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Practical application of advanced bridge assessments in Class 1 heavy vehicle access decision-making

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Abstract

In the last 7 years, the Department of Transport (DoT) has seen a significant increase in demand for heavy vehicles accessing the state's road network and subsequent permit requests requiring structural assessments. Stimulated by Victoria's Big Build and Clean Energy Future, Class 1 oversize overmass (OSOM) vehicles deliver critical components for major projects including concrete prefabrications, steel girders, wind turbines, and superconductors. Accurate structural assessments are essential for managing the structural risk that these large indivisible loads pose on the ageing bridge stock. Given conventional desktop assessments are inherently conservative, an advanced measure is desired to assist in route access decisions for Class 1 OSOM vehicles. This work details how a framework combining accurate bridge capacity quantification, measured data from structural health monitoring (SHM), and state-of-the-art structural reliability methods can provide such a measure. Specifically, the work presents how the framework has been applied in practice, assuring and ensuring the heavy loads could safely travel and provide the successfully efficient delivery of project critical components. This practical application highlights potential benefits both nationally and internationally in the rational decision-making on access for all heavy vehicle classes.

Keywords: bridge safety assessment; higher-tier assessment; probability-based bridge assessment; structural health monitoring; class 1 heavy vehicles

1. Introduction

In Victoria, the Department of Transport (DoT) is obligated to provide safe access to the state's arterial road network for heavy vehicle operators[1]. The network includes more than 5,900 road carrying structures (bridges and major culverts), which may require assessment as part of the access permit process. Recently, the demand for heavy vehicle access in Victoria has grown exponentially, with access permit requests requiring structural assessments for Class 1 vehicles increasing significantly in 2020-21 compared to 2014-15. These vehicles include large oversize overmass (OSOM) platform convoys or 'superloads' vital in the delivery of critical indivisible loads such as concrete prefabrications, steel girders, wind turbines, and superconductors required for the state's Big Build and Clean Energy Future projects.

One major project is the largest wind farm in the southern hemisphere, with plans approved by the Victorian Government in 2010. Located in the state's regional west, the facility boasts 149 wind turbines with a combined energy generation of up to 530 MW[2]. Construction of the wind farm began in 2019 and required multiple Class 1 OSOM vehicle movements to transport the components of each turbine. Additionally, a massive single-trip "superload" was necessary to deliver the 663 t transformer for the terminal station. However, DoT's existing structural assessment paradigm concluded it was unsafe these heavy vehicles to travel on the most efficient 165 km transport route from the Port of Geelong to the wind farm site.

Decisions on the suitable route for overmass indivisible loads are primarily governed by the ability of existing bridges to sustain the large vehicular loads. Much like the rest of Australia, DoT adopts a tiered approach to bridge assessments, typically ending with the rating factor (RF) as per the national standard for bridge assessment, Australian Standard (AS) 5100.7[3]. It is often noted that such desktop assessments can be conservative[4]. As a result, such methods may indicate lower safe load-carrying capacities compared to modern and more advanced techniques, under-utilising bridges and suggesting no feasible transport routes.

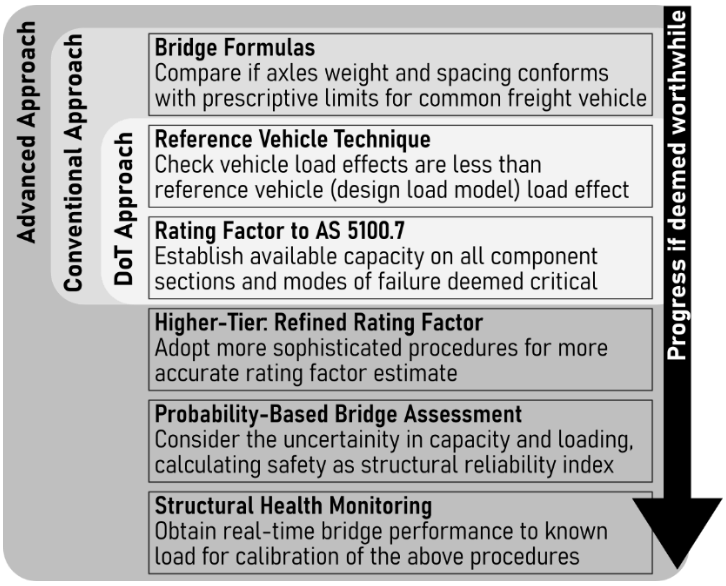
DoT considered the multiple Class 1 OSOM vehicle movements as the perfect opportunity to engage with academia and trial a framework for advanced bridge assessments. This paper presents on this project-driven research collaboration, to provide informed access decisions for the overmass indivisible loads. The work eventually enabled the construction of the landmark wind farm and the community impact to be calculated.

2. Tiers in Bridge Assessments

Overview

Figure 1 depicts the tiers in bridge assessments, indicating those adopted by DoT, conventionally across Australia, and more advanced methods observed overseas[5,6]. The mainly desktop assessments increase in accuracy, but also complexity. The simplest and likely conservative methods are conducted first, filtering out the critical limit state for the critical structures. Note, bridge formulas will not be discussed as they are generally not adopted by DoT.

Figure 1 Bridge assessment tiers for route planning overmass load deliveries.



Source: Melhem et al. (2021)

Comparative Assessments

Also known as the reference vehicle technique, bridge load effects from a reference vehicle are compared with effects from the proposed subject vehicle[5]. In most cases, the reference vehicle is the notional load model stipulated in the design of existing bridge as a proxy for structural capacity.

Each structure in the proposed route is generally represented as 1D line model to obtain load effects for the superstructure (moment and shear) and substructure (reaction). This process can be expedited through in-house[7] or open-source software[8]. Load distribution factors may be adopted to refine the results to specific bridge components[9]. Since it is a comparison between vehicle load effects, other bridge loads are not considered. However, potential differences in dynamic load amplification (DLA) and live load factors from AS 5100.7[3] between the subject and reference vehicles must be considered.

The structure is deemed acceptably safe if the subject vehicle load effects are less than the reference vehicle load effects. If the next tier is not conducted for the remaining structures, varying restriction for the structure is placed on the Class 1 OSOM vehicle depending on the overstress ratio. Restrictions include slow-down, centre-line straddling, combination of both, and no-go.

Rating Factor

Details on the rating factor (*RF*) are documented in AS 5100.7[3]. The rating factor is carried out for all limit states of bridge component sections deemed critical per Clause 10.7 and/or the relevant authority. As a ratio of available supply to demand, both the section capacity and load effects must be quantified, with relevant partial safety factors applied as per the code. The available supply is the factored section capacity after subtracting factored load effects not pertaining to the subject vehicle. Generally, for short-span bridges, load effects from non-permanent loads (ie. temperature, shrinkage, creep, etc.) are seldom considered. Meanwhile, the demand is the subject vehicle factored load effect including DLA.

As per Clause 10.6.1, the factored capacity is found using the relevant contemporary design standard in the same AS suite. For load effects, grillage models using commercial or open-source software[10] is typically used. The structural bridge component is deemed acceptably safe if $RF > 1$. Otherwise, it may be possible to refine the rating factor through a more sophisticated analysis and/or field investigations for a more accurate capacity/loading prediction[6]. Alternatively, partial safety factors calibrated to a selected level of safety can be adopted. However, guidance on these methods is not provided in the standards.

Probability-based Bridge Assessment (PBBA)

PBBA adopts the tenets of structural reliability theory to directly quantify the level of safety for a structure[11]. The limit state function is defined, describing the boundary between safety and failure. The uncertainty of random variables within the limit state function are characterized through probability models. The level of safety is calculated as the probability of limit state failure, typically expressed as a reliability index β, using structural reliability methods[12].

The structural bridge component is deemed acceptably safe if β exceeds a selected target reliability index β_T – chosen for the provision of adequate public safety and optimised socio-economic costs. The comparison between reliability indices allows greater awareness on risk acceptance and flexibility on risk appetite compared to lower-tier methods. There are several published guidelines on PBBA, including a recent Austroads study that demonstrated PBBA can reveal a margin of safety otherwise not shown by conventional bridge assessments[4,13].

Structural Health Monitoring (SHM)

Around the world, various SHM systems have been implemented on bridges to measure structural responses to different loads[14]. SHM must consider appropriate sensors, data acquisition, signal analysing, and power management[15]. Either wired or wireless networks are used, with strain gauges regarded as the most cost-effective option.

SHM is most useful for practitioners when they include the measured data to improve bridge assessment, particularly for such Class 1 OSOM vehicles movements. Output measurements can be used to update parameters and structural models created for the assessments. That is, SHM is one approach to refine the rating factor[15]. Alternatively, although expensive, SHM may be used as part of proof-loading program for a structure. Most significantly, SHM data reduces uncertainties in PBBA, improving estimates on β.

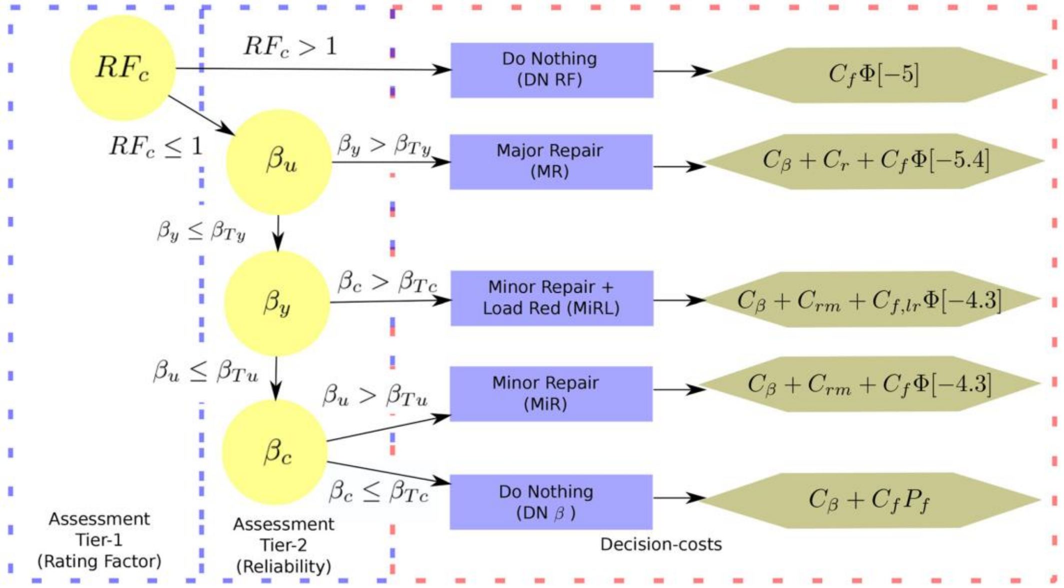
Tier Progression

Given financial constraints, the choice to adopt a higher-tier assessment when lower-tier assessments conclude the bridge is unacceptable to carry the loads should occur only if deemed worthwhile, given that the higher tier assessments can be expensive to conduct due to their complexity. Whilst there might be socio-politico-economic pressure that necessitate higher-tier assessment, it is possible to quantify the benefit of a tier progression using the value of information (VoI) framework[16,17].

Value of Information (VoI) Framework

VoI is based on the Bayesian decision theory and is undertaken in two parts – prior analysis and preposterior analysis. In the prior analysis, expected costs for decisions without additional information are quantified. Here, the set of all possible decisions must be noted and the uncertain parameters that influence each decision. Such an approach is best achieved through a decision tree (Figure 2). Next, the expected cost with additional information is calculated in the preposterior analysis. The difference between the prior and preposterior costs is defined as an absolute measure of the expected value of information[17].

Figure 2 Decision tree example



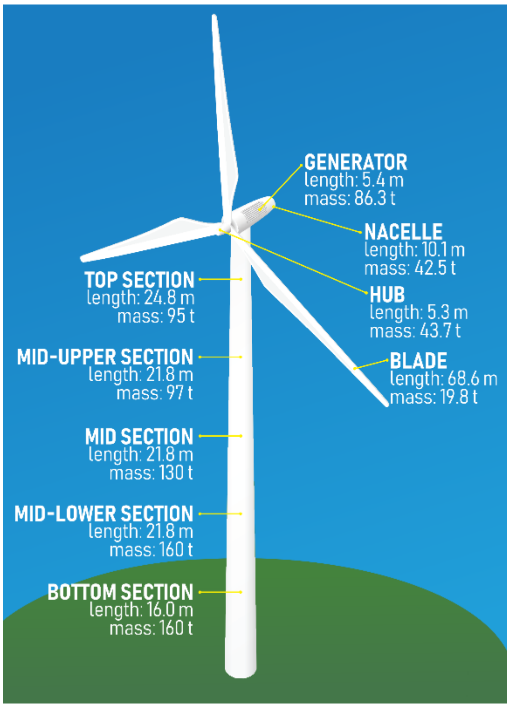
Source: Khan et al. (2022)

3. Case Study

Context

The Stockyard Hill wind farm is located approximately 35 km west of Ballarat, with a terminal station located more than 50 km south of the wind farm site, providing connection to the nearest high voltage electrical transmission infrastructure. The terminal station houses Victoria's largest transformer, longer than an Airbus A380 and weighing 663 t. Meanwhile, each 180 m high wind turbine consists of 9 large and heavy components (Figure 3).

Figure 3 Components of wind turbines.



Source: Stockyard Hill (2022)

The transformer and turbine components were shipped from overseas and each required delivery from the Port of Geelong to site via the road network. For the transformer, which was delivered first, a single-trip access permit was requested for a 115 m long, 5.5 m high, and 5.12 m wide platform convoy ‘superload’ hauled by four prime movers. On the other hand, of the 9 wind turbine components (Figure 3), 5 sections that comprise the tower required period-trip transport through platform convoys between 95 t and 160 t. Table 1 details the configurations adopted for each section by the road transporter.

Table 1 Overmass load deliveries configurations for tower components.

		Transport Convoy		
Tower Section	Mass (tonnes)	*Prime Movers*	*1st Platform (axles x wheels)*	*2nd Platform (axles x wheels)*
Top	95	1	2 x 8	4 x 8
Mid-Upper	97	1	2 x 8	3 x 8
Mid	130	1	1 x 4	7 x 8
Mid-Lower	160	1	10 x 8	-
Bottom	160	1	9 x 8	-

Initial Assessments

As per DoT's bridge assessment paradigm, comparative assessments were conducted for various potential routes for the transformer 'superload'. Nine structures were flagged for requiring load ratings, which was procured and completed by consultants. It was found the most efficient 165 km transport route was was not viable due to 6 deficient (no-go) concrete bridges. After months of planning, an alternative four-day journey was necessary to deliver the transformer. Level 2 inspections were conducted for all structures, with temporary propping installed for some bridges, prior to the 'superload' transport.

Advanced Assessments

With 149 wind turbines being constructed, the most efficient route was essential to accommodate the multiple moves required for each tower component. Here, DoT engaged with Monash University to apply their ongoing research and conduct advanced bridge assessment for the 6 deficient bridges.

Refined Rating Factor

Load rating reports from the consultants were reviewed and concluded shear failure was the most critical limit state. To refine the rating factors, the computer software Response2000[18], which adopts the modified compression field theory (MCFT), was used to provide a more accurate shear capacity prediction. However, it was noticed for some reports the codified-MCFT design provisions seen in the Australian standards were directly applied, ignoring the need for iteration for predicting shear capacity[19].

Upon refining rating factors with correct application of the concrete shear provisions and Response2000, the concrete pier crossheads were filtered as critical for shear.

Probability-based Bridge Assessment

A desktop PBBA was conducted for the pier crossheads. The uncertainty for section shear capacity, load effect, and prediction models (model error) were characterized[20]. Using two independent software products, the first order reliability method (FORM) was used to quantify β, with the second order reliability method (SORM) used to validate that the limit state function was linear.

For capacity, an approximate and state-of-the-art probability models were created. The approximate model uses Monte Carlo Simulation (MCS) on the code provision, noting the basic random variables that comprise the section capacity (eg. concrete strength, section depth, etc.)[13]. Meanwhile, the state-of-the-art Response Surface Methodology (RSM) was used to create a surrogate model of the Response2000 outputs[21].

For traffic load, given such Class 1 OSOM vehicles have well-defined and controlled loads, it can be considered that axle spacings and axle mass are normally distributed. A range of different coefficient of variations (ratio of standard deviation and mean) were explored. Literature values were adopted for permanent loads, dynamic load allowance, and model error[20].

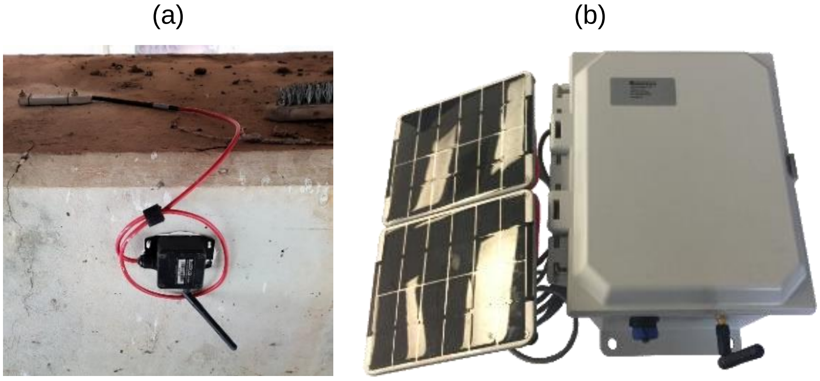
The initial quantified structural reliability indices β were within the range of international acceptance. Discussions were held between DoT and Monash to determine the acceptable level of safety β_T, resulting in some bridges being deemed unsafe and requiring further assessments. Given the PBBA considered the structure in pristine condition and was desktop-based, SHM and field testing was recommended.

Structural Health Monitoring

A bridge monitoring campaign was established for all six deficient bridges. For one bridge, a low frequency wireless system by Resensys was installed, allowing the potential for long-term monitoring. All other bridges adopted a short-term high frequency wired system.

In the wireless system, light-weight strain transducers SenSpots were quickly installed without the need for physical or chemical protection (Figure 3a). The sensors communicate with a data logger SeniMax, which is powered by 5V lithium batteries recharged via solar panels (Figure 3b). The results can be accessed using the software SenSpot on-site immediately or viewed remotely after 30 minutes.

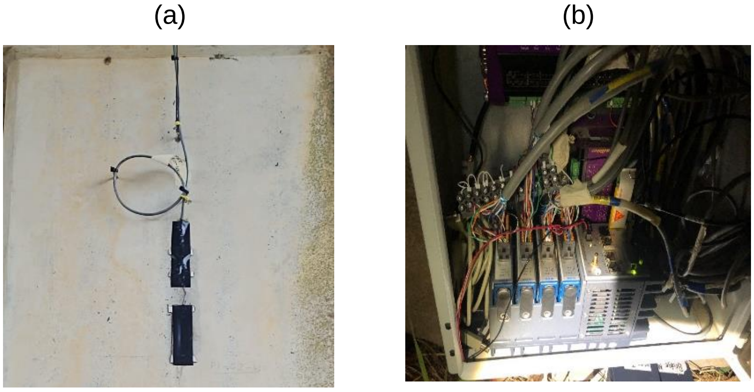
Figure 4 (a) Installed wireless strain transducer on-site (b) SeniMax data logger with solar panel.



Source: Zhang et al. (2021)

The wired system required greater resources, but provides more accurate data, compared to the wireless system. Foil strain gauges were installed at problem areas as identified in previous assessments, each requiring different layers of protection to ensure durability and good surface contact (Figure 4a). Cables connected the sensors to a high-class data logger, requiring a battery source of power and storing results on a local USB (Figure 4b). Using a modem and bespoke software, it was possible to access data remotely.

Figure 5 (a) Wired foil strain gauged installed on-site with protection (b) High-class data logger with strain module, power supply, and USB.



Source: Zhang et al. (2021)

After calibrating devices to known baseline values under normal traffic, the initial overmass load deliveries (Table 1) were permitted network access and the bridge response data recorded. The results were then used to refine the load ratings, adopting strains as load effects rather than shear forces[15]. Whilst some assessments of key locations significantly passed, some concrete pier crossheads in shear were still unsatisfactory. For these cases, PBBA was re-conducted but using the SHM data and noting now reduced uncertainties in load effect and loading model error. The quantified β was higher than first calculated, demonstrating the further movements could safely continue, provided the same bridge response was detected with each move.

4. Discussion

Immediate Outcomes

SHM and PBBA are individually well established in international practice. However, this is one of the first known works that explored combining these aspects in the field, given prior laboratory research[22]. Together with accurate bridge capacity quantification, a framework for advanced bridge assessments has been developed, particularly in route planning of overmass load deliveries with Class 1 OSOM vehicles.

At the start of the approximately 750 deliveries required for the turbine components, the structural response under the Class 1 OSOM vehicle was observed for all six critical bridges through the framework and confirmed to match with previous performance. This validation was firstly conducted on site (Figure 5), then remotely, and assured loads could safely access the road network. Consequently, period permits were issued, ensuring access for subsequent overmass deliveries.

Figure 6 On-site monitoring of tower mid-lower section transport

Source: Colin Caprani (2019)

The deepened collaboration with acedemia, government, and the transportation industry provided a practical outcome with construction of the wind farm completed in mid-2021.

Community Benefit

In this case study, progression to a higher-tier assessment was deemed worthwhile based on necessity. However, through calibration of a VoI framework, it is possible to back-calculate the benefit in having progressed to a higher-tier assessment. Specifically, the value of adopting strain-based SHM for one bridge was investigated[17].

For SHM to have any notable value as a decision support in vehicle access, the VoI calibration exercise indicated the total cost of a bridge failure to be beyond millions of dollars for the desired outcome of removing the restrictions to be a requirement. The substantial value considers both costs to reconstruct the structure and more importantly the indirect costs such as perceived reputation. In other words, through VoI, a cost estimate for the community benefit of a structure is found to be significant.

Knowledge of this community benefit as a cost measure greatly assists asset owners to realign infrastructure budgets and not only consider direct costs of bridge maintenance, rehabilitation and construction.

On-going Impact

The presented framework is already making an impact both in Australia and internationally, with anecdotal evidence of applications seen beyond Class 1 vehicles and road assets. Ultimately, greater training is needed in the areas of PBBA, SHM, and improved bridge capacity quantification. Workshops, conferences proceedings, and journal articles provide the opportunity to educate practitioners. Most significantly, the published free-to-access Austroads guidelines on PBBA[13] is one means in assisting removing any perceived organisation barriers.

There might be some reluctance to train staff in these advanced bridge assessment methods under a competitive market. For the framework to be implemented and adopted more widely, easier cost-benefit considerations for the projects that would gain from the assessments need to be developed. However, those who invest first are likely to reap in the rewards[23]. In this way, rational decision-making on access for all heavy vehicle classes is possible, efficiently and safely utilising structures, resulting in a sustainable and productive road transport network.

5. Conclusion

Bridge assessments for heavy vehicle access decision-making does not need to end as per the conventional deterministic approaches currently the norm in Australia. Overseas practice indicates more advanced and accurate methods exists, which should be explored if deemed economically worthwhile. Through a practical application of multiple Class 1 OSOM vehicle movements in Victoria, a framework combining improved bridge capacity quantification, measured data from structural health monitoring (SHM), and PBBA based on state-of-the-art structural reliability methods has been shown to provide a positive impact. Indeed, the framework allowed the effectual construction of the largest wind farm in the southern hemisphere. Already there has been potential to extend such a framework in granting access to other vehicles and even rail assets. Moreover, through a VoI analysis, the community benefit of structures can be quantified as a cost, assisting asset owners in budgetary planning.

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