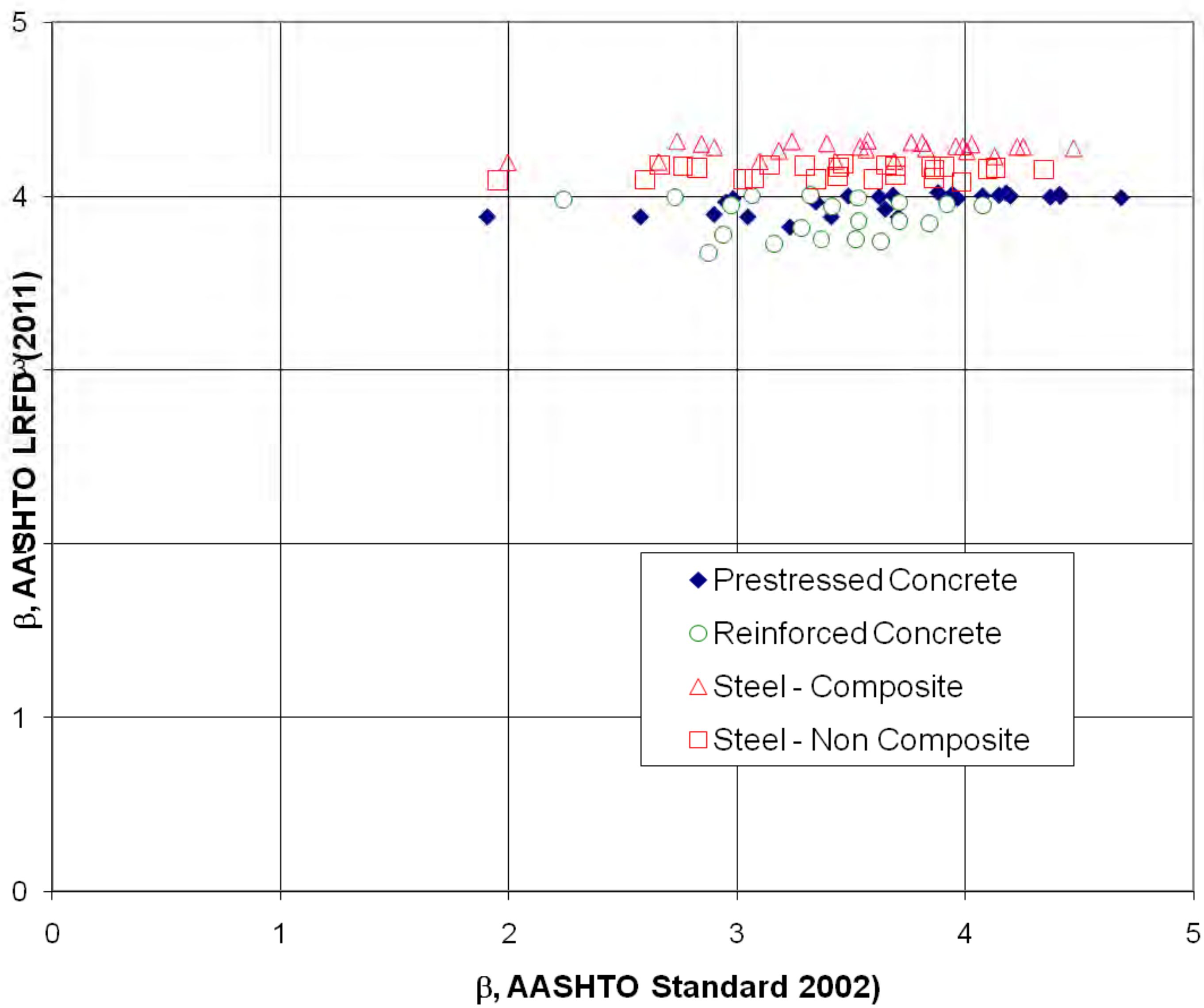
Load Factor
Frequency
Q, load effect
A_i
0
$\overline{Q}_i$
(mean load)
Q_i
$\gamma_i\, Q_i$
(factored load)
Q
(design load)

Resistance Factor

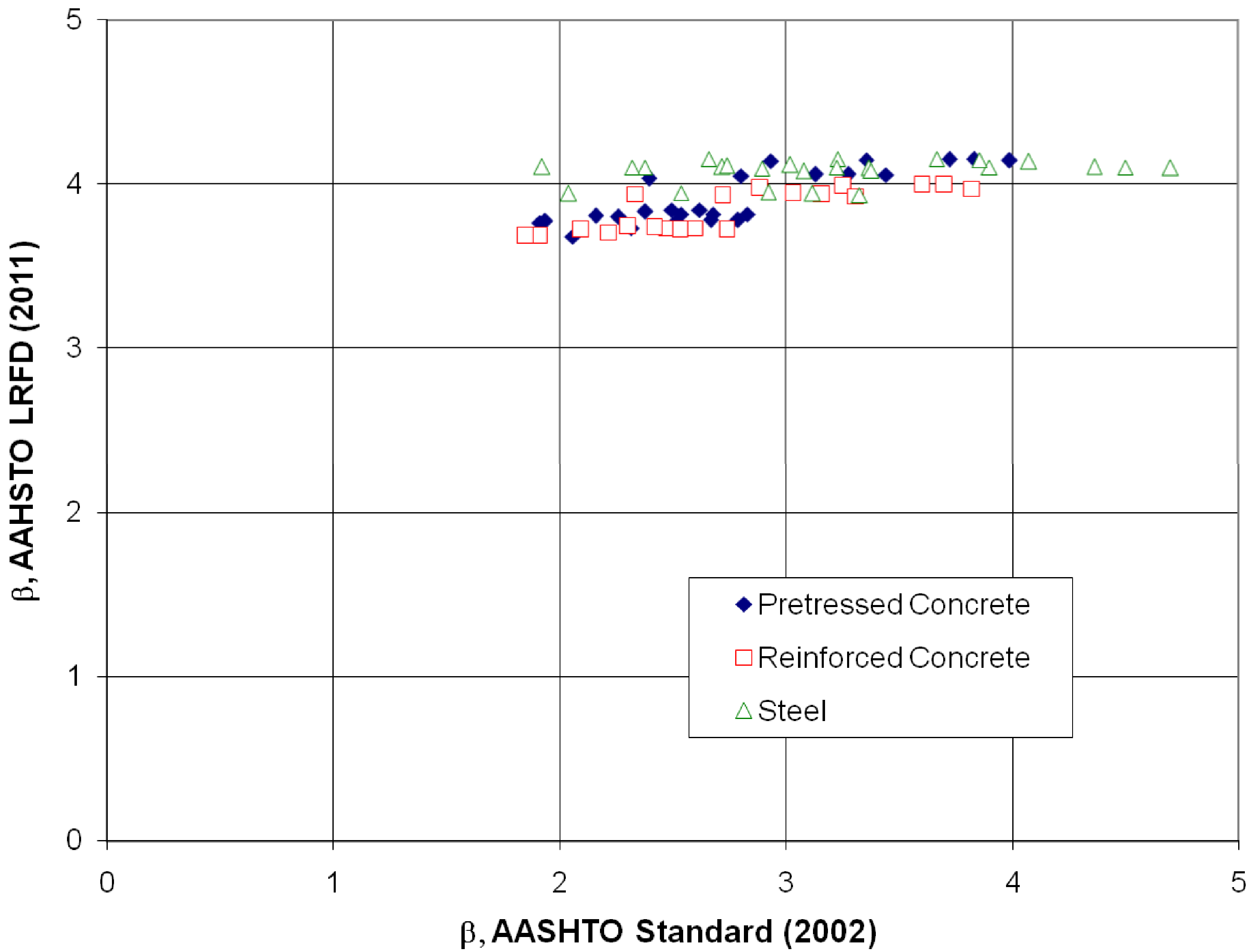


ϕ is calibrated to get $\beta = \beta_T$

Nebi UNI



Reliability Indices for AASHTO (2002) and AAHSTO LRFD (2011) - Moment



<u>Reliability Index for AASHTO (2002) and AASHTO LRFD (2011) -Shear</u>

Conclusions

- Prior to calibration, there is a considerable spread of reliability indices. After calibration, the reliability indices are close to the target value
- Limit state design or LRFD codes provide for a consistent reliability level
- The format is flexible, and it can be used for new structural types, new materials
- Improved quality can be reflected in increased resistance factors and reduced load factors

Thank you