Short-Span Bridge Friendly Suspensions—Research Element 6 Of The OECD DIVINE Project

Robert J. Heywood
Queensland University of Technology, Australia

Figure 1. The six-axle articulated test vehicle fitted with air suspensions crossing Cameron's Creek.

ABSTRACT

A study of the response of short-span bridges was conducted to investigate the influence of vehicle suspensions on the dynamic response of bridges. Three bridges have been tested with plans to test two more bridges as part of the series. This paper refers to the tests conducted on the bridge over Cameron's Creek. The objectives of this study were i) to measure the dynamic responses of short span bridges to vehicles fitted with air or steel suspensions, ii) to rate the steel and air suspensions in terms of the European Community requirements for road friendly suspensions, iii) to determine how the dynamic bridge response for air and steel suspended vehicles varied when axle hop was excited, iv) to identify and understand the important parameters involved in the dynamic response of short span bridges, and v) to recommend measures for reducing the dynamic response of bridges to the passage of vehicles.

The results of the study indicate i) air suspensions met the requirements for road friendly suspension unlike the steel suspensions, ii) the significant differences between air suspensions and steel suspensions lead to different dynamic responses in short span bridges, iii) when axle hop vibrations were excited, the dynamic response of the bridges was sensitive to vehicle speed, bridge natural frequency and road roughness.

The study demonstrated that maintaining smooth approaches and profiles across bridges is imperative to reducing damage to bridges. When the road roughness excited axle hop, the bridge and the suspensions coupled leading to large dynamic increments for vehicles fitted with air suspensions travelling at critical speeds. It is believed 'road friendly' suspensions are likely to be short span 'bridge friendly' except for bridges that dynamically couple with axle hop vibrations and provided suspension dampers are operating efficiently. For vehicles to be friendly to short-span bridges, wheel forces with axle hop frequencies need to be controlled.

INTRODUCTION

The OECD DIVINE (dynamic interaction between vehicles and infrastructure experiment) international research project is investigating scientifically the influence of vehicle suspension on road and bridge infrastructure[1,2]. One of the six research elements is investigating the effects on bridge infrastructure. Dr Cantieni[3] is investigating the response of longer span Swiss bridges. This paper discusses the results from Australian research focused on short span (less than 15 m) bridges.

To date three bridges have been tested with plans to test two more bridges as part of the series[4,5]. This research has shown that the dynamic response of these short-span bridges can, under certain conditions, lead to large increases in both the peak deflections/stresses and the number of stress cycles experienced during the passage of a vehicle fitted with air suspensions. Under other conditions the dynamic response was small for air suspended vehicles compared with similar vehicles fitted with steel suspensions.

This paper illustrates the dynamic response of short-span bridges using bridge and vehicle response data collected during the passage of air or steel suspended six-axle articulated test vehicles crossing the bridge over Cameron's Creek. Two of these vehicles were almost identical except for their suspensions. In this way the relative effects of a steel and an air suspension were investigated. The reasons that the air suspended vehicles induced large dynamic responses in the bridge over Cameron's Creek are discussed and recommendations for improving the short span bridge friendliness of vehicle suspensions are discussed.

BRIDGE OVER CAMERON'S CREEK

Cameron's Creek is a relatively modern (1976) four span, simply supported, prestressed concrete deck unit bridge, the most common short span bridge in Australia (Figure 1 and Figure 2). It is located on Bucket's Way to the north of Sydney, New South Wales, Australia. The

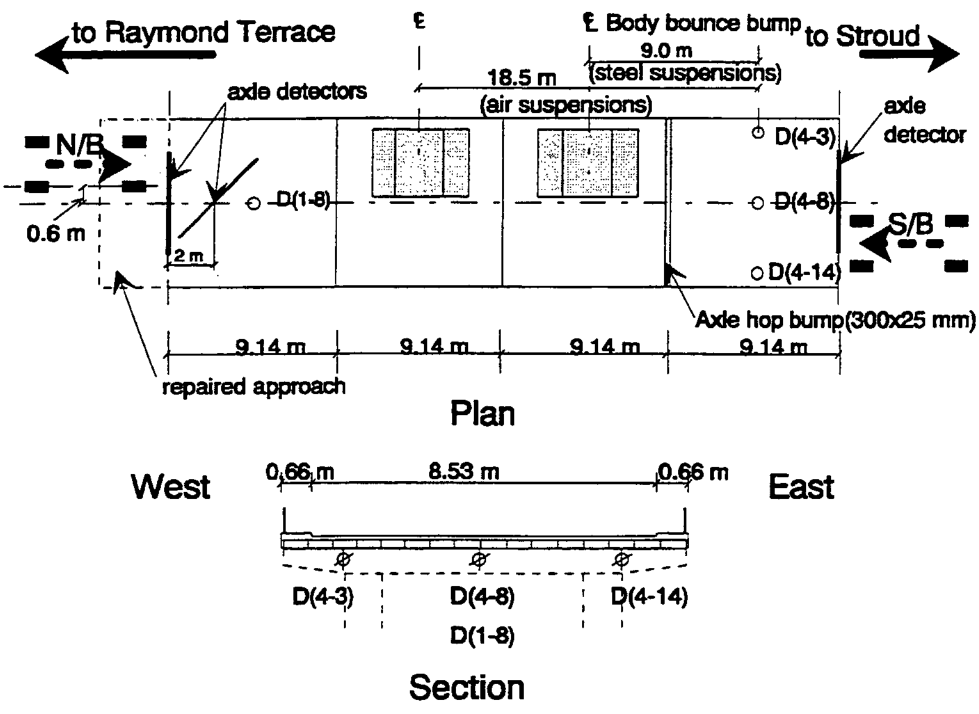
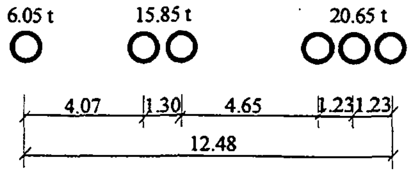
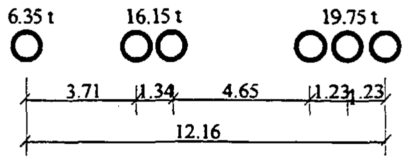


Figure 2. Cameron's Creek - Details and instrumentation layout.

Table I Details of test vehicles

Prime-mover	Trailer	Gross Laden Mass (t)	Vehicle Code
Freightliner, air suspension	Over the rear axle tri-axle tipper, BPW air suspension, 1.23 m spacing 	42. 5	BA 42.5 1.23
Freightliner, Hendrickson walking beam, steel suspension	Over the rear axle tri-axle tipper, York 8 leaf steel susp'n, 1.23 m spacing 	42.5	BS 42.5 1.23

prestressed concrete deck units act compositely with a cast-in-situ reinforced concrete slab which is the running surface. The superstructure is supported on reinforced concrete abutments and piers via elastomeric rubber bearing strips.

The 9.14 m (30 ft) spans have a fundamental natural frequency of 11.3 Hz and damping coefficient (ζ) of 1.5% (logarithmic decrement $\delta = 0.51$). One span has a mass of 110 t and a stiffness of 165 kN/mm determined from the midspan deflection due to a 20 t tri-axle group placed at midspan. The bridge was chosen because its natural frequency is similar to the frequencies associated with axle hop, providing the possibility of resonance.

TEST VEHICLES

A test vehicle with either steel or air suspensions fitted was used to excite the dynamic response of the Cameron's Creek bridge. In this way, the influence of the suspensions were compared. The trailer body was constant throughout the tests. The tri-axle groups and the prime-movers were interchanged to provide vehicles with almost identical dimensions and properties except for the steel or air suspensions. The details of the vehicles are provided in Table I. The vehicles were loaded to their legal load of 42.5 t.

The suspensions have been characterised using the European Communities drop test which defines a 'road friendly' suspensions as one with natural frequency less than 2.0 Hz and damping greater than 20%. The air suspended vehicle BA 42.5 1.23 satisfied the requirements for 'road-friendly' suspensions. The mechanical suspensions of vehicle BS 42.5 1.23 did not[6]. Thus the research was able to compare the bridge response for geometrically similar vehicles with either 'road-friendly' or 'non-road-friendly'.

ROAD ROUGHNESS

THE ROAD PROFILE

This research has highlighted the importance of road roughness on the dynamic response of short-span bridges. The road profiles were measured by the Roads and Traffic Authority of NSW using a laser profilemeter. A typical profile is presented in Figure 4. In order to artificially increase the roughness in a controlled manner, 300 by 25 high bumps designed to excite axle hop (AHB) and 6000 by 25 bumps to generate body bounce (BBB) were fitted to the bridge surface (Figure 4). The southern approach to Abutment A exhibited settlement and was repaired using cold-mix asphaltic concrete. The result was a substantial increase in short-wavelength roughness immediately before the bridge.

PSD VERSUS SPATIAL FREQUENCY

The power spectral density versus spatial frequency[7] for the road profile has been determined (Figure 3). This road is quite rough and clearly not of freeway standard. However it is consistent with the quality of an ageing infrastructure of secondary roads.

COMMENTS

The approaches to the bridge are much rougher than the bridge itself. The reinforced concrete running surface is in good condition. It is quite smooth except for the upward camber in each span (induced by creep in the prestressed

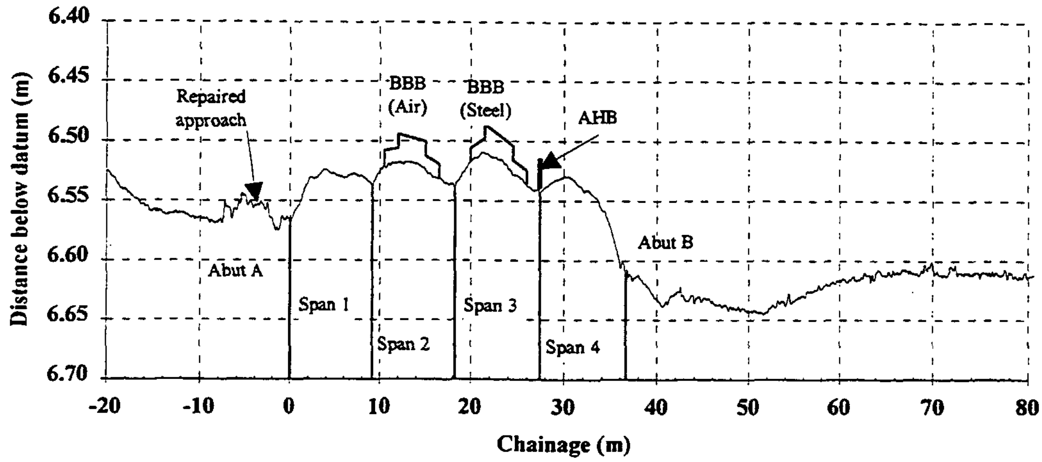


Figure 4. Road profile - Cameron's Creek, northbound.

concrete deck units). Compared with the approaches, the bridge surface does not exhibit the short wave length roughness required to induce axle hop.

As the vehicles move onto the bridge they are excited by the rough road profile. As they leave the bridge they have been driving over the relatively smooth profile of the bridge. The dynamic response of the first and the last spans with and without the axle hop bump (AHB) fitted provides important data for comparing the influence of road roughness on the dynamic response of the vehicles and the bridges.

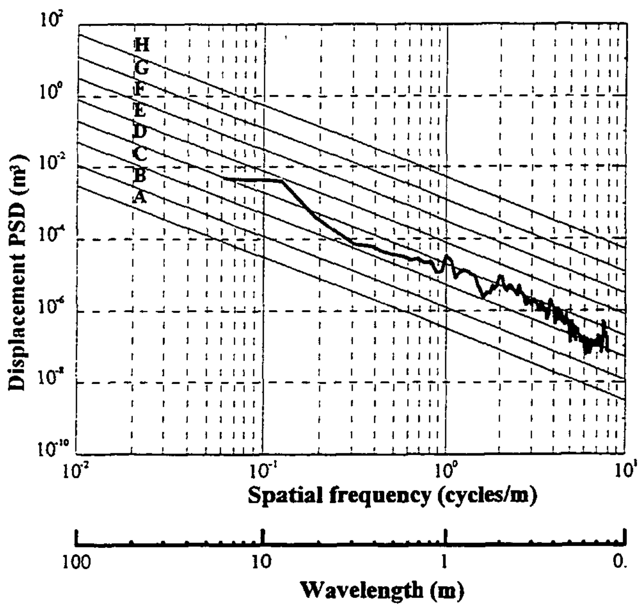


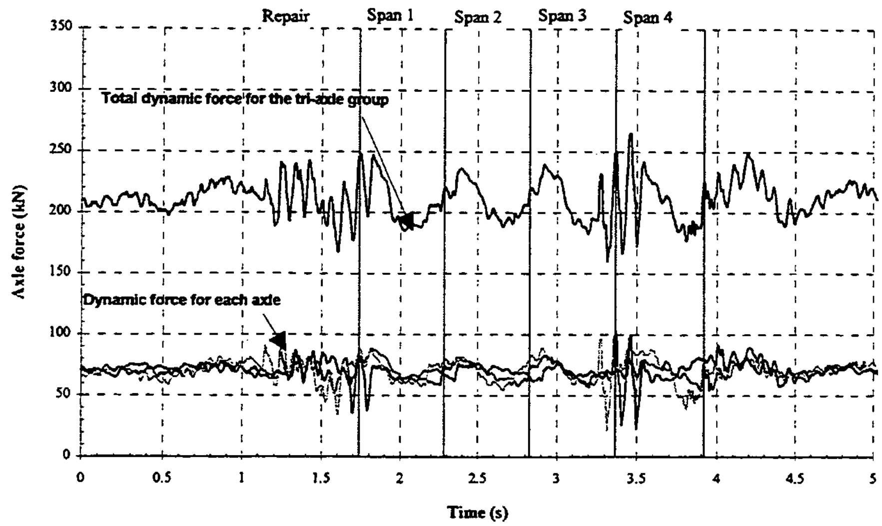
Figure 3. Power spectral density versus spatial frequency for the road profile at Cameron's Creek.

DYNAMIC WHEEL FORCES

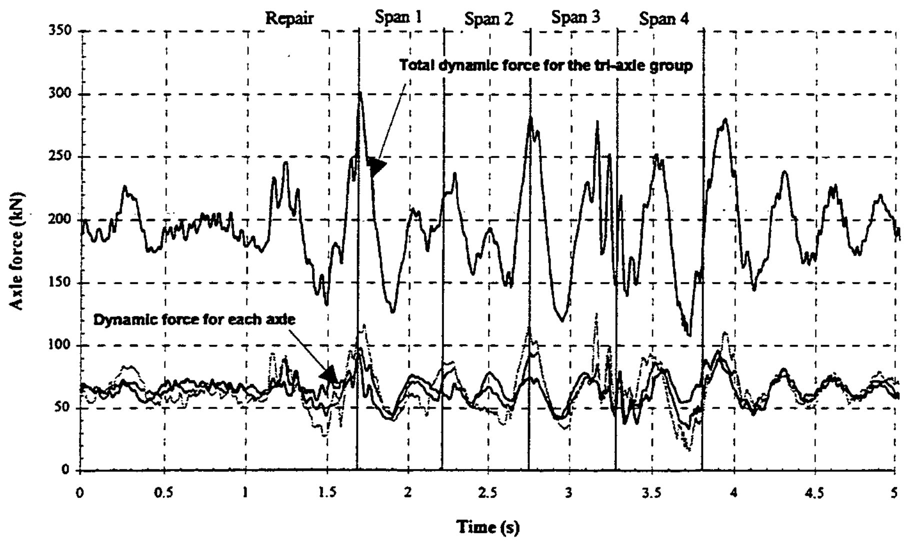
The dynamic load applied by each wheel of the tri-axle group was measured simultaneously with the bridge response. Figure 5 presents the dynamic force on each axle and the sum for the three axles in the tri-axle group. From a bridge response standpoint, this total dynamic force for the tri-axle group is more important than the force on individual axles. For example two axles vibrating 180° degrees out of phase are unlikely to excite a bridge but two axles vibrating in phase will excite a short-span bridge.

The dynamic force waveforms (Figure 5) are characterised by body bounce (1 to 3 Hz) and axle hop (8 to 15 Hz) frequencies. The sample power spectral densities illustrate these differences (Figure 6). The dynamic forces associated with the steel suspensions' body bounce frequencies have a larger amplitude and a higher frequency than the those of the air suspension. The peak total force for the tri-axle group is approximately 270 kN for the air and 300 kN or 10% more for the steel (Figure 5). An analysis without considering dynamic effects would suggest that the bridge would deflect 10% more under the influence of the truck fitted with steel suspensions. This would ignore the dynamic interaction between the bridge and vehicle, which is very important for this bridge.

The natural frequency of the bridge over Cameron's Creek is approximately 11.3 Hz. This corresponds to the axle hop frequencies of the dynamic axle group forces. These high frequency vibrations are clearly evident in the time and frequency domains (Figure 5 and Figure 6). They are most evident when the tri-axle group is traversing the repair prior to abutment A, the axle hop bump at pier 3 and the approaches. When the tri-axle group is on the bridge and the axle hop vibration has been damped, the high frequency axle hop component is quite small. This is consistent with the observation that the bridge surface is much smoother and induces far less axle hop vibrations than the approaches or the axle hop bump (Figure 4 and Figure 3). A comparison of the axle hop vibrations for the air and the steel suspensions shows that they are more prominent for the air suspension. This conclusion is even stronger when the comparisons are made for the total dynamic force. This increase in activity in the frequency range of the bridge leads to substantial amplification of the bridge response for some critical speeds.

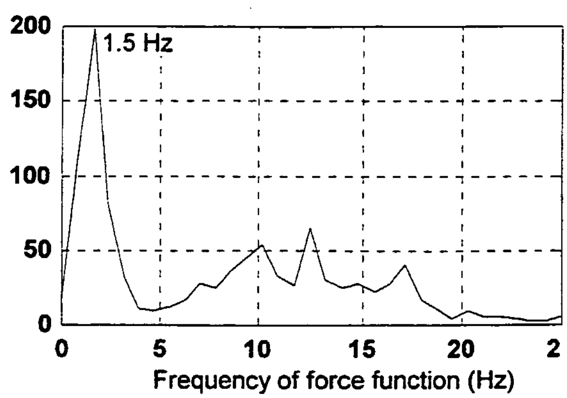


(a) Air suspensions, 59 km/hr over the axle hop bump (AHB), BA 42.5 1.54.

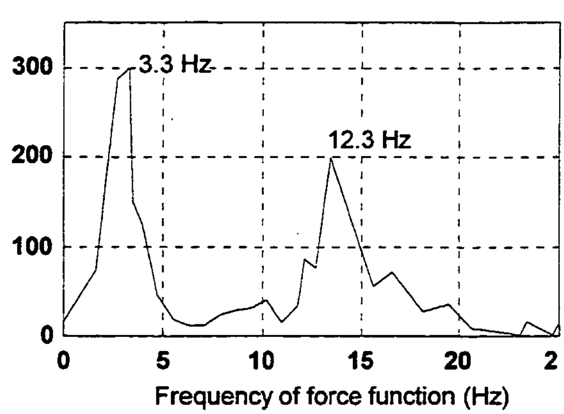


(b) Steel suspensions, 62 km/hr over the axle hop bump (AHB), BS 42.5 1.23.

Figure 5. Cameron's Creek - Dynamic axle forces for trailer tri axle group.

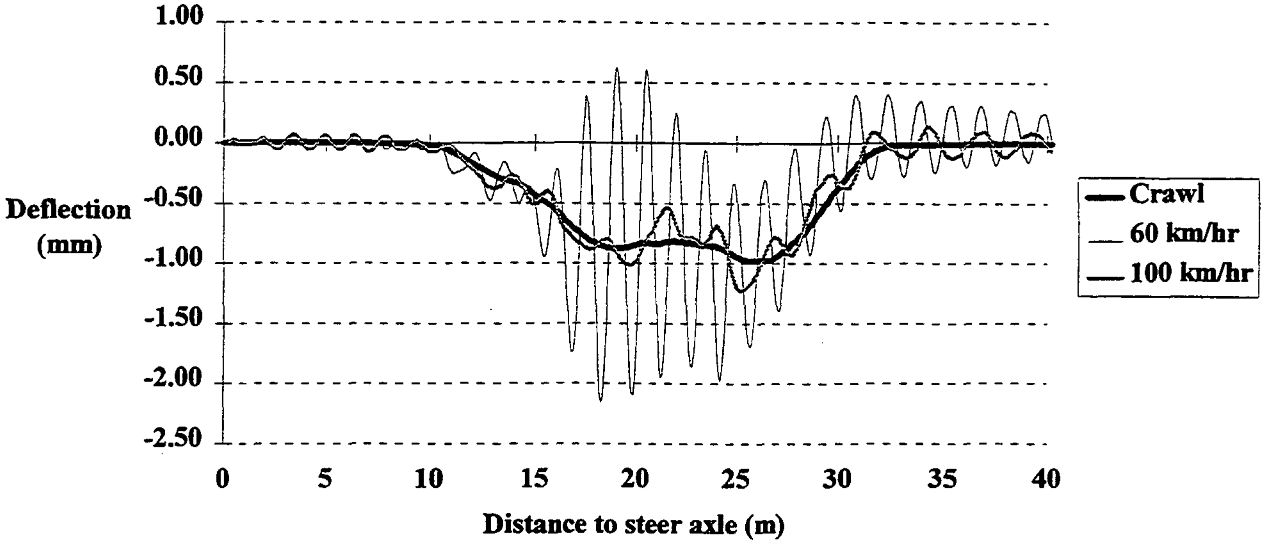


(a) Air suspensions, 47 km/hr, Axle hop bump, BA 42.5 1.23.

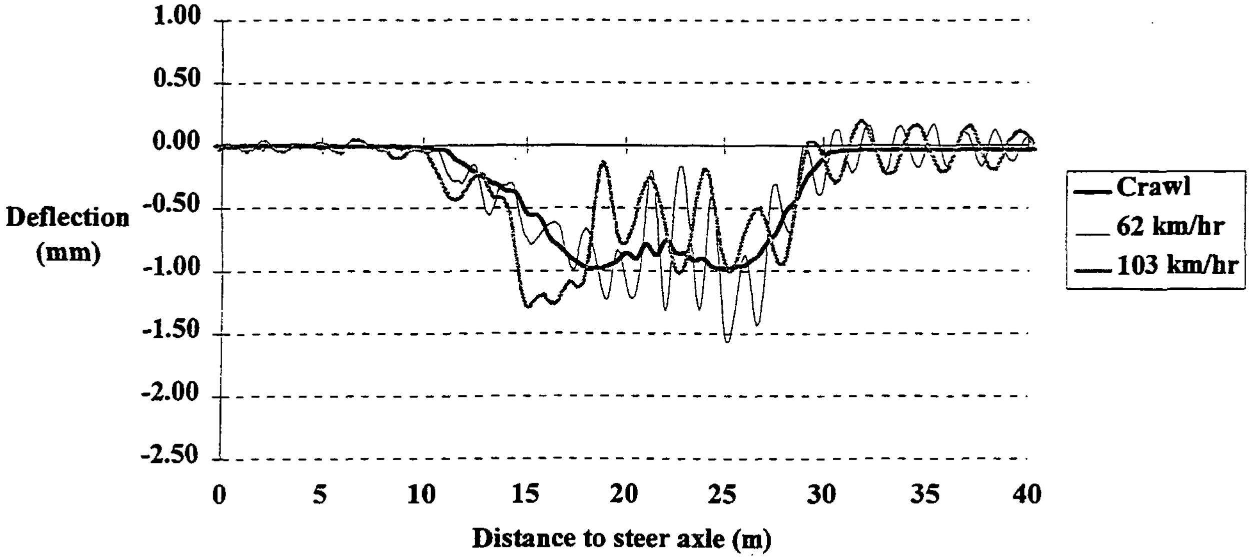


(b) Steel suspensions, 67 km/hr, Axle hop bump, BS 42.5 1.23.

Figure 6. Cameron's Creek - Power spectral densities of dynamic wheel force- drivers side centre wheel for trailer triaxle group.



(a) D(4-8), Truck BA 42.5 1.23, Northbound, Axle hop bump.



(b) D(4-8), Truck BS 42.5 1.23, Northbound, Axle hop bump.

Figure 7. Cameron's Creek deflection waveforms.

BRIDGE RESPONSE

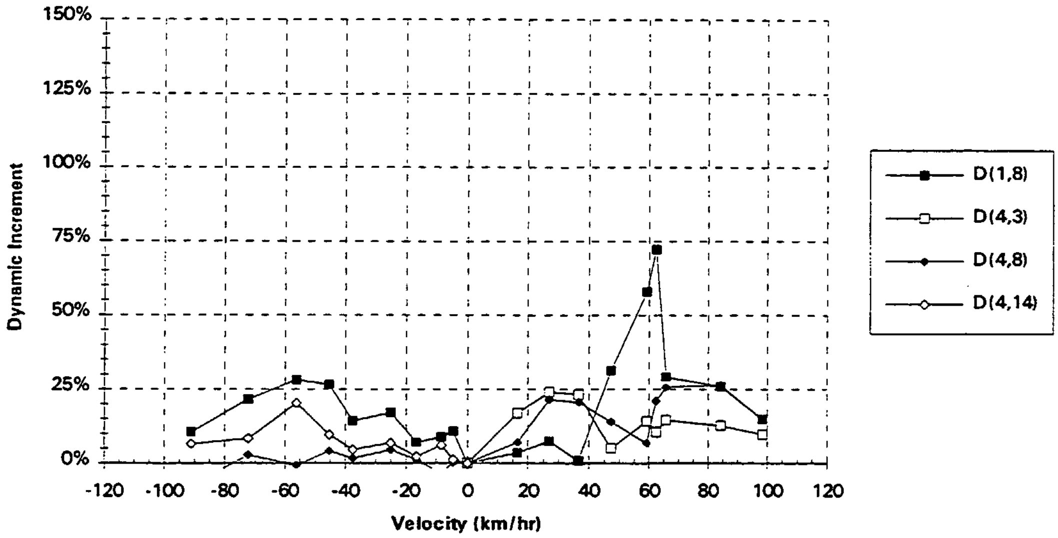
SAMPLE WAVEFORMS

The response of Cameron's Creek bridge was found to be sensitive to speed, roughness and vehicle suspension. Figure 7 demonstrates the influence of speed and suspension type. The deflection D(4,8) is located in the centre (8th bridge plank from the left) of the 4th span of the bridge, the span immediately after the axle hop bump (Figure 2).

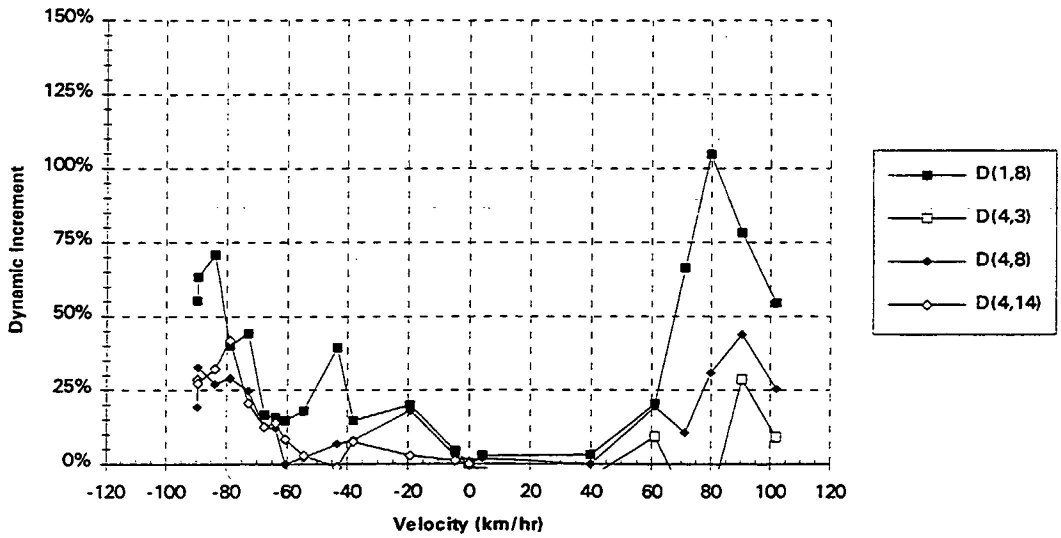
With the axle hop bump (AHB) in place, vehicles travelling at speeds approximately 60 km/hr induced up to 10 substantial stress reversals during the passage of the vehicle. At 100 km/hr the number of cycles had reduced. In the case of the air suspended vehicle, the peak deflection was much larger at 60 km/hr than at 100 km/hr whereas for the steel suspension the peaks were similar at these speeds. Despite the softer air suspension giving smaller peak dynamic wheel forces, the largest peak deflections induced in Cameron's Creek bridge corresponded to the passage of air suspended vehicles, provided axle hop had been excited. To assist in a more general comparison of the bridge response it is helpful to consider the peak dynamic deflection scaled against the peak deflection for a vehicle traversing the bridge at a crawl speed.

DYNAMIC INCREMENT

The dynamic increment (*DI*) provides a means of comparing the peak dynamic deflection with the peak



(a) Air suspensions - BA 42.5 1.23.



(b) Steel suspensions - BS 42.5 1.23.

Figure 8. Cameron's Creek - Dynamic increment versus speed, No bumps

deflection reported at crawl speeds[8,9,10]. It is defined[8] as follows:

$$DI = \frac{(\delta_{dyn} - \delta_{static})}{\delta_{static}} \times 100\% \qquad (1)$$

where δ_{dyn} = peak dynamic deflection and δ_{static} = peak static deflection.

Dynamic increment (*DI*) versus vehicle velocity graphs are shown in Figure 8 and Figure 9. Positive velocities refer to northbound traffic and negative velocities correspond to the vehicles travelling in a southerly direction. It should be noted that the vehicles travelled within their lane and that Australian traffic drives on the left side of the road (Figure 2). Further, the dynamic increment (*DI*) has been calculated only for the deflections that are directly under the zone of influence of the vehicle.

DISCUSSION

The following general observations are made:

1. The dynamic increment (*DI*) is small (less than 25%) for speeds less than 40 km/hr.

2. *DI*s greater than 50% are relatively common. *DI*s of 100% or more were recorded. The largest *DI* recorded was 137% for another air-suspended vehicle which was excited by the pavement repair. These are much larger than the 30% dynamic load allowance used in Australian bridge design[11].

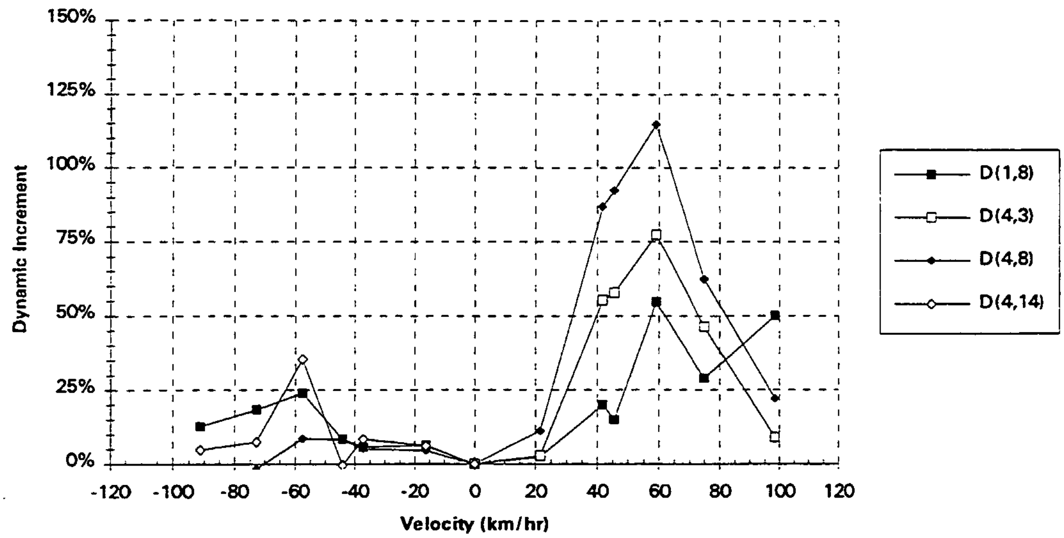
3. The relationship between *DI* and speed was different for each suspension.

4. The *DI* due to air-suspended vehicles was less than the *DI* associated with steel suspensions, unless axle hop was excited and it coupled dynamically with the bridge.

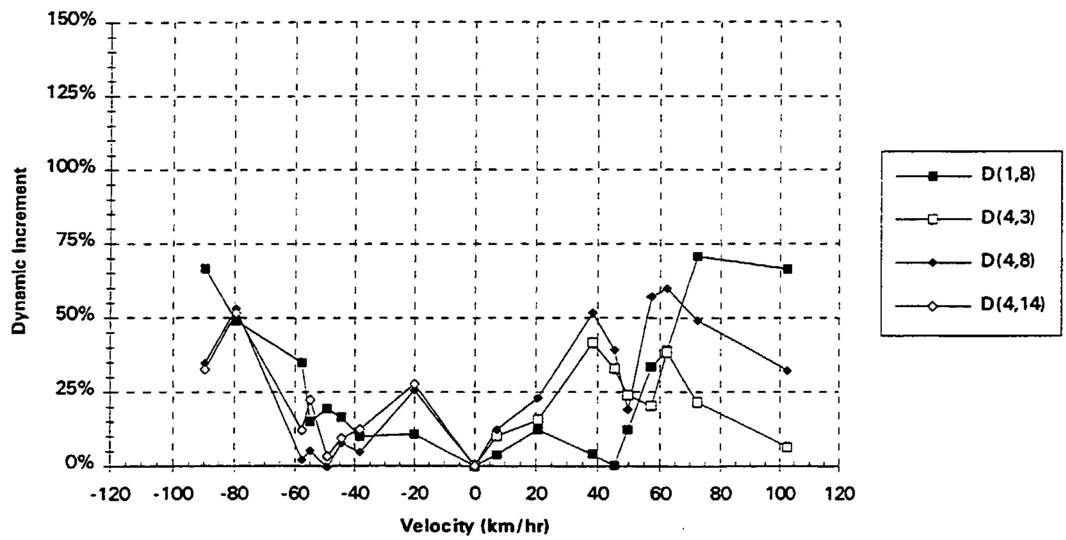
5. The *DI* due to steel-suspended vehicles tended to increase with speed.

correspond to the deflections at the centre of the first and last span of the bridge. Given a smooth road one would expect their response to be similar to each other and for both northbound and southbound traffic. This is not the case.

Figure 8a (air suspension and no bumps) illustrates that the dynamic increment for D(1,8) is dramatically different for northbound and southbound traffic. Generally the DI is less than 25% except for speeds around 60 km/hr



(a) Air suspensions - BA 42.5 1.23 AHB.



(b) Steel suspensions - BS 42.5 1.23 AHB.

Figure 9. Cameron's Creek - Dynamic increment versus speed, Axle hop bump.

INFLUENCE OF ROAD ROUGHNESS

A more detailed consideration of the influence of road roughness is beneficial. Deflections D(1,8) and D(4,8) northbound where the dynamic increment jumps to almost 75%. This is related to the response of the bridge to the axle hop induced by the repair immediately before span 1 for northbound traffic. By the time the vehicle has reached the fourth span most of the axle hop has been damped out and D(4,8) registers a small DI. The reverse did not occur for the southbound traffic as the northern approach to span 4 does not exhibit the short wavelength features required to induce axle hop despite a relatively large depression.

The above pattern is repeated when the axle hop bump was installed over the pier immediately to the south of span 4 for northbound traffic (Figure 9a). The response of D(1,8) is similar with and without the axle hop bump as it is too far away from the AHB to be substantially influenced by it. However for D(4,8) the maximum DI increases from 25% to a maximum of 115% for northbound traffic whilst exhibiting minimal changes for southbound vehicles. The southbound vehicles have crossed the transducer prior to crossing the AHB. This pattern is repeated for D(4,3).

SUMMARY

Thus it is concluded that the existence of short wavelength defects in the running surface dramatically increase the dynamic response of the bridge over Cameron's Creek for the air suspended test vehicle travelling at speeds of approximately 60 km/hr.

For the steel suspended vehicle (Figure 8b and Figure 9b) the response is different. Firstly the AHB tends to induce confusion rather than the clear cut response of the air suspension. Likewise the differences between northbound and southbound are not as distinct. For example, D(1,8) experiences large responses in both directions, with and without the AHB. It is concluded that the response of the bridge over Cameron's Creek to vehicles fitted with steel suspensions is more consistent with body bounce forces rather than axle hop.

The evidence suggests that the dynamic response of short span bridges will be small for high quality roads and freeways for both steel and air suspensions.

SUSPENSION BEHAVIOUR

The differences in design philosophy for steel and air suspensions are substantial. Steel suspensions rely on interleaf friction for damping whereas air suspension utilise hydraulic dampers. Under static loads, load sharing is achieved in air suspensions by air pressure equalisation. Under axle hop conditions this does not occur as the air does not have time to flow between the airbags. Thus air suspensions behave independently for these high frequency loads. If each axle in an air-suspended group strikes a defect one axle hop cycle apart then each axle will vibrate in phase and the total force for the group will include a significant axle hop component (Figure 5).

In contrast, steel suspensions rely on pivoted beam and rocker mechanisms to achieve load sharing within a group. In this case, when an axle encounters a short wavelength defect it induces a response in the other axles in the group ('cross-talk'). This tends to confuse the axle hop behaviour, limiting the opportunity for the axle hop vibrations to be in phase for steel suspensions. Figure 5 confirms the notion that the axle hop component of the total dynamic force for the tri-axle group is more significant for the air suspended vehicle at approximately 60 km/hr - the critical speed for air suspensions at Cameron's Creek.

Speed is important in determining the extent to which axles in an air suspended group vibrate in phase. The natural frequency of the bridge is most important. In the case of Cameron's Creek this is 11.3 Hz which is consistent with axle hop vibrations (Figure 6). For the purpose of illustration, consider a series of axles with a static plus a dynamic component with a 11.3 Hz natural frequency and an amplitude of 10% of static. Assuming the dynamic component is induced by striking a defect then the dynamic wheel forces will add as illustrated in Figure 10. For typical axle group spacings, speeds of 50 to 60 km/hr are likely to result in the axle hop components summing whereas at higher speeds they will tend to cancel. This is consistent with observed behaviour. Thus speed is a critical issue for air suspensions and the critical speed ($v_{crit.ah}$) is approximately the axle hop frequency (f_{ah}) times the axle spacing (s).

$$v_{crit.ah} \approx s^* f_{ah} \qquad (3)$$

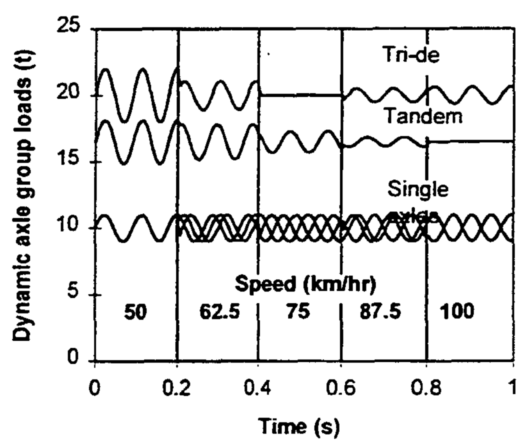


Figure 10. Influence of speed on dynamic axle group loads

In the case of an axle hop natural frequency equal to the bridge natural frequency (11.3 Hz) and a spacing of 1.30 m (drive tandem), the critical speed would be 11.3*1.23 = 13.9 m/s = 50 km/hr. This is similar to the peak at 60 km/hr evident in the *DI* versus velocity graphs.

BRIDGE VEHICLE INTERACTION

A constant axle load crossing a bridge will induce a dynamic response in a bridge due to the pulse experienced by the bridge. This effect increases with speed but is relatively small at normal operating speeds. Of greater significance is the dynamic response due to the dynamic variation in the axle and axle group loads. For the purpose of illustration, assume that the bridge can be represented as a single degree of freedom system with a natural frequency (ω) = 11.3 Hz and damping (ζ) = 1.5%. The corresponding classical amplification factor versus the frequency of a sinusoidal forcing function is presented in Figure 11. This illustrates that body bounce frequencies are unlikely to be amplified by the bridge but that the axle hop components can be substantially amplified. The amplification factor is 33 for continuous forcing frequencies equal to the natural frequency. Smaller amplification factors are anticipated as a consequence of the limited number of cycles of load applied as a vehicle crosses the bridge.

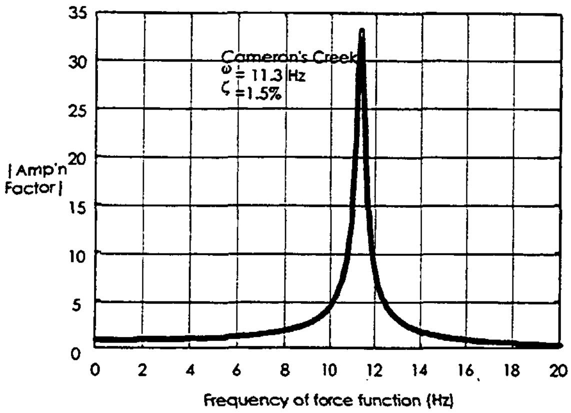


Figure 11. Magnification factor versus frequency of force function for a single degree of freedom approximation of Cameron's Creek bridge.

Figure 12 illustrates the simulated midspan deflection due to a single 10 t axle with a 2 t (20%) dynamic component at 1.5, 4.0 and 11.5 Hz crossing the single degree of freedom model of Cameron's Creek at 50 km/hr. There are two lines for each frequency in Figure 12. The central line is the deflection response if the bridge were to respond in a linear relationship with the axle load. The outer line includes the dynamic amplification. This figure further illustrates that the body bounce modes (1.5 and 4 Hz) are transmitted without significant magnification whereas at the axle hop frequency of 11.5 Hz significant dynamic amplification occurs.

Thus it is concluded that the axle hop components of the dynamic wheel force can induce large dynamic fluctuations in bridges with natural frequencies in the axle hop range (8 to 15 Hz). Axle hop components are amplified by short-span bridges. In the case of the air suspensions, the axle hop components within a group add at some critical speeds before being amplified by the bridge, inducing a large number of damaging stress cycles. This behaviour was far less noticeable for the steel suspensions tested.

In contrast, the dynamic body bounce components are transmitted to these short-span bridges without significant amplification. Road friendly suspensions are softer and generate smaller peak loads than conventional suspensions. As these body bounce forces are not amplified, the corresponding bridge response is generally smaller for road friendly suspensions.

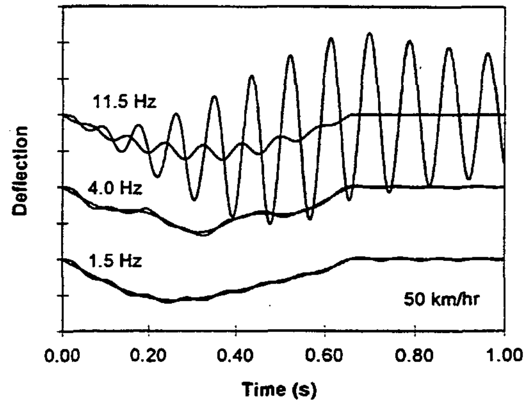


Figure 12. Influence of frequency

SHORT-SPAN BRIDGE FRIENDLY SUSPENSIONS

The softer air-suspensions result in smaller peak dynamic wheel forces. However there is a tendency for axle hop to become more important. To minimise the short-span bridge response, the component of the total axle group force at axle hop frequencies must be controlled in addition to the forces associated with body bounce.

Dampers provide the major control of axle hop in the case of air suspensions. Their quality, performance, geometric positioning and condition are vital in controlling axle hop. Bridge responses induced by a petrol tanker fitted with similar air-suspensions to that of the test vehicle showed even larger excitation due to axle hop when the tanker crossed the bridge at its critical speed. The tanker's dampers were fitted in a less geometrically efficient manner, confirming the importance of axle hop damping (Heywood, 1995). The response of short-span bridges to an air-suspended vehicle with non-functioning dampers requires investigation.

It is suggested that the bridge response to axle hop may be controlled on a axle group basis as well as for individual axles. Should the axle hop vibration of adjacent axles be out of phase to the extent that when added they cancel, then the bridge will experience a smaller response. For single axles this is not possible and it is anticipated that the bridge response would be significant over a wide range of speeds. For tandem and tri-axle groups, the existence of the other axles in the group means that axles will be out of phase except for a critical range of speeds. It is for these critical speeds that other solutions are required. Possibilities include adjacent axles having different natural frequencies and in the case of tri-axle groups, unequal axle spacings.

CONCLUSIONS

The dynamic responses of three short span bridges to vehicles fitted with air or steel suspensions have been measured experimentally.

The air suspensions met the European Community requirements for road friendly suspensions whereas the steel suspensions did not.

The peak bridge deflections were less for the air suspended vehicles than for steel suspended vehicles unless axle hop was excited and the vehicles travelled at critical speeds.

When axle hop vibrations were excited, the dynamic response of the bridges was sensitive to vehicle speed and bridge natural frequency. At these critical speeds, multiple fatigue cycles were induced.

The steel suspended vehicle applied the largest dynamic wheel forces. These are associated with truck body bounce modes which are not amplified by short-span bridges.

The maintenance of smooth approaches and profiles across bridges is a very important factor in reducing damage to bridges. This applies to short and long wavelengths. It has been demonstrated that a cold mix repair to a bridge approach induced axle hop which coupled dynamically with the bridge.

'Road friendly' suspensions are likely to be short-span 'bridge friendly' except for those bridges that dynamically couple with axle hop vibrations and provided suspension dampers are operating efficiently.

Short-span bridge-friendly suspensions require axle hop to be controlled. For groups of axles, different natural frequencies between axles and/or unequal spacing if tri-axle groups could reduce the dynamic response of sensitive bridges.

ACKNOWLEDGMENTS

This research has been funded by the Roads and Traffic Authority of New South Wales with in-kind contributions from the National Road Transport Commission, Boral Transport (trucks), Transpec Australia (air suspension), BPW Germany (instrumented axles), York Australia (steel suspensions), Hamalex Australia (suspension fabrication) and Mercedes Benz (video). The contribution of Road User Research, colleagues from OECD DIVINE project and QUT, and the Australian Road Research Board are gratefully acknowledged. In particular

REFERENCES

1. Road Transport Research. *Dynamic loading of pavements*. Report prepared by an OECD scientific expert group, OECD Publications, Paris 1992.

2. Sweatman, P.F. *OECD Research in Dynamic Loading of Pavements*, OECD DIVINE Project Dynamic Loading of Heavy Vehicles and Road Wear Mid-Term Seminar, Paper 4. Sydney, Feb, 1995.

3. Cantieni, R.I. and Barella, S. *Swiss Testing of Medium Span Bridges.* OECD DIVINE Project Dynamic Loading of Heavy Vehicles and Road Wear Mid-Term Seminar, Paper 18. Sydney, Feb, 1995.

4. Heywood, R.J. *DIVINE Element 6 Dynamic Bridge Testing Short Span Bridges.* OECD DIVINE Project Dynamic Loading of Heavy Vehicles and Road Wear Mid-Term Seminar, Paper 19. Sydney, Feb, 1995.

5. Heywood, R.J. *'Road-friendly' suspensions and short span bridges*, Australian Road Research Board Research Report ARR 260, Dynamic Interaction of Vehicles and Infrastructure, Proceedings of DIVINE Special Session: 17th ARRB Conference, Ed K.G. Sharp, Melbourne, 1994, pp. 39-65.

6. Sweatman, P.F., McFarlane S., Ackerman C., George, R.M., *Ranking of the road friendliness of heavy vehicle suspensions: low frequency dynamics*, National Road Transport Commission, Melbourne, 1994.

7. ISO Draft 8608. International Organisation for Standardisation. *Mechanical vibration - Road Surface profiles - Reporting of measured data*, Berlin, Germany, 1991.

8. Cantieni, R.I. *Dynamic Behaviour of Highway Bridges Under the Passage of Heavy Load.* EMPA Report No. 220, Dubendorf, 1992

9. Billing, J.R. and Green, G. *Design provisions for dynamic loading of highway bridges.* TRR 950/1, 1984.

10. Ministry of Transportation and Communication. *Ontario Highway Bridge Design Code - Commentary.* Published by the Highway Engineering Division, Toronto, Canada, 1993.

11. AUSTROADS. Bridge Design Code. AUSTROADS, Sydney, Australia, 1992.