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THE EFFECT OF THE DESIGN OF GOODS VEHICLE SUSPENSIONS ON LOADS ON ROADS AND BRIDGES

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ABSTRACT

This report examines the ways in which Heavy Goods Vehicle suspensions apply unexpectedly large loads to road pavements. Roadside surveys show that for many multi-axle bogies the axle loads are not equal, and tests with an instrumented semi-trailer show that these inequalities persist with the vehicle in motion. Air suspensions show good equalisation. Goods vehicles in motion bounce continuously on the tyres and suspension; this can increase the loads applied to the road. Tests have shown that the pattern of loads along a length of the road during repeated runs at the same speed is rather consistent for a particular vehicle. Instruments in the road have shown that at a given speed the strains in the road structure are approximately proportional to the instantaneous load applied to the road by an axle. Tests of a semi-trailer on alternate air and steel suspensions running over the same road profile have shown that on some parts of the road the air suspension produced smaller dynamic loads, but on other parts of the road the air suspension produced higher dynamic loads. The TRRL suspension research programme is described. It is seeking to identify what characteristics of goods vehicle suspensions minimise road loading.

1 INTRODUCTION

Virtually all the normal structural wear* of roads and bridges traffic is due to heavy vehicles. This is a consequence of the finding, from tests conducted by AASHO (Highway Research Board, 1962), that the 'damaging power' of a vehicle axle is approximately proportional to the 4th power of the static load on the axle. This means that a typical 32 tonne 4 axle heavy goods vehicle causes about 75 000 times as much wear as does a 1.2 tonne car. It also means that anything that increases goods vehicle axle loads increases road wear disproportionately (a 20 per cent increase in axle load doubles road wear), and any reduction in axle loads reduces road wear substantially, provided the 4th power law still applies.

This report reviews the processes which cause goods vehicles to have axle weights that are either higher than they need to be to carry the weight of the vehicle, or are higher than would be expected. It then reports studies by the British Transport and Road Research Laboratory (TRRL) of the loads transmitted to road pavements and bridge decks by goods vehicles. Finally, it describes a current research programme at TRRL which it is hoped will lead to a means of objectively rating goods vehicle suspensions in terms of their potential for causing wear to roads and bridges.

* The Department of Transport has decided in future to restrict the term 'damage' to that arising from direct impact and to use the terms 'normal' and 'abnormal wear and tear' to represent other effects of traffic on roads and bridges. This report follows the new practice.

2 CAUSE OF HIGH AXLE LOADS ON GOODS VEHICLES

There are at least four reasons why axle loads on goods vehicles can be higher than would be expected. These are—

(i) The operator has put too much payload on the vehicle.

(ii) The operator has put the payload in the wrong place.

(iii) Axle loads are not equally divided between separate axles of a bogie.

(iv) The vehicle bounces while it is in motion and applies dynamic loads to the road pavement that are higher than the static axle loads.

This list excludes load transfer between axles due to hills, braking and accelerating, and laterally on curves or due to cross-slopes. These effects can be substantial but occur at localised points and can be estimated readily.

2.1 OPERATIONAL FACTORS

Since 1980 TRRL has carried out 9 roadside surveys of heavy goods vehicles. In these surveys vehicles are stopped, weighed, photographed to allow dimensions to be measured, and the drivers interviewed about their journey and load. The vehicles are selected at random from the traffic stream and the results from them provide the only data available in Britain on the distribution of vehicle and axle weights occurring on motorway and trunk road network (Shane, 1987). These surveys show that typically 14 per cent of goods vehicles are overloaded in some respect. Of these, about $\frac{2}{3}$ are overloaded on gross weight and $\frac{1}{3}$ on one or more axles, despite being below their plated gross weight.

The amount of road wear that could be avoided if overloading were eliminated is quite small. Provided the same tonnage of payload is moved, using extra vehicles to carry the excess payload from overloaded vehicles, then total road wear would only be reduced by some 6 per cent by perfect adherence to plated weight limits. In a complementary study, Urquhart and Rhodes (1986) have used some of the TRRL survey data to show that if the actual loads carried by goods vehicles were positioned to minimise road wear, then total wear would be reduced by some 8 per cent.

It therefore appears that the current level of goods vehicles weight limit enforcement has ensured that in Britain any reductions in road wear that could be achieved by changes in vehicle loading by operators are comparatively small, at least on the motorways and trunk roads on which the TRRL surveys were conducted.

2.2 DESIGN FACTORS

The surveys described above showed that on many goods vehicles fitted with bogies the weight on the bogie was not equally distributed between the two or three axles of the bogie. This problem has only recently been recognised in Britain, though it has been discussed for Australian vehicles by Sweatman (1983). Experimental studies of axle load equalisation are reported in Section 3 of this paper.

It has been known for some time that the bouncing of goods vehicles on their tyres and suspensions on smooth roads causes substantial changes to the instantaneous loads applied to the roads by vehicles. The effects of goods vehicle suspensions on road pavement loads have been reviewed by Magnusson et al (1984) and by Forschungsarbeiten aus dem Strassenwesen (1983).

More detailed studies of dynamic wheel forces have been reported by Page (1973(a); 1973(b); 1974), Dickerson and Mace (1981), Ervin et al (1983), Sweatman (1983), Gorge (1984), Woodrooffe (1986) and Cebon (1985). There is repeated evidence of suspension dynamics increasing axle loads by 20-30 per cent over static, which implies at least a doubling of road wear at points where high loads occur. While the issue of axle load inequalities applies only to bogies, in which axle static loads are less than the loads on single drive axles, the effects of dynamic bouncing applies to all axles on all vehicles, including the most heavily loaded single axles. It seems likely that the effects of suspension dynamics may well be increasing road wear significantly, and this implies that there is the possibility of reducing road wear by improving the dynamic response of goods vehicle suspensions to road roughness. Current TRRL studies on this subject are described in Section 4 of this paper.

3 QUASI-STATIC AXLE LOAD EQUALISATION

3.1 EQUALISATION IN SERVICE

The British Construction and Use Regulations (Department of Transport 1978) require the multiple axles of heavy goods vehicle bogies to be interconnected through a 'compensating system' to maintain the axle loads reasonably equal despite road surface irregularities or chassis tilt (this requirement does not apply to the comparatively lightly-loaded steering axles of vehicles with twin forward axles— almost always 4 axle rigid goods vehicles). In the late 1970s the Department of Transport started to introduce, as standard enforcement equipment, weighbridges that weigh each axle of a goods vehicle separately and then sum the axle weights to determine the vehicle's gross weight. This equipment showed that while some compensating systems did indeed equalise axle weights within a bogie, others did not.

Three main types of bogie suspension and compensating systems are used in Britain, although occasional examples are found of many other types and variants. These three principal systems, shown in Figure 1, are:

(a) steel leaf springs connected by a balance beam which is intended to equalise axle loads

(b) air springs interconnected by air pipes for level control

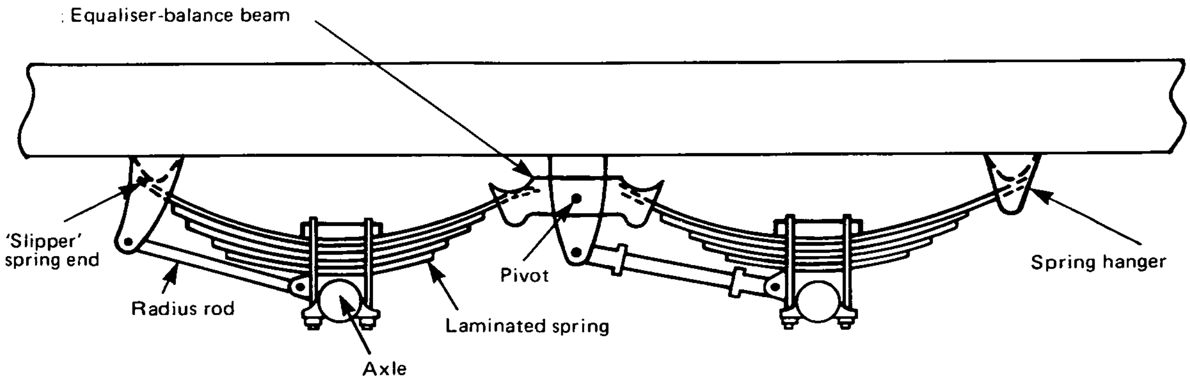
(c) centrally-pivoted bogie beam, attached to the vehicle chassis by rubber or steel leaf springs

Steel leaf springs and air springs tend to be used on semi-trailer bogies, with steel leaf springs fitted to some 85-90 per cent of semi-trailers in the UK in 1986. All three types are used on the rear bogies of rigid goods vehicles.

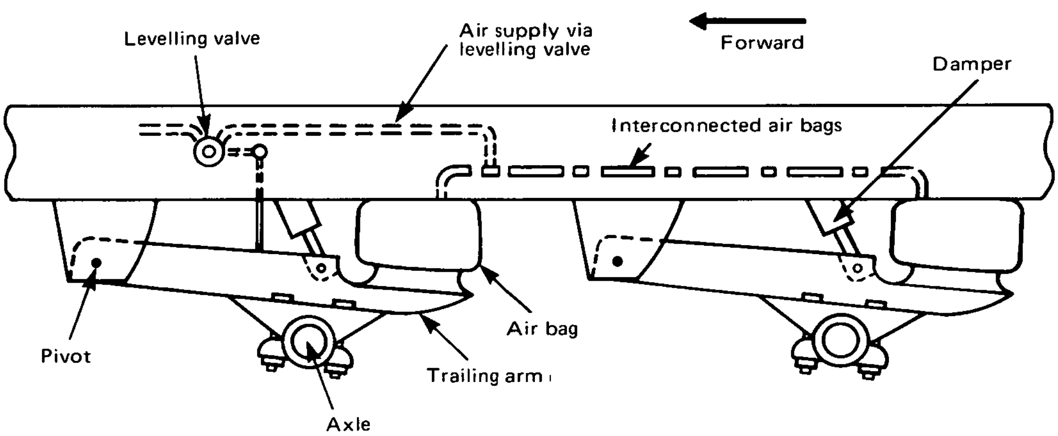
An example of the equalisation achieved in service by 3-axle bogies on semi-trailers is provided by a survey conducted in 1985 on the M6 Motorway. The axle weights of 145 3-axle semi-trailers and 114 2-axle rear bogies on rigid vehicles were measured on a slow-speed axle weigher, and the results are shown in Figure 2. In the figure the range of axle weights for each bogie is plotted against the total weight on the bogie.

If the compensation systems worked perfectly then each bogie would be represented by a single point at an axle weight of $\frac{1}{3}$ of the bogie weight on the semi-trailers, and $\frac{1}{2}$ on the rigid vehicles.

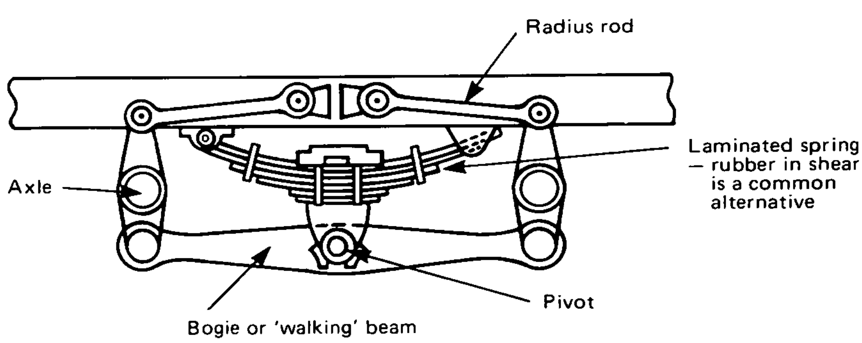
The survey shows that for steel leaf suspended bogies on semi-trailers the lightest axle is often 60-70 per cent of the heaviest, and on occasions only 30-40 per cent. However, for the air suspended bogies on the



(a) Steel leaf spring

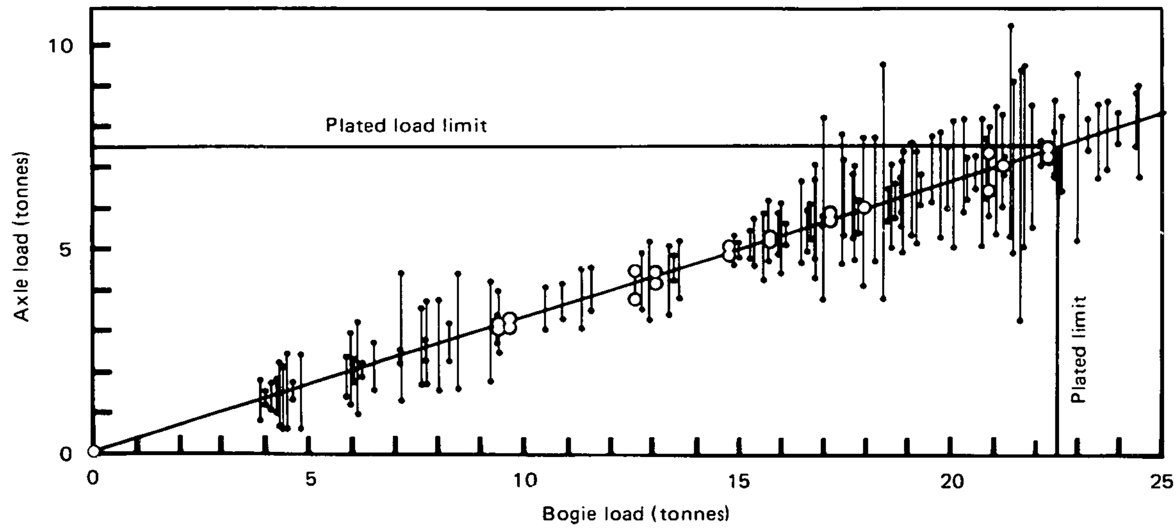


(b) Air spring

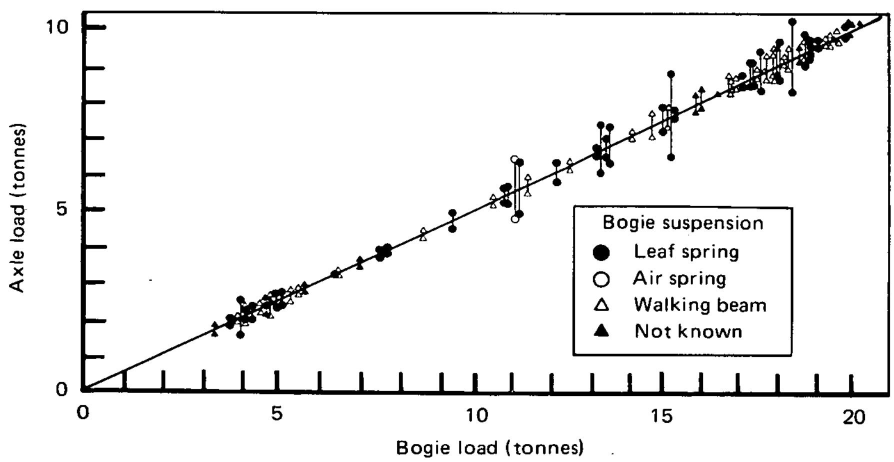


(c) Walking beam (many design variants)

Fig. 1 Three types of goods vehicle bogie suspension



(a) 145 3-axle semi-trailer bogies



(b) 114 2-axle rear bogies on rigid vehicles

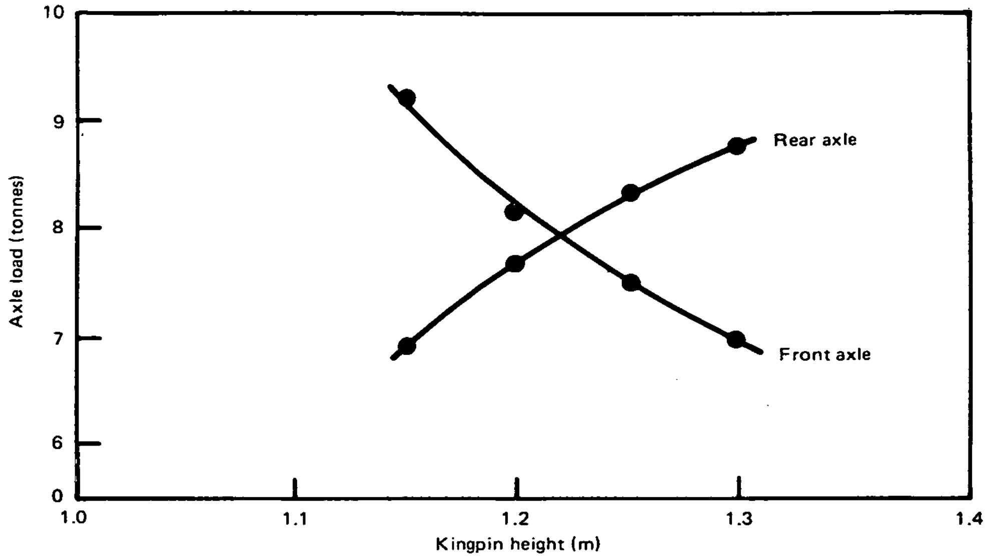
Fig. 2 Axle and bogie loads measured in a roadside survey on the M6 at Stafford, 1985

semi-trailers the lightest is typically more than 90 per cent of the heaviest. The bogies on the rigid vehicles equalise much better than do those on the semi-trailers, although one air suspended bogie performs relatively poorly.

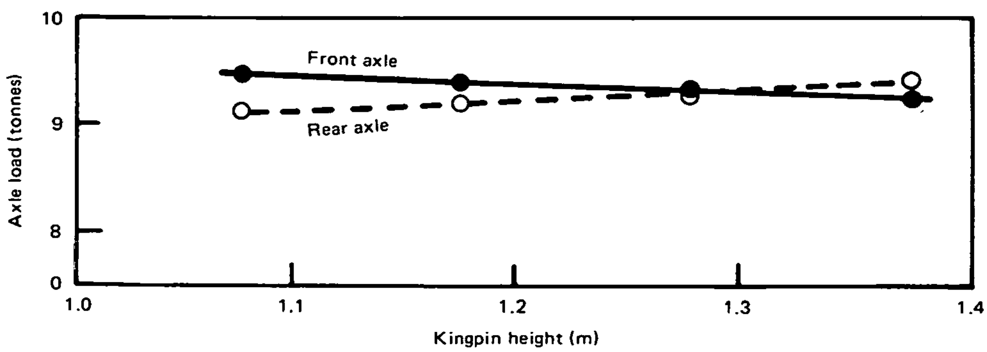
3.2 LABORATORY TESTS

Laboratory tests in which semi-trailers are tilted by raising or lowering the trailer king pin show progressive load transfer between axles with trailer tilt. With steel leaf bogies Figure 3(a) shows that a trailer bed angle of some $1\frac{1}{2}^{o}$ will produce load irregularities similar to those observed in the vehicles surveyed on the M6. Air suspended bogies show excellent equalisation (Figure 3(b)), at least under static conditions. On both types of bogie the sum of the axle weights is approximately constant at all trailer tilt angles.

Measurements at TRRL of the instantaneous axle loads on a 2-axle semi-trailer on the TRRL track show that load transfers between axles as the trailer moves over the profile of the track (which was as smooth as a good main road). This transfer occurs at all speeds from walking to 64 km/hour, the fastest tested. Figure 4 shows this transfer, on which is imposed a higher frequency dynamic load, to be discussed later. Because this transfer is a result of the trailer responding quasi-statically to the road profile, the load transfer is the same at all speeds tested, and high loads occur at the same point on the track at all speeds. On the track section tested, which contains undulations of 15 mm height, the axle loads vary by ± 25 per cent of static load due to this effect.



(a) Monoleaf steel spring suspension



(b) Air suspension

Fig. 3 Loads on the front and rear axles of a 2-axle semi-trailer as the trailer attitude is changed

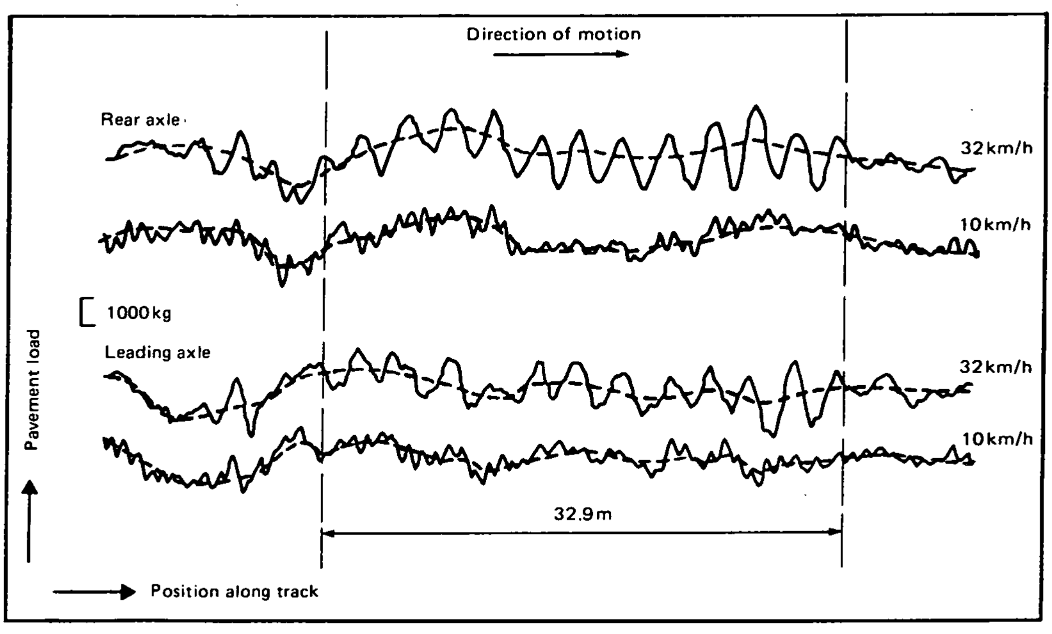
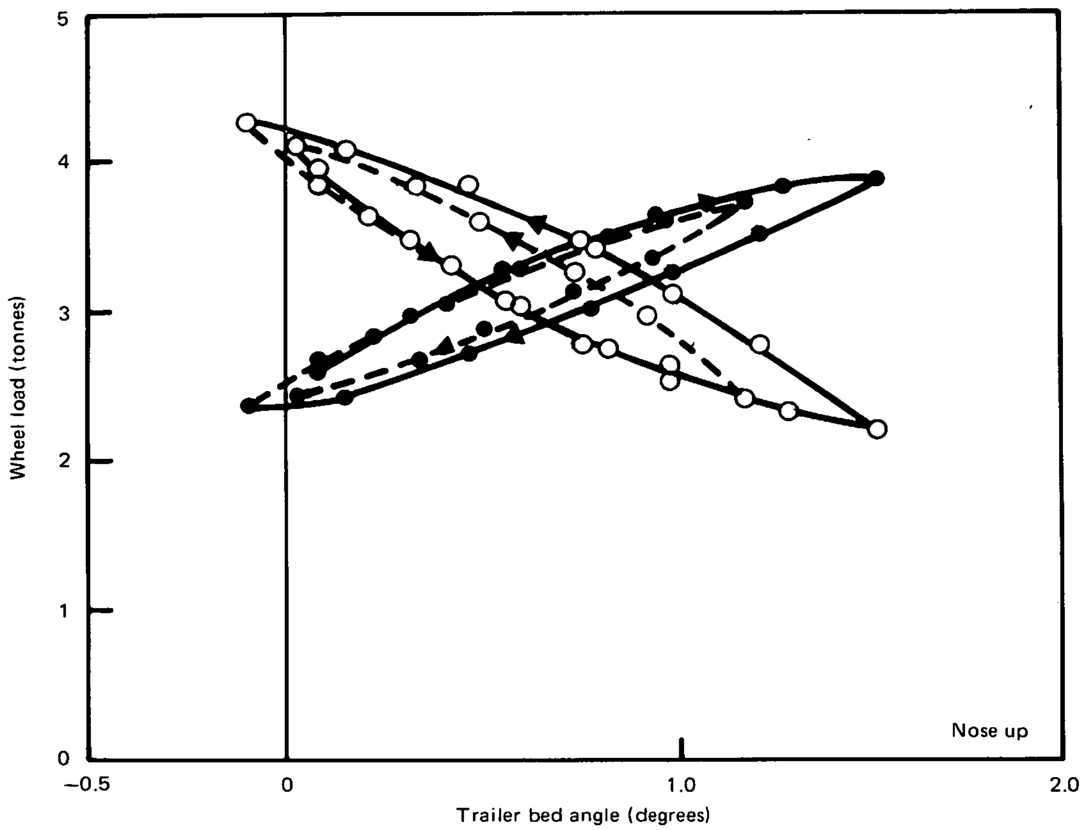
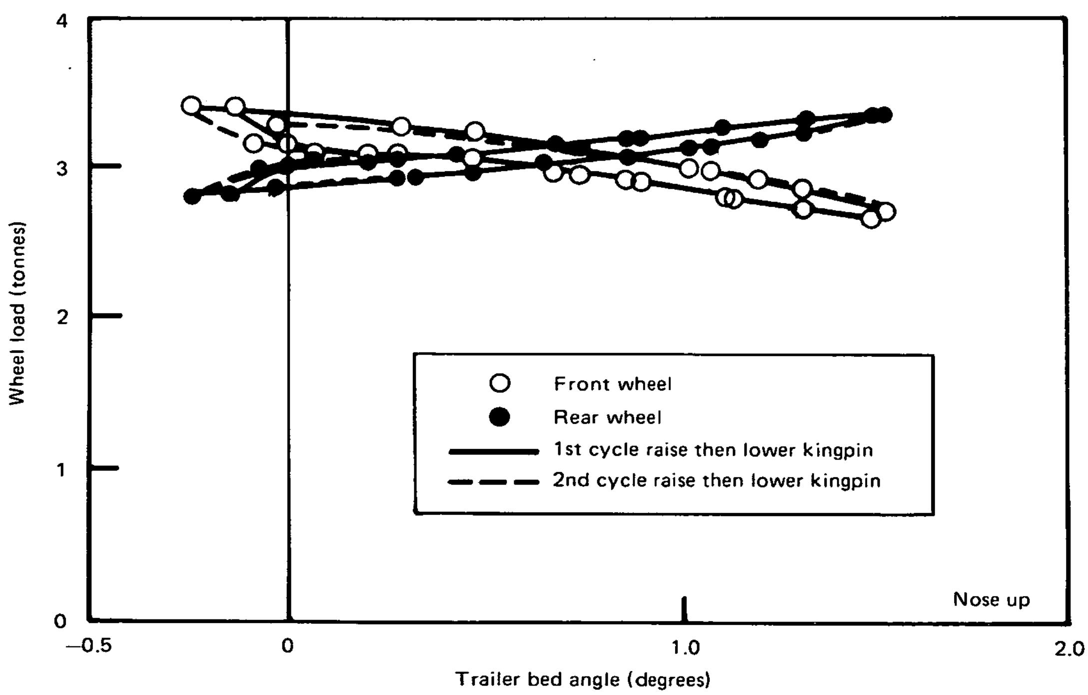


Fig. 4 Quasi-static load transfer between axles on a 2-axle semi-trailer bogie at 10km/h and 32km/h on the TRRL track



(a) Standard spring ends



(b) Spring ends on PTFE (Teflon) slides

Fig. 5 Wheel load inequality on a 2-axle semi-trailer bogie with steel monoleaf springs

At speeds above creep the quasi-static load transfer has superimposed on it a dynamic oscillation which is described in the next section. It is possible that at higher speeds or on rougher roads the axle loads would shake into equality, but this has not yet been observed at TRRL.

One reason for the inability of the compensating systems that use balance beams to equalise axle loads is that the pivot bush can apply a torsional moment to the balance beam. This has been analysed by consultants to TRRL (Stoker and Jones, 1986) but does not at present appear to be the major cause of load inequalities.

Recent experimental work at TRRL has shown that if the ends of the steel leaf springs (that normally slide on cams in the spring hangers and balance beam) are separated from the cams by sheets of PTFE plastic (Teflon), the load inequality at a given trailer tilt is reduced by a factor of about three (Figure 5). Mathematical modelling is in progress to try to better understand the reason for this experimental observation.

4 DYNAMIC BOUNCE

4.1 EARLY STUDIES

When a vehicle travels along a road at any speed above creep it bounces on its tyres and suspension, and this causes the axle loads to fluctuate. Because this is a dynamic phenomenon, the sum of the vehicle's instantaneous axle loads will not generally equal the vehicle's static weight; the difference will cause the vehicle or the unsprung masses (the axles, wheels, hubs and tyres) to accelerate vertically.

In 1976 Page measured the dynamic wheel loads exerted by a 2-axle rigid goods vehicle on a number of bridges to establish the dynamic factor to use for the design of bridge decks (Page, 1976) (Figure 6). Page also analysed theoretically the dynamic loads on a 2-axle rigid vehicle and a 2-axle bogie running over discrete bumps (Page 1973(a); Page 1973(b)). In the late 1970s Mace measured the dynamic wheel loads on a 2-axle rigid vehicle at various speeds over sections of public roads, using a vehicle-mounted system in which the vertical deflection of the tyres was used as a measure of the instantaneous wheel load (Dickerson and Mace, 1981).

Mace showed that on the 2-axle rigid goods vehicle the wheel loads fluctuated continuously at about 3 Hz and that on smooth roads the springs scarcely moved (Figure 7). The amplitude of the dynamic wheel load on any one road section had a Gaussian distribution to at least two standard deviations. The standard deviation of the dynamic loads increased with increasing speed and road roughness; at a speed of 64 km/hour on main roads it ranged from 0.1 to 0.3 of the static wheel load. The effects of tyre pressure, tyre type and wheel load were examined.

4.2 DYNAMIC WHEEL LOADS AND ROAD STRAINS

Mace's measurements showed the scale of the dynamic wheel loads produced by a goods vehicle, but did not show the effect of these loads on the strains in the road structure. To produce this information the instrumentation system from the 2-axle goods vehicle was fitted to a 2-axle semi-trailer and driven over a section of the TRRL track in which strain gauges had been installed (Addis, Halliday and Mitchell 1986). The vehicle was also run over public

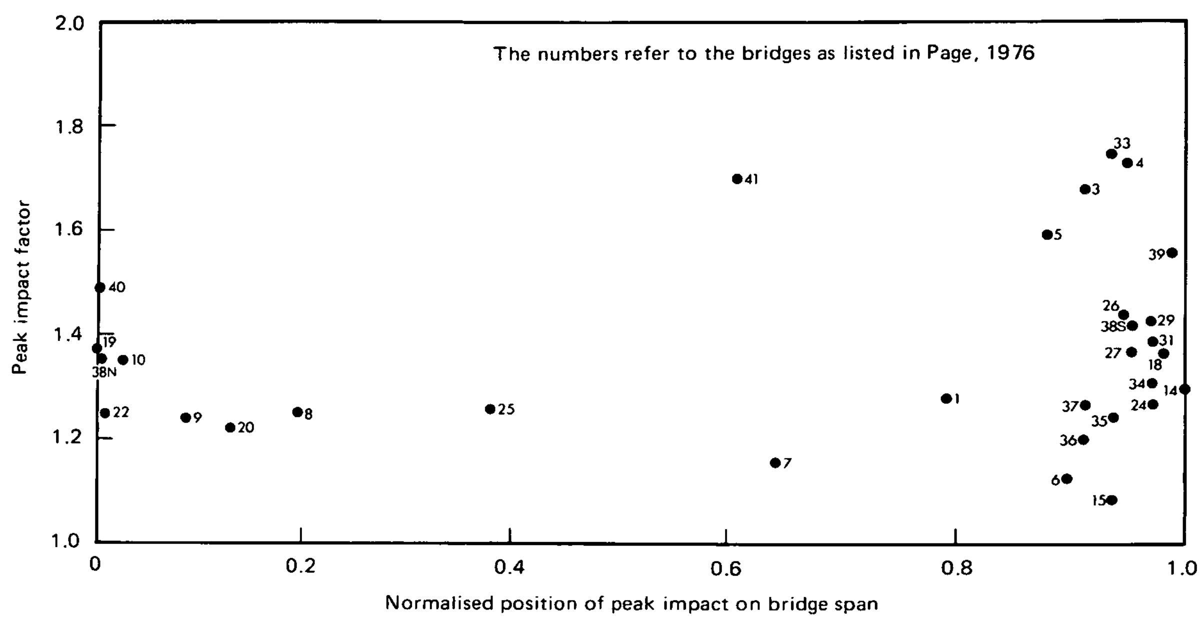


Fig. 6 Position on bridge where the peak impact occurs during a crossing by a 16 tonne 2-axle goods vehicle (Page, 1976)

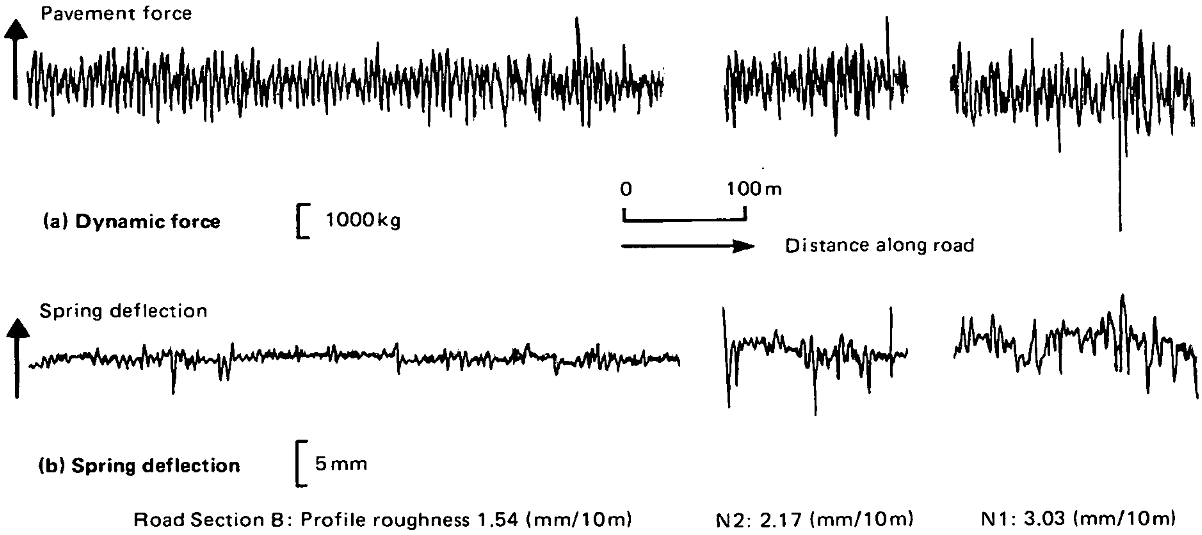


Fig. 7 Dynamic pavement force and spring deflection vs. distance. Rear axle of 2-axle rigid vehicle, 64km/h, twin wheels, static load 4500kg (from Dickerson and Mace, 1981)

roads and the standard deviations of the dynamic loads found to be similar to those previously reported by Dickerson and Mace. In particular, the semi-trailer bounced at about 3 Hz with all four wheel loads fluctuating in phase, but with the rear axle loads having a slightly larger amplitude than the loads on the front axle of the trailer bogie. Although the trailer springs were tapered steel monoleaf, they moved very little when the trailer was running on reasonably smooth roads. The wavelength of the dynamic load oscillations increased linearly with the vehicle speed (Figure 8 for the trailer on one axle only).

To check whether the 3 Hz trailer bounce that was observed was due to self-excitation by wheel and tyre eccentricities, or was due to the unevenness of the road, the trailer was run on a dynamometer with a drum that was circular to ± 0.5 mm. In this test the dynamic wheel loads showed oscillations both at about 3 Hz and at a frequency corresponding to the number of wheel revolutions per second. The amplitude of the oscillation varied as would be expected if the 3 Hz oscillations were being excited by an out-of-balance mass on the wheel. This showed that, on an almost perfectly level road, dynamic oscillations could be self-

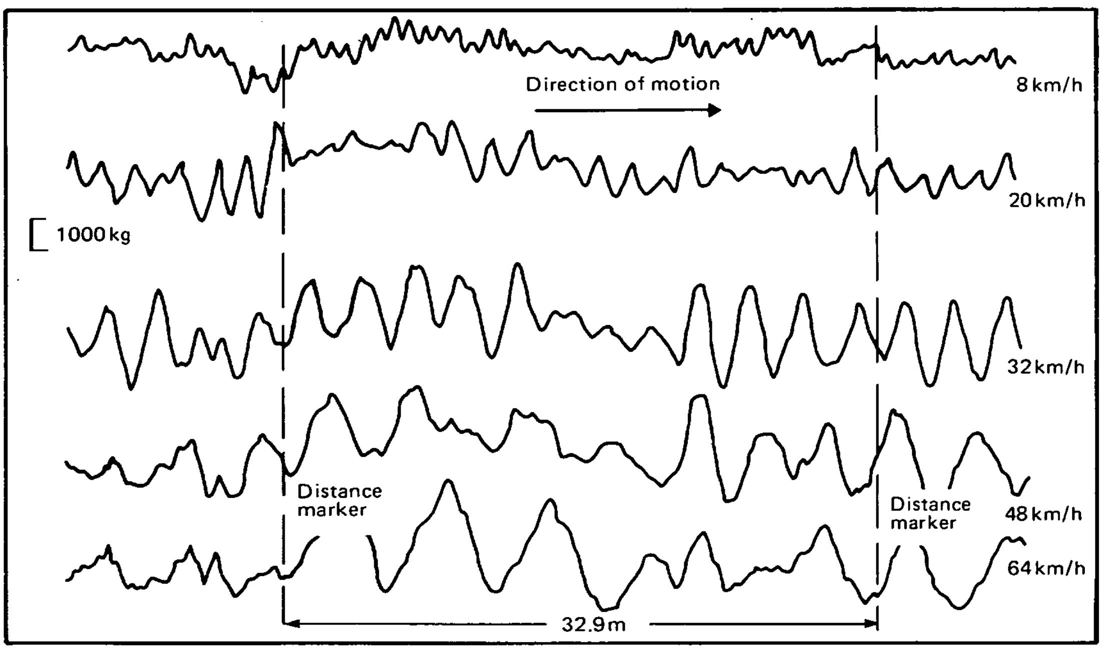


Fig. 8 Measured dynamic pavement forces for the semi-trailer axle of a 3-axle articulated vehicle on the TRRL track (9tonne static axle load) (Addis, Halliday and Mitchell, 1986)

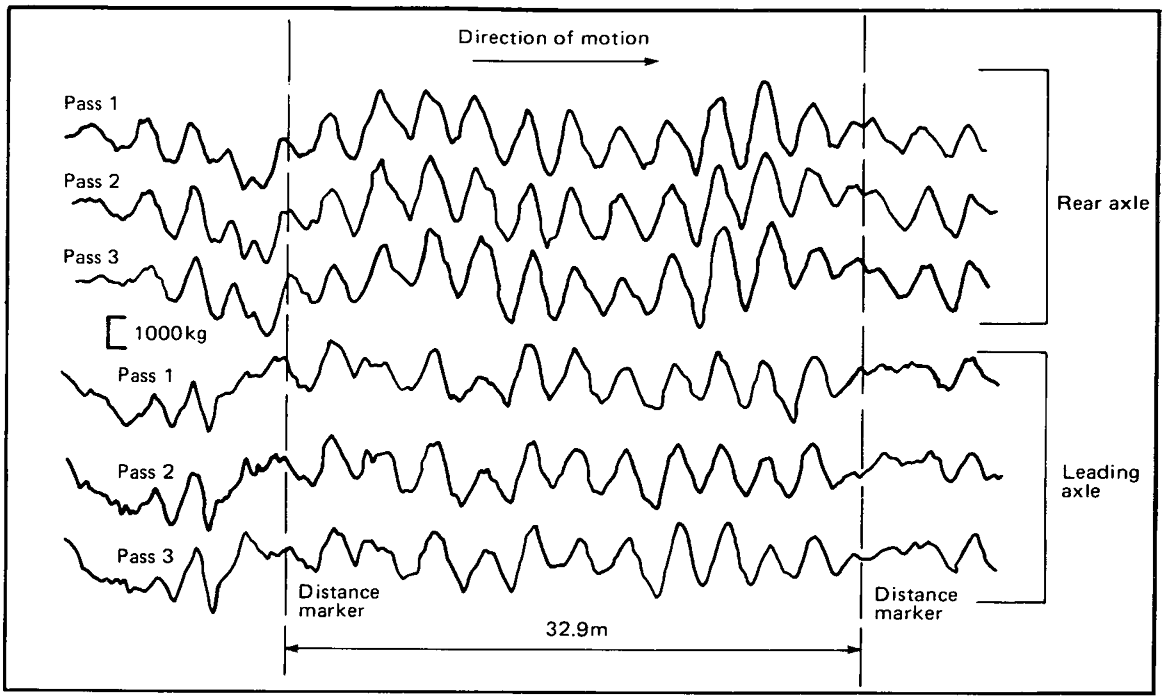


Fig. 9 Measured axle load variations on a 2-axle semi-trailer at 32km/h on the TRRL track showing repeatability
(Static loads 9tone/axle) (Addis, Halliday and Mitchell, 1986)

excited. However, when repeated passes over the test section of the TRRL track were made at a set speed, the positions along the pavement at which the minimum and maximum loads occurred remained constant for each pass (Figure 9); the peak amplitudes varied between passes by some 10-20 per cent. As no attempt had been made to index the trailer wheels to ensure they were in the same rotational position on each pass, the repeatability of the results suggests that the dominant cause of the dynamic load oscillations on realistic road profiles is the unevenness of the road pavement.

The strain gauges in and under the road structure showed that the strains in the road and the subgrade under it were repeatable when the vehicle passed over the road at a given speed and weight. The strains in the road varied as the dynamic loads applied to the road surface. The strain pulse caused by a single axle lasted about ⅓ second at 32 km/hour and ⅙ second at 64 km/hour. This implies that at highway speeds on smooth roads the transient form of the road strain pulse is dominated by the movement of the wheel along the road rather than the dynamic variation of the load on the wheel. This in turn suggests that conventional road life tests with a steadily-loaded rolling wheel may well give a good estimate for the life of the road under combinations of static load plus 3 Hz dynamic loads. This comment does not apply to the dynamic loads that occur at higher frequencies, such as those due to wheelhop (axle tramp) at 10-15 Hz.

The form of the dynamic loads can be described as a modulated sine wave. This is the response expected when a lightly damped single-degree-of-freedom system is randomly excited. It appears that the response of the semi-trailer to random unevenness of the road is to bounce on its tyres at about 3 Hz, with the amplitude of the bounce increasing with distance aft from the kingpin. Because the tyres provide little damping, this mode will be excited by any oscillary forces, and produce the modulated sine-wave response observed. The tests described demonstrate that tyre forces due to the road profile dominate the excitation, but that on an idealised, perfectly smooth, road the forces due to wheel and tyre eccentricities will excite similar oscillations.

Load could be observed shifting between the two axles of the trailer bogie in response to the road profile. This appeared to be a quasi-static effect of the compensating mechanism. Addis et al (1986) shows that the load transfer was proportional to the geometric mismatch between the road profile and the heights of the trailer axles. Addis et al (1986) concluded that:

1. Dynamic loading of the test pavement was brought about by the vehicle bouncing on its trailer tyres at a frequency of 3 Hz. This was a lightly damped movement excited by small variations in longitudinal profile such as might be expected on a high speed principal road built to normal United Kingdom standards.

2. On a good longitudinal profile, dynamic loads up to ±15 per cent of the nominal static axle load were recorded for tandem axles. For a single axle trailer the dynamic component was ±25 per cent.
3. These variations in loading were accompanied by measured variations in stress and strain in the pavement of up to ±20 per cent of that expected for the nominal static load. It was calculated that the consequence of the increased strain at the bottom of the roadbase could be to reduce the life of particular areas of some pavements by up to 50 per cent.
4. An additional component of dynamic loading was induced by long wavelength variations in pavement profile and caused an increase of 19 per cent in the rear trailer axle load on a smooth pavement. This was attributable to the inadequacy of the mechanism for sharing load between the two axles of the semi-trailer.
5. These results were obtained from one vehicle operating over one pavement. Further measurements on a range of vehicle/suspension types would be needed before conclusions of more general applicability could be drawn.

5 THE CURRENT TRRL RESEARCH PROGRAMME ON GOODS VEHICLE SUSPENSIONS

The current TRRL research programme on goods vehicle suspensions has the aim of recommending an objective test that will rate suspensions on their potential for wearing road pavements and bridges. It falls naturally into 3 phases, each lasting about 1 year, which are—

(i) Measure the loads applied to road pavements and to real and simulated bridges by existing suspensions.

(ii) If necessary, develop modified suspensions to reduce their wearing potential.

(iii) Develop and prove a practical test to rate the potential 'damaging power' of a suspension or suspension/vehicle combination.

At all stages the practical work is being guided by the predictions of a computer model of the dynamic loads applied to the surface of road or bridge. This is being developed and validated against the measurements being made for existing suspensions.

Instantaneous wheel loads are being measured using strain gauges to measure axle bending between the wheel hubs and spring attachments, with accelerometers on the hubs to enable allowance to be made for inertia loads from the masses between the strain gauges and the tyre contact patch. Spring movement is being measured using displacement transducers and sprung mass movements with accelerometers. To date this instrumentation has been fitted to one 2 axle rigid vehicle, one 2 axle tractor, two 2 axle semi-trailers and one 3 axle semi-trailer. The rigid vehicle and tractor have steel multi-leaf springs and the semi-trailers are currently fitted with steel mono-leaf springs and balance beam equalisers. During the first half of 1987 it is planned to obtain and instrument two air-sprung semi-trailers. The results from some earlier preliminary tests comparing air and steel suspensions are given in the Appendix.

Tests consist of obtaining load histories for passages over five test sections of the TRRL track. These represent road surfaces ranging from good/average to poor for main roads. One surface is instrumented with strain gauges in the road structure. Measurements will be made at speeds between 8 km/h and 96 km/h and at full, half and zero payload. Additional measurements will be made of axle load equalisation for the semi-trailer bogies, using a low-speed axle weigher already installed on the track. Finally measurements will be made of the peak dynamic loads caused by discrete bumps or trenches once the profiles to be used have been decided.

TRRL is also co-operating with two universities, one of which is instrumenting a haul road which could provide a useful facility for measuring road structural strains under un-instrumented goods vehicles and also for studying the day-to-day variations in strains caused by a relatively small fleet of goods vehicles engaged in a repetitive bulk soil shifting operation.

At this stage it can only be speculative to consider ways in which goods vehicle suspensions can be improved. Such improvements must involve some combination of reduced stiction and friction in the suspension; changes to spring stiffness and to suspension damping once the stiction has been reduced and the axles are moving relative to the chassis; and possibly reductions in unsprung mass. If modifications to suspensions are made it will be important to check that they do not compromise safety. In particular, it will be necesssary to examine roll stiffness and roll-over speed, braking performance (both retardation and directional stability), and handling in normal driving and manoeuvring. It will also be important to be certain that any changes are practical and economic, and this part of the programme could well be one in which industrial participation is invited. The vehicle and road freight industries are, in any case, being kept informed on progress and invited to comment on plans for the research programme.

6 CONCLUDING DISCUSSION

Measurements using roadside axle weighers and vehicles instrumented to measure instantaneous axle loads have shown that there are at least two processes by which heavy goods vehicles apply higher loads to roads and bridges than would be expected. The first is that on semi-trailers bogies with steel leaf springs and balance beam equalisers do not, in practice, equalise the loads between the two or three axles of the bogie. Where an axle is above a high spot of the road profile it carries a disproportionate share of the bogie load, and if the semi-trailer or vehicle chassis is tilted relative to the road the loads are redistributed unequally. This is a quasi-static effect which is independent of vehicle speed and load, and which leads to particular points on the road always seeing loads that are higher, by typically 15-20 per cent, than might be expected. Air or fluid suspensions for bogie axles leads to excellent load equalisation. Bogies on rigid vehicles appear to equalise axle loads better than do bogies on semi-trailers.

The second effect is due to bouncing of the vehicle on its tyres and suspension. This occurs with all vehicles and seems to be mainly excited by the road profile. It increases the instantaneous loads on the road typically 2-4 times per second. The amplitude of the increased loads are randomly distributed with a standard deviation, on a good main road at a speed of 64 km/h, that is typically 10-20 per cent of static load. This is a dynamic process which is affected by vehicle speed and weight as well as the design of the vehicle suspension. Tests have shown that a given vehicle at a set speed and weight will apply dynamic loads to the same points of a stretch of road on repeated runs, and that the amplitude of the loads will vary by only 10-20 per cent between runs. Changing the suspension of the vehicle will change the position, the number and the amplitude of the dynamic load peaks. No suspension has yet been found that produces lower dynamic loads at all points on different road profiles with roughness of different wavelength and amplitude.

Measurements on the TRRL track show that dynamic loads applied to the track at 3 Hz by a goods vehicle increase the measured strain in the road structure. Measurements reported in this paper suggest that the combination of quasi-static axle load inequalities and dynamic bounce approximately doubles the amount of wear to the road at particular points per vehicle pass by a steel leaf suspended semi-trailer.

The extra loading caused by dynamic bouncing occurs on all vehicles and all axles, single or multiple, while the quasi-static load inequality applies only to bogie axles. Furthermore, bouncing of a bogie usually increases the load on all axles of the bogie simultaneously, while quasi-static load inequality increases load on one axle and reduces it in another. For these reasons, and because the most heavily loaded axles on goods vehicles are usually single drive axles, it seems likely that dynamic bouncing is contributing more to excess road wear than poor equalisation, but that neither process can be ignored. There is clear evidence that changes to the design of goods vehicle suspensions can reduce excess road damage in particular conditions, but no suspension has yet been found that is better than existing conventional suspensions under all conditions.

The TRRL research programme on heavy goods vehicle suspensions is (i) measuring the road loads caused by existing suspensions, (ii) examining ways of modifying suspensions to reduce excess loads applied to roads and bridges, (iii) developing a test procedure to rank the road wear potential of suspensions and/or vehicles. This programme is using vehicles instrumented to measure instantaneous axle loads, instrumented road pavements and computer simulation.

7 ACKNOWLEDEMENTS

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9 APPENDIX A—A COMPARISON OF AIR AND STEEL SPRINGS

9.1 TEST VEHICLE

An opportunity arose in 1985 to compare the load imposed on road pavements by air and steel leaf sprung semi-trailers on a road simulator at the Fruehauf Corporation, Detroit. The test vehicle was a van-bodied semi-trailer 45 ft long. The kingpin was attached to the turntable of a 3-axle cab-over-engine tractor. The height of the turntable could be adjusted between a height of $46\frac{1}{2}$ in (trailer level) and 52 in (trailer nose up $\frac{3}{4}^{\circ}$). The trailer was loaded to apply a static load of 34 000 lb (15.4 tonnes) to the bogie. The trailer bogie was mounted on a sub-frame which allowed it to be slid along the underside of the trailer (to adjust the wheelbase for manoeuvring). This allowed the bogie to be changed relatively easily.

For the dynamic load tests two bogies were used. These were identical in dimension and each had 2 axles fitted with twin 10.00 × 20, 12 ply tyres. One bogie was fitted with air suspension units which consist of axles mounted on rigid trailing arms, supported by rolling-bag air suspension units and fitted with $2\frac{1}{2}$ in diameter hydraulic dampers. The other was fitted with a steel spring suspension, in which the 3 leaf steel springs were linked by an equalizer balance beam. The radius rods were pin-jointed to the axles and no dampers were fitted.

The tractor and semi-trailer were mounted on the road simulator, which consists of a flat base onto which a vehicle can be driven and into which are set six electro-hydraulic rams capped by platforms large enough to support a pair of truck wheels at one end of an axle. For the test described here only 4 rams were used. These rams are driven independently to move up and down to represent humps and hollows in the roads as it passes under the vehicle. The signals between the rams under the front and rear wheels on one side of the bogie are linked to ensure that the rear wheel sees the same profile as the front wheel, displaced in time by the time the vehicle would take to travel the distance between the 2 axles. The rams are servo-controlled to provide the desired displacement regardless of the load applied to them by the vehicle. Each of the wheel pairs rested on a strain-gauged load cell which measured the vertical force between the tyres and the platform on the ram that represented the road surface. The signals from the 4 load cells were digitised and stored in the control and instrumentation computer during test runs, as well as being displayed visually on a digital voltmeter.

9.2 TEST PROCEDURE

The test procedure for each suspension was similar. The trailer was set level and the road simulator operated for 8 minutes to represent the vehicle travelling over a rough paved road at 40 mph (64 km/h, the speed used for all the tests). The road profile, which was the same for all the rough road tests, had been generated artificially by filtering random white noise. The rms of the road surface displacements under each of the 4 wheel pairs during the 8 minute runs was 0.25 in. The mean vertical force on the road surface, and the standard deviation of the force, were recorded for each wheel pair. The vertical force was also analysed to provide its power spectral density. The turntable on the tractor was then raised $5\frac{3}{4}$ in to tip the trailer $\frac{3}{4}°$ nose up and the 8 minute rough road run repeated.

The trailer was kept in the nose-up attitude and run over a 20 second length measured road profile that included some large discrete bumps that were considered typical of bridge abutments.

Finally, the vehicle was run over profiles representing artificial bumps on an otherwise flat surface. These bumps were 20, 40 and 60 mm high, were 90 ft long ($1\frac{1}{2}$ sec duration) and were approached and left by ramps approximtely 6 ft long (0.1 sec duration). The ramps were applied symmetrically to the road-side and curb-side wheel sets.

9.3 TEST RESULTS

9.3.1 Axle load distribution

Table 1 gives the static axle loads measured on the road simulator and the mean axle loads during 8 minute runs on rough roads. It shows that the static load inequality for the steel suspension when the trailer is nose up also appears as an inequality in the mean loads in motion. The mean loads on the two axles of the air suspended bogie are almost exactly equal with the trailer nose up as well as level.

9.3.2 Dynamic loads

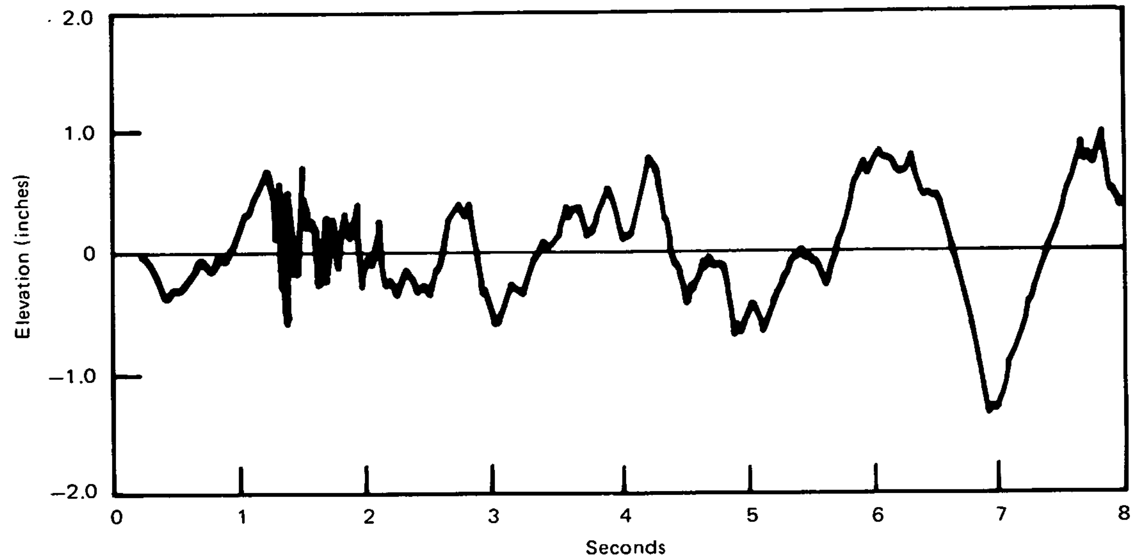
The dynamic responses of the two bogies was quite different, as is shown in Figure 10. The steel suspended trailer applies dynamic loads to the road continuously at 4 Hz (trailer bounce) and occasionally

TABLE 1

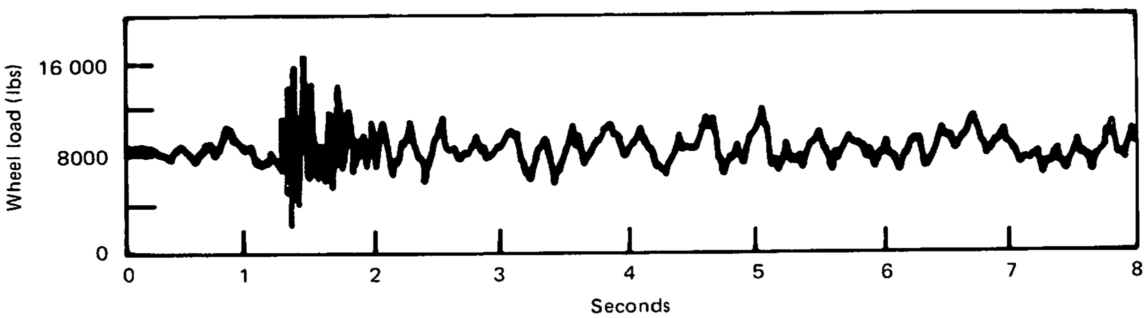
Static axle loads and means of loads on rough roads—2 axle semi-trailer bogie

Vehicle loads, lbs (percentage of bogie total in brackets)

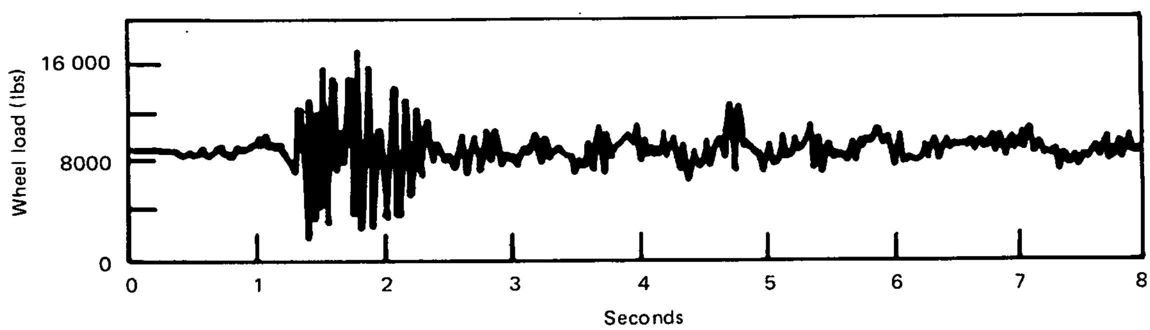
Case/trailer attitude	Steel leaf suspension			Air suspension		
	Front axle	Rear axle	Bogie total	Front axle	Rear axle	Bogie total
Level						
Static before run	17 400 (51.8%)	16 100 (48.2%)	33 500 (100%)	—	—	—
Mean during run	17 500 (52.2%)	16 000 (47.8%)	33 600 (100%)	17 300 (50.0%)	17 300 (50.0%)	34 600 (100%)
Static after run	17 500 (52.0%)	16 100 (48.0%)	33 600 (100%)	17 300 (49.7%)	17 300 (50.3%)	34 700 (100%)
Nose up ($\frac{3}{4}°$)						
Static before shakedown	14 500 (43.3%)	18 800 (56.6%)	33 300 (100%)	—	—	—
Static after shakedown	15 600 (46.7%)	17 800 (53.3%)	33 400 (100%)	—	—	—
Mean during run	15 800 (47.3%)	17 600 (52.7%)	33 400 (100%)	17 300 (49.7%)	17 500 (50.3%)	34 800 (100%)
Static after run	15 800 (47.3%)	17 600 (52.7%)	33 400 (100%)	—	—	—



(a) Road profile



(b) Wheel load, steel springs



(c) Wheel load, air springs

Fig. 10 Road loads under the offside rear wheel of a 2-axle semi-trailer on a defined road profile at 64km/h

at about 18 Hz (wheel hop). A power spectral analysis also shows energy at 1 Hz (roll) and 2.2 Hz (pitch). For the air suspended trailer the frequency of the bounce mode has fallen to 1.8 Hz and its amplitude is much reduced, but wheel hop at 10-15 Hz has much increased.

On the random rough road the standard deviations (rms) of the loads from the air sprung bogie are about 7% less than those from the steel, and on the simulated steps the peak dynamic load is about 10% less for the air bogie. However, on the real road profile with bridge abutments the air bogie produced similar peak road loads to the steel, wholly as a result of wheel hop being excited by short wave-length roughness. The measured peak wheel loads were 15 010 lb (dynamic factor 1.73) for the air suspension and 15 230 lb (dynamic factor 1.72) for the steel. The highest dynamic factor was 1.80 for the steel suspension.

9.4 CONCLUSIONS

The conclusions from this short (2 day) test programme were:

(i) The steel spring suspension did not equalise static axle loads when the trailer attitude was changed, but the air suspension did.

(ii) The mean dynamic wheel loads for the steel and air suspensions when the trailers were driving at 40 mph were almost identical to the wheel loads measured with the trailer at rest after shaking down; any static inequalities persisted.

(iii) On a simulated rough road the rms dynamic load and the peak dynamic load, both expressed in terms of the mean static load, were about 7% less for the air suspension than the steel spring suspension.

(iv) The steel suspension responded to road roughness in the frequency range 1-4 Hz in rigid body modes, with slight wheel hop at about 18 Hz, while the air suspension responded in the ranges 1-2 Hz and 10-15 Hz (rigid body modes and wheel hop respectively).

(v) On a short length rough real road profile the air suspension produced higher peak loads than the steel suspension, as patches of short wavelength roughness excited the wheel hop mode.

(vi) In simulations of driving over discrete step bumps on level surfaces the air suspension produced peak loads some 10% less than the steel suspension.

(vii) These results apply specifically to the air and the steel spring suspensions tested. There appears to be some scope for further improving the performance of the air suspension by reducing the extent to which its wheel hop mode is excited. Without further tests it is not possible to generalise these results to all air suspensions or all steel spring suspensions.

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