Bridge Assessment Beyond the AS5100 Deterministic Methodology

30 April 2020

Austroads

Today's moderator

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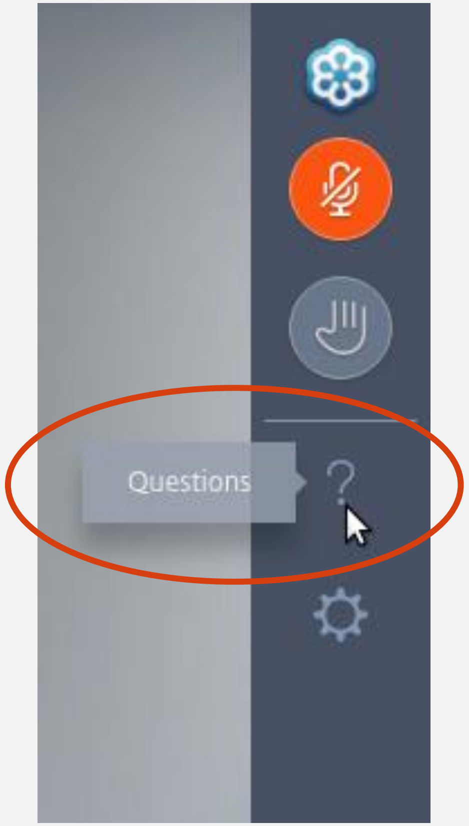

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Austroads acknowledges and respects the Treaty of Waitangi and Maori as the original people of New Zealand.

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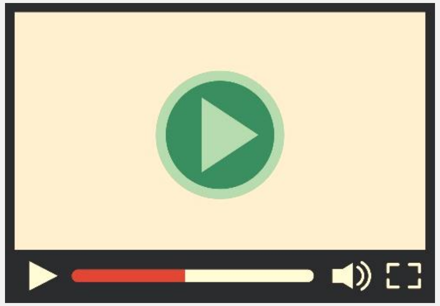
Presentation = 40 mins

Question time = 15 mins



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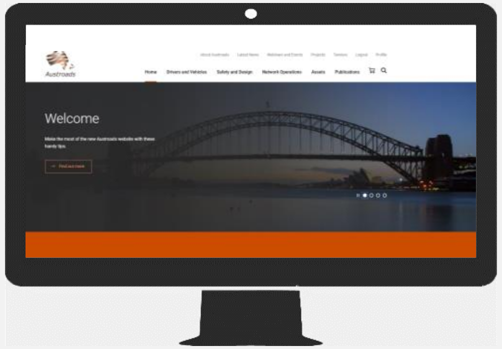

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- Department of Planning, Transport and Infrastructure South Australia
- Department of State Growth Tasmania
- Department Infrastructure, Transport, Regional Development and Communications Northern Territory
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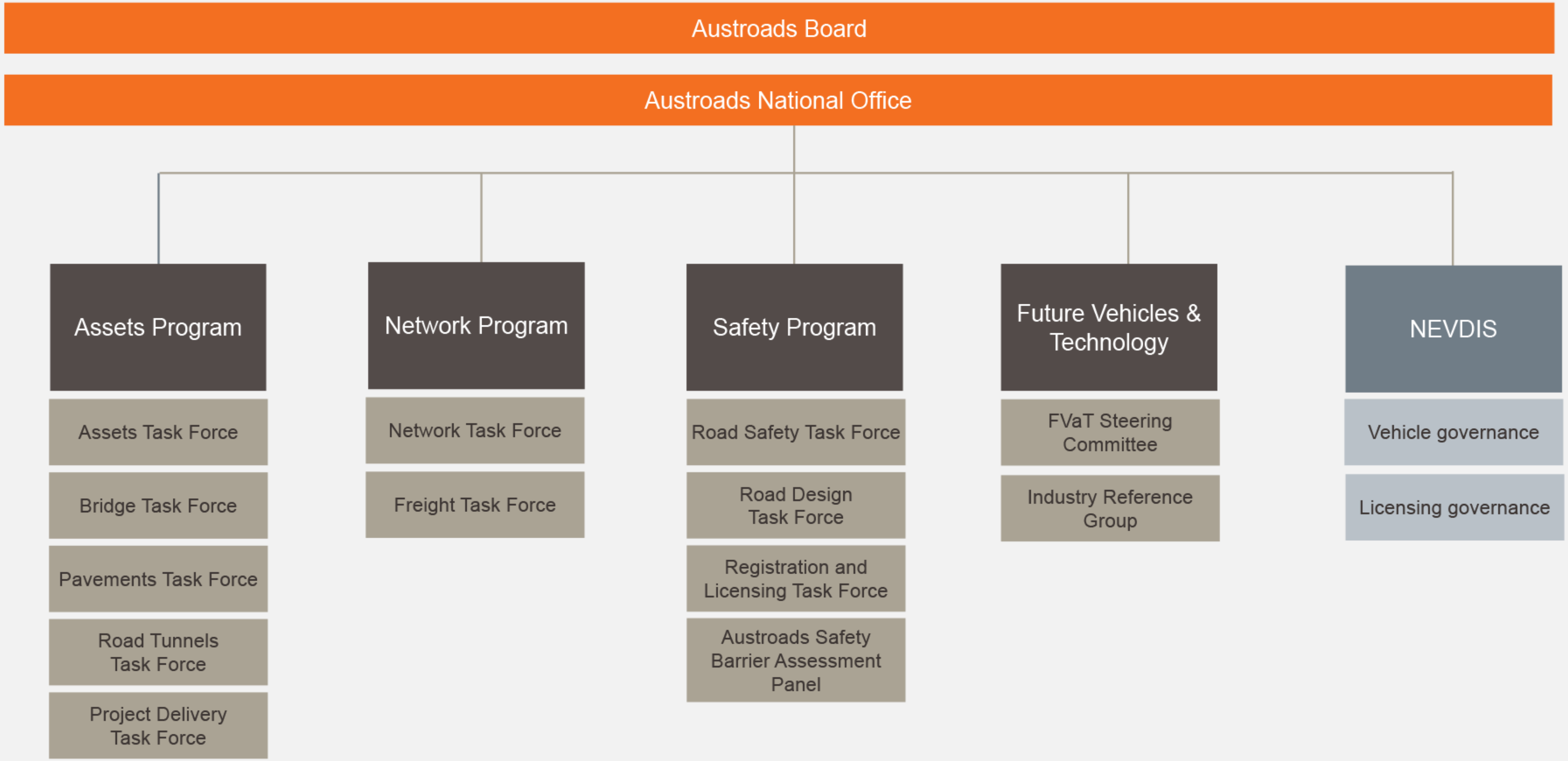
Our Structure



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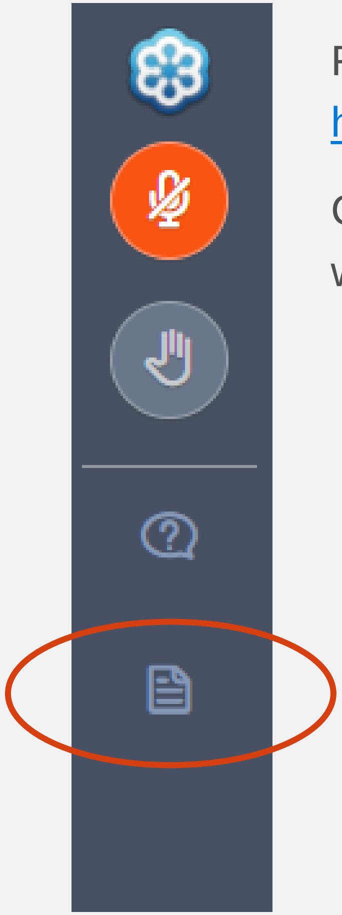

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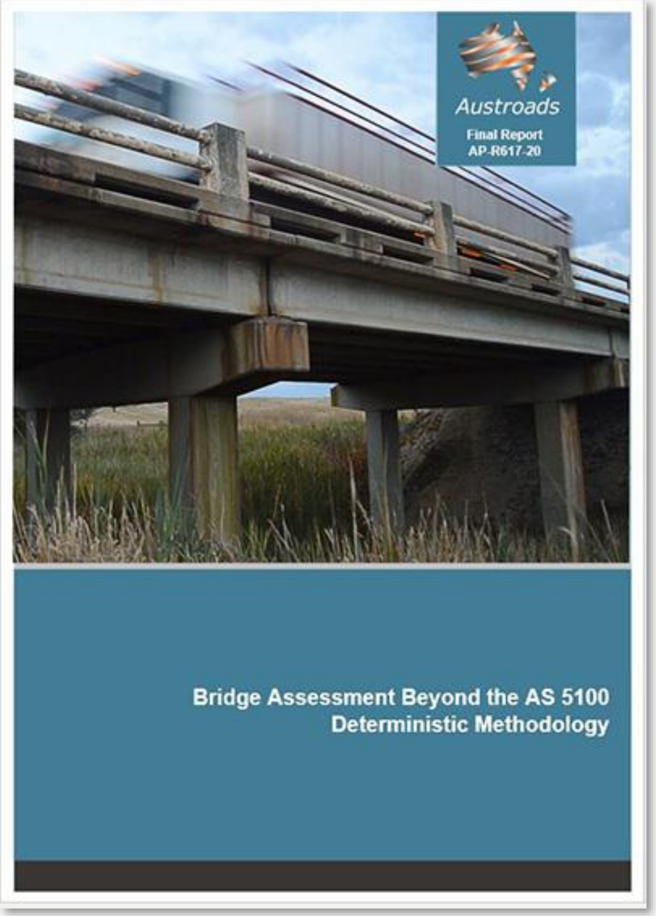

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Today's Presenters and Agenda

Topic	Presenter
Project Overview	Dr Colin Caprani
Structural Reliability Theory	Professor Mark G Stewart
Probability-based Bridge Assessment Framework	Dr Mayer M Melhem
Framework Example Application	
Conclusions and Recommendations	Dr Colin Caprani
Q+A	All Presenters + Mr Andy Ng

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Project Overview

Dr Colin Caprani

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Introduction to the Team

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Project Team

Austroads Project Manager
Andy Ng

Project Lead
Dr Colin Caprani

Project Research and Dissemination
Prof Mark Stewart

Project Researcher
Dr Mayer Melhem

Project Administration
Dr Shaohua Zhang

Review Team

Austroads Working Group

↓

Austroads Road Safety Task Force ← International Advisory Committee

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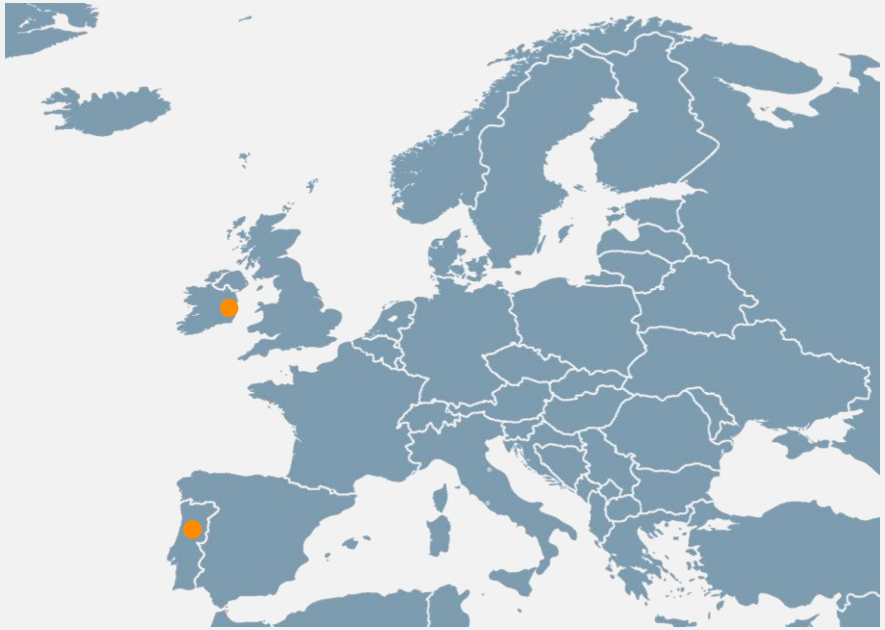
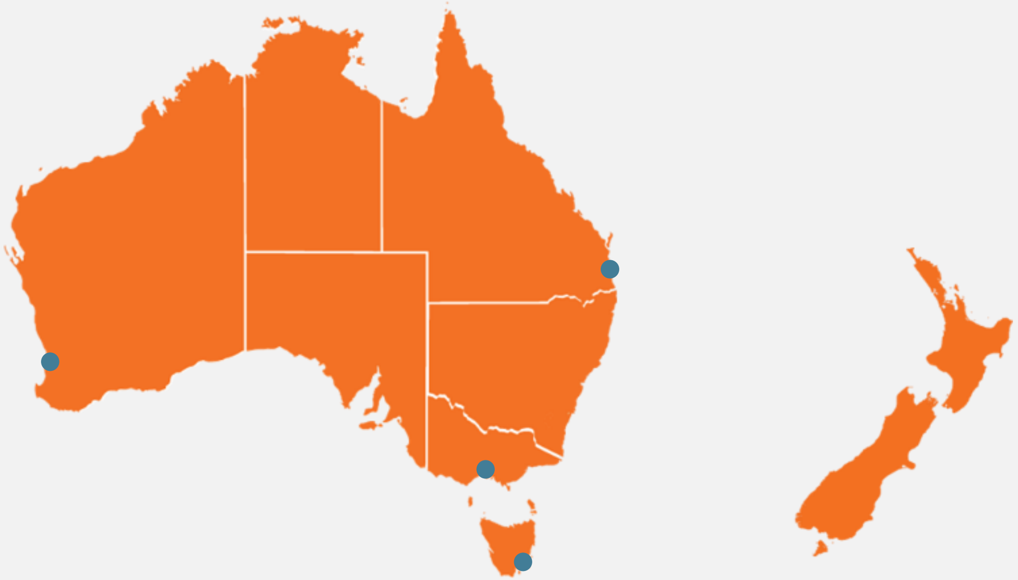
Introduction to the Team



Austroads Working Group

- Jewely Parvin, Main Roads Western Australia
- Alex McAuley, Department of Transport and Main Roads Queensland
- Vincent Tang, Department of State Growth Tasmania
- Sukie Shen, Department of Transport Victoria



International Advisory Committee

- Professor Jose Campos e Matos, Minho University, Guimaraes, Portugal
- Professor Alan O’Connor, Trinity College, Dublin, Ireland

Project Overview

Aim

To develop a higher-tier assessment framework using the tenets of reliability and safety engineering for adoption in Australia/New Zealand above AS 5100.7

Demonstration

Step 1: Determine the safety level of "as-built" bridges under their design load as found in the historical codes (***Code-Implied Safety***)

Step 2: Determine the actual safety levels of bridges given current as-of-right freight vehicles and traffic (***Current Safety***)

Project Purpose

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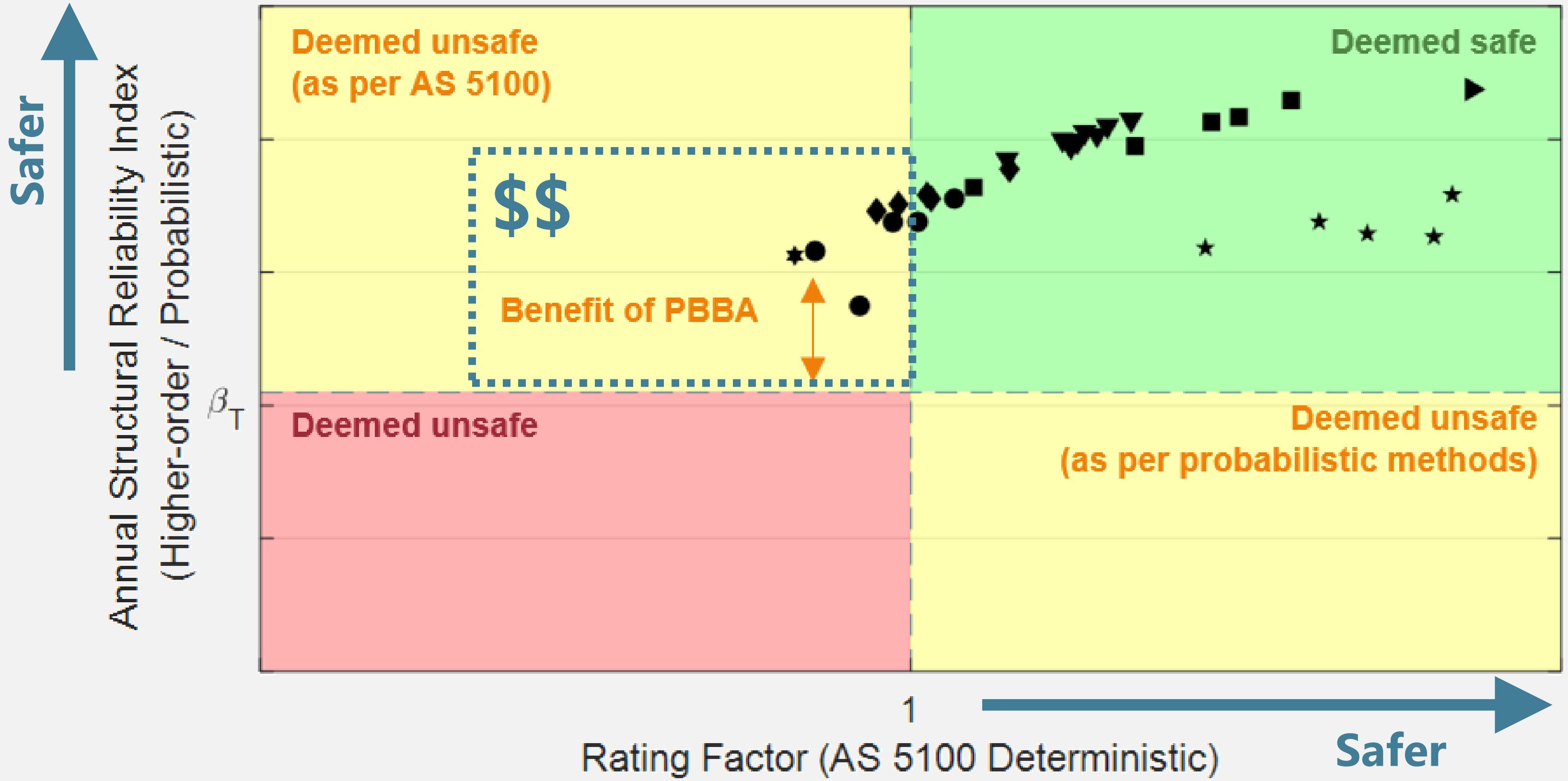
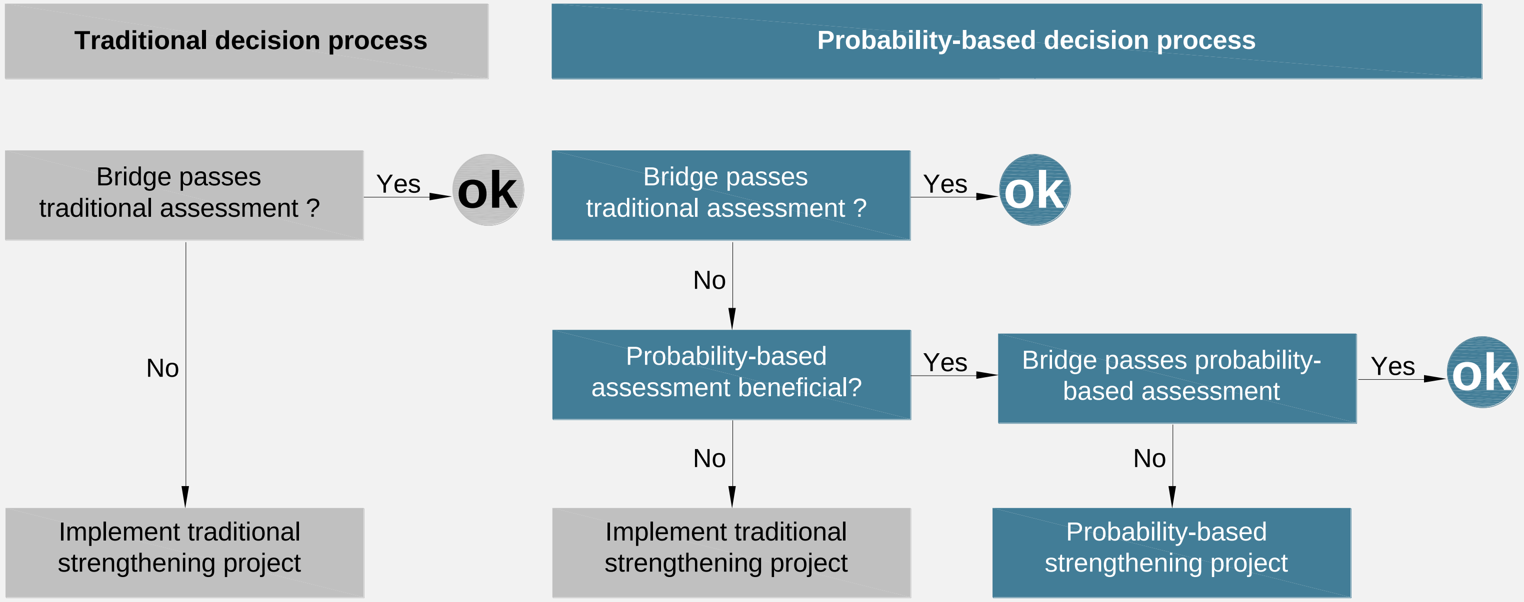
Figure 1-1: Rating factors vs Structural Reliability Index Plot



Probability-based Bridge Assessment

Rationale

Figure 2-1: Probability-based Bridge Assessment



- Note, conventional Rating Factor is still conducted
- PBBA is adopted as best practice for higher-tier assessments as published guidelines of the United Kingdom, United States and various European countries
- PBBA is the development or writing of a bridge or component-specific code of practice.

Structural Reliability Theory

Professor Mark Stewart

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Structural Reliability Theory

- Zero risk does not exist
- Uncertainty and Variability:
  - Material properties, dimensions, etc.
  - Permanent and imposed loads, and how they vary with time
  - Accuracy of predicted models (no model is perfect!)
- Limit state function $G(\boldsymbol{X})$; definition of failure
  - e.g., Collapse occurs when Load (S) exceeds Resistance (R)

$$G(\boldsymbol{X}) = R - S$$

- Probability of failure: $p_f = \Pr(G(\boldsymbol{X}) < 0)$
- Reliability Index: $\beta = -\Phi^{-1}(p_f)$

Figure 2-2: Uncertainty in load and resistance

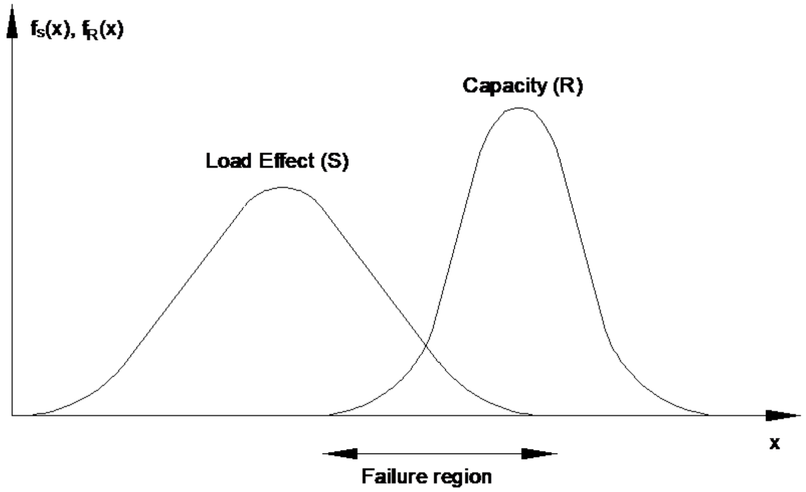
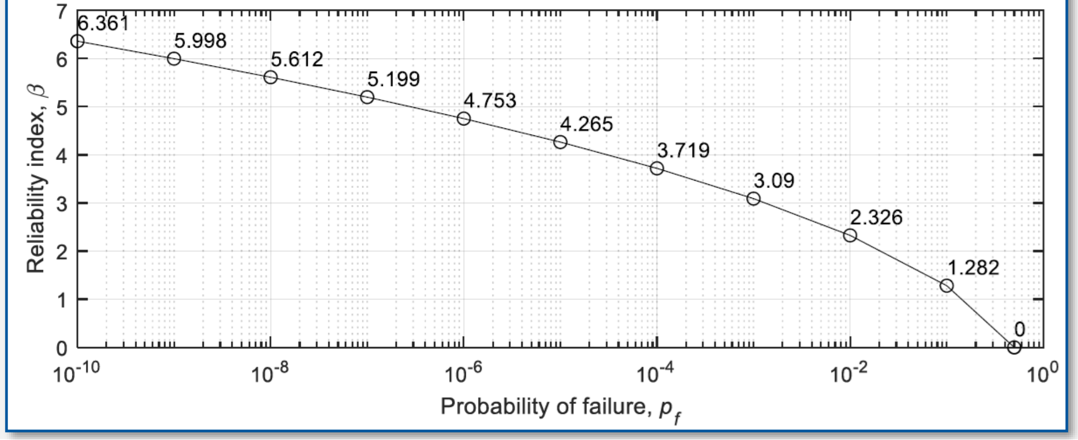


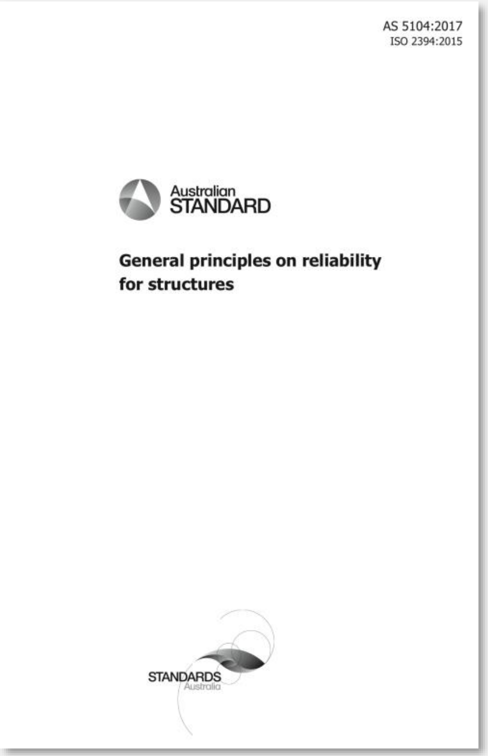
Figure A-2: Relationship between β and p_f.



Applications of Structural Reliability

- Structural reliability theory underpins many recent advances in structural and safety engineering
  - Reliability-based calibration of design codes in Europe, U.S., Canada and Australia
  - Performance based design of new structures such as the Confederation Bridge (Canada), Great Belt Bridge (Denmark), and Messina Strait Bridge (Italy)
  - Service life and safety assessment of existing structures
  - Optimal maintenance of ageing or deteriorating structures

- Reliability-based code calibration
  - Based on AS5104-2017 and its predecessors
  - Concrete Structures AS3600-2018 (Stewart and Foster 2016):
    - Increased $\phi = 0.6$ to 0.65 for compression
    - Increased $\phi = 0.7$ to 0.75 for shear
    - Increased $\phi = 0.8$ to 0.85 for flexure
  - Masonry Structures AS3700-2011 (Stewart and Lawrence 2007):
    - Increased $\phi = 0.45$ to $\phi = 0.75$ for compression


AS 5104:2017
ISO 2394:2015

Australian STANDARD

General principles on reliability for structures

STANDARDS Australia

Acceptable Risk: How Safe is Safe Enough?

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- Target Reliability Index (β_T)
- Australian and International guidance
  - AS5104-2017, ISO 2394-2015
- Failure consequences:
  - Class 2 - minor
  - Class 3 - losses of societal significance, causing regional disruptions and delays in important societal services over several weeks. Expected number of fatalities fewer than 50 (Example: medium spanning bridges that form part of the HPFV network).
  - Class 4 - Disastrous events causing severe of societal services and disruptions and delays at a national scale.

Table 2-1: Annual target probability of failure based on economic optimisation (AS 5104-2017)

Relative Costs of Safety Measures	Consequences of Failure		
	Class 2 (Minor)	Class 3 (Moderate)	Class 4 (Large)
Large	1.0×10^{-3} (β = 3.1)	4.8×10^{-4} (β = 3.3)	1.1×10^{-4} (β = 3.7)
Medium	1.1×10^{-4} (β = 3.7)	1.3×10^{-5} (β = 4.2)	5.4×10^{-6} (β = 4.4)
Small	1.3×10^{-5} (β = 4.2)	5.4×10^{-6} (β = 4.4)	1.3×10^{-6} (β = 4.7)

- Relative cost of safety measures:
  - Large for existing bridges if bridge replacement if an existing bridge fails a safety assessment
  - Medium if the decision is to restrict vehicle loads rather than recommend full bridge replacement.
- International benchmarking would *suggest*:
  - Annual β_T = 4.2 - ultimate bending
  - Annual β_T = 4.4 - ultimate shear
    - Structural element which would be likely to collapse suddenly without warning is designed for a higher level of reliability

Final decision depends on the "risk appetite" of asset owner

Probability-Based Bridge Assessment Framework

Dr Mayer Melhem

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Proposed PBBA Framework

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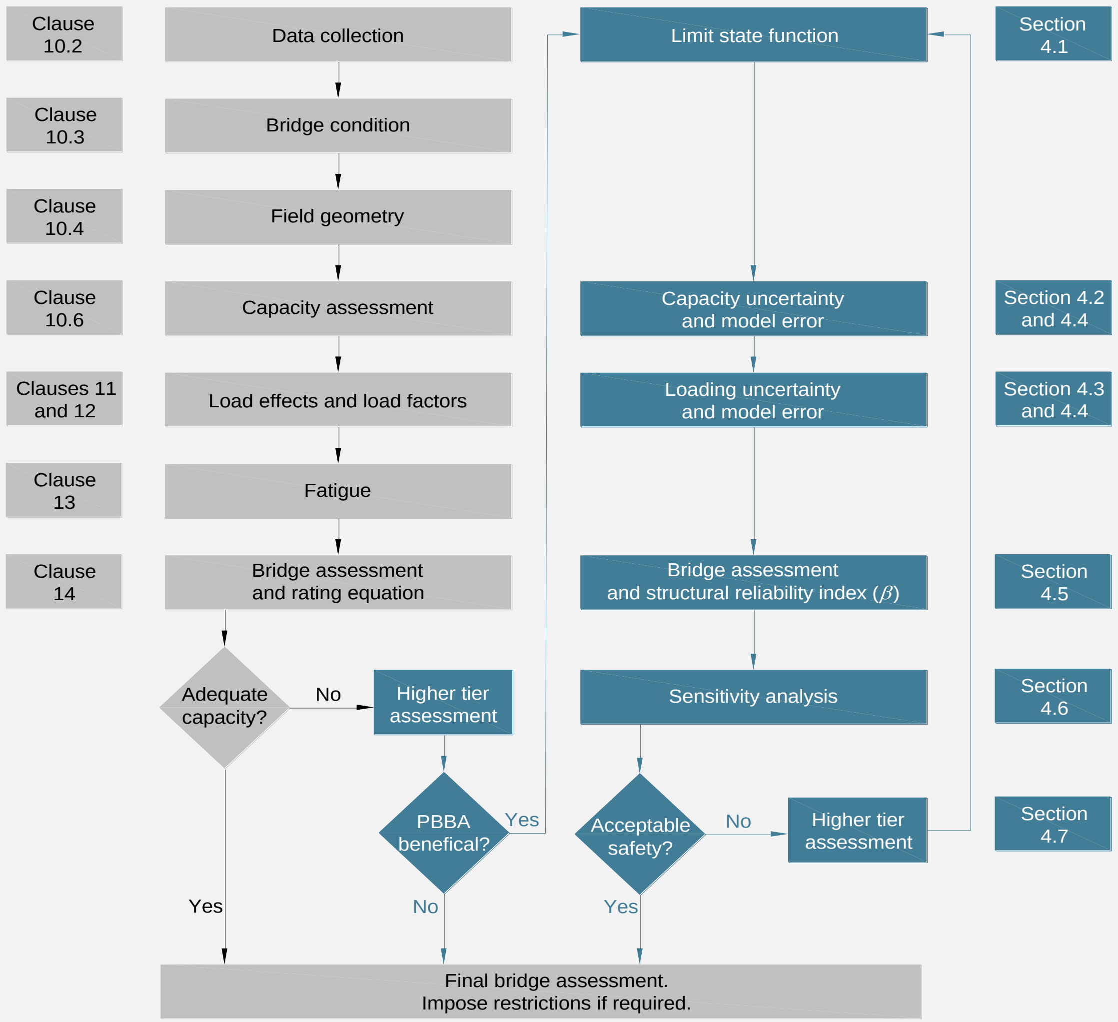
- Adaptation of already well-established international PBBA frameworks (DRD, 2004)
- Follow AS 5100.7 flowchart but now considering variable uncertainties
- Selected limit state function:

$$G = \omega_R R - \omega_S \left(S_i + S_{slab} + S_{SIDL} + S_{LL} \right)$$

- Feedback loop for increasing level of complexity
- Time-invariant recommended reference period $\tau = 1$ year
  - Stochastic variables (eg. S_{LL}) must be annually based

Figure 3-1: Proposed PBBA Framework



PBBA Framework Elements

Probability Modelling

Tables 4-1, 4.3, I-1, I-3: Example Probability Distributions

Basic Variable	Symbol	Type	Bias (μ/d)	CoV (σ/μ)	Source
Concrete compressive strength	f'_c	Log-normal	1.084	0.154	Foster et al., 2016
Prestress Losses	ΔP	Normal	1	0.30	Mathieu, 1991
Prestress strands cross-sectional area	A_p	Normal	1	0.013	Wisniewski et al., 2012
Steel rebar yield strength	f_{sy}	Normal	1.15	0.05	Foster et al., 2016
Distance from top fibre to rebar layer centroid	d_s	Normal	0.99	0.04	Foster et al., 2016
Self-Weight	S_i	Normal	1.03	0.08	Rakoczy and Nowak, 2013
Capacity Model Error	ω_R	Normal	1.06	0.05	Foster et al., 2016
Loading Model Error	ω_S	Normal	1.00	0.10	JCSS, 2000

Figure 5-3: Example Probability Model for *R* (1 of 64 fits)

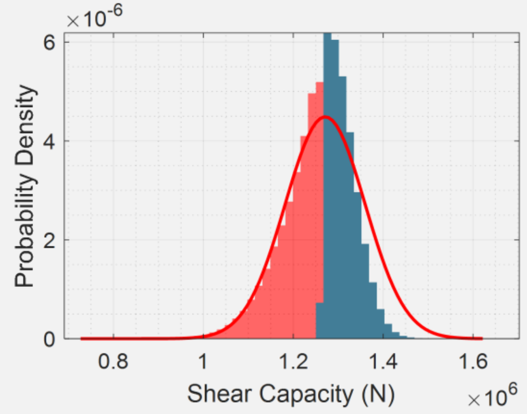
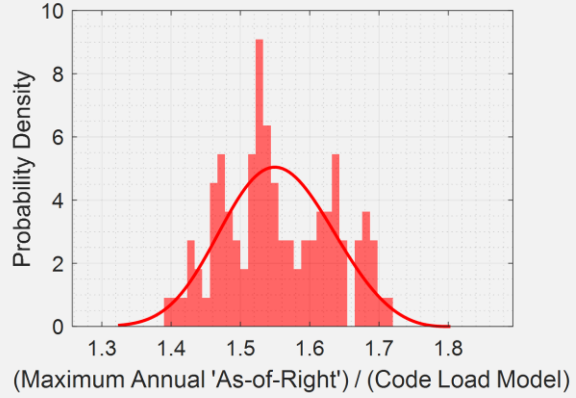


Figure 5-5: Example Probability Model for S_{LL} (1 of 384 fits)



PBBA Framework Elements

Structural Reliability Methods

The algorithm used to calculate the level of safety / reliability index (β)

- Project adopted the state-of-the-art reliability methods and software.

Sensitivity Analysis

The influence of assumptions in probability models is tested

- Enhances confidence and robustness in final output (β)
- Guides deeper dives into controlling parameters (e.g. DLA)

Framework Example Application

Dr Mayer Melhem

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Framework Example Application

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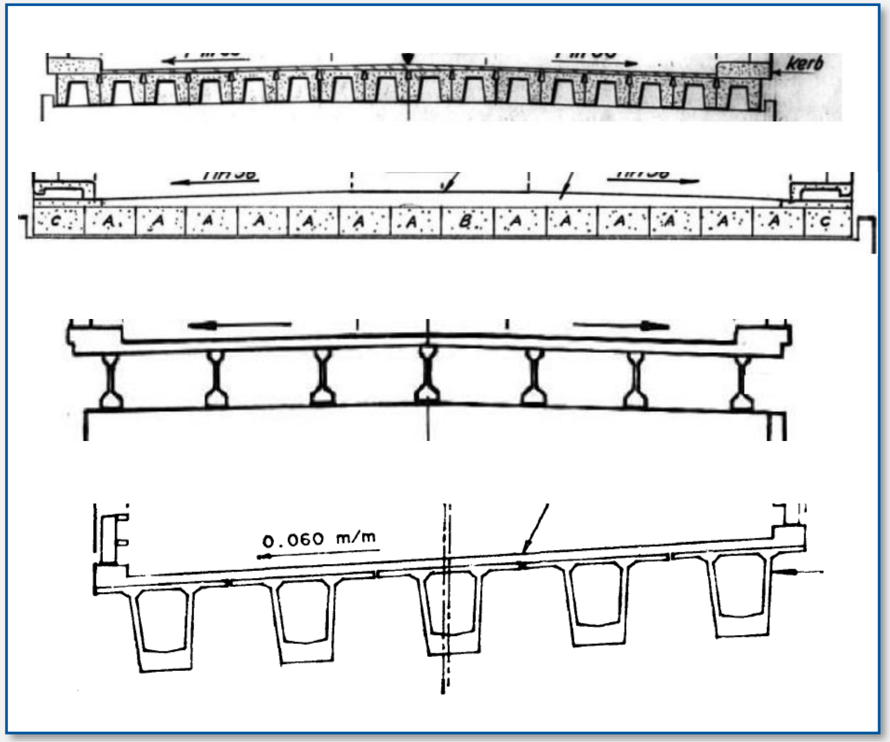
Table 3-1: Adopted Bridge Subset (Two-Traffic Lanes)

Design Code (Load)	Structural Form	Era	No.	Sections and Spans
NAASRA (MS18)	High-strength RC U-slabs	1953 – 1976	5	(15’) 4.57 m - (20’) 6.10 m - (25’) 7.62 m (30’) 9.14 m - (35’) 10.67 m
NAASRA (MS18)	PSC Precast Planks	1953 – 1976	5	(15’) 4.57 m - (20’) 6.10 m - (25’) 7.62 m (30’) 9.14 m - (35’) 10.67 m
NAASRA (MS18)	PSC I-girders	1953 – 1976	5	(35’) 10.67 m - (40’) 12.19 m - (45’) 13.72 m (50’) 15.24 m - (60’) 18.29 m
NAASRA (T44)	PSC I-girders[1]	1976 – 1992	1	19 m
ABDC (T44)	PSC Precast Tee Slabs	1992 – 2004	5	(450 mm) 11 m (450 mm) 13 m (550 mm) 14 m (650 mm) 16 m (750 mm) 19 m
ABDC (T44)	PSC Super-T Girders	1992 – 2004	1	26.5 m
AS5100 (SM1600)	PSC Super-T Girders[2]	2004 – 2017	10	(T1) 15 m (T1) 20 m (T2) 17 m (T2) 23 m (T3) 18 m (T3) 27 m (T4) 22 m (T4) 32 m (T5) 28 m (T5) 37 m



[1] Detailed example seen in Section 5 of report
[2] Designed precisely to the specifications of AS 5100 (2004) for selected limit state. Practical detailing and construction staging is not considered and therefore slimmest possible complying designs meeting the code requirements

Step 1: Code-Implied Safety

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Capacity

Capacity Models (Appendix G)

- *Bending*: Rectangular Stress Block (AS 5100.5 Clause 8.1)
- *Shear*: Simplified Modified Compression Field Theory (AS 5100.5 Clause 8.2) adapted for assessment (Caprani & Melhem, 2020)

Loading

Analysis Models (Appendix H)

- *Surface Model*: U-Slabs, PSC Planks
- *Grillage Model:* I-Girders, Precast Tee Slabs, Super-T Girders
- *Provided by TMR*: I-Girders (T44)

Reliability Assessment

- Limit State Function $G = \omega_R R - \omega_S \left(S_i + S_{slab} + S_{SIDL} + S_{LL} \right)$

Step 1: Code-Implied Safety

Figure 6-3(a): Ultimate Bending

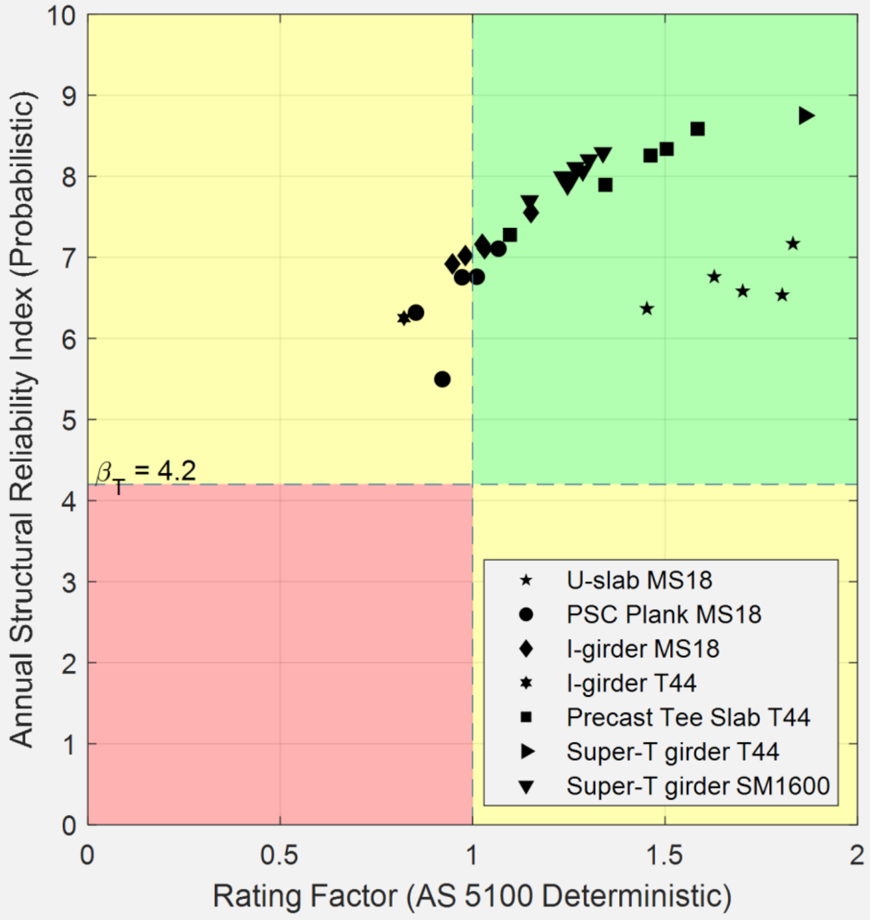
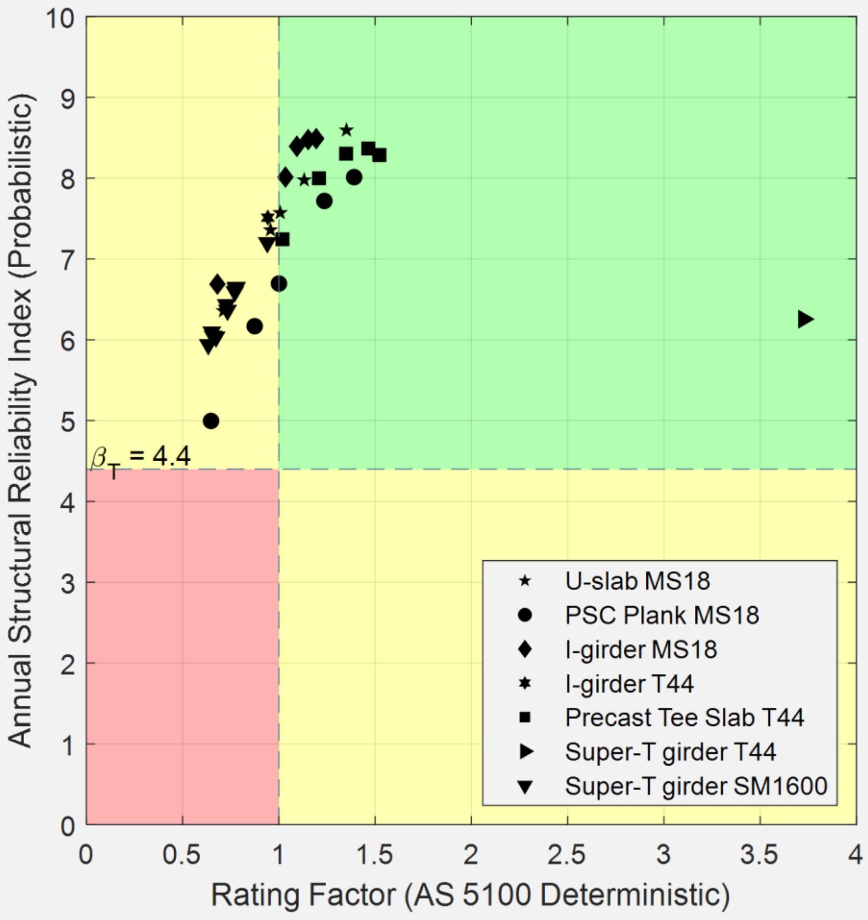


Figure 6-3(b): Ultimate Shear



Step 2: Current Safety

Vehicle Fleet

- Higher Mass Limits on West Gate Bridge

Traffic Simulation

- Bridge traffic is simulated for 6 flows using in-house BTLS software (Figure 3-2, Appendix D)

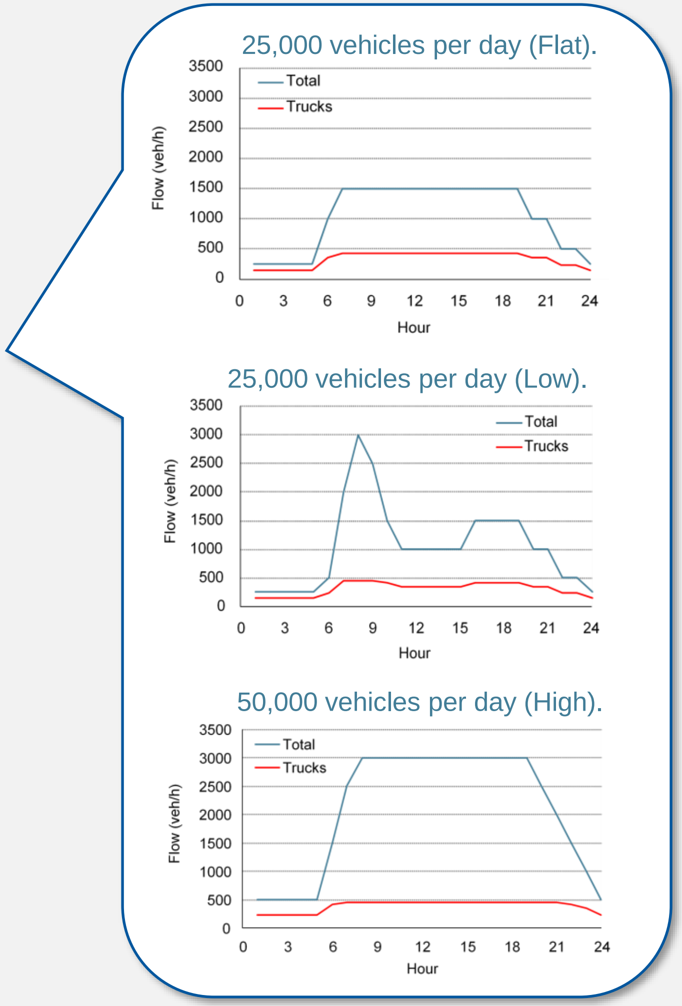
Loading

- Influence lines covert loading to load effects realisations using in-house BTLS software (Appendix H)

Reliability Assessment

- As per Step 1
- Limit State Function: $G = \omega_R R - \omega_S \left(S_i + S_{slab} + S_{SIDL} + DLA \times S_{LL} \right)$

Figure 3-2: Flow Schemes (Appendix D)



Step 2: Current Safety

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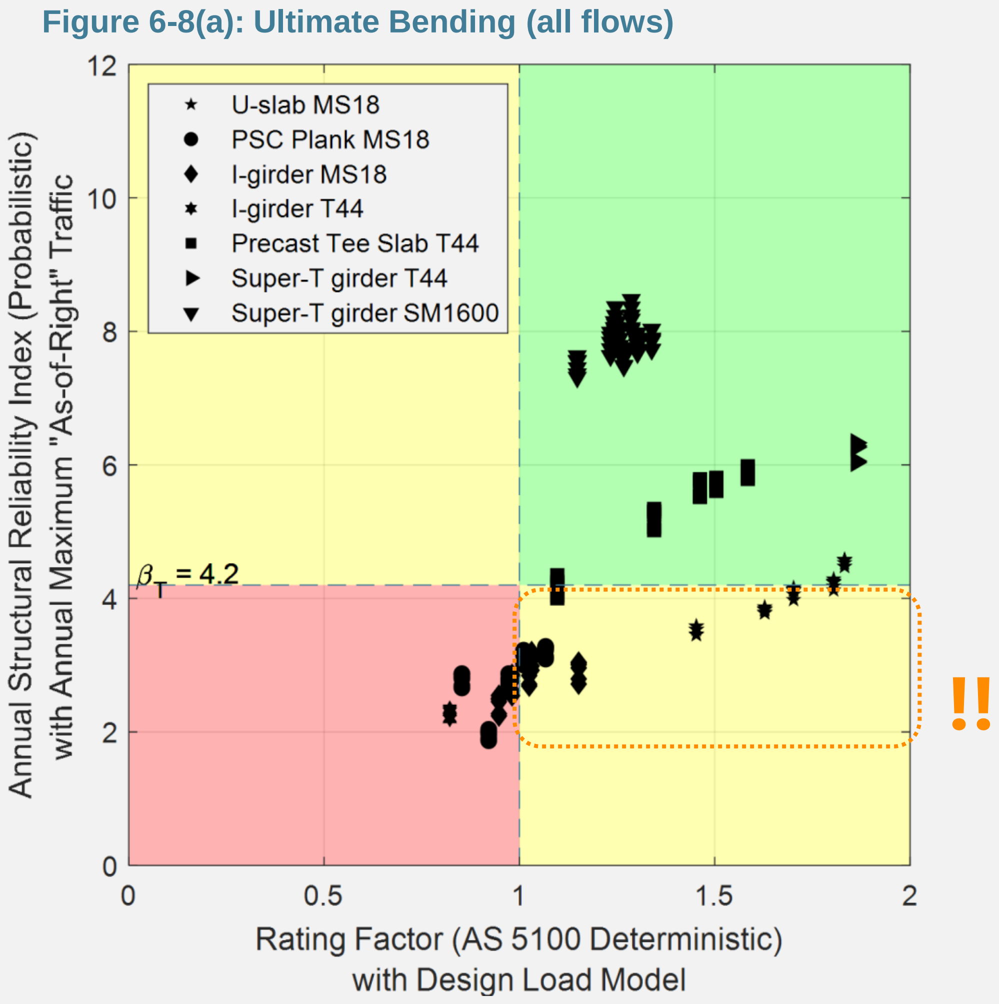

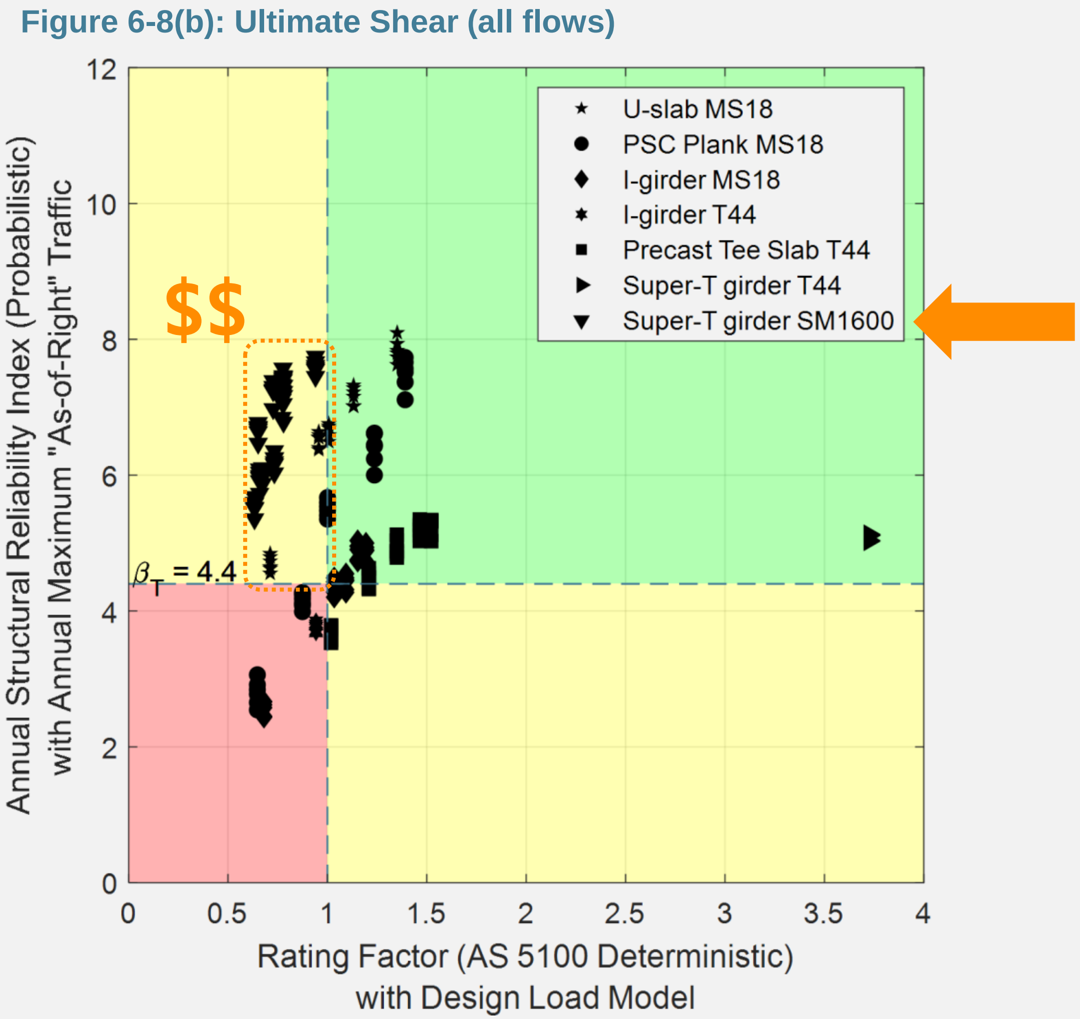

Conclusions and Recommendations

Dr Colin Caprani

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Main Findings

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- **PBBA**: Through adoption of state-of-the-art structural reliability theory, a probability-based bridge assessment framework has been developed to provide objective means of determining quantified safety offered by bridges in the Australian/New Zealand context.
- **Step 1** indicates the level of safety implied by the historical codes. It is generally larger than typical target levels. The probabilistic method reveals a margin of safety available that the otherwise conservative deterministic approach does not illuminate, most noticeably for shear.
- **Step 2** infers the current level of safety for HML traffic streams of two-traffic lane bridges. The level of safety is reduced for bridges of lower design traffic load models, especially for bending. For shear, 75% of bridges that failed a deterministic assessment (RF < 1) are shown to have a reliability index higher than that typically acceptable – for these bridges a margin of safety is still available.

Limitations

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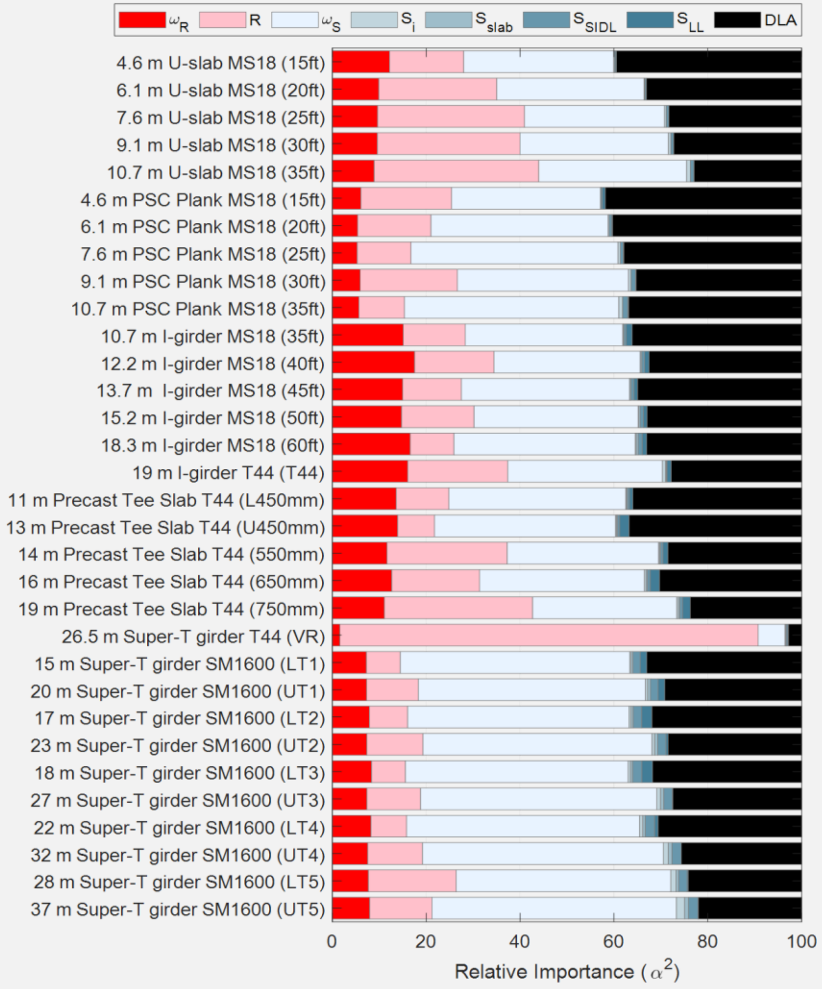
- Other **Modes of failure** (eg. fatigue), **other traffic flows schemes**, **different number of traffic lanes**, **skew**, specific **restricted access routes**, and **other bridge loads** (e.g. thermal, settlement).
- Use of **WIM data** from just one site (West Gate Bridge, Melbourne) as the basis for the traffic load modelling, which is shown to be a most influential factor in assessing bridge safety.
- No **substructure assessments**, which would require highly site- or region-specific consideration of the uncertainty in ground conditions and river flows.
- Only **single components considered**, rather than the entire bridge system, which typically has redundancies.

Further Research

- Incorporations of **time-dependent factors** like corrosion and the structure condition, as well as traffic growth, including vehicle modal shifts, requiring appropriate statistical models.
- The **probabilistic dynamic interaction** of the Australasian vehicle fleet on the bridge stock, which is shown through the importance coefficients that this is a key parameter.
- The updating of reliability assessments using **structural health monitoring (SHM)** outputs and using burgeoning **Value of Information approaches.**

Figure 6-10: Relative Importance Example Results



Final Remarks

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- **Take home message**: Rating factors are not the final instrument to measure safety. Instead, the probability of failure (reliability index) is more robust.
- There is enormous potential benefit in the use of probability-based assessment in Australia/New Zealand as a higher-tier form of assessment.
- PBBA approach is now common internationally.
- It reveals the true levels of safety and provides quantitative data for further asset management, including risk quantification, and prioritisation of rehabilitation measures.
- Through AS5104, this higher-tier form of assessment can be conducted in Australasia for optimal bridge safety and cost outcomes.

Recommended Literature

Text Books

- Nowak, A. S & Collins, K. R (2012) *Reliability of Structures,* CRC Press, Boca Raton
- Melchers, R. E. & Beck, A. T. (2018) *Structural Reliability Analysis and Predictio*n, John Wiley & Sons, Chichester

Journal Papers

- Caprani, C., C & Melhem, M. M. (2020) On The Use of MCFT Per AS 5100.5 for the Assessment of Shear Capacities of Existing Structures. *Australian Journal of Structural Engineering*, 21, 53-63
- Caprani, C. C., Obrien, E. J. & McLachlan, G. J (2008). Characteristic Traffic Load Effects From A Mixture Of Loading Events On Short To Medium Span Bridges. *Structural Safety,* 30**,** 394-404.
- Enevoldsen, I. (2011). Practical Implementation Of Probability Based Assessment Methods For Bridges. *Structure And Infrastructure Engineering,* 7**,** 535-549.
- Foster, S. J., Stewart, M. G., Loo, M., Ahammed, M. & Sirivivatnanon, V. (2016) Calibration of Australian Standard AS3600 Concrete Structures: Part I Statistical Analysis Of Material Properties And Model Error. *Australian Journal Of Structural Engineering,* 17**,** 242-253.
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Guidelines and Standards

- AS 5104-2017. General principles on reliability for structures standard by Standards Australia.
- Cost Action 345. Procedure Required For The Assessment Of Highway Structures - Final Report. Europe The European Cooperation In Science And Technology (COST).
- Danish Road Directorate (2004). Reliability-Based Classification Of The Load Carrying Capacity Of Existing Bridges. Danish Road Directorate (DRD), Denmark.

Questions?

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