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Impact Studies on a Small Composite Girder Bridge

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IMPACT STUDIES ON A SMALL COMPOSITE GIRDER BRIDGE

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Synopsis

Two impact studies on a small-span, composite girder highway bridge have given widely scattered impact fractions, with a maximum of 1.32 as compared with the AASHTO code value of 0.30 for this bridge. Field strains were used to measure maximum mid-span bending moments for 170 trucks in normal traffic, and these were compared with equivalent static values computed from axle weights measured by a weighbridge. Impact fractions varied from - 0.08 to + 1.32 for gross vehicle weights from 27 - 44 ton. Large impact values occurred for both light and heavy vehicles and were repeated in two independent series of tests. The scatter of the results suggests that impact is vehicle dependent, and that it may vary with suspension geometry. Possible causes of high impact are discussed.

CONTENTS

1. INTRODUCTION

This paper describes two impact studies on Six Mile Creek bridge, a short span, steel and concrete highway bridge, located on the Cunningham Highway, 28 km west of Brisbane, Australia.

The bridge was instrumented in 1981 for the Australian Road Research Board to determine histograms of mid-span bending moment, for use in the preparation of a new highway bridge design code in limit states format. Some results of the study have been presented in References 13, 14, 20 and 21.

The work described in this paper is additional to the main programme and has resulted in two series of impact values, computed from mid-span bending moments obtained by strain measurements under random service loading. The values reported here are larger than those obtained by other workers. The paper discusses possible reasons for this and indicates the direction of future work.

The term "impact" is generally used to describe the increase in stress (or deflection) due to the dynamic nature of traffic loads. The AASHTO (American Association of State Highway and Transport Officials) bridge design specification (Ref. 26) defines the impact fraction, I, as the ratio of additional stress to the equivalent static live load stress. It follows that the ratio of dynamic to static live load stress is I + 1. Various workers use I or I + 1 to report their results. The maximum value for I observed in this study is 1.32.

2. LITERATURE REVIEW

There is a considerable literature on bridge - vehicle interaction and impact. That which is most relevant to this study concerns (a) code provisions, (b) experimental impact values, and (c) the quality of models for vehicle suspension systems used in analytical studies.

The AASHTO code (Ref. 26) is the basis for the design of highway bridges in many countries, including Australia. It specifies

$$I = 50/(L + 125) \tag{1}$$

but $\ngtr$ 0.30,
where L is the loaded length (feet).

For a simple span, L is the span length. The maximum value of 0.30 applies for L less than 41.7 feet (12.7 m).

The current formula is a variant of one originally recommended in 1931 (Ref. 7).

$$I = 50/(L + 160) \tag{2}$$

but $\ngtr$ 0.25,
where L is the span length in feet.

Although this formula had an experimental basis, this is hardly relevant today; it included work, for example, on solid rubber tyres.

The AASHTO rule, equation (1), has been left unaltered in a recent review. "No structural distress problems appear to have resulted from their use, and that fact plus their simplicity would seem to mitigate against drastic change" (Ref. 2).

However, the new Ontario Bridge Code (Refs. 15,16) has introduced more conservative values of I. It requires the use of not less than 0.40 for deck slabs, and 0.35 for floor beams supporting deck slabs and for all beams of span less than 12 m. For main longitudinal components it specifies values between 0.30 and 0.45, the higher values being for structures with a first natural frequency between 2.5 and 4.5 Hz.

A recent review has been made of observed impact values for steel bridges, for use in fatigue design (Ref. 22). It lists 40 values of I obtained from stress traces, from 0.03 to 0.31, and another 41 values from deflection measurements, from 0 - 0.52. It is noticeable that the deflection tests gave the higher values. Only one value of I from the stress records exceeded 0.30, whereas for deflection readings there were five - 0.46, 0.35, 0.45, 0.52 and 0.48. The first of these was for a simply supported 65 ft (19.8 m) span; the second was for a continuous girder; and the last three for a cantilever.

The AASHO road test bridges (Refs. 3,4) gave values of I from about 0.03 - 0.25 for strain readings, and 0.02 to 0.42 from deflection readings. Fourteen test vehicles were used, two with two axles, and twelve with three. Observations were made over the period 1958-1960.

Theoretical studies associated with the AASHO road test were carried out by Veletsos, Huang, Wen and others (Refs. 6,29,30). Much of this used a three-axle vehicle, with a tractor and a semi-trailer, in which the suspension at each axle was modelled by a linear elastic spring and parallel friction device - to represent the leaf spring - in series with another linear elastic spring - to represent the tyre. No mass was allocated to the axle; that is, the model acted as a single, three component system between the chassis and the ground (Refs. 6,29). Some other studies in the series used simple elastic springs without damping (Ref. 30).

The Transport and Road Research Laboratory, Crowthorne, England, has carried out work on impact and truck suspensions, with work by Page, Leonard, Grainger and others (Refs. 9,17-19). An instrumented wheel was used to measure forces between the tyre of a two-axle truck and the surface of a series of 31 motorway bridges (Ref. 19). The main programme of 30 bridges gave values of I from 0.09 to 0.75. Seventeen of the values exceeded 0.30. Another value, of 1.77, (i.e. I + 1 = 2.77), was obtained for a minor overpass with the bridge surface 1 in (25 mm) higher than the approach, the step occurring over a length of 5.9 in (150 mm).

A comparative study was made in the laboratory of 8 trucks (Ref. 9). Each vehicle was driven over a plank 1.6 in (40 mm) high, 9.8 in (250 mm) wide, mounted on the first of a series of weighbridges arranged to measure forces from the off-side wheels. Typically, I rose from 0 at zero velocity to about 1.1 at 46.6 mph (75 km/h). However, some higher values were observed - up to 2.0 (I + 1 = 3.0) for the front axle of a dual trailer group, and 1.6 for the front axle of a twin drive group. In the former case, the suspension arrangement at each side of the vehicle had twin leaf springs, one for each axle, interconnected with a linkage system for load sharing. In the second case the two axles were supported by a single leaf spring (at each side of the vehicle) pivoted at its centre. High impact values (I up to 2.0) were also measured from the second steer axle of two vehicles with twin-steer arrangements, but in these cases the axle forces were relatively small.

Page (Refs. 17,18) reported a related set of theoretical studies on single axle and linked, twin-axle suspension systems. These gave maximum values of I, due to passage over a smoothed 1.6 x 9.8 in (40 x 250 mm) hump of -

1.6 for twin springs connected by end linkages;

1.7 for a walking beam on a single spring;

1.3 for independent twin springs.

In this case the walking beam unit is only slightly worse than linked twin-springs. However both of these were worse than the case with independent springs, and were shown to be prone to high impact for speeds in the range 12.4 - 37.3 mph (20 - 60 km/h).

Shepherd, Aves, Sidwell and Wood (Refs. 23-25,32) have reported impact values for New Zealand bridges. These were obtained from deflection readings caused, for the most part, by the passage of a standard two-axle truck. Values of I for 14 bridges (Ref. 32) lie in the range 0.1 - 0.7, with nine in excess of 0.3. The highest value, of 0.7, is reported for two cases. In one of these, values of 0.2 - 0.7 were obtained for 11 vehicles in the general traffic over the bridge. The standard vehicle gave 0.3 for this bridge. It is concluded that "the vehicle characteristics have a significant influence on the recorded impact".

Studies have also been carried out in Ontario (Refs. 5,16) on a range of bridges, using deflection measurements and a standard vehicle. For continuous bridges, values of I have been recorded in the range 0.1 - 0.87; values for other bridges were from 0.07 - 0.75.

Sweatman (Refs. 27,28) of the Australian Road Research Board (ARRB) has used an instrumented hub to measure wheel forces for a series of vehicles driven over a standard route, with a mixture of road conditions. He records 95th percentile impact factors, I, for all road surfaces at 46.6 mph (75 km/h) (Ref. 28) as -

0.14 for a torsion bar suspension;

0.17 - 0.21 for trailer suspensions;

0.23 - 0.33 for pivoted drive tandem systems;

with a maximum recorded value of 0.37.

He quotes results from Whittemore and others (Ref. 31) which also suggest higher impact values from axles in articulated tandem systems.

ARRB has also sponsored two studies in Australia on bridge-vehicle interaction. Work at the University of New South Wales (Refs. 1,11), by Mulcahy, Pulmano, Traill-Nash, Balint and others, was initially concerned with impact effects from vehicle braking (Ref. 11), while sponsored work at the University of Queensland has been concerned mainly with the measurement of bending moments due to service loads.

Coincidentally, both have studied similar two-axle vehicles, and have reported similar suspension characteristics. The Queensland results have been reported by O'Connor, Kunjamboo and Nilsson (Ref. 12). Spring behaviour is non-linear, and characterised by the effects of inter-leaf friction, separating the loading and unloading load-deflection curves (Refs. 11,12). Excessive simplification of suspension models can cause significant losses in analytical accuracy, particularly if the frictional nature of spring damping is altered (Ref. 8). Miller and Swannell (Ref. 10) have developed a refined analysis for bridge-vehicle interaction, and have compared experimental and theoretical behaviour for Six Mile Creek bridge.

3. DESCRIPTION OF THE BRIDGE

The general arrangement and cross-section of Six Mile Creek bridge are shown in Figures 1 and 2. The bridge was built at separate times in two halves, divided down the median strip. The instrumented span is the first crossed by traffic from Ipswich to Brisbane (Australia's traffic drives on the left). The 7 in (178 mm) slab is composite with six rolled steel joists 24 in x 7-1/2 in x 95 lb (610 x 190 mm x 140 kg/m) spanning 37 ft (11.28 m) between bearings with 37 ft 6 in (11.43 m) between the centres of the piers.

The bridge is instrumented with six weldable electric resistance strain gauges, one at the centre of the underside of each lower flange, 0.45 m on the Ipswich side of mid-span. These are read by a special purpose data logger with a cycle time of 1/300 sec. recording digital information onto a 10-1/2 in (267 mm) 9-track magnetic tape for subsequent computer processing (Ref. 20).

Care has been taken to ensure that the bridge slab is correctly isolated from its neighbouring span, and the abutments. The main bearings consist of mild steel plates sliding on phosphor-bronze, but to reduce friction this end of the bridge was jacked and stainless steel/teflon inserts were added.

The central bending moment is calculated as the section modulus for an inner girder multiplied by the weighted sum of the strains, using the following weighting factors to allow for differences in section modulus -

kerb girder	1.38
inner girder	1.0
median girder	1.13

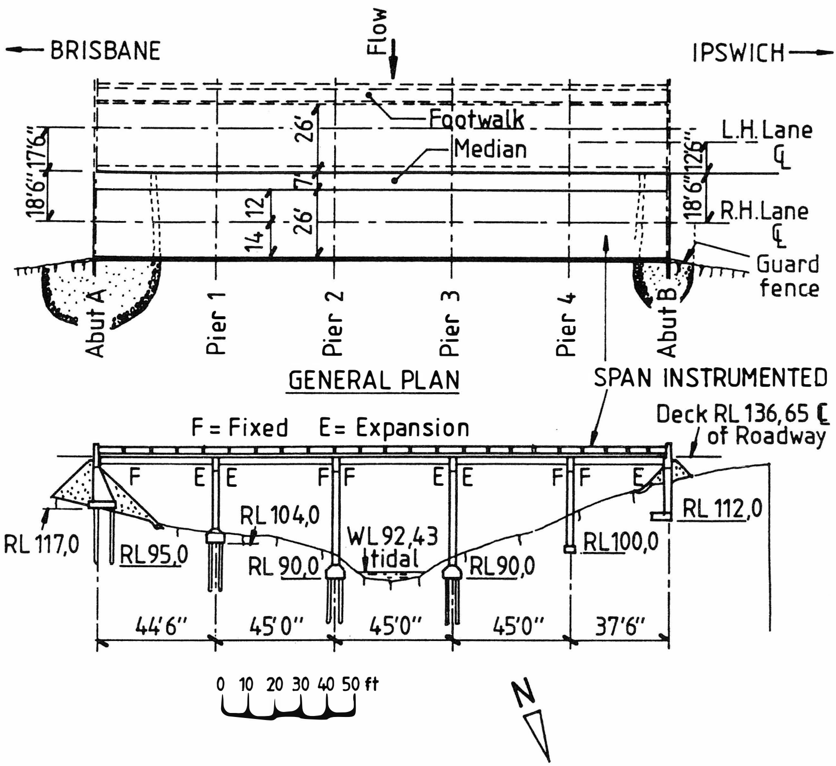

FIGURE 1 : General arrangement of Six Mile Creek bridge

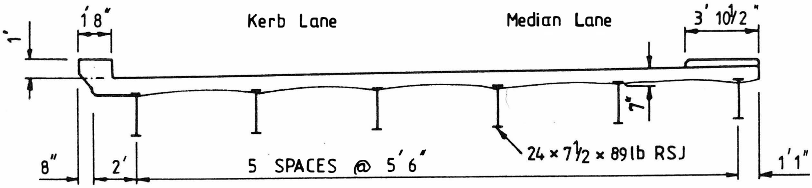

FIGURE 2 : Cross-section of Six Mile Creek bridge

The results of calibration tests (Ref. 20) are presented in Figure 3 which compares the theoretical weighted sum of strains with those measured in static tests. Experimental behaviour is close to that which would be expected.

The instrumented bridge was designed in 1961 using the H20-S16 AASHO truck. Assuming the code distribution factor of 0.55, the calculated total design stress in an inner girder is 0.90 x the then allowable stress (18 ksi or 124 MPa). Grid analyses suggest that a more accurate distribution factor would be 0.38.

The maximum live load bending moment observed from 65 909 heavy vehicles over an effective observation period of 261 days (to July 1983) was 2.67 times that calculated for a single H20-S16 truck (with an assumed impact factor I = 0.30).

A computer grid analysis gave the following natural frequencies for the bridge -

first symmetrical mode	9.6 Hz
asymmetrical modes	10.2, 14.6 Hz.

Stress records gave values from 10.0 to 12.3 Hz, with a mean of 11.4.

Traffic on the bridge runs directly on the surface of the concrete slab. The approach road is surfaced with asphaltic concrete carried up to the rear face of the end wall of the abutment. The gap between the top of the end wall and the bridge slab is trimmed with a sliding plate. The approach profile was surveyed for another project and will not be reproduced here. It is sufficient to say that the initial accuracy of the profile was good and that initial disturbance to vehicles by the approach was small. However, the roadway surface was resealed between

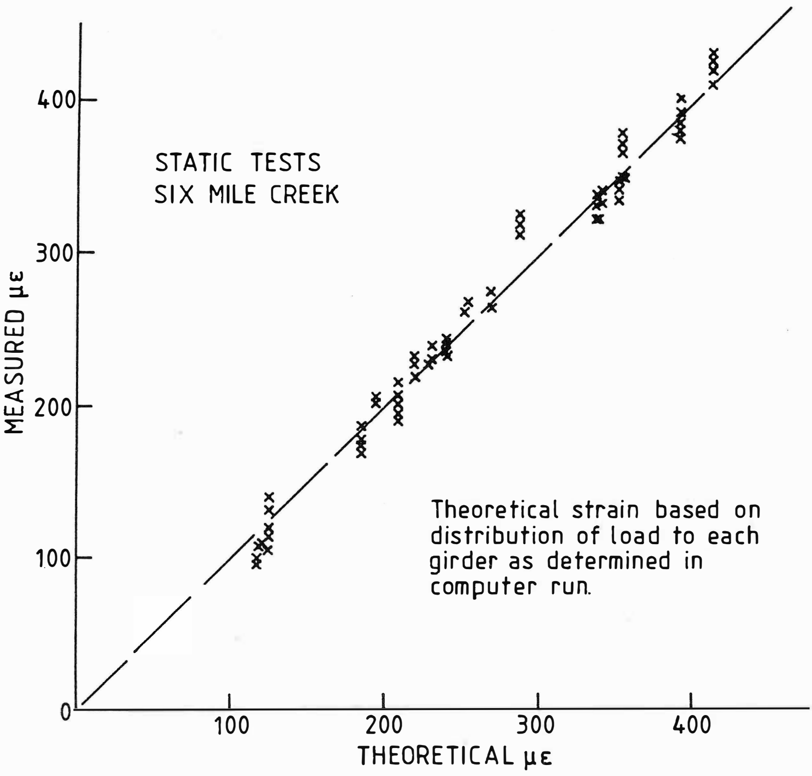

FIGURE 3 : Calibration test results

the two impact studies. In the second study, therefore, the approach was slightly higher, with a gradually tapered drop to the bridge.

The legal speed limit at the bridge is 49.7 mph (80 km/h) and most truck traffic would be at about this speed. It is unlikely that velocities of trucks in the impact studies would exceed 55.9 mph (90 km/h).

4. DESCRIPTION OF IMPACT TESTS

A compulsory 24 hour weighbridge is located at Gailes, on the Cunningham Highway 7 km towards Brisbane.

The initial impact study was carried out between 9 am and 3 pm on one day, December 8, 1981. Observers stationed at the bridge noted, for each heavy vehicle, time of arrival, registration number and axle configuration. Observers at the weighbridge noted time of arrival, registration number, vehicle configuration, gross weight, weight of each axle group, and spacing between centres of axle groups.

Of 356 vehicles recorded at the bridge site, 137 effective correlations were achieved.

The data logger recorded detailed traces for the dynamic effect of each vehicle on the bridge, from which maximum values of mid-span bending moment were obtained. Equivalent static values were computed from the weighbridge records, assuming 4.92 ft (1.5 m) as the spacing between adjacent axles in a group. Studies of axle spacings in Australia indicate that this is a reasonable estimate. Although some variation in axle spacings would have occurred, the effect of this on mid-span bending moment is small.

Values of I + 1 were computed as the ratio of observed dynamic to computed static mid-span bending moments.

The maximum value of I recorded in this study was 1.32, much higher than the code value of 0.30. It was decided therefore to repeat the study. Accordingly, on September 7, 1983, a further 33 correlations were made.

5. RESULTS OF IMPACT STUDY

The results of the first impact study are presented in Figures 4 and 5, with the factor I + 1 plotted against computed static bending moment and gross vehicle weight. Values of I vary between - 0.03 and + 1.32 with a mean of 0.38. It is assumed that the occasional negative values result from transfer of load between axles.

The full lines shown in these diagrams (and in Figure 6 and 7) are the results of linear regression analyses. The dotted lines are estimates of 95% confidence lines - 5% of values may be expected above the upper bound, and another 5% below the lower bound. It may be seen that results are widely scattered, with little tendency for a reduction in I as the weight of the vehicle increased. The maximum Australian legal truck weight is 41.9 tons (38 t). It is clear therefore that large impact values occurred with both heavy and light trucks.

Figures 6 and 7 are similar graphs for the second impact study.

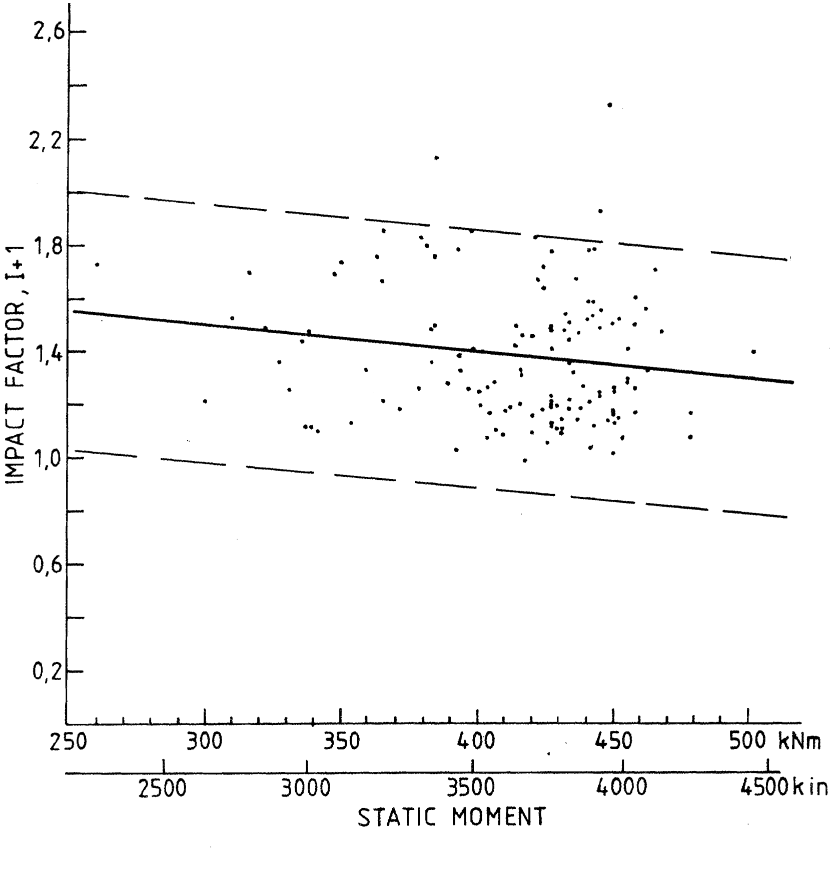

FIGURE 4 : First impact study - 1 + 1/computed static bending moment

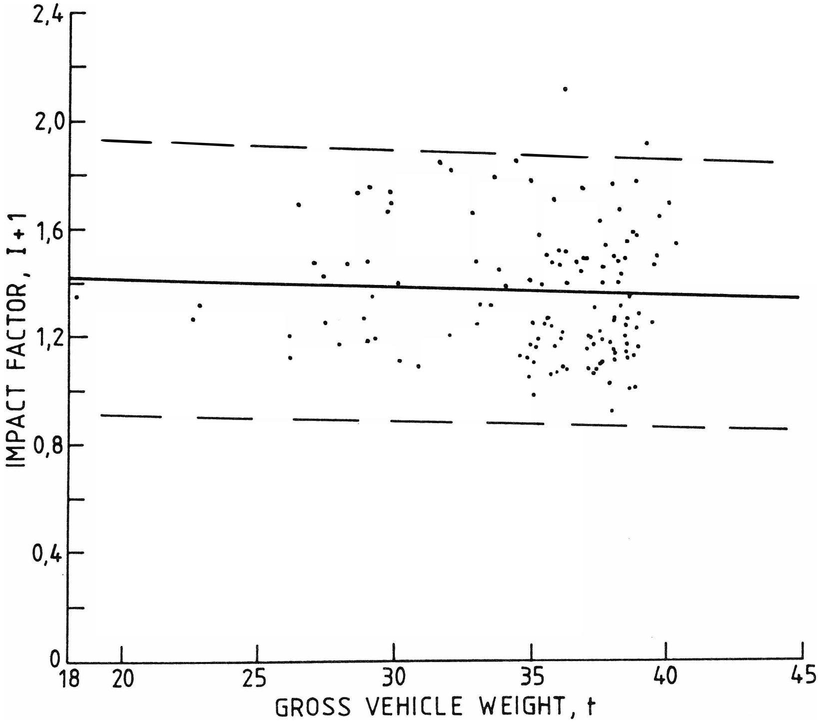

FIGURE 5 : First impact study - I + 1/gross vehicle weight

In this case I varied from 0.21 to 1.31. The worst case is at a lower load than in the first study, and is in this way less extreme. However there is an overall tendency for larger impact values, as would be expected to result from the revised roadway surface.

Twenty-seven acceptable load sharing suspension systems are recognised and classified by the Australian road authorities. The suspension classification was obtained for 20 Queensland trucks in the second study. Of these, 11 had twin drive axles and a rigid walking beam (Australian classification DA). These cases are identified in Figure 8, with their regression line compared with that for this full group of 20 vehicles. The most extreme impact values found in this study (I = 1.31 at low load, and three values of I from 0.98 to 1.18 at high loads) occurred with DA units. The regression line for DA units is higher than that for the complete sample of vehicles. However the number of incidents is insufficient to demonstrate with certainty that DA units are worse than others.

Some typical curves of central bending moment/time are shown in Figures 9 and 10. The vertical scale, marked micro-strain, represents the weighted sum of the strains in the six girders. It may be converted to bending moment, in inch kips, by multiplying by 9.5 (or by 1.07 to give the bending moment in kNm). The case numbers refer to Table 1 which lists theoretical static bending moments, experimental bending moments and values of I + 1 for seven typical cases. Case 1 had the maximum recorded impact value. Cases 1 - 3 form a series down the right hand side of Figure 4; 1, 4 - 7 are representative cases with high impact for successively smaller values of static bending moment.

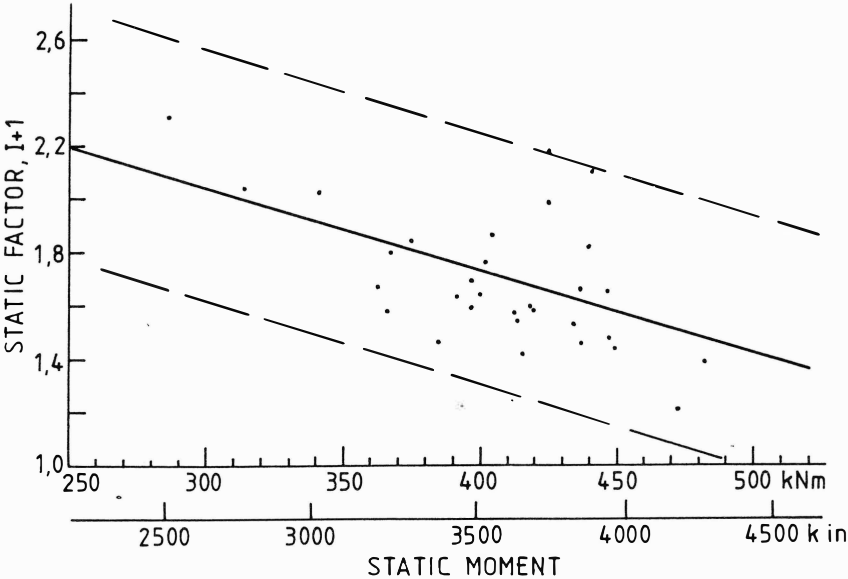

FIGURE 6 : Second impact study - I + 1/computed static bending moment

FIGURE 7 : Second impact study - I + 1/gross vehicle weight

TABLE 1. - Impact Values

Case	Theoretical Static BM, in.kips (kNm)	Experimental BM, in.kips (kNm)	I + 1	I + 1 after smoothing
1	3 970 (448)	9 220 (1041)	2.32	2.26
2	4 100 (463)	7 190 (812)	1.75	1.49
3	4 450 (502)	6 240 (704)	1.40	1.26
4	3 740 (422)	6 200 (700)	1.66	1.34
5	3 360 (379)	6 120 (691)	1.82	1.26
6	2 800 (316)	4 740 (535)	1.69	1.30
7	2 300 (260)	3 990 (451)	1.73	1.59

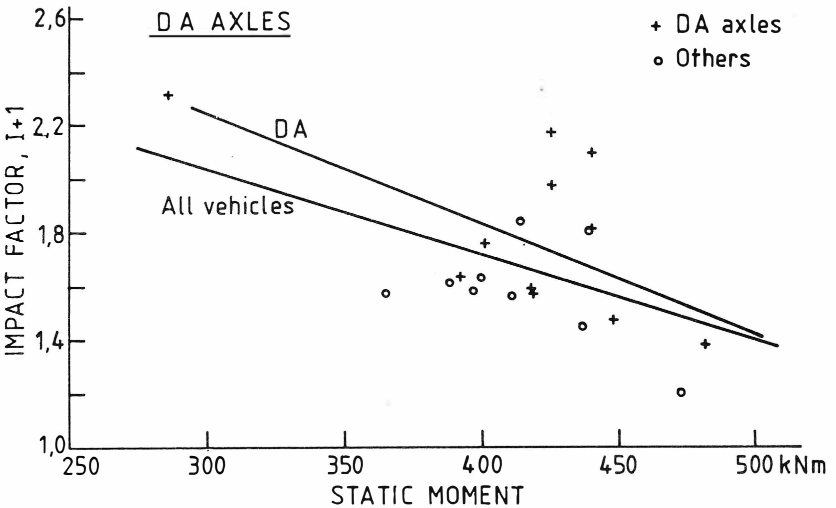

FIGURE 8 : Second impact study - effect of suspension geometry

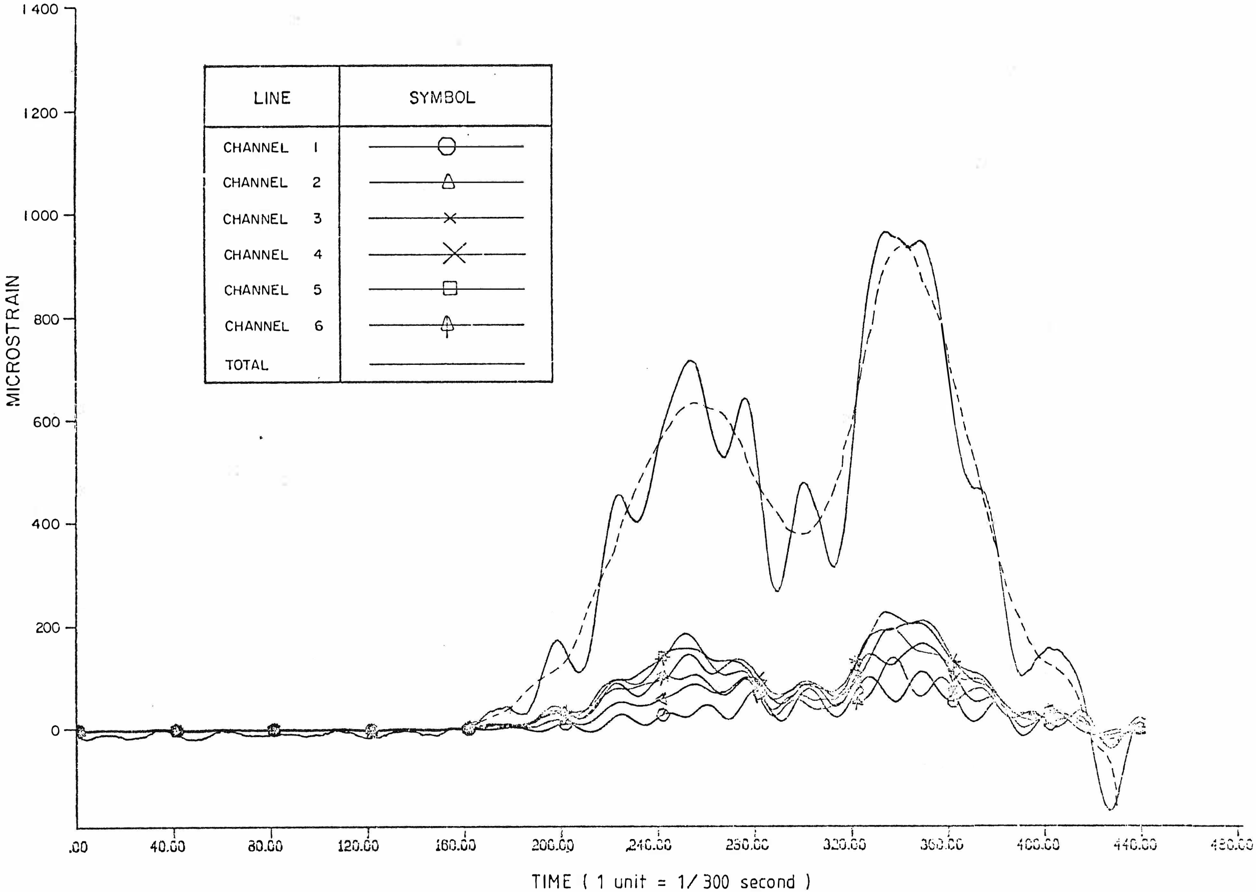

FIGURE 9 : Strain-time curve for event with I = 1.32, max static BM = 448 kNm (Case 1)

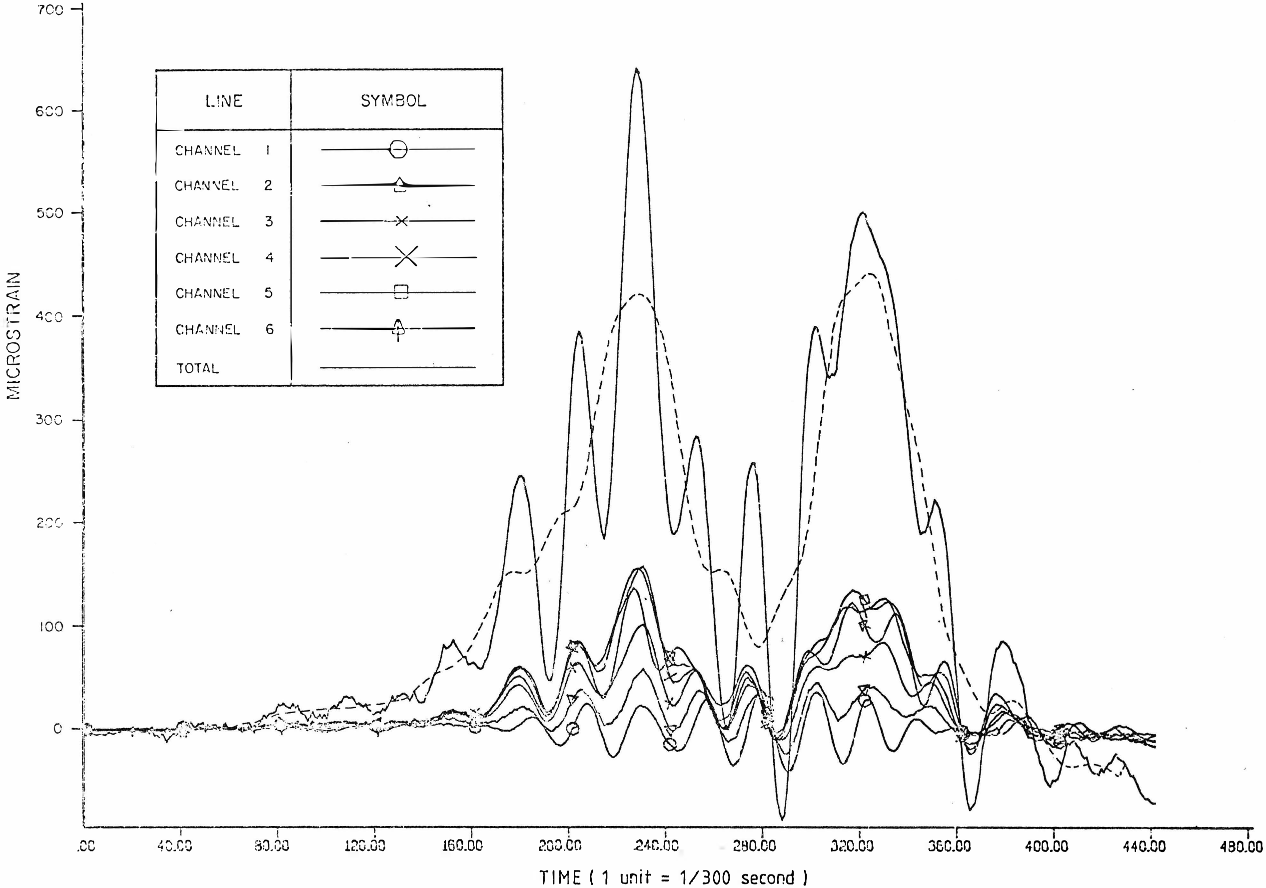

FIGURE 10 : Strain-time curve for event with I = 0.82, max static BM = 379 kNm (Case 5)

Figure 10 shows a significant high frequency component. As mentioned earlier, this corresponds to a frequency of about 11.4 Hz, or a period which corresponds to about 26 readings at the sampling rate of 300 Hz. It was decided therefore to attempt a numerical smoothing operation in which each value was replaced by the mean of 27 values centred around the current value. The results are illustrated in Figures 9 and 10, and quantified in Table 1. The efficacy of smoothing clearly varies with the record and is influenced by such factors as the relative magnitude of the 11 Hz component, and the chance coincidence of an 11 Hz peak with a general peak. In some cases the 11 Hz component is clearly a significant factor in producing high impact (as in Case 5, Fig. 10) while in other cases (such as Case 1, Fig. 9) some other contributing factor needs to be sought.

6. POSSIBLE CAUSES OF HIGH IMPACT

This study has given values of I larger than those commonly reported in the literature. In seeking explanations for this some preliminary points should be made.

(1) These results are for a single bridge and there is, at present, no justification for the extrapolation of these results to other cases.

(2) Nevertheless, it is also true that the methodology of this study is virtually unique in the literature. Results have been obtained from (i) strain measurements, and (ii) a wide range of modern vehicles in service, and should be of more direct practical significance than those from other studies.

By contrast, many recent studies use deflection readings and a standard test vehicle (Refs. 16,32). Tests with a range of vehicles either quote values for tyre forces (Ref. 19) or have used vehicles that are now obsolete (Ref. 4).

It is quite clear from this and other studies that I is vehicle dependent. Some evidence suggests that high impact values are caused by linked dual axles, particularly those with rigid or flexible walking beams. However it is difficult at present to identify with assurance those design features which are at fault.

Vehicle defects may also contribute to high impact values. The most obvious of these is lack of balance in the wheels and tyres. The effect of dynamic tyre forces in steer wheels on driving characteristics is such that these are likely to be correctly balanced. Drive wheels and trailer wheels could, however, have significant out-of-balance forces.

The natural frequency of Six Mile Creek bridge is about 11 Hz, and impactive forces at about this frequency may excite the bridge. The first natural frequency for vertical movements of the main body of a truck is likely to be lower than this, of the order of 2 - 5 Hz (Refs. 16,32). It is important, therefore, that dynamic analyses for bridge - vehicle interaction have the capacity to model higher frequency effects.

One case of interest is axle-hop. The axle, with associated masses such as the drive housing, is a relatively small mass restrained by both the spring and the tyre. Both factors - low mass and high stiffness - tend to increase the natural frequency. It is important, therefore, that axle movements be represented correctly.

Interleaf friction causes separation of the loading and unloading load-deflection curves of leaf springs. Axle vibrations and chassis moments are superimposed on initial, dead-load deflections. During these displacements, the curve of spring force/displacement follows transition curves between the upper and lower branches of the load-deflection curves (Ref. 8).

Kunjamboo and O'Connor have shown (Ref. 8) that, for a particular case, moderate changes in the slope of the transition curve have a minor influence on chassis movements. It is possible that other aspects of behaviour - such as axle vibration - may be more sensitive to change. Future research is required, therefore, to define the correct models for transition curves in leaf springs.

Many studies have included the effects of roadway roughness. Approach roughness may cause the vehicle to bounce onto the bridge causing high impact. Analytical studies of Six Mile Creek bridge have been made which include the effect of measured profiles and to date these do not suggest that approach roughness has been the cause of the high impact values recorded in the first stage of this study. However, further work needs to be done in this area also; for example, to examine the effects of small defects of a periodic kind.

7. PRACTICAL SIGNIFICANCE OF THIS STUDY

The large impact values found in this study are disturbing. However, they have been shown to occur in only one bridge and it would be premature to use these values in design before other bridges are tested.

The large scatter of values suggests that impact is vehicle dependent and that some truck suspensions are worse than others in causing high impact in this bridge. It is to be expected that the same may occur with other bridges and on pavements. Impact studies using a restricted range of test vehicles are unlikely to give realistic values.

Vehicle suspensions are designed primarily to give suitable ride and handling characteristics and to achieve acceptable load sharing between axles when the vehicle traverses an irregular surface at low speed. Dynamic impact effects are important to the bridge designer, particularly if they are of the order of magnitude shown in this study. It is essential that those features of truck suspension units that contribute to high impact be identified. If it is shown that impact values of the present magnitudes are widespread, then it may be necessary to modify the design and specification of truck suspension units so as to achieve reduced impact, or alternatively to design bridges for larger impact.

8. CONCLUSIONS

(1) Impact values measured on Six Mile Creek bridge have been shown to be repeatable in two series of tests. These tests used measured strains to estimate impact factors for a wide range of service vehicles.

(2) The largest value of I reported in this study is 1.32 and is much higher than the value of 0.3 specified by the AASHTO code for this bridge.

(3) A wide scatter of impact values has been observed. Although there is a slight tendency for impact to reduce as the truck weight increases,

this effect is small; large values of I tended to occur with both light and heavy vehicles over a range of static vehicle masses from about 27.5 to 44.1 tons (25 - 40 t.).

(4) The range of observed values shows that impact is vehicle dependent. The literature suggests that it may vary with the geometry of the suspension units and the present study provides some limited evidence in support of this. However the matter is unclear and it would be more correct to say that the cause of the high impact values is unknown.

(5) Further work is required -

(a) to investigate other bridges, and

(b) to identify causes of high impact.

9. ACKNOWLEDGEMENTS

Six Mile Creek bridge was instrumented for Project 321 of the Australian Road Research Board. The work described in this paper was carried out with the assistance of the Queensland Department of Main Roads and used staff from that Department and the University of Queensland. This assistance is gratefully acknowledged.

APPENDIX A - NOTATION

Symbol		Meaning
B.M.	=	bending moment
DA	=	Australian classification for a dual axle suspension unit with a longitudinal rigid beam (walking beam) pivoted at its centre to a single longitudinal leaf spring (on each side of the vehicle)
I	=	impact fraction = additional dynamic component divided by the static live load effect
L	=	span length or loaded length

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