**Proceedings of The Institute of Acoustics**

# SIMULATION AND MEASUREMENT OF VEHICLE RESPONSE TO ROAD ROUGHNESS

D J Cole and D Cebon

Cambridge University Engineering Department, Cambridge CB2 1PZ.

## SUMMARY

A four-axle articulated vehicle with leaf spring suspensions was instrumented and run over a test track for a range of operating conditions. The instrumentation measured the dynamic tyre forces generated by all of the axles, as well as accelerations of the sprung and unsprung masses. Road profile data was measured for the test sections of interest. The experimental data was used to validate a theoretical calculation of the dynamic behaviour of the vehicle. The paper presents two mathematical models of the vehicle: a six degrees of freedom trailer suspension model, and an eleven degrees of freedom tractor and semi-trailer model. Both models are two-dimensional. Theoretical predictions are compared with measurements from the road tests, and the discrepancies are discussed.

## 1. INTRODUCTION

A validated simulation of a four-axle articulated lorry is being developed as part of an integrated programme of research into the effects of heavy vehicles on roads and bridges. The simulation will allow the mechanisms by which heavy vehicles cause road loading to be studied, and thus enable vehicle design improvements to be recommended. This paper presents the initial results of the validation.

Although many simulations of heavy lorry vibration have been developed, relatively few have been validated with measurements. Of the more recent work, Sayers and Gillespie [1] calculated the response of a tandem axle suspension to measured road profile inputs, and concluded that good agreement with measurements could be achieved if realistic leaf spring models were used. Heath and Good [2] used linear models to predict the response of a number of articulated lorries. However, lack of detailed information on the vehicles and the road profile limited the extent of the validation. Cebon [3,4] tested a three-axle rigid tanker on a rough pavé test track to obtain data for validating the nonlinear simulation program used in this study. The results were satisfactory, but the vehicle and test track were not representative of the most common heavy vehicles and operating conditions in the UK.

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## ACKNOWLEDGEMENT

The authors are grateful to the Director of the Transport and Road Research Laboratory and members of the TRRL Vehicles and Environment Division for making available the test vehicle and track, and for assistance in carrying out the tests.

SIMULATION AND MEASUREMENT OF VEHICLE RESPONSE TO ROAD ROUGHNESS

## 2. MEASUREMENTS

The test vehicle comprised a typical two-axle tractor and tandem axle trailer, having a maximum gross weight of 32.5 tonnes. The tractor had multileaf springs and hydraulic dampers on both axles; the trailer was fitted with monoleaf springs and a load-levelling mechanism. The tractor drive axle and trailer axles were equipped with dual tyres. All four axles were strain gauged at each end, between the spring and brake drum, to measure bending due to vertical wheel forces. The strain gauges were calibrated statically, and it was assumed that the distance between the gauge and the line of action of the vertical wheel force remained constant. Accelerometers were fitted to each axle and to the tractor and trailer sprung masses. A total of twenty-four transducers were fitted to the vehicle; their conditioned signals were recorded onto tape using two 14-channel FM recorders. The recorded data was digitised for analysis; a 1kHz reference signal common to both tapes was used to synchronise the digitising of the two tapes. Wheel forces were calculated from the strain gauge signals, and corrections for the linear and angular inertias of the masses outboard of the strain gauges were made using the axle accelerometer signals. The signals from the sprung mass accelerometers were reduced to bounce, pitch, and roll accelerations. The torsion and bending of the trailer frame were also calculated.

Two straight lanes, each 600m in length and of motorway standard, were used for the tests. Lane 1 was a flexible pavement with a smooth asphalt surface, and lane 2 was a rigid concrete pavement. The profiles of left and right hand wheel tracks were measured using the TRRL high-speed profilometer; the displacement spectral density of the nearside track of lane 2 is shown in figure 1. The vehicle was tested at three speeds (30,40,50 mph) and three loads (unladen, half laden, fully laden). Three runs down both lanes were completed for each condition of speed and load.

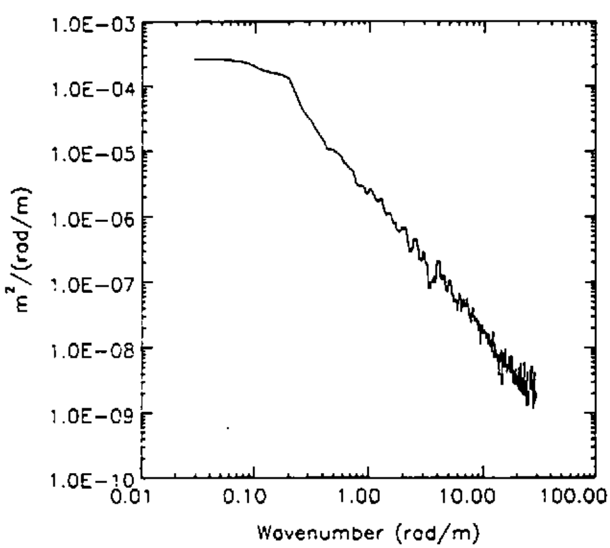


Figure 1. Displacement spectral density of lane 2, nearside track.

SIMULATION AND MEASUREMENT OF VEHICLE RESPONSE TO ROAD ROUGHNESS

## 3. MATHEMATICAL MODELS

Cebon [3,4] has developed a nonlinear vibration simulation program, suitable for modelling lumped parameter vehicle models of up to three dimensions. The method uses a matrix formulation of the equations of motion, but the geometry of the model is treated independently of the constitutive elements. This enables nonlinear (time domain) or linearised (frequency domain) calculations to be performed using one input description. An advantage of the method is that derivation of the equations is simple compared to the methods of d'Alembert or Lagrange. This program has been used to develop two two-dimensional models of the test vehicle:

(i) a six degrees of freedom (DOF) trailer suspension model, figure 2,

(ii) an eleven degrees of freedom tractor and trailer model, figure 3.

Important features of the models are:

- Rigid tractor and trailer frames.
- Nonlinear leaf spring elements, the hysteresis characteristic being modelled according to the equation devised by Fancher et al [4,5,6].
- Viscous damping on the tractor axles, with different rates in bump and rebound.
- Tyres modelled as linear springs in parallel with light viscous dampers.
- Tyres can lose contact with the road.
- Simple tyre contact patch averaging for envelopment of short wavelength irregularities.

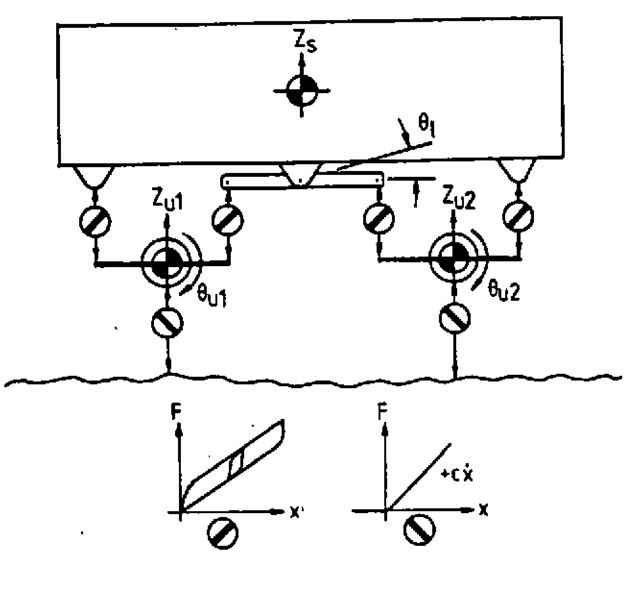


Figure 2. Six degrees of freedom trailer suspension model.

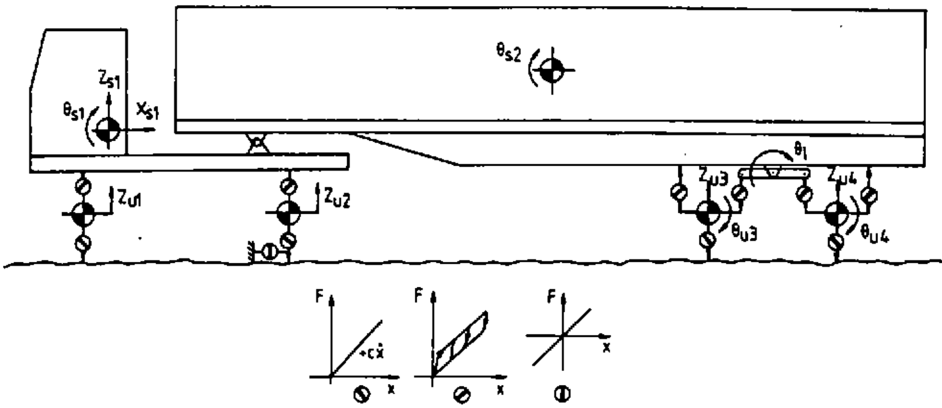


Figure 3. Eleven degrees of freedom tractor and trailer model.

The nearside measured road profile was used as the input to the two-dimensional nonlinear time domain simulation. Previous work has shown this approach to give satisfactory results for frequencies above the sprung mass modes, although the absence of roll motions in the simulation may lead to less accuracy in predicting the wheel forces at lower frequencies [3,4]. The spectral densities of the simulated tyre force and acceleration time histories were computed, and then compared with the corresponding results from the test vehicle.

## 4. RESULTS

The responses of the six DOF and eleven DOF models were compared, and it was noted that the spectra were very similar at frequencies above the sprung mass modes; at lower frequencies there were slight differences only. This confirms that suspension group models are adequate for predicting wheel forces at frequencies above the sprung mass modes [1].

Space limitations prevent presentation of the complete set of results. Spectral densities of responses from the eleven degrees of freedom model are compared with those from the laden test vehicle on lane 2 at 30 and 50mph (figures 4 and 5). The simulated responses are generally in good agreement with the measured responses, but there are discrepancies and characteristics which require explanation.

At high frequencies (>20Hz) the experimental spectral densities of tractor pitch and trailer bounce do not decay with frequency as quickly as the simulation predicts. This is because the tractor and trailer frames have flexural modes of vibration which are not modelled by the simulation. In addition, it was noted that the signals from the accelerometers mounted on the rear of the tractor frame contained large amplitude high frequency components, probably due to excitation from the drivetrain.

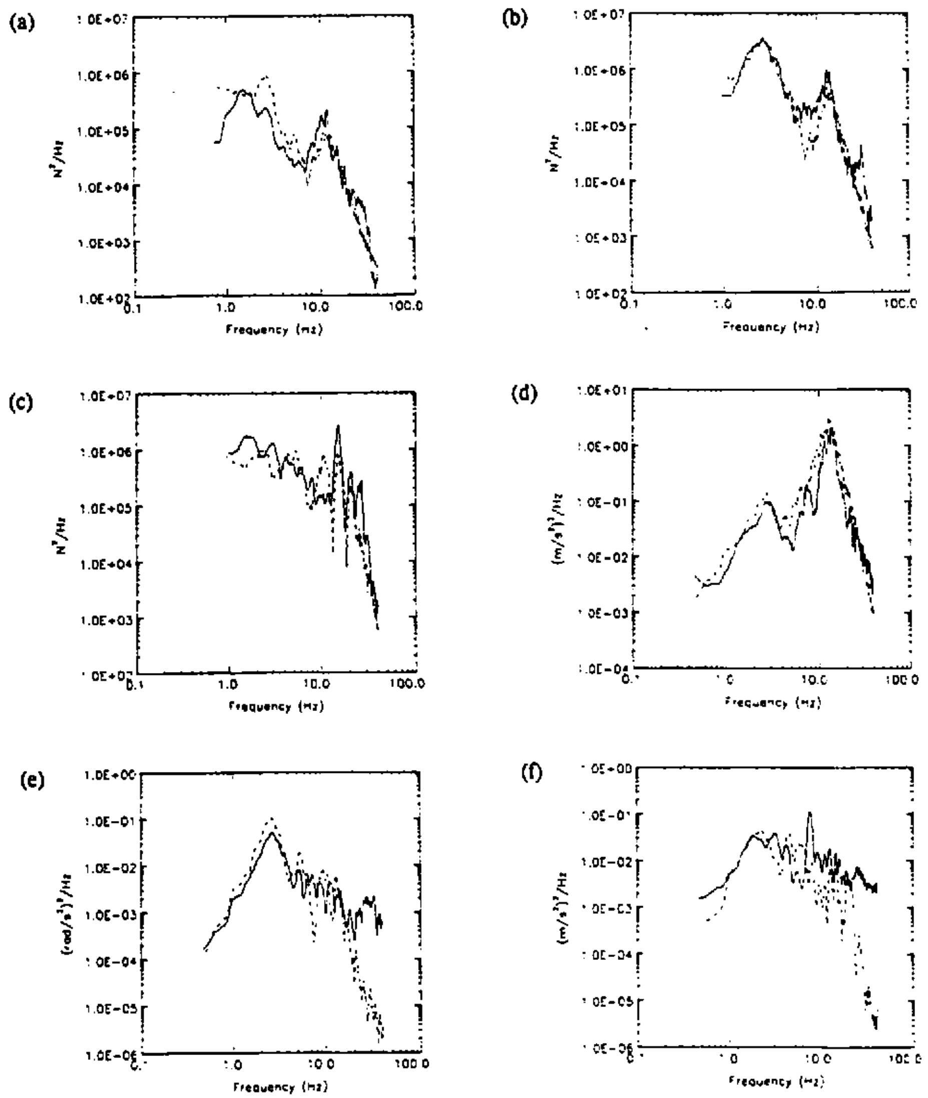


Figure 4. Spectral densities of measured and simulated responses of the laden vehicle at 30mph (13m/s) on lane 2. ——— = experiment, - - - - - - = simulation.

(a) Steering axle, nearside tyre force
(b) Driving axle, nearside tyre force
(c) Leading trailer axle, nearside tyre force
(d) Driving axle, nearside wheel vertical acc'n
(e) Tractor sprung mass pitch angular acc'n
(f) Trailer sprung mass CG vertical acc'n

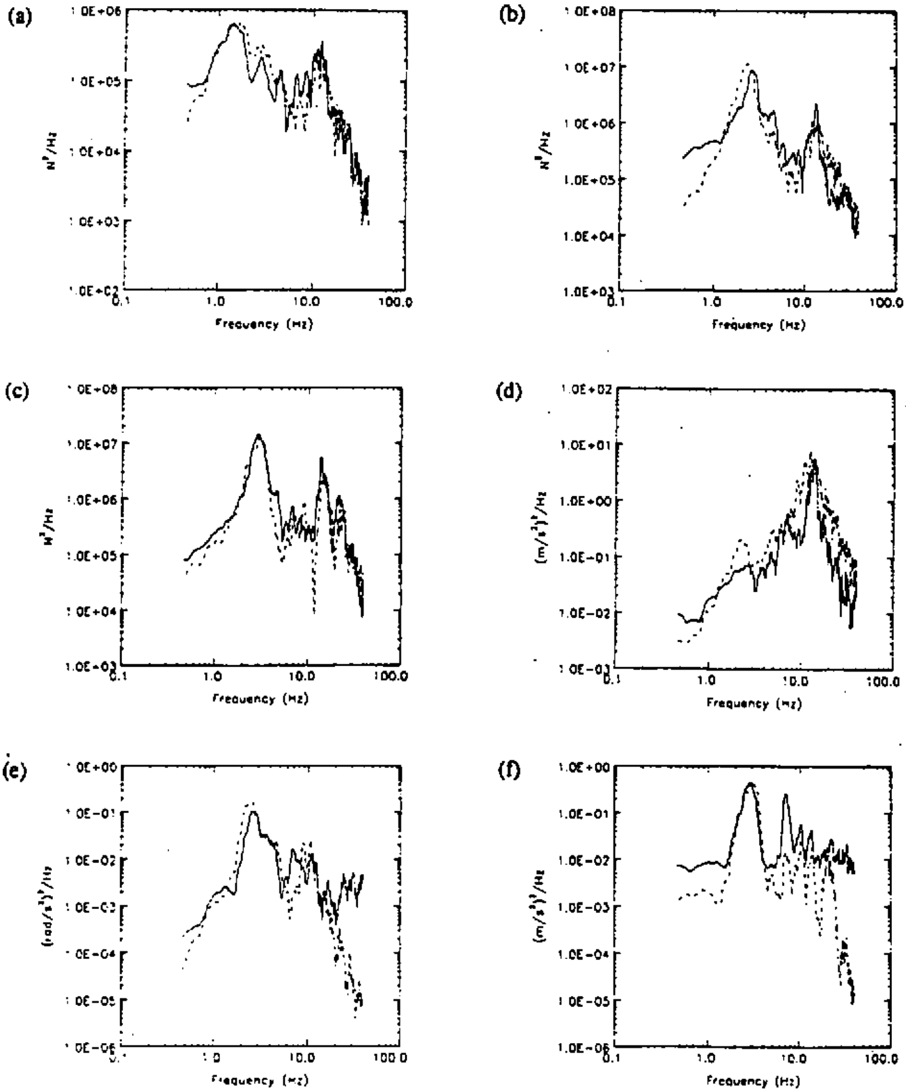


Figure 5. Spectral densities of measured and simulated responses of the laden vehicle at 50mph (22m/s) on lane 2. ———— = experiment, - - - - - - = simulation.

(a) Steering axle, nearside tyre force
(b) Driving axle, nearside tyre force
(c) Leading trailer axle, nearside tyre force
(d) Driving axle, nearside wheel vertical acc'n
(e) Tractor sprung mass pitch angular acc'n
(f) Trailer sprung mass CG vertical acc'n

SIMULATION AND MEASUREMENT OF VEHICLE RESPONSE TO ROAD ROUGHNESS

The experimental spectra of trailer bounce show sharp peaks at 7Hz which do not appear in the simulated responses. Figure 6 shows that these discrepancies are due to bending accelerations which are measured by the trailer accelerometers.

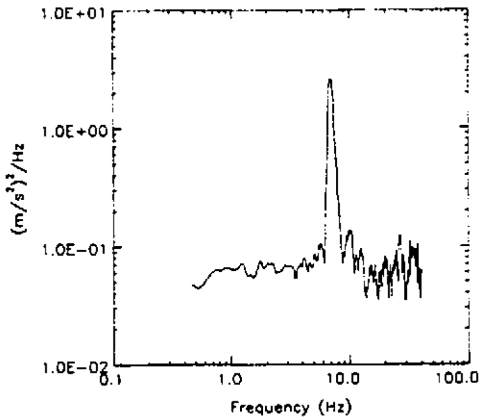


Figure 6. Trailer bending spectral density at 50mph.

There are peaks and troughs for both the measured and simulated responses which do not correspond to resonant modes of the vehicle. Many of these may be explained by "wheelbase filtering" [1,2]. For example, the pitch excitation of the trailer suspension is zero at frequencies corresponding to a whole number of wavelengths of road roughness in the 2m axle separation. At 50mph (22m/s) troughs are therefore expected at whole multiples of 11Hz (see figure 5(c)).

The remaining discrepancies cannot be explained easily. One source of error may be inaccurate leaf spring models, which were based on specifications provided by the vehicle manufacturers. Discrepancies in the region of the sprung mass modes may be due to roll motions of the test vehicle.

Future work aimed at improving the agreement between measurement and simulation will include measuring the characteristics of the springs whilst they are on the vehicle, and extending the model to three dimensions.

## 5. CONCLUSIONS

An instrumented articulated heavy lorry was tested under representative UK operating conditions. Measured responses were compared with predictions from two mathematical models, and agreement between measurement and simulation was generally good. It is thought that agreement will be improved by using measured spring characteristics, and by extending the model to three dimensions.

The vehicle model will be the basis of future work aimed at improving the design of heavy vehicles to minimise road damage.

## REFERENCES

[1] Sayers, M., and Gillespie, T.D. "Dynamic pavement/wheel loading for trucks with tandem suspensions", Proc. 8th IAVSD Symposium on The dynamics of vehicles on roads and on railway tracks, Cambridge, MA, 1983, p517–533, Swets and Zeitlinger, 1984.

[2] Heath, A.N., and Good, M.C. "Heavy vehicle design parameters and dynamic pavement loading", Australian Road Research, 15(4), December 1985, p249–263.

[3] Cebon, D. "Heavy Vehicle Vibration – A Case Study", Proc. 9th IAVSD Symposium on The dynamics of vehicles on roads and on tracks. Linkoping, Sweden, 1985, p30–43, Swets and Zeitlinger.

[4] Cebon, D. "An investigation of the dynamic interaction between wheeled vehicles and road surfaces", PhD dissertation, University of Cambridge, 1985.

[5] Fancher, P.S., Ervin, R.D., MacAdam, C.C., and Winkler, C.B. "Measurement and representation of the mechanical properties of truck leaf springs", SAE Trans. 800905, 1980, 16p.

[6] Cebon, D. "Simulation of the response of leaf springs to broad band random excitation", Vehicle System Dynamics, 15(1986), p375–392.