

Use of a force measuring mat to compare the road damaging potential of heavy vehicles

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A portable mat for measuring the dynamic tyre forces of commercial vehicles is described. The mat is 56m long, 13mm thick, and has 141 capacitive strip sensors, spaced at 0.4m intervals. Preliminary results of tests on three articulated commercial vehicles are presented, and it is concluded that the road damaging potential of vehicle suspensions should be assessed by considering the whole vehicle.

1. INTRODUCTION

The estimated annual expenditure on road maintenance in the UK is £2.6 billion, of which £1.2 billion is spent on resurfacing and patching. Of the £1.2 billion, approximately half can be attributed directly to lorries and much of the remainder, to the weather [1]. (These costs do not allow for the time lost in traffic hold ups.) The dynamic interaction between heavy vehicles and road surfaces is the subject of this paper. This interaction is believed to be one of the main causes of the premature failure of roads. It is not well understood, however, because it requires knowledge of both the civil (road) and mechanical (vehicle) systems. The overall objective of the research project described (in part) in this paper is to improve understanding of this interaction with a long term view to reducing road damage and the associated costs.

The research is being performed with a 'load measuring mat', developed by the authors, in conjunction with Golden River Traffic Limited, for measuring the dynamic tyre forces generated by heavy commercial vehicles [2]. The mat contains capacitive strip sensors encapsulated in polyurethane 'tiles' as shown schematically in Figure 1. The tiles are of dimensions 1.2m x 1.2m x 13mm thick, and each one contains 3 sensors (1.2m long) laid transverse to the wheel path, 0.4m apart. This system has been used in one other study as part of the SHRP project in the USA [3].

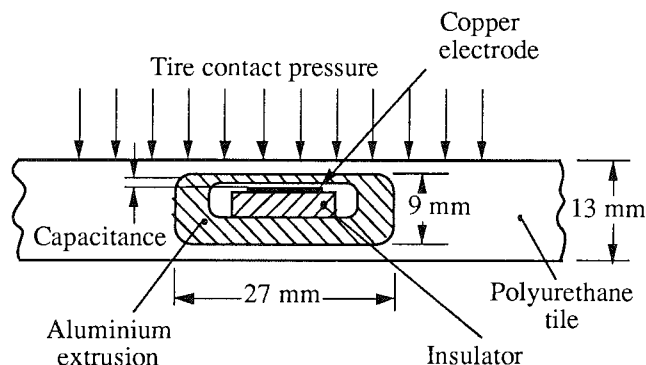


Fig. 1. Cross-section of a capacitive strip sensor cast into a polyurethane tile.

In the first experimental stage of the research, the mat was installed on the TRL test track. Fifteen articulated vehicles, with a variety of suspension designs, tyre types, payloads, and speeds were driven over it, for a range of speeds. In the second experimental stage, which was recently completed, the mat was installed on a public road (the south-bound A34, near Oxford) for three days, and data was collected for approximately 2000 commercial vehicles, travelling at speeds in the range 65–80 km/h.

This paper presents preliminary results from the first part of the study only.

2. MAT TESTS

2.1 Mat installation

The first set of tests was performed on the TRL test track during the winter months of 1991/92. The mat was installed by TRL personnel on a long straight section of the track. Each mat tile was attached to the brushed concrete surface by an adhesive sheet and six screws. There were 47 tiles in total, containing 141 sensors, giving an overall instrumented length of 56.4m. Sheets of plywood were used to provide a ramp up to the mat, and a run-off section, both 15m long.

The outputs of the sensors were logged and processed by nine Golden River 'Marksman M600' data-loggers. The data stored by each logger was transferred to a personal computer by a serial communications line. Figure 2 shows a vehicle with its nearside wheels on the mat. The data-logging boxes can be seen beneath the crash barrier.

2.2 Calibration and validation

The mat sensors were initially calibrated against the known static weights of the front axles of three different vehicles. The front axle usually has low dynamic force variation, and therefore at low speeds, the force applied to the sensor will be close to the measured static weight. The results from nineteen low speed tests were used to determine initial calibration factors for the mat sensors. The static axle weights of the vehicles were measured by portable weighpads.



Fig. 2. The load measuring mat on the TRL test track.

Correct operation of the mat was confirmed by using a vehicle instrumented to measure dynamic tyre forces. The vehicle was a two-axle rigid lorry, with single tyres on the front axle and dual tyres on the rear axle. Steel spring suspensions were fitted to both axles and the gross mass was 17 tonnes. The instrumentation fitted to the end of each axle consisted of strain gauges to measure axle bending and an accelerometer to correct for the inertia of the mass outboard of the gauges [4]. The data was logged by a digital data-logger onboard the vehicle.

Synchronisation of the onboard measurements with the mat sensor measurements was achieved by means of an infra-red transmitter and detector mounted on the vehicle. The detector sensed reflective markers placed along side the mat. Five markers were used along the length of the mat.

The vehicle was driven over the mat about 40 times for a range of speeds between 2m/s and 27m/s. Figure 3 shows a preliminary comparison of rear axle tyre force measured by the mat sensors (crosses joined by dotted line) and measured by the onboard vehicle instrumentation (solid line), for a vehicle speed of 27m/s (97 km/h). It is apparent from this figure that the sensor measurements closely follow the onboard measurements, except for the last 5m of the mat. Final analysis of the data is not yet complete, but discrepancies between the two sets of measurements are thought to be due to the following:

- (i) Mat sensor error. Previous tests have shown the mat sensors to have a 'baseline' error of 4% rms [3].
- (ii) Vehicle instrumentation error. An analysis of the vehicle instrumentation suggests a contribution to the error of approximately 1.5% rms [5].
- (iii) Vehicle speed variation along the mat, leading to lack of synchronisation between the markers.

- (iv) Vehicle off-tracking. Figure 3 shows considerable discrepancy in the last 5m of the test distance. This was caused by the vehicle moving off the correct path so that the whole of the tyre width was not over the sensors.

2.3 Vehicle tests

Following the instrumented vehicle tests, a large number of uninstrumented articulated vehicles were tested on the mat. All the vehicles belonged to TRL and each comprised one of three tractor units (two-axle with steel suspension; two-axle with air suspension; three-axle with steel suspension) and one of five trailers (two-axle air, steel, rubber, wide-spread steel; and three-axle steel). Fourteen of the fifteen possible combinations of tractor and trailer were tested. Each vehicle was fully laden and driven over the mat about fifty times at speeds between 2m/s and 27m/s.

3. ROAD DAMAGE ANALYSIS

3.1 Road damage criteria

In order to quantify the effects of fluctuating wheel loads on pavement deterioration, it is necessary to examine the accumulated damage due to all axles of a passing vehicle at specific points on the road surface. The points must be sufficiently closely spaced to resolve damage peaks at the highest frequency of interest in the tyre forces (20 Hz). The total number of points should be sufficient to ensure reasonable statistical accuracy in the results. The spacing of sensors in the load measuring mat, and its overall length were selected after consideration of these factors.

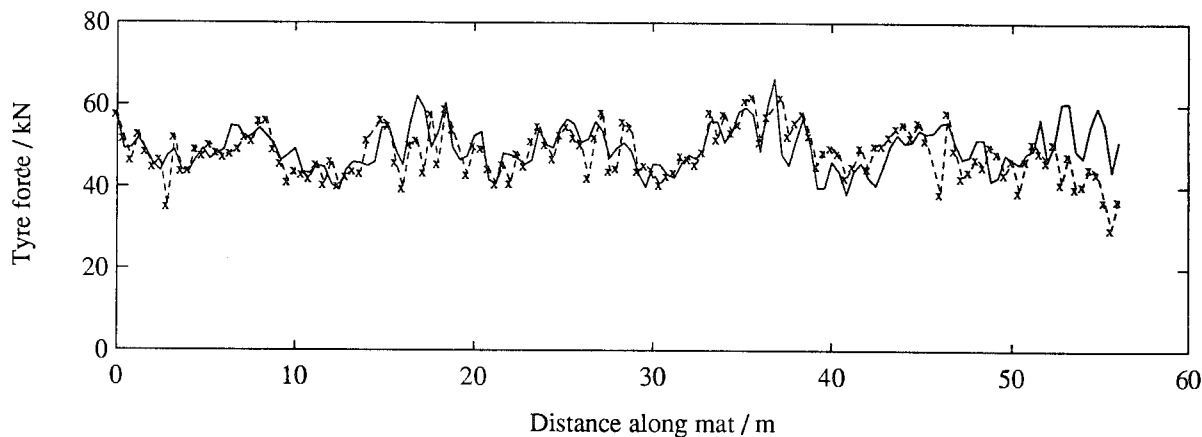


Fig. 3. Comparison of wheel forces measured by the mat and the drive axle of the instrumented vehicle, travelling at 27m/s (97 km/h). - - - - - Mat, ——— Instrumented Vehicle.

A simple measure of road damage at sensor location k along the mat is the '4th power aggregate force' which is defined as [6]:

$$A_k^{(4)} = \sum_{j=1}^{N_a} P_{jk}^4, \quad \text{for } k = 1, 2, 3, \dots, N_s \quad (1)$$

where

P_{jk} = force applied by wheel j to sensor k ,

N_a = number of axles on the vehicle,

N_s = total number of sensors along the mat.

The exponent 4 was chosen because it is representative of the sensitivity of asphalt fatigue damage to strain level [7]. The main disadvantages of using the 4th power aggregate force as a measure of road loading are that it does not reflect: (i) the mechanisms of road damage, (ii) the effects of tyre and axle configurations (iii) the effects of weak spots in the road. These disadvantages can only be overcome by simulating the response of a standard road to the wheel forces [8], but this will not be done here.

Analysis and interpretation of the damage data depends on assumptions concerning the phenomenon of 'spatial repeatability'. Several authors have postulated that most vehicles in the highway 'fleet' are likely to apply their peak forces near to the same locations on the road surface [9–14]. On this basis it is reasonable to assume that loss of serviceability will be governed by a small proportion of locations at which large damage is incurred: so called 'hot spots'. It is not necessary for the entire surface area of the road to fail before it becomes unserviceable.

A useful statistic of peak damage due to dynamic tyre forces is the 95th percentile level of $\{A_k^{(4)}\}$ [8] (the parentheses $\{\bullet\}$ indicate the ensemble of data values of $A_k^{(4)}$). The basic premise is that 5% of the surface area of the road in the wheel paths incurs damage exceeding the 95th percentile level. The 95th percentile damage level can be calculated by simple statistical analysis of $\{A_k^{(4)}\}$.

An alternative damage hypothesis is that all points along the road incur a statistically similar distribution of wheel forces and that road failure is governed by the points which are inherently weaker, due to construction defects: so called

'weak spots' [15, 16]. In this case the *mean* level of the damage criterion $\{A_k^{(4)}\}$ is a better indicator of relative damage.

The real situation must lie somewhere between these two extreme viewpoints; with high damage occurring both at 'weak spots' and at 'hot spots'. The mechanism that dominates the degradation of a particular road surface will depend on many variables, including the uniformity of the initial road construction, the types and thicknesses of materials used, the initial surface roughness, the uniformity of the vehicle fleet using the road, and various environmental factors. For this reason, both the mean and 95th percentile 4th power aggregate force levels are considered in this paper.

3.2 Wheel forces generated by three articulated vehicles

The wheel forces generated by three of the 15 vehicle uninstrumented vehicle combinations are compared in this section.

The vehicles all had 4 axles, two on the tractor and two on the trailer. Each vehicle was loaded with concrete blocks to the same nominal gross combination weight of 32.5 tonnes. The suspensions were as follows:

Vehicle 1 – tractor: steel multi-leaf springs; trailer: wide-spread tandem '4-spring' suspension with steel mono-leaf springs.

Vehicle 2 – tractor: steel multi-leaf springs, (as vehicle 1); trailer: walking beam suspension with rubber springs.

Vehicle 3 – tractor: steel sprung steer axle, air sprung drive axle; trailer: air suspension with hydraulic dampers.

The wheel forces measured on the mat were converted into 4th power aggregate forces using equation 1 and then normalised by dividing by the damage due to the static tyre forces. Figure 4 shows normalized 4th power aggregate force histories for the trailer axles of vehicles 2 and 3, travelling at 27m/s. A value of one corresponds to the 4th power aggregate static force. The rubber suspended trailer (vehicle 2) shows significant long wavelength (low frequency) components associated with motion of the sprung mass (chassis and payload), whereas the air suspension is

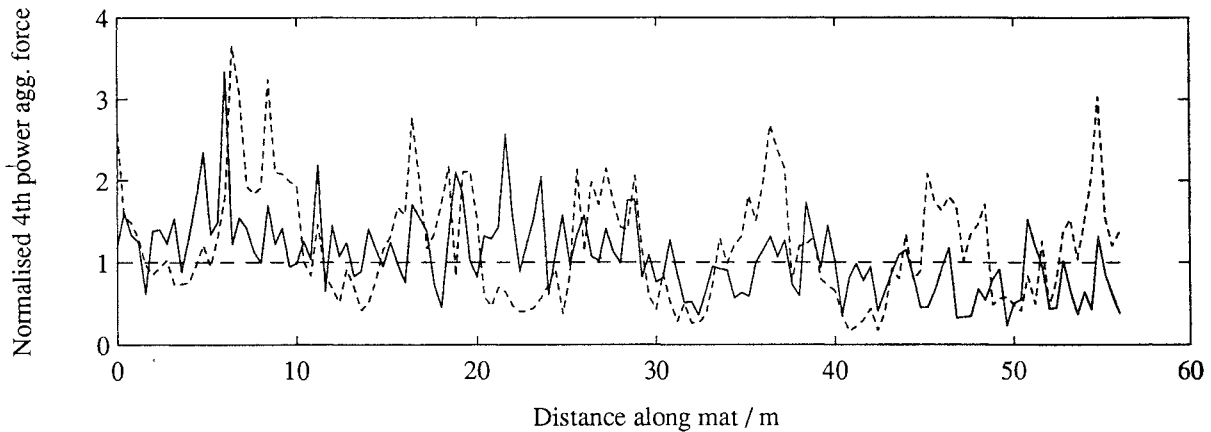


Fig. 4. Normalised 4th power aggregate wheel forces generated by the tandem trailer of vehicle 2 (rubber suspension), and the tandem trailer of vehicle 3 (air suspension), travelling at 27m/s (97 km/h). - - - - - Vehicle 2 (rubber), ——— Vehicle 3 (air)

characterized by shorter wavelength (high frequency) components associated with vibration of the unsprung mass (wheels and axle). In both cases the peak damage is approximately 3.5 times the damage that would be caused by the static loads alone (shown by the horizontal dotted line at a value of one). The peaks caused by the rubber suspension are generally higher than those caused by the air suspension, and the peaks for both suspensions do not always occur at the same locations along the mat.

The graphs in figure 5 show normalised 4th power aggregate forces, calculated for the three vehicles at various speeds. There are three data points for each vehicle at each speed. These points are joined by vertical lines (analogous to error bars) to indicate the spread of results. In some cases there is a quite a large spread. This is because the test distance was only 56m; a longer distance would give more statistically reliable results.

The left hand set of figures 5a, 5c and 5e show the mean damage levels, whilst the right hand figures 5b, 5d and 5f show the 95th percentile levels. The damage criteria have been calculated for the tractor drive axle alone (Figs. 5a and 5b); the trailer tandem axles alone (Figs. 5c and 5d); and for the whole vehicle (Figs. 5e and 5f).

Figure 5a shows the mean normalized aggregate force for the tractor drive axle of each vehicle. For most speeds the three drive axles cause similar damage, approximately 7–10% more than that due to static loads alone. At higher speeds, the drive axle of vehicle 1 (steel) shows slightly higher damage than the others. Figure 5b shows the 95th percentile damage for the same axles. For typical highway speeds (20–30m/s) the peak damage generated by the drive axles is approximately double that due to the static loads alone. This is consistent with previous theoretical studies [6, 8]. Interestingly, the drive axle of vehicle 1 does not generate the highest *peak* damage at the higher speeds, despite generating the highest *mean* damage.

Figure 5c shows the same damage criterion calculated for the force histories of the tandem trailer axles of the three vehicles. In this figure, it is apparent that the rubber suspension of vehicle 2 causes significantly more damage than the other two, particularly at the higher test speeds.

Figure 5d shows a similar trend, but the magnitude of the peak damage is again much greater than the mean: the normalised 95th percentile damage caused by the rubber tandem is about 2.7 at 25m/s, whereas in figure 5c the normalised mean damage is 1.25 at the same speed. The issue of spatial repeatability is therefore of considerable importance when apportioning the influence of dynamic forces on road damage.

Figures 5e and 5f show the mean and peak damage due to all four axles of each vehicle. The performance of all of the vehicles is apparently quite similar. The effect of the rubber suspension on the damage caused by vehicle 2 is much less marked than when the trailer suspension is considered alone, because the tractor of vehicle 2 generates relatively low dynamic loads. This is thought to be due to dynamic interaction between the suspensions of the tractor and trailer, through whole-vehicle pitch modes [17].

The results shown here are of a very preliminary nature. Much further analysis of the performance of the mat and the road-damaging potential of the vehicles will take place in the near future.

4. CONCLUSIONS

- (i) The wheel load measuring mat has been shown to be sufficiently accurate for assessing the dynamic tyre forces of heavy vehicles.
- (ii) The mean road damage generated by three typical articulated vehicles is approximately 7–25% greater than the damage due to static loads alone, whereas the 95th percentile damage is typically 2 to 3 times the damage due to static loads.
- (iii) Conclusions about the road-damaging effects of vehicle suspensions depend on whether individual suspensions are considered in isolation, or whether the road damage generated by the whole vehicle is considered.
- (iv) The issue of spatial repeatability is central to the assessment of road-damaging ability of heavy commercial vehicles. This issue will be investigated in

the second part of this research project using the data collected recently with the mat for 2000 vehicles on a highway.

5. ACKNOWLEDGEMENTS

The authors are very grateful to the Science and Engineering Research Council for funding the research described in this paper; to the Director of the Transport Research Laboratory and members of the Vehicles and Environment Division, for providing the test track, vehicles and technical support, and for installing the mat; and to Golden River Traffic Limited for their assistance with the provision of the load measuring mat.

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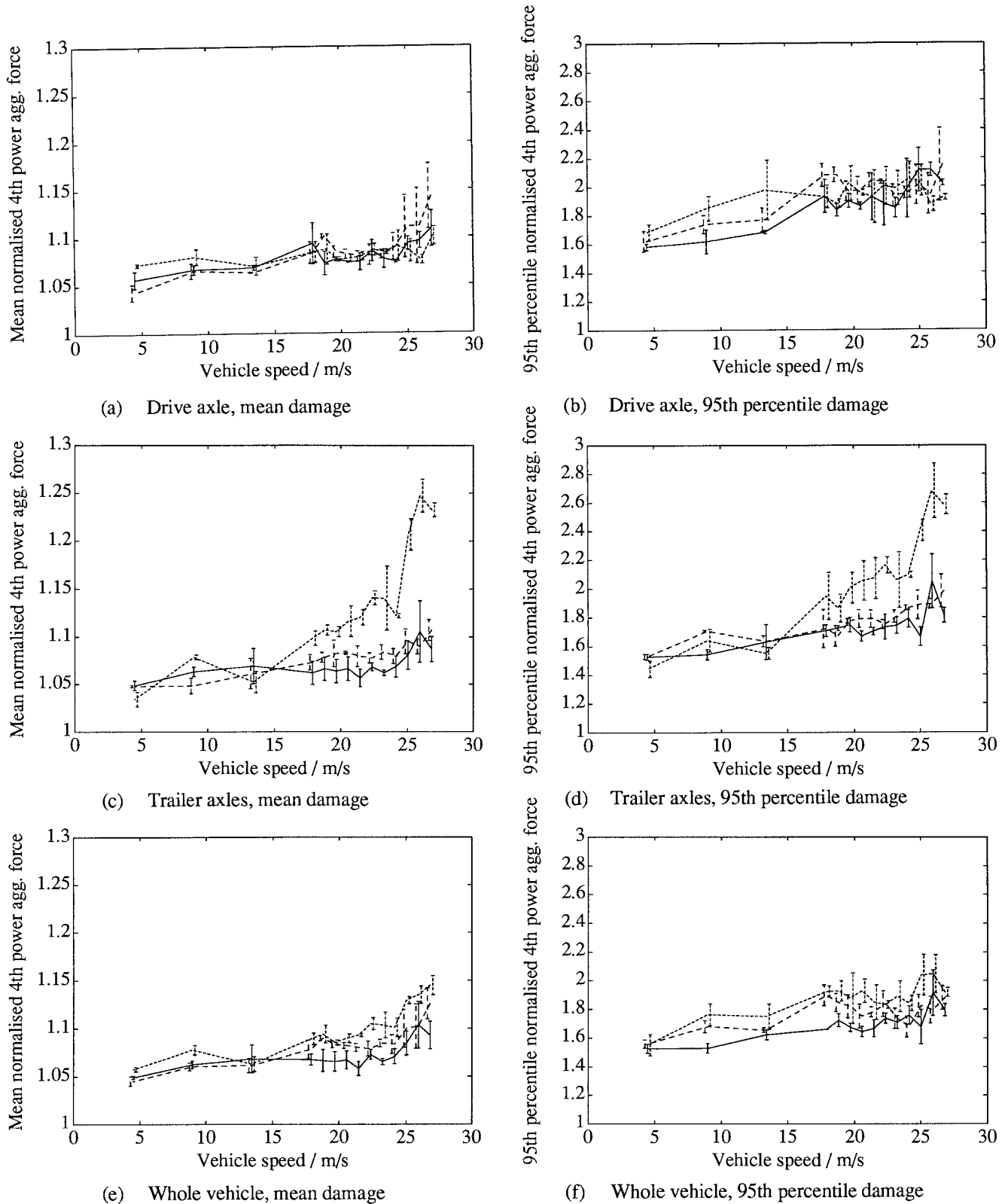


Fig. 5. Normalised 4th power aggregate forces as a function of speed for the three vehicles.
 - - - - - Vehicle 1 (steel, steel); - · - · - · - Vehicle 2 (steel, rubber); ——— Vehicle 3 (air, air).