Dynamic tests on two highway bridges

M. F. GREEN, PhD, NSERC, Postdoctoral Fellow, Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada, and D. CEBON, PhD, Lecturer, University Engineering Department, Trumpington St., Cambridge, UK

The results of dynamic tests on two highway bridges near Reading, UK are presented. The dynamic characteristics of the bridges were derived from measurements using an instrumented hammer. Two instrumented, articulated vehicles were driven over the bridges. Dynamic wheel loads were measured simultaneously with bridge responses and the measurements were used to validate mathematical models of bridge dynamics. These models were used to compare the theoretical effects of leaf spring and air spring suspensions on dynamic bridge responses. It is concluded that air suspensions are likely to cause consistently lower dynamic bridge responses than steel suspensions because they generate lower dynamic wheel loads.

1 INTRODUCTION

Dynamic testing provides valuable evidence of bridge behaviour. For this reason, many researchers have conducted dynamic experiments on bridges. Dynamic tests have been used to assess bridge deterioration; to measure modal characteristics, dynamic wheel loads, or dynamic bridge responses; or to validate bridge models.

This paper presents the results of dynamic tests on two highway bridges. The main objective of the tests was to validate a calculation procedure for predicting the dynamic response of highway bridges to dynamic wheel loads. To accomplish this objective, two phases of testing were conducted. The first phase involved measuring the modal characteristics of the bridges. In the second phase, test vehicles were driven over the bridges and dynamic wheel loads were measured simultaneously with the resulting bridge responses.

The experimentally validated calculation procedure is used to conduct a parametric study into the effects of heavy vehicle suspension design on the dynamic response of bridges. The dynamic responses caused by an air-suspended vehicle are compared with those induced by a similar vehicle with leaf-spring suspensions.

2 TEST PROCEDURES

2.1 Bridges

Several typical highway bridges were evaluated for testing by the following criteria:

- (i) convenient location for testing by Transport and Road Research Laboratory (TRRL) vehicles,
- (ii) straightness of the bridge and approaches so that the vehicles could attain a wide range of speeds,
- (iii) easy access for instrumentation,
- (iv) low traffic density.

Two bridges located near Reading in south-east England were selected as the most suitable for testing.

The first bridge was the Drift Road bridge over the M4 motorway. This four-span, continuous bridge was constructed of a prestressed concrete box-girder. Some of the construction details are shown in Fig. 1. For the second set of tests, a two lane bridge over the River Lodden at Lower Earley was selected (Fig. 2). The prestressed inverted T-beams are simply supported, but the top slab and reinforced concrete diaphragms provide continuity over all three spans.

2.2 Instrumentation

Four accelerometers were attached to the underside of each bridge at the positions indicated in Figs 1-2 and Table 1. A digital data logger was used to collect the data at a sampling rate of 500Hz. Anti-aliasing filters were set to a cut-off frequency of 150Hz.

2.3 Impulse Tests

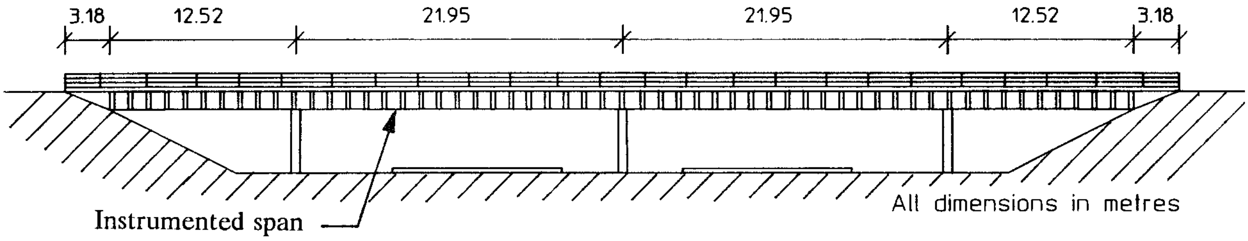
For the modal tests, excitation was applied with an instrumented hammer. The applied force was measured with a combination of a force transducer on the hammer face and an accelerometer attached to back of the hammer head. The wheel tracks of the test vehicles were marked on the surface of the bridges, and the hammer was dropped at several positions along the tracks.

Linearity of the dynamic responses of the bridge was checked by dropping the hammer from three different heights. The bridge exhibited linear behaviour over this

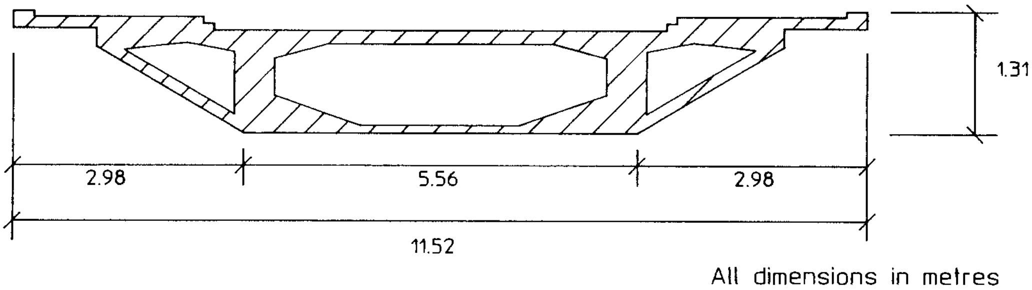
Table 1 Accelerometer positions

Position Number	Location
1	midspan, centre-line
2	1/3 point of span, centre-line
3	1/4 point of span, centre-line
4	midspan, offset

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

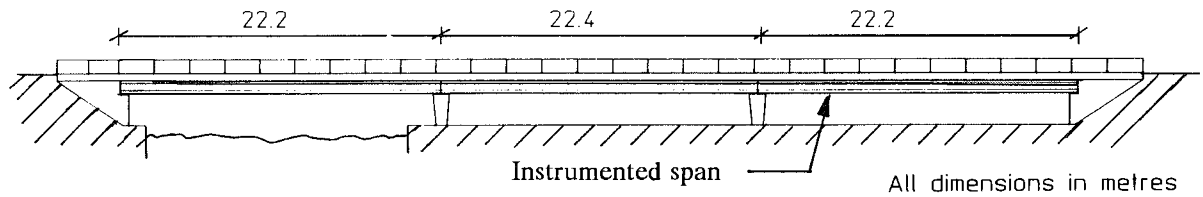


(a) Elevation

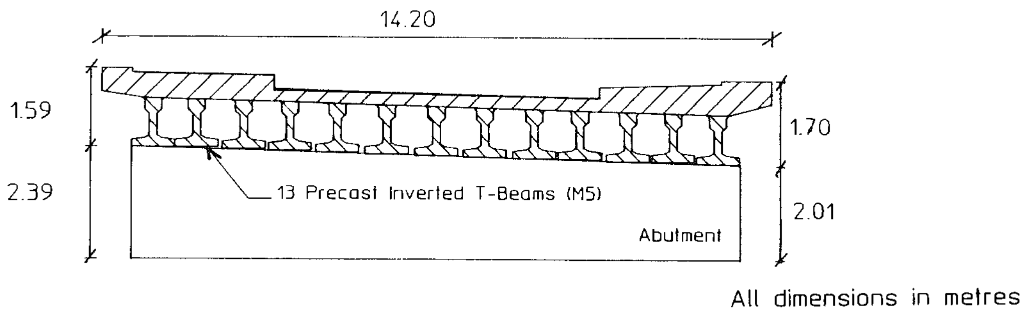


(b) Cross-section

Fig. 1. Details of the Drift Road bridge



a) Elevation



(b) Cross-section

Fig. 2. Details of the Lower Earley bridge

testing range (ref. 1). Repeatability was demonstrated by dropping the hammer several times at one position.

2.4 Vehicle Tests

The second phase of the experiments involved measuring the dynamic response of the bridge to the passage of the instrumented vehicle. A reflector and light beam set was erected at each end of the bridge to enable synchronization of the data logger on the vehicle with that by the roadside.

Two four-axle, 32 tonne, articulated vehicles were provided by the Transportation Road Research Laboratory (TRRL). Dynamic wheel loads were measured with strain gauges and accelerometers mounted on each axle.

The test vehicle for the Drift Road bridge had a two-axle tractor with a leaf spring suspension coupled to a two-axle semi-trailer with an independent air-spring suspension. The test vehicle for the Lower Earley bridge had a two-axle tractor with leaf springs on the steering axle and air springs on the drive axle; and a two-axle semi-trailer with a tandem 'four-spring' leaf-spring suspension.

The test vehicles were driven over the bridges in both directions at speeds of 15, 30, 50, 55, and 65km/h. Two runs were made at each speed in each direction. The maximum speed was limited by the length and nature of the approaches to the bridges.

3 RESULTS

3.1 Impulse Tests

The first stage in the extraction of the modal parameters from the impulse tests was the calculation of transfer functions (frequency response functions). The tests at each hammer position generated four averaged transfer functions: one for each accelerometer position. The transfer functions were calculated by dividing the discrete Fourier transform (DFT) of the accelerometer outputs by the DFT of the hammer force. The details of the procedure are provided in (ref. 1).

To extract the modal parameters from the transfer functions, the circle fitting modal analysis technique described by Ewins (ref. 2) was employed. The circle fit is performed by plotting the real parts of the mobility transfer function (velocity frequency response) against the imaginary parts. According to theory, the data will trace a circular arc near resonance. The location of the natural frequency is determined by finding the position at which the 'sweep rate' of the circle is maximum. Damping estimates are obtained by considering the spacing of the data points. The magnitude of the modal constant is determined from the diameter of the modal circle. All of the modes were assumed to be real. More details regarding the modal analysis can be found in (refs. 1-2).

Figs 3-4 show the first flexural mode for each bridge. The measured points are compared with theoretical results from simple beam models of the bridges. The theoretical curves match the measured points quite well.

Eight modes were analysed for the Lower Earley bridge, but only five modes were analysed for the Drift Road bridge. Table 2 contains averaged values of measured natural frequencies and damping ratios for both bridges.

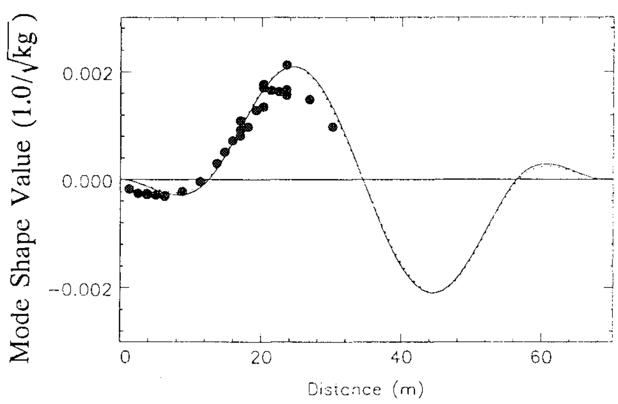


Fig. 3. First flexural mode of the Drift Road bridge. Measured ● Theory ———

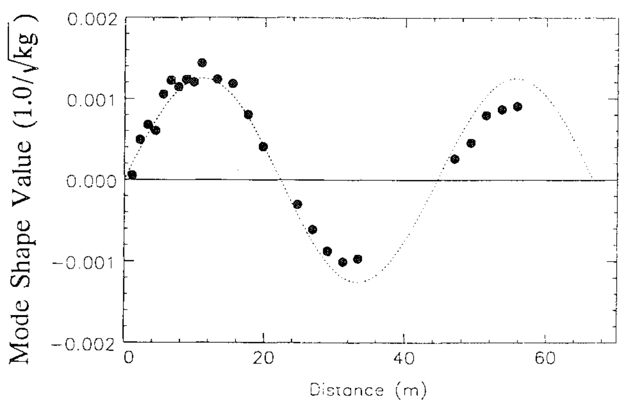


Fig. 4. First flexural mode of the Lower Earley bridge. Measured ● Theory - - - -

Table 2 Bridge modal parameters

Bridge	Mode	Freq. (Hz)	Damping Ratio
Lower Earley	1	5.7	0.045
	2	6.9	0.088
	3	7.4	0.086
	4	9.7	0.026
	5	11.3	0.014
	6	13.3	0.026
	7	18.0	0.038
	8	24.4	0.019
Drift Road	1	6.8	0.019
	2	8.6	0.021
	3	11.2	0.033
	4	12.3	0.019
	5	18.0	0.034

3.2 Vehicle Tests

Dynamic wheel loads were determined for each vehicle test run. For the purposes of illustration, one vehicle run per bridge has been selected for presentation in this paper.

Fig. 5 shows typical wheel loads measured on the Drift Road bridge with the vehicle travelling at 50 km/h. At time zero, the front axle of the vehicle encounters the bridge while the trailing axle leaves the bridge 6.1 seconds later. The large dynamic tyre forces at both ends of the bridge are caused by discontinuities in the surface profile at the expansion joints. Fig. 5a illustrates that the loads can be almost double the static values. For this vehicle, the largest variations in the tyre forces occur on the tractor axles which have leaf-spring suspensions. The trailer axles are connected to an independent air suspension and this generates lower dynamic wheel loads, although Fig. 5b shows that relatively more high frequency (wheel-hop) motion is present than for the leaf-spring suspension. This behaviour is typical of air suspensions (ref. 3).

A set of wheel loads for a south to north run over the Lower Earley bridge is presented in Fig. 6. The vehicle speed is 50km/h and the front axle enters the bridge at time zero. The trailing axle leaves the bridge 5.6 seconds later. This vehicle has leaf springs on the steering axle, air-springs on the tractor drive axle and leaf-springs on the two trailer axles. The drive axle generates lower dynamic wheel loads, but exhibits more wheel-hop motion than is present for the leaf-spring trailer suspension.

In general, the wheel loads are smaller for the Lower Earley tests and the expansion joint at the bridge entrance does not excite the vehicle to same degree as on the Drift Road bridge. This suggests a smoother riding surface on the bridge as well as better quality expansion joints. It was not possible to measure the surface profiles of the bridges.

The wheel load data was also formulated in terms of maximum dynamic load increments, *DLI*, which are defined as follows:

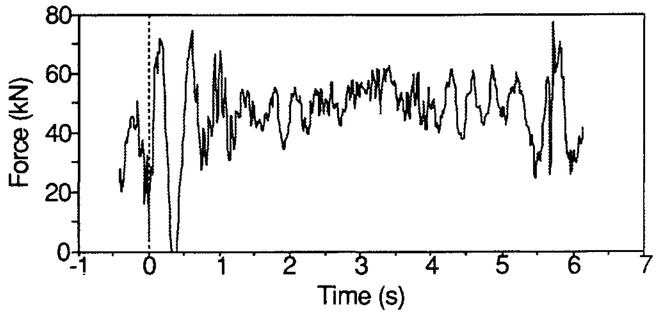
$$DLI = \frac{P_{\max} - P_{stat}}{P_{stat}} \qquad (1)$$

where P_{max} is the maximum value of the dynamic wheel load and P_{stat} is the static wheel load.

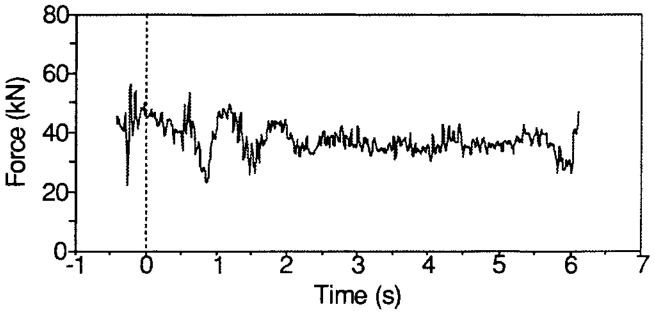
The maximum dynamic load increments for the Drift Road bridge are plotted in Fig. 7 while the values for the Lower Earley bridge are shown in Fig. 8.

For the Drift Road bridge, the maximum dynamic load increment is approximately 1.0 which corresponds to doubling the static wheel load. The dynamic load increments increase with speed. The largest values of dynamic load increment occur with the steel suspensions (steer and drive axles). For the air suspensions (trailer axles), the largest value of dynamic load increment is 0.5.

For the Lower Earley bridge, the largest increments are only about 0.5 which indicates smaller dynamic loads than were applied to the Drift Road bridge. Notice that the dynamic load increments for the air suspension (drive axle) are approximately the same as those computed for the two

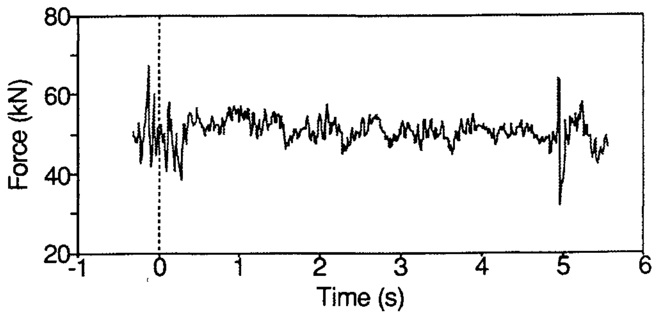


a) Tractor Drive Axle (Leaf-spring)

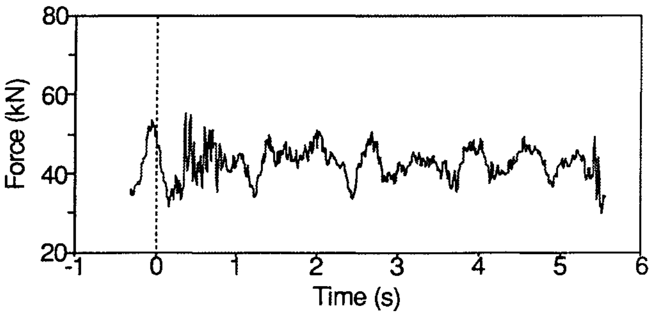


b) Front Trailer Axle (Air-spring)

Fig. 5. Tyre forces on the Drift Road bridge. South-east to north-west at 50 km/h. Curbside wheels.



a) Tractor Drive Axle (Air-spring)



b) Front Trailer Axle (Leaf-spring)

Fig. 6. Tyre forces on the Lower Earley bridge. South to north at 50 km/h. Curbside wheels.

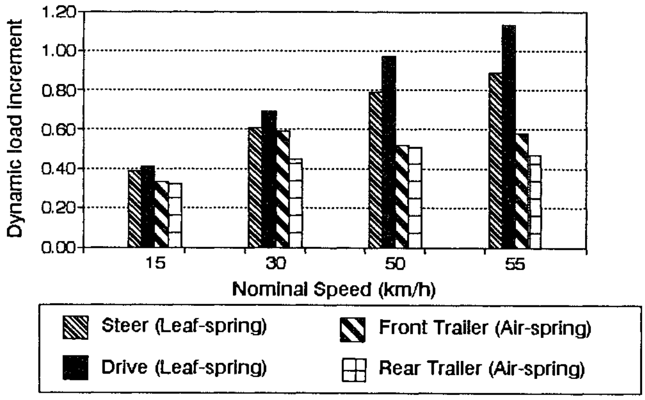


Fig. 7. Maximum dynamic load increments for the Drift Road bridge.

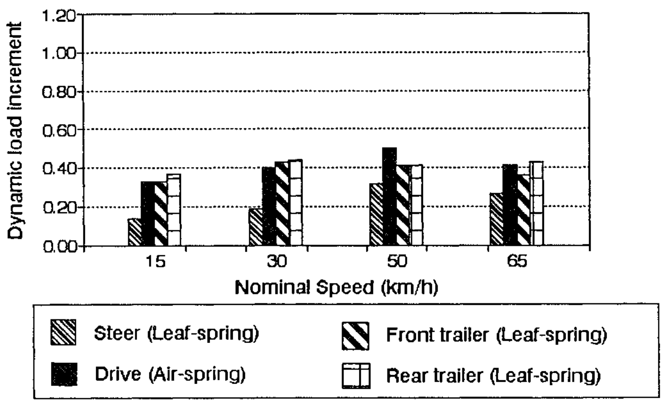


Fig. 8. Maximum dynamic load increments for the Lower Earley bridge.

trailer axles (leaf-spring suspensions). In contrast to the observations for the Drift Road bridge, the maximum dynamic load increments for the Lower Earley bridge are less dependent on the type of vehicle suspension.

4 VALIDATION OF THE BRIDGE MODELS

The main objective of this experimental programme was to validate a method for predicting the dynamic response of highway bridges to heavy vehicle loads.

The calculation method involves the convolution of dynamic wheel loads with impulse response functions of the bridge. The resulting convolution integral is solved in the frequency domain by using fast Fourier transforms. More details can be found in (ref. 1).

The convolution method was validated by combining the measured wheel loads with the measured impulse response functions (derived from the measured modal parameters) to predict the dynamic response of each bridge. These predicted bridge responses were then compared with measurements of the bridge responses made during the passage of the vehicle over the bridge. Comparisons of the predicted responses with the measured responses are shown in Figs. 9-10.

A typical validation result for the Drift Road bridge is shown in Fig. 9. In this case, the bridge response is measured at midspan and the vehicle is travelling towards the north-west at 50km/h. The comparison between theory and measurement is favourable both in amplitude and form. The traces are generally in phase with each other, but the predictions are consistently larger than the measured responses.

Fig. 10 presents a typical validation result with the vehicle travelling south to north on the Lower Earley bridge. The speed is 50km/h and the response is shown at the midspan of the instrumented span. The agreement is very good.

5 APPLICATION

This section considers the effects of leaf-spring and air-spring vehicle suspensions on the dynamic response of three bridges.

5.1 Vehicle validation

Over the last few years, the authors have developed and validated a realistic vehicle simulation package. Initial validation was performed by Cebon (ref. 4) and followed by an extensive programme of field tests with an instrumented vehicle on the Transport and Road Research Laboratory (TRRL) test track in the U.K. (refs. 5-6).

For this study, the simulation package was used to model a four-axle, 32.5 tonne, articulated vehicle typical of a large class of vehicles in the U.K. The model had 11 degrees of freedom as shown in Fig. 11. Non-linear suspension elements simulated the action of the leaf-springs and a schematic plot of the leaf-spring behaviour is shown on the figure (see (ref. 5) for more details of the model and its validation).

This vehicle model was used to investigate the effects of a typical leaf-sprung vehicle on bridges. In addition, the model was modified to represent a typical vehicle with air suspensions. The leaf-spring elements on the drive axle and the two trailer axles were replaced by models of air springs with parallel viscous dampers. The suspension on the steer axle was the same for both vehicle models. The air suspensions were assumed to be the popular trailing-arm type with each spring being dynamically independent (ref. 1).

Each vehicle model was two-dimensional, and did not simulate roll motions. Cole and Cebon (refs. 5-6) showed that this is a reasonable approximation for predicting wheel loads for typical highway conditions.

Table 3 presents the natural frequencies and damping ratios of linearized versions of the vehicle models.

5.2 Bridges

Three bridges were used for the parametric study. The first two bridges were the Drift Road and Lower Earley bridges described in section 2.

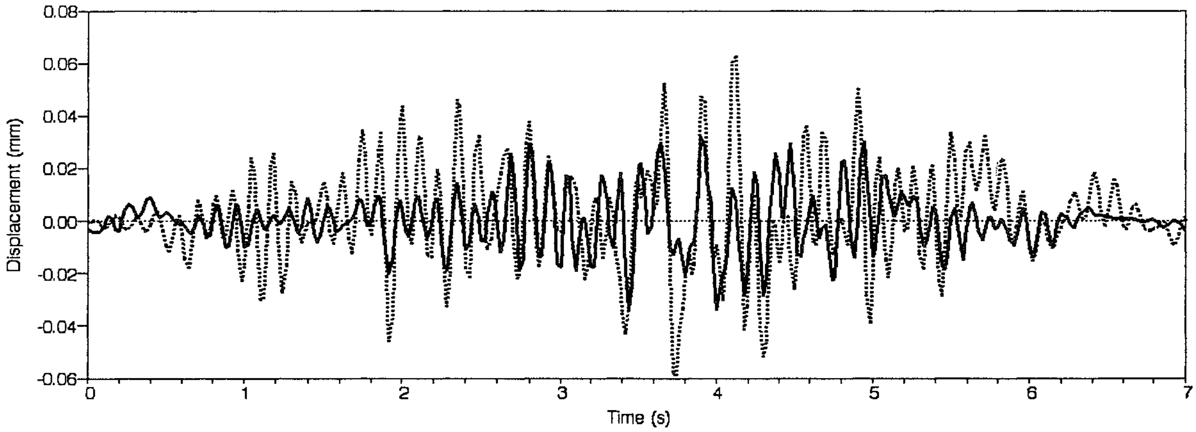


Fig. 9. Validation results for the Drift Road bridge. Bridge responses measured at midspan. Vehicle travelling south-east to north-west at 50 km/h. Measured ——— Predicted - - - - -

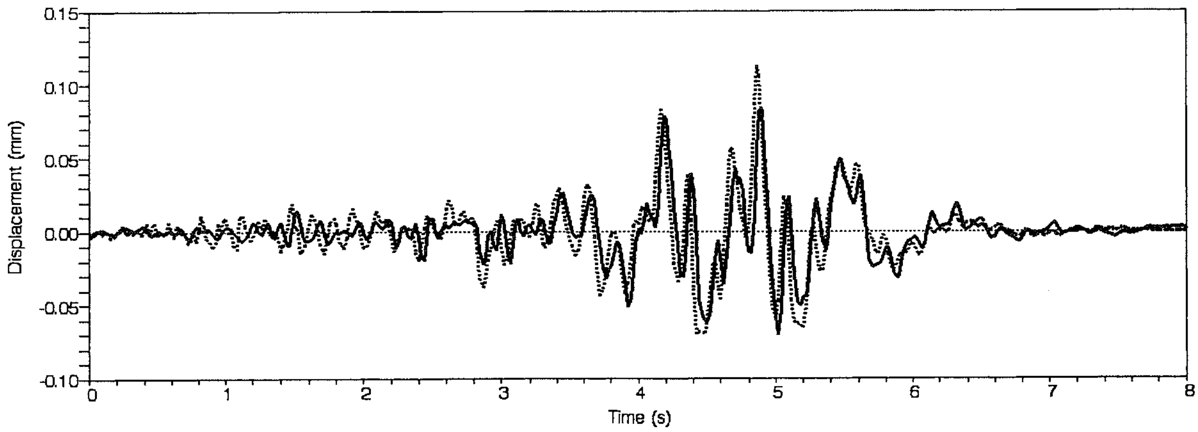


Fig. 10. Validation results for the Lower Earley bridge. Bridge responses measured at midspan. Vehicle travelling south to north at 50 km/h. Measured ——— Predicted - - - - -

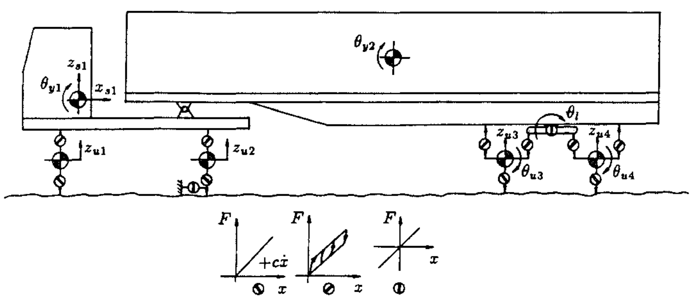


Fig. 11. 11 degree of freedom, 2 dimensional tractor and trailer vehicle model with leaf-spring suspensions (After Cole (ref. 5))

Table 3 Natural frequencies and damping ratios of the linearized vehicle models (low frequency modes only)

	Freq. (Hz)	Damping Ratio	Description of Mode Shape
Leaf Sprung Vehicle	2.3	0.06	tractor bounce
	2.9	0.08	tractor pitch
	3.2	0.04	trailer pitch
Air Sprung Vehicle	1.5	0.15	tractor+trailer bounce
	1.7	0.16	trailer pitch
	2.4	0.10	tractor pitch

The third bridge was the simply-supported Pirton Lane bridge tested by the TRRL (ref. 7). This bridge has a length of 40 metres, and a first natural frequency of 3.2 Hz with a damping ratio of 0.02.

The surface profile of all three bridges was assumed to be smooth except for a 20mm step up at the entrance. This step modelled differential settling of the abutments, or poorly maintained expansion joints.

5.3 Parametric study

5.3.1 Speed Six different vehicle speeds were chosen for the study: 10, 15, 20, 25, 30, and 40m/s. Speeds of 20, 25, and 30m/s are typical of freeways.

5.3.2 Bridge Responses Fig. 12 shows responses at three different speeds for the Pirton Lane bridge. The horizontal axis is the position of the steer axle of the vehicle, with the entrance to the bridge defined as position zero. The solid curves were obtained for a speed of 1m/s, and represent the quasi-static bridge response. The dotted and dashed curves show midspan bridge displacements for speeds of 15 and 40m/s, respectively. Fig. 12a illustrates the responses to the leaf-sprung vehicle while the responses to the air suspended vehicle are shown in Fig. 12b.

The theoretical dynamic responses induced by the air-suspended vehicle are significantly smaller than those induced by the leaf-sprung vehicle.

The air-sprung vehicle reduces the dynamic response for two reasons. Firstly, the air-sprung vehicle applies smaller dynamic loads to the bridge. This is typical of air suspensions (ref. 8). Secondly, the air suspensions are better damped than the leaf-spring suspensions and the vehicle dampers also absorb energy from the bridge vibration.

5.3.3 Dynamic Response Increments To quantify the comparison between the two different suspensions, maximum dynamic response increments were calculated according to the following definition:

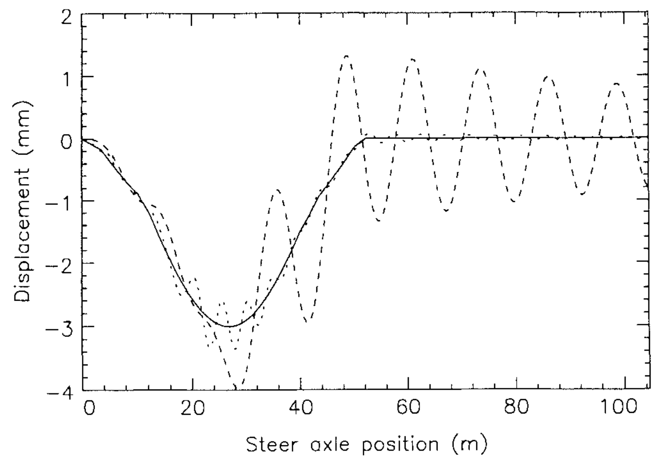
$$DI = \frac{y_{\max} - y_{st}}{y_{st}} \tag{2}$$

where DI is the maximum dynamic response increment, y_{st} is the static bridge response, and y_{max} is the maximum dynamic response of the bridge.

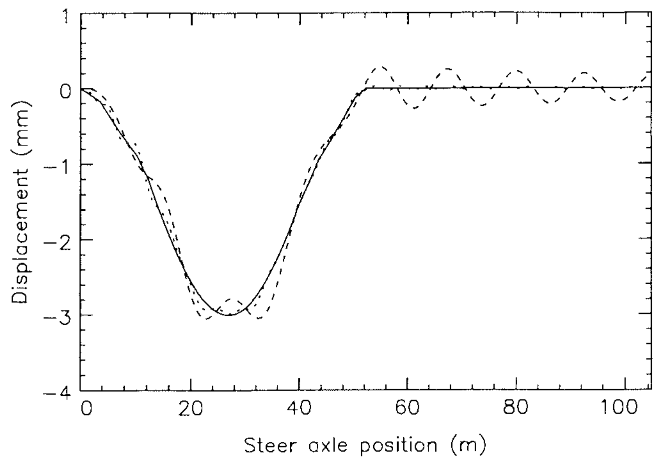
The maximum bridge displacement response increment generated during each vehicle pass was computed for each parameter combination and the results are shown in Fig. 13. Three major features should be noticed:

Frequency: The Pirton Lane bridge (Fig. 13c) generally has the largest dynamic increments at all speeds for both vehicles. This bridge has a first natural frequency of 3.2Hz which is close to the dynamic wheel load frequencies generated by the vehicles. This agrees with other research (refs. 9-10).

Suspensions: The simulated bridge responses to the air suspended vehicle are significantly less than for the steel suspensions for all three bridges. The maximum dynamic response increments for the air suspension are less than 10% while those for the steel suspension are as high as 50%.



(a) Response to vehicle with leaf-springs



(b) Response to vehicle with air-springs

Fig. 12. Midspan displacements for the Pirton Lane bridge. 1m/s ——— 15m/s · · · · 40m/s – – – –

Speed: Peaks at certain speeds are evident on all the dynamic response increment plots. These peaks are caused by a combination of factors including the vehicle speed, axle spacing, and natural frequencies of both the bridge and the vehicle. This result is also dependent on the distance between the measurement point and the abutment. The largest increments occur when these factors combine to produce a maximum of the dynamic bridge response in phase with the maximum quasi-static bridge response.

6 CONCLUSIONS

(i) Modal parameters were measured on two bridges and found to compare favourably with theoretical estimates.

(ii) Measured dynamic wheel loads were largest at the expansion joints of the bridges. In extreme cases, the dynamic load increments were as large as 1.0 (corresponding to a doubling of the static wheel load). The dynamic load increments were generally smaller for axles with air suspensions than for axles with leaf-spring suspensions.

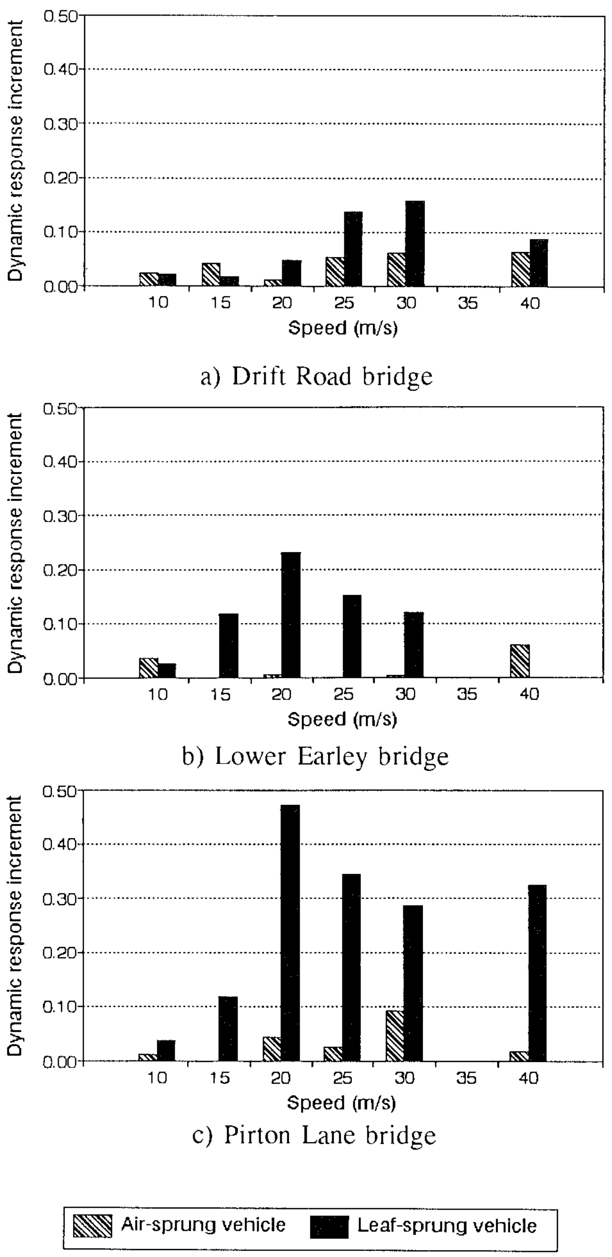


Fig. 13. Maximum dynamic response increments at midspan of each bridge.

(iii) The results of the experiments were used to validate successfully a calculation method for predicting the dynamic response of bridges to heavy vehicle loads.

(iv) A theoretical parametric study found that air-spring vehicles are likely to generate smaller dynamic responses than leaf-sprung vehicles on typical bridges.

(v) Based on the theoretical analysis performed here, there is tentative evidence to suggest that air-sprung vehicles could be allowed to carry larger loads than vehicles with leaf-spring suspensions. Nevertheless, more theoretical and experimental work is required before this conclusion can be extended to apply to bridges and heavy vehicles in general.

7 ACKNOWLEDGEMENTS

The authors are grateful to the Director of the Transport and Road Research Laboratory (TRRL) and to the members of the Bridges Division and Vehicles and Environment Division for assistance with the experiments described in this paper. Any views expressed in this paper are those of the authors and not necessarily those of the Department of Transport or the TRRL. The authors would also like to thank Dr. D.J. Cole for the use of his vehicle models in the parametric study.

8 REFERENCES

1. GREEN M.F. Dynamic Response of Short-Span Highway Bridges to Heavy Vehicle Loads. Ph.D. thesis, Cambridge University Engineering Department, 1990.
2. EWINS D.J. Modal Testing: Theory and Practice. Research Studies Press, Letchworth, England, 1984.
3. MITCHELL C.G.B. and GYENES L. Dynamic pavement loads measured for a variety of truck suspensions. Proceedings of the 2nd International Conference on Heavy Vehicle Weights and Dimensions, Kelowna, B.C., June 1989.
4. CEBON D. The dynamic interaction between wheeled vehicles and road surfaces. Ph.D. thesis, Cambridge University Engineering Department, 1985.
5. COLE D. Measurement and analysis of dynamic tyre forces generated by lorries. Ph.D. thesis, Cambridge University Engineering Department, 1990.
6. COLE D.J. and CEBON D. Simulation and measurement of dynamic tyre forces. Proceedings of the 2nd International Conference on Heavy Vehicle Weights and Dimensions, Kelowna, B.C., June 1989.
7. LEONARD D. Damping and frequency measurements on eight box girder bridges. TRRL Laboratory Report 682, Transport and Road Research Laboratory, Crowthorne, England, 1975.
8. CEBON, D. Vehicle-generated road damage: A review. Vehicle system dynamics, 1989, vol. 18, 107-150.
9. BILLING J.R. Dynamic loading and testing of bridges in Ontario. Canadian Journal of Civil Engineering, 1984, vol. 11, 833-843.
10. CANTIENI R. Dynamic load testing of a two-lane highway bridge. International Conference on Traffic Effects on Structures and the Environment, Strbske Pleso, Czechoslovakia, Dec. 1987.