ROAD FRIENDLY SUSPENSIONS
HOW CAN THEY SAVE

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How much can they save?

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Introduction

As a vehicle proceeds it applies loads to the pavement which generate road wear. These loads vary dynamically in a way which is determined by the response of the vehicle and its suspension to an excitation which depends on the road profile and the vehicle speed.

In the late 1950s a major study was undertaken by the American Association of State Highway Officials (AASHO) [1] to investigate the relationship between vehicle loads and pavement wear. This experiment used six pavement test loops each of two lanes comprising a total of 644 test sections. Each lane was subjected to repeated loading by a single vehicle type with one load condition. At fortnightly intervals data were collected on accumulated axle load applications, environmental conditions, and types and magnitude of pavement distress. Extensive analysis has been undertaken on these data and is continuing even today. Probably the best known result of this analysis is the fourth power law which states that the amount of pavement wear attributable to a vehicle is proportional to the fourth power of its axle loads. This formula is based on a measure of pavement wear called the pavement serviceability index (PSI) and a statistical fit between this and the loading data. Although this result has been the subject of considerable debate for many years it is widely used in pavement design and in New Zealand it forms the basis of the road user charges approach to highway funding. Criticisms of the fourth power law range from fundamental issues of the original experimental design, such as the construction of the test pavements, the validity of using repeated applications of an identical loading, and the timing of the tests in relation to the environmental conditions (testing began in spring), to issues of data interpretation such as the relevance of PSI as a measure of pavement distress and more recently factors such as changes in pavement construction and vehicle design.

The AASHO study did not consider dynamic effects. Although not specified the vehicles appear to have been fitted with steel leaf springs and, in the case of the tandem axles, walking beams. Clearly as dynamic effects were present during the study, the pavement wear data include them but it is not possible to separate the contribution of the dynamic loading component from that of the static. Thus the fourth power law includes the dynamic behaviour of typical suspensions of the late 1950s.

In the late 1960s attempts were made to measure the dynamic wheel forces imparted by a vehicle to the pavement [2]. Following this a number of studies [3],[4],[5] were undertaken to investigate the relationship between dynamic wheel forces and suspension configuration, road roughness, vehicle speed, tyre pressure and other factors. To characterize dynamic wheel force behaviour under particular test conditions a measure known as the dynamic load coefficient (dlc) was developed. This is defined as,

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

The dlc was shown to increase with vehicle speed and road roughness and to depend on suspension type and configuration. In one study, [3] the best and worst suspensions under the same operating conditions (80 km/h on moderate roughness pavement) differed by a factor of two in the dlc recorded. This is typical. However, dlc does not represent pavement wear directly.

Dynamic Wheel Forces and Pavement Wear

The relationship between the dynamic wheel forces applied to a pavement and the resulting pavement wear is by no means obvious. On the one hand, one might expect a vehicle showing greater dynamic load variations to cause more pavement damage. If the relationship between wheel forces and pavement wear were linear (not fourth power) it could be argued that the occasions when the loads are above the static load are offset by equivalent occasions where the load is below the static and thus the overall effect cancels. That is, the dynamic variation in wheel loads causes no increase in pavement wear.

If the fourth power relationship is assumed then the contribution of the higher loads to road damage is greater that the beneficial effects of the corresponding lower loads. Eisenmann [6] assumed the distribution of dynamic loads is Gaussian and followed this logic through to obtain a pavement wear measure he called the road stress factor which is defined as follows

$$\Phi = KP_{stat}^4 [1 + 6\bar{s}^2 + 3\bar{s}^4]$$

where P_{stat} = *mean axle load*

$\bar{s}$ = *coeff of variation of dynamic wheel load*

K = *constant*

A dynamic road stress factor which represents the damage due to dynamic effects can then be defined as

$$v = \frac{\Phi}{KP_{stat}^4}$$

$$ie \quad v = 1 + 6\bar{s}^2 + 3\bar{s}^4$$

There is a difference in definition between dlc in Sweatman [3] and $\bar{s}$. However, in general, the measures may be regarded as being interchangeable.

The range of dlc values measured in various studies is typically 0.01 for a good suspension on a smooth road at low speed to 0.4 for a poor suspension on a rough road at highway speed. Applying these dlc values in the dynamic road stress factor formula gives a range for this factor of 1.006 to 2.04. To compare suspension effects the roughness/speed conditions should be equivalent. Sweatman [3] shows statistically that dlc is approximately related to $VR^{0.5}$, where V is the vehicle speed in km/hr and R is the road roughness in NAASRA counts/km. On this basis he suggests a test condition for comparison of $VR^{0.5} = 850$ which corresponds to highway speed over a road of moderate roughness. For this condition, the range of dlcs he observed was 0.13 to 0.27 between best and worst suspensions. The corresponding dynamic road stress factors are 1.10 to 1.44. Woodrooffe et al [4] find a range of dlc of 0.16 to 0.39 for the suspensions they tested at 80 km/hr over a moderate roughness road. (The road roughness measure is different from Sweatman). This gives a range for dynamic road stress factors of 1.16 to 1.98. Mitchell and Gyenes [7] report dynamic road stress factors in the range 1.04 to 1.25 at 90 km/hr on a "medium" roughness pavement. The suspensions considered in all three studies were similar and it seems likely that the differences in measured dlcs reflect differences in roughness of the test conditions. This reinforces a finding of these studies that the differences in dynamic loading between suspensions increase with increasing road roughness.

The dynamic road stress factor represents an expected value of road wear which is essentially the average wear along the pavement. Furthermore, there is an underlying assumption in the derivation of the dynamic road stress factor that the distribution of wheel forces is random. This is clearly not the case. All the experimental studies on measuring dynamic wheel forces have shown good repeatability for the same vehicle over the same pavement at the same speed. The vehicle is a dynamic system which responds to a displacement excitation generated by passing over a road profile. Its response is deterministic not random. As the characteristics of heavy vehicle suspensions are, to a degree, similar and as the dynamic loads are generated in response to the pavement profile, the higher loads will tend to recur at specific locations on the pavement increasing the damage. To reflect this Sweatman [3] proposed using the 95th percentile of dynamic wheel forces to predict road damage. The 95th percentile impact factor he estimated as (assuming a Gaussian distribution).

$$IF_{95th} = 1 + 1.645dlc$$

with an associated road stress factor, based on the fourth power law, of

$$\Phi_{95th} = (IF_{95th})^4$$

Applying this measure, for example, to Sweatman's range of dlcs at $VR^{0.5} = 850$ gives a range for road stress factor Φ_{95th} of 2.14 to 4.37. There is a lower limit of 1 for the case of zero dlc.

The analysis of the dynamic wheel forces described so far has for the most part regarded the dynamic wheel force as a force versus time distribution which is where the notions of randomness come from. Cebon [8] suggests that as it is pavement wear that is under consideration, the spatial distribution of wheel forces along the pavement should be considered, that is, a force versus distance distribution. For a vehicle then, he accumulates the force contribution of each of the axles at a location. Based on this spatial distribution of forces he develops four different criteria for road wear, two of which also involved a model of the pavement structure. These criteria were evaluated using a computer simulation of a vehicle on computer generated pavement. For a "good" road at 80 km/hr the 95th percentile road damage factor due to dynamics varied from approximately 1.25 to 3 depending on which criterion was used for the same four spring steel suspension vehicle. The OECD Road Transport Research programme currently has a project on Dynamic Loading of Pavements in progress. The first part of this project is a state-of-the-art report by a scientific expert group representing the member countries. This report says that depending on analysis methods and assumptions dynamic road stress factors between 1.2 and 4 have been obtained. The group is proposing a coordinated research project on an accelerated pavement test facility be undertaken to resolve this issue.

Even if this dynamic road stress factor were known with absolute certainty, considerable analysis and a number of assumptions are needed to calculate the reduction in pavement wear that is possible. In the first place the dynamic wheel forces depend on the pavement roughness. Thus, the same vehicle passing over the same pavement at different stages in the pavement's life will generate different pavement wear. (Following this idea through, it may be better economically to repair pavements earlier than is currently done and keep the roughness value low, so reducing the rate of wear per axle loading.) To assess the potential savings through better suspensions the mix of road roughnesses of the highway system needs to be known (or estimated) and related back to traffic volumes. The mix of vehicles and suspensions also needs to be known (or estimated) as do their loadings. Mitchell and Gyenes [7] make a very rough estimate based on UK vehicle data and suggest a possible reduction in road wear of 10-15%. This comes from a survey of the vehicle fleet mix, an estimate of the suspensions used, dlc measurements at TRRL at 90 km/hr on a moderate roughness road and the Eisenmann dynamic road stress formula. If the 95th percentile road stress factor, Φ_{95th} as described by Sweatman is used instead of the Eisenmann formula, the potential savings based on the same dlc values become about 35-40%! This difference represents a substantial sum and so it is important to resolve this issue. A research project along the lines of the OECD project but specifically related to New Zealand pavements and vehicles to be undertaken on the CAPTIF (Canterbury Accelerated Pavement Testing Indoor Facility) has been proposed for funding. Submissions have been made to the OECD to have their project undertaken here as well.

The cost of pavement wear is substantial. In New Zealand in 1990/91 Transit New Zealand spent over $340M on road mantenance [9]. Consequently even a small reduction can result in significant savings. Clearly the use of better suspensions should be encouraged. However, this raises the issue of how to determine whether a suspension is better and how much does this assessment cost.

Assessing vehicles and suspensions

Dynamic wheel forces have been measured by a number of researchers. Two principal approaches have been used with success, the wheel force transducer developed by General Motors, and strain gauging the vehicle axles. Other approaches involving measuring tyre pressure changes or tyre deflections with optical/laser sensors have been tried with mixed results.

The wheel force transducer consists of a strain gauged structure which transmits (and monitors) the wheel loads from the wheel rim to the axle hub. It requires an appropriate hub adaptor for the axle which is under test. The signals are transmitted to a recording device via slip rings. This transducer is expensive but has the advantage of being totally separate from the vehicle and so relatively quick to install.

The alternative method is to apply strain gauges directly to the vehicle axle and measure either the bending or the shear strains in this axle. Accelerometers are used to measure the behaviour of the mass outboard of the gauges and to correct for the inertia effect this generates. Using bending strains provides higher signal levels and so a better signal to noise ratio. However, any transverse tyre forces will also generate bending strains and consequently an error in the computed vertical wheel force. Shear strain measurement does not generate this error but generally produces lower signal levels. These transducers are attached to the vehicle structure and require some time and expertise to install. Neither of these methods is well suited to routine use.

A number of European countries allow higher axle load limits for axles fitted with air suspensions. This is the crudest form of assessment. As the research studies to date have consistently shown air suspensions to have low dynamic load coefficients compared to steel or rubber suspensions they have been granted this concession. The EEC regulations which are being developed to obtain some consistency in the regulations across Europe retain concessions for air suspensions but include the words "or their equivalent". However, the definition of what constitutes "equivalent to air" is still under discussion. A proposal regarding single drive axles was put to the Commission in 1990. It defined "equivalent to air" as having a natural frequency of less than 2 Hz and a damping ratio greater than 20% of critical with less than 50% of the damping being friction damping. Three alternative test procedures are proposed:- the first is to drive the vehicle at low speed up a ramp over an 80 mm step (of prescribed geometry) and monitor the response, the second is to pull the vehicle down by the chassis until the axle load reaches 1.5 times static and then release it suddenly and monitor the response, the third is to lift the chassis by 80 mm and suddenly release it and monitor the response. Experiments at MAN trucks [10] have shown good correspondence between the results of these three tests for vehicles with a single drive axle but not for vehicles with tandem drive axles. These tests are intended as a form of suspension assessment for road damage. They are relatively straightforward to undertake and should give repeatable and reproducible results. However, the link between the assessment criteria and the road damage potential of the suspension is tenuous. It is worth noting that there is a very strong trend towards air suspensions in Europe. Although the weight limit concessions may be a factor, it appears that the principal motivation is improved ride resulting in less cargo damage and increased driver comfort. Reductions in tyre wear and fatigue damage to chassis structures have been reported but the evidence is largely anecdotal.

Three research groups are currently undertaking projects looking at techniques for assessing suspension performance. A group at Cambridge University, UK [11] have been developing weigh-in-motion sensors incorporated into a flexible mat. These mats are laid end to end along the pavement. As they are flexible, the basic roughness characteristics of the pavement underneath are transmitted to the vehicle and so the response of the vehicle should be unchanged by the presence of the mats. An acquisition system then monitors the spatial distribution of wheel forces as the vehicle passes over the mats. The underlying philosophy of the approach is that the whole vehicle needs to be assessed not just the individual suspension units. By laying the mats down over normal pavement the system is intended to be transportable. Early testing, however, has shown that it is necessary to attach the mats to the pavement with epoxy adhesive in order to get good results. This reduce the portability of the system a little from what was originally envisaged, but within this limitation reasonable results have been achieved. A prototype system, 55m long has been installed recently (Nov 1991) for trials at the TRRL test track. Proposals to install it on a public highway are under consideration but there is some opposition because of possible liability problems should an accident occur.

At the National Research Council in Canada a suspension testing trailer is being developed. The first prototype has been built. This vehicle consists of a short trailer structure with a light long drawbar. It has purpose built strain gauged axles and is set up so that any suspension can be fitted to it. By making the vehicle short and keeping the load directly over the axles, the pitch mode, which depends not only on the suspension but also on the load configuration, is eliminated. The long light drawbar is an attempt to minimize the influence of the towing vehicle. This vehicle would be used to generate comparative assessments of different suspensions under the same test conditions and so the aim is to generate a vehicle independent rating for the suspension.

The third programme of research is being undertaken at DSIR, Industrial Development in Auckland. The project is centred on using a two post servo-hydraulic shaker facility to replicate the on-road dynamic behaviour of the suspension system. Initially a three axle liquid tanker trailer on steel leaf spring suspension has been used as the test vehicle. Each wheel position was instrumented with strain gauges to measure the shear forces, an accelerometer on both the axle and the chassis, and a displacement transducer to measure the suspension motion. This vehicle was then driven over five pavement sections encompassing a range of roughnesses, using three vehicle speeds at each site. To complete the picture the road profiles were measured using the ARRB laser profilometer. The vehicle was then returned to the laboratory and mounted on the shaker facility as shown in figure 1.

The vehicle was then excited with the shakers to try to match the suspension displacements at the wheels being excited with those measured during the road trials. This process is an iterative one which is theoretically quite straightforward. Random excitations are applied to the wheels and the response (ie suspension displacements) recorded. From these excitations and responses, transfer functions are calculated. The inverses of these transfer functions are then applied to the target responses (ie the displacements measured during road trials) to calculate the new excitations to be applied. Underlying this process are assumptions that the dynamic system is linear and that the two excitations are independent. Linearity for a dynamic system means that an excitation at a given frequency elicits a response at that frequency only and that the magnitude of the response is linearly related to the magnitude of the excitation. The dynamic behaviour of the steel springs on the vehicle under test is highly non-linear. At low levels of excitation the friction between the leaves prevents much response. Once this stiction has been overcome the spring stiffness is greatly reduced.

The first algorithm used for this process recalculated the inverse transfer functions at each iteration. Because of the highly non-linear suspension behaviour this procedure was divergent. To improve the stability of the procedure, a relaxation factor was introduced so that, at each iteration, a portion of the new inverse transfer functions was added to a complementary portion of the old inverse transfer functions. However, as the road test data were generated by exciting both wheels with the same road profile with a small time lag, the excitation signals for the two rams would not be expected to be independent as assumed. This lack of independence manifests itself as spikes in the inverse transfer functions. These spikes had to be removed and this was done by a manual editing process. With these

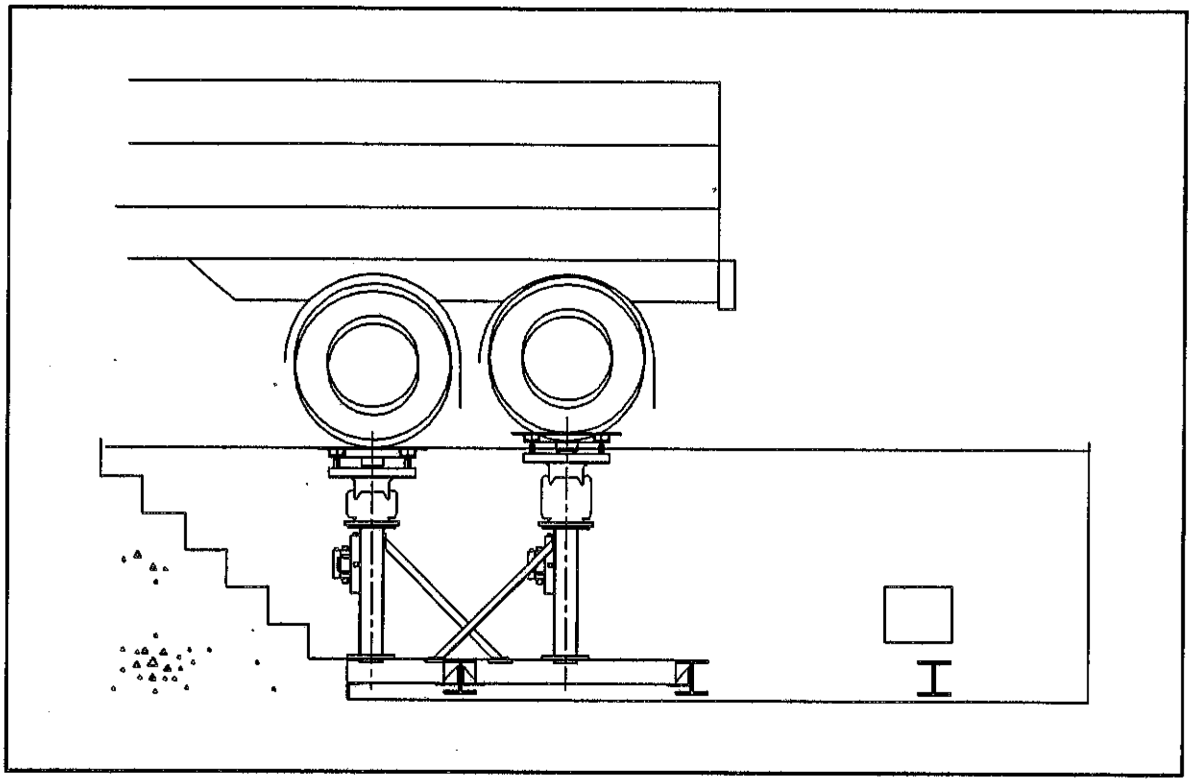

Figure 1. Vehicle support for shaker rig.

modifications the algorithm worked reasonably albeit slowly. To close in on a given target signal took 4-5 hours of iterations. At this stage, a fair match was achieved between the road and lab data in the time domain. The fit in the frequency domain was better. Figures 2-5 show an example of the fit achieved.

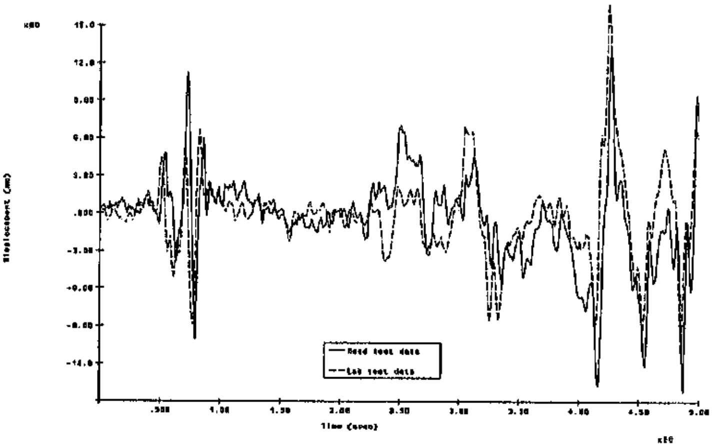

Figure 2 Sample suspension deflection signal for rear wheel.

The original intention of the method was that a vehicle being assessed would be instrumented with displacement transducers and axle accelerometers only which is relatively cheap and fast compared to strain gauging. The vehicle would then be submitted to a road test program and

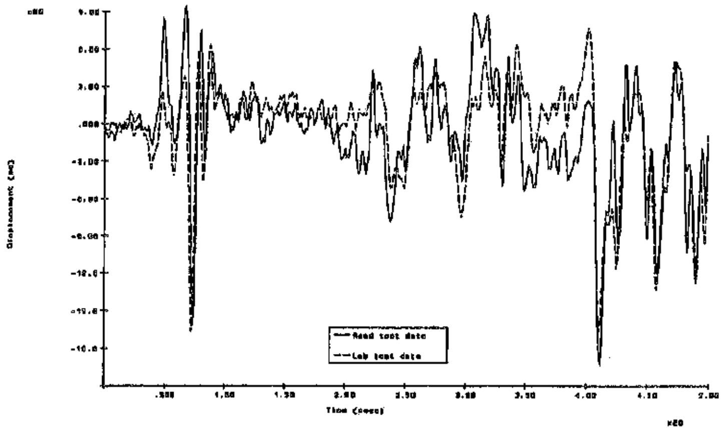

Figure 3 Sample suspension deflection signal for middle wheel.

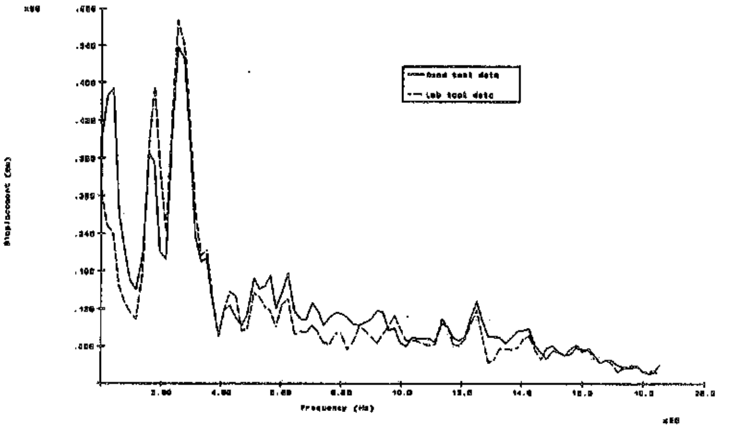

Figure 4 Spectral distribution of rear suspension deflections

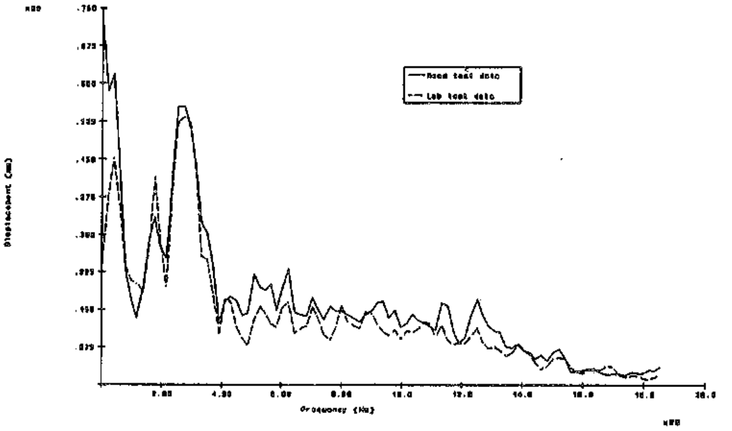

Figure 5 Spectral distribution of middle suspension deflections.

the instrumentation readings recorded. Back in the laboratory, the suspension's on-road behaviour would be recreated and the wheel forces measured from load cells in the ram platforms. The axle accelerometers would be used to correct for differences in the unsprung mass behaviour between the two tests. In terms of this concept, the algorithm above is unsatisfactory in that the time required per road test is too long and the level of manual interaction in the process is too great.

Two modifications to the algorithm were made in an attempt to overcome the difficulties. As the road behaviour was generated by the same excitation (ie road profile) being applied to both wheels with a time lag (which depends on vehicle speed) between them, it was thought that the same approach might work in the laboratory trials. Thus, the control software for the servohydraulics was modified to allow a single excitation with a time lag to be applied to both rams. This eliminates the independence requirement for the two excitation signals and hence the problem with spikes in the inverse transfer function disappears. With this algorithm a much more rapid convergence of the iteration procedure was achieved, usually taking less than an hour. However, at convergence, that is, where further iterations do not significantly improve the solution, the match between the road and laboratory data is not quite as good as previously achieved. Typically, the fit for the front wheel of the rear tandem group was better than that of the rear wheel. Comparing frequency distributions the rear wheel appears to be under-responding at the body resonance frequencies (2-4 Hz) while the middle wheel is over responding. This is illustrated in figures 6 - 9 which use the same road test data as the previous figures. No explanation for this behaviour has been found.

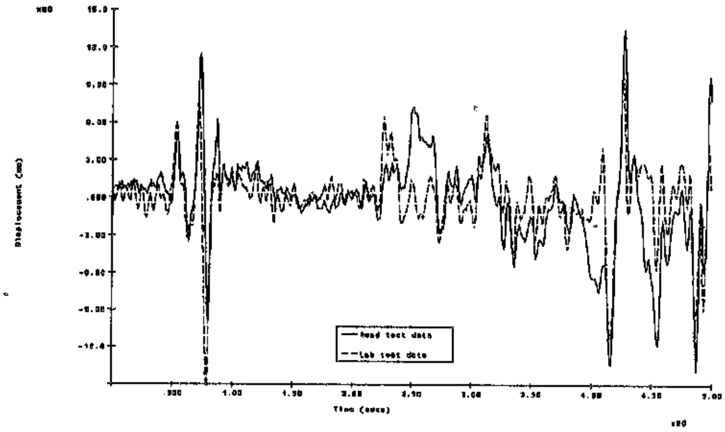

Figure 6 Suspension deflection signal for rear wheel.

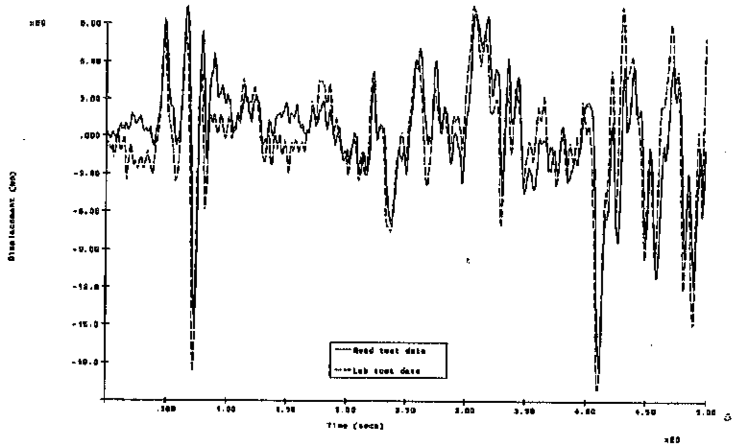

Figure 7 Suspension deflection signal for middle wheel.

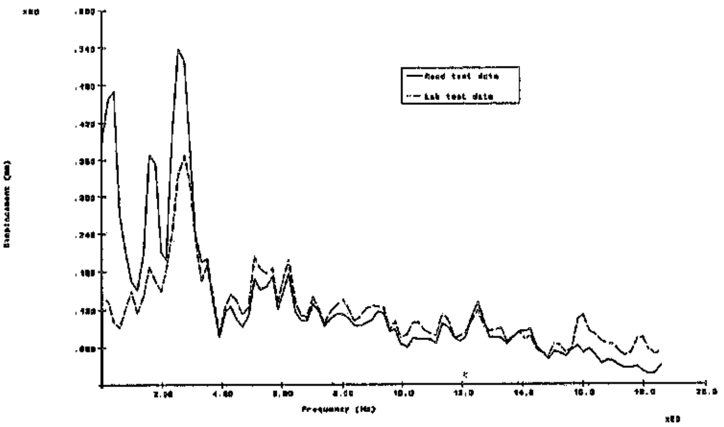

Figure 8 Spectral distribution of rear suspension deflections.

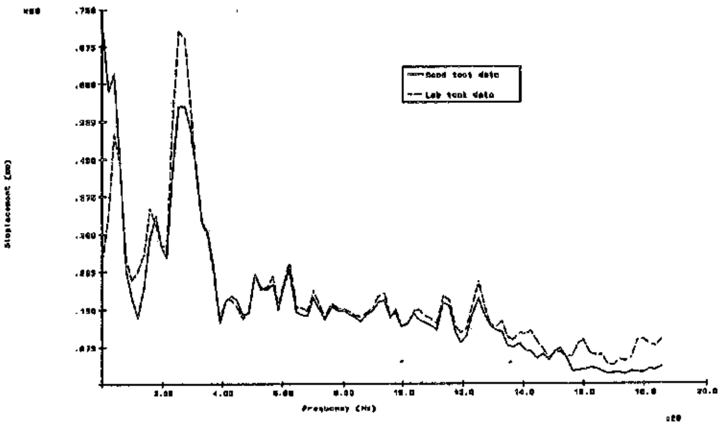

Figure 9 Spectral distribution of middle suspension deflections.

The second modification to the shaker control algorithm was more extensive. Initially the shakers were run with random noise excitations and the inverse transfer functions determined. As before this was applied to the target responses to calculate the required excitations. At subsequent iterations the difference between the actual responses and the target responses was used to calculate incremental excitations which were then added to the excitations used in the previous iteration. Thus no recalculation of the inverse transfer functions was undertaken. For stability it is necessary to add on only a portion of the incremental excitations each iteration. This algorithm was fast and required a minimum of operator intervention. For the single excitation signal for both shakers case, the solution was of similar quality to that previously achieved, though more quickly obtained. For the case of two independent excitations, solution which are superior to those obtained with the original algorithm were achieved rapidly (in less than an hour). Figures 10 - 13 show the results for the same road test example as previously.

The aim of the test procedure is to replicate the on-road wheel force behaviour not just the suspension deflections. Figures 14-15 show a comparison of the wheel force signals between the laboratory and road tests. As can be seen the match is quite good. The wheel forces in the laboratory were determined without applying the inertial correction for differences in the unsprung mass behaviour. This effect is small and the procedure is significantly simpler if it can be ignored.

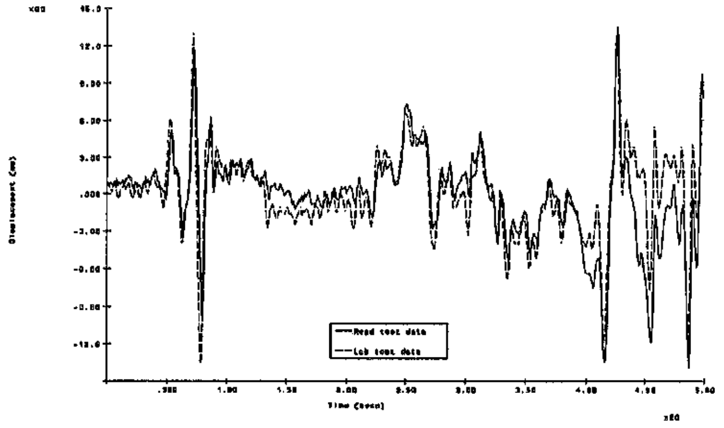

Figure 10 Suspension deflection signal for rear wheel

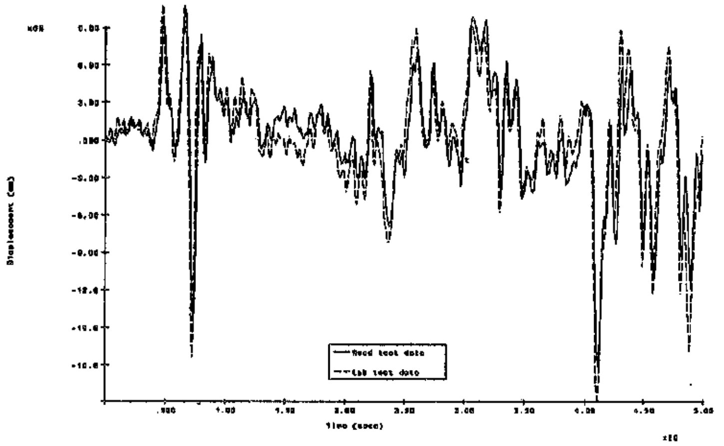

Figure 11 Suspension deflection for middle wheel.

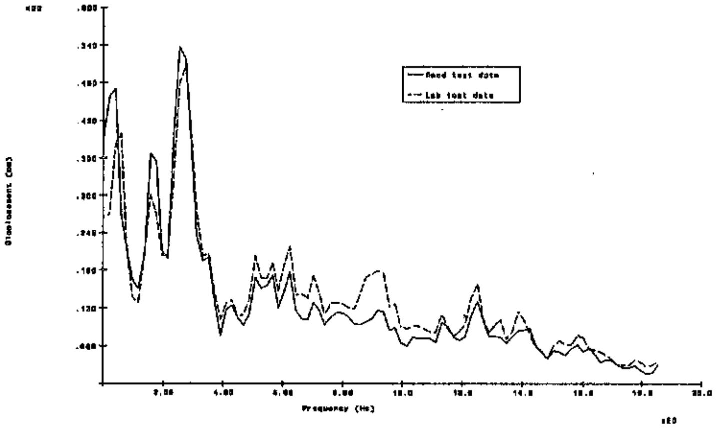

Figure 12 Spectral distribution of rear suspension deflections.

As the dynamic behaviour of the suspension is achieved in the laboratory by exciting only two wheels and on the road by exciting six wheels, it is reasonable to expect that the shaker displacements and the corresponding road profiles are not the same. However, similarities exist. The difference between these signals and the road profiles is dependent on the

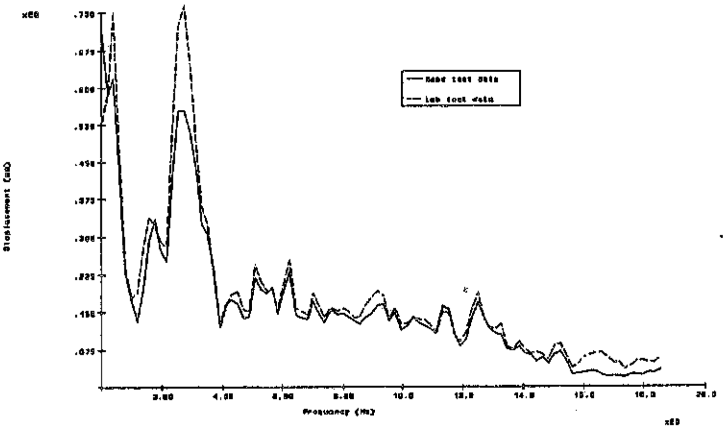

Figure 13 Spectral distribution of middle suspension deflections.

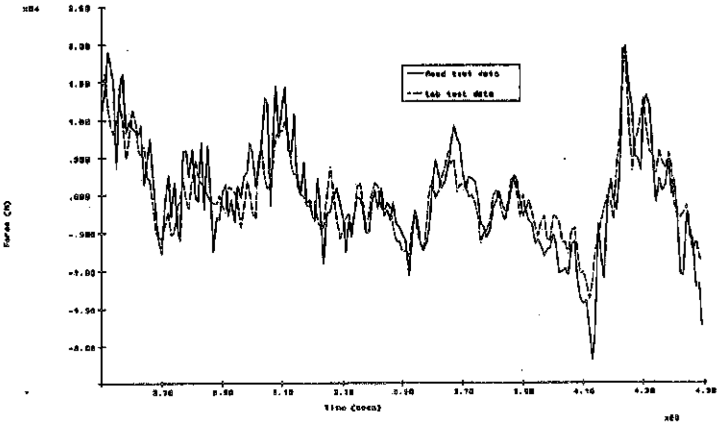

Figure 14 Force signal for rear wheel.

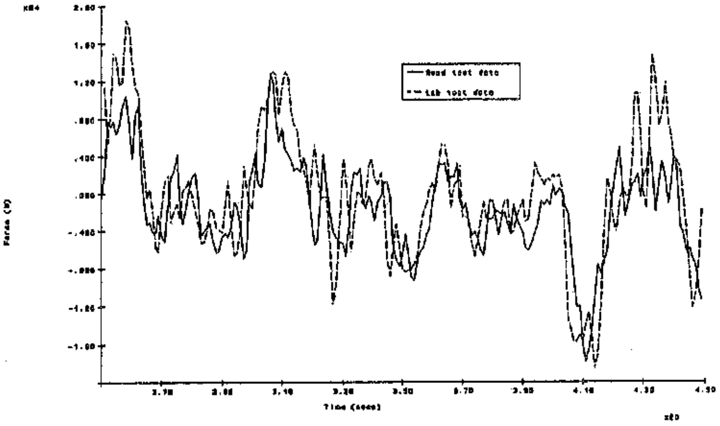

Figure 15 Force signal for middle wheel.

vehicle's dynamic characteristics. Thus it is postulated that by measuring the vehicle's characteristics, it may be possible to develop a method of modifying the road profile data to generate required shaker displacements directly. If successful this would eliminate the need for road tests as part of the procedure and more importantly make the test totally consistent and repeatable. Work is currently underway on this aspect of the problem.

Conclusions

The problem of reducing pavement wear through encouraging "road friendly" suspensions has two aspects. First, it is necessary to determine the scale of the problem to know how much money it is worth spending on solving it. Then, it is necessary to be able to assess a suspension's performance from a road damage point of view.

Although there have been a number of attempts to relate dynamic wheel forces to pavement wear, the results differ substantially and there is no generally accepted answer. The most optimistic approach suggests that the worst suspensions do 30% more damage than the best on moderately rough pavements at highway speeds, while the least optimistic indicate 100% more damage on the same pavements. Both these values would be considerably lower on less rough pavements but the difference remains. An experimental program on an accelerated pavement testing facility has been proposed to resolve this issue and is currently under consideration. Even if this is resolved there is still a substantial step in applying this value to the actual vehicle fleet, and the mixture of pavement roughnesses, traffic volumes and operating speeds to estimate the magnitude of the problem for a country or a region.

Three research programs are currently investigating techniques for assessing vehicle and suspension performance. The Cambridge University approach is based on assessing vehicles rather than suspensions with the tests being done on actual pavements. While this has the advantage of realism, a possible drawback is that pavement characteristics change with time and location and so repeatibility may be limited.

The National Research Council of Canada method is based on using a special test vehicle and so assessing suspensions in a vehicle-independent manner. This test also uses actual pavement. The outcome would be a suspension rating which would be applied to any vehicle using it. Type testing on suspensions only may be a more practical than testing vehicle-suspension configurations.

The third program is being undertaken at DSIR Industrial Development in Auckland using a servo-hydraulic shaker facility. This method could be used for whole vehicle assessment or for type testing of suspensions. Progress is being made towards eliminating the need for a road test to provide the base data on the vehicle behaviour.

All three of these programs are making good progress and the prospects for developing a satisfactory assessment procedure are excellent. It is possible that some hybrid of two of the techniques (eg using the test trailer on a servo-hydraulic facility) may be the most appropriate. The research leaders of each of the three teams are members of the OECD Scientific Expert Group IR2 on Dynamic Loading of Pavements and the cooperation and communication between them is excellent.

Acknowledgements

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