Are Road-Friendly Suspensions Bridge-Friendly? OECD DIVINE

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This paper presents the results of an investigation aimed at developing an understanding of the influence of truck suspensions on the dynamic response of short span bridges. The work forms part of the Organization for Economic Cooperation and Development (OECD) Dynamic Interaction Between Vehicle and Infrastructure Experiment (DIVINE). The hypothesis is based on the assumption that soft, so-called "road friendly" suspensions induce less damage in pavements than stiff suspensions. This paper concentrates on the extension of this hypothesis by discussing its application to short span bridges. Three bridges were instrumented and their dynamic response to the air- or steel-suspended test vehicles was recorded. For two of these bridges, the dynamic wheel forces and the bridge response were acquired simultaneously. The bridges chosen were to have natural frequencies in the range of axle hop frequencies in order to investigate possible resonance effects. The paper details both the vehicle and the bridge responses and the interaction between them. Dynamic increments in excess of 100 percent were recorded. Dynamic coupling between axle hop vibrations and the bridge resulted in up to 10 damage cycles during the passage of a vehicle. The bridge response is shown to be sensitive to the natural frequency of the bridge, the suspension of the vehicle, its speed, and the road roughness. The bridge-friendliness of road-friendly suspensions is discussed in the light of experimental evidence.

The transport industry, vehicle designers, government agencies, and researchers have recognized the reduction in damage afforded to infrastructure and cargo that can be achieved through improved suspension design. The new generation of soft, highly damped "road-friendly" suspensions are rapidly gaining acceptance around the world. In Australia, government authorities are investigating the possibility of increasing axle loads and consequently road transport efficiency in return for fitting road-friendly suspensions.

Future increases in the legal loads will be limited by the strength of an aging infrastructure of bridges in Australia. Hence older short span bridges are the major concern. Seventy-five percent of Australia's bridges have spans less than 15 m, and many of the larger spans have subelements in this range. The possibility of safely carrying heavier loads across short span bridges in return for reduced dynamic loads applied by bridge-friendly suspensions is an attractive option.

The Organization for Economic Cooperation and Development (OECD) has sponsored the international research projects IR2 and IR6 to investigate road-friendly suspensions in a scientific manner. The IR2 project reported its findings in 1992 (*1*). The IR6 project known as the Dynamic Interaction Between Vehicle and Infrastructure Experiment (DIVINE) is well advanced. This paper is based on research conducted as part of dynamic bridge load research (Element 6) of OECD DIVINE and parallel studies on behalf of the

Roads and Traffic Authority of New South Wales, Vicroads, AUSTROADS, and the Australian National Road Transport Commission.

It is well recognized that the dynamic response of bridges is largest when the natural frequencies of the bridge and the vehicle are equal (2,3). Vehicle vibrations can be organized into two groups: body bounce and axle hop. Body bounce frequencies are in the 1.5- to 2-Hz range for air suspension and 2.5- to 4-Hz range for steel suspensions. Thus dynamic coupling between the body bounce vibrations and bridges will occur for bridges with natural frequencies between 1.5 and 4 Hz corresponding to a span between 80 and 30 m.

Axle hop frequencies (8 to 15 Hz) would be expected to dynamically couple with bridges of similar frequencies (8- to 15-m span). Little research has been undertaken for such short span bridges. An experimental program designed to investigate the influence of axle hop vibrations on the dynamic response of short span bridges and the influence of suspension type is discussed.

The response of medium span bridges with natural frequencies in the range of body bounce is being investigated under the direction of Reto Cantieni of the Swiss Federal Laboratories for Materials Testing and Research (EMPA). The influence of suspension type on this range of spans will be reported as part of OECD DIVINE.

Description of Bridges

The details of the three short span bridges used during this study are presented in Table 1 and Figure 1. The bridges were selected with a view to investigating possible dynamic coupling with axle hop vibrations. They are representative of short span bridges that are fairly common in Australia.

The Yarriambiack Creek bridge is a three-span, simply supported, cast-in-situ, reinforced concrete T-beam bridge built in 1927 [Figure 1(a)]. Cameron's Creek is a more modern (1976), four-span, simply supported, prestressed concrete deck unit bridge, the most common short span bridge in Australia [Figure 1(b)]. The three-span semicontinuous timber girder bridge over Cromarty Creek is uniquely Australian [Figure 1(c)]. Timber girder bridges were constructed from a plentiful supply of hardwood logs (450-mm diameter), which were used as girders. Hardwood deck planks (300 × 125 mm) span between the girders. The ends of the girders were made semicontinuous by vertical bolts into corbels, which are in turn supported on timber piers. The 10,000 of these bridges that remain in service present a major management challenge for Australian authorities.

Table 1 summarizes the characteristics of the test bridges. The stiffness was calculated from the measured midspan deflection when the test truck was positioned with its 20-ton triaxle group (tridem) at midspan. The natural frequency and damping attributes of the bridges were derived from the free vibration after the test vehicles left the bridge. The damping has been characterized as low, average, or high in accordance with the limits defined by Cantieni (2).

Road Profiles

The surface profiles for each of the bridges are presented in Figure 2. The surface roughness is consistent with secondary roads rather than high-quality highways. The profiles across Cameron's and Cromarty creeks were measured using the Australian Road Research Board laser profileometer. In the case of the Yarriambiack Creek bridge, the profile was measured using the conventional dumpy level and staff survey.

Depressions in the southern approaches to Cameron's and Cromarty creek bridges had been repaired with cold mix asphalt concrete. (Note that Australian traffic travels on the left-hand side of the road.) These repairs are clearly evident on the longitudinal profiles as they exhibit significant short wavelength roughness,

TABLE 1 Characteristics of Test Bridges

Bridge	Spans (m)	Skew	Mass of span (t)	Stiffness (kN/mm)	Natural frequency (Hz)	Damping coefficient (ζ)	Logarithmic decrement (δ)
Yarriambiack Creek	3@8.2 Reinforced Concrete	32 deg	85	110	14.1	2.4% (high)	0.15
Cameron's Creek	4@9.14 P/S Concrete	square	110	165	11.3	1.5% (average)	0.509
Cromarty Creek	7.62/9.14/7.62 Timber Girder	25 deg	25	18	8.6 to 9.4	2.6% (high)	0.15

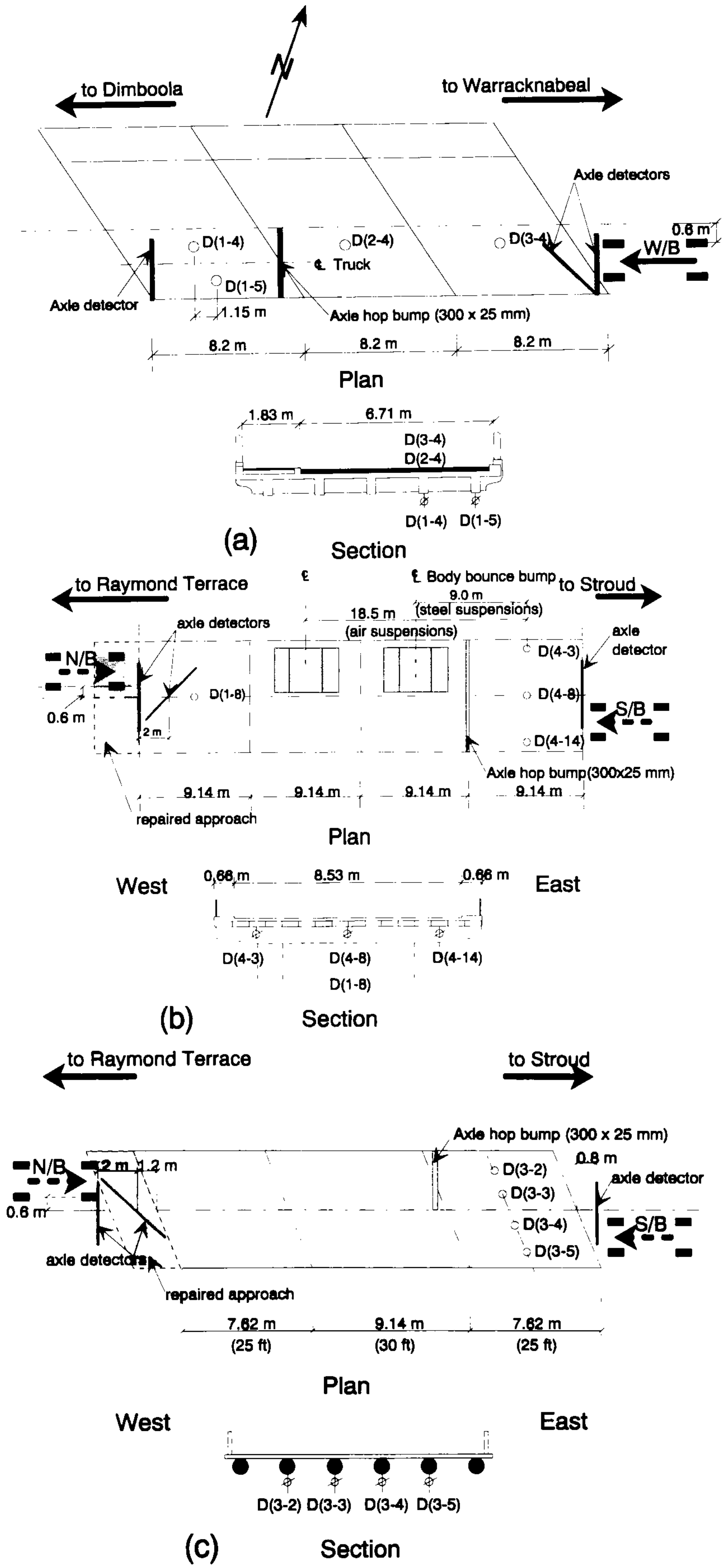
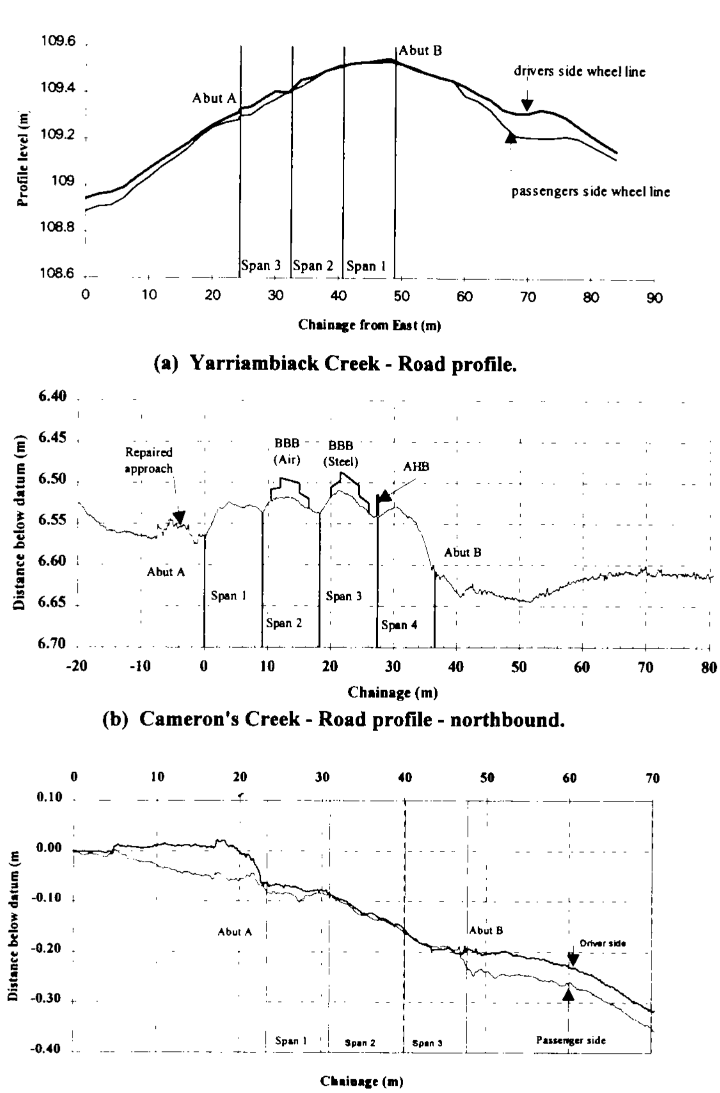


FIGURE 1 Details of test bridges: (a) Yarriambiack Creek bridge, (b) Cameron's Creek bridge, (c) Cromarty Creek bridge.



(a) Yarriambiack Creek - Road profile.

(b) Cameron's Creek - Road profile - northbound.

(c) Cromarty Creek Bridge - Road profile - northbound.

FIGURE 2 Road profiles over test bridges.

which proved to be an important factor in the dynamic bridge/vehicle interaction.

The prestressed concrete bridge over Cameron's Creek was designed before partial prestressing was accepted practice. Consequently each span exhibits an upward deflection due to creep (also known as a hog) of approximately 20 mm. Some settlement of the abutments is also evident.

Two bumps were designed to generate axle hop and body bounce behavior. These became known as the axle hop bump (AHB), 300 × 25 mm, and the body bounce bumb (BBB), 6000 × 24 mm. Their profiles were added to the longitudinal profile for Cameron's Creek [see Figure 2(b)]. The BBB was positioned approximately one wavelength of body bounce before the center of the instrumented span 3 of Cameron's Creek for vehicles traveling at 80 km/hr. Since the body bounce frequencies for steel- and air-suspended vehicles are different, the BBB was placed in different positions for the air and steel suspensions. The body bounce wavelength for the steel suspension is approximately one span, whereas for the air suspension it is approximately two spans. This was conceived for flat bridges, but the hogs in Cameron's Creek complicated the profile and thus reduced the value of the BBB in terms of direct comparisons between the steel and the air suspensions.

Test Vehicles

Six-axle articulated gravel trucks were used in the test program. They were loaded to their 42.5-ton legal limit (steer = 6 tons; tandem = 16.5 tons; tridem = 20 tons). Steel or air suspensions were fitted throughout in order to facilitate a direct comparison of the bridge response to vehicles fitted with air and those fitted with conventional mechanical steel suspension. A description of the prime movers and the suspensions is presented in Table 2.

The suspensions were characterized using the European Community drop test, which defines a road-friendly suspension as one with a natural frequency less than 2.0 Hz and damping greater than 20 percent. 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. Thus the research was able to compare the bridge response for geometrically similar vehicles fitted with either road-friendly or non-road-friendly suspensions.

BRIDGE RESPONSE

Instrumentation

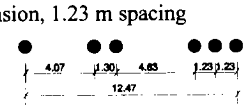
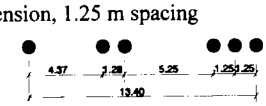
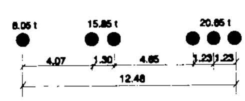
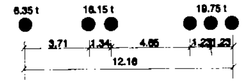
Midspan deflections were monitored. The locations of the deflection transducers are shown in Figure 1. For example, at Cromarty Creek, *D(3-5)* refers to the deflection of the fifth girder from the left of the bridge in the third span.

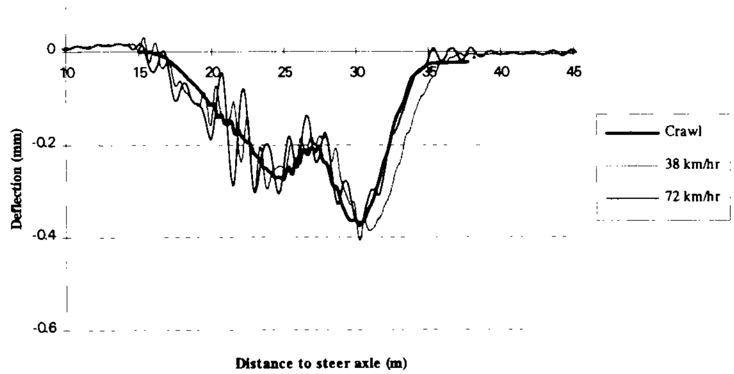
The dynamic deflections of the bridge were measured using an adapted version of the spring and wire system used for many years by EMPA and the Ontario Ministry of Transport (2,4). The system was specifically designed to provide accurate measurements of the dynamic response for frequencies up to the 15 Hz anticipated. The signals were conditioned at the transducer and sampled by a Blastronics data acquisition system after having passed through a 50-Hz low pass filter.

Time Domain

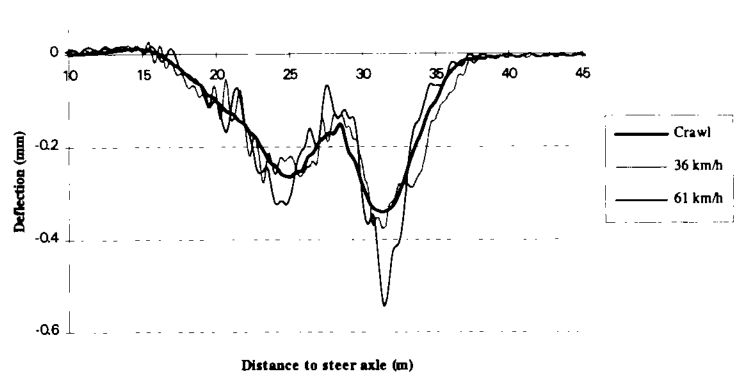
Sample waveforms selected from the hundreds collected are presented in Figures 3, 4, and 5. To facilitate the comparison of multiple waveforms, the time domain responses were converted to the spatial domain. This is achieved by multiplying the elapsed time by the speed of the vehicle. It is clear from Figures 3–5 that speed, roughness, and vehicle suspension are very significant parameters.

TABLE 2 Test Vehicle Suspensions

Prime-mover	Trailer	Gross Laden Mass (t)	Vehicle Code
Freightliner, air suspension	Over the rear axle tri-axle tipper, Evotrac air suspension, 1.23 m spacing 	42.5	FA 42.5 1.23
Mack, Camel back, steel suspension	Over the rear axle tri-axle tipper, York 8 leaf steel suspension, 1.25 m spacing 	42.5	MS 42.5 1.25
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



(a) D(1-4), Truck BA 42.5 1.23, Axle hop bump.



(b) D(1-4), Truck BS 42.5 1.23, Axle hop bump.

FIGURE 3 Yarriambiack Creek: deflection waveforms.

A comparison of the peak deflections showed that the vehicles fitted with air suspensions generally induced deflections at least 10 percent smaller than their steel-suspended counterpart except when axle hop coupled with the bridge. In this case, the peak deflections resulting from air-suspended vehicles were 10 to 20 percent larger than those from the steel-suspended vehicles.

Dynamic Increment

The dynamic increment (*DI*) has been determined in accordance with the following definition:

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

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

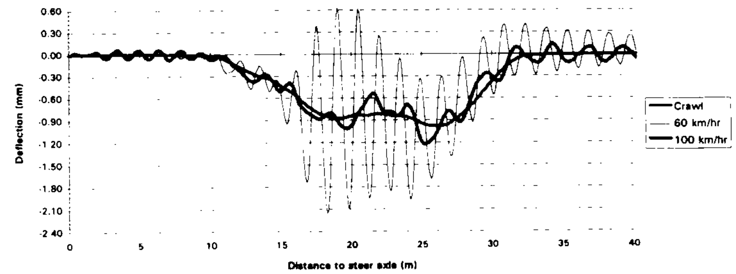
Graphs of *DI* versus vehicle velocity are shown in Figures 6, 7, 8, and 9. Positive velocities refer to northbound traffic and negative velocities correspond to the vehicles traveling south.

Note that the dynamic increment (*DI*) has been calculated only for the deflections that are directly under the zone of influence of the vehicle.

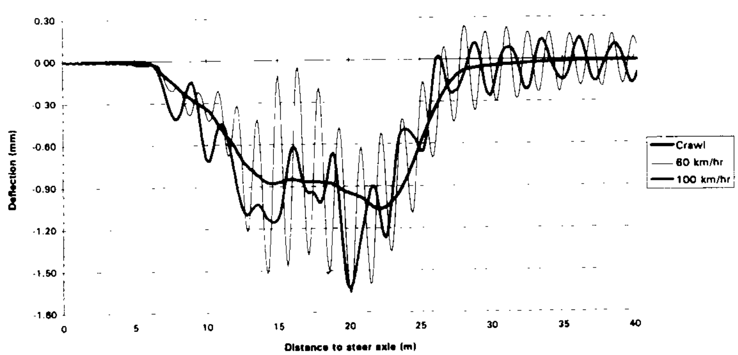
Discussion

The following observations are made:

1. The dynamic increment (*DI*) is small for speeds less than 40 km/hr.
2. *DI*s greater than 50 percent are relatively common. *DI*s of 100 percent or more were recorded. The largest *DI* recorded was 137 percent for another air-suspended vehicle that was excited by the pavement repair at Cameron's Creek.



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



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

FIGURE 4 Cameron's Creek: deflection waveforms.

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

4. The *DI* from air-suspended vehicles is less than the *DI* associated with steel suspensions unless axle hop is excited and coupled dynamically with the bridge. This was strongly evident at Cameron's Creek.

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

Bridge Damage Accumulation

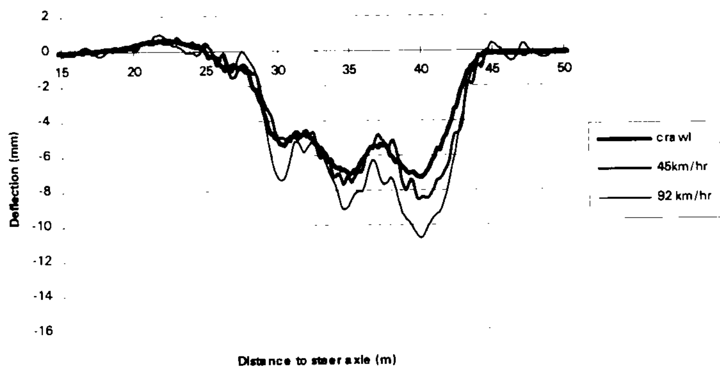
The dynamic coupling between the vehicles fitted with air suspensions and the Cameron's Creek bridge raises questions as to whether comparisons of maximum deflections or stresses are appropriate methods to compare the effects of different vehicle suspensions (see Figure 4).

There seems to be reasonable consensus that the linear Miner's rule is an appropriate model for damage accumulation. Since steel bridges are generally more susceptible to fatigue, a cubic damage accumulation model and a linear Miner's rule were adopted here to provide an approximate comparison of the damage by suspension type and vehicle speed (*5–8*).

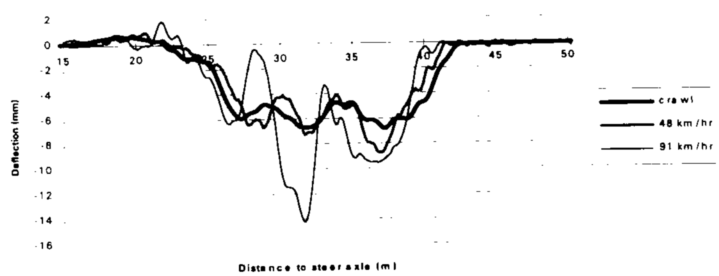
If it is further assumed that the midspan deflections ($d_{v,\ il}$) are linearly related to stress, the relative total damage induced by a vehicle (D_v) can then be compared with that induced by a standard vehicle (D_{std}). This comparison can be achieved by using the following equation when the summation is for the l cycles that occur during the passage of a vehicle:

$$\text{Relative total damage} = \frac{D_v}{D_{std}} \approx \frac{\sum_{i=1}^{l} d_{v,i}^3}{\sum_{i=1}^{l} d_{std,i}^3} \qquad (2)$$

For the purposes of this study, the standard vehicle was taken as the BS 42.5 1.23 (B series, steel suspension, 42.5 tons and 1.23 m between axles on the tridem) at crawl speed. In this way, the relative damage can be determined for different vehicles and speeds. The endurance limit was assumed to be zero. The number (l) and the range of cycles ($d_{v,i}$) while the truck is on the bridge were determined using the rainflow technique (see Figure 10). Using the method detailed above, the



(a) D(3-3), Truck BA 42.5 1.23, No bumps.



(b) D(3-3), Truck BS 42.5 1.23, No bumps.

FIGURE 5 Cromarty Creek: deflection waveforms.

relative damages for selected vehicles traveling in a northbound direction are presented in Table 3. When the vehicle fitted with air suspension coupled dynamically with the Cameron's Creek bridge, the damage was approximately six times that for the worst event for a steel-suspended vehicle loaded to 50 tons. Away from these critical speeds, the situation is reversed.

As the damage is speed sensitive, a representative distribution of vehicles and their speeds should be considered before a thorough comparison of accumulated damage can be made. Nevertheless, the strong coupling between this bridge and the vehicles fitted with air suspensions must be understood further and the extent of this coupling for other spans and structural types established.

Vehicle Response

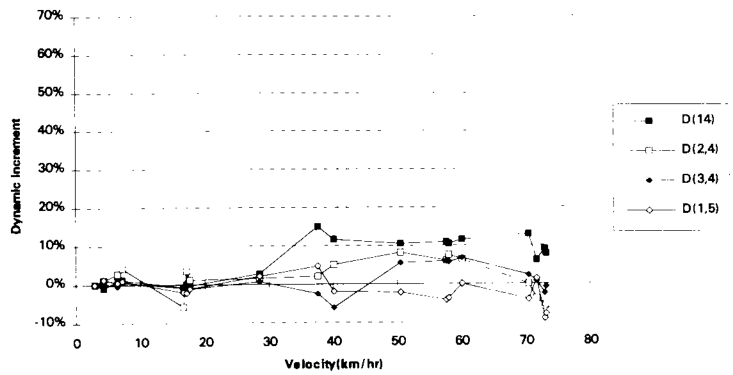
In the tests conducted for Cameron's and Cromarty creek bridges, the triaxle group was instrumented and the dynamic wheel forces measured simultaneously with the bridge response. This was achieved by measuring the principal strains induced by the shear in the axle stub and the acceleration of the outboard mass (*4*).

Time and Frequency Response

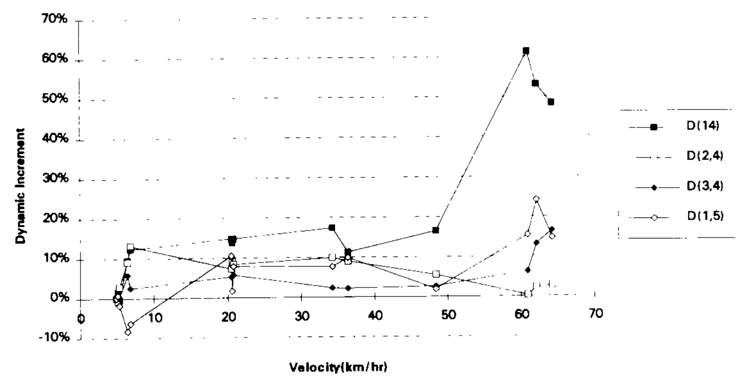
Figure 11 shows the differences between the dynamic wheel forces applied to the bridge by the triaxle group fitted with air or steel suspensions. The dynamic wheel forces applied by the front, central, and rear axles of the tridems are presented along with the total dynamic force applied by the six wheels of the tridem.

The body bounce modes of vibration for the steel suspension exhibit higher frequencies and larger amplitudes than those for the air suspension for these particular waveforms (see Figure 12). This observation is consistent with those at other speeds for soft, highly damped air suspensions versus conventional suspensions. The differences in the frequencies are illustrated in the power spectral densities for individual wheel forces presented in Figure 12.

The power spectral densities highlight the body bounce and axle hop modes. The amplitudes of the axle



(a) Air suspensions - Truck FA 42.5 1.23.



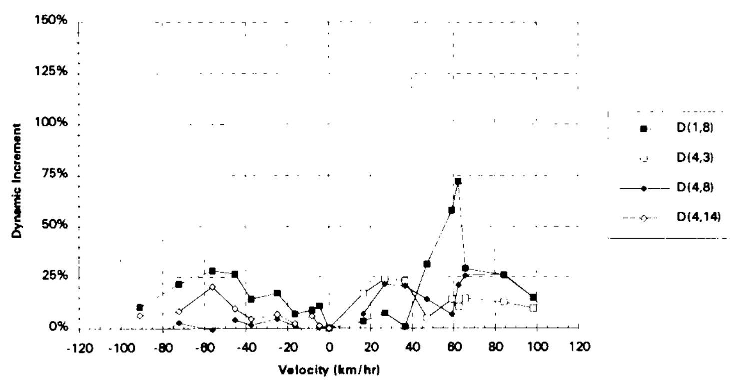
(b) Steel suspensions - Truck MS 42.5 1.25.

FIGURE 6 Yarriambiack Creek: dynamic increment versus speed, axle hop bump.

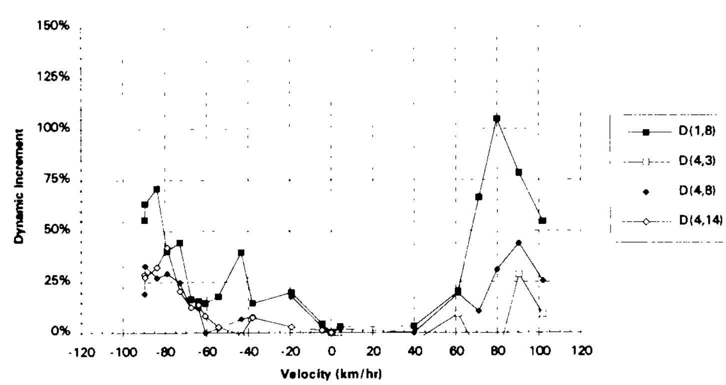
hop modes are much smaller than the amplitudes of the dynamic wheel forces associated with the body bounce. However, for short-span bridges with natural frequencies corresponding to those of axle hop, dynamic coupling with these small-amplitude, high-frequency loads can and does occur (Figure 12). Since the frequencies are high, 10 cycles of dynamic load can be appied to a 9-m span bridge during the passage of a tridem at 60 km/hr.

Close inspection of the wheel force waveforms (Figure 11) illustrates the influence of the axle hop bump that was placed between spans 3 and 4. The total force response illustrates that the higher frequencies are very "confused" for the steel suspension, whereas they are evident for the air suspension. Although these differences are relatively subtle, they are important and a consequence of suspension design. The air-bag suspensions are load sharing through pressure equalization. However, under high-frequency dynamic loads, this equalization does not occur. Each axle acts independently of the others for dynamic loads. Steel leaf suspensions include a series of rockers that provide the load sharing when the vehicle is stationary but also transmit dynamic forces between axles. Thus when the first axle in a group strikes a bump, a portion of the shock is transmitted to the other axles in a manner that is likely to be out of phase with the first axle. As the axle group continues over the defect, this cross-talk continues, thus diminishing the opportunity for each axle to vibrate independently. A similar argument applies for the steel walking beam suspension fitted to the prime mover.

These differences are further exacerbated by the speed of the vehicle. At a critical speed, the time between each axle's striking an axle hop exciter is equal to the natural period of vibration of each axle. When this occurs, each axle in an air-suspended group vibrates in phase and the effects accumulate. With the steel suspensions used in these tests, the cross-talk diminished this effect. Thus, one would expect speed to be a critical



(a) Air suspensions - BA 42.5 1.23.



(b) Steel suspensions - BS 42.5 1.23.

FIGURE 7 Cameron's Creek: dynamic increment versus speed, no bumps.

issue for air suspensions and that the critical speed ($v_{crit.ah}$) would be approximately the axle hop frequency (f_{ah}) times the axle spacing (s).

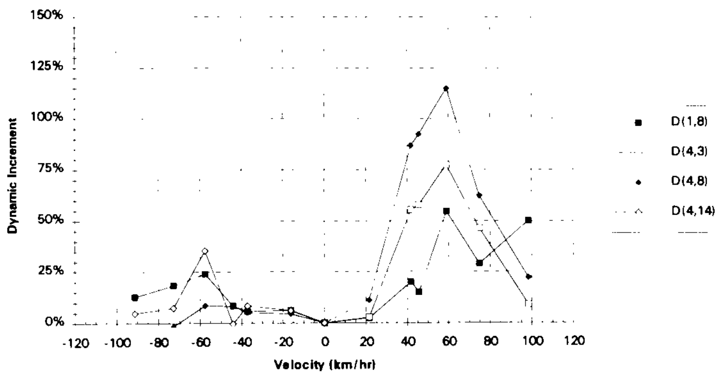
$$v_{crit.ah} \approx s * f_{ah} \tag{3}$$

In the case of an axle hop natural frequency of 12 Hz and a spacing of 1.30 m (drive tandem), the critical speed would be 12∗1.30∗3.6 = 56 km/hr. This is similar to the peak at 60 km/hr evident in the graphs of *DI* versus velocity (Figure 8). This response was also observed for another air-suspended test vehicle (*4*). The peaks associated with the steel suspensions are for higher speeds.

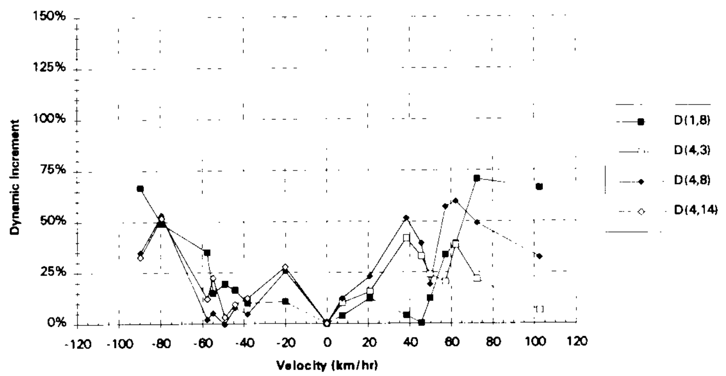
Bridge-Vehicle Interaction

It is informative to consider the forced response of a single-degree-of-freedom system with a natural frequency and damping equivalent to the first flexural mode of vibration measured in the field (see Table 1). The response spectra for the equivalent single-degree-of-freedom systems corresponding to the three bridges are presented in Figure 13. If these are compared with the power spectral densities for the air and steel suspensions (Figure 2), a clearer understanding of the behavior emerges.

The short-span bridge response is influenced by both the axle hop and body bounce modes of the vehicles. For body bounce modes, the frequencies of dynamic wheel forces are typically less than 4 Hz, and any dynamic amplification of the bridge response will be small (see Figure 12). However, for axle hop modes, large dynamic amplification is possible. That is, for the body bounce modes, the magnitude of the bridge response is proportional to the total of the dynamic wheel forces when the axle group is in the critical region of the bridge. As the road-friendly air suspension induced



(a) Air suspensions - BA 42.5 1.23 AHB.



(b) Steel suspensions - BS 42.5 1.23 AHB.

FIGURE 8 Cameron's Creek: dynamic increment versus speed, axle hop bump.

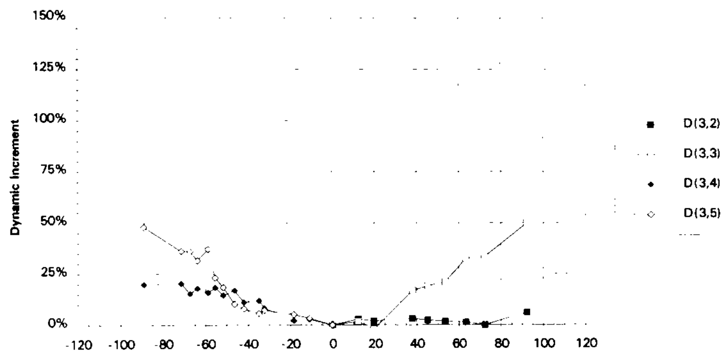
smaller peak dynamic forces, it is expected that the dynamic response induced by the body bounce modes will also be less than those induced by non-road-friendly suspensions. This is consistent with observations. The body bounce forces respond to longer-wavelength (λ) bumps. The critical speed ($v_{\text{crit.bb}}$) is thus dependent on the wavelength (λ) and the body bounce frequency (f_{bb}):

$$v_{\text{crit.bb}} \approx \lambda * f_{\text{bb}} \tag{4}$$

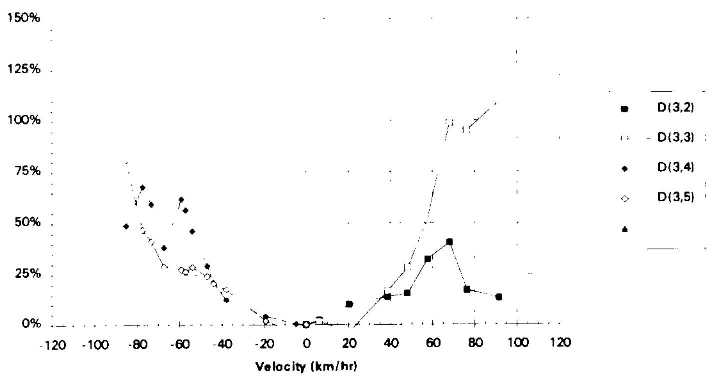
In the case of the bridge over Cameron's Creek that exhibits hogs due to prestress, the critical wavelength is equal to the span length of 9.14 m. Hence for the steel suspension one would expect the critical speed to be of the order of 9:14∗3.3 = 30 m/sec(108 km/hr), whereas for the air suspension $v_{\text{crit.bb}} \approx 1.5*9.14 = 14$ m/sec(50 km/hr). Although this is an oversimplification, the maximum dynamic increments for the steel suspension correspond to high speeds (see Figure 2). In the case of the air suspension, the situation is complicated by the dynamic amplification of the axle hop forces that occurs at similar speeds.

Figure 13 illustrates that for structures with small damping characteristics (such as bridges) the dynamic amplification can be of the order of 20 to 30 should resonance occur. For the range of natural frequencies and damping measured, it is consistent that Cameron's Creek showed the most dynamic coupling with the air suspension at axle hop frequencies. It should be observed that the Cromarty Creek and Yarriambiack Creek bridges are skewed. This immediately puts each wheel of an axle out of phase for a defect such as a poorly aligned deck joint and makes the superstructure mode shapes less sympathetic to resonance with the traveling vehicle.

Hence it is concluded that vehicles fitted with air suspensions will dynamically couple with short span bridges provided that (*a*) the bridge natural frequency



(a) Air suspensions - BA 42.5 1.23.



(b) Steel suspensions - BS 42.5 1.23.

FIGURE 9 Cromarty Creek: dynamic increment versus speed, no bumps.

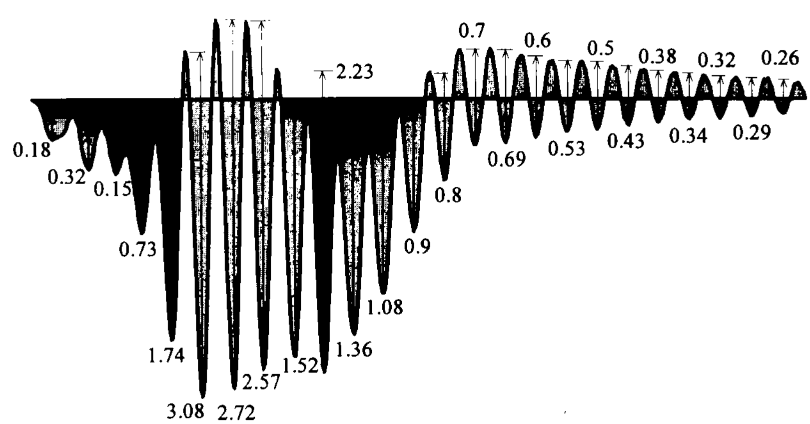
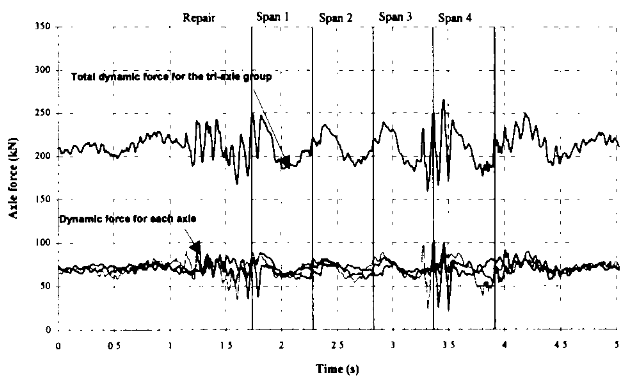


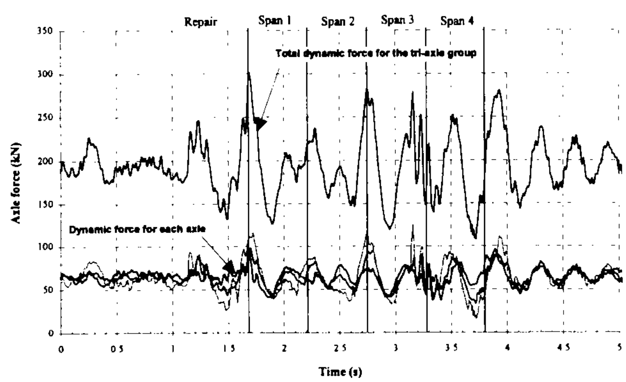
FIGURE 10 Deflection cycles for Cameron's Creek: D(4,8), BS 42.5 1.23 at 59km/hr AHB, northbound.

TABLE 3 Comparison of Relative Damage Induced in Bridge over Cameron's Creek by Test Vehicles

Deflection	Vehicle	Speed	Relative Damage
D(1,8)	BS 42.5 1.23	Crawl	1.0
D(1,8)	BS 50.0 1.23	79 km/hr	17.5
D(1,8)	BA 42.5 1.23	Crawl	1.0
D(1,8)	BA 42.5 1.23	60 km/hr	16.5
D(1,8)	BA 42.5 1.23	100 km/hr	4.7
D(4,8)	BS 42.5 1.23	Crawl	1.0
D(4,8)	BS 42.5 1.23 , BBB	81 km/hr	15.1
D(4,8)	BA 42.5 1.23 , AHB	59 km/hr	103

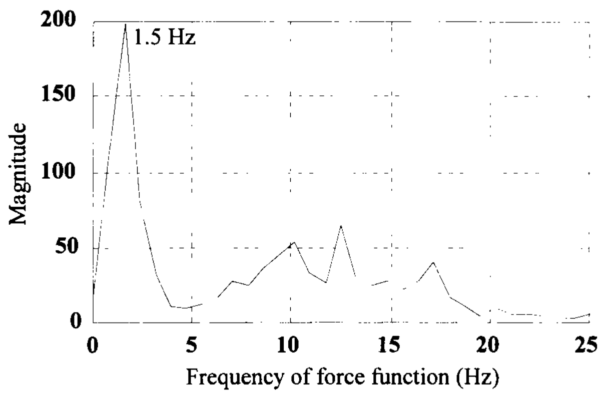


(a) Air suspensions, 59 km/hr over the axle hop bump (AHB), BA 42.5 1.54.

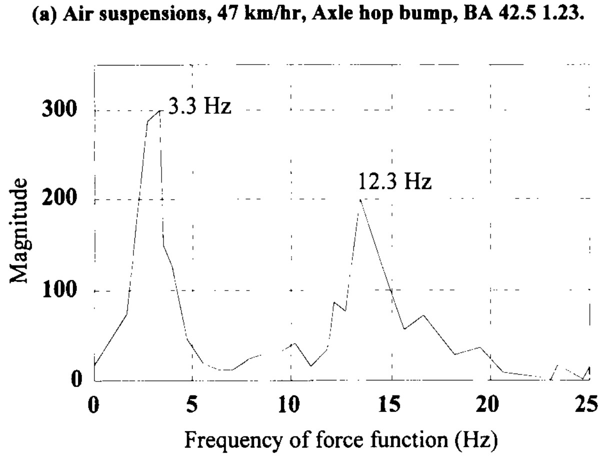


(b) Steel suspensions, 62 km/hr over the axle hop bump (AHB), BS 42.5 1.23.

FIGURE 11 Cameron's Creek: dynamic axle forces for trailer triaxle 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 12 Cameron's Creek: power spectral densities for dynamic wheel force, driver's side center wheel (DC).

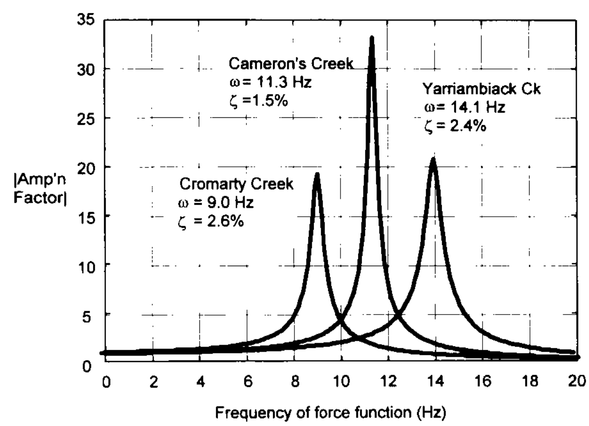


FIGURE 13 Magnification factor versus frequency of force function for single-degree-of-freedom approximation of Cameron's Creek.

is in the range of axle hop frequencies, (*b*) axle hop is excited by some short-wavelength defect in the road surface, and (*c*) the vehicle is traveling at a critical speed so that each axle in the group vibrates in phase.

Discussion of Results

Canadian and Swiss research has demonstrated increased dynamic amplification for bridges with first flexural frequencies in the range of 2.5 to 4.5 Hz (*2,3*). Outside of this range the Commentary on the Ontario Highway Bridge Design Code (*9*) states: "The dynamic response of a component to moving loads results in some additional dynamic load but the frequencies of a longitudinal component with a span less than 22 m are usually sufficiently high that any frequency match between component and vehicle is unlikely." This research has shown that quite severe dynamic coupling can occur for bridges with frequencies in the 10- to 15-Hz range and the new generation of air suspensions.

Analysis of the experimental data shows that a single vehicle registering 100% dynamic increment for the Cameron's Creek bridge induces similar maximum responses as two vehicles plus the AUSTROADS Bridge Design Code (*10*) dynamic load allowance of 25 percent. Dynamic coupling has also been shown to induce multiple fatigue cycles for the passage of a single vehicle traveling at a critical speed. However, to understand the complete picture, damage should be accumulated over representative speed ranges.

The implications of these findings on bridge design, evaluation, and life prediction must be considered closely. Further testing is necessary to validate the theories presented above and to extend them to the point where recommendations for bridges can be made. Issues associated with multiple presence, speed, and the reduction expected in dynamic increment for grossly overloaded vehicles will reduce the dynamic increment that could be experienced at the strength limit state. However, this is not the case for the fatigue of short span bridges or short span elements within larger structures.

Road-friendly suspensions rely on efficient dampers. These components are subject to wear and must be regularly maintained. A worn damper results in substantial increases in dynamic wheel forces. The consequences for bridges of an air suspension operating with worn dampers has yet to be investigated, but it is expected to be significant.

Conclusions

The dynamic responses of three short span bridges to vehicles fitted with air or steel suspensions were measured experimentally. The air suspensions met the European Community requirements for road-friendly suspensions, whereas the steel suspensions did not. Peak bridge deflections were less for the air-suspended vehicles than for steel-suspended vehicles unless axle hop was excited. 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 dynamice wheel forces. These forces 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-wavelength bumps. 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 that suspension dampers are operating efficiently.

ACKNOWLEDGMENTS

This research was funded by the Roads and Traffic Authority of New South Wales and Victorian Roads 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 contributions of Road User Research, colleagues from OECD DIVINE and QUT, and the Australian Road Research Board are also gratefully acknowledged.

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