DYNAMIC BRIDGE-VEHICLE INTERACTIONS

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ABSTRACT

The interaction between vehicles and bridges remains a complex yet important concept in the assessment of dynamic loading on existing structures. The dynamic impact of vehicular loading on a structure is typically accounted for in the assessment procedure by the application of a dynamic load allowance (DLA) factor to the assessment load, with a factor of 0.4 specified in the Australian bridge design code AS 5100. This factor is historically based on empirical dynamic load test data that underpins the Canadian bridge design codes. The Queensland Department of Transport and Main Roads (TMR) has adopted the AS 5100 DLA factor in its base level, Tier 1 Bridge Heavy Load Assessment Brief (2013). However it is looking to develop a better understanding of a family of bridges for higher-order bridge assessments when adopting dynamic load factors, taking into account various vehicle and structure types and dynamic influences. This in turn may lead to a review of vehicle access and ensure efficient use of resources. To address these issues and to improve understanding on bridge-vehicle interactions, TMR has initiated a three-year research program in conjunction with ARRB Group. This paper presents the findings from the first year of the program.

In summary, a detailed literature review has yielded valuable information pertaining to various factors influencing the assessment of bridge-vehicle dynamic interactions and the background to the adoption of the current DLA factors. A gap analysis has shown that very little practical information has been published regarding the dynamic impact of hydro-pneumatic cranes and road trains on bridges. A significant review of previous load test reports from national and international jurisdictions revealed that various structure types, vehicle types, and materials can influence the dynamic response of a structure to dynamic loads. Frequency matching between vehicles and structures can also result in significant load amplification. A recent load test on Canal Creek Bridge in Cloncurry, Queensland, using various vehicle types and suspensions supports these observations. Finally, a review of the viability and applicability of the development of a Vehicle-Bridge Interaction model for TMR use has been conducted. Additional field tests are scheduled as part of the program, with validation and calibration of models and experimental findings and recommendations to be completed in the final year.

INTRODUCTION

TMR is responsible for over 3000 bridges and 4000 major culverts, with a gross replacement asset value in excess of $11 billion. Of this number, there are bridges that are subject to load and permit restrictions. Costs to upgrade or maintain these structures in order to address these limitations are in the order of $120 million.

In the assessment of these structures, the dynamic interaction between bridges and vehicles remains a key consideration. To account for the amplification of live loads imposed on a structure due to the passage of vehicles, the application of numerous published and codified load factors is required, to ensure that acceptable factors of safety are maintained. This is particularly important where maintenance and strengthening of structures require deferral.

A significant amount of national and international research has been conducted in the last few decades regarding such interactions and the amplification of wheel loads on structures, of which various Dynamic Load Allowance (DLA) factors have been recommended and discussed. The current Australian Bridge Design Code AS 5100 (2004) applies an additional DLA factor of 0.4 to existing live load factors, regardless of vehicle or structure type. This factor is historically based on empirical dynamic load test data predominantly carried out in Ontario in the mid 1980s and underpins the Canadian bridge design codes, which has formed the basis of many other international design codes. TMR has adopted the AS 5100 DLA value in its base level Tier 1
Bridge Heavy Load Assessment Brief (2013). However, it is looking to develop a better understanding of a family of bridges for higher-order bridge assessments when adopting dynamic load factors, accounting for various vehicle and structure types and dynamic influences. This is particularly of interest with the evolution of ‘road-friendly’ suspension-type vehicles (such as hydro-pneumatic cranes and air suspension vehicles), improved vehicle design/technology, and the move towards performance-based (PBS) heavy vehicles in recent times. An improved understanding of vehicle-specific interactions with supporting structures may lead to a review of vehicle access, increases in network efficiencies and eventual wide-ranging economic benefits.

At present, limited testing and information exists regarding the dynamic influence of newer vehicle types on bridges, particularly regarding the actual DLA factors that might be associated with such vehicles and particular bridge types. Furthermore, whilst detailed models have been developed nationally and internationally in regard to bridge-vehicle interactions, no predictive tools have been established to provide an estimation of anticipated DLA factors for certain vehicle-bridge combinations, a key factor in the assessment of at-risk structures. To address these challenges and improve understanding on bridge-vehicle specific interactions, TMR has initiated a three-year research program in conjunction with ARRB Group. This program includes a review of existing literature, field testing and detailed instrumentation, and modelling. The following sections provide an overview of the outcomes and recommendations made in the first year of this program.

**REVIEW OF DYNAMIC LOADING AND AMPLIFICATION**

**Background**

Recognition of the influence of dynamic loads on supporting structures has been long established. Willis (as cited by Cantieni (1983)) conducted a series of systematic laboratory tests in 1849 that determined that the dynamic response of railway bridges to live load was influential in the event of the collapse of several rail bridges in Britain (Cantieni, Krebs & Heywood 2010). Renewed research interest in bridge-vehicle dynamic interactions has taken place in the last few decades with the advent of increasing mass limits on bridges, increasing pressure to extend the service life of existing structures, and the evolution of new vehicle designs and technology (Bakht & Pinjarkar 1989; Cantieni 1984). There is also an increasing need for asset owners to understand the dynamic implications such live loads pose on existing structures, and to predict how vehicles and structures interact dynamically to enable the development of appropriate maintenance measures and permit requirements.

Dynamic loads imposed by a vehicle are described as a function of the static or stationary live load applied to a structure. The system is described graphically in Figure 1. The ratio between the maximum dynamic and static structural response induced determines the magnitude or the dynamic amplification of static loads, and has historically been quantified using terminology such as the Dynamic Load Factor (DLF), Dynamic Amplification Factor (DAF), Impact Factor (IF), or Dynamic Increment (DI). This terminology has been in existence since the early 1930s, where Fuller et al. (as cited by Bakht and Pinjakar (1989)) defined the ‘impact increment of dynamic force’ as being ‘the amount of force, expressed as a fraction of the static force, by which the dynamic force exceeds the static force’.

[Source: Bakht and Pinjakar (1989).]
Acceptable limits for dynamic load amplification are typically defined in various codes, with
Australian design codes adopting the terminology of DLA factor. This terminology will be used
herein when referring to code requirements for dynamic amplification, whereas reference will be
made to DI when reviewing the measured dynamic response of a structure.

Factors influential on the amplification of dynamic loads

The magnitude or the amplification of the dynamic load is dependent on a number of factors,
predominantly the mass and dynamic properties of the vehicle, the dynamic characteristics of
the supporting structure, and the condition of the pavement that provides the interface between
the vehicle and the bridge. There have been several significant reviews regarding factors that
are influential in the amplification of dynamic loads between bridges and vehicles (Austroads
2003; Bakht & Pinjarkar 1989; Billing & Agarwal 1990; Cantieni 1983; Gonzalez 2009a;
O’Connor & Pritchard 1985; Paultre, Chaallal & Proulx 1992; Wekezer et al. 2008). These can
be differentiated between the dynamic characteristics of the bridge, the influence of the road
profile itself and the vehicle. A brief summary of these influential factors is provided in the
following sections.

Dynamic bridge characteristics

The extent to which a bridge will respond dynamically to the passage of vehicles is dependent
on factors relating to the geometric, material and inherent dynamic characteristics of the bridge.
In summary these factors are:

- Natural/fundamental frequency of the bridge – related to the span length and the stiffness of
  the bridge. Bridges with shorter spans can be more sensitive to dynamic effects, resulting in
  significant dynamic load amplification (Hwang & Nowak 1991).
- Bridge geometry – certain structure types are known to result in amplified or reduced
dynamic loads, i.e. skewed or curved structures (Burdet & Corthay 1995).
- Damping capability of the bridge – the natural level of bridge damping ranges between 1-5%,
  with the greater the damping the smaller the induced dynamic effects (e.g. (Moghimi &
  Ronagh 2008a). Damping characteristics are more likely to be critical for successive vehicle
  loadings.
- Boundary conditions on a structure – the fixity, bearing, or restraint details of a bridge are
  known to influence its dynamic response (Gonzalez 2009a).

Road profile

The condition of the deck and approaching road surface has consistently been identified as a
significant factor in the amplification of dynamic loads on a bridge (Austroads 2002a;
Cantieni 1992; Fryba 1972; O’Brien, Li & González 2006). With decreasing road surface quality,
dynamic loads imparted to the bridge increase, thus increasing the potential for structural
damage. This factor combined with poor vehicle suspension/damping characteristics can
magnify the damage incurred. Heywood et al. (2001) showed that dynamic effects were greater
for road profiles with an International Roughness Index (IRI) greater than 4mm/m (i.e. an older
pavement with some surface imperfections).

Vehicle characteristics

Vehicles have their own inherent dynamic properties that individually contribute to the dynamic
loading on a supporting structure. Some of the key variables are:

- Speed – certain critical velocities result in peak dynamic amplification. Higher vehicle
  velocities do not necessarily result in greater dynamic loading, whereas the combination of
  road profile condition and vehicle speed does (Ashebo, Chan & Yu 2007; O’Brien et al.
  2009).
Vehicle mass – several publications state that an increase in vehicle mass will result in a decrease in dynamic load amplification. Conversely, lighter vehicles are capable of inducing significant relative dynamic responses (Pritchard 1982).

Suspension type – certain suspension types can result in significantly amplified or reduced dynamic effects. For example, steel suspension systems are more likely to result in greater load amplification in comparison to air or pneumatic suspension types (Green, Cebon & Cole 1995).

Shock absorber type – similar to suspension types, the damping capability of the vehicle’s shock absorbers will determine the severity of the dynamic effects (more sensitive for air suspension types (Austroads 2003)).

Axle spacing and configuration – the length and axle configuration is known to be influential in the dynamic amplification of loads. Generally, vehicles with shorter axle configurations are more likely to induce an increased dynamic response in the supporting structure (Billing & Agarwal 1990). Similarly, single or tandem axle configurations are more likely to result in higher dynamic loading than tridem axles configurations (Cantieni, Krebs & Heywood 2010; O’Connor & Pritchard 1985).

Vehicle type – rigid trucks are more likely to induce greater dynamic loads than articulated semi-trailers and road trains. There has been very little published in relation to hydro-pneumatic cranes, however research conducted by Heywood (1998) suggests that these vehicle types produce the smallest dynamic effects of the above-mentioned heavy vehicles.

Vehicle position – the dynamic response of a bridge can be significantly altered depending on the transverse location of the vehicle on the bridge. Deck and girder bridges are known to be more sensitive to the position of dynamic wheel loads (Bakht & Pinjarkar 1989; Rattigan, OBrien & Gonzalez 2005).

Multiple presence of vehicles – this accounts for multiple vehicles in a single or multiple lanes, either in the same or opposing directions. The presence of multiple vehicles is associated with a reduction in dynamic amplification (Rattigan, Gonzalez & O’Brien 2009).

Significant dynamic load amplification can also be achieved if the fundamental frequency of the bridge harmonises with one or more of the vehicle’s inherent dynamic frequencies (such as the body-bounce or axle-hop frequencies). This is known as ‘quasi-resonance’ or frequency matching (Austroads 2003).

The determination of dynamic load amplification

For the quantification of dynamic load amplification, there are a variety of methods and terminology that have been published and utilised over the last few decades. The base concept has been in use since the late 1800’s (first applied by Willis, as cited by Cantieni (1983), defining the amplification as the ratio between the maximum dynamic and static strains, stresses or deflections induced in a system. Subtle differences in terminology exist, from DI, DLA, IF and DAF. DI is adopted herein.

Bakht and Pinjarkar (1989) reviewed various numerical methods used to quantify dynamic amplification in previous investigations. The review included a comparison of values calculated using different methods, showcasing the significant variations that can be obtained depending on the definition adopted. The study also highlighted inconsistencies and lack of uniformity in the presentation of dynamic data. Cantieni (1983), in an attempt to normalise results from the extensive Swiss Federal Materials Testing and Research Institute (EMPA) field test database, also provided a small review of the methodology historically adopted by EMPA in the quantification of dynamic effects. From both reviews, a preferred numerical method was confirmed, which is shown in Equation 1, defining the resulting factor as the DI. The relationship is also shown graphically in Figure 2. This method has traditionally been implemented in the majority of Australian field tests and other similar investigations (e.g. Senthilvasan et al. (1997)), also adopting the terminology of DI. Peak DI values for a specific bridge are subsequently compared to DLA values specified in AS 5100.2. This methodology has been adopted for the current project.
\[ \Phi = \frac{A_{\text{dynamic}} - A_{\text{static}}}{A_{\text{static}}} \times 100 \]

where

\[ \Phi = \text{Dynamic Increment (DI) (expressed as \%)} \]

\[ A_{\text{dynamic}} = \text{the peak dynamic strain or deflection in relation to live load at elevated speeds} \]

\[ A_{\text{static}} = \text{the peak static strain or deflection in relation to live load at speeds less than 5 km/h} \]

\[ \Phi \text{ dynamic} = \text{the peak dynamic strain or deflection in relation to live load at elevated speeds} \]

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Historically, the first significant report on the standardisation of dynamic load amplification in bridges was conducted in 1931 by a committee of the American Society of Civil Engineers (cited by Paultre et al. (1992)). From this report, a number of amplification factors were recommended for various superstructure elements for the application to similar structures. Several field tests were carried out by a number of international jurisdictions to investigate the dynamic behaviour of structures, noting that deflection limits were not always an accurate representation of dynamic behaviour and that the amplification of dynamic loads required further research and quantification. Results from several significant research programs were published, the findings of which have been thoroughly reviewed by Paultre et al. (1992).

Specifically, recommendations on DLA factors from research conducted by the Ontario Ministry of Transportation and Communications (MTC) (Billing 1982; Billing & Green 1984) and the
EMPA form the basis of current DLA factors adopted by AS 5100.2 and adopted by most state road jurisdictions. These recommendations are based on empirical dynamic data compiled by these agencies from records dating back to the late 1800s, which are summarised in Figures 3 and 4 below. The fundamental frequency of the bridge is noted to be significant in the dynamic response of the structure, with DLA factors specified based on this data. The 1992 Austroads Bridge Design Code specifies DLA factors with a similar relationship, as shown in Figure 5, with the peak DLA factor of 0.4 to be applied for bridges with a fundamental frequency between 2.5 and 4.5 Hz. The DLA factor currently recommended by AS 5100.2 is a 0.4 constant, regardless of bridge frequency or dynamic characteristics, vehicle type or road profile. This value has also been subsequently adopted by TMR in its bridge assessment procedures.


**Figure 5: DLA recommendations from the 1992 Austroads Bridge Design Code**

### REVIEW OF HISTORICAL BRIDGE DYNAMIC PERFORMANCE

To provide a more informed approach regarding dynamic amplification based on vehicle loading and structure, a review of historical experimental load test data (based on actual dynamic responses of structures to heavy vehicles) conducted by international and national jurisdictions was undertaken. The aim of this review was to identify any trends that may be apparent in relation to DI, where dynamic amplification of loads is more likely to occur where specific conditions exist, including:

- vehicle or structure type
- material properties
- suspension characteristics
- dynamic properties of the vehicle
- the inherent stiffness and damping characteristics of the bridge.

A summary of the data collected from the current review, alongside data collected by Cantieni (1983) and Heywood (2000) is shown in Figure 6. A review of the data reveals that a wide scatter exists and that there are no immediate obvious trends. By further interpreting the data in relation to the abovementioned conditions, the following observations were made:

- The DI value for a significant number of structures did not subscribe to the AS 5100.2 DLA limit of 0.4.
- DLA is evident at vehicle axle-hop frequencies (8-15 Hz, typical of short-span bridges in Australia (Austroads 2003)) and, to a lesser degree, at body-bounce frequencies (1.5-3 Hz) (indicating frequency matching between the test bridges and vehicles).
- Hydro-pneumatic cranes generally result in DI values less than 0.4, regardless of weight (up to 48 t) and speed.
- Vehicles with steel suspension are more likely to result in elevated DI values, particularly where frequency matching occurs.
- Vehicles with air suspension are more likely to result in lower DI values (less than 0.4), unless frequency matching occurs between 8-12 Hz.
• DI values are typically less than 0.4 where speeds are less than 40 km/h.
• Dynamic responses are more likely to peak at speeds between 60-80 km/h.
• Where timber materials have been used, the dynamic response of the bridge is generally greater. This is most likely due to the lower stiffness and higher deflections characteristic of timber bridges.
• Deck unit structures generally yield lower dynamic responses.
• Steel and concrete beam/slab structures typically yielded peak DI values less than 0.5.
• The largest gross vehicle mass yielded the highest DI value, but similarly large DI values were also produced at masses between 30-50 t. There is no immediate evidence to suggest larger masses induce lower dynamic responses.
• Anecdotal evidence suggests road profiles are influential on the magnitude of DI, however further data interrogation is required.
• There is minimal information relating to the dynamic effects of road trains.

The current DI results shown in Figure 6 also highlight the inconsistencies between the DLA recommendations in AS5100.2. The solid line identifies the limits currently adopted by Swiss authorities. Whilst there is a trend in the current data to follow the Swiss model where bridge frequencies are low (most likely due to longer-span structures), additional code recommendations may be required for structures between 8-15 Hz.

![Figure 6: Combined dynamic increment versus fundamental bridge frequency (Current results + Heywood (2000) + Cantieni (1983) from the DIVINE project)](image)

Comment also is required on the derivation of the dynamic increment value. Whilst the majority of the reports have derived DI values based on Equation 1, the specific input of peak dynamic and static was found to be relatively subjective. Methodologies range from the use of averaged or ultimate maximum peak DI values per span or per group of girders to peak values. The implementation of static values ranged from global to individual maximaums achieved by the bridge during testing, with resulting DI values varying greatly.

A review of the methods used to derive DI is also recommended. The current method has been recommended by Bakht and Pinjarkar (1989) (see previous section) after conducting a review of various methods. In particular, significant DI values have been recorded for some structures despite very low or insignificant strains or deflections being achieved. This overestimation may change the resulting outcome considerably, potentially leading to excessive or unnecessary structural or economic maintenance recommendations. The calculation of negative DI values provides further evidence that a revision of these methodologies is recommended.
To improve or further validate the findings in this report, the following recommendations for further research are suggested:

- More data from other jurisdictions (nationally and internationally) is required to improve the statistical base of data. This would include obtaining raw data from sources such as Cantieni and Heywood in relation to previous work conducted for the DIVINE Element 6 project.
- A more detailed review of previous test reports into the accuracy and relevance of the currently adopted DLA factors is required.
- A review into the relevance of the current method for quantifying dynamic load amplification (i.e. DI) is required.
- More research is required regarding the influence of axle-hop, body-bounce, frequency matching, and vehicle suspension types on the dynamic effects induced in bridges.
- More data is to be obtained regarding the dynamic influence of road trains.
- Additional information regarding pavement condition over abutments is required to be included in the database.
- Further verification is required regarding the influence of pavement condition on dynamic amplification.

**REVIEW OF VEHICLE-BRIDGE INTERACTION (VBI) MODELS**

The ability to predict the response and behaviour of a structure to dynamic loads has become increasingly important to asset owners and managers. Whilst the concept of modelling the dynamic interactions between vehicles and supporting surfaces is not new (Frýba 1972; Hwang & Nowak 1991; Paultre, Chaallal & Proulx 1992), it has received renewed interest in the last few decades. The development of such models not only serves to highlight the dynamic performance of a structure and vehicle in combination, but to provide a predictive tool to be used to inform structural assessments of at-risk or permitted structures, negating the need for expensive and time-consuming physical testing.

The combination of the dynamic characteristics of the bridge, vehicle and road profile and subsequent load effects as a whole can be idealised for various time steps and load increments by solving a series of equations of motion, allowing the prediction of instantaneous loading on the supporting structure and embodied in a Vehicle-Bridge Interaction (VBI) model. A simplified function of a VBI model is shown in Figure 7, although in reality these systems can be quite complex (Cantieni, Krebs & Heywood 2010). The development of a VBI model for use by TMR is currently under review.

The creation of a VBI model is complex, and whilst there are a number of commercial software packages now available on the market, it is sensitive to the input parameters used and still requires validation against real-life field information. Despite the perceived complexities, the development of a reasonable model combining vehicles and bridges will provide insight into the principal vehicle and bridge governing dynamic response.

![Figure 7: A simplified Vehicle-Bridge Interaction (VBI) model](image)
There are a number of ways to dynamically model the bridge and vehicles individually and in combination. These range from simple planar methods to complex 3-dimensional models. Several excellent reviews have been published in relation to the development of VBI models, predominantly under the auspices of large research projects such as the ARCHES project (González 2010; Gonzalez 2009b; O’Brien et al. 2006), Federal Highway Administration (FHWA) (Szurgott et al. 2011; Wekezer & Taft 2011; Wekezer et al. 2008), and Austroads (Austroads 2002a, 2002b, 2003). The following sections present the key features of each model component, aligning with TMR’s preferences and objectives.

**Vehicle models**

The dynamic and inertial properties of vehicles is required to be captured within the VBI model, and remain the most complex factors to model. Models have moved beyond a moving point load to also capture dynamic aspects such as the stiffness and damping characteristics of the suspension system, shock absorbers, and tyres, and the dynamic and inertial contributions of the vehicle body mass (taking into account pitch, roll and movement characteristics). This is best represented using a spring-and-dashpot system for a 2-dimension model, idealised in Figure 8. The stiffness and damping characteristics of the suspension and shock absorber systems and the tyres can be modelled using established linear or non-linear individual models or from empirical data.

![Spring-and-dashpot system](image)


**Figure 8: Quarter-truck model representation for a dynamic vehicle**

Individual axle characteristics and spacing can subsequently be accounted for, improving the accuracy of the model. This is shown in Figure 9, and is the most commonly used method for vehicle dynamic assessment due to its simplicity. Pitch and roll inertial characteristics can be included, however this increases the complexity of the model. Three-dimensional (3D) models have been developed previously and published, which incorporate very complex, non-linear details of elements such as air lines, braking systems and vehicle specifics. As would be expected, such complex models require sophisticated software and a significant number of resources to solve for resulting dynamic effects. For the purposes of the current research, 3D models were not deemed appropriate or cost-effective for utilisation.

![Three-dimensional model](image)

Source: Hwang and Nowak (1991); Wekezer et al. (2008).

**Figure 9: Inclusion of multiple axles as an extension to the quarter-truck model**
Bridge models

There are several ways to model a bridge structure. This ranges from the simplest planar form using the Euler-Bernoulli beam formulation to 3D finite element (FE) analysis, which have been reviewed by Gonzalez (2008; 2009b; 2010). The use of FE or grillage models has been the most popular method for use in VBI models due to the degree of detail and improved accuracy. However, for the purposes of the current research project, a simplified approach is preferred, employing the use of a line model with the ability to incorporate span lengths and inherent dynamic characteristics such as stiffness and damping capabilities.

Road profile

Due to the significant influence of the road profile on the dynamic effects imposed on a vehicle and through to the supporting structure, the road profile input into the VBI model is crucial for accurate representation of dynamic effects. The road profile itself was recognised in dynamic models developed by Frýba (1972), and has since been modelled by Hwang and Nowak (1991), Heywood and Prem (Austroads 2003) and O’Brien et al. (2006) to name a few. The profile itself can be physically measured or theoretically simulated, typically in an elevation versus distance travelled format.

Interaction model

Dynamic responses between the bridge and passing vehicle, and the road profile that interfaces between them, are determined using an interaction model. The contact points (i.e. the wheels) provide the common point where data is shared between the models, and the governing equations of motion identified for the bridge and the vehicle can thus be solved (González 2010; Nassif, Liu & Ertekin 2003; Yang & Lin 2005), determining the dynamic forces in the bridge and vehicle at any location and at any time. The equations are solved using an iterative approach, with the processes for various methods simplified in Figure 10. The Newmark-θ is the most commonly used iterative method and has been successfully implemented on a number of VBI model developments (González 2010; Moghimi & Ronagh 2008a, 2008b).

Once the equations have been solved for each time step, the predicted dynamic and static deflections and strains can be obtained from the model, which in turn can be used to determine peak bending moments and shear forces, and likely dynamic amplification.
Local VBI models

A number of existing locally-developed VBI models with the potential to be adapted for the current project were identified in a literature review. These included:

- Austroads – Heywood et al. (Austroads 2003)
- University of Queensland (UQ) – Moghimi & Ronagh (2008a, 2008b)
- Queensland University of Technology (QUT) – Senthilvasan et al. (1997).

Each model varied in complexity, detail, and program architecture and was assessed on the degree of applicability and ease of adaptability for the current project. Due to various issues associated with each model, such as out-dated code, intellectual property and its project specific nature, the adaption of an existing model was abandoned and the need to develop a new model incorporating the learnings of these existing models for application across the entire network is currently being considered by TMR.

CANAL CREEK BRIDGE, CLONCURRY, QLD

In May 2014, a detailed program of load testing was carried out on the Canal Creek Bridge east of Cloncurry, QLD. To maximise the benefit for TMR, the load test program was extended to achieve some early research objectives for the current research project. This included investigating the amplification of loads for various vehicle types (2 x semi-trailers, an all-terrain mobile crane, and a road train) with various suspension types (air-bag, steel leaf and hydropneumatic). The results of the load test program are presented in a concurrent paper for the present conference (see ‘Load testing and in-service monitoring of a transversely stressed deck unit bridge’), however a summary of findings specifically relating to dynamic interactions is as follows:

- All peak and average DI values were generally less than 40%, with the exception of one outlier for the steel suspension semi-trailer travelling at 100 km/h (not considered to be representative of the structure as a whole).
- The pneumatic crane and road train generally resulted in DI values less than 40%, with responses less than 20% in both directions for speeds less than 60 km/h.
- The air-bag suspension semi-trailer generally induced a low dynamic response, with the exception of speeds greater than 80 km/h.
- DI values generally increased with increasing speeds.
- The road approach travelling towards Cloncurry induced a greater dynamic response in the bridge (a sinusoidal-type road profile and a depression behind the abutment were evident for this road approach).
- Frequency matching/quasi-resonance may be evident for the semi-trailers and the crane at higher speeds, particularly for vehicles travelling to Cloncurry, based on the DI response of these vehicles at higher speeds and the accelerometer data obtained.
- Negative DI values for the road train travelling to Cloncurry at higher speeds may be indicative of out-of-phase axle-hop or the influence of the length of the vehicle, suppressing the dynamic response of the bridge.

A summary of average peak DI values (the average peak DI value obtained for each midspan deck unit) recorded for each vehicle type in each travel direction is shown in Figure 11.

FUTURE PROGRAM

With the conclusion of a substantial literature review, preliminary investigations regarding VBI models, and the load testing of Canal Creek Bridge, the following program for the second year is currently being considered:

- The further development of a VBI model.
• Full instrumentation and load testing of selected test vehicles (particularly a pneumatic crane and PBS-type vehicle), with particular focus on:
  − behaviour of different suspension types
  − axle-hop and body-bounce characteristics
  − the real-time dynamic response of the bridge to vehicular loading (instrumentation of an additional bridge may be required).

The findings of this research will be published in due course.

**Figure 11: Average peak dynamic increments for each vehicle type at various speeds**

**CONCLUSION**

The dynamic interaction between vehicles and bridges remains an important concept to understand and model for the improved management of bridge assets, particularly where older structures and budgetary constraints exist. A review of the current literature has identified the factors influential in the amplification of dynamic loads on a structure as well as the historical development of the current DLA factors specified in AS 5100.2. The collation and interpretation of historical load test data has yielded a wide scatter in data relating to the bridge dynamic response (quantified by DI), however preliminary observations noted that vehicle and structure types, materials, and suspension characteristics may be influential in the dynamic response of a bridge. Whilst the data obtained from the load test of Canal Creek Bridge in Cloncurry supports these observations, additional data is required for further validation. The development of a VBI model will assist in the improved prediction of dynamic bridge-vehicle interactions and will be investigated further.

**REFERENCES**


Austroads 1992, *Bridge design code*, Austroads, Sydney, NSW

Austroads 2002a, *Guide to road profile unevenness and bridge damage*, AP-T13-02, Austroads, Sydney, NSW.

Austroads 2002b, *Validation of dynamic load models -- technical documentation*, AP-T12-02, Austroads, Sydney, NSW.
Austroads 2003, Dynamic interaction of vehicles and bridges., AP-T23-03, Austroads, Sydney, NSW.


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Torill Pape is a senior structural engineer at ARRB delivering consulting and research projects in bridge, structural engineering and management from ARRB’s Brisbane office. She has over 14 years’ experience across various engineering sectors, including construction, consultancy, public service and academia. She was awarded her PhD from the University of Newcastle in 2009 for works investigating the accuracy of non-destructive test method in the assessment of corroded concrete structures. Her area of expertise includes asset management, bridge

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assessment and inspection techniques, and the durability and performance of older reinforced and prestressed concrete structures. She has recently been awarded the Palmer Prize for the best paper published in 2013 by Proceedings of the Institution of Civil Engineers: Structures and Buildings.

Hanson Ngo has a senior structural engineer role at ARRB delivering consulting and research projects in bridge, structural engineering and management in the Brisbane office. With over 17 years of experience in bridges and structures, Hanson has delivered a number of research projects for Austroads and engineering contracts for industries. His areas of expertise include structural engineering research, inspection, design, assessment and load testing of bridges and civil structures. In 2005, Hanson gained his PhD at the University of New South Wales in the field of limit and shakedown analysis of engineering structures with emphasis on mathematical programming and finite element method applications.

Rudolph Kotze has 30 years’ experience in road and rail bridge design, bridge asset management, maintenance and project delivery. This includes 15 years in senior leadership and management roles in consulting practices in South Africa and New Zealand (NZ). After moving to NZ in 1996, he held the positions of Technical Manager of the NZ Cement and Concrete Association, Technical Manager Bridges with Holmes Consulting and National Structures Manager of the New Zealand Transport Agency (NZTA) with responsibility for asset management, maintenance and design standards. He is currently National Technical Leader, Bridges and Structures with ARRB Group based in Brisbane.

Dr Ross Pritchard has worked for TMR since he graduated from the University of Queensland in 1976. Currently he is Deputy Chief Engineer (Structures). During his career, he has been involved principally in the design and construction of bridges and recently became involved in the structural aspects of road and bus tunnels. Since joining TMR in 1977, Ross has been involved in a number of major projects including the Gateway Bridge, Port of Brisbane Motorway, Pacific Motorway Upgrade and Western Corridor. Ross also has involvement on Standards Australia committees and Austroads committees. His current interests include improvement of design codes and quality in construction.

Wayne Roberts is a Principal Engineer with TMR Structures – Bridge Construction Maintenance and Asset Management and has 23 years’ experience in research, load testing, construction and asset management of bridges, including specialist experience with all aspects of precast concrete. Wayne has worked for both private consulting and government organisations, including the last 11 years with TMR.

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