Heavy vehicle suspension performance and road wear

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Introduction

Before looking at the relationship between suspension performance and hence dynamic vehicle loads and road wear, it is worth reviewing the currently used relationships between applied loads in the form of vehicular traffic and pavement performance. A pavement manager (such as Transit New Zealand, or a local authority, or a forest owner) plans on the basis of projections of future traffic flows which consist of a mix of vehicle types and weights. To simplify these data, they are converted to an equivalent number of standard axle loads. This is done on the basis of the so-called "fourth power rule" which says that the amount of road wear caused by the passage of an axle is proportional to the fourth power of its static load. To show how this works, consider a single axle on dual tyres. In New Zealand, the standard axle of this configuration carries 8.2 tonnes. The same configuration carrying 6.15 tonnes would be considered to be $(6.15/8.2)^4 = 0.31$ of a standard axle, while the same axle carrying 10.25 tonnes would be deemed to be 2.44 standard axles. Other configurations such as single tyres and tandem axles have different reference loads but the same principle is applied. This "fourth power rule" also forms the basis of the scale of road user charges in New Zealand.

So where does the "fourth power law" come from? A series of full scale (real trucks on real roads) pavement tests were conducted in the United States in the 1950s culminating with the AASHO (1962) road test. In this test 644 different pavement sections spread over six test loops each of two lanes were subjected to continuous repeated loadings. Each lane was loaded with only one vehicle and load configuration. Thus it was possible to compare the performance of identical pavement sections where the only difference was in the applied loadings. From the results of these experimental tests, the "fourth power rule" was derived.

Although this "fourth power rule" is widely used in New Zealand it is worth noting that the thin-surface chipseal pavement which is very widely used in the New Zealand highway network was not properly tested in the AASHO test. In terms of the topic of this paper, the AASHO test included dynamic loads because the loading was done with real vehicles but these were not quantified and no attempt was made to identify their effect.

Suspensions and dynamic wheel loads

Starting in the late 1960s but primarily in the late 1970s and 80s, a number of researchers (Sweatman, 1983, Hahn, 1985, Woodrooffe et al 1986, Mitchell and Gyenes, 1989) started measuring dynamic wheel forces on heavy vehicles and comparing suspension performance. To characterise a suspension's dynamic wheel force behaviour, a measure called *dynamic load coefficient* (dlc) was defined as,

$$dlc = \frac{\text{standard deviation of wheel load}}{\text{static wheel load}}$$

Using this measure a heavy vehicle's suspension performance under given test conditions can be represented by a single number. The distribution of wheel forces was shown to be approximately normal and so that 65% of the time the wheel forces will be within (1 ± dlc) static loads, 95% of the time within (1 ± 2dlc) static loads and 99% within (1 ± 3dlc) static loads.

As these researchers operated in different countries under different test conditions it is not possible to compare results in detail but generally the findings are consistent. Key points are:

- dynamic wheel forces increase with vehicle speed and road roughness. On very smooth roads there is not much difference in performance between "good" and "poor" suspensions because neither of them are required to do much work.
- centrally pivoted tandem drive axles, such as "walking beams" and "single point suspensions" generate the highest dynamic loads because of their lightly damped axle tramp modes, although one researcher found these could be improved significantly by suitable use of hydraulic dampers.
- "four spring" tandem suspensions generally performed better than walking beams with air and torsion bar suspensions producing the lowest dynamic loads.
- modern single-spring parabolic suspensions with good hydraulic damping are "not significantly worse" than stiff air suspensions.
- poorly (or un-) damped air suspensions can generate dynamic loads which are significantly higher than those produced by steel suspensions.
- lower tyre pressures usually result in lower dynamic wheel loads, though very low pressures as used off-road in logging applications have not been investigated.
- in several studies tridem suspensions were better than tandems.
- dlc values at highway speed ranged from 0.05 for a good suspension on a smooth road to 0.35 for a poor suspension on a rough road. On a medium roughness road, dlc values vary approximately between 0.07 and 0.21 depending on suspension.

Dynamic wheel loads and pavement wear

Having established that different suspensions generate different levels of dynamic loading the next question is; "What impact do these levels of dynamic loading have on pavement wear?". The most widely used estimate is a theoretical one developed by Eisenmann (1975). He assumed that the "fourth power rule" applies and that the dynamic wheel forces are randomly distributed. On this basis he calculated that amount of road wear that could be attributed to dynamic loads in the form of a dynamic road stress factor, v which is given by the equation,

$$\upsilon = 1 + 6dlc^2 + 3dlc^4$$

This factor is applied to the amount of wear caused in the theoretical case when there is no dynamic loading to give the actual wear. To understand the implications of this factor consider two suspensions which under identical operating conditions generate dlc values of 0.1 and 0.2 respectively. (These values would be reasonably typical on a road of medium roughness for a "good" and a "fair" suspension. They do not represent extreme values.) The corresponding dynamic road stress values are 1.06 and 1.245. This suggests that the poorer suspension would do 17.4% more damage to the pavement than the better one.

The two assumptions from which this factor is derived are the subject of debate. The "fourth power rule" has been contentious for many years and different powers (some higher and some lower) have been postulated for different pavement failure mechanisms. The other assumption, that the dynamic wheel loads are randomly distributed is more straightforward. There have been suggestions that dynamic loading patterns are repeated along the road with some sections of pavement receiving consistently higher loads. This is currently being investigated by researchers and the early indications are that variations of ±20% occur in the average loads seen by sections of pavement along the road. The implication of this is that the road wear attributable to dynamic loads is greater than predicted by the dynamic road stress factor and thus the potential savings are higher.

Other issues related to dynamic loads

As well as the benefits to the highway network there are other potential benefit to transport operators through the use of more "road-friendly" suspensions. Some of the evidence for these benefits is anecdotal and they have not all, as far as I am aware, been scientifically proven.

The first of these is reduced cargo damage. There have been a number of studies in this area relating to bruising of fruit , for example, and there is clear evidence of the benefits of using better suspensions. In this sector of the transport industry, this benefit alone can be sufficient economic justification for using a "road-friendly" suspension.

There have been reports from operators of decreases in tyre wear with the introduction of air suspension to their fleets and it has been suggested the these savings alone can repay the extra cost of the suspension within a few years. This evidence has not been rigorously documented but there are obvious reasons why this could occur. Air suspensions have better load sharing characteristics than steel and generate lower dynamic loads. As these loads all act through the tyres, the tyres also are received lower levels of load cycling.

There are also reports from manufacturers of lower warranty repairs when air suspensions are fitted. Again there is no hard evidence for this claim but it is easy to see why it might be so. The wheel forces are transmitted to the vehicle chassis through the suspension and so lower dynamic loads will mean lower levels of load cycling at the suspension attachments and longer fatigue life.

Policy options

It is generally accepted that some suspensions generate lower levels of dynamic load and hence road wear than others. Thus it is in the interest of pavement managers to encourage the use of these "road-friendly" suspensions. In determining policies for doing this they are faced with two issues. The first is how to determine the "road-friendliness" of a suspension or vehicle-suspension configuration. The second is quantifying the pavement wear which could be attributed to suspensions so that appropriate incentives can be offered. Neither of these has been resolved, but research initiatives, which will be described in the next section, are in progress to address these issues.

It is possible to broadly estimate the scale of the potential benefits. Transit New Zealand (1991) in 1990-91 spent $340M on road maintenance excluding safety work. While this is not all traffic related, a substantial portion of it is. If the "fourth power rule" or some similar relationship is valid, the bulk of the traffic related pavement wear can be attributed to heavy vehicles. The New Zealand heavy vehicle fleet is predominantly fitted with suspension types which would not be classed as "road-friendly". Using dynamic road stress factor values, a reduction in pavement wear of around 15% or more could be achieved by converting these vehicles to more "road-friendly" suspension types. Even if only half the fleet were converted, savings of tens of millions of dollars per annum could be realised. There are some assumptions in this analysis but clearly the scale of the benefits is large.

In spite of not having very good means of assessing "road-friendliness" a number of policy initiatives have been tried internationally to encourage these suspensions. The simplest approach which has been tried in Belgium, for example, is to grant higher allowable static axle loads to specific types of suspension, in this case air. The basis for this is that the research findings all found air suspensions to be generally better than steel. The weakness of this type of policy is that it discourages innovations with other suspension types and places no performance requirements on the approved types. It is possible to have an air suspension perform poorly if the damping is inadequate. However, this policy would still give that suspension special status.

A slightly more sophisticated approach is that of the EC (Council of the European Communities, 1992) "equivalent-to-air" regulations. These specify that a suspension will be classified as "equivalent-to-air" and hence entitled to higher allowable axle loads if it meets certain design parameters. This approach is better because it allows other suspension types to qualify for the benefits. Its weakness is that there is no direct link between the design parameter values and the on-road performance.

In both these instances, the incentive offered to users is higher allowable axle loads. In New Zealand we have opportunities through the road user charges system to offer benefits directly back to the users in a way that is not possible in these other countries. However, to do this effectively the two fundamental issues need to be resolved.

Research initiatives

The two fundamental issues identified in the previous section are being addressed by researchers both in New Zealand and internationally. In New Zealand there are two major projects (de Pont and Pidwerbesky, 1994) in progress to address these issues.

The first project is being carried out at Industrial Research Ltd in Auckland and is funded through Transit New Zealand and the Public Good Science Fund (PGSF). It is developing methods for assessing the "road-friendliness" of suspensions using a servo-hydraulic shaker facility to replicate the on-road behaviour of the suspension. With this approach most of the instrumentation needed to measure the wheel forces can be located on the facility and not on the vehicle thus simplifying the testing procedure. By using a laboratory based facility, the variability inherent in using in-service roads can be eliminated and thus the test should be repeatable and transferable. The first stage of this project was to measure dynamic wheel forces during road trials and to see whether by matching suspension displacements on the servo-hydraulic rig, the same wheel forces could be measured. This was successfully undertaken for a vehicle with a steel four-spring suspension. The tests were then repeated for the same vehicle fitted with an air suspension. Interestingly the dynamic wheel forces measured on this vehicle were not significantly lower than those recorded with steel suspension. It is suspected that this is due to poor damping but this is still being investigated. This reinforces the earlier comment that a generic type approval approach risks giving benefits to suspensions which do not warrant them. The original shaker rig generated a good match of on-road suspension deflections but a poor match of the wheel forces. The shaker rig has been modified and a good correspondence between the road and laboratory measured forces has been achieved. Figure 1 shows a sample of the suspension deflection comparison and figure 2 a sample of the wheel force comparison for the air suspension.

The next stage in this project is to develop methods of generating the appropriate shaker excitation signals from the road profile information without having to road test the vehicle. This work is described in more detail by de Pont (1992, 1993)

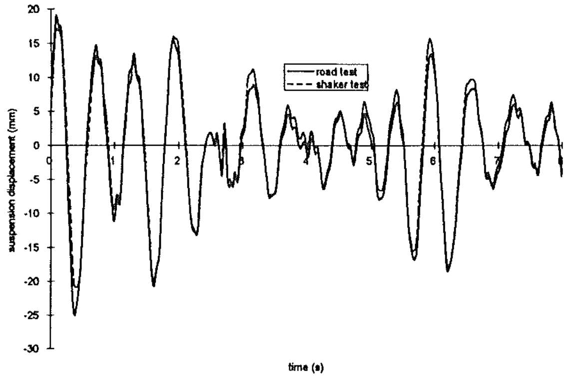

Figure 1. Comparison of suspension deflections

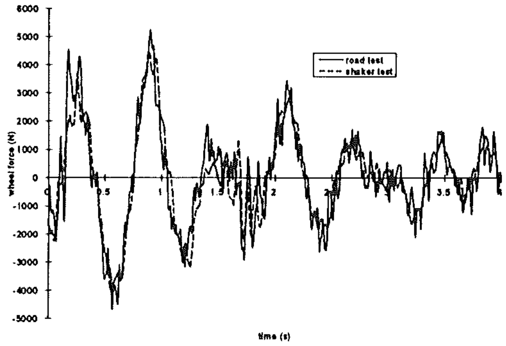

Figure 2. Comparison of wheel forces

The second project is being carried out at the Canterbury Accelerated Pavement Test Indoor Facility at Canterbury University. This is being undertaken jointly by Canterbury University and Industrial Research Ltd and is also funded through Transit New Zealand and the PGSF. CAPTIF consists of a 58 m long circular track contained within a 1.5 m deep x 4 m wide concrete tank so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame which can move horizontally by 1 m. This radial movement enables the wheel paths to be varied. At the ends of this frame, two radial arms connect the "vehicles" to the frame. These arms are hinged in the vertical plane so that the "vehicles" can be removed from the track during pavement construction, profile measurement etc. and in the horizontal plane to allow vehicle bounce. The "vehicles" consist of an axle-wheel assembly with a hydraulic drive motor attached which is connected by a suspension system to a frame on which weights are hung. As much as possible these "vehicles" use standard heavy vehicle components. For this project, CAPTIF has been modified so that different suspensions can be fitted. The project compares pavement performance throughout its life when subjected to different dynamic loads by different suspensions. The first test in this programme compared a parabolic leaf spring with hydraulic dampers with a multi-leaf steel spring on a typical New Zealand style thin-surface pavement. Some interesting results have emerged showing, for the first time ever, a direct correspondence between dynamic load peaks and pavement damage locations. Figures 3 and 4 show these results.

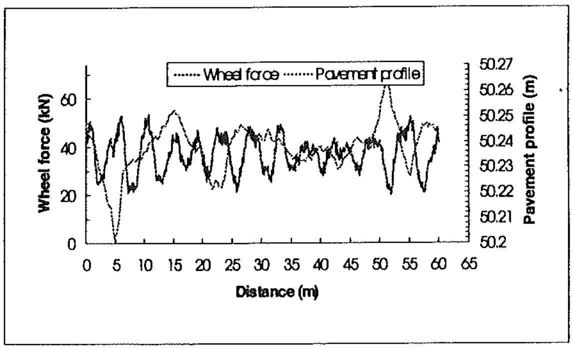

Figure 3. Wheel forces vs pavement profile for multi-leaf spring

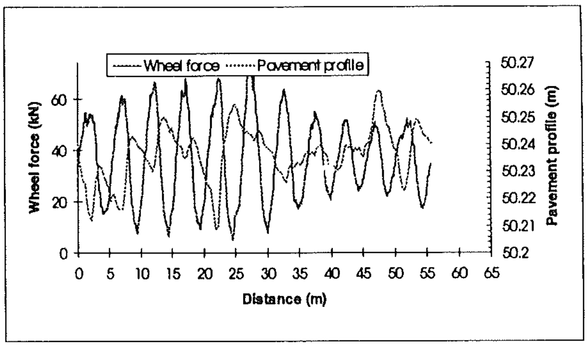

Figure 4. Wheel force vs pavement profile for parabolic spring

The next test in this programme is being undertaken as part of an OECD international cooperative research programme. It compares the performance of an air suspension with hydraulic damper with the traditional multi-leaf steel spring on a thicker asphalt pavement which is a compromise between the thin surface structures used in New Zealand and Australia and the thick asphaltic concrete structures used in Europe and North America.

The need for research to resolve these fundamental issues was recognised by an OECD Scientific Expert Group on dynamic loading of pavements (OECD, 1992) who recommended an international cooperative research programme. This programme which consists of six research elements is currently underway. The first and largest research element is an accelerated pavement test which is being undertaken at CAPTIF in New Zealand. Element two is looking at pavement response to dynamic loads using instrumented sections of pavement and subjecting them to loading with instrumented vehicles. Element three is using a large scale servo-hydraulic facility to simulate on-road vehicle behaviour. This has a lot in common with the first New Zealand project described above and close cooperation exists. The fourth research element is assessing the performance of the various computer simulation models to see how well they can model real vehicle behaviour. Element five is investigating the spatial concentration of dynamic loading on in-service roads under normal traffic and element six is investigating the interaction between vehicle dynamics and bridge dynamics. The New Zealand researchers involved in the two local projects are directly involved in the OECD programme and so very strong links exist between these projects and the international programme.

Conclusions

Dynamic wheel loads from heavy vehicles contribute significantly to pavement wear. There are opportunities to reduce the effects through the use of more "road-friendly" suspensions. These suspensions have other benefits for the operator which may in some cases be sufficient to justify their use. There are gaps in our knowledge on how to assess the performance of these suspensions and how to quantify the benefits. Research is being undertaken both in New Zealand and internationally to address these issues.

Acknowledgements

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