ASSESSING SUSPENSION SYSTEMS FOR ROAD DAMAGE

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ABSTRACT

It is recognized that heavy vehicles cause damage to pavements. Furthermore it is generally accepted that the dynamic wheel forces contribute to this damage. Clearly the nature and magnitude of these dynamic loads are a function of the vehicle's configuration and its suspension system. If a user pays approach of relating vehicle taxation to the road damage caused by that vehicle is applied then the effects of the vehicle's suspension system should be included. To date this has not been possible because there is no practicable method of assessing suspensions.

In this paper a brief review of previous work on dynamic wheel force measurement and assessment of suspension systems is presented. This is followed by an outline of a research program currently underway to develop a simple method of measuring dynamic wheel loads and hence assessing suspension systems.

A BRIEF REVIEW.

It is intuitively obvious to the observer that the damage caused to a pavement by a vehicle passing over it is proportional in some way to the axle loadings and will be affected by the behaviour of the suspension system.

One of the first and most comprehensive studies of the relationship between road damage and axle loadings was conducted by the American Association of State Highway Organizations (AASHO) over the period 1958-60. The major result of this study was the now generally accepted "fourth power law" which says that the average damage per application to a pavement is proportional to the fourth power of the axle loading. This fourth power law was derived statistically from a large amount of experimental data and averages the effects of suspension systems.

In more recent times researchers have worked on ways of measuring the dynamic wheel forces on pavements. Two techniques have been developed and used successfully [1]. The first of these is a specially designed wheel force transducer developed at General Motors. This transmits the wheel forces from the rim to the axle via some beam elements which are strain gauged. It requires an adapter at the hub but otherwise is easily fitted and calibrated. Its main drawback is that it is relatively expensive. The second approach to measuring wheel forces has been to use strain gauges and accelerometers attached to the vehicle axles. The strain gauges measure the bending strain which is directly related to the wheel forces and the accelerometers are used to adjust for the inertial effects of the masses outboard of the strain gauges. Although, with this method, the transducers are relatively cheap, the installation and calibration is time consuming. Other methods such as monitoring tyre pressure variations have been tried but without success. More recently some work has been done using weigh-in-motion (WIM) load sensing mats [2] which shows some promise.

In the late 1970's Sweatman [3][4] at the Australian Road Research Board (ARRB) undertook a major study on the relationships between suspension systems and the dynamic wheel forces imparted to the pavement. Using a GM wheel force transducer he measured the forces generated by nine vehicle-suspension configurations travelling over six test sections of road of different roughness at three different speeds and two tyre pressures. For each of these combinations of conditions the dynamic wheel force signals were digitised and treated as samples from a distribution. Hence the usual statistical measures of a distribution, the mean and the standard deviation could be calculated. Figure 1 shows an example of a wheel force signal from [4] and figure 2 gives the corresponding force distribution.

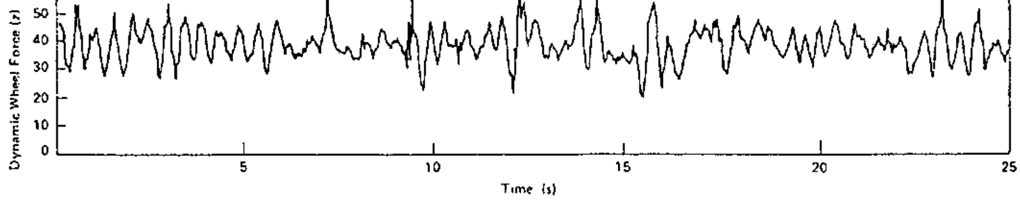

Figure 1. Example of a Dynamic Wheel Force Signal.

The behaviour of a vehicle-suspension configuration under a specific set of conditions was characterized by a measure called the dynamic load coefficient (DLC) which is defined as

$$\mathrm{DLC} = \bar{s} = s/\bar{Z}$$

where s = standard deviation of the wheel force distribution
and $\bar{Z}$ = overall mean of the wheel force

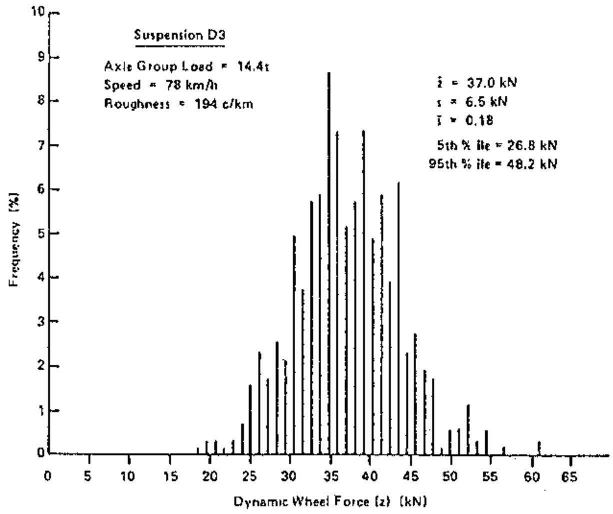

Figure 2. Example Wheel Force Frequency Distribution.

The DLC relates to the suspension's behaviour but only indirectly to the pavement damage caused. To characterize the pavement damage effects two other measures were used. These are the dynamic road stress factor and the 95th percentile road stress factor. If we assume that the distribution of dynamic wheel forces is a normal distribution (which appears reasonable in practice) it can be shown that the expected value of the fourth power of the wheel forces is given by

$$\phi = P_{stat}^{4} (1 + 6\bar{s}^2 + 3\bar{s}^4)$$

where P_{stat} = mean axle load
and $\bar{s}$ = coefficient of variation of dynamic wheel loads

The dynamic road stress factor is then defined as

$$\mu = 1 + 6\bar{s}^2 + 3\bar{s}^4$$

This measure assumes that the dynamic wheel loads are randomly distributed and so can be considered a lower estimate. In fact the dynamic loading occurs in response to the pavement profile and will tend to occur at specific locations on the roadway. Thus it is important to know what the higher loads are for a particular suspension system. The 95th percentile impact factor is given by

$$IF_{95th} = 1 + 1.645\,\bar{s}$$

and the associated road stress factor is

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

All these measures provided the same ranking for the suspensions tested though the magnitudes of the differences varied.

Sweatman also performed some multivariate regression analysis to try to relate the DLC to the other variables in the study. He found that he could achieve quite good correlation between DLC and one other variable $VR^{0.5}$, where V is the vehicle velocity and R is the road roughness as measured by the NAASRA roughness meter [5]. That is, reasonable predictions of DLC could be obtained from a formula

$$DLC = a + b\, VR^{0.5}$$

where a and b are constants which are vehicle specific.

In terms of dynamic performance it was found that, in general, air suspensions performed better than steel springs which in turn were better than walking beams. Surprisingly, perhaps, the torsion bar suspension tested performed very well.

Subsequently, in the mid 1980's another major study was carried out at the National Research Council, Canada by Woodrooffe et al [6] as part of the Roads and Transportation Association of Canada (RTAC) Heavy Truck Weights and Dimensions study. In this work a semi-trailer was modified to accept various suspension configurations each mounted on its own subframe. Both the tractor and trailer units were instrumented with strain gauges and accelerometers to measure dynamic wheel forces. Three generic suspension types; walking beam, air suspension, and steel spring, were considered because they represented the majority of the Canadian fleet. As with the ARRB study dynamic wheel forces were measured for a range of speeds over a number of different road roughnesses. The effects of altering the position and spacing of the axles as well as increasing the number of axles by use of a lift axle were investigated. Related issues such as the effect on load sharing of different pitch attitudes of the semi-trailer and load transfer under braking were also studied. An attempt was made to relate the pavement deflections to the vehicle wheel forces.

As expected the relative performance of the suspension types was much the same as previously found by Sweatman. Axle spacing was found to have little effect on dynamic wheel forces though for other reasons minimizing spacing was recommended.

Also in the mid 1980's Cebon [7] [8] at Cambridge University was completing his PhD work in which he developed a computer simulation model of the dynamic behaviour of a semi-trailer which he validated with experimental measurements carried out in conjunction with TRRL. Cebon proposed an alternative approach to characterizing vehicle performance in relation to road damage. Measures such as DLC are based on the dynamic wheel force vs time signal. Cebon suggested that the roadway should be divided up into short sections and that as the vehicle passed along the roadway the wheel forces applied to each section should be accumulated effectively generating a wheel force vs distance signal. Based on this notion he proposed a number of road damage criteria, some which were dependent only on the force distribution and some of which included a model of the pavement structure.

The work described in this review has primarily been oriented towards the vehicle dynamics and only some of the more recent studies have attempted to incorporate the pavement behaviour in any way. Over the same period significant work has been done on pavements without much consideration of vehicle characteristics. This lack of interaction between the two sides of the same problem is now changing for the better.

CURRENT SITUATION.

In Europe some countries have already moved to incorporate some consideration of the pavement damage potential of suspension systems into their regulations governing vehicle weights and dimensions. For example, in Britain a heavy vehicle using air suspension is allowed a maximum axle loading which is 0.5 tonne higher though the same gross vehicle limits apply. These rules are based on the fact that all the studies to date have shown air suspensions to perform relatively well in terms of reducing dynamic wheel forces. However, they provide no incentives to designers and manufacturers to develop better suspension systems.

The OECD, at the instigation of Australia, is initiating a project on the dynamic loading of pavements. This project, which is being co-ordinated by Peter Sweatman, has a number of specific aims.

- To produce a report based on scientific evaluation of research data and consideration of manufacturers' and road managers' views.
- To co-ordinate research into suspension/vehicle/pavement dynamics and develop suspension performance criteria for reducing road wear and enhancing safety.
- To provide scientific and technical advice based on research to vehicle and suspension manufacturers and to provide a forum for manufacturers' views.
- To contribute to the development of dynamic wear relationships and their use in forming policy on commercial road user charges and taxation.
- To recommend appropriate implementation for the research results via standards, codes of practice or pricing mechanisms.

Although the formal start time of this project is likely to be early 1990, some co-ordination of research effort is already occurring.

In Britain, Cebon is now teaching at Cambridge and has a group of five graduate students working on various aspects of vehicle-pavement interactions, mostly in conjunction with TRRL. Some of this work is concerned with dynamic behaviour of pavement and bridge structures, some with the mechanisms of vehicle-pavement interactions and, of more relevance to the topic of this paper, some is on the development of a WIM system for assessing suspension performance [2]. This consists of capacitive strip force sensors which are embedded into a tough polymer mat. The mat is sufficiently flexible to follow the road profiles for the wavelengths of interest. By laying a series of these mats over a section of pavement it will be possible to measure wheel forces without any instrumentation on the vehicle. Preliminary results are encouraging.

TRRL also have an ongoing program of measurement both of vehicle behaviour and of pavement response. They also have a proposal to develop a computer simulation model of the vehicle's dynamics.

At NRC, Canada, there are two proposed programs for investigating suspension dynamics. The first of these involves the development of a specialised trailer for assessing suspension systems. This vehicle will have relatively short frame to which any tandem or triple bogey and suspension could be attached. The payload will be carried as a concentrated mass located directly over the wheels and the trailer will be towed by a long drawbar of very low mass as illustrated in figure 3. In this way the effects of the whole body modes of oscillation will be eliminated and the assessment would effectively be of the suspension system alone rather than the vehicle-suspension configuration.

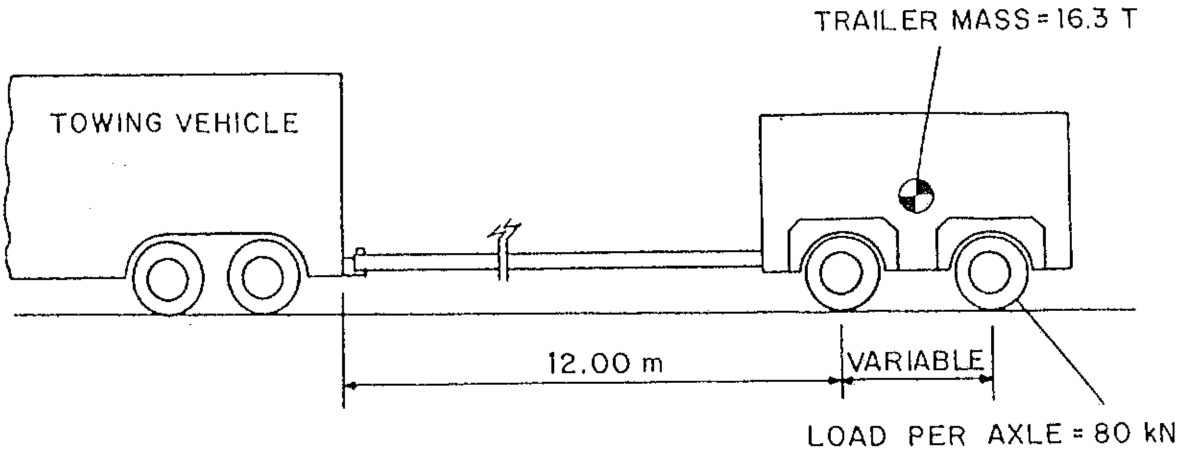

Figure 3. Proposed Suspension Testing Trailer.

The second program involves building a laboratory based vehicle half model which will be driven by servo-hydraulic shakers. The basis of this idea is that in practice on the road the roll modes of oscillation are not a significant contributor to the dynamic wheel forces and so a two dimensional representation will be sufficient. This rig will allow any suspension system to be attached and can be used to investigate the behaviour of the configuration.

THE DSIR - NATIONAL ROADS BOARD PROGRAM.

An experimental program is being undertaken at Auckland Industrial Development Division, DSIR with joint funding from the National Roads Board to develop a cost-effective method of assessing suspension systems. A liquid tanker full trailer has been purchased and will be the basis of the study. It has a single steer axle at the front, tandem axle bogey, as shown in figure 4, at the rear with steel leaf springs and dual tyres all round.

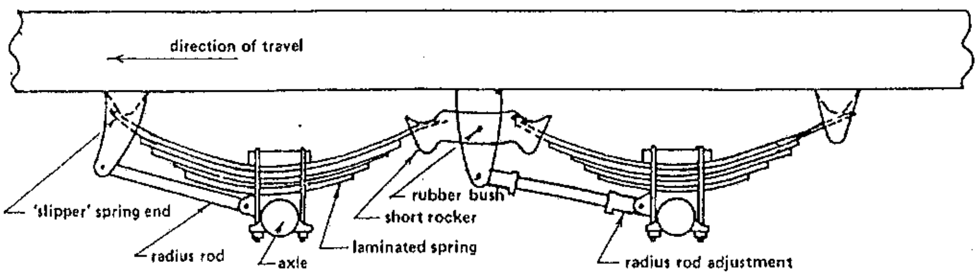

Figure 4. Steel Spring Tandem Axle.

The first stage of the program is to gain a comprehensive understanding of the dynamic behaviour of this vehicle under a range of typical operating conditions. The roads which will be used for the testing will be measured using the ARRB laser profilometer so that details of the excitations are known as well as the average measures such as road roughness. On each axle, at each wheel position, the vehicle will be instrumented with strain gauges and an accelerometer to determine the wheel forces, along with an LVDT (displacement transducer) between the axle and chassis to measure the suspension deflection and an accelerometer on the chassis to determine the behaviour of the sprung mass. Additionally there will be a "fifth" wheel to measure vehicle speed. The output of these transducers will be logged with a Hewlett Packard data acquisition system over a number of test sections of road at a range of speeds.

The second stage of the program involves placing the vehicle on a two post servo-hydraulic shaker facility with both actuators on the same side of the vehicle under the tandem axle wheels as illustrated in figure 5.

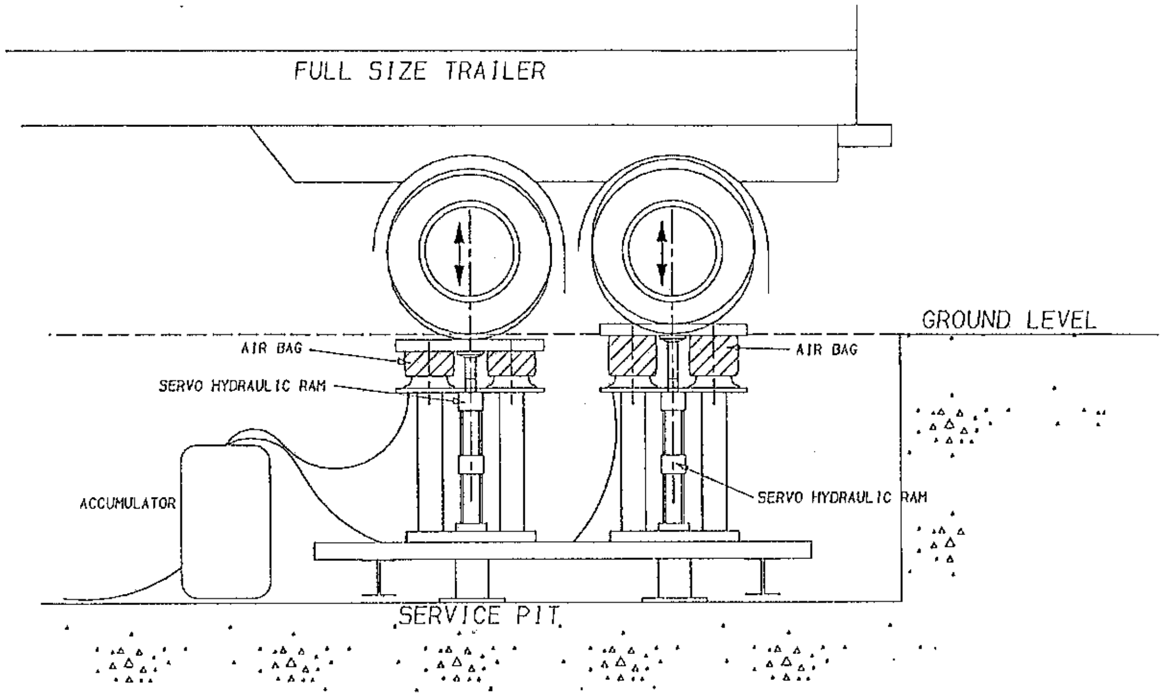

Figure 5. Sketch of Shaker Configuration.

Using a computer based control system the shaker will replicate the LVDT signals measured during a road test. The wheel forces will be measured directly from load cells located between the actuators and the tyres. As only two wheels are being excited the vehicle behaviour will not be identical to what it was during the road test and so it will be necessary to adjust the load cell force signals by the difference in the accelerometer signals between the laboratory and the road multiplied by the mass. The wheel forces calculated from the strain gauges will provide validation data. If this method succeeds it means that a vehicle-suspension configuration can be assessed by instrumenting the wheels of interest with only an LVDT and an accelerometer which can be done quickly and cheaply. The vehicle can then be driven over a test section of road and then brought into the laboratory where the shaker can replicate the road behaviour and produce the associated wheel force signals. From these appropriate road damage measures, such as DLC or road stress factors or Cebon's criteria, can be extracted. Although the computing involved in this is complex it would be relatively automatic once the method was proven. The test could be carried out in less than a day.

The project as described has been funded and is currently in progress. Following on from this it is proposed that a vehicle with a totally different suspension type (probably air) be fully instrumented and tested across the same test roads. This would expand the database of knowledge and provide further verification of the assessment technique. Then, using the assessment technique, a selection of vehicle-suspension configurations typical of those operating on New Zealand roads would be tested to obtain the range of performance of suspensions currently in use. By analysing the shaker driving signals from these tests and relating them to the original road profiles and some vehicle parameters it is proposed to attempt to find a way of generating a shaker driving signal equivalent to a known road profile without needing to first do the road test. This would make the test procedure independent of test roads which will change with time and make it repeatable at other locations. Clearly, this problem would be simpler if the shaker had actuators for each of the vehicle's wheels but this would make the facility very expensive.

Finally the development or adaptation of a computer simulation model should be considered. Data from the two fully instrumented tests would provide for comprehensive validation. The model would provide manufacturers and designers with a facility for predicting dynamic performance before construction and researchers with a tool for investigating the limits of what is achievable.

CONCLUSION.

It is widely recognized that suspension performance has a significant effect on pavement damage. Current regulations and taxes do little to encourage the use of "pavement friendly" suspensions. International concern over suspension/vehicle/pavement dynamics and related issues of wear and safety has resulted in the OECD project outlined in this paper. Within the framework of this project a number of research groups from different countries are developing techniques for assessing the dynamic wheel forces generated by heavy vehicle suspensions, each using their own approach to the problem. The co-ordination provided by the OECD program should ensure that the individual programs remain complementary and that results are shared. Clearly the NRB-DSIR project fits well into this international framework and so New Zealand can contribute to and will benefit from the co-operative effort.

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