NEW ZEALAND PAVEMENT LIFE AND SUSPENSION ASSESSMENT RESEARCH

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ABSTRACT

Different heavy vehicle suspensions produce different levels of dynamic loading on pavements. A corollary of this is that some suspensions generate less road wear than others and that the use of these suspensions should be encouraged. This raises two fundamental issues: How should the "road-friendliness" of a suspension be assessed? and How can the reduction in road wear attributable to the use of these suspensions be quantified? These issues are universal but in the New Zealand context there are local factors such as relatively low axle load limits and the widespread use of chip-seal pavement construction which need to be accounted for.

In this paper two current research projects aimed at addressing these issues are described. One project is investigating the use of a servohydraulic shaker facility to replicate the on-road behaviour of a heavy vehicle suspension and to assess its performance. The other project, which is being undertaken at the CAPTIF facility, compares pavement performance and life under loading by different suspensions. Although this work is still in its early stages, measurements have been taken which show, for the first time, direct links between dynamic wheel force peaks and pavement damage locations. Both projects have strong links to the work being conducted in the OECD DIVINE programme which establishes a framework for cross referencing the work to other related international studies.

1. INTRODUCTION

Underpinning pavement management processes are various models of pavement life and pavement performance. These models generally incorporate a direct dependence on the number of applied standard axle loads to which the pavement has been subjected. Actual axle loads are converted to equivalent numbers of standard axle loads by relationships which are usually based on the so-called "fourth power law". For example, in New Zealand, a standard dual-tyred single axle is one applying a static load of 8.2 tonnes. A similar axle applying a static load of P tonnes is considered to be equivalent to $(P/8.2)^4$ standard axles. These relationships to applied loads are all based on the *static* axle loads.

However, it is well known that the wheel loads applied to pavements are dynamic and that they depend not only on the static axle load but also on the suspension performance, the vehicle speed, and the road unevenness (Sweatman 1983, Mitchell and Gyenes 1989, Woodrooffe et al 1986, Hahn 1985). To characterise these dynamic wheel forces, a measure known as dynamic load coefficient (dlc) has been widely used. This is defined as:

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

As wheel force distributions have been shown to be approximately Gaussian this measure completely describes the dynamic variation of wheel forces. Having characterised the wheel force behaviour, it is necessary to determine its effect on pavement wear. A widely used method for doing this is that developed by Eisenmann (1975). He assumes a "fourth power law" relationship between wheel forces and pavement wear and that the wheel forces are randomly distributed. On this basis, he calculates a dynamic road stress factor, ν.

$$\nu = 1 + 6 * dlc^2 + 3 * dlc^4$$

This factor is used as a multiplier on the road wear to account for dynamic load effects. One difficulty with using this factor is that its baseline value of unity corresponds to the situation where no dynamic loads are applied which, of course, cannot occur. It should be remembered that, in practice, the road wear values obtained from experimentally derived models include dynamic effects without explicitly accounting for them. The dynamic road stress factor does provide a mechanism for comparing suspensions. However, the two assumptions implicit in its derivation are not universally accepted. In particular, the assumption that the distribution of wheel forces is random implies that there is no spatial concentration of peak loadings. Any concentration of peak loadings will increase the importance of dynamic loads as a factor in road wear. Equally the assumption of a fourth power relationship has a large impact. In the case where the dlc value is 0.2, the corresponding dynamic road stress factor is 1.24. Changing the value in the power relationship to, for example, either three or five changes the dynamic road stress factor to either 1.12 or 1.42. This has a substantial effect on the impact of dynamic loading. (If an alternative relationship were developed it would not necessarily be of the same power form). In the New Zealand context it is worth noting that although the fourth power relationship is widely used, it was derived from experimental results on pavement structures which are quite different to those currently in use here.

It is clear that increased use of more "road-friendly" suspensions would reduce pavement wear. However, in order to devise appropriate policies for encouraging their use it is necessary to resolve two issues. Firstly, the reduction in pavement wear attributable to improved suspensions must be able to be quantified so that incentives can realistically reflect benefits. Secondly, the performance of suspensions in terms of "road-friendliness" must be able to be assessed. The two projects described below are aimed at addressing these two issues.

2. VEHICLE DYNAMICS AND PAVEMENT LIFE RESEARCH

2.1 Accelerated Pavement Testing in New Zealand

Because of the unique situation in New Zealand, with respect to both the road user charges and our dependence on low cost, thin-surfaced flexible pavements, a primary research subject has been vehicle/pavement interaction. Laboratory testing and computer analysis are inappropriate to the nature of the work involved; trials utilising full scale equipment and pavements are necessary. Field trials of the life-cycle performance of pavements take too long (15 years or more) and lack the environmental control available in an enclosed accelerated test track facility.

The main feature of the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) is the Simulated Loading and Vehicle Emulator (SLAVE). The standard SLAVE vehicles are equipped with half-axle assemblies and multi-leaf suspensions that can carry either single- or dual-tyres; each vehicle can carry the same or a different suspension for simultaneous testing. Testing can be conducted with any pair of similar vehicles or with a different vehicle on each arm. The load on each half-axle can be adjusted to between 21 and 60 kN (42-120 kN axle loads) by adding or removing steel weights. Recently completed modifications to the standard vehicles permits the suspension to use either multi-leaf steel, parabolic steel leaf or air springs.

Some of the instrumentation systems at CAPTIF are discussed here. The CAPTIF Deflectometer measures the elastic response of a pavement under the influence of a wheel load. The Deflectometer probe is positioned between the tyres of a dual-tyred wheel and, as the wheel is moved away, the elastic vertical rebound of the pavement is read, to the nearest 0.01 mm, every 50 mm of horizontal movement. An electro-magnetic gap measuring sensor at the end of the beam measures the vertical distance between the sensor and a target disc placed on the pavement surface. An Analogue Data Acquisition Module (ADAM) and other electronics, which digitise the signals, are contained within the aluminium box section. The CAPTIF Profilometer measures transverse surface profiles. Both devices produce digital data output that is captured by a Psion hand held computer. The output from temperature probes installed in the pavements and subgrade are recorded hourly and automatically by a Taupo F-10-24K-48A datalogger. A Hewlett Packard 3852S microprocessor-based unit and Hewlett Packard PC-308 controller capture data signals from accelerometers mounted on the chassis and axles of each vehicle, for measuring the dynamic loads being applied by the axles. The data is downloaded from all the units to a desktop computer for analysis.

The soil strain measuring system measures subsurface strains and deflections with high resolution using Bison Soil Strain sensors. The sensors use the principle of inductance coupling between two free-floating, flat, circular wire-wound induction coils coated in epoxy. The strain discs are installed during the formation of the subgrade and the overlying pavement layers, resulting in negligible disturbance to the materials, which thereby yields more representative measurements. The strain data-acquisition system is essentially a computer containing a custom-built General Purpose Input/Output (GPIO) capturing data from custom-built control, transmitter and receiver boards in a separate unit. Once triggered, the sensors in the arrays are scanned simultaneously every 30 mm of vehicle travel, and a continuous bowl shape of strain/displacement versus distance travelled is obtained.

The research conducted at CAPTIF since it began operations in 1987 has contributed to the understanding of the behaviour and performance of thin-surfaced unbound granular pavements and the effect of vehicle dynamics on pavement wear. The purpose of the inaugural project was to commission the SLAVE and evaluate its capabilities and to monitor the performances of four prototype pavements. There was no significant difference in the performances of the four pavements. Unbound granular pavements consisting of compacted well-graded crushed aggregate can sustain large numbers of 80 kN axle load repetitions in the absence of deleterious ground moisture and environmental factors (Pidwerbesky, 1989).

Subsequent projects investigated the comparative rutting of tyre types, the behaviour of lime stabilised subbases, the response of unbound granular pavements to different loading conditions, the effect of binder modification on asphalt pavement performance, and the life-cycle testing of a thin-surfaced unbound granular pavement.

Some of the most significant findings are briefly presented here. With respect to pavement response to loading, and for the specific conditions of the investigation, the tire type (10.00R20 radial and 10.00x20 bias ply) had an insignificant effect on the elastic vertical strain, the tire inflation pressure (between 550 kPa and 825 kPa) had a minor effect on the response of the pavement, and the effect of increasing the wheel load was approximately linear (Pidwerbesky, 1992). The relationship between vertical compressive strains in the materials and the cumulative loadings becomes stable after the pavement is compacted under initial trafficking (in the absence of adverse environmental effects). The actual strain magnitudes measured are substantially greater than the levels predicted by the models that are the basis of current flexible pavement design procedures, for the same number of loading repetitions to failure. In other words, the subgrade strain criterion is very conservative. Any procedures for determining load equivalency factors must also consider the type of pavement and the bearing capacity of the subgrade. The facility has been beneficial in evaluating the performance of aggregates and pavement design assumptions by collecting data describing the long-term performance of pavements, and investigating the relationship between vehicle dynamic loading conditions and the deterioration of pavements for a wide spectrum of pavement and loading characteristics.

2.2 Project Aim

The aim of this project is to determine the impact of dynamic wheel loads on pavement life and pavement performance for typical New Zealand pavements. During the testing comprehensive data on the applied loads, pavement condition and pavement response will be collected. This will provide a basis for validating existing pavement performance models and developing new ones related specifically to New Zealand style pavements.

2.3 Method

This test program is being undertaken at CAPTIF. CAPTIF is unique among accelerated pavement test facilities in that it was designed to generate realistic dynamic wheel loads rather than attempt to eliminate them. The CAPTIF "vehicles" which apply the loads are fitted with suspensions based on actual heavy vehicle components. The original suspension was a two stage multi-leaf steel spring similar to those in common use on New Zealand roads. For the purposes of this project the "vehicles" were modified to enable different suspensions to be fitted. The two other suspensions currently available are a parabolic steel leaf spring with shock absorber, and an air spring also with shock absorber. Both these suspensions are more modern than the original and would be expected to be more "road-friendly".

The CAPTIF "vehicles" can be set up to run in different wheel paths and so by fitting different suspensions to each of the vehicles the performance of a pavement subjected to loadings which are nearly identical in terms of static load and vehicle speed but quite different dynamically can be monitored throughout its life. During each test, at regular load intervals a series of measurements will be taken. These include dynamic wheel forces, longitudinal pavement profile, transverse pavement profile, and strain levels in the various pavement layers.

The program consists of five tests. For four of these tests, the pavement will be constructed to the a design which represents a typical New Zealand chipseal pavement. The other test is part of the OECD DIVINE project and this pavement is designed to represent an in-service pavement in all the participating countries. By European standards, this pavement is weak while in New Zealand, it is relatively strong. In order to compare results between tests, one suspension is being used as a reference and the other will be changed from test to test.

2.4 Current Status

The first pavement tested was a thin-surfaced flexible pavement, consisting of 30 mm asphalt layer, over 250 mm of crushed rock basecourse, over a silty clay subgrade. This pavement had an expected design life of approximately 350,000 standard axle loads.

The CAPTIF "vehicles" were fitted with wide-based single tyres in order to maximise the separation between the wheel paths of the two "vehicles" and were loaded to 3.8 tonnes. One "vehicle" was fitted with the original CAPTIF multi-leaf steel suspension and the other was fitted with a steel parabolic leaf spring and a shock absorber. The suspensions were characterised using an EC (1992) test procedure for rating a suspension "equivalent-to-air". This procedure involves driving the vehicle at crawl speed up a ramp of specified dimensions which culminates in an 80 mm drop and measuring the suspension response. To be rated "equivalent-to-air" a suspension must respond with a natural frequency less than 2 Hz and have a damping greater than 20% of critical with at least half this damping being provided by the shock absorber. The forces measured in this test are shown in figure 1.

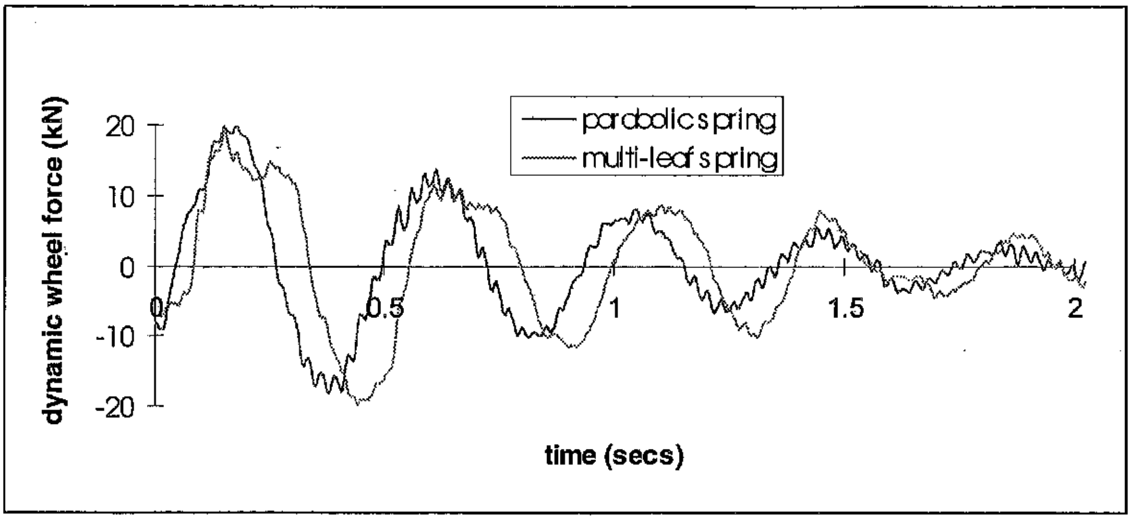

Figure 1. Results of EC bump test

Neither suspension met the above criteria. In the case of the steel multi-leaf spring , this is expected. The parabolic leaf spring used had been selected for the maximum design load of the CAPTIF "vehicles" which is 60 kN and hence is rather too stiff for the actual load of 37 kN. This situation does occur in practice with vehicles being fitted with over-rated springs or operating at lower than design loads. Of greater concern was the relatively low level of damping (8-9%) provided by the shock absorber. To some degree this is related to the spring stiffness in that a lower spring stiffness would give a lower value for the critical damping and hence the actual damping would be a bigger percentage of critical. Although considerable testing went into measuring and analysing the performance of this suspension, no simple solution for altering it substantially was found and because of timetabling requirements for the following pavement test, the loading trial proceeded. The two suspensions used have qualitatively different dynamic characteristics as shown in figures 1 and 2 but could not clearly be classified as having significantly different "road-friendliness".

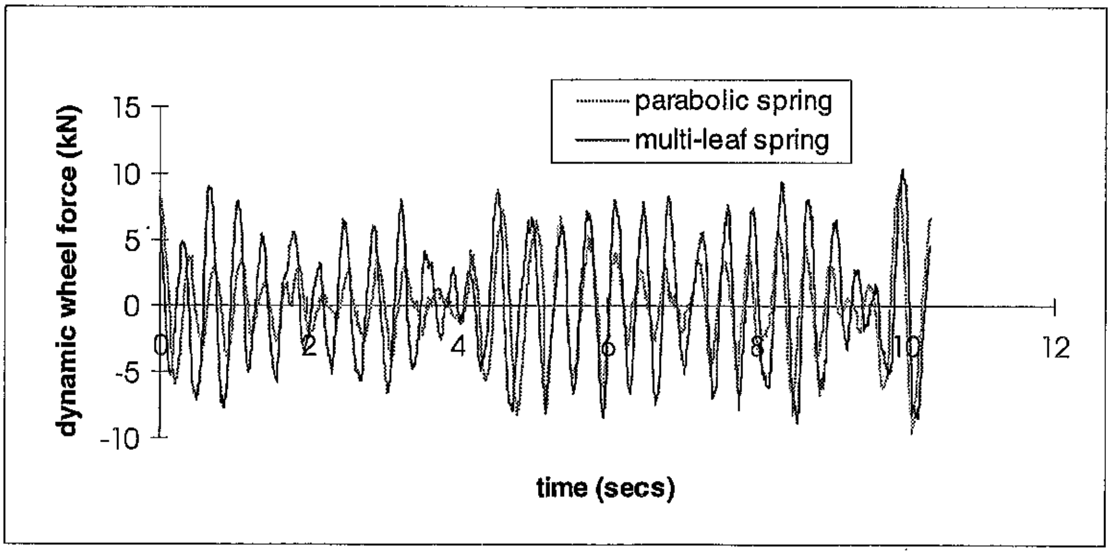

Figure 2. Wheel forces at 20 kph

Table 1 below shows the dlc values measured for the two suspensions at the start of the test.

Table 1. Dynamic Load Coefficient vs Speed.

Speed	*Vehicle with multi-leaf spring*	*Vehicle with parabolic spring*
20	0.126	0.084
45	0.120	0.164

The pavement failed after only 35,000 load cycles (ie at approximately 10% of design life). Because of this rapid failure, only three measurement cycles were completed. The failure was localised with severe rutting and cracking of the surface. It was significantly more severe in the wheel path of the parabolic spring suspension. On excavation of the pavement it appeared that the failure was caused by post-construction compaction of the basecourse layer indicating inadequate compaction during construction. There is a correspondence between the peak wheel forces applied to the pavement and the locations of the major damage zones as indicated by dips in the profile, particularly for the parabolic spring suspension as shown in figures 3 and 4. This is the first measured evidence of a direct link between peak dynamic loads and pavement damage ever reported. A more detailed analysis of the results is yet to be completed.

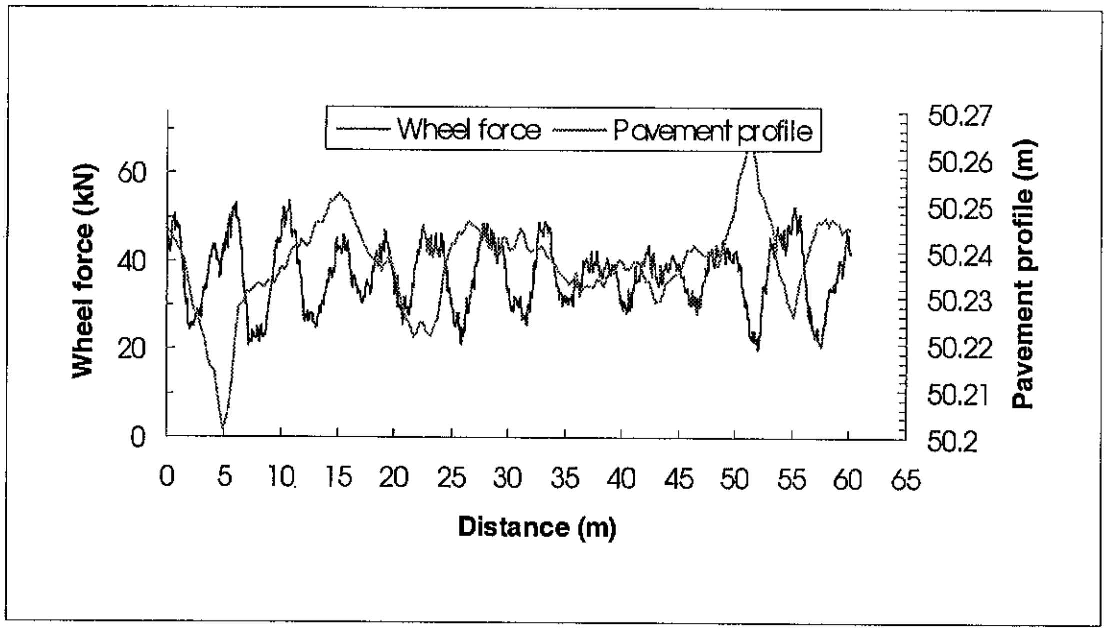

Figure 3. Wheel forces and pavement profile for multi-leaf spring.

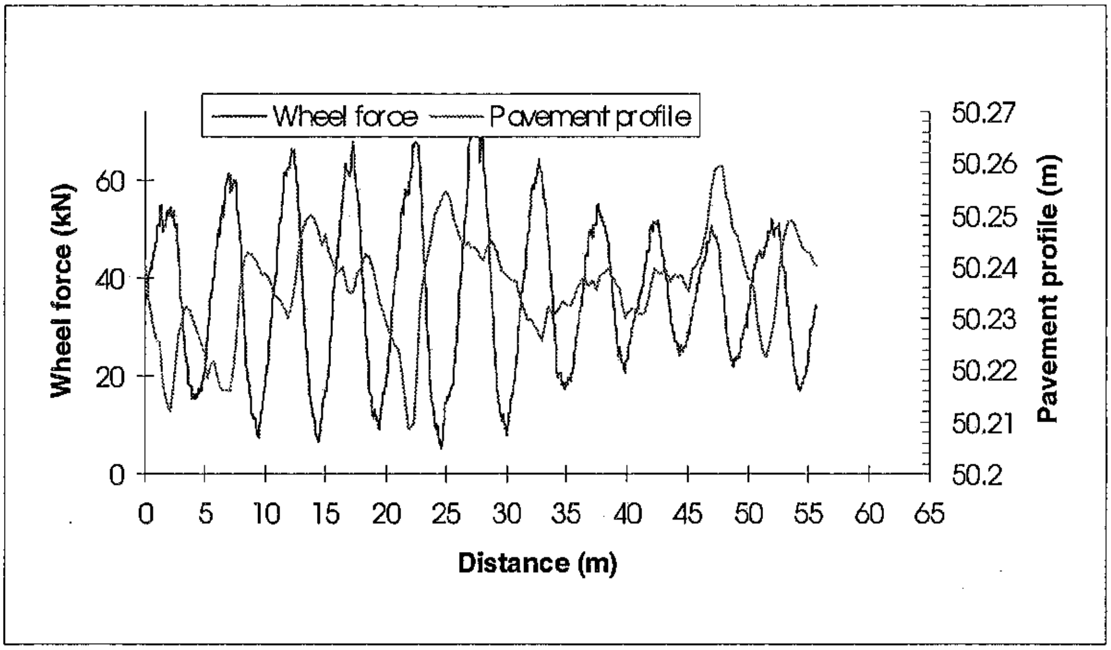

Figure 4. Wheel forces and pavement profile for parabolic spring.

The next test in the program is the one to be undertaken for the OECD DIVINE project. For this test, the pavement design consists of 80 mm of asphalt over 200 mm of crushed rock basecourse over a silty clay subgrade. The "vehicles" will be fitted with the multi-leaf steel suspension on one and an air suspension with shock absorber on the other. The suspensions will exhibit considerable differences in dynamic behaviour. Each vehicle will be loaded to 50 kN and will run on wide-based single tyres. The pavement is being extensively instrumented and a large number of measurements will be taken after each set of load applications. Currently, pavement construction has just been completed and vehicle testing is in progress.

3. SUSPENSION ASSESSMENT RESEARCH

3.1 Aims

The aim of this project is to develop a technique for assessing the dynamic performance of a heavy vehicle suspension in terms of "road-friendliness" using a small scale general purpose servohydraulic shaker facility.

3.2 Methodology

The underlying concept behind this project is the notion that if the suspension could be made to exhibit the same displacement behaviour on the shakers as it did on the pavement then the reaction forces at the wheels would be the same as they were on the road and could be measured directly at the support platforms on the top of the shakers. This would enable the wheel forces to be monitored without using vehicle-based strain gauges or wheel force transducers. Instrumentation would still be required to measure the suspension deflections and axle accelerations but this is simpler and cheaper to fit and calibrate.

To validate this concept a liquid tanker trailer with steel spring suspension was comprehensively instrumented to measure wheel forces, suspension deflections, and both chassis and axle accelerations. This vehicle was then road tested on five sites each at three speeds. The vehicle was then returned to the laboratory and mounted on a two post servohydraulic shaker facility so that both wheels on one side of the tandem axle group could be excited. A complex software control algorithm was developed so that by an iterative calculation process the shaker excitation signals needed to produce the suspension displacements measured on the road could be determined. Once this is achieved the wheel forces can be measured and compared with the on-road values. This work is described in more detail by de Pont (1993). The road profiles of the test sites and the dynamic characteristics of the vehicle were also measured. It is intended that in the longer term a relationship between these values and the shaker excitations can be established and thus the need for a road test can be eliminated.

This validation process was repeated for the same vehicle fitted with air suspension and then also with a changed pitch inertia. This was achieved by loading the vehicle with lead concentrated at the ends instead of with water which is uniformly distributed.

Finally, to inter-relate the two projects, one of the CAPTIF "vehicles" will be demounted from the rig and mounted on one of the servohydraulic shakers. The measured dynamic behaviour recorded during the pavement tests will be replicated, and all the suspension configurations evaluated. This will enable the shaker system to be tested with a simplified vehicle which should make it easier to isolate differences between the road and laboratory tests. In the CAPTIF testing, the pavement condition is measured much more comprehensively than is practicable with the road vehicle tests and so much more complete data will be available for model validation. From the CAPTIF test program viewpoint, these tests will calibrate the wheel force measurement instrumentation and will provide the link between its "vehicles" and the real vehicle fleet.

3.3 Current Status

The tests with the steel suspension have been completed. Considerable development work was undertaken on the shaker control software (de Pont 1992). The algorithm now achieves a good match between the road and laboratory suspension motions in a reasonable number of iterations. For the steel spring suspension, once this match of suspension deflections was achieved, there was a good match between the wheel forces, as shown in figure 5.

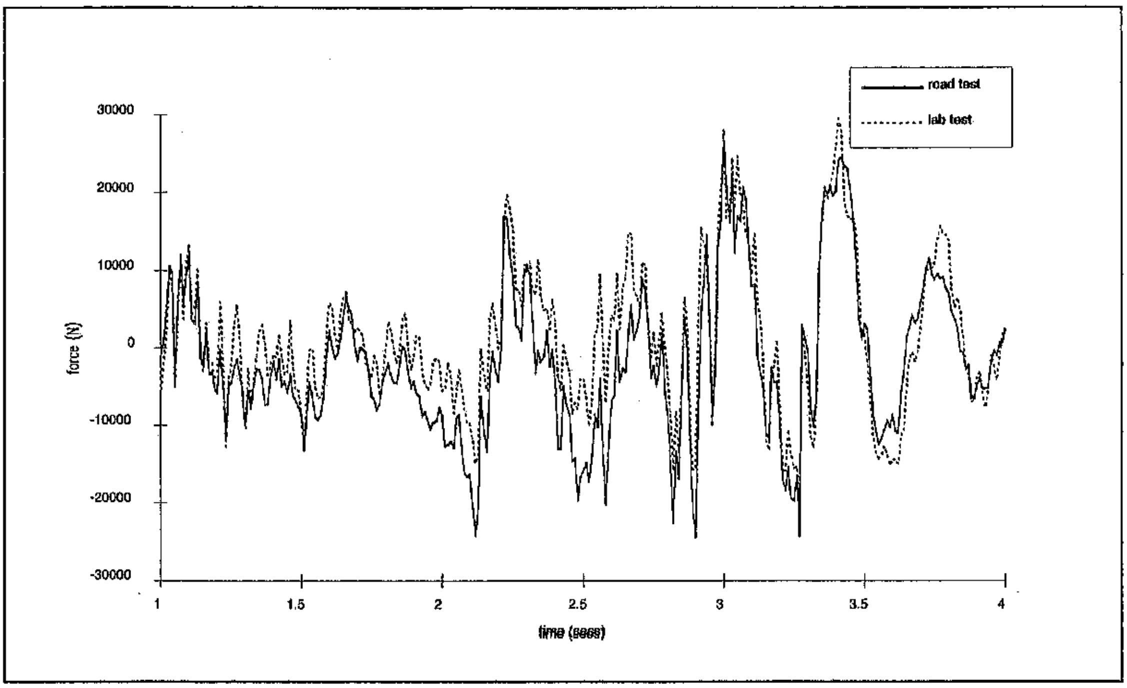

Figure 5. Comparison of Wheel Forces.

Road tests of the same vehicle fitted with the air suspension, with both water and lead loading, have been completed. Following this, shaker tests were conducted as before. As with the steel suspension, the shaker control algorithm successfully determined the excitations required to replicate the on-road suspension deflections. However, the vehicle motions these generated were much more vigorous than those observed during the road tests and the wheel forces were substantially (4-5 times) higher. In fact, only the smoother test sites could be simulated safely. After considerable head-scratching and checking, it was postulated that the auxiliary roll stiffness generated by the suspension geometry was greater than that of the air springs themselves. Shaking the wheels on only one side of the vehicle induces roll motion in the vehicle which generates a reaction force from the auxiliary roll stiffness without a corresponding suspension deflection. With the steel leaf springs, the auxiliary roll stiffness was significantly less than that of the suspension springs and this effect was not significant enough to be observed.

To test this hypothesis the vehicle was mounted transversely on the shakers so that both wheels of one of the axles could be excited. This eliminates all roll behaviour but does not account for load sharing effects. The result of this test produced wheel forces which, although still too high, were considerably closer to those measured on the road. This remaining discrepancy was probably caused by only shaking one axle and thus not replicating the load sharing between the two axles. Subsequently the vehicle supports on the shakers have been modified so that each servohydraulic ram can shake both wheels of an axle. Thus a tandem axle set can be tested with two rams as long as roll behaviour is ignored. A number of studies in the past have shown that, except on very rough roads, vehicle roll is not significant. Shaker tests with this new rig are currently in progress.

4. INTEGRATION WITH OECD DIVINE PROJECT

The OECD DIVINE project described by Mitchell (1994) and Sweatman (1994) at this conference is an international effort aimed at addressing some major issues in vehicle/pavement interaction. Two of these issues are those being addressed by the two projects outlined here. These projects have been adapted to fit in with the OECD program in order to maximise the benefits to New Zealand. Both authors of this paper are participants in the OECD expert group undertaking this research.

In the case of the accelerated pavement testing project, the corresponding OECD research element is being conducted at CAPTIF. The pavement used in this is not typical of New Zealand construction practice but is acceptable to pavement engineers from other OECD countries as being representative (although weaker) of their pavements. The results will be cross-referenced to other pavements used in the other research elements of the DIVINE program and through pavement behaviour models to pavements used in other research. By using the same suspensions on a New Zealand style pavement in a subsequent test it will be possible to relate the performance of this type of pavement to the more universally used flexible pavements.

Research element three of the OECD program involves servohydraulic shaker testing of vehicles and also has an aim of investigating potential suspension assessment techniques. The results of this work will be available to the New Zealand project and will provide additional input for validating the models relating road profiles to shaker excitations. The shaker control software developed as part of the New Zealand project has been made available for use with the shaker facility at the Federal Highways Administration in the United States which will conduct tests as part of the DIVINE project. The shaker testing of the CAPTIF "vehicle" will provide an important cross-link between both the two New Zealand projects and from the New Zealand projects to the other DIVINE projects.

5. CONCLUSIONS

Two major issues relating to the dynamic interaction of vehicles and pavements have been identified and research projects to resolve them have been initiated. The importance of these issues has been corroborated by an OECD scientific expert group on dynamic loading of pavements who recommended an international coordinated research program to address these and other related issues. The New Zealand projects are an integral part of this OECD program but also go further in looking to particularise the results to the New Zealand situation.

ACKNOWLEDGMENTS

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