Dynamic pavement loads and tests of road-friendliness for heavy vehicle suspensions

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Heavy goods vehicles apply higher than expected loads to road pavements because of dynamic bouncing. The Transport Research Laboratory has measured these loads for a variety of steel, rubber and air suspensions on their research track and on public highways. Bouncing of goods vehicles in motion causes dynamic pavement loads with standard deviations that are typically 10-30% of static loads, depending on the suspension type and road roughness. Tests indicate clearly how much these dynamic loads can be reduced by suitable choice of suspension. An estimate is made of the amount that road wear could be reduced if all goods vehicles used the best of current suspensions. Some measurements have been made of the effect of different suspensions on the peak dynamic axle loads on bridges.

Work is in progress to develop simple instrumentation that can be fitted quickly to vehicles for measuring dynamic wheel loads, and test procedures to enable the road-friendliness of different types of suspension to be assessed. The European Communities have defined road-friendliness in terms of suspension frequency and damping. Experimental evidence linking dynamic loads on roads to the parametric characteristics of suspensions is described. Other potential procedures for rating suspensions are discussed.

1. INTRODUCTION

Heavy goods vehicles in motion apply loads to road pavements that often are higher than the static wheel loads. This is partly because of dynamic bouncing and partly because of quasi-static effects that cause loads to transfer from one wheel or axle to another (Sweatman, 1983). These higher loads increase the road wear caused by heavy goods vehicles. The dynamic effects and some of the quasi-static effects are influenced by the design of the vehicle suspension. Parameters that are important are the vertical stiffness of the tyres, the stiffness, damping and friction of the suspension, the roll stiffness, the unsprung masses and the design of the mechanism that equalises the loads between the axles of a bogie group.

Both the static and dynamic processes that increase pavement loads can be analysed mathematically and predicted for different types of suspension and different road conditions. But suspensions are complicated and any mathematical models require validation against experimental results. Until the models are proven, the only way to assess the effect of different suspensions on pavement loads is by experimental measurements, linked perhaps to computer modelling of the response of pavements to dynamic loads.

This paper is concerned with the experimental measurement of dynamic pavement loads under heavy goods vehicles made by the Transport Research Laboratory (TRL) since 1987 (Mitchell, 1991), and on possible test procedures for assessing the 'road- friendliness' of such suspensions. It does not consider the equalisation of static axle loads. For conciseness, only sample results are given here. More detailed results are given by Mitchell (1991).

2. TYPES OF SUSPENSION

Heavy goods vehicles use a wide variety of suspensions, most of which are listed and described by Sweatman (1983). Single drive axles of both tractors and rigid vehicles use steel leaves or air bags as springs, now almost always with hydraulic dampers. Double drive axles use these suspensions and also beams carrying both axles, with steel or rubber springs between the beam and the chassis ("walking beams"). Trailers and semi-trailers usually use steel leaves or air bags on trailing arms as springs. Hydraulic dampers are used with air suspensions but rarely with steel leaf springs.

The research programme at TRL has tested steel leaf, air and rubber suspensions on semi-trailers. In addition, measurements have been made on tractors and rigid vehicles with steel leaf or air bag sprung single drive axles. Both multi-leaf and mono-leaf steel springs have been used on trailers. These tests have been planned to assess the road-friendliness of different types of suspension.

Semi-trailers with different suspensions have been run with the steel leaf and air bag sprung tractors. This is to assess the extent to which the suspension of one part of an articulated vehicle affects the pavement loads for the other part.

3. INSTRUMENTATION

Many researchers in this field have used instrumented hubs to measure the instantaneous forces applied by a wheel to the road (Sweatman, 1983; Hahn, 1987). These allow lateral forces to be measured as well as vertical forces. They are expensive and are usually applied to a single wheel at a time. TRL used strain gauges to measure the bending of the axle between the spring and the hub, plus an accelerometer to estimate the inertia forces of the axle mass outboard of the strain gauges. The outputs of these transducers can be combined to measure the instantaneous vertical force applied to the road by the wheel on the instrumented axle. The instrumentation is cheap and can be applied to all the wheels of a vehicle. Its disadvantage is that it will be inaccurate in the presence of lateral pavement loads and on very rough surfaces.

The strain gauge instrumentation is calibrated statically by loading and unloading the axle, which shows the system to be linear and repeatable. The gain of the electronic system is checked before each measurement run by inserting a standard calibration resistance. The position of the vehicle along the road is measured by counting prop-shaft revolutions and by the use of a light beam to identify the start and finish of a test section.

4. CONDITIONS FOR MEASUREMENTS

Measurements of dynamic pavement loads have been made at a series of steady speeds on straight sections of the TRL research track with rough, medium and smooth surfaces. These correspond respectively to a main road in need of resurfacing, a new trunk road or a motorway in service, and a new motorway. Some measurements have been made on public roads to confirm the positions of the track sections in the spectrum of road roughnesses that occur in practice. In addition, measurements have been made of the dynamic pavement loads on a small number of bridges, some of them on motorways.

These measurements have been analysed to provide the variation of the pavement load, plotted either against time or distance along the road, the maximum dynamic load, the standard deviation of the dynamic load and its power spectrum. The maximum load and the standard deviation are usually normalised by the static load, in which case they are referred to as the maximum load coefficient and the dynamic load coefficient. Figure 1 shows examples of the dynamic load on two sections of the TRL track and on a motorway bridge.

Additional tests have been made over artificial bumps at various speeds to excite separately low frequency vertical bouncing of the sprung mass (typically at 1.5 to 4 Hz) and high frequency bouncing of the axles (wheel hop, typically at 10 to 15 Hz). These

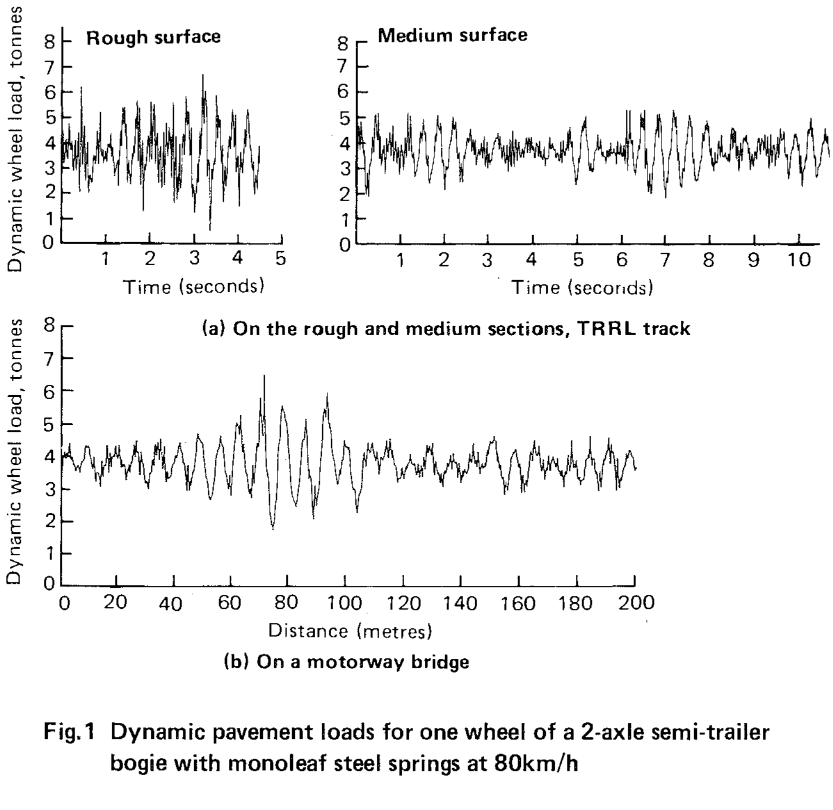


Fig.1 Dynamic pavement loads for one wheel of a 2-axle semi-trailer bogie with monoleaf steel springs at 80km/h

enable the frequency and damping of the principal response modes of the vehicle to be measured. These form the basis of a simplified parametric rating of the road-friendliness of a suspension which has recently been adopted by the European Communities (Council of the European Communities, 1992).

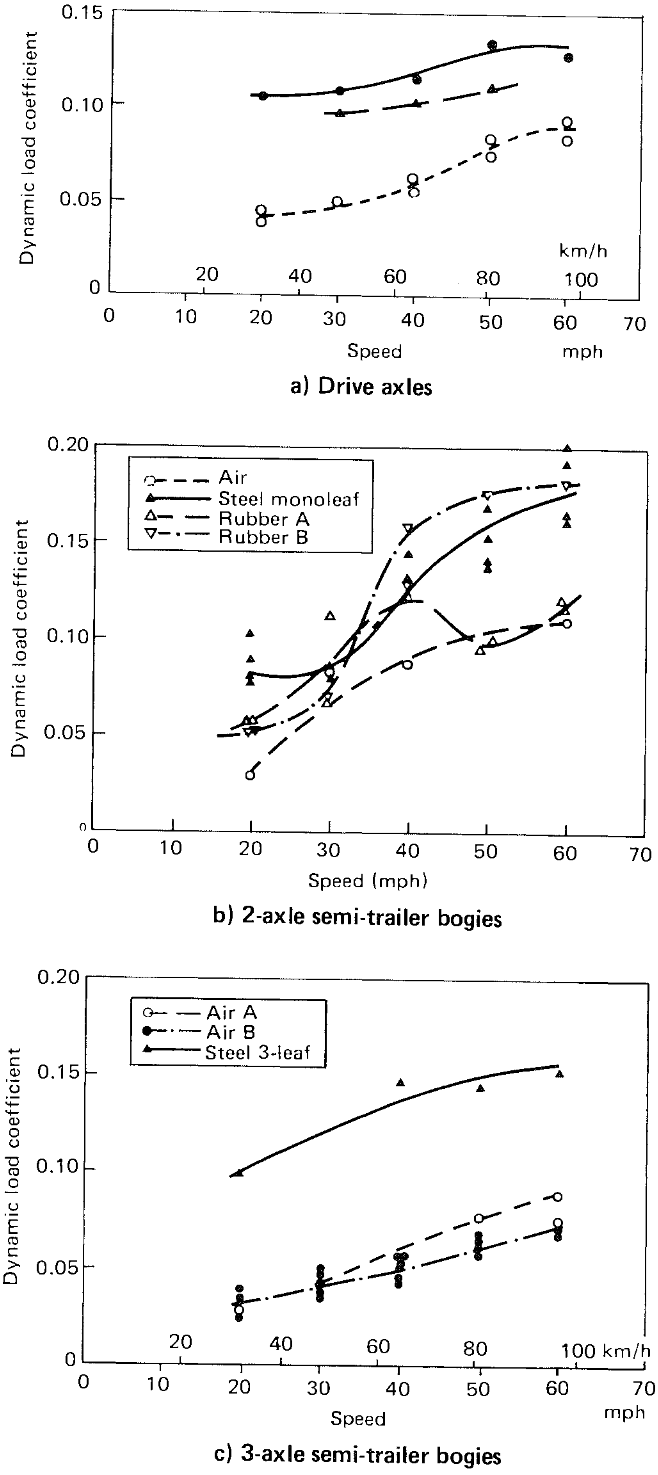
5. RESULTS

The most straightforward measure of the dynamic loading caused by different suspensions is a plot of the variation of the dynamic load coefficient with speed on a road of given roughness. Figure 2 shows results for drive axles and 2- and 3-axle semi-trailer bogies on the medium roughness section of the TRL track. The air suspensions on the bogies are conventional with trailing arms and the rubber sprung suspensions use a beam to link the axles ("walking beam"). It is clear that there are large differences between the dynamic loads under different types of suspension, with air suspensions always producing lower dynamic load coefficients than steel or rubber suspensions. Three axle bogies tend to produce lower dynamic loads than do 2-axle bogies. The dynamic load coefficients usually increase with increasing speed, and the beam suspensions also show a response peak at a lower speed.

The responses of the air suspensions have been found to increase with increasing road roughness, but those of the steel and rubber do not necessarily do so. For the steel suspensions the variation in response with road roughness reflects the friction in the suspension, which causes the springs to stick on smooth roads. As the roughness increases the springs unstick, and hence become softer. At some speeds some of the steel suspensions experience higher dynamic load coefficients on the smooth track section than on the medium section.

The dynamic load history for a given vehicle on a given test section at a given speed is highly repeatable. Since many goods vehicles have similar geometries, masses and suspensions, this suggests that, on roads where speeds are relatively constant, high dynamic loads will repeatedly occur at the same points along the road (Hahn, 1987; Gyenes and Mitchell, 1992).

The maximum dynamic loads that occur on bridges are important for some aspects of bridge design. The currently used dynamic axle load factor of 1.8 used in bridge design is based on measurements by Page (1976). These were made at 40 mph on a steel leaf sprung 2-axle rigid vehicle.



a) Drive axles

b) 2-axle semi-trailer bogies

c) 3-axle semi-trailer bogies

Fig.2 Dynamic load coefficients measured on the medium section of the TRL track

Figure 3 shows the maximum load coefficients measured recently for various 2-axle semi-trailer bogie suspensions on a number of bridges. On the relatively smooth motorway bridges, and on most of the over-motorway bridges, air suspensions cause lower maximum loads than steel. Figure 3a plots the load coefficient for a single wheel on an air suspension against the

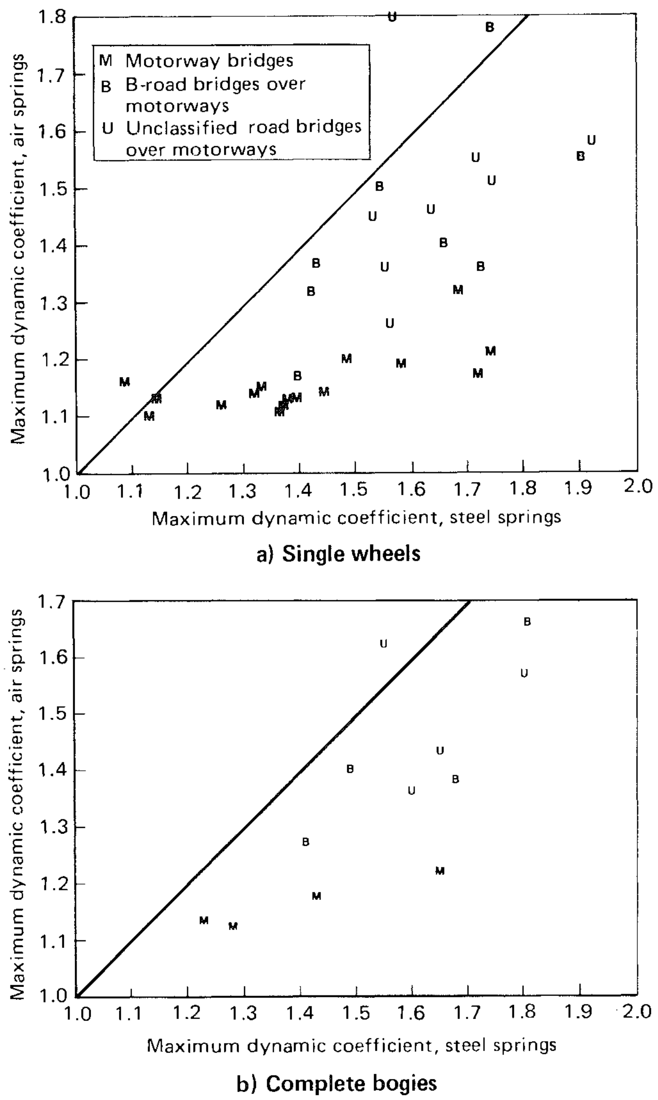


Fig.3 Maximum dynamic coefficients for 2-axle bogies on various bridges

coefficient for a single wheel on a steel suspension. For over 90 percent of the measurements, the maximum load coefficients for air are lower than for steel.

The total load on the 2-axle bogie on the bridges was also measured. Figure 3b shows that the maximum dynamic coefficients for the bogie loads were similar to those for the individual wheel loads. This implies that bogies tend to bounce as a unit with the dynamic loads on each wheel in phase, even though the dynamic coefficients for each wheel are not identical. The improvement of air suspensions over steel is slightly greater for total bogie loads than for single wheel loads.

It must be emphasised that the dynamic axle and bogie loads only affect culverts, short bridges and the local deck structure of long bridges. The overall design loads for long bridges are set by the static weight of the vehicle. On most bridges the maximum dynamic axle load is caused by low frequency bouncing of the sprung mass. In these cases the air sprung bogies experience lower dynamic loads than steel sprung bogies. In about 10 percent of cases the maximum dynamic load is caused by wheel hop at some short wavelength bump. In these cases the air suspensions can give similar or larger dynamic axle loads than steel suspensions.

6. IMPLICATIONS FOR ROAD WEAR

The processes that cause road wear are extremely complicated and only some of them are affected by the vertical loads applied to the road surface. As an approximation it is usually assumed, on the basis of tests using vehicles on trial roads in the USA (HRB, 1962), and subsequent tests in several countries using road fatigue testing machines, that road wear is proportional to the 4th power of the applied loads. Using this approximation, and assuming that dynamic loads are applied at randomly located points along a road, Eisenmann (1975) derived an expression for the increase in road wear due to a fluctuating load with a dynamic load coefficient (dlc). This is:

$$\text{dynamic pavement wear factor} = 1 + 6\,(\text{dlc})^2 + 3\,(\text{dlc})^4$$

If the high dynamic loads tend to cluster at particular points along the road, instead of being randomly distributed, then the pavement wear will be greater than predicted by Eisenmann's expression. For example, if the high loads were always at the same points, the wear factor at a point where the load was one standard deviation greater than static would be $(1 + \text{dlc})^4$, or approximately $\{1 + 4(\text{dlc}) + 6(\text{dlc})^2\}$.

Figure 4 shows the dynamic pavement wear factors for several types of suspension on the rough section of the TRL track. This shows clearly how much additional road wear is caused by dynamic pavement loads, and how much wear could be saved if all vehicles had the best of existing suspensions. Table 1 lists estimates of the excess road wear due to dynamic loads based on work at TRL and the University of Hannover. On medium roughness roads the use of an air suspension rather than a steel leaf suspension for a trailer bogie reduces wear by at least 10 percent; on rough and smooth surfaces the savings would be greater. The reduction for the drive axle of a modern tractor is less, but for that of an older rigid vehicle the saving is similar, provided the rigid vehicle on air springs responds in the same way as a tractor on air springs.

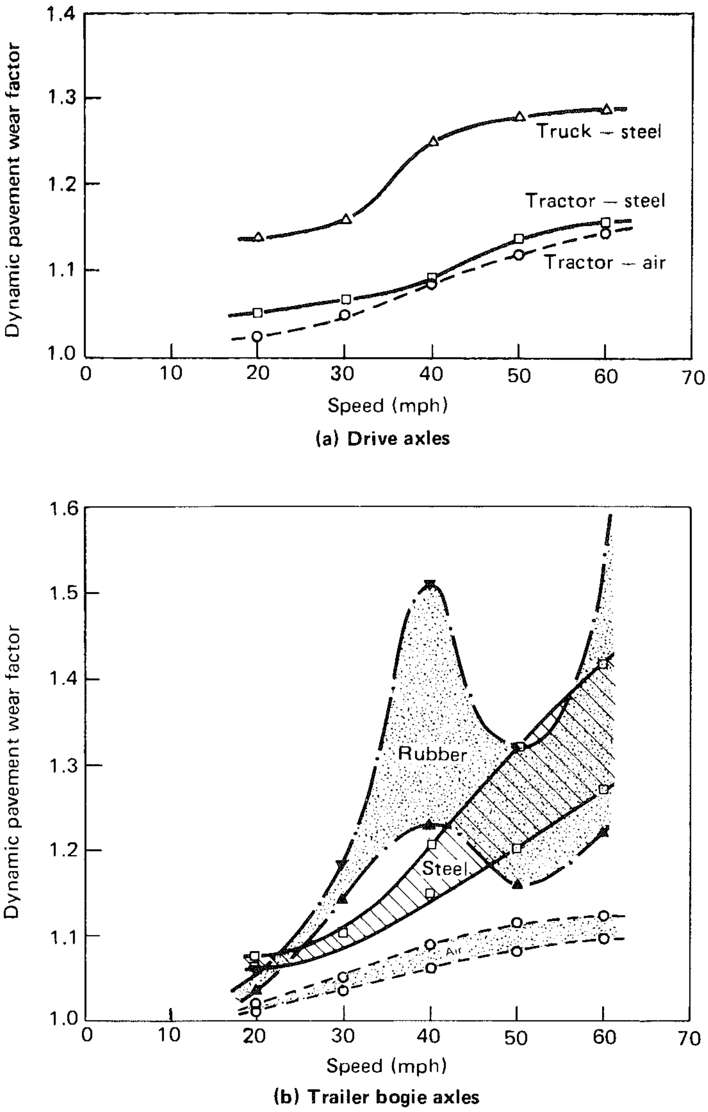


Fig.4 Dynamic pavement wear factors, rough section, TRL track

The National Audit Office (1987) estimated that in 1986 - 87 the cost of road wear caused by heavy lorries was £610 million, of which £500 million was structural wear to roads and £30 million was bridge wear. A Department of Transport estimate of road track costs for 1991/92 (Department of Transport 1991) quotes the wear caused by standard axles of heavy goods vehicles as £850 million. An analysis, using the results given above, suggests that if all heavy goods vehicles used the best available suspensions then the cost of road wear could, in theory, be reduced by at least £50 million. If high dynamic loads cluster significantly along the road, as seems likely, then the savings could be even greater. On the other hand, to the extent that only some heavy vehicles will be fitted with road-friendly suspensions, so the actual savings will be less than those potentially achievable.

7. TESTS FOR ROAD-FRIENDLINESS

7.1 Test requirements

A test of road-friendliness needs to assess the performance of the suspension with respect to low frequency bouncing of the sprung mass, high frequency bouncing of the axles, and equalisation of axle loads within a bogie.

Quasi-static equalisation is easy to test. It can be measured statically by tilting the bogie or by standing each axle in turn on a bump on a weighbridge. It can be measured at low speed by driving over a defined hump. The principles and practice of such a test are straightforward and details of it and the criterion for acceptance will be possible to specify for regulatory purposes.

The dynamic behaviour of the suspension affects the dynamic road loads and the maximum axle loads applied to bridges. The test would require the running of a suspension over a series of standardised road sections and bridges and measuring the dynamic loads produced.

It is not possible to build and maintain road and bridge test sections to defined longitudinal profiles that are the same in all countries, so the specification of absolute standards for dynamic behaviour (the normalised standard deviation of wheel load and the peak wheel load, for example) is unlikely to be practicable. but there are other possible approval procedures which are not based on absolute standards of dynamic behaviour of the suspension.

7.2 Design restrictive type approval

Research shows that some generic types of suspension cause more road wear for a given static weight than others. The current UK legislation on 3-axle bogies has taken this into account and permits a maximum bogie load of 24 tonnes for semi-trailers fitted with springs operated by air or other compressible fluid. For all other types of suspensions, the maximum permitted load is 22.5 tonnes. In Australia there is a list of specific designs of suspension considered suitable for heavy vehicles (Advisory Committee on Vehicle Performance, 1979). Although this design restrictive regulation has encouraged the use of road-friendly suspensions, it could hinder innovation in suspension design.

7.3 Parametric tests

The simplest approach to assessing a suspension is to define acceptable limits for the frequency and damping of the low frequency bounce mode, since these are known to correlate with the dynamic response of the suspension (see, for example, Magnusson et al, 1984 or Cebon, 1989). These parameters can be measured by any of a number of methods. These include driving slowly off a step, dropping the vehicle, or performing a frequency scan on a road simulator. This is the approach being taken by the European Communities (Council of the European Communities, 1992) in defining suspensions that are equivalent to air suspensions with regard to road-friendliness. The relationship between frequency and dynamic loads measured on the TRL track is shown in Figure 5. It can be seen that there is a good correlation between bounce frequency and dynamic load coefficient on the two sections of the track, but that the relation is different for the different axle groups.

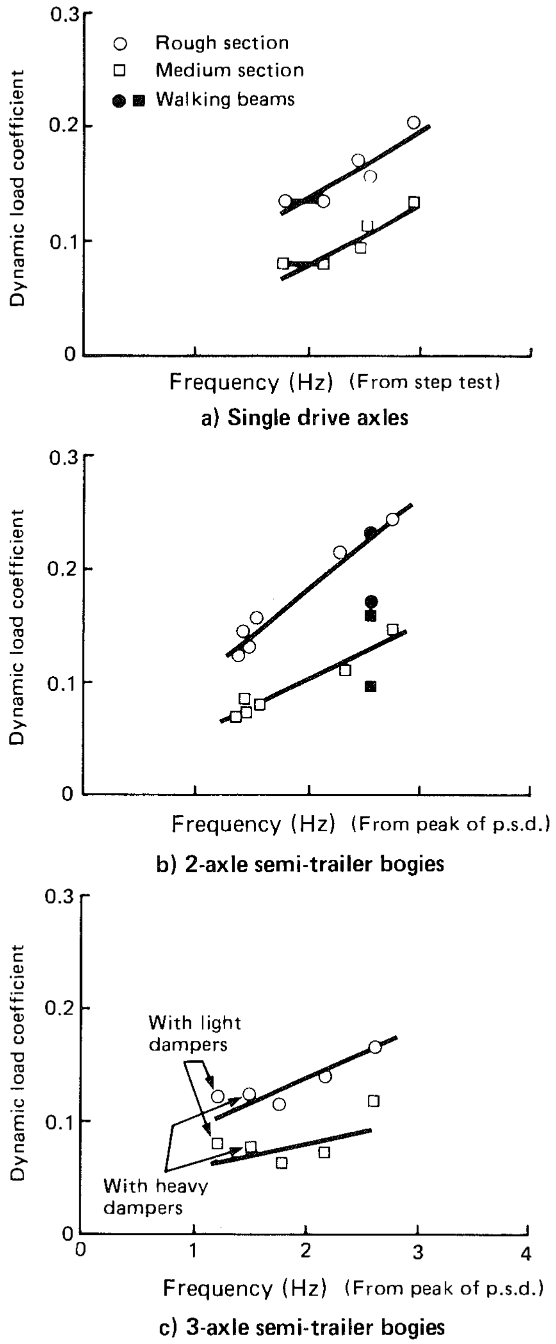


Fig.5 Effect of heave frequency on the dynamic load measured at 80km/h on the TRL track

7.4 Relative performance tests

The procedure would be based on the assumption that valid standards on dynamic behaviour could be set relative to the performance of known designs, using the same local test sections to measure the dynamic loads for the standard suspensions and the suspension to be rated.

Dynamic performance standards would be specified for locally nominated test sections, by measuring the performance of agreed 'good' and 'bad' current suspensions over the sections. The suspension rating procedure would consist of measuring the dynamic wheel loads of the design to be tested over the same test sections. The criterion of acceptance would be based on performance relative to the standards already set for the test sections.

7.5 Simulated performance tests

The aim of this procedure would be to obtain dynamic wheel loads from tests or calculations that represent the vehicle on real roads and bridges, and to compare these loads with absolute performance standards. There are three methods being considered by TRL, the road simulator, the artificial road profile and the computer simulation method.

7.5.1 Road simulator

In this approach a road simulator is used to apply standardised excitation to a vehicle so that dynamic loading on standard roads and bridges can be measured experimentally. A road simulator consists of a flat base onto which the vehicle can be driven and into which are set four, six, or more electro-hydraulic rams capped by platforms large enough to support the wheels. The rams are driven independently to move up and down to represent the humps and hollows in the road as it passes under the vehicle. The signals to the rams are generated by computer from the measured longitudinal profiles of both wheel tracks. Wheel loads are measured using load cells under the tyres or in the rams close to the wheel platforms.

Road simulators can provide accurate and repeatable dynamic measurements gquickly using standard road profiles without the need for any vehicle instrumentation. However, road simulators are expensive and the few that exist in Europe are heavily occupied in product development.

7.5.2 Artificial road profile

In this approach a very short length of artificial road profile that could be built in any country would be used to provide standardised excitation so that dynamic loads could be measured explicitly under standardised conditions.

The test procedure would be based on vehicle runs at very low speeds over an artificially constructed road profile. This profile would have had its longitudinal scale contracted and its vertical scale expanded to provide the same spectral density of the surface unevenness at low speeds as a normal road profile at normal operating speeds. It would be necessary to process the measured dynamic loads to correct for wheel base filtering, which could not be scaled pro rata with the profile.

7.5.3 Computer simulation

In this approach a computer model would be used to predict the dynamic loads produced by a vehicle running over a number of standard road and bridge profiles.

There are a number of standard computer simulation programs available, and some of these have been validated by comparing predicted and measured dynamic loads and vehicle motions on roads of known longitudinal profile (Cole and Cebon, 1989a). Use of such programs could, in principle, provide a way of predicting the dynamic loading due to a suspension under standardised conditions, and hence form the basis of a performance standard. However, at the present time it appears that considerably more validation is needed before the computer simulation programs can be regarded as reliable enough to be used for legislative purposes, and there would always need to be an option available to demonstrate road-friendliness experimentally. In addition, the existing computer simulation programs are not easy to use and no validated program is available off the shelf as a package that could be run by any design office.

7.6 Instrumentation

Although the instrumentation used in the TRL tests is simple for a research application it is too expensive to install and use in routine tests to demonstrate the road-friendliness of new designs or applications of suspensions. If regulations are introduced that require such a test over a normal or artificial road profile, then it will be necessary to develop or identify instrumentation that can be installed quickly, is self-contained, and provides a reasonably accurate measurement of dynamic pavement loads.

One possibility is to use a laser to measure the distance from the road surface to the chassis and a displacement transducer for the distance from the chassis to the axle. From these measurements the vertical deflection of the tyres, and hence the vertical load on the wheels, can be calculated. Dynamometer measurements of the vertical stiffness of heavy vehicle tyres show that this does not vary much with road speed, although it is sensitive to inflation pressure and temperature (Ramshaw, 1985).

Another possibility is to measure the width of the tyre above the contact patch. This can be done with a pair of strain-gauged cantilever arms that follow the tyre sidewall. As the vertical load increases, the tyre bulges sideways and tests with a prototype transducer suggest that this can be measured to an accuracy of about 5 percent at frequencies of up to at least 20 Hz. The transducer could be developed into a bolt-on unit with a self-contained recorder.

A series of strain gauges embedded in the road surface and mounted so as to measure longitudinal strain can be used to estimate the dynamic pavement loads as a vehicle travels over the test section. The main drawbacks are the sensitivity of pavement strains to temperature variations in the road pavement and to the position of the vehicle's wheels relative to the gauges.

A refinement of this method uses strip capacitive sensors set in the road surface or placed inside a mat or tiles and mounted onto the road surface. The pressure of a wheel on the road changes the capacitance of the strip. Tests have shown that this type of sensor is insensitive to changes in temperature and the position of a wheel along the sensor (Cole and Cebon, 1989b).

8. CONCLUSIONS

TRL has measured the dynamic loads on road pavements and bridges under a variety of heavy goods vehicle suspensions. On all road surfaces and on over 90 percent of bridges air suspensions cause lower dynamic loads than do other types of suspension. Soft steel springs with hydraulic dampers on tractor drive axles cause dynamic loads that are only slightly higher than those with air suspensions. Stiff steel springs on semi-trailers and the drive axles of older vehicles cause high dynamic loads. Rubber sprung walking beam suspensions may cause high dynamic loads, but these can be similar to the loads for steel suspensions if sufficiently powerful dampers are fitted.

Research is needed to validate a set of parametric criteria to define road-friendly suspensions, and to establish acceptable ways of measuring the suspension parameters required. The recent directive of the Commission of the European Communities which uses a parametric definition of suspensions equivalent to air suspensions is a promising start. Considerable research would be required to develop and validate a realistic performance test for road-friendly suspensions.

9. ACKNOWLEDGEMENTS

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TABLE 1

Potential reduction in dynamic pavement wear at 90 km/h on medium roughness test sections

Axle/Suspension	Dynamic pavement wear factor ≈ 1 + 6 (dlc)^2		Wear saving, air instead of steel or rubber, percent	
	T R L	Hannover*	T R L	Hannover
2-axle rigid, drive, multi-leaf steel	1.10	1.20	6%	8%
Tractor drive, steel leaf	1.07	1.20	3%	8%
Tractor drive, air or improved steel	1.04	1.10		
Trailer 2-axle bogie, steel leaf	1.25	1.22	15%	14%
Trailer 2-axle bogie, rubber/walking beam	1.19	1.33	11%	21%
Trailer 2-axle bogie, air	1.06	1.05		
Trailer 3-axle bogie, steel leaf	1.14	1.38	9%	24%
Trailer 3-axle bogie, air	1.04	1.05		

* Source - Hahn (1987)