Dynamic Suspension Characteristics: Is There Research Beyond the Fourth Power Law?

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ABSTRACT

Considerable progress has been made in identifying the essential characteristics of dynamic wheel forces. This is of particular importance for truck size and weight technology. The Australian Road Research Board has identified suspension types causing severe dynamic loading and has recommended related performance test procedures. The effects of whole vehicle dynamics, while secondary to the suspension, also need consideration. Other recent developments have highlighted pitch dynamics of some tandem suspensions, the need to make simultaneous pavement response measurements and the need to consider the effects of all axles at particular points on the pavement. Expanded activity should be directed in three areas: the introduction of improved suspension characteristics, dynamic vehicle/suspension/pavement interaction research and a longer term commitment to ensuring that mainstream pavement design and research take account of dynamic effects.

1. INTRODUCTION

Over the past 15 years, considerable progress has been made in identifying the dynamic loadings experienced by pavements and bridges with the passage of heavy vehicles with multi-axle suspensions. Researchers have used combined experimental and theoretical (Whittemore et al. 1970; Sayers and Gillespie 1983, Gorge 1984), experimental (Leonard, Grainger and Eyre 1974; Sweatman 1983) and theoretical (Heath and Good 1984; Cebon 1985) approaches to the magnitudes and frequencies of dynamic wheel forces applied normal to the pavement surface under a variety of pavement surface roughness, bump, speed and load conditions and as dependent on suspension configuration and vehicle type. While this work has by no means provided a complete picture, the essential characteristics of these dynamic forces are now known.

The impetus for this research has come from the emergence of a new science: truck size and weight technology. The complex issues of pavement and vehicle technology, combined with safety, economic and environmental issues, which need to be addressed in setting truck limits has required a new language to provide a meeting place between the essentially static pavement technology, vehicle dynamics, accident statistics and aggregated economic data. A cornerstone of attempts to relate the essentially microscopic pavement and vehicle disciplines to the macroscopic economic discipline has been the fourth power law. This does not deal with state variables such as stresses and strains but relates the deterioration of a pavement to the number and magnitude of loads passing over it. In Australia, it has spawned the Equivalent Standard Axle (ESA), axle group load equivalency, number of ESA's to failure, etc., and similar concepts are used in other countries. The size and weight technologist wishes to know the number of ESA's per tonne payload for a particular vehicle configuration and set of limits. It is then possible to introduce complex engineering principles and design practices from different disciplines into the size and weight decision process.

While this is a great step forward, it raised arguments about the quantitative nature of the "law" which are, currently, impossible to resolve. This is hardly surprising when the "law" compresses different pavement types, failure modes, climatic effects and vehicle configurations into a single quantitative statement. The time has arrived when we can deal with a less devastatingly simple approach.

It is worth the effort. Road freight transport continues to outstrip rail in terms of cost and service. Governments are increasingly faced with decisions to liberalise and rationalize size and weight regulations and to arrive at equitable infrastructure cost recovery arrangements for the road freight industr_. At the same time, vehicles

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are becoming more diverse, particularly in terms of axle group and tyre configurations.

Research into suspension dynamics is a key element in any move beyond static concepts and the fourth power law. While controls are exercised over the static loads and, to some extent, tyres, the role of suspensions has been neglected, particularly in a regulatory sense.

It is the purpose of this paper to present Australian Road Research Board research findings on suspensions, to briefly consider other recent developments and to indicate future research needs and possible regulatory approaches.

2. ARRB SUSPENSION RESEARCH

Following a recommendation from Australia's first truck size and weight study (Economics of Road Vehicle Limits) (Fry et al. 1976), an experimental investigation of dynamic wheel forces in a number of "load-sharing" axle group suspension systems was carried out by ARRB (Sweatman 1983). Subsequently, work was undertaken in conjunction with the University of Melbourne to investigate whole-vehicle dynamics affecting dynamic road loading using a largely theoretical approach (Heath and Good 1985). This was intended to supplement the earlier work and indicate whether pavement-protecting guidelines for suspension selection should have regard to overall vehicle configuration.

2.1 EXPERIMENTAL WORK

Following the ERVL Study, a regulation was introduced which required axle group suspensions to be load-sharing, or suffer a reduced load limit. A load sharing system was defined as utilising hydraulic, pneumatic, mechanical or other means to effect substantially equal sharing of the total load and having effective damping characteristics on all axles. The government published a guide to acceptable suspension systems (ACVP 1979) and known load sharing types were listed.

However, this was clearly recognised as a first step and research into the relative pavement-damaging effects of different suspension systems, particularly with regard to dynamic loading, was required. There was concern that some "load sharing" types may increase dynamic loading due to rigid inter-axle connections and lack of damping ("effective" damping being difficult to define). ARTB researcher therefore set out to identify those axle group suspensions producing severe dynamic pavement loads. The research approach was based on the principles of:

(i) direct measurement of wheel forces under typical operating conditions,

(ii) controlled and quantifiable conditions of road surface and vehicle operation,

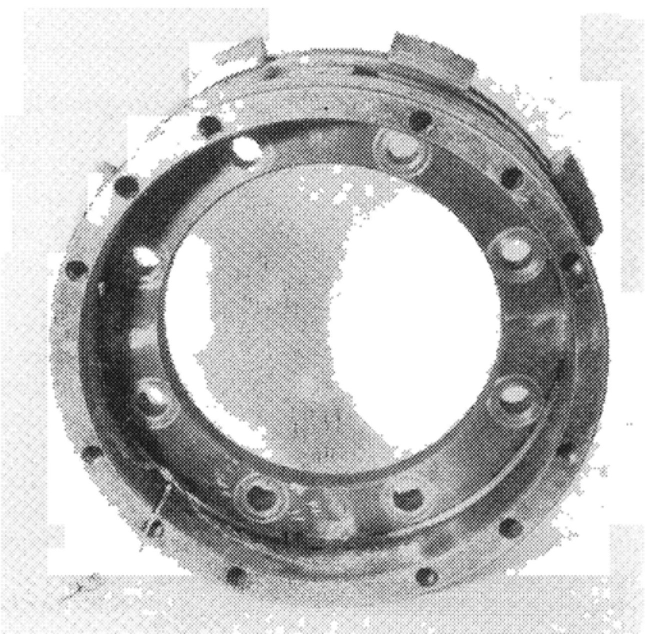
(iii) experimental design to permit valid comparisons between suspensions and subsequent advice to regulating authorities.

2.1.1 Dynamic Loading Experiments

Full details are given in Sweatman (1983). Only the essential elements are given here.

- *A wheel force transducer* (Figure 1) was obtained on loan from General Motors, U.S. It was developed by Whittemore et al. (1970) and provided excellent wheel force data.

- As an extensive test program was required for the experimental design, simple *descriptors of the dynamic wheel forces* were required and reduced to the mean and standard deviation measured at one wheel position in the axle group suspension under test. The mean value quantified the "dynamic" loading sharing, when compared to the desired equal share of the static load on the axle group. The standard deviation quantified the dynamic variation



GM wheel force transducer

FIGURE 1

about the mean, and hence the degree of impact loading.

- Figure 2 shows a typical Australian 6-axle articulated vehicle. Five tandem drive axle *suspensions* and four semi-trailer suspensions (two tandem and two triaxle) were tested in the laden condition (see Figure 3). These represented the majority of the Australian heavy truck fleet.

- A standardised method of representing the surface *roughness* of various sections of the test route was adopted. NAASRA Roughness is determined using a vehicle mounted Response Type Road Roughness Measurement System (RTRRMS), the generic type used extensively in both developed and developing countries (Gillespie et al. 1980). Calibration and inter-correlation of such meters has been the subject of extensive research and all can be related to actual profile measurements through the "quarter-car" simulation technique. Roughness on the test route ranged from as-new construction to values exceeding the desirable reconstruction limit in Australia.

- Test speeds were nominally 40, 60 and 80 km/h and the prevailing legal loads of 15 t (tandem) and 18 t (triaxle) were used.

- The experimental design was a factorial with 3 speeds, 6 road roughnesses and 2 tyre pressures.

2.1.2 Results

Mean wheel forces were converted to a Load Sharing Coefficient (LSC), defined as the mean value divided by the expected equal share of the static load. These are listed in Table 1 and show that, in general, the mean wheel force is within 10 per cent of the desired value. It was also found that minor variations in LSC occur from time to time caused by:

(i) road camber or crossfall (up to 4 per cent),

(ii) re-settling of the load sharing mechanism when the static load is altered (up to 4 per cent),

(iii) tyre pressure changes (up to 2 per cent),

(iv) shifting load distribution related to the dynamic loading history (1 per cent).

These considerations do not include the large variations caused by severe braking and high levels of tractive effort: all tests were at constant speed.

Specific instances of poor design or installation caused two suspensions (D1 and D5) to have LSC values as low as 0.79, and corresponding overloads could be expected on associated wheels within the axle group.

Dynamic wheel forces were converted to a Dynamic Load Coefficient (DLC), defined as the standard deviation divided by the mean. The data are complex, and typical results covering the extremes of performance are given in Figure 4, showing DLC versus speed and roughness for two suspensions.

Rigorous statistical analysis showed that, in terms of their sensitivity to speed and roughness effects, suspensions fall into two natural groupings. One suspension, was significantly less sensitive to changes in speed and roughness than the group of centrally-pivoted tractor suspensions (D1, D2, D4). One suspension (D5) did not fall into either group, had very high DLC values under most

Typical Australian 6-axle articulated vehicle

FIGURE 2

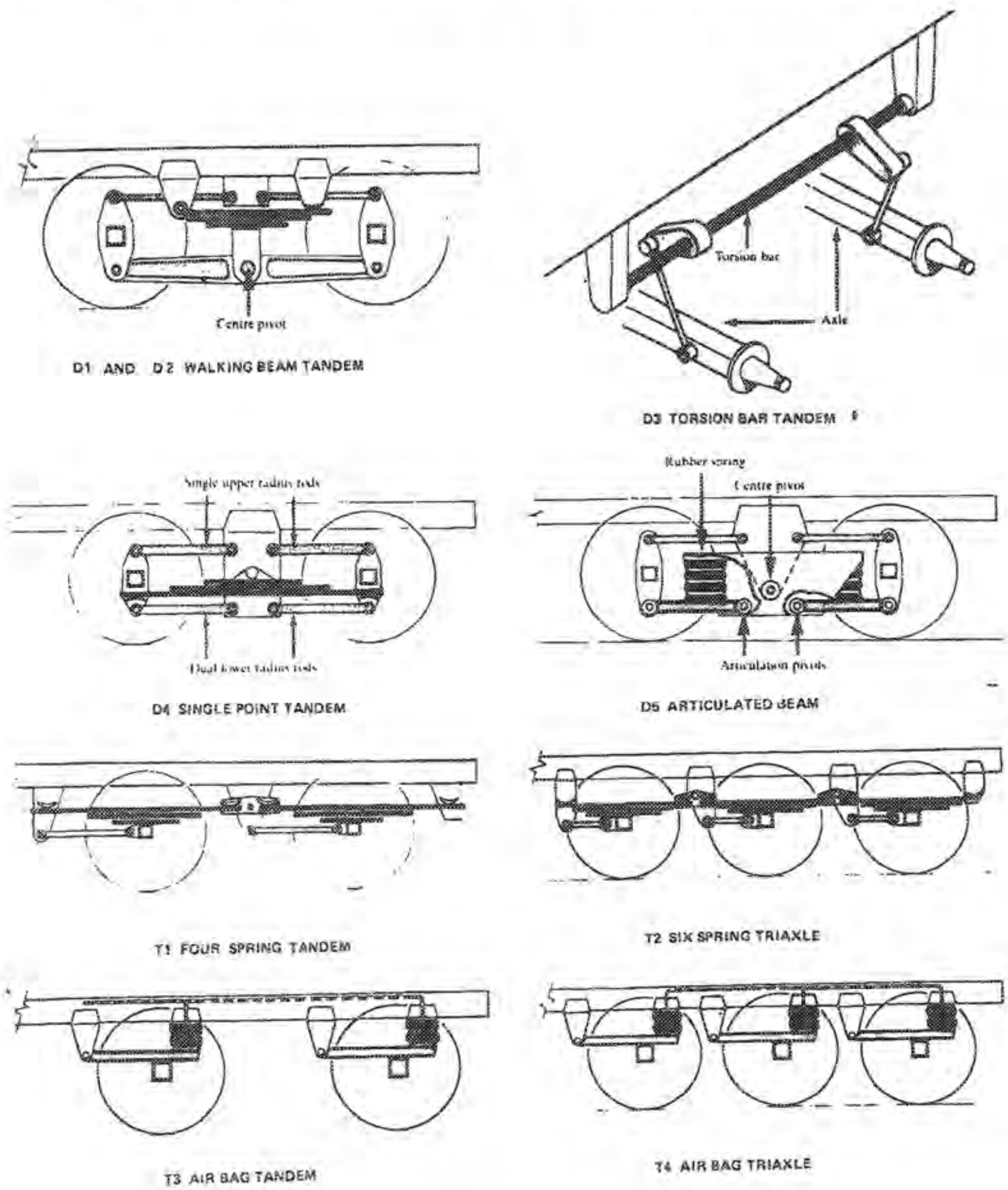
Table 1 – Mean and standard deviation of LSC for each suspension

Suspension type	Mean LSC	S.D. of LSC
D1	.791	.036
D2	.961	.010
D3	1.049	.008
D4	.983	.009
D5	.806	.009
T1	.925	.014
T2	.957	.013
T3	.904	.014
T4	.924	.012

conditions and showed a particular sensitivity to roughness. It is also a suspension which has gained poor acceptance in Australia.

The discovery of the above natural groupings greatly simplifies the ranking of suspensions: within the groups it is independent of speed and roughness, and the two groups are clearly separated for speeds above 65 km/h on roads of medium or higher roughness. Ranking was also assisted by simple and robust DLC regression equations derived for each suspension (Table 2) and involving the term VR0.5 (where V = speed in km/h and R = NAASRA roughness value in c/km).

Under criterion conditions of speed and roughness for Australian operating conditions (VR0.5 = 850), the comparable DLC values are given in Table 3 for each suspension type. It is apparent that the group of centrally-pivoted tractor suspensions is inferior to the larger group of mainly semi-trailer suspensions and that there is a wide range of variation within the centrally-pivoted group. The best of the centrally-pivoted group, the single-point 6-rod (D4), is only slightly worse than the worse semi-trailer suspension and the DLC gap between D4 and D1 is the largest. On this basis, suspensions above D4 (i.e. D1, D2 and D5) were identified as severe in a dynamic sense. Dynamic

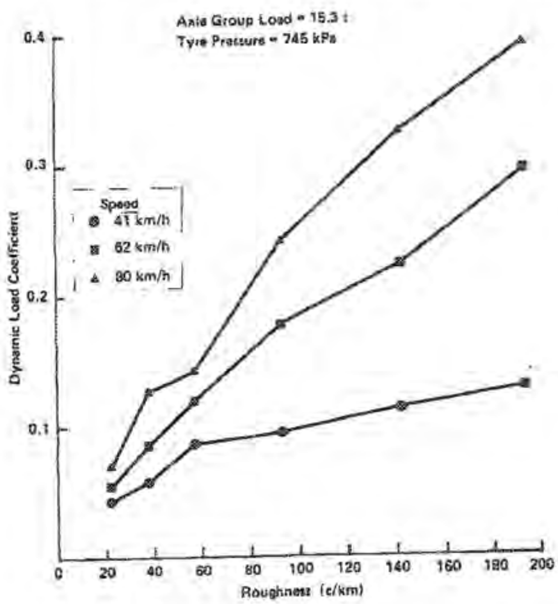


Suspension types tested by ARRB

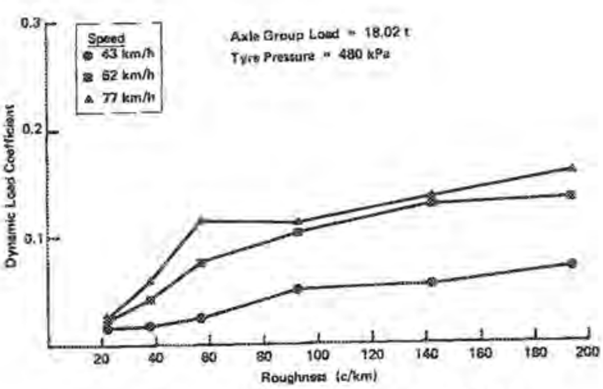
FIGURE 3

loading with all suspensions is, in absolute terms, large.

The question of the road damaging effect of dynamic loading was tentatively addressed in two ways, which could perhaps be viewed as lower and upper estimates of this effect. One approach is to apply the fourth power law to dynamic load fluctuations above and below the mean (Eisenmann 1975) and to derive a dynamic road stress factor (DRSF) in the form of a coefficient to be applied to the conventionally-determined ESA value of an axle or axle group. These coefficients are given in Table 3 and range from 1.10 to 1.16 for the superior group os suspensions and from 1.20 to 1.38 for the inferior group (suspension D5 went as high as 1.46). The upper-bound approach is to look at the high dynamic loadings occurring at specific points on the pavement. 95th percentile impact factors and their corresponding road stress factors (using a fourth power transformation) are given in Table 3. These range from 2.1 to 2.6 for superior suspensions and from 2.8 to 4.0 for inferior types (with D5 recording 4.4). Thus we can do no better than estimate that inferior suspensions do between 20 and 200 per cent more damage than superior types. Similarly, current superior types are between 20 and 200 per cent worse than a "perfect" suspension.



Suspension D5: walking beam suspension — articulated beam — Dynalastic



Suspension T4: triaxle air suspension — trailing arms

Dynamic loading (DLC) versus roughness and speed for two suspensions

FIGURE 4

2.2 THEORETICAL WORK

Models of a 6 x 4 rigid truck and a 5-axle tractor-semi-trailer have been developed (Heath and Good 1985) and preliminary results indicate that the overall vehicle configuration does have a significant effect on the DLC of a particular suspension. Simulation results for the rigid truck test vehicles used in the ARRB experimental work are given in Figure 5 and indicate that the rank order of suspensions is substantially maintained regardless of test vehicles. Further simulations

Table 2 – DLC regressions for each suspension type

$$DLC_{D1} = -0.0272 + 2.93 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.95)$$

$$DLC_{D2} = -0.0294 + 3.28 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.93)$$

$$DLC_{D3} = -0.0144 + 1.67 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.91)$$

$$DLC_{D4} = -0.0406 + 2.58 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.92)$$

$$DLC_{D5} = -0.0588 + 3.88 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.97)$$

$$DLC_{T1} = -0.0872 + 1.81 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.88)$$

$$DLC_{T2} = -0.0172 + 1.77 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.93)$$

$$DLC_{T3} = -0.0375 + 2.30 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.85)$$

$$DLC_{T4} = -0.0304 + 1.95 \times 10^{-4}\ VR^{0.50} \quad (r^2 = 0.95)$$

where the rigid truck was converted to a tractor-semi-trailer showed reductions in DLC, but the ordering of suspensions was again substantially maintained. However, we do not as yet have comprehensive validated results for the effects of vehicle configuration parameters. Indications are that the effects of wheelbase, pitch moment of inertia and sprung mass centre-of gravity longitudinal location are fairly minor.

Simulation of the suspensions themselves shows a strong beneficial effect of auxiliary dampers on suspensions D1, D2 and D5, and relatively minor effects of spring stiffness, inter-leaf friction and tyre stiffness for suspension D1. However, these results are again preliminary and further work is proceeding.

3. RECENT DEVELOPMENTS

The author is aware of considerable research underway in a number of countries studying suspension performance, road loading and consequent pavement damage effects. There are also recent instances of suspension-specific load limits in several countries where higher loads are permitted on suspensions with superior dynamic performance, usually air suspensions. There is considerable interest in trying to regulate suspension performance in the context of size and weight economics and, in Australia, a draft design rule has been prepared for the Federal Department of Transport.

Sayers and Gillespie (1983) have reported road testing and simulation of three tractor suspensions which had been identified as representing the spectrum of suspension performance quality in the ARRB work. The trend of the ARRB results was confirmed and the lightly-damped pitch mode of the walking-beam suspension was identified as a major contributor to dynamic loading. Other effects of tyre bounce and axle group wheelbase filtering of the profile input were also identified. One interesting variation from the ARRB work was in the interpretation of road roughness. Gillespie and Sayers consider it a profile/speed property rather than a pavement property and effectively remove the speed effect discussed in Section 2. However, the notion of roughness as a unique pavement profile characteristics is familiar to the road community and is required if dynamic loading results are to interface with size and weight economics models (which use roughness as the prime indicator of road network utilization) and are to relate to reconstruction criteria for highways.

Under joint sponsorship from government and industry, a major study of improved truck characteristics with regard to pavement damage is being carried out in the Federal Republic of Germany. The research is being done cooperatively by road and vehicle institutes. The program ranges through conventional pavement response-to-load testing, simultaneous measurement of dynamic wheel loads and dynamic pavement response and measurement of lateral force effects on a circular test track. In the second stage of this work, it has been shown (Gorge 1984) that a 10 t single axle with improved suspension (including damping) generates peak loads comparable to those of a conventional 11 t axle. It has also been demonstrated that the road responds to dynamic loadings. In recommending suspension quality implementation the two extreme approaches of Section 2 are used in different contexts: in justifying higher loads on improved suspensions, extreme dynamic loads are equated while the dynamic road stress factor approach is advocated for economic evaluations.

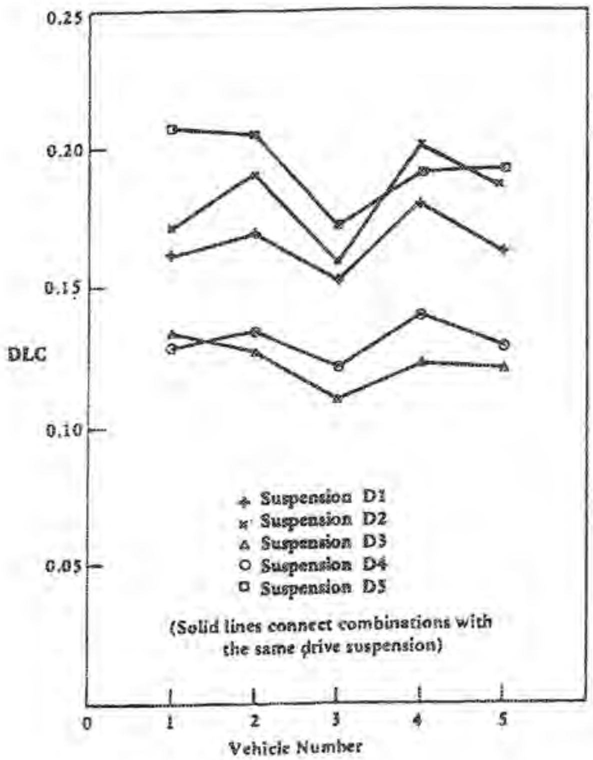
Table 3 – Comparison of dynamic loading between suspension types

Suspension type	Reference DLC1	Dynamic road stress factor	95th percentile: Impact factor	95th percentile: Road stress factor
D1	.222	1.30	1.37	3.47
D2	.249	1.38	1.41	3.95
D3	.127	1.10	1.21	2.14
D4	.179	1.20	1.29	2.81
D5	.271	1.46	1.45	4.37
T1	.163	1.16	1.27	2.59
T2	.133	1.11	1.22	2.21
T3	.158	1.15	1.26	2.52
T4	.135	1.11	1.22	2.23

1 Computed for operating conditions $VR^{0.50} = 850$ (V km/h; R c/km)

A significant departure in approach is used in recent research by Cebon (1985) in the United Kingdom where the dynamic loads exerted by all wheels are considered. Mathematical models of the vehicle, including the suspension, and the roadway response have been brought together for the first time. However, estimates of the damaging effect of dynamic loading again vary by an order of magnitude: pavement fatigue consideration indicate pavement life reductions down to one fifth or one sixth of that associated with a "perfect" (non-dynamic) axle group while permanent deformation considerations indicate pavement life reduction to approximately two thirds the non-dynamic case.

Cebon's combined vehicle and pavement model computes the successive forces applied to each point along the pavement profile by the passage of successive axles. The net effect of these forces at particular points on the pavement depends not only on suspension dynamic quality (i.e. the level of dynamic variation at a particular axle) but on the speed, inter-axle spacing in a group and on whole-body effects involving tractor or trailer pitch, relevant suspension properties and wheelbases. For particular speeds of travel, net dynamic



Effect of test vehicle on suspension ranking (after Heath and Good 1985)

FIGURE 5

effects in excess of those on individual axles are obtained. At low speeds, around 40 km/h, suspension and tractor pitch modes predominate, while at high speeds, around 110 km/h, semi-trailer pitch is predominant.

In addition to the above reported investigations, related work is currently underway in several countries. Dynamic wheel load measurements are being made under the Roads and Transportation Association of Canada's Vehicle Weights and Dimensions Study, and these are being related to pavement response measures. Similar work is being done at the Transport and Road Research Laboratory in the U.K. and comparative tests of passenger coaches and heavy trucks have been done by FHWA in the U.S.

A personal view of the major contributions to dynamic suspension and pavement research is summarized in Table 4. A number of other studies of either suspension or pavement have of course been carried out and there is a large body of research into pavement response to load as well as pavement performance under load (for example the use of accelerated loading facilities).

4. FUTURE DIRECTIONS

There is a need to expand activity into at least three areas:

(i) the introduction of improved suspension characteristics,

(ii) dynamic research involving vehicle, suspension and pavement (Table 4 indicates that this is beginning to happen),

(iii) a longer-term commitment to improving on the fourth power law.

These areas all need to be addressed if we are to cope with future truck size and weight options and appropriate cost recovery measures.

4.1 IMPROVING SUSPENSION CHARACTERISTICS

We have seen that the contribution of dynamic suspension characteristics to pavement wear-and-tear appears to be at least significant and could be critical. We have also seen that there is a wide variation in suspension performance, and, in Australia, some types have been identified as severe in their characteristics.

Table 4 – Summary of dynamic suspension/pavement research

Source	Dynamic load measurement: Vehicle	Dynamic load measurement: Pavement	Dynamic modelling: Vehicle	Dynamic modelling: Pavement	Parameters	Pavement damage approach	Prime output	Implementation emphasis
Whittenmore et al. (1970) (U.S.)	wheel transducer		suspension		pavement profiles		methods and typical data	highway load prediction
Leonard et al. (1974) (U.K.)		electronic scale			bumps		tandem dynamics	effect of gross weight
Sweatman (1983) (Aus.)	wheel transducer				RTRRMS roughness	• factored 4th power • 95th percentile 4th power	suspension ranking plus performance test	suspension controls
Sayers and Gillespie (1983) (U.S.)	wheel transducer		suspension		pavement profiles		validated suspension models	suspension design
Heath and Good (1984)(Aus.)			suspension/ vehicle				whole vehicle effects	suspension controls
Gorge (1984) (Germany)	wheel transducer	strains	suspension			factored 4th power	pavement strains under dynamic loads	more productive vehicles plus suspension-specific load limits
Cebon (1985) (U.K.)	strains for model validation		suspension/ vehicle	visco elastic beam	pavement profiles	• aggregate force • fatigue • permanent deformation	integrated vehicle/ suspension/ pavement model	more productive vehicles
Woodrooffe and Christison (current)(Canada)	strains	strains					pavement strains under dynamic loads	uniformity of suspension acceptance
Mitchell and Addis (current) (U.K.)	laser transducer		strains				pavement strains under dynamic loads	

Axle loads and tyres are controlled in most countries, yet the suspension tends to be neglected. It has already been mentioned that some countries allow higher loads on air suspensions, yet this is not necessarily supported on pavement damage grounds and is design-restrictive. The introduction of a performance test would ensure the removal of the worst characteristics and would be fair to operators of non-air suspensions with acceptable characteristics.

Another important advantage of performance-based suspension controls is that the important safety aspect of suspension design can be included. Suspensions have a major effect on roll stability, handling and braking.

The various options for suspension control are:

(a) a laboratory test and/or computer simulation

(b) a road test measuring pavement response instead of wheel forces,

(c) higher load limits for specific suspensions (eg. air suspension),

(d) a tax related to the road damage of the suspensions,

(e) a road test measuring wheel forces.

Each of these possibilities will be considered in turn.

4.1.1 Laboratory Test or Computer Simulation

It may be possible to formulate dynamometer, bump, or drop tests, or perhaps a shaker or suspension test rig (Winkler and Hagan 1980) to measure suspension performance. The difficulty here is to relate test results to on-road performance. This constitutes a substantial research task in itself.

Computer simulation is favoured by some manufacturers. Some model development has already been undertaken (Heath and Good 1985; Sayers and Gillespie 1983) but extension of this work to cover a broad range of suspensions and to validate the models is, again, a substantial research task.

4.1.2 Instrumented Pavement

One major suspension manufacturer has suggested the use of an instrumented pavement section so that manufacturers simply test candidate suspensions on non-instrumented vehicles. Such pavement sections, near Ipswich, Queensland, were used recently in ARRB's study of wide single tyre effects (FS 1137). The current Roads and Transportation Association of Canada's study of truck size and weight is carrying out this type of suspension test, in conjunction with instrumented vehicle tests as called for in the type of road performance test under consideration in Australia.

This method has the advantage of: (i) direct measurement of pavement effects, and (ii) reduced burden on manufacturers. Some further research would be needed to establish test requirements, although the Canadian research, in which ARRB is cooperating, will be helpful. Disadvantages of the method include the variety of pavement types in use and measurement difficulties including temperature effects in the pavement. It would also be difficult to formulate on an international basis.

Another related possibility is the use of a weight-in-motion (WIM) system together with a perturbation to excite the suspension. The viability of this method depends on the type of WIM system used and research to determine the appropriate type of perturbation needed.

4.1.3 Suspension - Specific Load Limits

The approach taken in Germany and Belgium, with perhaps other European countries to follow, is to allow higher loads on certain suspension types in specific instances. In Germany, passenger coaches are allowed 11 t instead of the regulation 10 t on air suspended axles. In Belgium, air-suspended triaxles are permitted 24 t instead of the regulation 21.5 t.

The difficulties with this method in the Australian context are that it is design restrictive and that weight-of-load enforcement officers have difficulty in differentiating suspension types. However, the trade-off between load and suspension quality is a valid one. A similar effect is being achieved through a different approach in the U.K.: axles are weighted and prosecuted individually for triaxle groups, leading to a trend to the use of air suspensions.

4.1.4 Suspension Tax

It has been suggested that operators of suspensions with poor characteristics pay for additional road damage in the form of a tax or similar charge. This approach would have the effect of being design restrictive, more complex than other approaches in ranking suspensions and estimating relative damaging effects and more complex to formulate and administer.

4.1.5 Road Performance Test

Some consideration has been given to the introduction of such a performance test in Australia. It is entitled Draft Australian Design Rule (ADR) B6 and is based on the results of ARRB research.

The draft rule aims to limit loading under typical road and speed conditions and, for semi-trailer suspensions, a range of fifth wheel coupling heights. It involves a road test plus a static axle-raising test; instrumentation is needed in the road test to measure the force in one wheel. Selection of the test road and speed and data analysis are straightforward and involve particular speed and roughness combinations and calculations of DLC and LSC values. Criteria are selected to exclude severe suspension types. There are no restrictions on the test vehicle to which the suspension is fitted and the test and consequent approval apply to the suspension, not the vehicle. The draft rule applies to suspensions used on heavy vehicles and trailers with a maximum mass greater than 10 t.

The performance test centres on the ability of the measured wheel force to meet certain criteria. The draft rule therefore directly addresses the influence of the suspension on the road by measuring the intervening quantity - the wheel force. This is measured using an instrumented wheel or axle; the former is available primarily through research organisations while the latter is a low-cost method available to manufacturers or consultants.

Selection of test roads is made using a vehicle-mounted roughness meter, for which there is a NAASRA standard practice. Such vehicles are available in all States and State Road Authorities (SRA's) maintain inventories of roughness in their networks. Advice can be sought from SRA's as to the location of candidate road sections, and the roughness checked, as required in the draft rule, using a roughness vehicle.

Contrary to some beliefs the performance tests in the draft rule will not only challenge centrally-pivoted tandem drive axle suspensions, but also six-spring triaxle suspensions with short rockers. The eventual impact on the Australian truck fleet would be widespread.

To a large extent, drive axle suspensions on rigid trucks and prime movers are designed and manufactured by specialised suspension manufacturers who operate internationally. This is not the case for semi-trailer suspensions which are largely designed and built by domestic trailer manufacturers. Thus it could be expected that a design rule would immediately affect drive axle suspension usage (i.e. truck manufacturers' selection of alternative currently available suspensions) and trailer suspension designs. There are, however, a number of overseas truck manufacturers. Industry acceptance of the rule would depend on its compatibility with suspension regulations in major world markets. Some broad agreement as to the most appropriate form of suspension performance test would be a useful outcome of the International Symposium on Heavy Vehicle Weights and Dimensions.

4.2 SUSPENSION/PAVEMENT RESEARCH

There is a need for a genuine fusion of pavement and vehicle research interests. Much of the work to date has been a demonstration of dynamic effects on pavements, rather than systematic investigation. There is also a large gap between the factored fourth power law approach (dynamic road stress coefficient) used in economic studies and the arguments used to justify higher loads on certain suspension types. The underlying estimates of the dynamic effect are on order of magnitude different.

As we move further and further in time and technology from the AASHO Road Test, it becomes increasingly difficult to equate vehicles with different number axles and different loads, suspensions and tyres to those vehicles which were involved in the AASHO pavement performance tests. This is usually done by relating pavement response under a candidate vehicle to that under an AASHO axle, under unrealistic creep-speed conditions. Unfortunately, when one attempts to carry out these response comparisons under realistic operating conditions, suspension and other factors intervene.

Simultaneous measurements of dynamic wheel loads and dynamic pavement responses are needed which will allow study of the effects of the following parameters: vehicle configuration; axle groups; suspension types; tyres; road roughness; speed; and load

As far as the vehicle is concerned, measurements are needed on all axles. For the pavement, response measurements must allow for the effect of lateral position on the roadway, should involve standardised transducers (the OECD Road Research Program has recently investigated this) and should relate to fatigue and permanent deformation criteria for various pavement types. Such responses should also relate to those determined in accelerated loading pavement performance tests and repeated loading laboratory tests of pavement materials.

4.3 IMPROVING ON THE FOURTH POWER LAW

The fourth power law is an invaluable concept and we should not abandon it. Rather, we should seek to work towards a clearer recognition that such a far-reading relationship involves two parts: pavement response to the vehicle and pavement performance.

We should look to the mainstream of pavement design and research, both to influence it to take better account of pavement dynamic response to multi-axle vehicles and to obtain on indication of where we are headed. There are three major strands to consider:

(i) mechanistic pavement design, which seek to predict response to load and, through models such as VESYS, predict performance,

(ii) accelerated loading facilities which relate response to performance under accelerated loadings, and

(iii) long term monitoring under traffic.

We can expect to see considerable activity under (i) and (ii) in the immediate future and, particularly with the U.S. Strategic Highway Research Program, a longer term commitment to pavement monitoring. Of these, only pavement monitoring includes dynamic effects, yet pavement technology will rely on mechanistic design and accelerated load testing for the immediate future. It is therefore important to bridge a dynamic influence to bear in these areas.

5. CONCLUSIONS

(i) Truck size and weight studies need methods to assess relative pavement damaging effects of different vehicle, suspension and tyre configurations.

(ii) Research has identified dynamic loading related to suspensions and has ranked suspensions in this regard.

(iii) The damaging effect of the dynamic component of loading on pavements is not precisely known, but is at least significant and could be crucial.

(iv) Dynamic suspension characteristics need to be improved and a regulation based on a performance test should be introduced.

(v) Interaction between pavement and vehicle researchers is needed to study the dynamic response of vehicle, suspension and pavement.

(vi) In the longer term, pavement design and research, particularly mechanistic design, models and accelerated loading trials, shold account for dynamic effects.

6. REFERENCES

Advisory Committee on Vehicle Performance (1979). A guide to heavy vehicle suspension systems and acceptable axle groups. AGPS, Canberra.

Cebon, D. (1985). An investigation of the dynamic interaction between wheeled vehicles and road surfaces. Ph.D. Thesis, University of Cambridge, U.K.

Eisenmann, U. (1975) Dynamic wheel load fluctuations - road stress. Strasse und Autobahn, 4 pp. 127-8.

Fry, A.T., Easton, G.R., Ker, I.R., Stevension, J.McL. and Webber, J.R. (1976). A study of the economics of road vehicle limits: evaluation and conclusions. NAASRA ERVL Report R2.

Gorge, W. (1984) The influence of commercial vehicle development and design on road fatigue. International Road Transport Union, Geneva.

Heath, A. and Good, M. (1985) Heavy vehicle design parameters and dynamic pavement loading. Australian Road Research Board Internal Report AIR 387-1.

Leonard, D.R., Grainger, J.W. and Eyre, R. (1974). Loads and vibrations caused by eight commercial vehicles with gross weights exceeding 32 t. TRRL Lab. Rep. LR582.

Sayers, M. and Gillespie, T.D. (1983) Dynamic pavement/wheel loading for trucks with tandem suspensions. Proc. 8th IAVSD Symposium, MIT, 15-19 August, pp. 517-533.

Sweatman, P.F. (1983). A study of dynamic wheel forces in axle group suspensions of heavy vehicles. Australian Road Research Board Special Report 27.

Whittemore, A.P., Wiley, J.R., Schultz, P.C. and Pollock, D.E. (1970). Dynamic pavement loads of heavy highway vehicles. NCHRP Report 105.

Winkler, C.B. and Hagan, M. (1980). A test facility for the measurement of heavy vehicle syspension parameters. SAE Paper 800906.

SESSION 3
VEHICLE STABILITY 1

Chairman:

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