The Impact Of Vehicle Dynamics On Pavement Performance

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ABSTRACT

Models of pavement performance generally include the effects of traffic loading on the basis of static axle loads and numbers of applications. Vehicle dynamic effects are included implicitly when the models are validated but are not taken into account explicitly. On the other hand, it is recognised that different heavy vehicle suspensions produce different levels of dynamic loading on the pavement. From the simplest pavement performance models (fourth power law) and some assumptions it has been deduced that lower dynamic loads will produce lower levels of pavement wear. This is a derived result which has not been validated.

A program of testing is currently being undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to investigate the influence of vehicle dynamics on pavement performance. The first test in this program has been completed. The second test which is part of an internationally funded research program coordinated through the Organisation for Economic Cooperation and Development (OECD) is currently in progress.

CAPTIF is unique among accelerated pavement test facilities in that it has been designed to apply loads which have dynamic characteristics similar to those of the in-service vehicle fleet. The two CAPTIF "vehicles" which apply the loads are effectively each a quarter truck and use standard heavy vehicle suspension components. For the purposes of this work the "vehicles" have been modified so that different suspension types can be fitted. For the current test, one "vehicle" has an air spring suspension with viscous damping while the other has a multi-leaf steel spring which relies on inter-leaf friction for its damping. The two "vehicles" operate in separate wheel paths on the same pavement. The pavement has been extensively instrumented so that longitudinal and transverse strains in the asphalt, and vertical strains in the basecourse and subgrade can be monitored. The changes in pavement condition as reflected by the longitudinal and transverse profiles, rutting and cracking are monitored.

This paper describes the experimental program in depth and explains the pavement design, construction and instrumentation, the vehicle configurations and performance and the testing undertaken. It presents the results of the two tests showing changes in dynamic loading behaviour, pavement response and pavement condition with increasing numbers of applied load cycles.

INTRODUCTION

In recent years considerable research has been undertaken to measure the dynamic wheel forces applied by heavy vehicles to pavements, for example, Whittemore et al (1970), Sweatman (1983), Hahn (1985), Woodrooffe et al (1986), and Mitchell and Gyenes (1989). There are a number of key findings which are reasonably consistent for all the research. Dynamic wheel forces depend on road roughness, suspension type and vehicle speed. If the dynamic wheel forces are sampled in the time domain, the resulting distribution is approximately normal and thus a measure known as dynamic load coefficient (DLC), which is defined as the standard deviation of the dynamic wheel forces normalised by the mean wheel force, is used to characterise the behaviour. The spatial distribution of wheel forces is highly repeatable for a given vehicle traversing a given pavement at a given speed. There is some evidence of spatial repeatability of the wheel force distribution for the mixture of vehicles and speeds that occurs on in-service pavements (Gyenes and Mitchell, 1992). Research is continuing is this area.

The influence of suspension type on dynamic wheel forces is significant. On roads of moderate roughness a "good" suspension could generate DLC values less than half those of a "poor" suspension (Mitchell and Gyenes, 1989). However, what actually matters is not the level of dynamic loading is but what its effects on pavement wear and pavement performance are. Eisenmann (1975) proposed an approach for estimating the pavement wear implications of dynamic loading which has been widely used. He assumes that the dynamic wheel loads come for a random normal distribution and that the relationship between wheel loads and pavement wear follows the fourth power law derived from the AASHO road test. Thus by taking the expected value of the fourth power of the wheel load he derives a "dynamic road stress factor", ν which can be calculated as follows,

$$v = 1 + 6 * DLC^2 + 3 * DLC^4 \quad (1)$$

The normal distribution assumption implies a random spatial distribution of wheel forces. As mentioned previously there is some evidence to the contrary. The fourth power law was derived from experiments in which the applied wheel forces were dynamic. This approach applies the fourth power law independently to both the static and dynamic components of wheel force.

There have been other approaches to predicting the pavement wear impact of dynamic wheel forces which have tried to allow for the perceived shortcomings of the Eisenmann method. One approach used by Sweatman (1983) is to consider the 95th percentile dynamic loads and applied the fourth power law to these. This assumes a degree of spatial repeatability and thus that the damage at peak load locations is the critical factor in pavement life. Cebon (1985) developed a series of criteria using models of pavement response.

All these approaches suffer from a lack of experimental data from which they could be validated. The research programme described in this paper aims to provide the data necessary to develop credible models for relating dynamic wheel loads to pavement wear and pavement performance. A series of accelerated pavement tests are being conducted on the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) comparing the performance of pavements under wheel loads which are identical statically but quite different dynamically.

THE CAPTIF FACILITY

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. An elevation view is shown in figure 1.

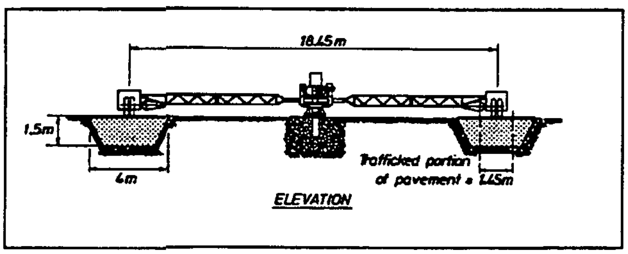

Figure 1. Elevation view of CAPTIF

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 to the Simulated Loading and Vehicle Emulator (SLAVE) units shown in figure 2. The arms are hinged in the vertical plane so that the SLAVEs can be removed from the track during pavement construction, profile measurement etc. and in the horizontal plane to allow vehicle bounce.

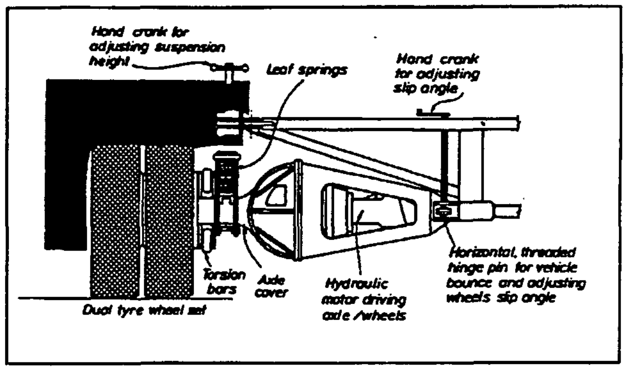

Figure 2. SLAVE vehicle unit.

The SLAVEs consist of an axle-wheel assembly with an attached hydraulic drive motor which is connected by a suspension system to a frame on which weights are hung. As much as possible these SLAVEs use standard heavy vehicle components. They can operate with wheel loads between 21 kN and 60 kN and at speeds up to 50 km/h. The "vehicles" can be fitted with air springs, parabolic steel leaf springs or trapezoidal multi-leaf steel springs, with or without shock absorbers. As the ratio of the sprung to unsprung mass is typical of real heavy vehicles and the suspensions use standard heavy vehicle components, the dynamic characteristics are very realistic in terms of the natural frequencies and relative magnitudes of the modes of vibration. The facility is housed within a building which, although not environmentally controlled, protects the pavement from precipitation and direct sunlight.

Pavement instrumentation which is used at CAPTIF (Pidwerbesky, 1989, 1992) includes: bison coil transducers for measuring vertical strains in the basecourse and subgrade layers of the pavement, h-bar strain gauges for measuring horizontal strains at the bottom of the asphalt layer in both the longitudinal and transverse directions and partial depth gauges for measuring the pavement layer deflections. As well temperature probes are used to monitor both the pavement and air temperatures. The vehicle instrumentation consists of accelerometers mounted on both the sprung and unsprung masses of each "vehicle" and displacement transducers to measure suspension displacements. As the "vehicles" are a fairly simple quarter vehicle structure, wheel forces can be calculated by combining the two accelerometer signals weighted by appropriate mass factors. Other measurement systems used at CAPTIF during testing are: a Falling Weight Deflectometer (FWD) which is used to monitor pavement condition by measuring the deflection response to loads applied by a falling weight, the CAPTIF deflectometer which is a modified Benkelman beam which also measures pavement deflection response but to loads applied by the wheels of the SLAVE unit, a DIPstick profiler which is used to measure the longitudinal pavement profile, and a transverse profilometer. Recently a laser profilometer has been installed which supplements the DIPstick.

THE EXPERIMENTAL PROGRAMME

The aim of the work is to determine the influence of dynamic wheel loads on pavement wear and pavement performance. The research began as a local New Zealand based programme focussing on New Zealand style pavements. Most pavements in New Zealand are thin surface unbound structures where the surfacing provides waterproofing and a running surface but contributes little to the pavement strength. The initial programme plan was to test up to five pavements using a typical New Zealand pavement design with each test comparing two different suspensions. To minimise the variability, the pavement design was to be identical and one of the suspensions would be common for each test. At the time this programme commenced the CAPTIF "vehicles" operated with only one suspension type, the steel multi-leaf spring. The first part of the project involved modifying the "vehicles" to accommodate different suspensions. While this work was underway, the OECD Dynamic Interaction Vehicle-INfrastructure Experiment (DIVINE) coordinated research programme was initiated. CAPTIF was selected as the site for element one of this programme which is an accelerated pavement test. This project has become the second pavement test in the series. However, the international nature of the OECD research has meant that a different pavement design was needed for this test.

PAVEMENT DESIGN

For the thin surface pavements, the design consists of a 30 mm asphalt layer, over 250 mm of crushed rock basecourse, over a silty clay subgrade. Using the Transit New Zealand pavement design guides, this pavement has an expected life of approximately 350,000 standard axle loads. This pavement was not suitable for the OECD test. The surface layer is considered too thin for this to behave like a typical flexible pavement as commonly used in many of the OECD member countries. Thus for the OECD test the pavement design used was 90 mm of asphalt over 200 mm of crushed rock basecourse over a silty clay subgrade. This is still a relatively weak pavement by European and North American standards but is considered sufficiently representative in terms of its structure for the experiment to have credibility with the pavement engineering community. It was necessary for the design to be at the weaker end of the spectrum in order for pavement failure to occur within a reasonable time frame.

PAVEMENT INSTRUMENTATION

For the tests with the thin surface pavements the instrumentation requirements are relatively simple. The surface is assumed not to contribute significantly to the pavement strength and so the important factors are the vertical strains in the basecourse and subgrade layers. To monitor these bison coil transducer sets are placed at six locations in the centre of each wheel path at one metre spacings. Each transducer set consists of four coils which are placed at the top of the basecourse, at the basecourse-subgrade interface, and at depths of 100 mm and 200 mm into the subgrade. From these the strains between each adjacent coil pair can be measured.

In the OECD pavement the surface layer is an important part of the structure. To monitor the horizontal strains in this layer, forty h-bar transducers were placed at the bottom of the asphalt. These consist of twenty in each wheel path of which half are in the longitudinal orientation and half in the transverse. The orientations alternate between adjacent gauges which are at 0.5 m spacing. The vertical strains in the lower layers are measured with the same array of bison coils as for the thin surface pavements. As a cross-check on these, three partial depth gauges were placed in each wheel path to measure deflections of the asphalt, basecourse and upper subgrade layers respectively.

For all tests an array of twelve temperature probes record the asphalt and air temperatures around the track.

VEHICLE CONFIGURATION

The CAPTIF "vehicles" are capable of being fitted with single, wide-based single or dual tyres. The two "vehicles" arms are connected so that radial movement of one of the "vehicles" results in a corresponding movement of the other "vehicle". The total movement available is one metre. With this mechanism the two "vehicles" can be set up to operate in independent wheel paths. The same mechanism is used to generate lateral wander for each "vehicle". The width of the untrafficked area between the two wheel paths is determined by the tyre widths and the level of lateral wander used. To maximise the separation while retaining acceptable operating conditions it was decided to use wide-based single tyres and to make the lateral wander normally distributed with a standard deviation (σ) of 50 mm but restricted to limits of $\pm 2\sigma$.

For the tests on the New Zealand style pavement the "vehicles" were loaded to 3.7 tonnes (7.4 tonne axle load) which is approximately equal to the equivalent design axle (EDA) for wide-based single tyres in the New Zealand pavement design guides. For the OECD test pavement the wheel load was increased to 5 tonnes (10 tonne axle). This is equivalent to the EC limit for a single drive axle fitted with wide single tyres.

The first test using the thin surface pavement was conducted with a traditional multi-leaf steel suspension on one "vehicle" and a modern two leaf parabolic steel spring with viscous damper on the other. The OECD test compares a multi-leaf steel spring with an air spring and viscous damper.

The EC (1992) have proposed criteria for suspensions to be considered "equivalent-to-air" for regulatory purposes. These specify a maximum natural frequency (2 Hz) and a minimum damping level (20%) which must be at least 50% viscous. Associated with these criteria are several approved test methods for measuring the parameters. One of these involves driving the vehicle at crawl speed up a specified ramp which culminates with an 80 mm vertical drop and measuring the suspension response. One of these ramps has been built at CAPTIF and is used to characterise the suspensions and to monitor their condition during testing.

TESTING PROGRAMME

The basic test programme for each test is as follows. During construction extensive quality control tests are undertaken so that the properties of the materials and the resulting pavements are well documented. Following construction the pavement is conditioned by running the vehicles for 5000 laps or so. For these laps the lateral wander is varied so that both "vehicles" transverse the entire trafficable width. This is followed by a set of zero measurements which aim to characterise the system as completely as possible. The test then proceeds as an alternating sequence of load applications and measurements. In the beginning a relatively small number of loads are applied between measurements. This increases as the pavement stabilises and the changes between measurements are observed to be small.

THE FIRST PAVEMENT TEST

The first pavement test was conducted on the thin surface pavement design using 7.4 tonne axle loads and comparing a parabolic steel leaf spring with viscous damping with multi-leaf steel spring with no additional damping. Because of all the vehicle modifications and measurement systems which were developed and/or modified for this programme, the first test ended up more as a testing prototype for the systems than a complete test. In spite of this some interesting results were obtained.

The results of the EC ramp test for the two suspensions are shown in figure 3. From this it can be seen that the natural frequency of the parabolic spring was, in fact, slightly higher than that of the multi-leaf spring and that its damping rate was similar. It was intended that the parabolic spring suspension would be more road-friendly than the multi-leaf and thus it was expected that it would have a lower natural frequency and higher damping. The reason this was not so appears to be that the parabolic spring was selected to cope with the maximum load the CAPTIF "vehicles" can operate with which is 60 kN. The actual static wheel load used for this test was 36 kN. Consequently the spring was underloaded and the natural frequency was higher than intended. This illustrates the negative effects of using over-rated springs - a practice which is not uncommon in New Zealand.

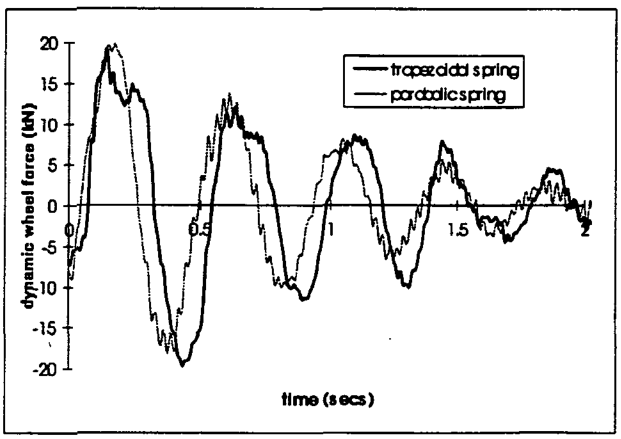

Figure 3. Bump test wheel force measurements.

The steady speed DLC values measured for the two vehicles at the start of the test are given in Table 1.

Table 1. Dynamic Load Coefficient vs Speed.

Speed	Multi-leaf spring vehicle	Parabolic spring vehicle
20	0.126	0.084
45	0.120	0.164

While the two vehicles cannot clearly be ranked in terms of relative road-friendliness their performance is clearly different from each other.

The pavement failed unexpected after only 35,000 load cycles (design life 350,000 cycles) with the profile under the parabolic suspension becoming so rough that it was impossible to continue operating safely. A post-mortem excavation of the pavement indicated that inadequate compaction of the basecourse layer at construction was a major factor in the failure. Because the failure occurred so rapidly only three measurement cycles were completed and thus insufficient data are available for detailed analysis. Nevertheless a comparison of dynamic wheel forces with longitudinal profile at failure as shown in figures 4 and 5 demonstrates a good degree of correlation between the wheel forces and pavement profiles. This result is, of course, expected but has never been measured before.

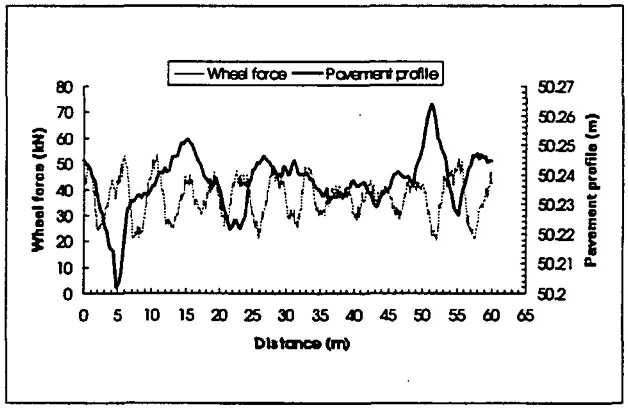

Figure 4. Wheel force vs pavement profile for multi-leaf steel spring.

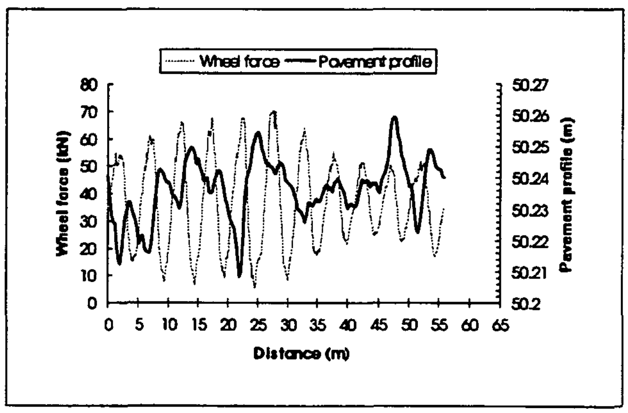

Figure 5. Wheel forces vs pavement profile for parabolic spring.

It appears from figure 3 that the parabolic spring is more linear in its behaviour as the shape of the response is more sinusoidal. This means that the wheel force distribution is likely to remain spatially repeatable as the amplitude increases. Coupled with the low levels of damping, this explains why this suspension was more damaging. This is clearly illustrated in figure 5 where the low frequency bounce behaviour generates high wheel forces which are only lightly damped.

THE OECD DIVINE PAVEMENT TEST

The OECD DIVINE test is being conducted using the flexible pavement design described previously using an air suspension on one "vehicle" and a multi-leaf steel spring suspension on the other. Because of the nature of DIVINE as an international coordinated research programme there is a need to be able to transfer the results and to relate them to the other research elements and so the range of measurements taken has been very comprehensive.

CONSTRUCTION AND MATERIALS TESTS

Prior to construction the subgrade and basecourse materials were subjected to a series of Proctor tests to determine optimum moisture content and densities. They were then subjected to repeated load tri-axial testing in accordance with AASHTO procedure T292. The asphalt mix design was done using the Marshall method and samples of the asphaltic concrete were be subjected to dynamic creep, static creep, indirect tension and fatigue tests by the Australian Road Research Board (ARRB) at their Melbourne laboratory. Quantities of all materials have been stored in case of a need for further testing.

The construction process was monitored intensively. The fines and crushed rock were be placed in lifts not exceeding 150 mm in thickness. At the completion of each lift the densities were measured at 1 m stations along three centrelines, which were the two wheel paths and a point midway between. At the top of the subgrade and basecourse layers, 12 sets of readings were taken where the densities were measured at 0.5 m intervals transversely across the full 4 m width of the track. The emphasis was on keeping the transverse variability to an absolute minimum. The large number of transverse measurements is aimed at demonstrating this.

The levels of each layer were determined using a profile beam with measurements being taken at 1 m intervals circumferentially and at 0.2 m intervals radially.

To monitor the transverse variability of the layers, a parameter equal to the difference in thicknesses between wheel path centres was calculated at each station for each layer. The aim was that this difference parameter should have a mean less than ± 3 mm and a standard deviation of less than 11 mm for the crushed rock basecourse layer (the maximum particle size of this material is 20 mm) and a mean less than ± 0.8 mm and a standard deviation less than 3 mm for the asphalt layer (the maximum particle size in this layer is 16 mm). The tolerances on the mean values are based on the 95% confidence interval for a mean of zero, given the standard deviations quoted and 58 sample points.

For the actual pavement the values achieved were: mean = -1.0 mm and standard deviation = 5.4 mm for the basecourse, and mean = -0.7 mm and standard deviation = 3.9 mm for the asphalt layer. The last value is slightly higher than the target.

To monitor the pavement's structural capacity, FWD tests were conducted at the top of each of the layers.

ZERO MEASUREMENTS

After construction the pavement profiles were measured and 6,000 conditioning laps were applied and the zero measurements commenced. These were very extensive.

The longitudinal profiles were measured in each wheel path and at ± 400 mm from each wheel path. (As the wheel paths are 800 mm apart this is a total of five profiles.) From these profiles IRI values were calculated. These are tabulated below.

Table 2. IRI values at zero loads

	Inner - 0.4m	*Inner*	*Centre-line*	*Outer*	*Outer + 0.4 m*
IRI mm/m	4.8	4.8	4.1	4.1	3.8

There is a trend for IRI values to decrease with increasing radius. The five profiles are reasonably consistent with each other when plotted against angular position. This means that as the radius decreases so also does the wavelength of any particular unevenness feature. This would then correspond to a higher frequency and hence generate a higher IRI. During testing this is offset by the inner vehicle operating at a lower speed than the outer. The ratio of the speeds is exactly the same at the ratio of the wavelengths. The level of IRI values is relatively high for a new pavement. It is thought that this is due to hand-screeding causing unevennesses to be of shorter wavelengths than would be the case with a paving machine.

Transverse profiles were measured at 58 equally spaced intervals (stations) around the track. These showed good levels of uniformity.

The CAPTIF vehicles were loaded incrementally and the tyre and suspensions deflections were measured. Tyre deflections were linear with a calculated stiffness of 1.28 kN/mm. The suspension deflections were much less linear. The vehicles were then subjected to the EC ramp test. The resulting suspension displacements are shown in figure 6

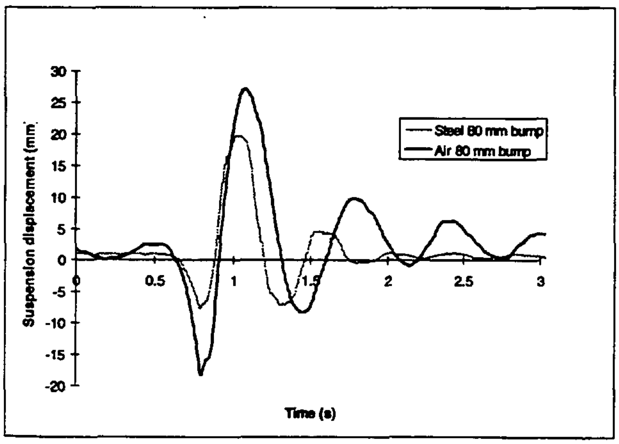

Figure 6. Suspension response to EC bump test.

The natural frequency of the air suspension is significantly lower (1.4 Hz compared to 2.0 Hz) but the damping ratio of the steel is actually higher than the air (26% against 19%) though for the steel suspension all the damping comes from friction. Additional ramp tests were conducted using 30 mm and 60 mm drops.

The steady speed wheel forces were then monitored at a eight vehicle speeds for each vehicle operating in each wheel path. This showed that relatively large speed changes were required to make a significant impact on the spatial distribution of the dynamic wheel forces. Some consideration had been given to trying to reduce the spatial repeatability of the loading by slightly variations in the operating speed. These tests indicated that this would only work if the variations were large and so this was not pursued. For the test operating speed of 45 km/h the DLC values measured were 0.15 and 0.04 for the steel and air suspensions respectively. These values were unchanged when the vehicles were operated in the opposite wheel paths. Thus the two wheel paths generated similar dynamic loading at the start of the test indicating similar roughness levels This supports the comments made previously regarding the change in IRI with radius. Note that the two suspensions generate significantly different levels of dynamic load. Looking at the wheel force spectra provides some insights into this. The air suspension has a fundamental mode at 1.4-1.5 Hz as expected with axle hop modes between 11-13 Hz which are the same order of magnitude. The steel suspension has its fundamental mode at 2.5-2.6 Hz and its axle hop modes between 12-14 Hz but these are considerably lower than those of the body mode. This body mode has a noticeably higher frequency than that measured on the EC ramp. If we calculate the natural frequency of a 5 tonne mass on a spring with the same stiffness as the tyre we get 2.55 Hz. Thus it would appear that the steel suspended vehicle is bouncing on its tyre rather than on its suspension. This motion is only lightly damped and thus explains the much higher levels of dynamic load.

An extensive series of pavement response measurement were conducted by monitoring all the pavement instrumentation under a range of loading conditions. The response to variations in transverse position was recorded by adjusting the transverse position of the vehicles in 50 mm increments from one extreme to the other of the range and monitoring all pavement transducers. These tests were conducted at 45 km/h.

The pavement response to vehicle speed variations was measured by monitoring all the pavement transducers at crawl speed, 42, 45 and 48 km/h. The effect of load was measured by running the vehicles at 45 km/h with 40, 49 and 58 kN loads.

As well dynamic loading was induced using artificial bumps placed on the tracks. The two bumps used were a short (300 mm long x 25 mm high) bump for stimulating axle hop response and a long (4000 mm long x 25 mm) bump for stimulating body bounce. Similar bumps were used in other projects in the DIVINE programme measuring pavement primary response to real vehicle loads and so these measurements were taken to facilitate comparisons between the results of the different projects. These bumps were traversed at 45 km/h. In the CAPTIF environment these bumps represent quite severe excitations. There were problems anchoring the bumps to the pavement and the vehicle motions were large. From reports of the testing with similar bumps in the other DIVINE projects this problem does not occur with real vehicles. It appears that wheelbase effects of whole vehicles reduce the impact of this type of perturbation.

The pavement's structural capacity was measured using both the FWD and the CAPTIF deflectometer in each wheel path at each station. The results of these two sets of measurements were remarkably consistent with the deflectometer measurements approximately 25% higher than the FWD. (This is expected from the difference in the loading method). The differences between the inner and outer wheel paths at each station are small, indicating that, as required, the transverse variability in the pavement is small. The pavement response to FWD loading was also recorded by monitoring the pavement transducers during FWD testing.

THE TESTING PROGRAMME

The testing programme consists of an alternating sequence of applying loads and taking measurements. As it was expected that there would be a settling period during which the pavement would change relatively rapidly followed by a period of stability and also because there was a degree of uncertainty about what would happen, the numbers of loads applied between measurements was planned to be relatively small early on and increase later. The planned sequence was that measurements would be taken after 10, 20, 30, 40, 60, 80, 100, and 150 thousand load cycles and in 50,000 increments from then on up to 500,000 loads when the pavement was theoretically expected to have failed. The pavement was designed using New Zealand pavement design guides to have an equal probability of cracking or rutting failure and a life of 1.5 million EDA. Based on the 5 tonne wheel loads this corresponds to 450,000 load cycles. Experience indicates that generally in ideal environment at CAPTIF, pavements exceed their design life. However, modeling work undertaken by other members of the OECD group, using the measured pavement material properties, predicted failure at much lower numbers of load cycles. The failure criteria set prior to testing are: maximum rut depth greater than 25 mm or cracking greater than $5 m/m^2$ over 50% of the trafficked area.

A complete set of measurements was taken after every third loading cycle. For the two intermediate cycles a reduced set of measurements was conducted. The complete set of measurements consists of:

- pavement performance measurements. The five longitudinal profiles specified previously are measured. The transverse profiles are measured at each station, and any cracking is recorded.
- structural condition monitoring. FWD and CAPTIF deflectometer measurements are undertaken at each station in each wheel path.
- pavement response measurements. All the pavement transducers are monitored under vehicle loading at 45 km/h and at crawl speed.
- vehicle condition monitoring. The EC ramp test is applied to both vehicles.
- wheel force measurements. The dynamic wheel forces are measured for each vehicle in each wheel path at 45 km/h.

For the reduced set of measurements, the longitudinal profiles are measured only in the wheel paths. The transverse profiles are measured only at every station in the instrumented section of the pavement and every fifth station over the rest. FWD testing is not conducted and the set of CAPTIF deflectometer measurements is reduced in the same way as the transverse profiles. Primary response measurements are only taken at 45 km/h and not at crawl speed.

CURRENT STATUS

Pavement testing commenced in November 1994. The 500,000 planned load cycles were completed in early April 1995. Apart from a single localised rut in the wheel path under the steel suspension which exceeded the failure criterion, the pavement has not failed yet. The number of load cycles between measurements has now been increased to 200,000 with some intermediate measurements being conducted every 100,000 cycles. At present (May 1995) 900,000 load cycles have been completed.

Although all the h-bar transducers were operational after construction they have failed progressively during the test and by 300,000 loads none were still functioning. Four channels (out of 23) of the bison coils failed at 400,000 loads. All other transducers are still functioning.

RESULTS AND TRENDS

The test is not yet complete and comprehensive analysis of the data is yet to be undertaken. However, the data to date have been processed and some results and trends can be identified.

A large rut has developed at station 21 in the outer wheel path which is the one being loaded by the steel suspension. This rut which is 5-6 m long was observed as early as 30,000 load cycles and grew very rapidly between 40,000 and 80,000 loads. It then stabilised and currently is increasing at a similar rate to the rutting in the rest of the pavement. It exceeded the failure criterion (25 mm) at about 130,000 load cycles. Although this rut occurred in the wheel path under the steel suspension it is not certain that the higher dynamic loadings caused the rut. It is possible that it was caused by some localised weakness but the structural capacity measurements made during construction and zero measurements (FWD and CAPTIF deflectometer) did not indicate any problems with the pavement in this locality. The post-mortem excavation of the pavement should enable the rutting mechanism to be identified.

More recently pavement cracking has been observed. This appeared at approximately 835,000 load cycles and is mainly in the outer wheel path (steel suspension) although there is some in the inner wheel path.

At the beginning of the test each suspension generated the same level of dynamic loading in both wheel paths. Since 100,000 load cycles both suspensions generate higher dynamic loads in the outer wheel path than they do in the inner one. This is also reflected in the IRI measurements where the value for the outer wheel path has deteriorated by more than the inner, although the changes are relatively small. Thus it appears that the wheel path under the steel suspension has deteriorated by more than the wheel path under the air suspension. Figure 7 shows the progression of IRI on the two wheel paths.

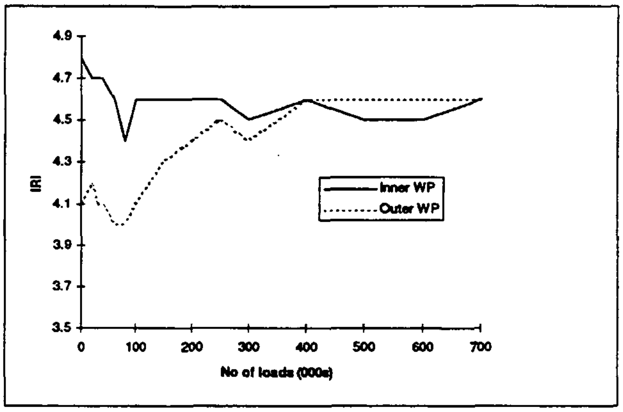

Figure 7. Progression of IRI with loading.

The IRI values at the beginning of the test represent approximately equivalent unevennesses for the two wheel paths. The profiles are quite similar when plotted against angular coordinates which means that any particular feature has a shorter wavelength on the inner profile and generates a correspondingly higher IRI value. This is offset by the fact that the vehicle speeds vary in exactly the same proportion. Taking this into account, it can be seen that the outer wheel path which was subjected to loading by the steel suspended vehicle has deteriorated more than the inner which was trafficked by the air suspended "vehicle".

The DLC values were calculated for each "vehicle" in both its own wheel path and the other "vehicle's" wheel path at each measurement interval. The changes are plotted in figures 8 and 9.

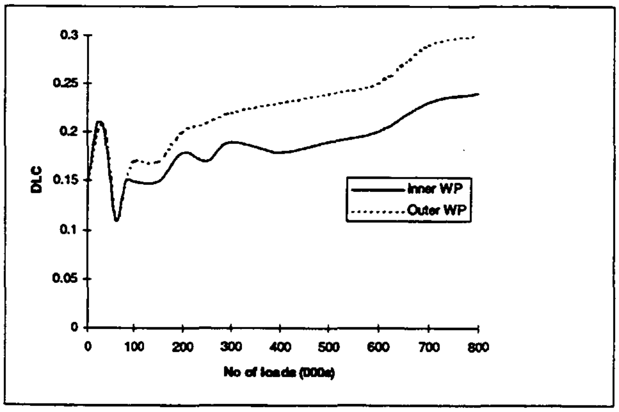

Figure 8. Changes in DLC with loads for steel suspension.

With the steel suspension the trends are clear. The dynamic loading is increasing on both wheel paths indicating an increase in roughness but the changes are greater for the outer wheel path which is the one being trafficked by the steel suspension. The changes for the air suspension are smaller (indicating that the suspension copes better with increasing roughness) but the same pattern is present.

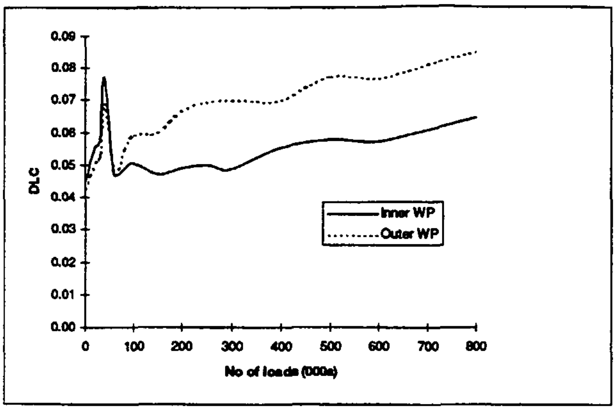

Figure 9. Changes in DLC with loads for air suspension.

The peak strain levels recorded in the pavement under vehicle loadings increased substantially during the first 100,000 load cycles or so and since then have stabilised. Figures 10 - 14 show examples of this trend for each of the strain measurements undertaken.

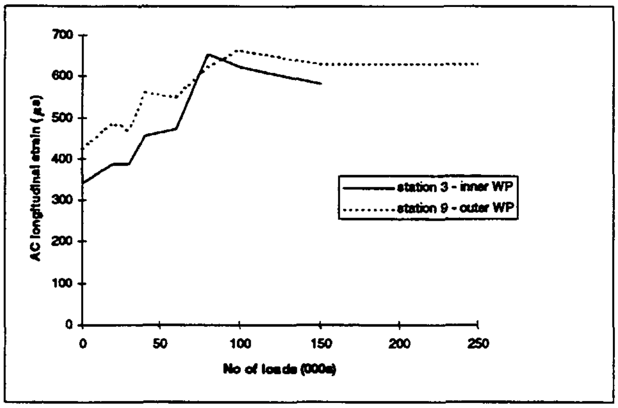

Figure 10. Changes in AC longitudinal strains with loads.

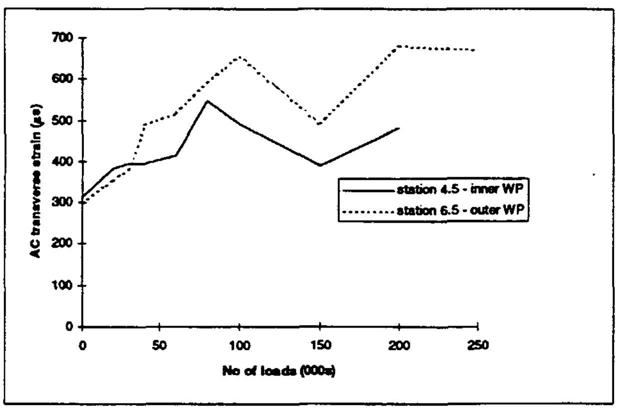

Figure 11. Changes in AC transverse strains with loads.

These figures only show trends. No attempt has been made to compensate for variations in pavement strength between the measurement locations or load variations due to vehicle dynamics. Whether or not there is a difference in strain response behaviour between wheel paths cannot be determined from these figures. The analysis required to establish this is far more detailed and has yet to be undertaken. Note that for the AC strains there are no measurements beyond 250,000 load cycles.

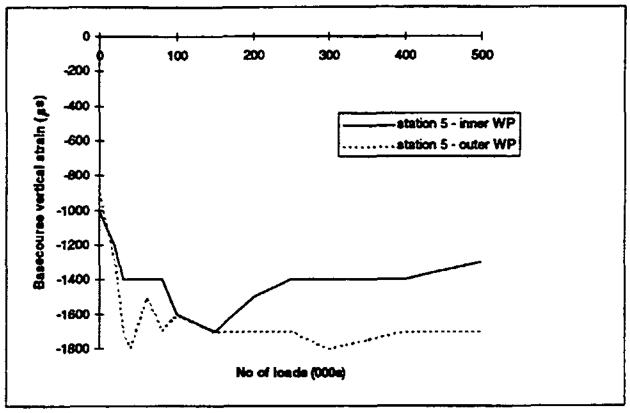

Figure 12. Changes in basecourse strains with loads.

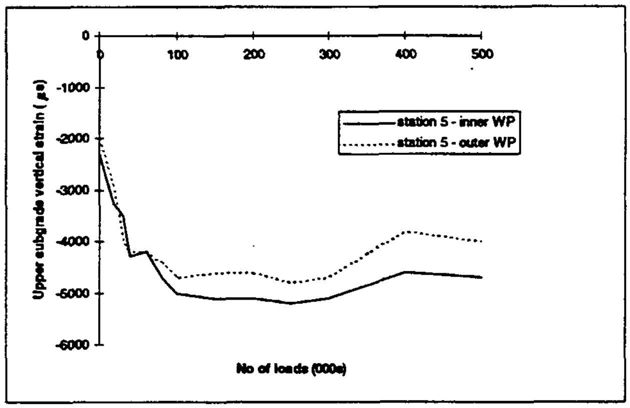

Figure 13. Changes in upper subgrade strains with loads.

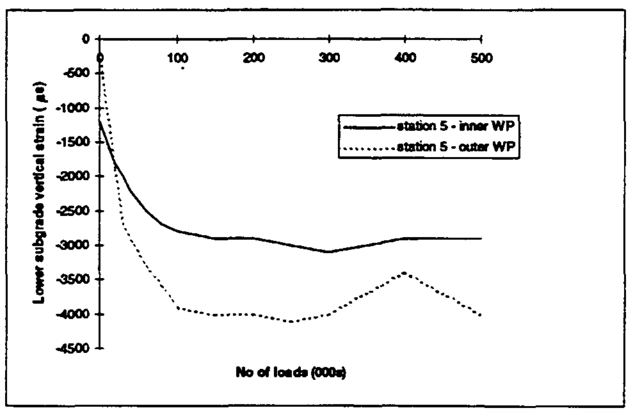

Figure 14. Changes in lower subgrade strains with loads.

CONCLUSIONS

An extended programme of research is currently in progress at CAPTIF to investigate the influence of dynamic loads on pavement wear and pavement performance. CAPTIF was always unique among accelerated pavement test facilities in that it attempts to apply realistic dynamic loads. All other facilities try to minimise dynamic loads. The CAPTIF vehicles have been modified to accommodate different suspension types and thus the characteristics of the dynamic loading behaviour can now be varied.

The first test in the programme was conducted on a thin surface pavement comparing a steel parabolic leaf spring suspension with hydraulic damping against a steel multi-leaf spring suspension with friction damping only. Due to construction defects this pavement failed prematurely. For this reason only limited data were collected and no definitive conclusions could be drawn. Nevertheless the wheel force and pavement profile measurements showed correlations between peak loads and rut maxima. This is, of course, totally expected but to the best of our knowledge has not previously been recorded.

The second test in the programme is being conducted as part of the OECD DIVINE international coordinated research programme. This test has now completed 900,000 load cycles and the pavement is now showing signs of wear. There are some indications that the wear is greater in the wheel path under the steel suspension. A large rut has formed in this wheel path and the cracking which has occurred is mainly in this wheel path. The pavement unevenness has also increased more in this wheel path as indicated by increases in measured IRI and also increased dynamic loads from the "vehicles" when operating in this track.

Pavement strains increased rapidly during the first 100,000 load cycles and have since stabilised. More detailed analysis is required before any differences between wheel paths can be identified. Overall the strain levels observed are high compared to theoretical expectations but in spite of this the pavement has generally performed well.

The quantities of data being collected during this experiment are immense and should provide a valuable resource for modeling and analysis studies well beyond the immediate project.

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