BRIDGE MONITORING AND DATA-DRIVEN STRUCTURAL ASSET MANAGEMENT

R. Heywood*, T. Pape, D. Ward, P. Shaw, A. Voll, M. Haldane
Department of Transport and Main Roads, Queensland, Australia
Robert.J.Heywood@tmr.qld.gov.au and Torill.M.Pape@tmr.qld.gov.au

ABSTRACT

The state of Queensland, Australia has a substantial road network with 32,000 km of road with approximately 3,300 bridges. This road network supports diverse economic activity including mining, agriculture, tourism, construction, supply chains, and renewable energy. Over recent years Queensland has experienced substantial growth in heavy vehicles transporting large indivisible items on low-loader and platform combinations.

Bridge monitoring has shown load platforms combinations induce the largest responses in Queensland bridges. Consequently, the management of combinations incorporating platform trailers provides a focus for this paper, which is relevant to all vehicle types.

Bridge monitoring, video and data analytics was used to close the loop between the assumptions and rules that underpin heavy vehicle access to bridges, observed bridge responses and heavy vehicle behaviour.

Observations made from monitoring data has identified non-compliance of mass, driveline and speed of low loader platform combinations accessing the network. Also highlighted are the interactions with other road users and traffic control, the influence of speed, roughness, loading level and vehicle type on the dynamic response of bridges. A trial weigh-in-motion (WiM) and classifier system is under development and aims to overcome the limitations of TMR's current WiM systems in relation to platform trailers and other wide vehicles.

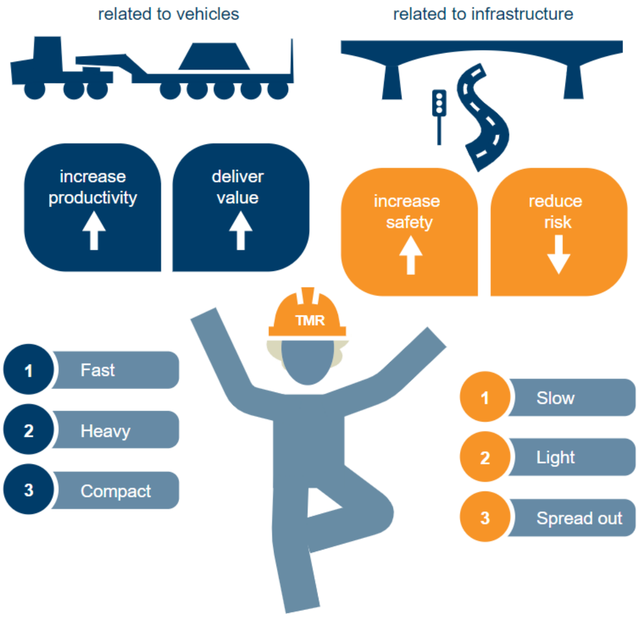
The comparison of bridge responses induced by combinations incorporating platform trailers with other vehicles presents opportunities to enhance data driven access and asset management decisions that will both enhance transport productivity and manage the risk to bridges including fatigue induced reduction in residual life.

1 INTRODUCTION

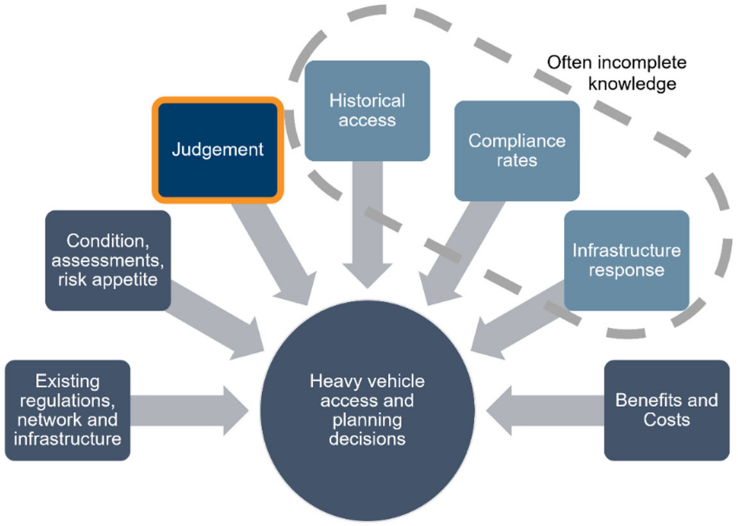
The continuing evolution of heavy vehicles and the increased demand for the transport of very heavy loads driven by the infrastructure and mining boom in Australia are applying pressure on the management of bridge assets. In this context, heavy vehicle access decision makers are regularly required to exercise judgment balancing productivity and risk of damaging bridges, as illustrated in Figure 1(a).

Decisions are often made with incomplete information. This can lead to sub-optimal decisions and potentially uneconomic or unsafe utilisation of bridge assets.

Credible decisions are aided by accessible quality data and information. Decisions that are informed about the actual heavy vehicles accessing the network, compliance rates and how the infrastructure responds are more credible and productive (Figure 1(b)).



(a) Heavy vehicle access and planning decisions are a balancing act



(b) Supporting credible decision-making by providing factual evidence of current and historical access

Figure 1 Credible heavy vehicle access, planning and asset management decision making (adapted from Figure S3 and S4, Karl et. al., 2022)

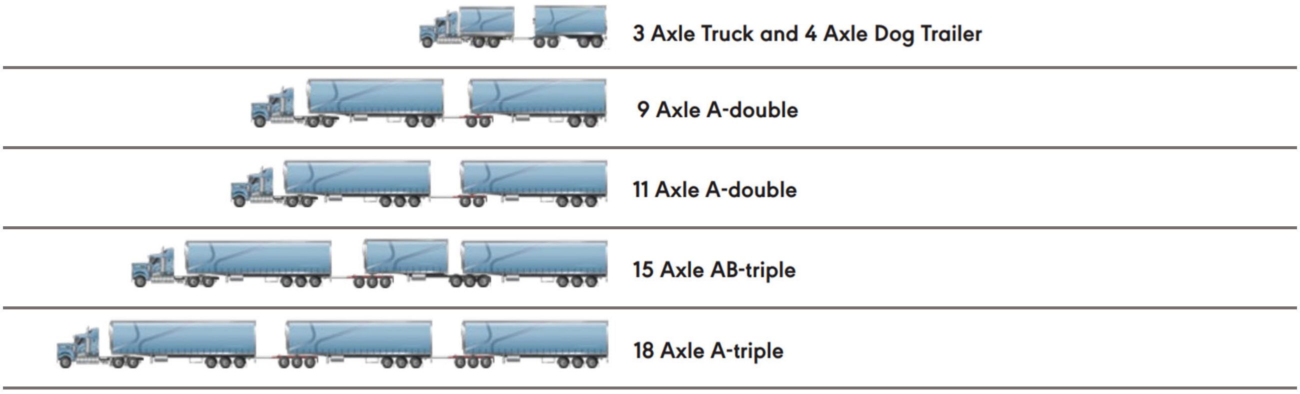
Developments in heavy vehicle data collection technologies and analytics are improving these decisions and challenging in-built assumptions through the delivery of credible, accessible information about the heavy vehicles accessing the network.

This paper sets the context in terms of the Queensland Department of Transport and Main Road's (TMR) bridge assets and the heavy vehicles that access the road network. A brief overview of theoretical assessments and damage to bridges supporting increased heavy vehicles loads follows. The heavy vehicle data, new technologies and data analytics is then discussed. This data provides a feedback loop that is challenging the 'old rules' and 'assumptions' traditionally used to grant access to heavy vehicles and manage the bridge asset. This feedback loop is discussed along with the 'new rules' being developed that incorporate the knowledge acquired and the benefits of new technologies to optimise access and planning decisions.

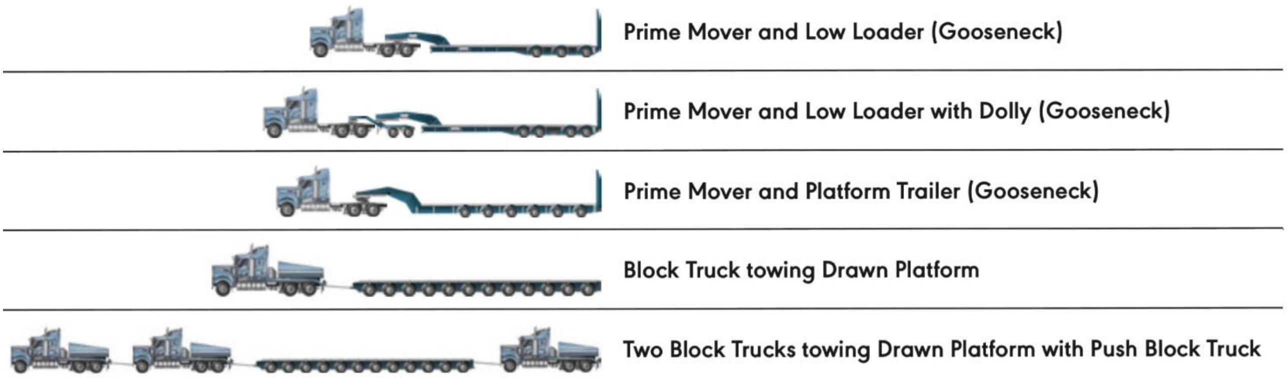
2 QUEENSLAND’S TRANSPORT TASK AND HEAVY VEHICLE FLEET

The state of Queensland, Australia has a substantial road network with 32,000 km of road and 3,300 bridges. This road network supports diverse economic activities including mining, agriculture, tourism, construction, and industry generally. This demand is distributed over a large area resulting in goods bring transported over long distances.

The combination of long distances, predominantly short span bridges, thin rural pavements, and the need for an economic efficient transport network has seen the evolution of a diverse fleet of freight vehicles. Semi-trailers and truck and dog trailer combinations facilitate local transport demand. B-doubles and road trains (refer Figure 2(a)) provide more efficient transport options over the longer distances of the freight network (NHVR, 2019). General access vehicles have triaxle loads of 20t. Higher mass limits of 22.5t for triaxle groups are accepted on selected freight routes for heavy vehicles with road-friendly suspensions. This increase followed the OECD DIVINE project (Cantieni & Heywood, 1997, Heywood 1995, Pape et. al, 2017)) and the subsequent Mass Limits Review (Pearson, 1996).



(a) Freight vehicles



(b) Oversize overmass vehicles (OSOM)

Figure 2 Examples of Australian heavy vehicles (from NHVR, Jan and Feb 2019)

The freight vehicle fleet shares the network with oversize over mass (OSOM) heavy vehicle combinations transporting large indivisible items[*] illustrated in Figure 2(b). Photographs of and these combinations and mobile cranes are presented in Figure 3.

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[*] A large indivisible item *means an item that— (a) can not be divided without extreme effort, expense or risk of damage to it; and (b) can not be carried on any heavy vehicle without contravening a mass requirement or dimension requirement.* Section 116(4) of the Heavy Vehicle National Law Heavy Vehicle National Law (Queensland) - Queensland Legislation - Queensland Government

Figure 3 Mobile cranes and combinations incorporating platform trailers and low loaders crossing the Bee Creek bridge and the Gateway Arterial Flyover.

These vehicles support the development of new infrastructure, industry, agriculture, and mining. Historically, platform trailers were rare, but now have become commonplace in Queensland. Some routes associated with mining have approximately 3,000 platform trailer movements a year.

The continued increase in the number and mass of heavy vehicles accessing Queensland's bridges is raising questions around asset consumption (progressive 'wear and tear' of an asset during its service life), compliance (overloading, driveline, speed, pilot vehicle operation, distribution of load within platforms), and the risk of bridge damage or collapse. Bridge monitoring has shown that heavy vehicle combinations incorporating platform trailers dominate peak bridge responses in Queensland's short span bridges. This is discussed further in Section 5.

3 BRIDGE ASSESSMENTS

Forty-five percent of the highway bridges in Queensland, Australia were constructed before 1976 and were designed to support a 3-axle, 33t truck (H20S16) or smaller. Over 90% were designed for a five-axle 44 tonnes semi-trailer or smaller. Contemporary heavy vehicles are much heavier than these design vehicles.

Consequently, an extensive theoretical assessment of the structural capacities of Queensland's bridges to support these heavy vehicles was undertaken over the last decade (Pritchard et. al. 2014, Heywood et. al. 2014, Shaw et. al, 2015, Heywood et. al. 2017, Moua et. al., 2017, Shaw et. al., 2017). Some of the key findings of these assessments for freight vehicles were:

1) Approximately 10% of the bridges on the freight network are overloaded by freight vehicles when assessed in accordance with AS 5100.7:2017 recommendations.
2) More substructures were assessed as overloaded than superstructures. This is a consequence of assumptions made in the 1960s and 1970s that only superstructures needed to be assessed, and the short spans that dominate Queensland's bridges. Consequently, transport productivity was enhanced by adding more axle groups rather than increasing axle loads. This change led to modest increases in superstructure loading on some bridges but resulted in significant increases in the loads applied to substructures. This oversight was discovered when the substructures were assessed.
3) Most theoretical assessments contained calculation errors and required thorough review. This is consistent with the findings of a review of the UK Highway bridge assessments (Brinckerhoff 2003). ISO/AS 13822:2010 requires assessments to satisfy a "plausibility check" of the assessment versus the in-service performance of a structure. TMR closed these plausibility 'gaps' and built assessments around families of bridges leading to confidence in the assessments.
4) Three categories of bridges were developed to support the risk and access management for freight vehicles (Heywood et. al., 2017):
    a) *Inventory bridges:* Inventory bridges meet the requirements of AS 5100.7:2017.
    b) *Operational bridges:* Operational bridges do not meet the requirements of AS 5100.7:2017 but can remain operational as the risks are considered acceptable following an assessment of the potential consequences of failure and the sensitivity of the assessment to a range of 'operational' parameters. These bridges are actively managed to limit increases in loading and deterioration.
    c) *Intervention bridges:* Intervention bridges risks significant enough to warrant an intervention in the form of load posting, lane reconfiguration, upgrade or replacement. The intervention bridges were characterised by bridges where the consequences of over loading were significant due to the lack of redundancy (e.g., two girder bridges), inspectability or ductility (RID). This philosophy follows the Canadian bridge design code (CSA S6-19), where the target reliability index and resulting load factors vary depending on the levels of redundancy, inspectability and ductility (RID).

TMR documented its policy position on how to manage the bridge asset, including the operational and intervention bridges. Figure 4 summarises the hierarchy of bridges by assessment and highlights the challenge of heavy vehicles such as combinations incorporating platform trailers accessing operational and intervention bridges.

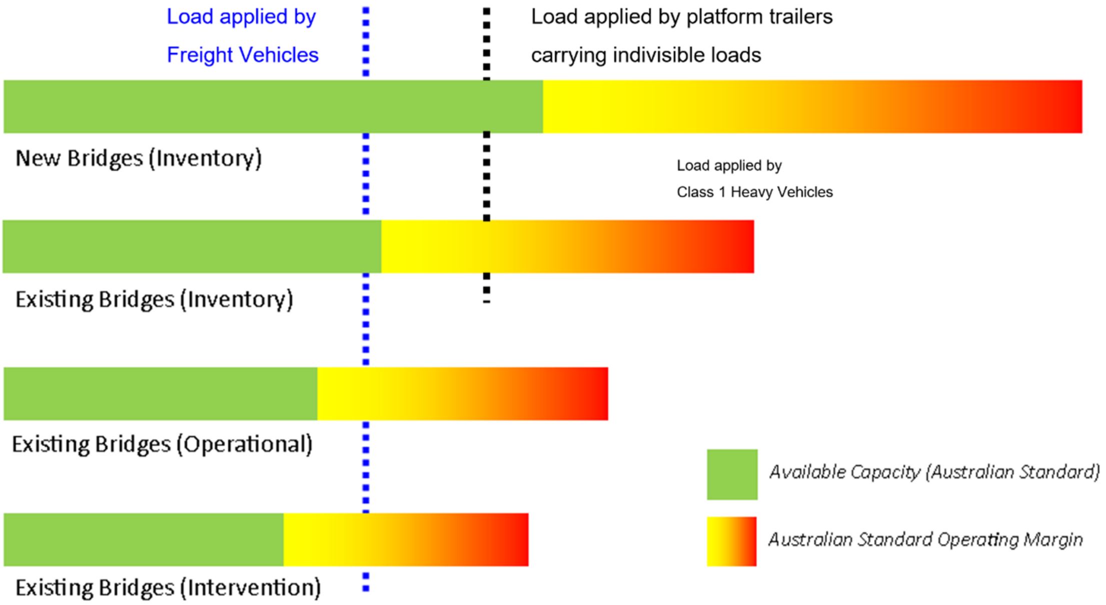

Figure 4 Hierarchy of bridges by assessment outcomes for freight heavy vehicles

Limit state methods for bridge design and assessment were not introduced in Australia until 1992. Most of the access provisions were prior to the introduction of limit state methods. Consequently, access was based around working stress concepts by allowing an ‘overstress’ for the rare passage of combinations transporting large indivisible items (Shaw et. al., 2017). The overstress provision was applied to both the dead and live loads. When assessing these bridges using ultimate limit state methods, the load factors for dead load are smaller than the live loads load factors whereas in working stress methods dead loads and live loads are treated equally. Consequently, ultimate and working stress assessments are quite different. This led to a new round of access changes for mobile cranes, and heavy vehicles supporting the transport of indivisible items (Pape et. al., 2018). In Queensland, extensive access was granted to platform trailers supporting indivisible items during an era when these vehicles were rare. As discussed, changes in demand have made these vehicles more common, as is outlined in subsequent sections.

4 BRIDGE DAMAGE RELATED TO HEAVY VEHICLE LOADS

Historically, in Queensland the most common deterioration issues were related to environmental factors such as corrosion and alkali-silica reactivity. However, in the last decade, there have been more frequent instances of bridges showing signs of structural distress or demonstrating rapid deterioration unrelated to environmental factors. These bridges are often “operational bridges” frequented by platform trailers and other heavy vehicles supporting economic development activities such as mining and industrial applications (Pape et. al. 2022).

The structural issues identified on bridges that relate to the increase in frequency and magnitude of heavy vehicle loads include:

a) *Pier settlement*: Two bridges have experienced settlement of driven piles after more than 60 years of service. The ongoing settlements at the Alice River bridge (refer Figure 5) ceased once the heavy vehicle loads were reduced (Wong et. al., 2022).
b) *Halving joints*: Cracking induced by traffic loading has led to concrete halving joint strengthening at some locations (Lin et. al, 2022).
c) *Bridge bearings*: Some pot or rocker bearings have failed through discharge of the polytetrafluoroethylene (PTFE) sliding material (Hourigan et. al., 2022).

Figure 5 Alice River bridge: Fitting jacking frames to rectify 120mm of pier settlement.
(*Source: Copyright of the Department of Transport and Main Roads, Queensland, Australia*)

d) *Fatigue*: Recently possible concrete fatigue has been identified in concrete bridge decks, as illustrated in Figure 6. Similarly, fatigue cracking has been identified in welded connections in steel girder bridges (Pape et. al. 2022).
e) *Deck joint failures*: There is an increasing number of failures of bridge deck joints and deck slabs adjacent to the trimming angles located at deck joints. (Pape et. al. 2022).

Figure 6 Bee Creek bridge deck slab deterioration

TMR has a responsibility, as a public asset owner, to invest in transport infrastructure wisely, respond to user demand and meet Level of Service requirements while ensuring safe reliable transport for the community. Where possible, optimised, and balanced approaches in accordance with ISO 55000:2014 principles are practiced.

With increases in demand and accelerated levels of deterioration, TMR is investigating the risks posed by heavy vehicles. TMR is investigating the appropriate levels of access to manage the risk of failure or reduced capacity from fatigue. The fatigue risks relate to both the number of heavy vehicles and the potential for the largest loads to damage components and make these components more vulnerable to fatigue from all heavy vehicles. Answering these questions will inform decisions as to when the deterioration and risks are significant enough to trigger investment, as illustrated in Figure 7.

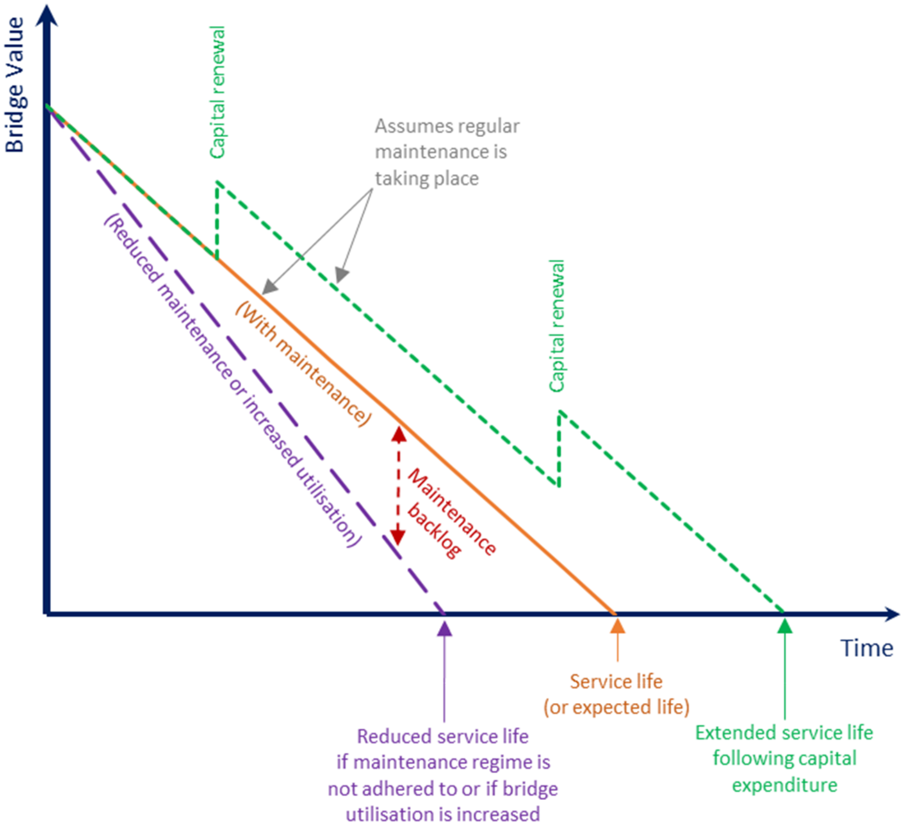

Figure 7 Simplified representation of bridge service life (Source: Austroads Engineering Guideline to Bridge Asset Management, 2021)

TMR has identified the need to improve its understanding on this topic to make risk-informed and optimised decisions in relation to its assets. Given the improvements in recent times in data collection and analysis for both infrastructure and vehicles, TMR has embarked on a journey to take advantage of the various and emerging datasets to inform decisions relating to structural asset management (Karl et. al., 2022, Austroads, 2021). The heavy vehicle monitoring data central to this journey presented Section 5 is informing these decisions.

5 QUEENSLAND HEAVY VEHICLE MONITORING DATA

5.1 Overview

TMR has collected weigh-in-motion (WiM) and classifier data for many decades. Challenges associated with remoteness, thin chip seal pavements, and suboptimal maintenance means that the quality of the data, particularly axle load information, is difficult to sustain over a long period of time (Karl et. al. 2022).

The WiM and classifier data is supplemented with bridge monitoring data. WiM aims to measure the spacing between axles, speed and the stationary axle loads of vehicles. Bridge monitoring aims to measure the dynamic response of the bridge due the vehicles and thus informs bridge risk.

Video recordings of vehicles inducing peak bridge responses has provided insights into the vehicles inducing large bridge responses and the behaviours of heavy vehicle operators.

5.2 Gateway Arterial Flyover

A bridge monitoring system was installed on the Gateway Arterial Flyover bridge (GAF) shown in Figure 8. This system supported the risk management of cracked halving joints during the investigations, design, and construction of the associated strengthening works (Heywood et. al. 2022).

Each span supported two lanes of one-way traffic. The structure featured three simply supported prestressed concrete 'U' girders cast integrally with the deck slab and with halving joints located at each of the piers. The bridge was designed in 1985 to support 44t trucks (i.e., T44 loading) and a 300t ‘abnormal load’ operating on the bridge centreline.

The simply supported instrumented span has a span of 27.3m between the bearings. Three midspan bending strains were monitored in each of the girders to inform the development of a bridge specific live load model for the bridge, and to support activities encouraging compliance with the access restrictions. This bridge monitoring was supported by forward and rear facing field view video cameras with automatic number plate recognition (ANPR) capabilities that only recorded the passage of heavy vehicles inducing large responses in the bridge. The implemented bridge monitoring system was solar powered. Additional data was sourced from upstream piezo based classifier and WiM systems.

Figure 8 Halving joints on cantilever piers supporting Gateway Arterial Flyover (GAF)

5.2.1 Bridge monitoring

Figure 9 summarises 12 months of bridge monitoring data. Each ‘data point' on the graph represents a peak dynamic bridge response induced by heavy vehicles crossing the bridge. During this time, heavy vehicle access to the GAF was restricted to single lane operation.
Each data point in Figure 9 corresponds to the peak dynamic strain induced by the vehicle divided by the peak static strain induced by a reference vehicle. The reference vehicle was the most severe freight vehicle permitted to access the bridge. The identified reference

vehicle was a 9-axle B-double fitted with road friendly suspensions, a regulation gross combination mass GCM = 68.0t, and a maximum wheelbase of 26m (NHVR, 2019).

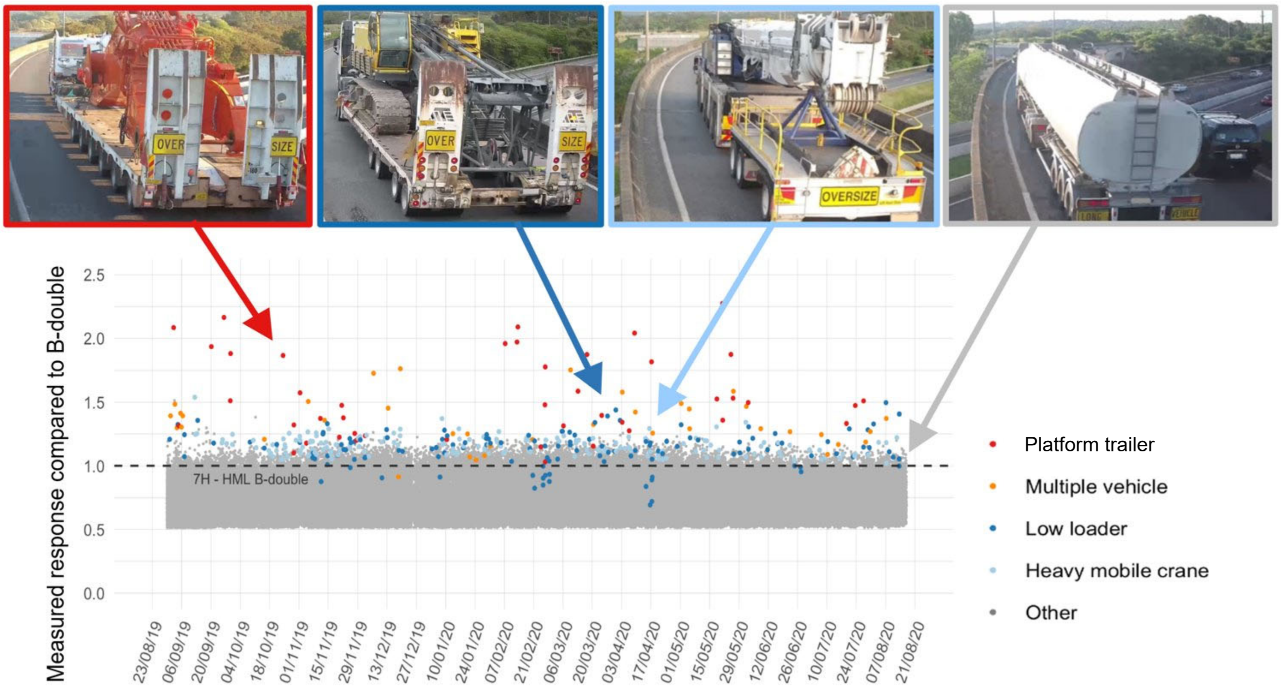

Figure 9 Gateway Arterial Flyover (GAF) bridge monitoring: Peak responses induced by heavy vehicles by vehicle group.

The observations made from the GAF bridge monitoring helped close the loop between the “assumed” and “observed” response of the bridge and the behaviour of heavy vehicles. Groups of heavy vehicles were identified from a combination of the monitoring data and video. This highlighted the significant differences between heavy vehicles presented in Figure 9 and discussed below:

1) *Freight vehicles* (‘other’ and grey dots in Figure 9):
    a) The largest response recorded for freight vehicles during the year of monitoring was 1.4 times the reference B-double. This event was considered a significant outlier as it was greater than estimates of effects corresponding to the ULS (0.05% probability of exceedance in 1 year).
    b) The level of compliance was excellent when compared to the ultimate limit state (ULS) loading used in the assessment of freight vehicles to AS 5100.7:2017. This allowed continued freight vehicles access during substructure strengthening works and avoided superstructure strengthening works.
    c) The ‘multiple vehicle’ or yellow dots in Figure 9, highlight non-compliant events where freight vehicles were identified in both lanes simultaneously. This behaviour was kept within acceptable limits by compliance management officers utilising supplied video and ANPR data of the event.
    d) The typical maximum dynamic increment (DI) induced by freight vehicles was equal to 0.2, as illustrated in Figure 10. This was half the DLA referenced in AS5100.7:2017 ($DLA = 0.4$) and more consistent with the ARCHES (2009) recommendations for smooth roads. This reduction was most likely due to the relatively smooth road profile and lack of frequency matching between the road-friendly suspensions (f = 1 to 2Hz) and bridge structure (f = 4.5Hz) (Cantieni & Heywood, 1997). There was one notable outlier – a grossly overloaded semi-trailer that induced large dynamic effects ($DI = 0.35$). This was consistent with truck mounted cranes fitted with steel suspensions, as discussed below.

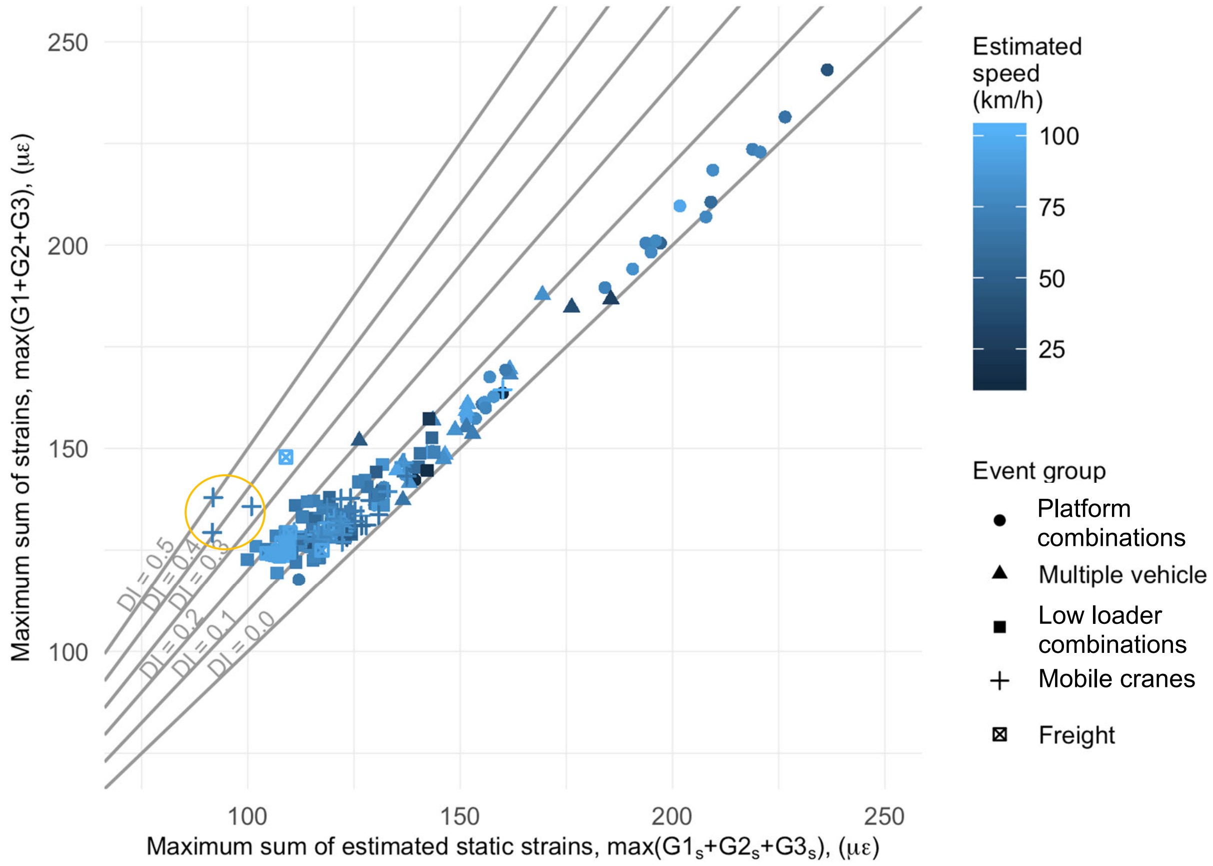

Figure 10 Gateway Arterial Flyover: Maximum observed dynamic strains versus estimated static strains together with lines indicating various dynamic increments (DI) and colour indicating estimated crossing speed for the top 20 crossings of each vehicle configuration on Span 2 of the Gateway Arterial Flyover. The circled mobile cranes are 4-axle truck-mounted cranes.

2) *Mobile cranes* (light blue dots in Figure 9): Four, five and six-axle mobile cranes accessed the GAF. Their peak responses corresponded to larger freight vehicles responses. Investigations revealed considerable variability in the bridge response for cranes despite being of similar type with the same number of axles. This was due to variation in axle spacing and axle loads between models and manufacturers, and some cranes operating non-compliantly with counterweights remaining in place. The dynamic effects induced by the hydro-pneumatically suspended cranes were generally modest ($DI < 0.2$) at GAF. This contrasted with truck-mounted cranes with steel suspensions, where frequency matching was evident producing dynamic increments (DI) up to 50% of the estimated static effects (refer circled markers in Figure 10).
3) *Low-loader combinations* (dark blue dots in Figure 9): The peak dynamic responses induced by low-loader combinations approached 1.5 times the static response of the reference B-double vehicle. The dynamic increments ($DI < 0.23$) were modest.
4) *Platform combinations* (red dots in Figure 9):
    a) The platform combinations operating at restricted load levels generated the largest structural responses at 2.2 times the reference B-double. Thus, the platform combinations had the most potential to damage the flyover. Consequently, they became the primary focus of risk management actions at the GAF.
    b) A persistent education program was required to obtain compliance for the centreline travel restrictions for platform combinations as it differed from the requirement for freight vehicles to travel in the left lane.

c) Compliance with the 10km/h speed restriction was poor. However, the bridge monitoring data at GAF showed the DI of the response was less than 10% over the range of operational speeds up to 100km/h (refer Figure 10). The speed restriction was consequently lifted. This provided road safety benefits from reduced differential speeds between the platform combinations and the general traffic and increased the operational times during the day. This observation applies to this bridge only with its smooth road profile, span length, and fundamental natural frequency.
d) Quasi-bridge WiM calculations also identified likely mass non-compliance.

5.2.2 WiM and classifier data

The presence and significance of the platform combinations contrasted with the data evident in the WiM and classifier data, where they were under-represented. A review of the raw pavement based WiM and classifier data revealed the analysis rules were rejecting events when wide heavy vehicles such as platform trailers occupy more than two lanes (Karl et. al, 2022).

Rejecting a small number of vehicles occupying two lanes is reasonable from a traffic counting and pavement damage perspective. However, there is a lack of visibility of the largest heavy vehicles that represent the greatest risk of severely damaging bridges. Upgraded ‘analysis rules’ stitched data from two or more lanes together identified more platform combinations in the WiM and classifier data but many less than identified by the nearby bridge monitoring system. This highlighted an advantage of bridge monitoring in that wide heavy vehicles are recorded irrespective of their driveline or configuration, which is is not necessarily the case for pavement based WiM and classifier systems.

The above and other observations led to recommendations to: (Karl et. al, 2022):

- Enhance WiM and classifier capabilities to ensure wide loads are accurately recorded, along with the ground contact width*, and the number of wheels per axle.
- Enhance the accuracy of axle spacing data to facilitate the differentiation between similar vehicles and to track similar vehicles through the network using their axle spacing ‘signatures’.

5.2.3 Traffic control

Maintenance activities at bridges occasionally need to restrict the lanes accessed by traffic. This creates a dilemma for truck drivers operating under a permit requiring centreline travel but being directed by traffic control to adopt a different driveline. Bridge monitoring and video observations show that heavy vehicles, including platform trailer combinations, follow the traffic control provisions rather than the permit conditions. At GAF, the largest bridge responses were generated when traffic control directed all vehicles to operate adjacent to a kerb, rather than the prescribed centreline travel. The bottom right photo in Figure 3 is of the platform trailer inducing the largest bridge response. It was operating in the right-hand lane consistent with traffic control but contrary to permit restrictions. This highlights a disconnect between asset management (i.e., maintenance) and access management.

5.3 Bee Creek Bridge Monitoring

5.3.1 Introduction

The Bee Creek bridge is a four span, two-way two lane prestressed concrete girder structure located in an agriculture and mining area of central Queensland. Each of the four spans is simply supported with a span length of 17.88m. A reinforced cast in-situ concrete deck slab

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* Distance between the outer edges of the tyres on an axle

acts compositely with three prestressed concrete 'I' girders. The bridge, located on the Peak Downs Highway, was constructed in 1968 for a H20S16 design vehicle (33t truck).

Statistically, the Peak Downs route supports the largest number of platform trailer movements in the state as well as road trains, mobile cranes, and low loaders. The Bee Creek bridge was identified as a critical asset on this road network because of the heavy demand and the distress evident in the deck slab (refer Figure 6). Site investigations and data analysis also revealed that it was most likely being overloaded from frequent movements of platform trailers combinations primarily transporting very heavy mining equipment to and from mine site for servicing (refer Figure 3).

The bridge monitoring system at Bee Creek quantifies the response of the bridge to the heavy vehicle traffic by measuring slab and girder bending strains, speed, direction, axle spacing, and ground contact width. This is supplemented with rear and forward-facing field vies video cameras that are ANPR capable. This data is only collected for heavy vehicles. The monitoring data set is supporting initiatives to enhance the sustainability of bridge assets and the efficiency of the transport system while encouraging improved behaviour of heavy vehicle operators.

5.3.2 Bridge monitoring observations

Figure 11 presents a comparison between the peak of the measured midspan bending strains induced by platform combinations (dark blue points) to that of other heavy vehicles (grey points) over 11 months in 2022. The other heavy vehicles include road trains, mobile cranes, and low loaders.

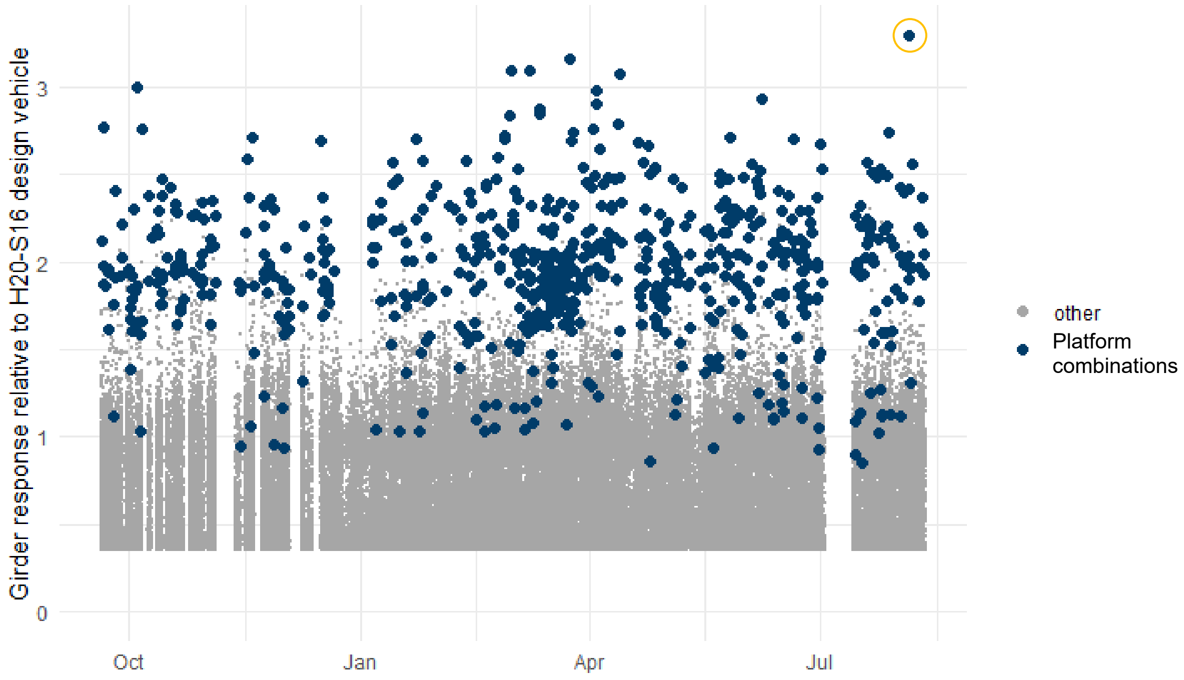


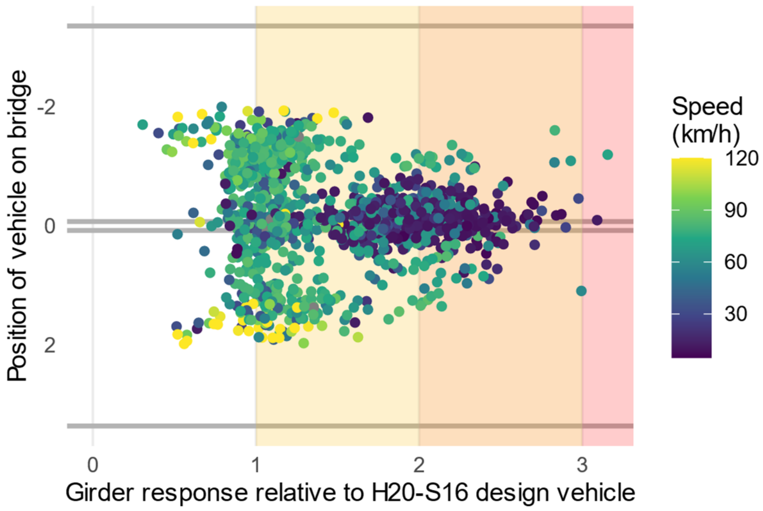
Figure 11 Bee Creek: Comparison of peak midspan girder bending response of platform combinations to that of other heavy vehicles (94,121 heavy vehicle events in 2022)

The platform combinations dominate the peak responses despite the presence of higher mass limits road trains, mobile cranes, and low loader combinations. The highest girder bending strain was 3.4 times that of the H20S16 design vehicle applied to both lanes and is circled in Figure 11. This is approximately 1.5 times the peak measured strains from all other vehicles. Every 2 to 3 days the bending strains from the platform combinations exceed largest response from all other vehicles over almost a year of monitoring. This highlights the high relative risk of bridge damage associated with the platform trailer combinations.

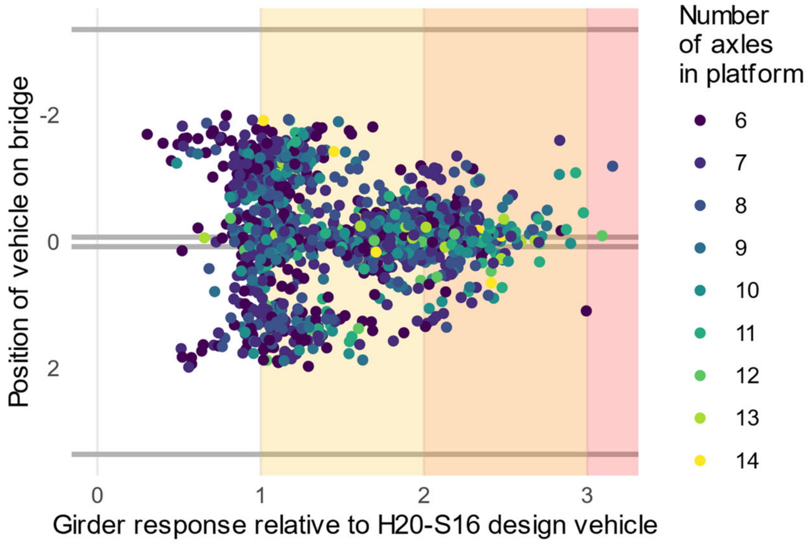
5.3.3 *Interaction between speed, driveline, and bridge response*

Platform trailers accessing the Peak Downs Highway route are typically configured with 6 to 14 axles and often include a tandem dolly. Generally, one prime mover pulls the trailer/dolly configuration but occasionally a block truck is used behind to support the configuration on uphill grades.

Platform combinations on Bee Creek were to operate on the bridge centreline with a speed restriction of 10km/h for platforms of more than 10 axles and axle loads exceeding 13.5t per axle. Figure 12 summarises the speed, peak load effects, and driveline of the platform trailer combinations crossing Bee Creek.



(a) by speed



(b) by number of axles in platform

Figure 12 Bee Creek: Influence of the position of the vehicle on the bridge, speed, and number of axles in platform trailers.

This data provides feedback on the assumptions under pinning access decisions and compliance with respect to driveline and speed. Observations from Figure 12 include:

1) Most platform combinations operated on the bridge centreline as per the permit conditions, however many operated in lane or partially in lane, even when loaded, rather than on the centreline.

[14] XXVIIth World Road Congress

2) Platforms travelled at speeds up to and above the 100 km/h speed limit. There was a tendency for smaller platforms to operate in lane at speed.
3) The larger midspan girder bending strains corresponded to:
    a) Large platform trailers with 10 or more axles operating slowly on the bridge centreline, as per the conditions of access. The largest effects were induced in the central girder had minimal dynamics due to the slow speed and centreline operation. This is the desired behaviour.
    b) Shorter platform trailers (i.e., with 6 to 8 axles) operating at speed and in lane induced significant dynamic effects and generated large responses in the edge girders. This is undesired behaviour.
    c) Platform trailers operating in lane due to road maintenance and traffic control on this narrow bridge, which is 7.32m between kerbs. This again highlights the conflict between necessary asset maintenance, access and managing the loads applied to bridges.

5.3.4 Fatigue

The concrete deck slab is cracking (refer Figure 6) and large areas of delamination have required repair. Potential contributors to this damage include inferior construction; 50 years of freight vehicle traffic; and increasing numbers of much heavier platform trailers. Bridge monitoring data shows that platform trailers induce much larger responses in the deck slab than other heavy vehicles. This is raising concerns that the platforms are cracking the deck slab thus making the deck slab vulnerable to fatigue damage from other heavy vehicles.

5.3.5 Load distribution within platform trailers

Bridge access decisions usually assume the loads are equally shared between axles in a platform. Related observations that challenge this assumption include:

a) Axles can be lifted as an alternative to stopping (in potentially unsafe locations) to replace tyres or to improve traction by transferring more load to the drive axles.
b) Hydraulic suspensions allow different axle groups to be connected to different hydraulic circuits. This is necessary to ensure trailer stability and leads to unequal load distributions. For example, the axle loads can vary by ±10% when the centre of gravity of the loading is offset from the centre of a drawn trailer. This translates into similar increases in bridge responses, especially in shorter span bridges.

5.3.6 Interaction between platform trailers and other vehicles

Wide platform trailers occupying two lanes operate with industry pilots or police escorts. This can require oncoming traffic to stop to enable wide platforms to pass, causing traffic delays. Mandating a 10km/h speed restriction over bridges exacerbates the consequent public safety issues, which in turn encourages heavy vehicle drivers to drive in-lane at speed rather than slowly on the bridge centreline to protect the bridge. Thus, there is a balance between managing bridge damage, public safety, and access by platform combinations.

5.3.7 Role of temporary plates on the dynamic bridge response.

Under the right combination of speed, vehicle mass, surface roughness and suspension, the suspension can couple dynamically with the bridge superstructure to generate large dynamic responses (Cantieni & Heywood, 1997). This behaviour is illustrated in Figure 13. The large dynamic response was induced by a steel plate covering a damaged deck joint causing each trailer axle to become airborne and ‘bounce’ across the following span.

The peak dynamic girder bending response in the span after the plate was 4.3 times the estimated peak static bending strains in the span before the plate was struck (i.e., $DI = 4.3$).

This is more than 10 times the nominal dynamic load allowance ($DLA = 0.4$) used for assessment. The dynamic response was so significant that the peak dynamic strain from this empty semi-trailer crossing the plate was larger than the peak responses from typical loaded B-doubles and road trains although less than the responses from the platform combinations, also crossing the plate.

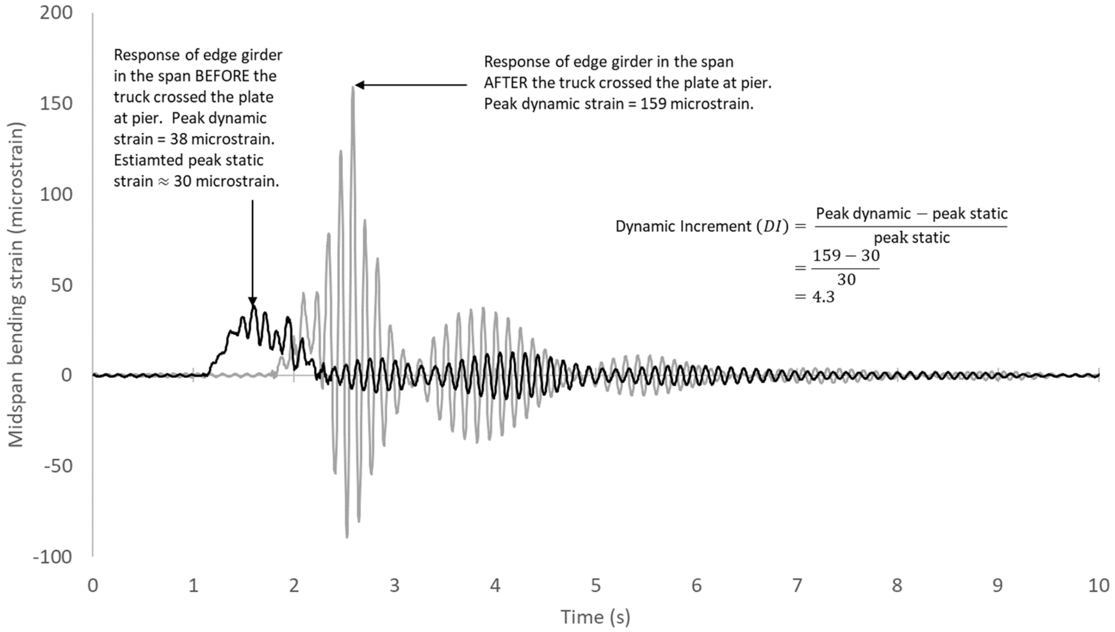


Figure 13 Bee Creek: Large dynamic response in edge girders induced by an unladen semi-trailer crossing a 300mm x 16mm steel plate at a pier.

The large dynamic response induced by heavy vehicles crossing the plate highlight the contribution of road roughness and maintenance to bridge response and fatigue induced wear. Fortunately, as the mass increases this dynamic component reduces (refer Figure 10 and Cantieni & Heywood, 1997). The removal of this plate has largely eliminated this effect. The periodic waxing and waning evident in the response were largely due to a combination of closely spaced flexural and torsional vibration modes in the bridge.

5.3.8 Bee Creek WiM System

A pavement based WiM system is currently being commissioned to the north of the Bee Creek bridge. This system is intended to capture wide vehicles such as low-loaders, mobile cranes, and platform combinations straddling multiple lanes. It aims to improve the quality and reliability of WiM and classifier data as well as measure the width of axles and the number of tyres per axle. The combination of the WiM system and bridge monitoring system will provide an opportunity to enhance the value of these systems by combining data sets.

6 DISCUSSION

Commonly, bridge access decisions are determined by applying bridge design codes that have been modified for assessment such as Australia's AS 5100.7:2017. Most bridge assessments in Australia use the ultimate limit state approach with prescribed live load factors and dynamic load allowances. Some but not all heavy vehicles accessing the network are overloaded according to AS 5100.7:2017.

Heavy vehicle related fatigue and structural distress provided the impetus to investigate bridge access both theoretically and through bridge monitoring. The datasets presented above challenge the traditional assessment assumptions embedded in AS 5100.7:2017. The bridge monitoring is providing a feedback loop that has challenged the traditional assumptions and rules managing access and asset management of Queensland bridges.

Compliance management of heavy vehicles focuses on overloading of axle groups. However, further statistical information is required to understand and manage the risks of damaging or collapsing bridges. Bridge monitoring over extended periods has proven a valuable technique for quantifying bridge response within the ‘system’, especially when supported by field view video cameras. This ‘system’ includes the laws and regulations governing access, the compliance management regime, transport demand, heavy vehicle driver behaviour, road roughness, speed, the dynamic interaction between bridges and heavy vehicles, vehicle configuration and dimensions, driveline, permit conditions, maintenance and traffic control, axle group loads, and the distribution of load within and between axle groups. These ‘system parameters’ are non-transparent components of assumptions adopted from design standards to ensure a safe and conservative design and then applied to assessment without the necessary refinements.

The power of the bridge monitoring data presented above lies in the identification of heavy vehicle groups and their parameters tied to the bridge’s response. This grouping made it visually obvious that platform combinations generated the largest bridge responses and were not well controlled. Conversely, the data showed freight vehicles were well controlled. This is the reverse of traditional thinking. Platform combinations transporting large indivisible items have traditionally been allowed to ‘overstress’ bridges (smaller live load factors) due to the control and rarity of these vehicles. However, freight vehicles have not been allowed to overstress bridge (larger live load factors) due to the lack of control and larger numbers. Consequently, this data set is challenging these assumptions and changing heavy vehicle access and bridge assessment assumptions.

Closing the loop between bridge assessment assumptions and the response of bridges lies at the core of a transparent sustainable bridge access and bridge risk management system. Bridge monitoring in combination with (or integrated with) WiM provides the data to close this loop and the statistical data needed to generate assessment parameters consistent with the loads accessing the network. Bridge monitoring allows fatigue stresses cycles to be measured to inform fatigue life, the combined effects of live load factors (LLF) and dynamic load allowances (DLA) or $LLF(1+DLA)$ to be estimated for the ‘system’. These key assessments cannot be measured with the same level of confidence any other way.

There are of course challenges. Estimating the $LLF(1+DLA)$ in Queensland short span is relatively straightforward for freight vehicles but is increasingly more difficult for cranes, and low loader and platform combinations. This is because it takes much longer to collect statistical sample from these vehicles compared to freight vehicles as there is considerable variability in vehicle configurations. The Bee Creek bridge project is providing insights into these statistical parameters and will inform the assessment, access management, asset management, planning, investment, safety and productivity of Queensland’s bridge network.

7 WHERE TO FROM HERE?

The access to Queensland’s bridge assets by low-loaders and platform combinations, and mobile cranes is under review. Through best practice engineering and industry collaboration, TMR is developing a new access regime. This is to optimise safe and sustainable access by managing risks posed to road users and bridge assets by these vehicles, while acknowledging the importance of industry productivity and community safety.

There is an opportunity to supplement independent heavy vehicle data collected by WiM, classifier, and bridge monitoring data with the in-vehicle telematic systems. Telematics Monitoring Application (TMA)[*] and Smart OBM[†] data is important to assessing access.

Video and video analytics linked with ANPR information is becoming more common. This data provides opportunities to merge existing data sets to increase quality and extrapolate WiM, classifier and bridge monitoring data to locations without WiM or bridge monitoring. This concept of 'virtual WiM' is discussed further in the NACOE S26: Virtual WiM – Enriching WiM and Enhancing Decisions (2018–21) (Karl. et. al., 2022). Technologies and systems are being investigated to provide enforceable mass, and speed and driveline data for heavy vehicles accessing the network linked to automated enforcement practices such as camera detection offences.

The developments in database and data analytics are providing opportunities to break down data silos to facilitate the integration of data sets to improve visibility, accessibility, and knowledge of heavy vehicles accessing the network. This assurance data provides confidence of mass and network usage to support engineering assessment assumptions. It is vital to sufficiently inform access and asset management, planning and investment in infrastructure, and structural fatigue models to understand what is aging bridges prematurely.

The keys to successful utilisation of these emerging datasets include ensuring quality data that is accessible, the intelligent application of the data, and the development of 'new rules' that enable incorporation of the knowledge into day-to-day evidence-based decision making. The development of an Austroads guideline for the assessment of bridges based on the risk informed philosophy encapsulated in ISO 2394:2015 is a step in the development of these new rules (Shaw et. al., 2022). Similarly important, is the proposed development of appropriate bridge assessment parameters such as appropriate $LLF(1+DLA)$ parameters that reflect the performance of the 'system' for all vehicle groups, especially load platform combinations.

The development of skills for the intelligent application of data also needs to be developed to close the loop and provide feedback on the consequences of past decisions on the current performance of the bridge asset and the productivity and fairness of the transport system. This includes the development of bridge specific live load models for families of heavy vehicles and short span bridges that close the loop between assumed heavy vehicle behaviour embedded in access decisions and the outworking of the compliance management regime, safely and transport demand.

8 CONCLUSIONS

Queensland has experienced substantial growth in heavy vehicles transporting large indivisible items on low-loader and platform trailer combinations. These vehicles represent the largest risk of damaging the bridges they access.

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[*] Telematics Monitoring Application (TMA) is an in-vehicle system that monitors parameters of location, time and identity. TMA can also monitor mass (with a Smart OBM system) and vehicle configuration, or the self-declaration of data through a user interface. Telematics Monitoring Application (TMA) - Transport Certification Australia (tca.gov.au). Accessed Feb 2022.

[†] Smart OBM systems are digitally connected on-board weighing devices that use digital technology to collect and transmit mass data from vehicles in a reliable and standardised way. Smart OBM Systems - Transport Certification Australia (tca.gov.au). Accessed Feb 2022.

The effects induced in bridges by freight vehicles, mobile cranes, and heavy vehicles transporting large indivisible items are challenging the assumptions and providing opportunities to enhance public safety, compliance management, bridge assessment, fairness, transport productivity and sustainability.

Bridge monitoring, video and data analytics is supporting evidence-based asset management of bridges subjected to these vehicles. This is challenging the assumptions and rules that underpin heavy vehicle access and asset management, while providing opportunities to enhance sustainable access through improved engineering and compliance, and evidence-based investment.

Observations from the bridge monitoring data highlighted the risks associated with non-compliance of mass, driveline and speed of platform trailers accessing the network. This evidence, in combination with new technologies and sound engineering is facilitating the development of a new access regime, policies and procedures to encourage higher levels of compliance, improved risk management, sustainability and better investment decisions.

The data is supporting a learning culture, information-driven decisions underpinned by the fundamentals of engineering and asset management.

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