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MCEER
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THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING

BRIDGE ENGINEERING PROGRAM

Distinguished Speaker Series

Sustainable Development in Bridge Engineering: Development of Multi-Hazard Design Guidelines

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Quotation

"Sustainability is a condition of existence which enables the present generation of humans and other species to enjoy social well being, a vibrant economy, and a healthy environment, and to experience fulfillment, beauty and joy, without compromising the ability of future generations of humans and other species to enjoy the same."

Sir George Porter August 26, 1973

Quotation

"Achieving sustainable development is perhaps one of the most difficult and one of the most pressing goals we face. It requires on the part of all of us commitment, action, partnerships and, sometimes, sacrifices of our traditional life pattern and personal interests."

Abraham Lincoln, 1864

Sustainable Development in Bridge Engineering: Development of Multi-Hazard Design Guidelines

Role of structural engineering in sustainable development is illustrated by an example of bridge engineering research project.

Outline

1. Introduction
2. Structural Design of Bridges in US
3. Development of Multi-Hazard LRFD
   – Progress Report
4. Summary

Introduction

Sustainability – An Emerging Multidisciplinary Field

- **A emerging field in science and engineering**
- **To achieve reasonable balance among economic, environmental and societal objectives**
- **A significant component of sustainable development is "EDUCATION".**

Introduction (contd)

Sustainability and Structural Engineering

- **Structural Engineering Emphases**
  - Safety
  - Serviceability
  - Cost
  - Other
- **Sustainability Emphases (examples)**
  - Environment/ecosystems quality
  - Natural resources conservation
  - Integrated consideration of present and future
  - Other

Introduction (contd)

Sustainability and Structural Engineering

- **Energy Consumption in US**
  - Buildings 40%
  - Industry 32%
  - Transportation 28%
- **Construction Waste:**

  More than 50% is concrete.
- **Issues in Design Codes**
  - Many "over-conservative" features
  - Some "unsafe" features

Issues Involving Structural Design

Demand ≤ Capacity

- **"Demand" involves all types of long term and short term load effects.**
- **"Capacity" involves materials, analysis methods, failure modes, life cycle cost and sustainability issues (e.g. reuse, retrofit and reuse, recycle, construction methods, energy, environmental quality, etc.)**
- **Sustainable design requires holistic consideration.**

Issues Involving Structural Design

Demand ≤ Capacity

- How to set reasonable level of demand, especially on extreme hazard load effects?
- How to design a structure that fails at a load level just exceeds the “demand” ?
- Is “no collapse” a reasonable seismic design criterion from the sustainability perspective?

Structural Design of Bridges in US

- **Load and Resistance Factors Design (LRFD) approach calibrated for non-extreme loads**
- **Individual design guidelines for various extreme hazard loads under development**
- **Recent MCEER initiative to develop all-hazard LRFD to achieve fully reliability-based design guidelines**

Load and Resistance Factors Design (LRFD)

- Current LRFD specifications for basic bridge structural components (5th Edition 2010) was initially adopted by American Association of Highway and Transportation Officials (AASHTO) in 1994.
- Fully calibrated for dead load and live load only
- Since then development of LRFD for other aspects of bridge systems have been initiated.

Significance of AASHTO LRFD

- **ASD (LFD) and LRFD have virtually identical design limit state equation based on load intensities.**

$$\phi R > \Sigma \gamma_i Q_i$$

where R = resistance, ϕ = resistance factor

Q_i = loads, γ_i = load factors

Significance of AASHTO LRFD (contd)

- LRFD provides additional information on failure probability for more rational decision making.

$$p_{failure} = P\,(\,\phi R \leq \Sigma \gamma_i Q_i)$$

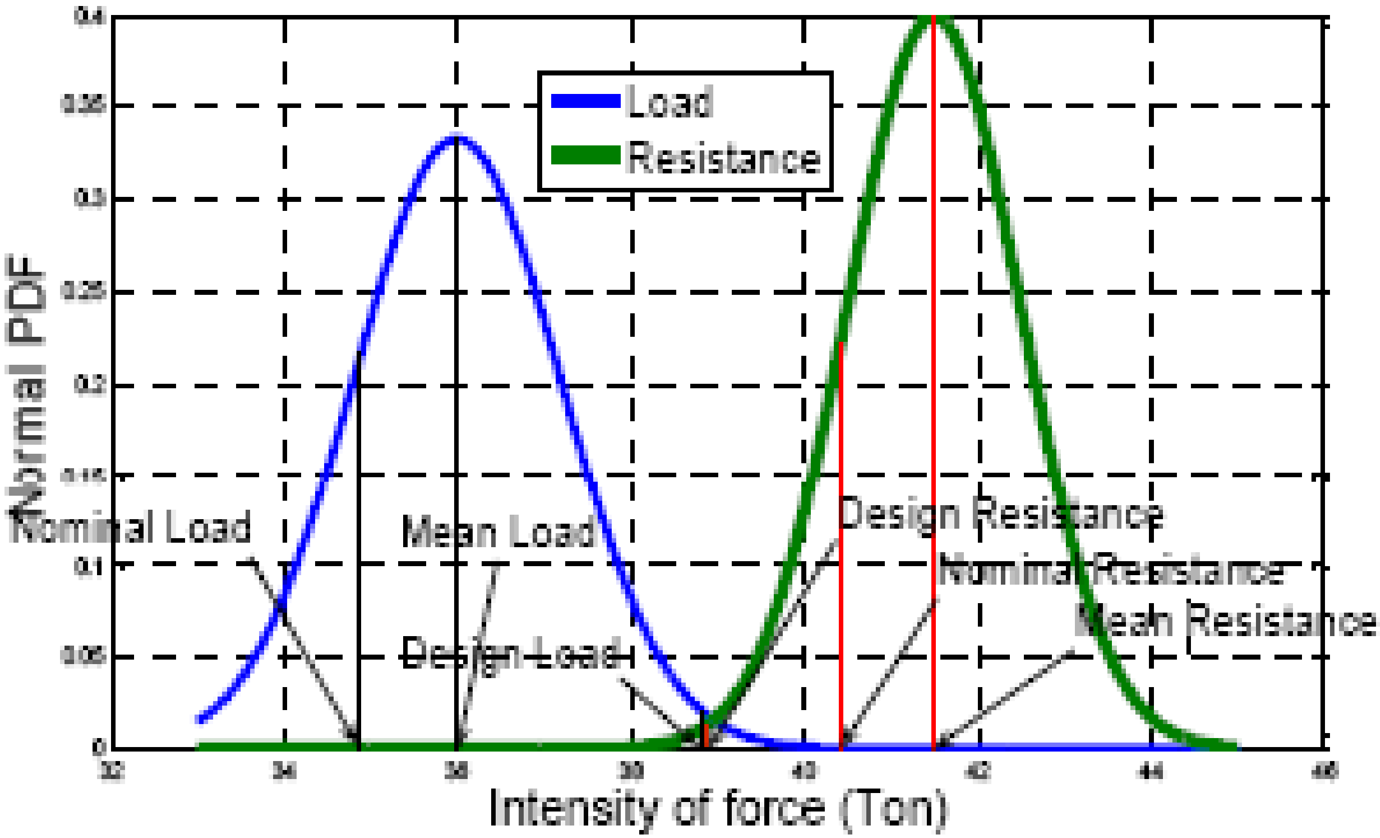
where

$p_{failure}$ = probability of failure

Structural Design of Bridges in US (contd)

LRFD (contd)

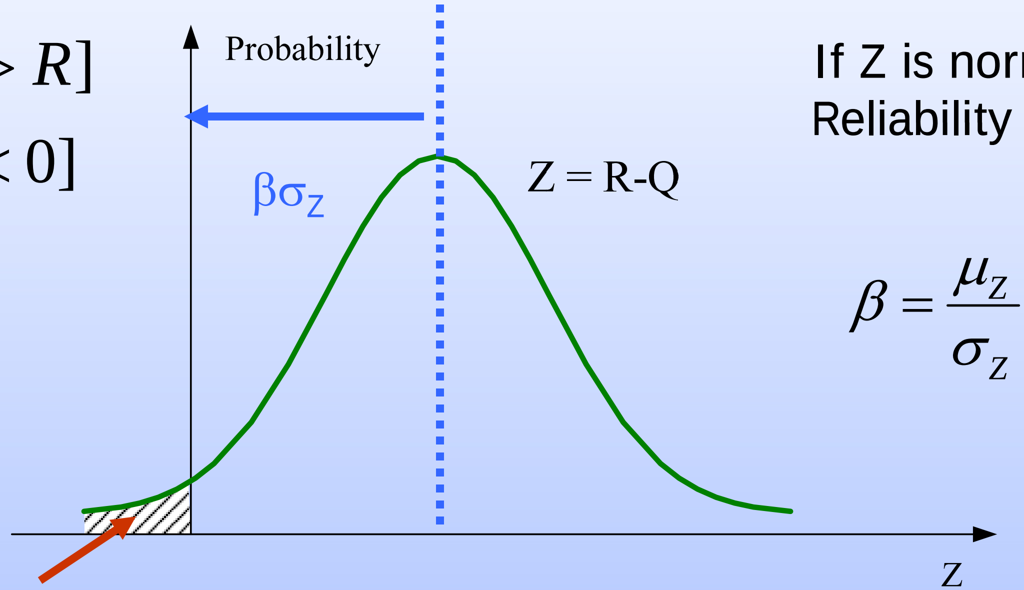
Probability Distribution of Load and Resistance



Load and Resistance Factors Design (LRFD) (contd)

- **Limit state function Z = R – Q**
- **Failure occurs when Q > R**

$$P_F = P[Q > R]$$
$$= P[Z < 0]$$



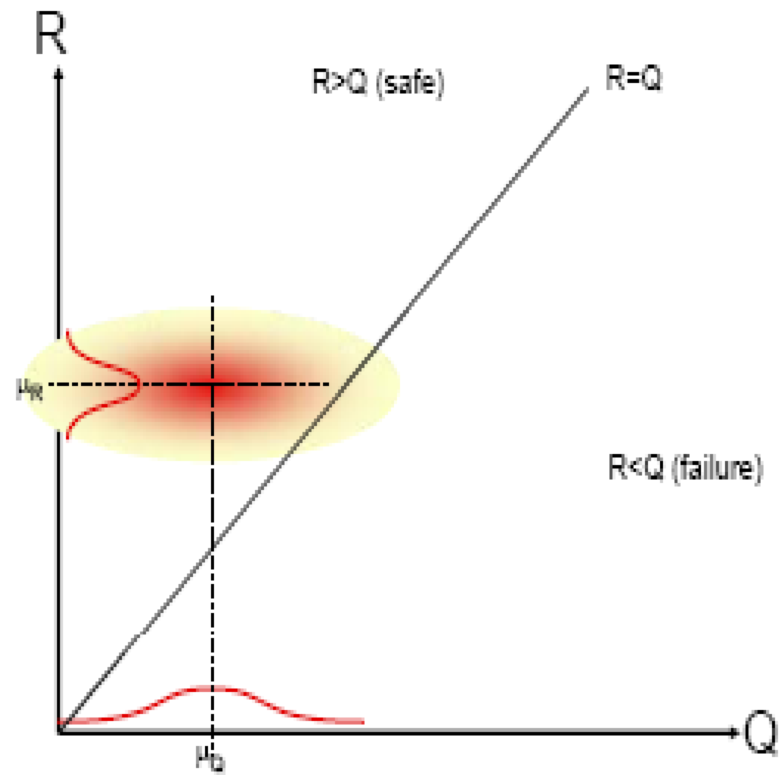
If Z is normal distribution, Reliability index β

$$\beta = \frac{\mu_Z}{\sigma_Z}$$

Load and Resistance Factors Design (LRFD) (contd)

Design limit state = Z = R – Q = 0

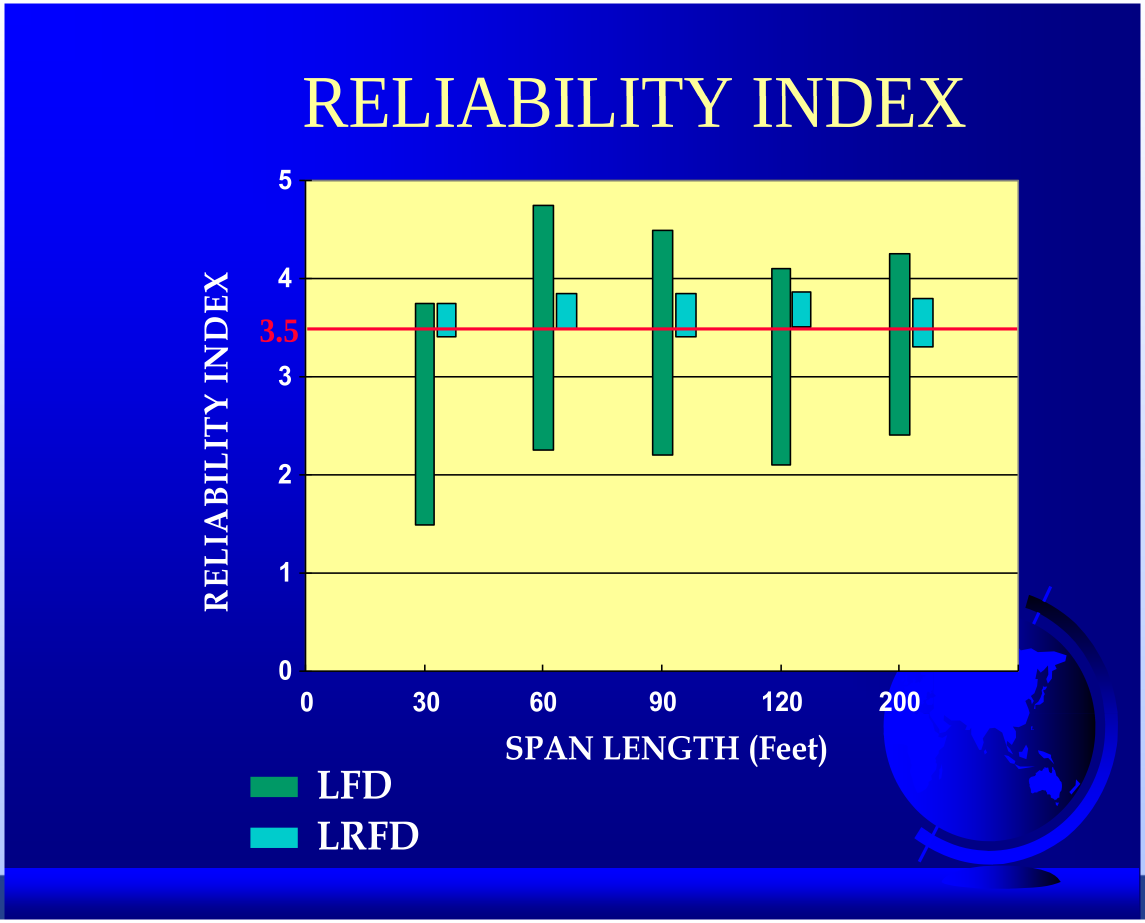
Probability distribution of Resistance and load with respect to the limit state



Structural Design of Bridges in US (contd)

LRFD (contd)

Risk and Reliability Assessment



Reliability Index and Corresponding Probability

	Prob. of exceedance	Rounded reciprocal (approx. 1-in-n)
0.1	0.4601722	2
0.5	0.3085375	3
1	0.1586553	6
1.5	0.0668072	15
2	0.0227501	50
2.5	0.0062097	200
3	0.0013499	1,000
3.5	0.0002326	5,000
4	3.167E-05	30,000
4.5	3.398E-06	300,000
5	2.867E-07	3,500,000
5.5	1.899E-08	50,000,000

Load and Resistance Factors Design (LRFD) (contd)

Reference:

Kulicki, J. M. (2005). "Past, Present and Future of Load and Resistance Factor Design", Journal of the TRB.

Current Practice of Bridge Design Against Extreme Hazard Loads

- **Various current research efforts are devoted to bridge component performance and design for individual extreme hazard load effects (e.g. earthquake, tidal waves, vessel collision, etc.)**
- **Very limited efforts to consider the combinations of extreme hazard load effects, either on the components or the bridge as a system of components.**

Structural Design of Bridges in US (contd)

Current Practice of Bridge Design (contd)

Extreme Loads in Current Design

Scour

Earthquake

Wind

Storm Surge

Vessel collision

Vehicular collision

Fire John Huseby, Caltrans

Landslide/debris flow

	Status in AASHTO LRFD
Dead Load	Calibrated
Live Load	Calibrated
Earthquake	Included (Guidespec), but not completely calibrated
Scour	Not in LRFD framework
Wind	Integrated in AASHTO LRFD strength limit state, not completely calibrated
Fire	New giudance information available from NCHRP study
Vessel Collision	Structurally consistent with LRFD, but not calibrated consistently
Vehicular Collision	Rough estimate based on limited data
Storm Surge	New Guidespec provide design procedures
Debris Flow	Provisions on debris raft (part of WA)

Recent Initiative to Develop Reliability Based, All- Hazard LRFD

- **Many bridge failures due to various extreme hazard events in recent years**
- **Multi-hazard design research project initiated at MCEER in 2008, funded by FHWA**
- **To establish guiding principles for the development of multi-hazard LRFD with emphasis given to "design limit states" for collapse failures due to combinations of non-extreme and extreme loads ("Demand" emphasis)**

Significant Challenge of Developing MH-LRFD

Demand	≤	Capacity
To establish reliable, simple, all-hazard design limit status considering non-extreme and extreme loads.		To design structures with predictable behavior for highly unpredictable hazard load effects.

MCEER Research Project

- Develop design principles and framework for MH-LRFD design limit states
- Establish selected design limit state equations as examples
- Work closely with AASHTO – T5, FHWA and experienced design professionals

Some Project Challenges

- Extreme hazard events are mostly random processes.
- Methodology to relate and combine the probability distribution functions of bridge failures due to two or more extreme load effects
- Very limited data on bridge failures due to extreme events for purpose of calibration
- Outcome must be simple to use.

Some Project Challenges (contd)

Two (or more) extreme load

$$p_{failure} = P\ (\ \phi R \leq \Sigma\gamma_i Q_i)$$

Probability distribution of R – developed for LRFD

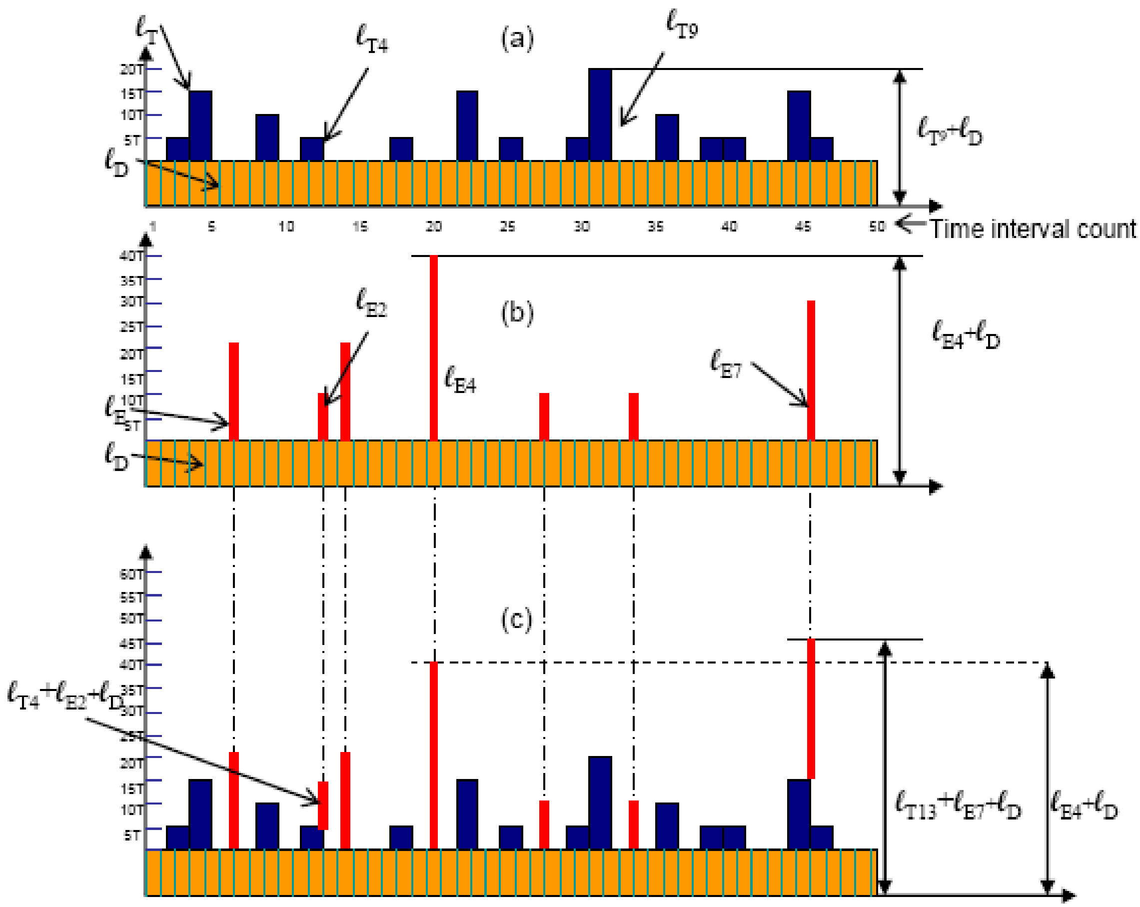
Example: Consider

D (dead load), T (truck load) and E (earthquake load)

$$P_f = f\ [\ P_D, P_T, P_E\ ]$$

Development of Multi-Hazard LRFD (contd)

Load Combinations



Example of TL and EL Combinations

DL: Normal distribution.

Nominal super-structural mass is 600 ton. (not used in this example)

TL: Triangular distribution.

- Max truck mass = 30 ton.
- Min truck mass = 1.0 ton.
- Max number of trucks passing through the bridge in 10 seconds is 8.

EL: Vertical component = lognamal distribution in 75 year period.

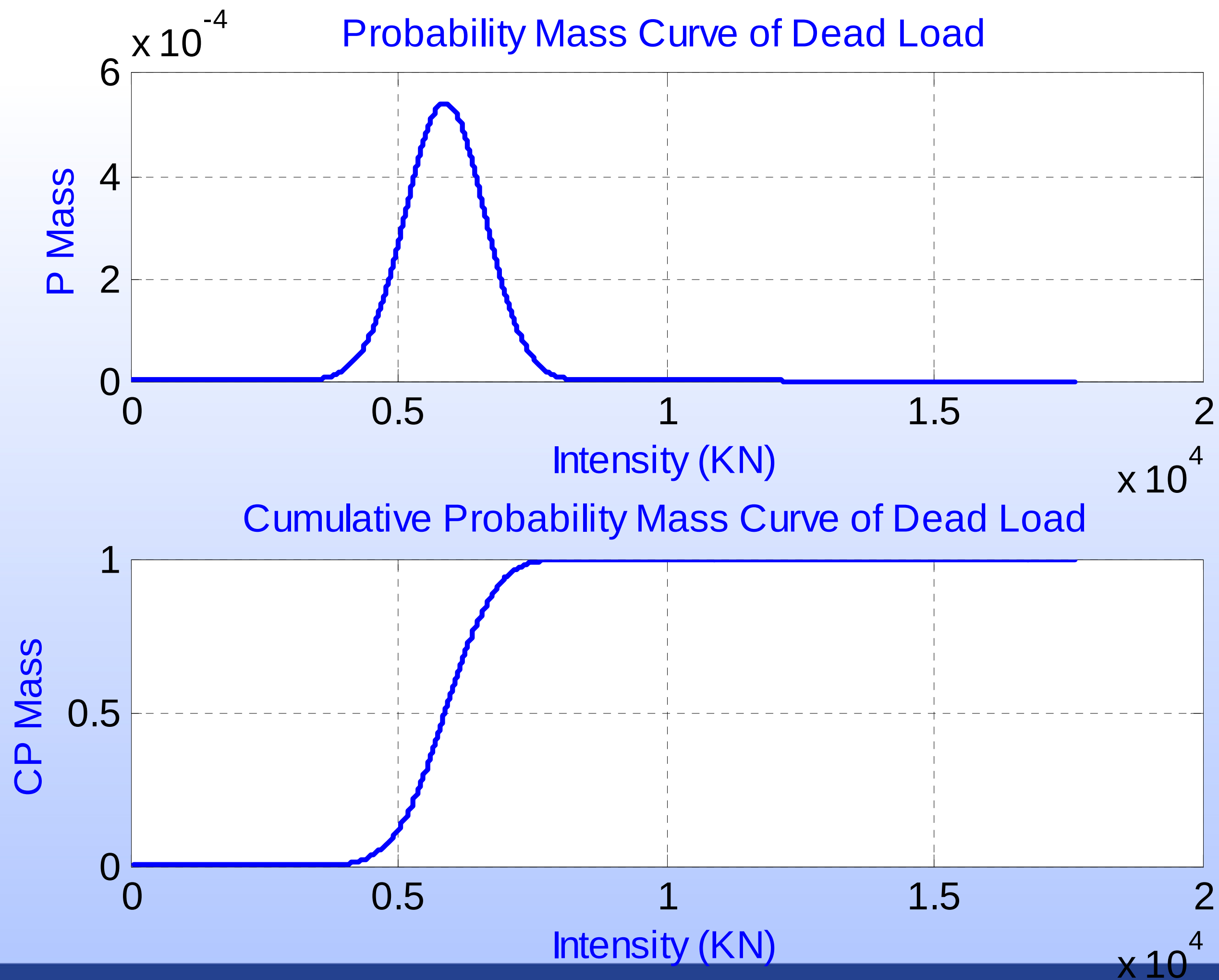
Example of TL and EL Combinations

Definitions:

- CP = Cumulative probability
- EDT = Event time interval (seconds)
- TSS = Total service life of bridge in seconds
- TSY = Total service life of bridge in years
- Earth Direct = Max. possible EL in TSY

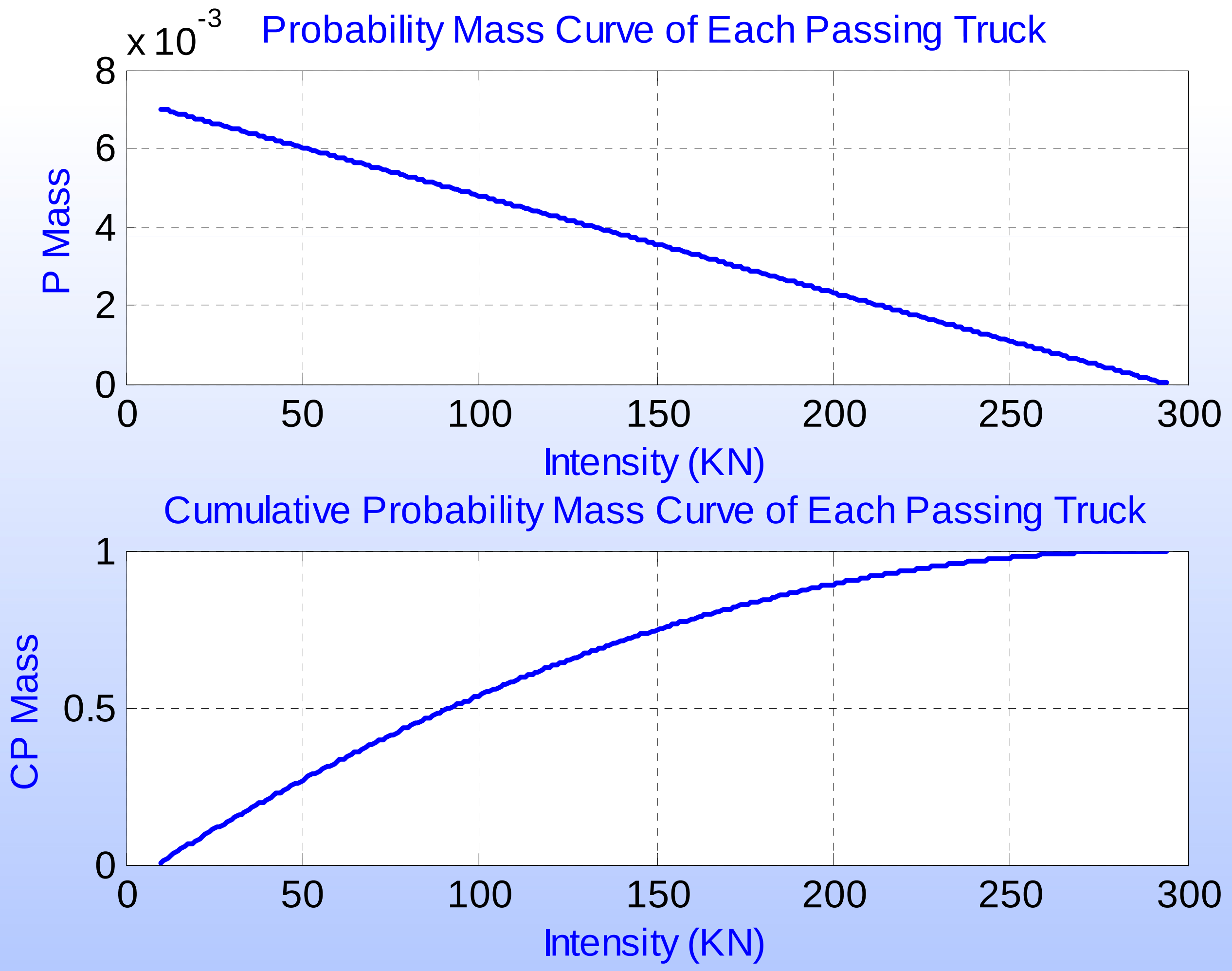
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



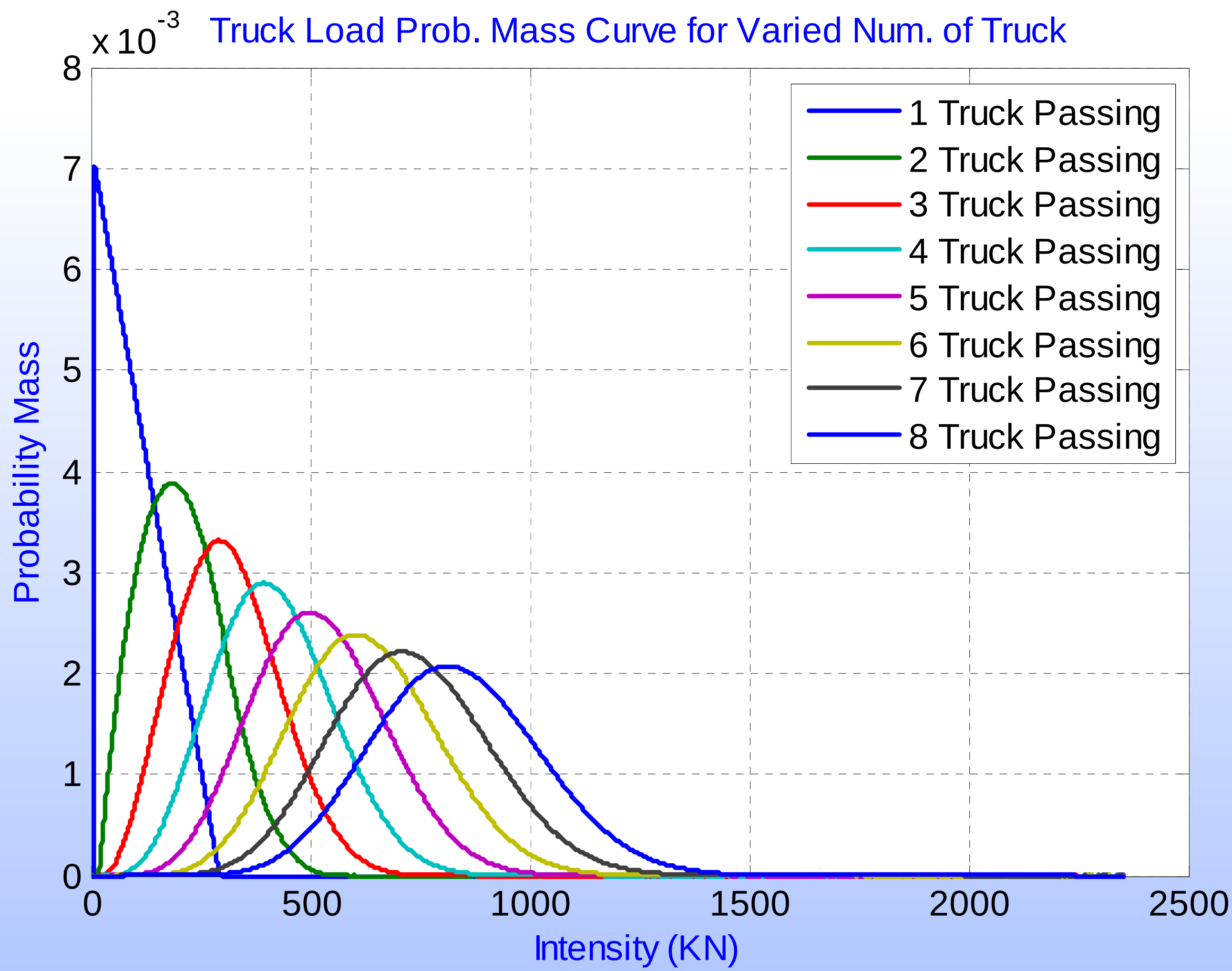
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



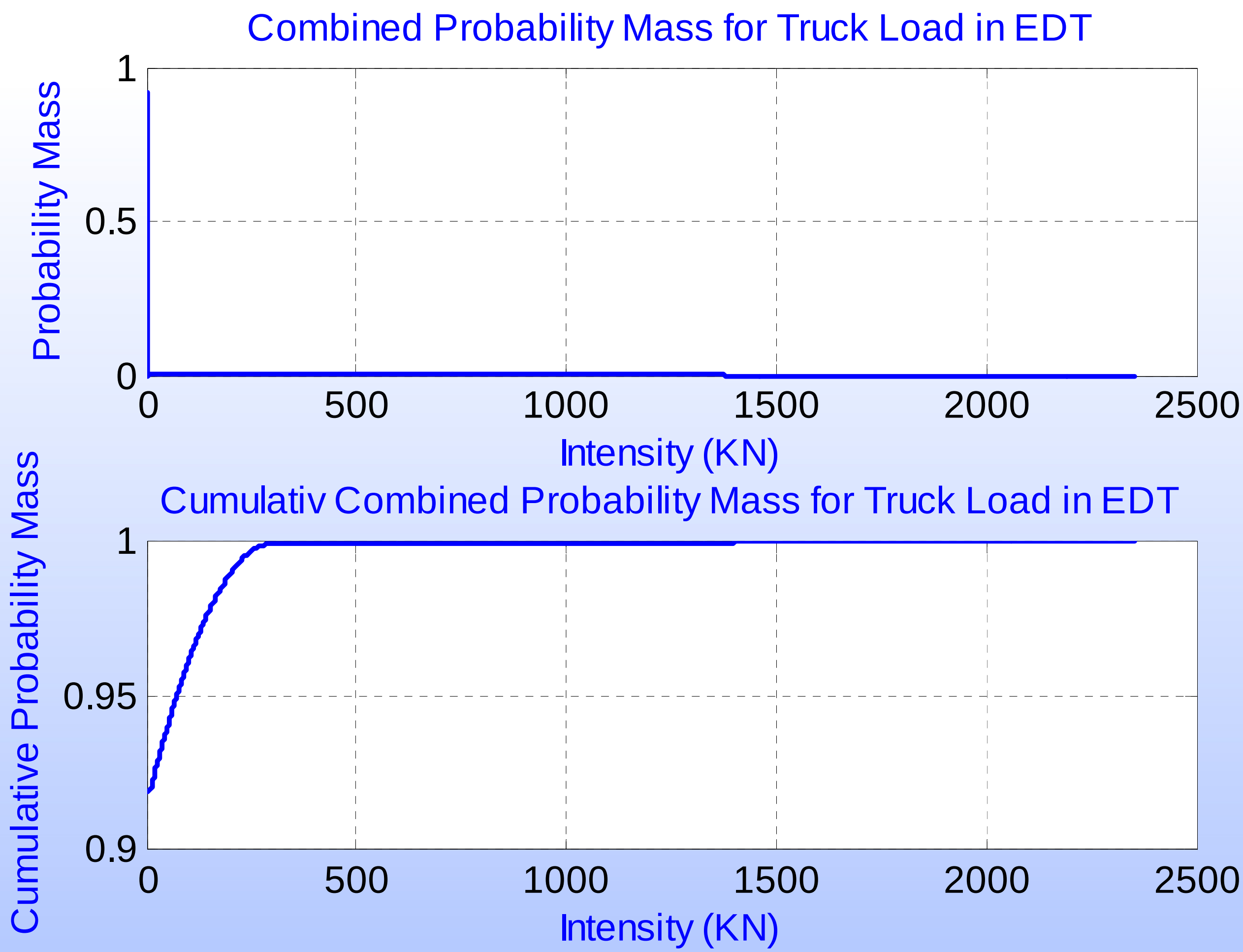
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



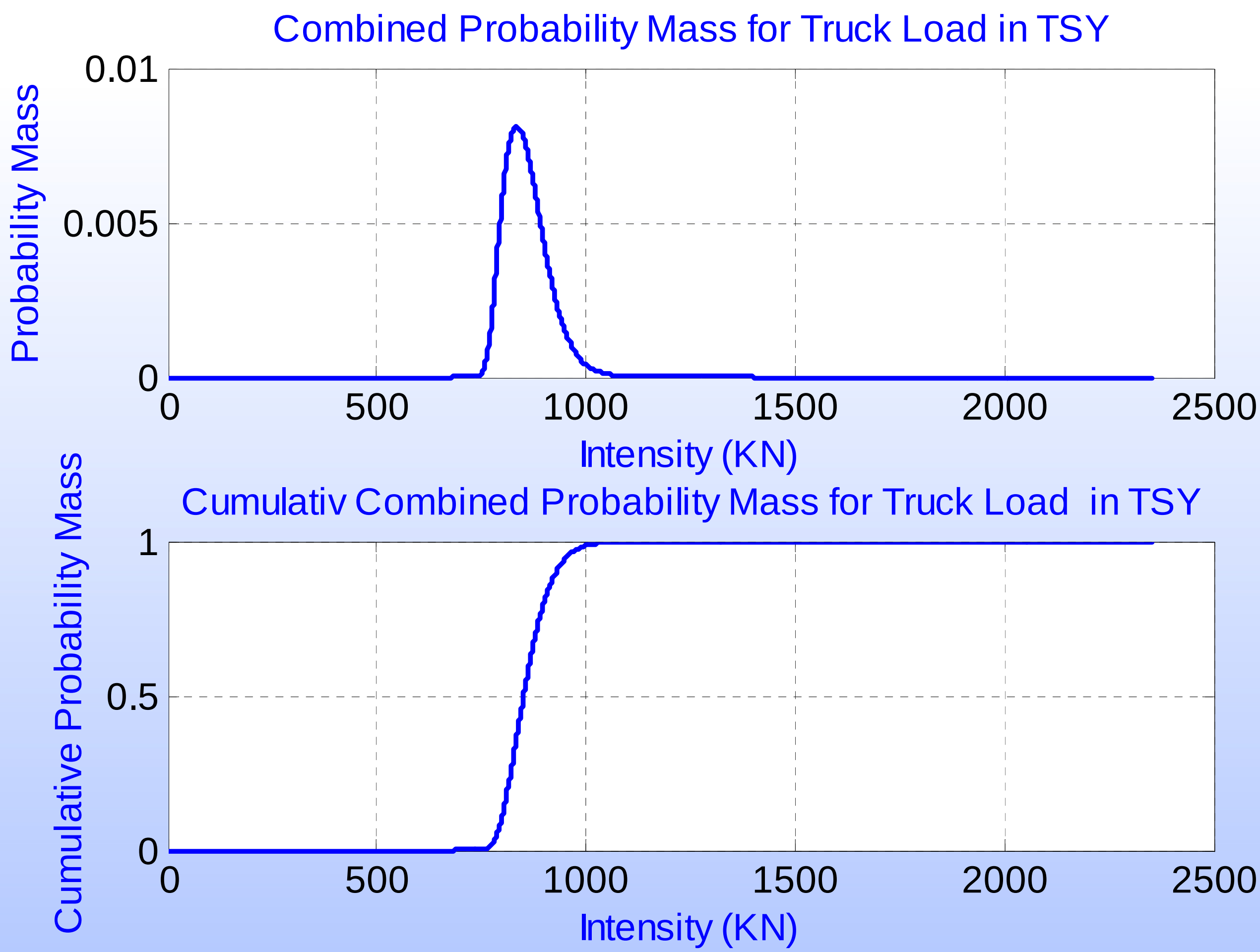
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



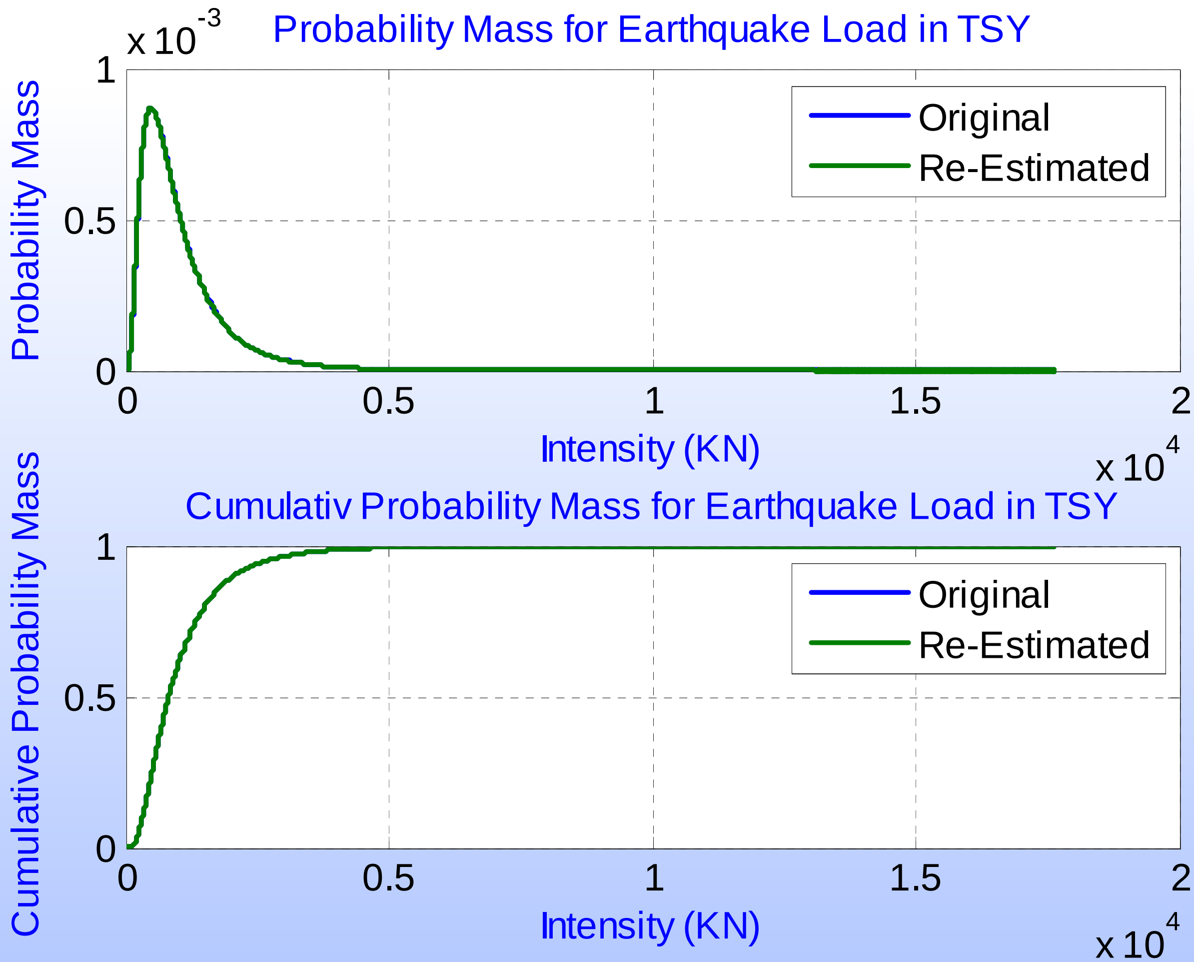
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



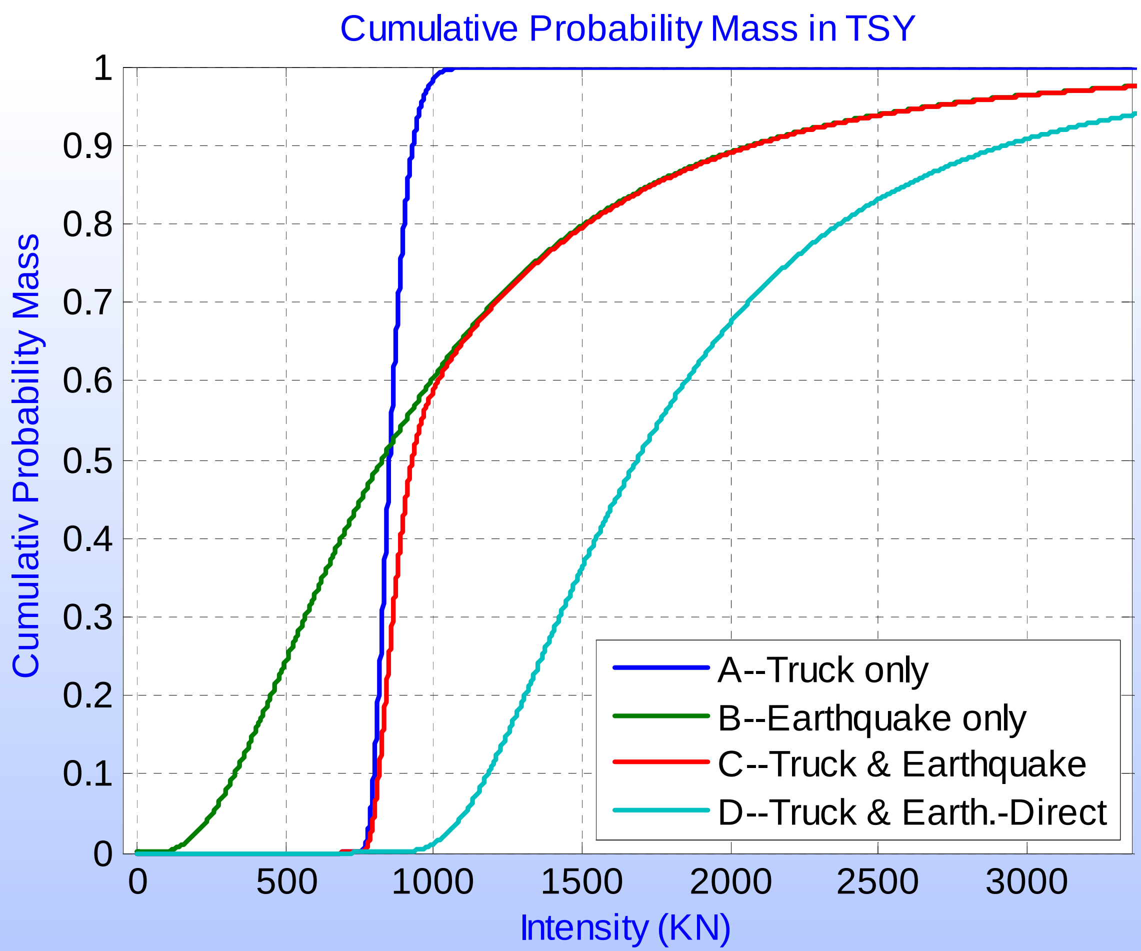
Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



Development of Multi-Hazard LRFD (contd)

Example of TL and EL Combinations (contd)



Progress Report

- **A major challenge in establishing multi-hazard LRFD equations is to provide a "simple" process for the bridge designers.**
- **One important task is to identify "significant" design limit status for a region vulnerable to multiple hazard threat to that region.**
- **A workshop was carried out for this purpose.**
- **Workshop Steering Committee: Harry Capers, John Kulicki, Thomas Murphy (Chair), George Lee (coordinator), W. Philip Yen**

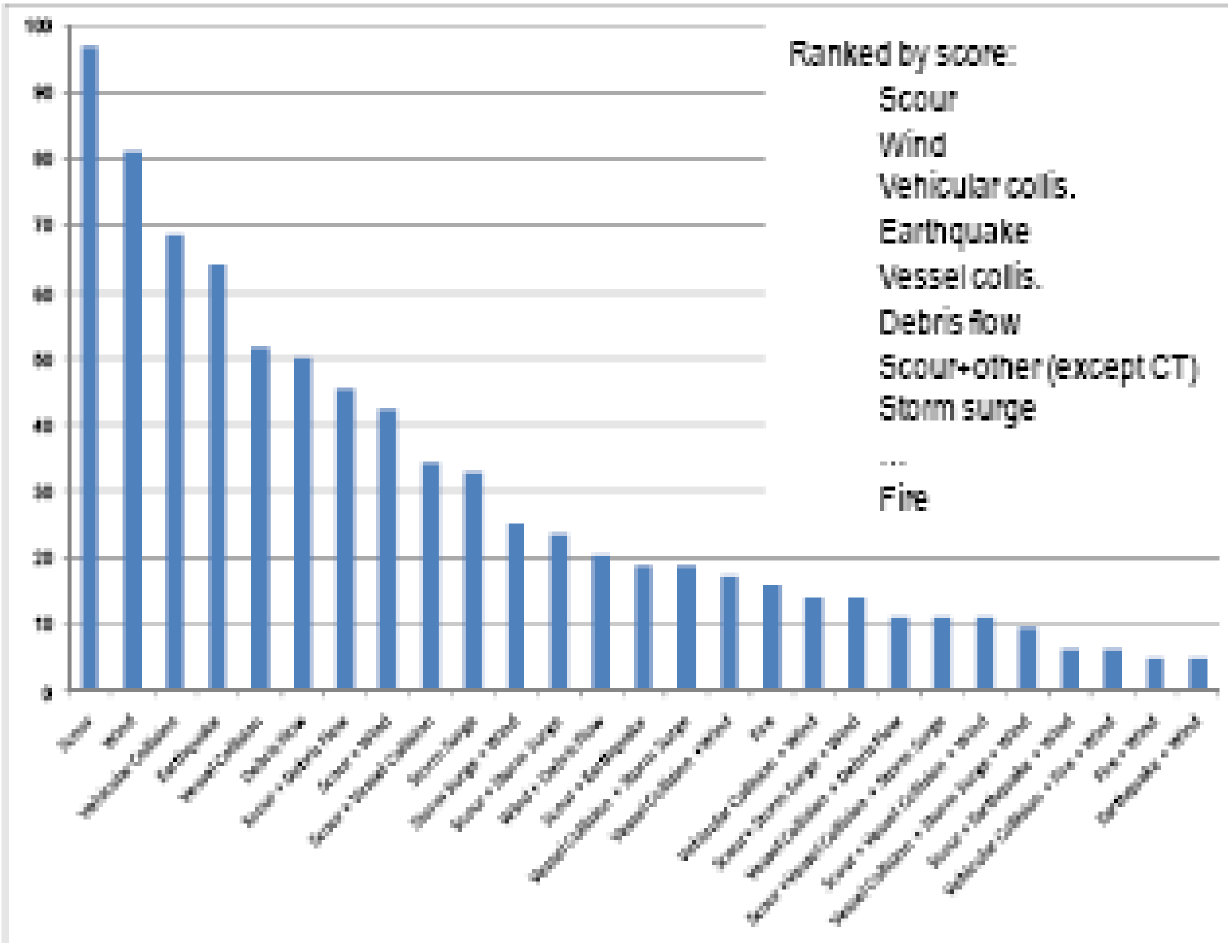
Progress Report (contd)

- **Questionnaire to all AASHTO bridge engineers for their opinion (for both typical bridges and special bridges)**
- **Followed by workshop participated by AASHTO bridge engineers, FHWA officials, bridge design experts and academic researchers to consider the survey results.**
- **Formulate regional design limit states in the US (work in progress).**

Progress Report (contd)

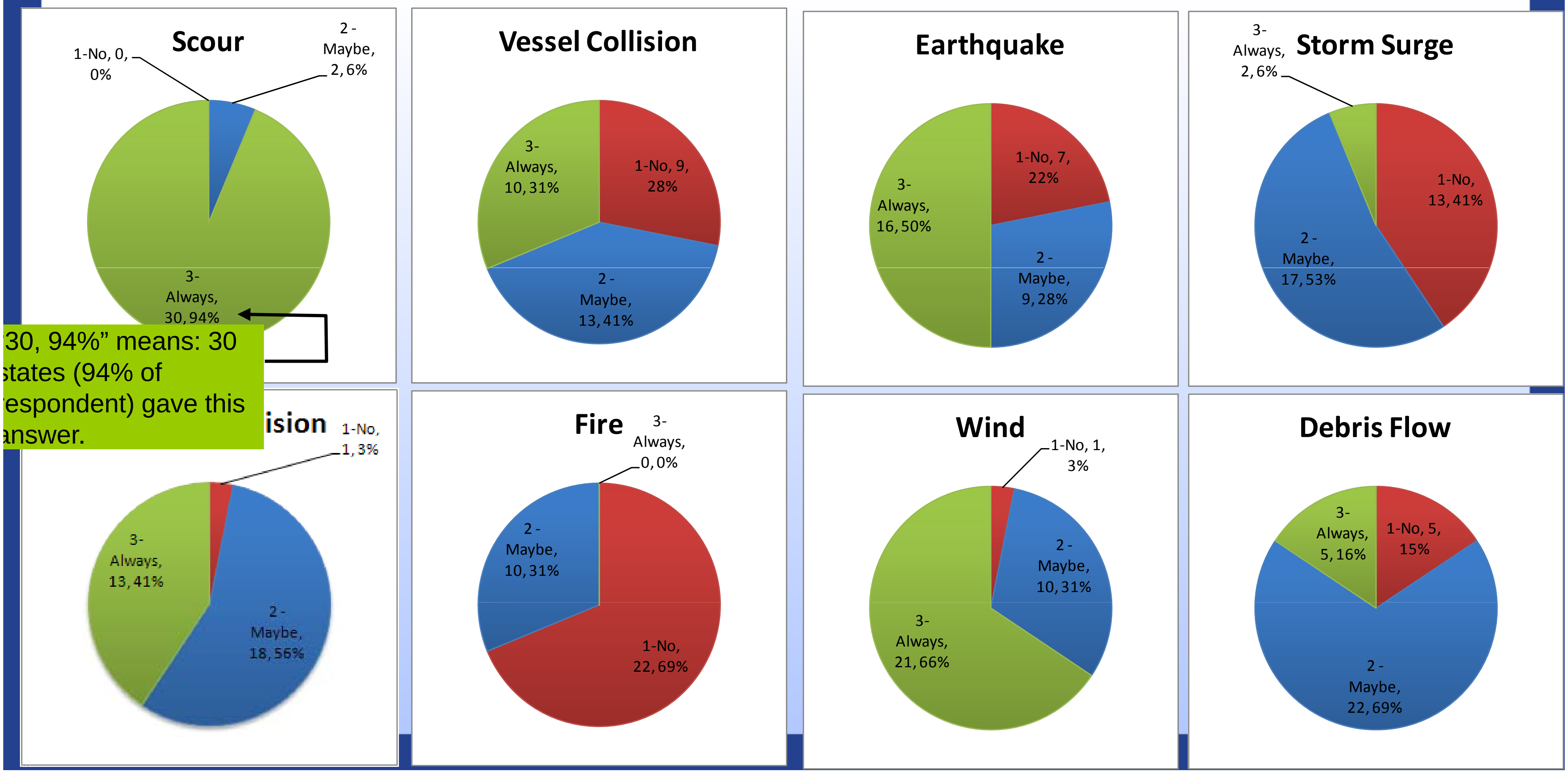
Sample Survey Results and Preliminary Messages

Rankings for Extreme Loads (standard bridges)



Development of Multi-Hazard LRFD (contd)

Pie Charts – Typical Bridges

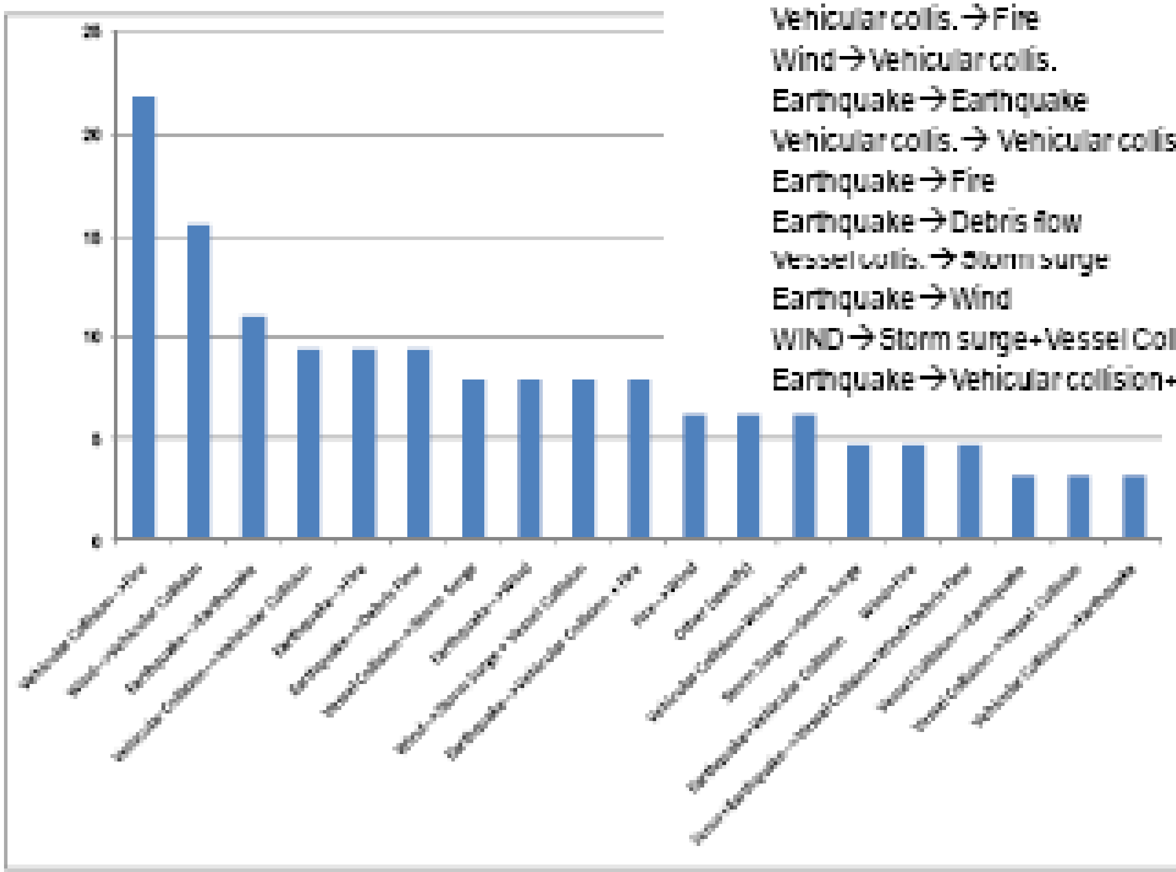


Development of Multi-Hazard LRFD (contd)

Average Scores for Cascading Events (standard bridges)

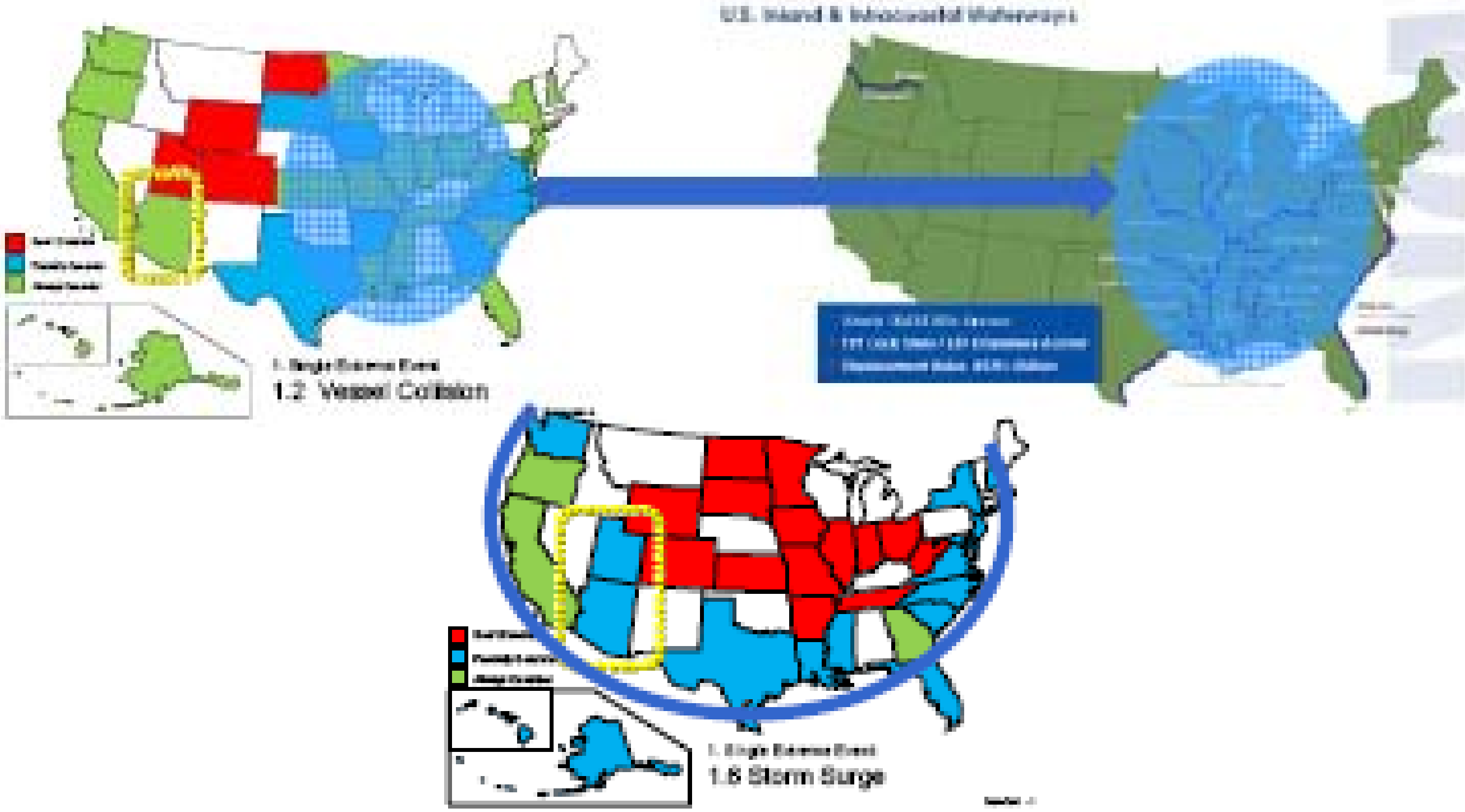
Ranked by score:

- Vehicular collis.→Fire
- Wind→Vehicular collis.
- Earthquake→Earthquake
- Vehicular collis.→ Vehicular collis.
- Earthquake→Fire
- Earthquake→Debris flow
- Vessel collis.→Storm surge
- Earthquake→Wind
- WIND→Storm surge+Vessel Collision
- Earthquake→Vehicular collision+Fire

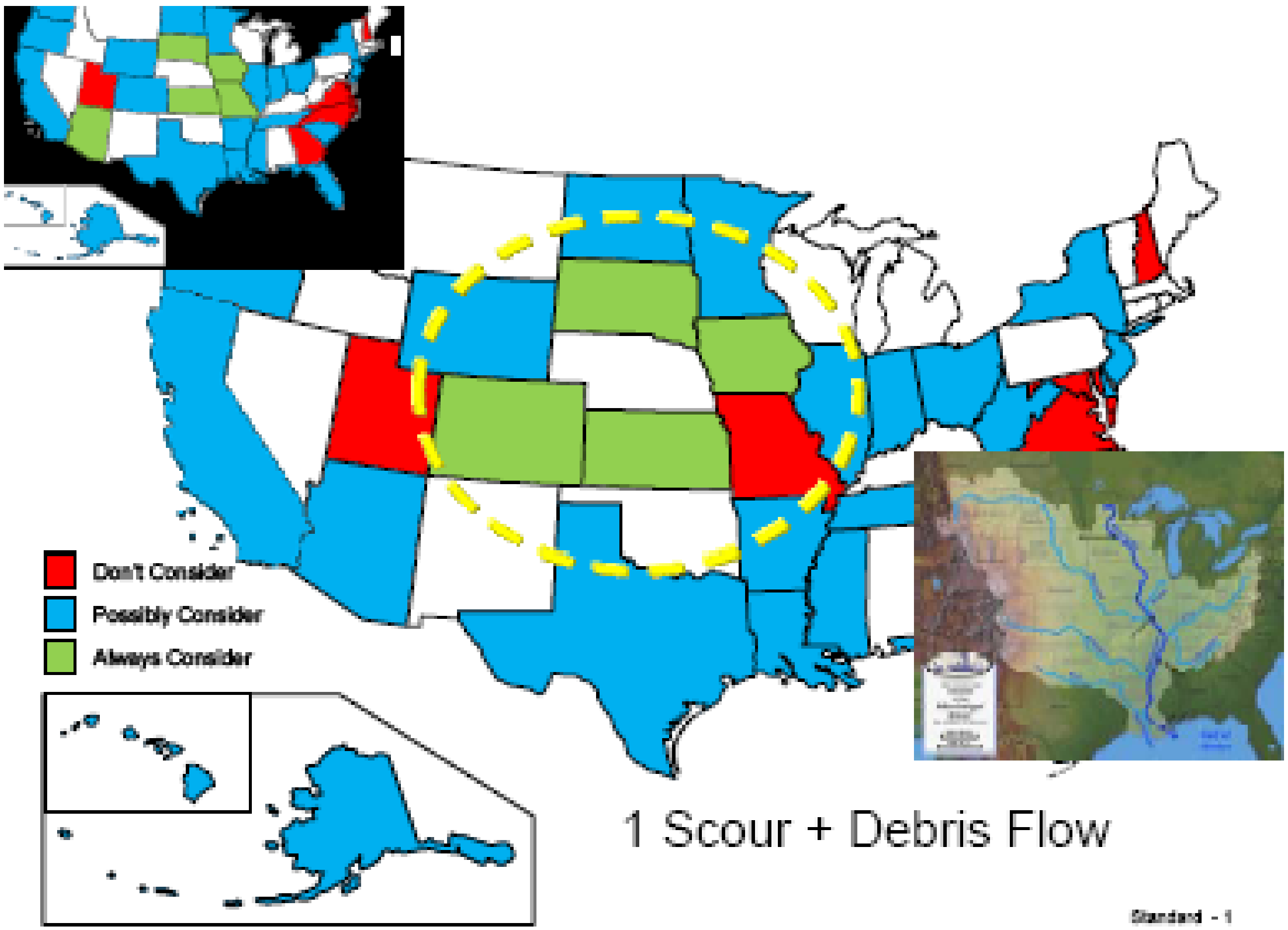


Development of Multi-Hazard LRFD (contd)

Regional Character: Navigable Waterways and Coastlines



Combination of Scour and Debris Flow



Potential Regional Simplification

- **To make it practical in design using the large set of limit states, a procedure to choose dominant limit states by region may be developed.**

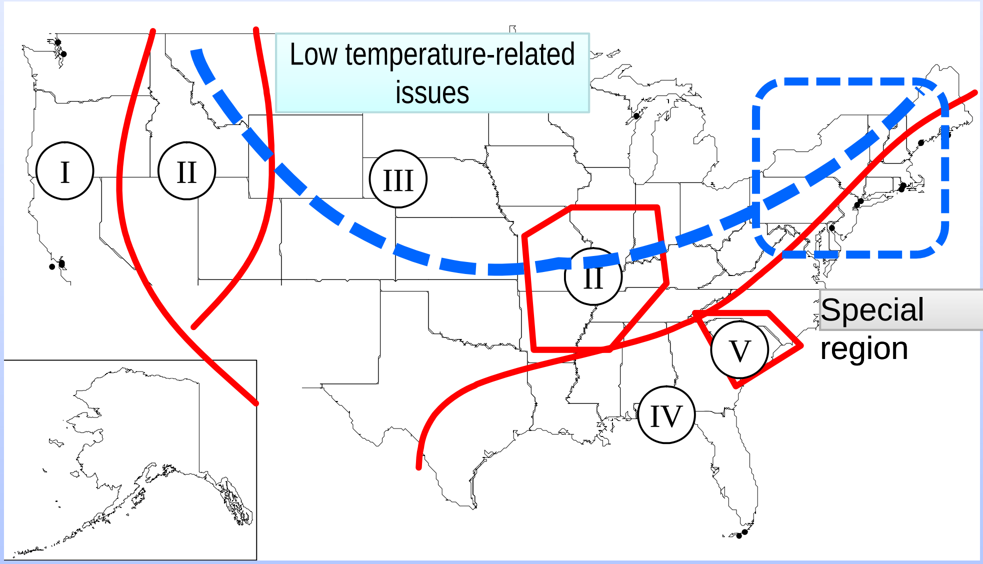
I: High seismicity, non-hurricane coastal wind

II: Long-term high seismicity, Inland wind

III: Inland wind

IV: Hurricane zone

V: Long-term high seismicity, hurricane zone



Potential Hazards in Each Region

- **Region I:**
  Earthquake, non-extreme wind, scour, fire, and vehicular collision. Vessel collision is possible in some area.
- **Region II:**
  Earthquake (long-term), non-extreme wind, scour, fire, and vehicular collision.
- **Region III:**
  Non-extreme wind, scour, fire, and vehicular collision, and vessel collision. Northern central plain: debris flow (ice)
- **Region IV:**
  Extreme wind (hurricane), scour, fire, and vehicular collision, and vessel collision.
- **Region V:**
  Earthquake (long-term), extreme wind, scour, fire, and vehicular collision, and vessel collision.
- **Special Region (NY, NJ, NH, DE, CA, …):**
  Earthquake, non-extreme wind, scour, fire, vehicular collision, vessel collision, and blast.

Preliminary Messages

- Geographical features and natural hazards are substantiated.
- Importance of cascading events for which our knowledge for design is extremely limited.
- Unique features for NE and CA corridors with high population density (strong emphasis on consequence)
- Significant limit-state equations may be formulated for several regions.

Next Step:

- Continue to address the major challenges for the development of MH-LRFD.
- Continue to refine the "regional" design concept and to establish a selected sets of design limit state equations.
- Workshop involving AASHTO, FHWA and design professionals to establish the values of the coefficients in the selected sets of design limit state equations.

Summary

- To establish the LRFD guidelines for all-hazard resilient, sustainable bridges is complex and intellectually challenging.
- Requires "sustained development" by multidisciplinary team research efforts.
- Requires sustained education effort to develop "new generation engineers" and "well-informed public."

Summary (contd)

- **This lecture is only intended to provide information on "emerging technology in bridge engineering" under early stage of development to the students, as an example of sustainable development in bridge engineering.**
- **The description of developing regional design limit states of combined hazards is research currently in progress. The final outcome may be different.**

Acknowledgement

- Federal Highway Administration (funding)
- Project Research Team Organizations

  Aurora & Associates, FHWA,
  University at Buffalo, UC Irvine

- UB Research Team

  Dr. Z. Liang, Dr. J. W. Song, visiting
  scholars and graduate students

Thank you

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Review Questions

1. **Why should bridge design include all hazards in order to satisfy "sustainability" in bridge engineering?**
2. **Why is "Education" a significant component in sustainable development?**
3. **Why are some aspects of current design specifications "too safe"?**
4. **Do we know how to design a bridge with a capacity equal to or slightly over the limit states?**
5. **What is the major difference between "Allowable Stress Design" (ASD) and "Load and Resistance Factors Design" (LRFD)?**
6. **Probability (reliability) based formulation provides answers in probabilitic terms. Design specifications are given as deterministic limit state equations. How did this happen?**