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SUSPENSION DYNAMICS AND PAVEMENT WEAR

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Recently a series of three accelerated dynamic loading tests was carried out at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF). The aim of these tests was to determine the influence of dynamic loading on pavement wear.
This paper presents an investigation into the relationships between the permanent vertical surface deformation (VSD) of the pavement, the applied dynamic wheel loads and the pavement structural stiffness. It is shown that the VSD was correlated with both the pavement stiffness and the dynamic wheel forces but that the relationship with wheel forces was highly dependent on the level of dynamic loading. A surrogate measure for pavement strain formed by combining pavement stiffness and wheel force into a single parameter provided the strongest correlation with VSD. Using this "strain" parameter as the independent variable of a power law predictor for VSD gives a best fit estimate for the exponent between one and two.

Key Words: dynamic wheel loads, accelerated pavement testing, pavement wear, suspension dynamics, road-friendliness.

1. Introduction

The concept of 'road-friendly' suspensions that reduce the amount of pavement wear for a given load, speed and road roughness conditions, has been the subject of considerable study in recent years (Addis *et al.* [1]; Cebon [2]; Cole and Cebon [3]; de Pont *et al.* [5]; OECD, [4]; Sweatman [9]; Woodrooffe *et al.* [10]). Underlying this concept is the notion that, if a suspension produces lower levels of dynamic loading on the pavement, this will reduce the pavement wear caused. Various approaches to determining the relationship between dynamic loads and pavement wear have been used. The best known and most widely used method is that of EISENMANN [7] who applied the fourth power rule to dynamic loads. The fourth power rule is used to relate static loads to pavement wear. Implicit in Eisenmann's analysis is an assumption that the dynamic wheel loads from the vehicle are randomly distributed in space along the pavement. This has been shown not to be the case. CEBON [2] used a more sophisticated approach of determining the load distributions by pavement location and relating these to pavement deterioration through models of the pavement wear mechanisms. This work is primarily based on computer modelling. Apart from the three accelerated dynamic loading pavement tests on which this paper is based, there have been no experimental studies relating pavement performance to dynamic loads.

In the context of the New Zealand situation there is a further issue related to the typical pavement designs used. Nearly all of the New Zealand highway network consists of thin-surfaced unbound pavement structures. While this type of structure is also widely used in Australia and South Africa, in North America and Europe its use is very limited. As a consequence, relatively little of the research on pavement performance considers this type of pavement structure. Results from thicker asphaltic concrete (AC) pavements are interpreted and extrapolated and then applied. For this reason two of the three tests were undertaken using thin-surfaced unbound pavements.

2. EXPERIMENTAL PROGRAMME

The data on which this study is based were obtained from a series of three accelerated pavement tests undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) between 1993 and 1998.

CAPTIF consists of a 58 m long (on the centreline) circular track contained within a 1.5 m deep × 4 m wide concrete tank so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame that can move horizontally by 1 m. This radial movement enables the wheel paths to be varied laterally and can be used to have the two "vehicles" operating in independent wheel paths. Elevation and plan views are shown in Figs. 1 and 2.

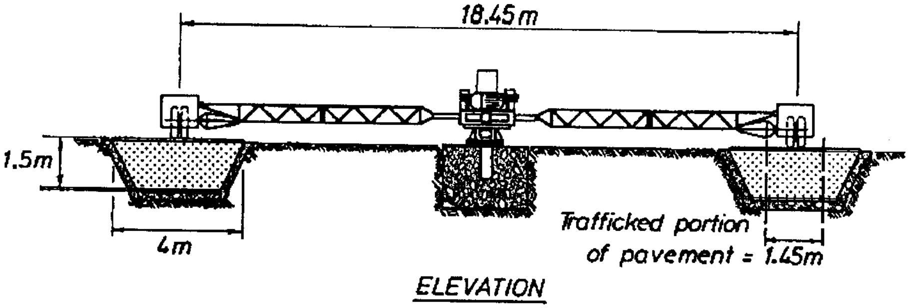

FIG. 1. Elevation view of CAPTIF.

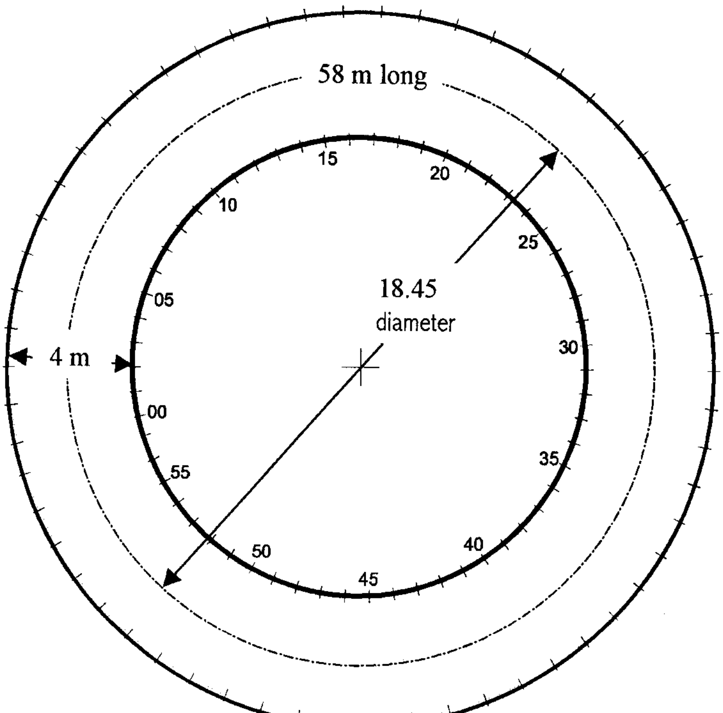

FIG. 2. Plan view of CAPTIF.

At the ends of this frame, two radial arms connect to the Simulated Loading and Vehicle Emulator (SLAVE) units shown in Fig. 3. These 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.

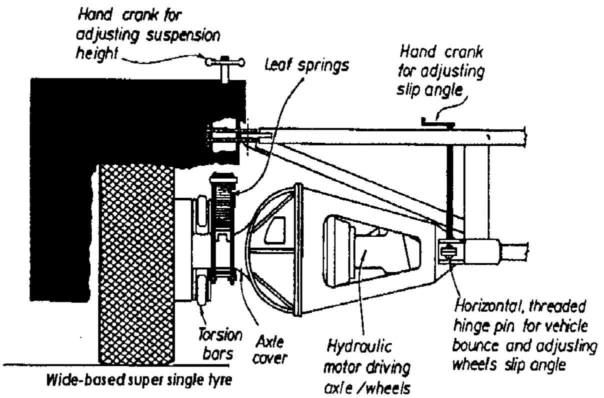

FIG. 3. The CAPTIF SLAVE unit.

CAPTIF is unique among accelerated pavement test facilities in that it was specifically designed to generate realistic dynamic wheel forces. All other accelerated pavement testing facility designs we are aware of, attempt to minimise dynamic loading. The SLAVE units at CAPTIF are designed to have sprung and unsprung mass values of similar magnitude to those on actual vehicles and use, as far as possible, standard heavy vehicle suspension components. The net result of this is that the SLAVEs apply dynamic wheel loads to the test pavement that are similar in character and magnitude to those applied by real vehicles. A summary of the characteristics of the SLAVE units is given in Table 1. The configuration of each vehicle, with respect to suspensions, wheel loads, tyre types and tyre numbers, can be identical or different, for simultaneous testing of different load characteristics. A more detailed description of CAPTIF and its systems can be found in PIDWERBESKY [11].

For all three tests the SLAVE units were fitted with wide single tyres. The main reason for this was to maximise the separation between the two wheel paths. Although wide single tyres are expected to be more damaging to the pavement than dual tyres, this effect should apply equally to both SLAVE units. For the first and third tests the pavement was a thin-surfaced unbound granular structure consisting of 250 mm of crushed rock surfaced with 30 mm of asphalt. The second test was undertaken as part of the OECD DIVINE project and used a conventional AC flexible pavement consisting of 85 mm of asphalt over 200 mm

Table 1. Characteristics of SLAVE units.

Test Wheels	Dual- or single-tyres; standard or wide-base; bias or radial ply; tube or tubeless; maximum overall tyre diameter of 1.06 m
Mass of Each Vehicle	21 kN to 60 kN, in 2.75 kN increments
Suspension	Air bag; multi-leaf steel spring; single or double parabolic
Power drive to wheel	Controlled variable hydraulic power to axle; bi-directional
Transverse movement of wheels	1.0 m centre-to-centre; programmable for any distribution of wheel paths
Speed	0-50 km/h, programmable, accurate to 1 km/h
Radius of Travel	9.23 m

of crushed rock. Although the AC layer on this pavement is relatively thin, by international standards it is considered thick enough for the pavement behaviour to be representative of flexible AC pavements. The reason for using a relatively thin pavement was to allow the pavement to be taken through to failure within a reasonable number of load cycles.

For each test both SLAVE units were loaded to the same static load but were fitted with different suspension systems so as to produce different dynamic loads. Details of the loads and suspensions are outlined in Table 2.

Table 2. CAPTIF configuration for the three accelerated dynamic loading tests.

Configuration	**First test**	**Second test**	**Third Test**
Pavement	thin-surfaced unbound granular pavement	85 mm AC over 200 mm crushed rock base	thin-surfaced unbound granular pavement
Tyre type	Wide-base single	Wide-base single	Wide-base single
Static wheel load	37 kN[1)]	49 kN[2)]	49 kN
Suspension – SLAVE A	two-stage multi-leaf steel spring	two-stage multi-leaf steel spring	two-stage multi-leaf steel spring
Suspension – SLAVE B	parabolic steel spring with viscous damper	airbag spring with viscous damper	airbag spring with viscous damper
Test speed	45 km/h	45 km/h	45 km/h

[1)] this corresponds to an axle load of 74 kN which is aproximately equal to the legal limit for wide single tyres in New Zealand.

[2)] this corresponds to an axle load of 98 kN which is the European limit for a drive axle with wide single tyres.

Very extensive sets of measurements were undertaken during each of these tests and many of these have been reported elsewhere (de PONT *et al.* [5]; KENIS and WANG [6]; OECD [7]). This paper focuses on the relationships between the permanent vertical surface deformations (VSD) of the pavement, the dynamic wheel forces and pavement structural capacity. At CAPTIF transverse pavement profiles are measured using a purpose-built device, which consists of a beam that is mounted on the rims of the concrete tank and straddles the track. A linear variable differential transformer (LVDT) attached to a small carriage runs along the beam and measures the distance to the pavement surface. A handheld computer data acquisition system records these measurements at 50 mm intervals. Longitudinal profile measurements were done initially with a DIPstick profiler, which gives readings at 250 mm spacing and more recently (third test only) with a laser profilometer, which provides readings at approximately 50 mm intervals. The longitudinal profiles are referenced back to absolute elevation using the transverse profile measurements at station 0 (see Fig. 2). By taking the difference of longitudinal profile measurements made at different stages in the test, the VSD of the pavement during that interval can be calculated. The dynamic wheel force measurement system consists of two accelerometers, one mounted on the SLAVE chassis and one on the axle. From the geometry and masses of the SLAVE components appropriate mass factors were determined so that the wheel forces can be calculated from the accelerations. The pavement's structural capacity was measured using the CAPTIF deflectometer, which is a modified Benkelman beam device. In the second pavement test a Falling Weight Deflectometer (FWD) was also used. The results from the FWD measurements were completely consistent with those from the CAPTIF deflectometer.

The first pavement failed prematurely due to poor compaction of the basecourse during construction. Both the second and third pavements lasted much longer than predicted and the tests were stopped before the pre-set failure criteria were achieved.

3. RESULTS

The EC (Council of the European Communities, [4]) directive on weights and dimensions defines a road-friendly suspension and how to test for it. One of the test methods involves driving the vehicle at crawl speed over a specified ramp which culminates in an 80 mm step and then measuring the suspension response. This test is used at CAPTIF as a repeatable method of characterising the suspension behaviour.

For the first test the response to this EC ramp test was as shown in Fig. 4. In planning the test it was expected that the parabolic leaf spring, being more modern, would be more road-friendly but it is not clear that this is the case. At large displacements the parabolic spring has a higher natural frequency and is therefore stiffer than the multi-leaf steel spring while at small displacements the converse is true. The parabolic spring is more linear in its behaviour with the force response being more sinusoidal in appearance and with its frequency not changing with amplitude. Both suspensions have a mean natural frequency of about 2.2 Hz. Damping levels are similar (7 – 9% of critical) although for the multi-leaf spring it is Coulomb rather than viscous damping. Comparing the dynamic wheel loads generated by the two suspensions at different speeds on the same pavement prior to the start of testing, as shown in Table 3, shows that the two suspensions behave differently but not that one is clearly better than the other.

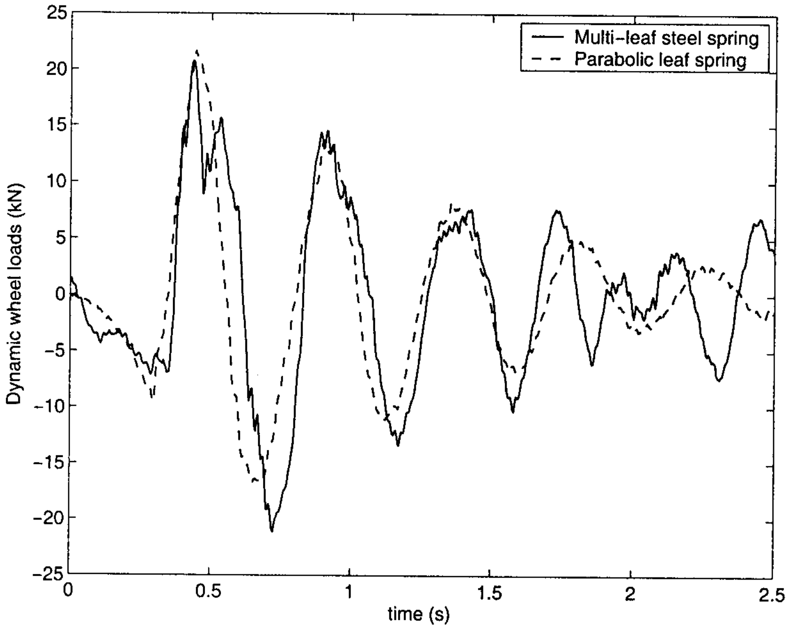

FIG. 4. Response to EC drop test for SLAVE units loaded to 37 kN.

Table 3. 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 in this test failed prematurely after only 35,000 load cycles. Based on the design guide in use in New Zealand, at the time it was expected to have a life of around 350,000 load cycles. The mode of failure was through excessive rutting, particularly in the inner wheel path, which was trafficked by the SLAVE fitted with the parabolic steel suspension. At the time the test was stopped the pavement was too rough to continue operating CAPTIF safely. At the post-mortem it was determined that the rutting occurred primarily in the basecourse layer with considerable lateral shoving of material. It was thought that the cause of the problem was inadequate compaction of the basecourse layer during construction.

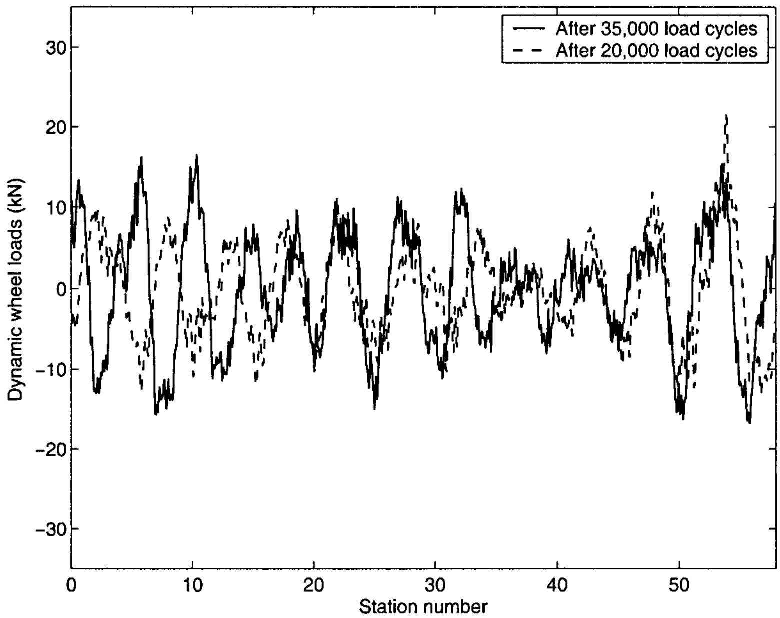

FIG. 5. Dynamic wheel forces from multi-leaf steel suspension on the outer wheel path.

Because of the premature failure only four sets of measurements were completed during this test. With the high level of rutting there was a significant increase in pavement roughness and as a consequence, an increase in dynamic wheel forces. Figures 5 and 6 compare the dynamic wheel forces of each suspension on the wheel path it trafficked after 20,000 and 35,000 load cycles. In both cases the dynamic wheel forces increased but the increase was much more substantial for the parabolic spring suspension on the inner wheel path. This wheel path also had a greater increase in roughness. The difference in linearity between the two suspensions is clearly visible. With the parabolic spring (Fig. 6) as the dynamic wheel force amplitude increases, the wavelength remains constant with the result that the spatial locations of the peak and troughs in the wheel force distribution do not change. That is, the same pavement locations were subjected to high wheel loads throughout the test. On the other hand, with the multi-leaf spring (Fig. 5), the wavelength changes with amplitude and thus there is some shifting in the locations of the peaks and troughs. So, while some locations (e.g. around stations 52 – 53) were subjected to consistently high loads, other locations (e.g. stations 7 – 8) were subjected to higher than average loads at 20,000 cycles and lower than average loads at 35,000 load cycles.

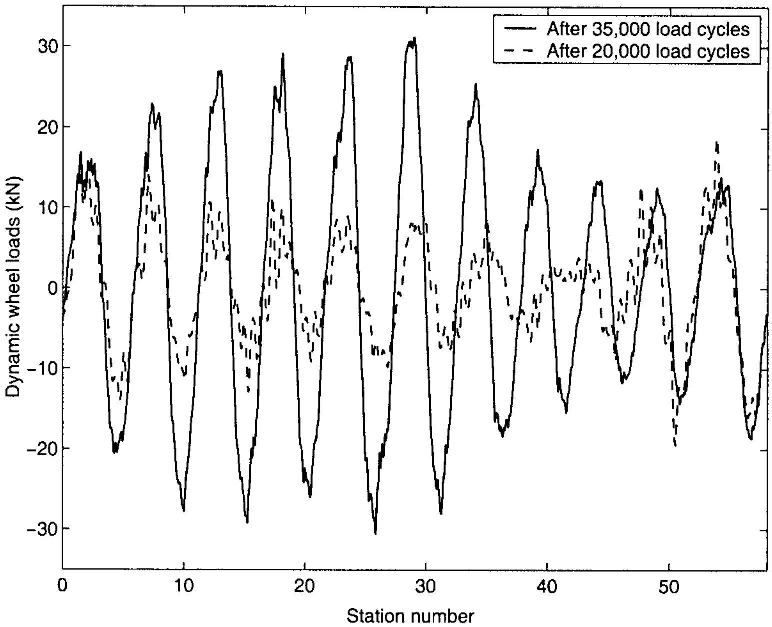

FIG. 6. Dynamic wheel forces from multi-leaf steel suspension on the outer wheel path.

Figures 7 and 8 show the longitudinal pavement profiles and how they changed during the test. The elevations are all relative to the height of the pavement at station 0 after construction. During the first 10,000 load cycles the pavement undergoes a substantial (about 10 mm), relatively uniform compaction. There is some smoothing of the pavement as the shorter wavelength irregularities are flattened off. Between 10,000 and 20,000 load cycles, this general compaction is much reduced but there are localised higher deformations indicating the beginning of the rut formations. Finally between 20,000 and 35,000 load cycles there is the development of substantial ruts at a number of locations. The VSD can be determined by taking the difference between the profile at 35,000 load cycles and the profile at construction. This is shown in Fig. 9. For the inner wheel path, in particular, we can see that the rut formation is periodic with the same wavelength as the SLAVE unit that applies the loads (see Fig. 6). Although the inner wheel path at the end of the test was significantly rougher than the outer

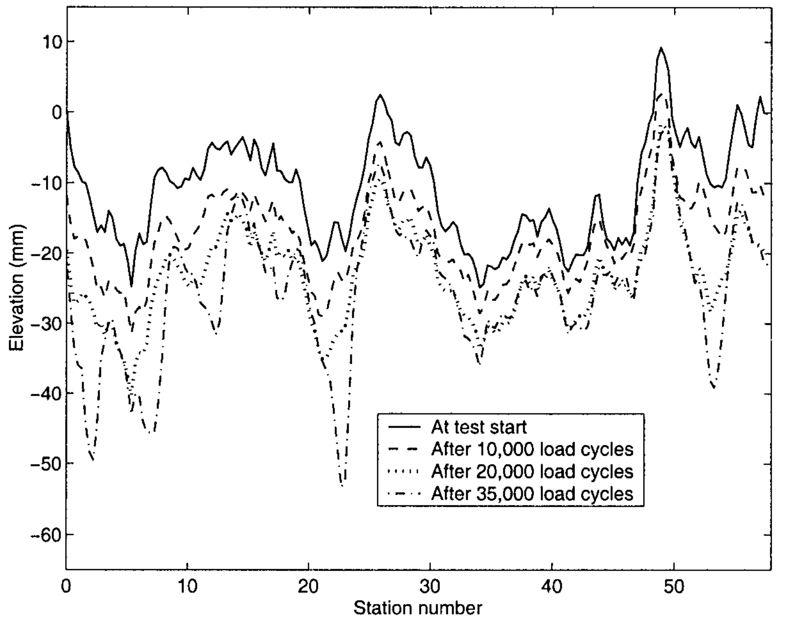

FIG. 7. Longitudinal profiles on inner wheel path for the first test.

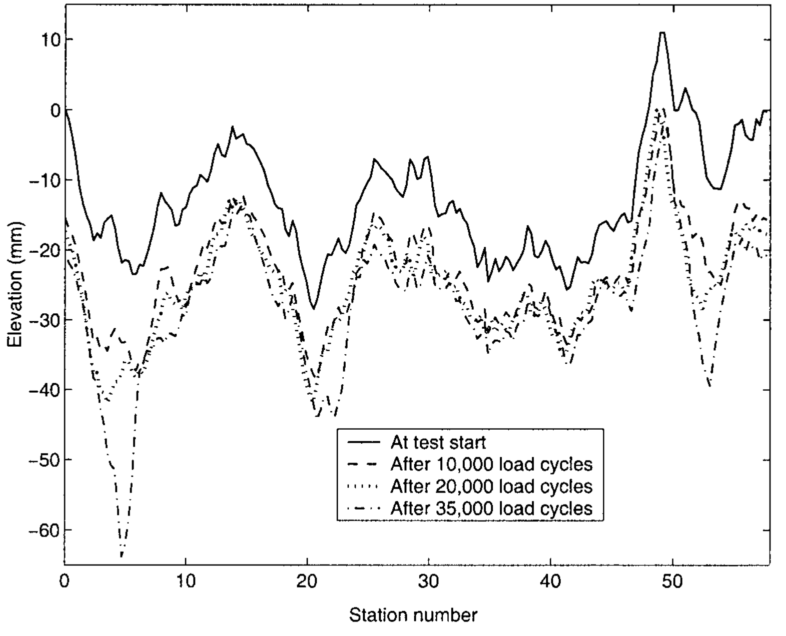

FIG. 8. Longitudinal profiles on outer wheel path for the first test.

wheel path as would be expected from the pattern of rutting, its mean VSD was slightly lower (−14.5 mm compared to −15.3 mm).

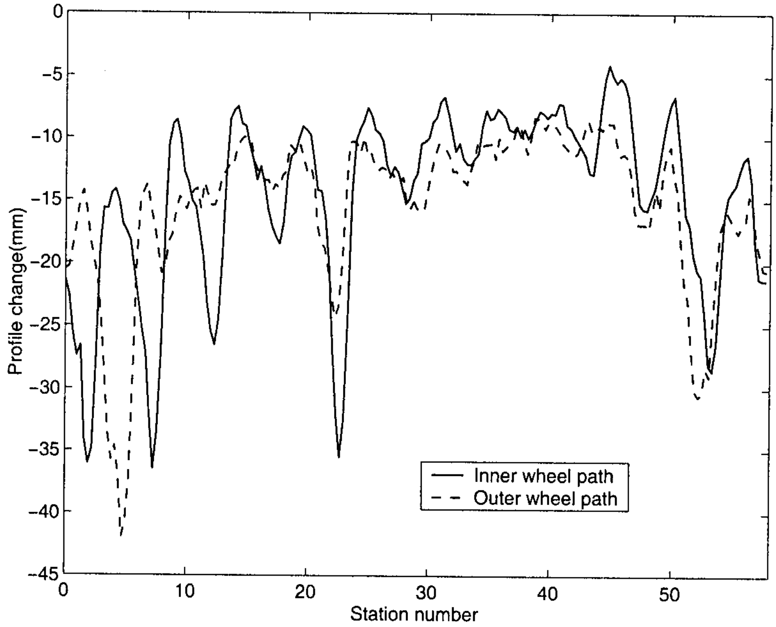

FIG. 9. VSDs in the two wheel paths for the first test.

We now look at the relationship between the pavement VSD and the dynamic wheel loads. Figure 10 shows the normalised cross-covariance function between the dynamic wheel forces at 35,000 load cycles and the VSD. For the multi-leaf steel suspension on the outer wheel path there is a negative correlation peak of -0.35 at about zero lag. The reason this is negative is that the wheel forces are measured as positive downwards and the profile elevation is positive upwards. The function is periodic and has a wavelength of about 5.5 m. At the test speed (47 km/h allowing for the larger radius of the outer wheel path) this corresponds to a frequency of 2.4 Hz, which matches well with the natural frequency of this suspension. With the same function for the parabolic steel suspension and the inner wheel path, the correlation is stronger with a peak value of −0.58. The periodicity of this function is even more marked and decays only slowly around the track. This is a reflection of the more linear response of this suspension and its low level of damping. The wavelength of this function is about 5.2 m, which corresponds to a frequency of 2.3 Hz at the test speed. As with the other suspension this is a reasonable match to the natural frequency.

Permanent deformation of the pavement surface is the result of the accumulation of repeated strains and therefore we would expect this to be related to the

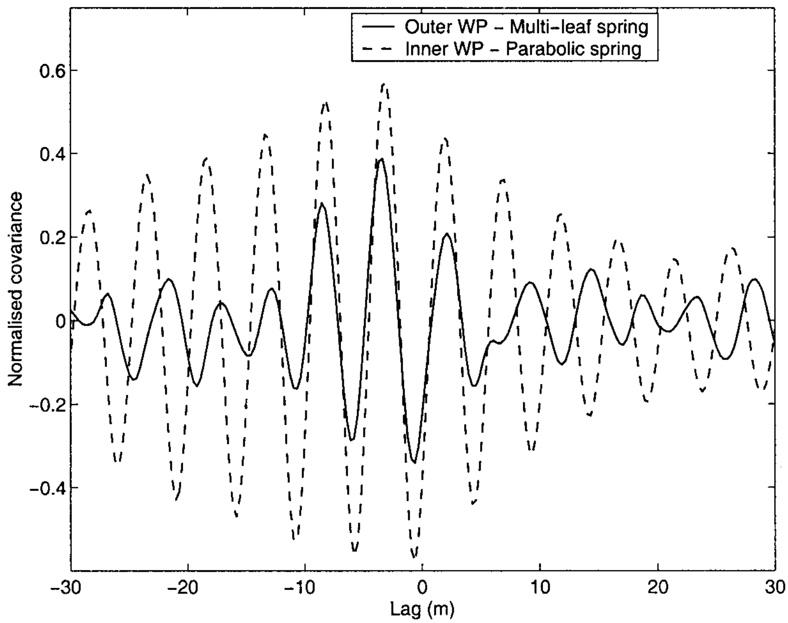

FIG. 10. Cross-covariance between wheel force and VSD for first test.

magnitude of the strains generated by the loading cycles. Based on linear elasticity, these pavement strains are proportional to the applied loads and inversely proportional to the pavement stiffness. It might therefore be expected that the changes in surface profile would also correlate with the pavement structural capacity. In this first test the pavement structural capacity was measured at 20,000 load cycles with the CAPTIF deflectometer. Readings were taken in each wheel path at 18 of the 58 1m stations around the track. These were not equally spaced and so we cannot easily do the same correlation analysis we did with the wheel forces. However if we calculate a simple correlation coefficient between the peak deflections and the VSD at those stations, we get 0.53 for the inner wheel path and 0.74 for the outer wheel path. Thus on the outer wheel path where the dynamic loads did not increase so dramatically the permanent surface deformation of the pavement was more strongly correlated with the pavement stiffness and less with the dynamic wheel forces. With the inner wheel path the converse was true. Taking this linear elastic model a step further, we would expect the pavement strains to be proportional to the product of the wheel force (static plus dynamic) and the deflection peaks. For convenience we call this product term the "strain factor". The correlation coefficient of the strain factor with the profile changes is 0.66 for both wheel paths. Thus, on the inner wheel path with the parabolic suspension, the strain factor provides a better correlation than either of its component variables. For the outer wheel path and the multi-leaf spring suspension, the pavement stiffness measure alone provides a slightly better correlation. For these correlation calculations the wheel forces as measured at 20,000 load cycles were used. Typical models for pavement wear assume that the wear is proportional to some power of the pavement strains. If we take logarithms of the VSD and the strain factor and apply a linear least squares regression fit, we obtain an estimate of the best-fit power term. The result of this is 1.05 for the outer wheel path and 1.4 for the inner wheel path.

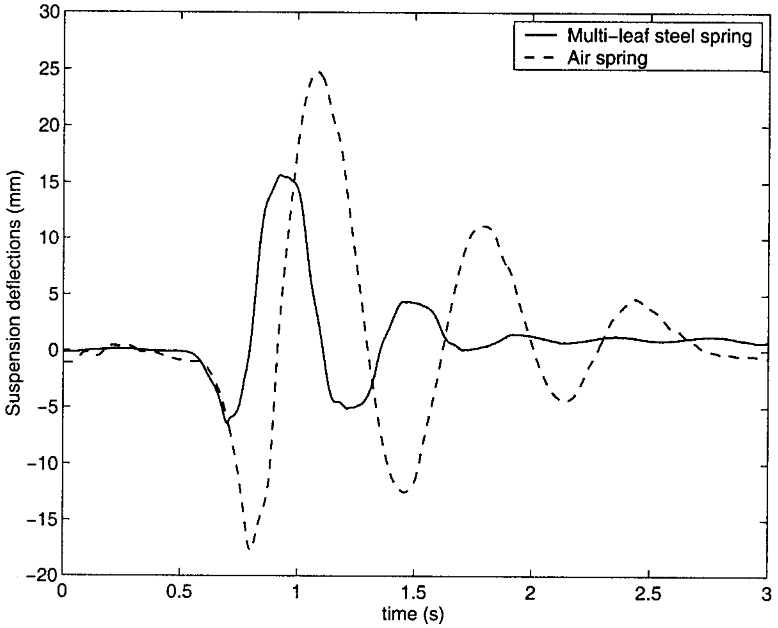

FIG. 11. Response to EC ramp test for SLAVE units loaded to 49 kN.

For the second pavement test one of the CAPTIF vehicles was fitted with the multi-leaf steel spring suspension while the other was fitted with an airbag suspension with a viscous damper. The response of these two suspensions to the EC ramp test is shown in Fig. 11. Note that the suspension response is shown is the suspension displacement rather than the dynamic wheel forces shown in Fig. 4. This measurement system was added to CAPTIF between the tests and provides a better signal for analysis. The airbag suspension is clearly significantly less stiff than the multi-leaf spring having a larger deflection and a lower frequency response. It is also more linear in its response but at these large displacements has less damping than the multi-leaf steel. However, at low excitation amplitudes the steel suspension is effectively locked and the SLAVE bounces on the tyre, which has very little damping.

As with the previous test, the initial trafficking caused some general compaction of the pavement with an overall smoothing effect. In the first 60,000 load cycles a localised rut about 5 m long developed in the outer wheel path, which was trafficked by the SLAVE with the steel suspension. This rut increased in severity through the first 250,000 load cycles before stabilising. From there onwards the increase in surface deformation at this location was similar to the rest of the pavement. The cause of this rut formation has never been satisfactorily established. The structural capacity measurements (FWD and CAPTIF deflectometer) did not show any evidence of weakness in the pavement structure at this location during or immediately post-construction. However, once the rut had started to form, the structural capacity measurements did give high deflections in the region. Because of the high relative magnitude of VSD in the rut relative to the rest of the track it dominates any correlation analysis and results in a strong correlation between VSD and pavement stiffness. For this reason the data from this rutted section of track in the outer wheel path were removed before undertaking the following analysis.

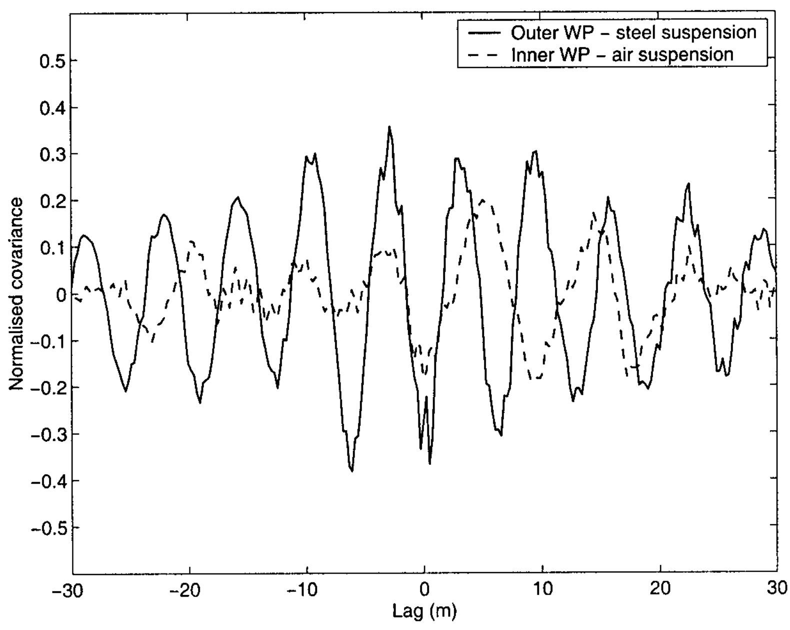

FIG. 12. Cross-covariance between wheel force and VSD for second test.

Figure 12 shows the normalised cross-covariance functions between wheel forces and VSD for the steel and air suspensions. The correlation is significantly stronger for the steel suspension, which is to be expected, as the level of dynamic loads generated by the air suspension is very low. As with the previous test these cross-covariance functions have a periodic character and their wavelength corresponds to the natural frequency of the suspension multiplied by the test speed. During this test the CAPTIF deflectometer was used to measure the pavement stiffness at each 1m station at regular intervals through the loading program. Figure 13 shows the cross-covariance between the deflection peaks and the VSD for the two trafficked wheel paths. The maximum correlation is very similar for the two wheel paths although slightly lower on the outer one, which was trafficked by the steel suspension. As with the previous test we now consider the cross covariance between the strain factor and the VSD. This is shown in Fig. 14. In both cases the peak correlation is better than that for the pavement deflections alone although for the airbag suspension on the inner wheel path the difference is very small. This again fits in with expectations because the level of dynamic loading generated by the airbag suspension is very small. Applying least squares regression methods to the logarithms of strain factor and VSD we can again obtain an estimate of the exponent for a power relationship between strain and wear. This gives 0.62 for the outer wheel path and 1.86 for the inner.

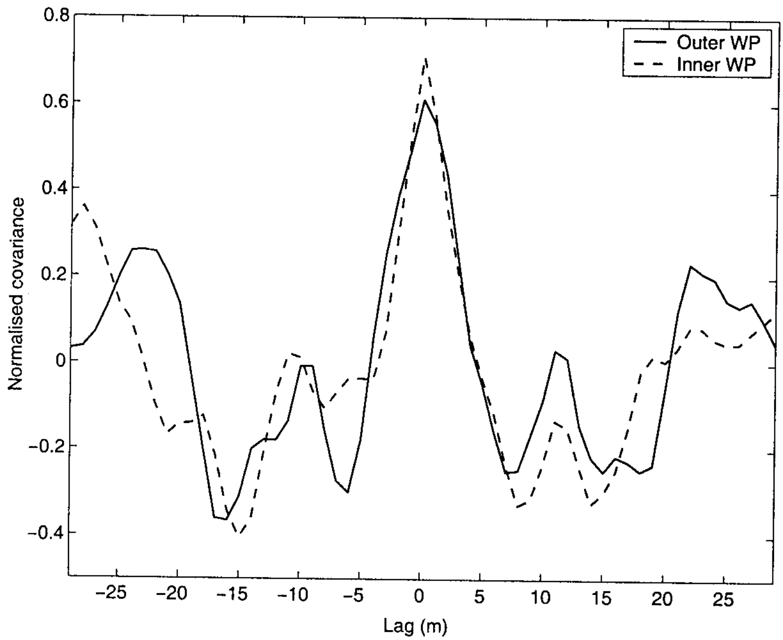

FIG. 13. Cross-covariance between pavement stiffness and VSD for second test.

For the third pavement test the vehicle loading and suspension configurations were the same as for the second test. The response to the EC ramp test was virtually identical to that shown previously in Fig. 11. Using the surface profiles at the start and finish of the test, the pavement deflection peaks measured at the

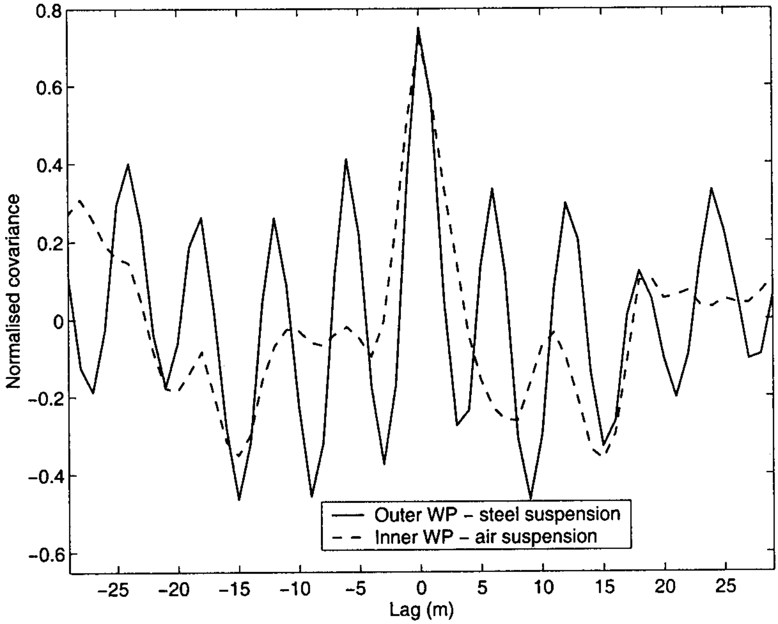

FIG. 14. Cross-covariance between strain factor and VSD for second test.

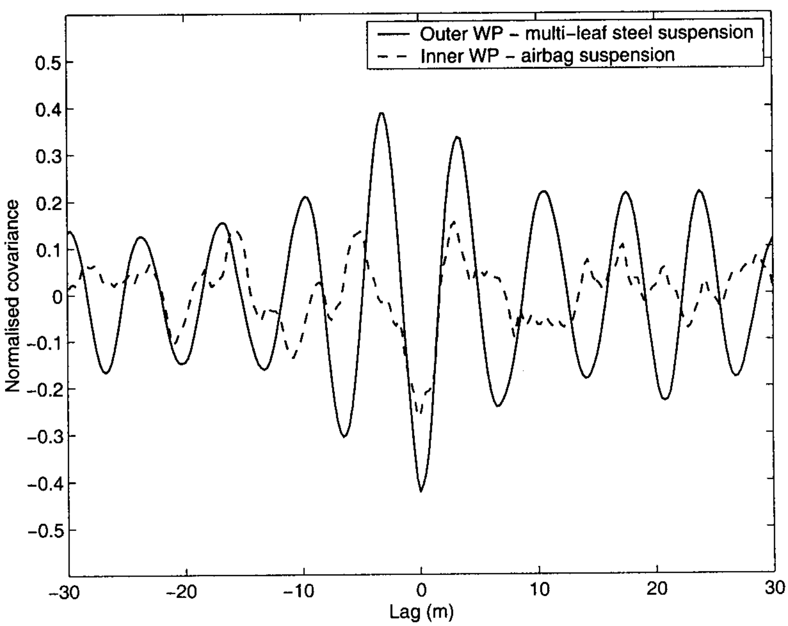

FIG. 15. Cross-covariance between wheel force and VSD for third test.

start of the test and the dynamic wheel forces measured midway through, we can repeat the analyses undertaken for the previous test.

Figure 15 shows the cross-covariance between wheel force and VSD. As with the previous test the correlation is stronger for the steel suspension than for the air. The magnitudes of the correlation at zero lag are similar to those of the previous test. Similarly the cross-covariance functions between pavement stiffness and VSD, as shown in Fig. 16, are similar in shape and magnitude as are those for strain factor and VSD shown in Fig. 17.

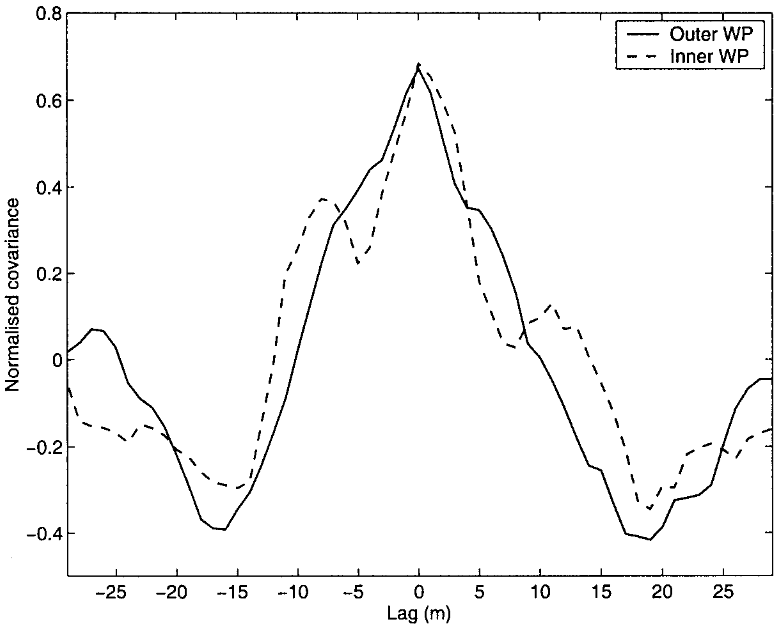

FIG. 16. Cross-covariance between pavement stiffness and VSD for third test.

Fitting a power relationship as with the previous tests gives an exponent of 1.33 for the inner wheel path and 1.51 for the outer. Comparing the VSD as predicted by these power relationships with the measured VSD (Figs. 18 and 19) shows that this model works reasonably well. The strain factor used as the independent variable for this model is rather crude as it uses only the pavement deflection response at the start of the test and the wheel forces midway through rather than taking into account how these parameters change during the test. Furthermore the pavement deflections reflect a composite stiffness for the whole pavement structure. Different combinations of stiffness values for the component layers could give the same overall stiffness but the contributions of the different layers to the overall surface deflection are not necessarily the same.

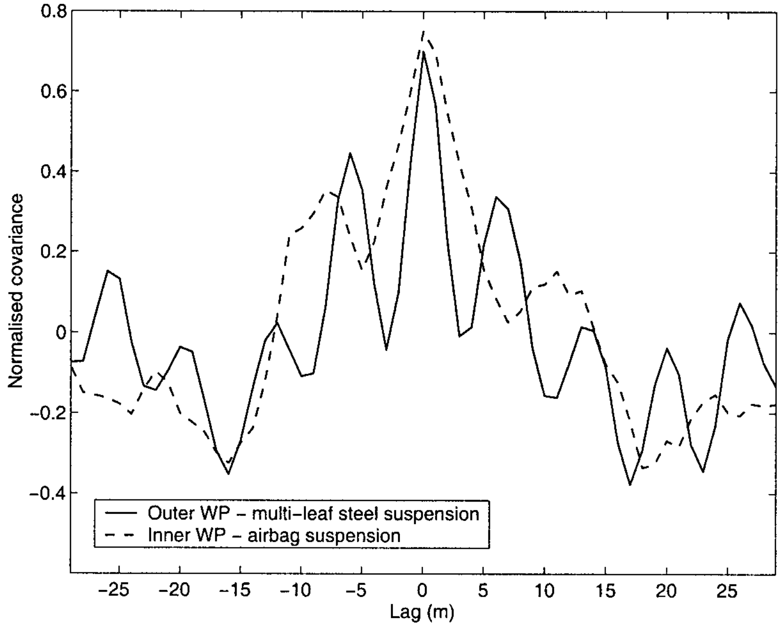

FIG. 17. Cross-covariance between strain factor and VSD for third test.

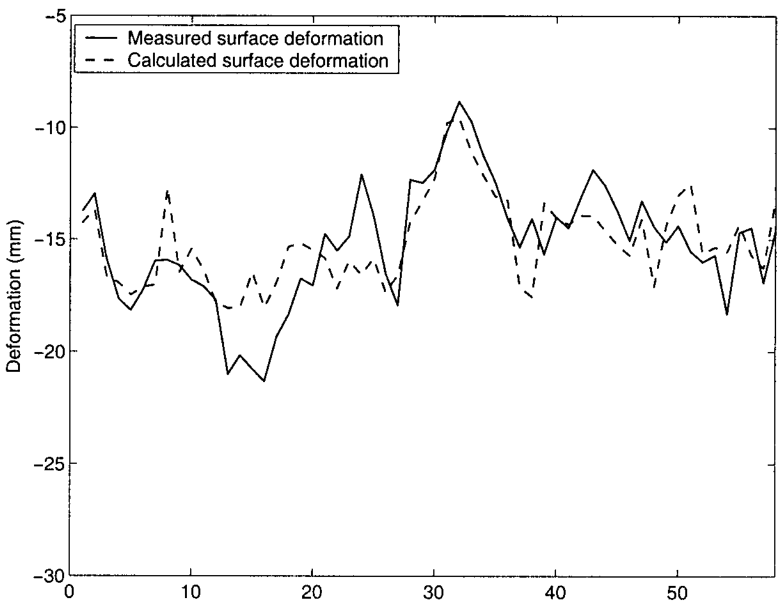

FIG. 18. Comparison of measured and predicted VSD for inner wheel path.

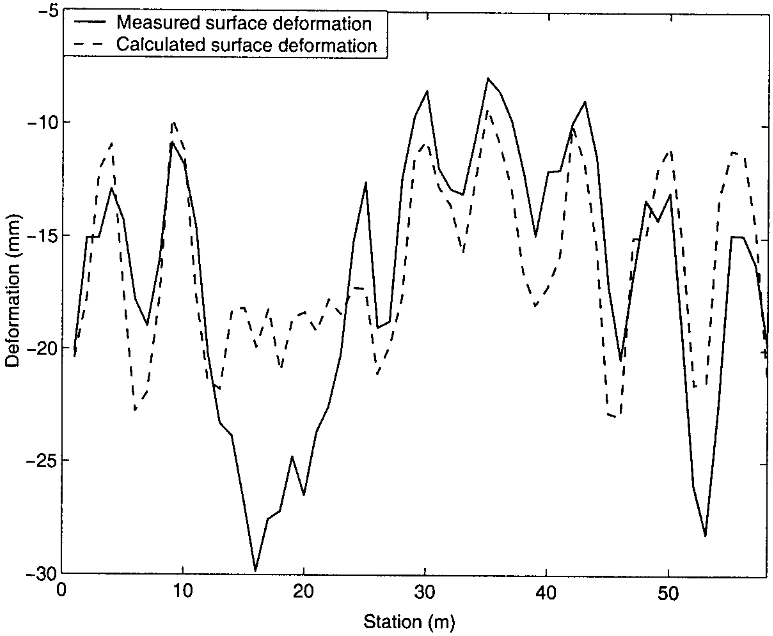

FIG. 19. Comparison of measured and predicted VSD for outer wheel path.

4. CONCLUSIONS

The results of the correlation analyses were remarkably similar across all three pavement tests. The main features of these can be summarised as follows:

- The correlation between the pavement deflection response (a measure which is inversely proportional to the pavement stiffness) and the VSD was about 0.6 – 0.7 in all cases and appears to be independent of the loading.

- The correlation between dynamic wheel loads and VSD depends on the level of dynamic loading. With a well-performing suspension, which generates low dynamic loads even on rougher pavements (the air suspension in the second and third tests), the correlation is weak with a magnitude of about 0.25. With higher dynamic loads as generated by poorer performing suspensions, the magnitude of this correlation increases. For the multi-leaf steel spring suspension, correlation coefficient magnitudes of 0.4 – 0.45 were observed while for the poorly damped parabolic steel spring the magnitude was 0.58.

- Even with the lower correlation magnitudes, the cross-covariance functions between wheel force and VSD were periodic with a wavelength that matched well with the natural frequencies of the suspension and the test speed.

- The product of wheel force and the pavement deflection response at a pavement location should be approximately proportional to the vertical pavement strains at that location. The correlation between this measure, which we call the strain factor, and VSD was, in general, better than the correlation with either component alone. Magnitudes ranged from 0.7 – 0.8.

- Models of pavement wear are usually based on the wear being related to a power of the pavement strains. By taking logarithms of the VSD and the strain factor and applying least squares regression, we can estimate a value for the exponent in a power relationship. The values for the best estimate of this exponent ranged from 0.62 – 1.86. The two extreme values come from the second test where the data relating to the unexplained rut were removed. It would appear that the best value for the exponent in this type of model would be in the range 1 – 2 and probably about 1.4. This is significantly lower that the exponent of 4, which is widely used in pavement design and management practice. Note that the only wear mechanism under consideration here is permanent deformation of the pavement surface. This indicator is used in New Zealand pavement designs as the majority of pavements are thin surfaced unbound granular pavements. These types of pavements do not have structural asphaltic concrete layers and thus fatigue cracking of the surfacing material is not considered.

This analysis is all based on measurements taken during accelerated loading tests at CAPTIF. Although these do differ in some respects from in-service pavements, we can draw some conclusions on the implications of these findings for pavement management.

- As VSD is correlated with pavement stiffness it is important that the pavement structural capacity should be as uniform as possible within the wavelengths that contribute to pavement roughness (< 50 m).

- The wheel forces on a wheel path at CAPTIF are generated by a single vehicle and are highly repeatable. On in-service pavements the wheel loads are generated by a fleet of vehicles with a range of masses, suspensions, speeds and wheelbases. Nevertheless, DIVINE research element 5 showed that for the vehicle fleet there is a spatial distribution of wheel loads where even on a relatively smooth pavement, the mean wheel loads at some locations vary by up to 10% from the overall mean. On rougher roads this can be up to 20%. The measurements from which these findings were derived were undertaken in England and France in the last five years and so the suspensions involved are a mixture of air and steel. Although it has not been shown, it is expected that as more vehicles in the fleet are fitted with better performing suspensions, this variation in wheel loads will decrease. Similarly lower road roughness does result in less dynamic load variation and hence less variation in VSD.

- A more uniform pavement structure and a more uniform load distribution will not reduce the mean VSD significantly but it will reduce the variation in VSD. This means that rutting will be more uniform along the pavement, which reduces the need for maintenance. It also implies that the pavement roughness will not increase as rapidly which also extends the pavement's life.

Some aspects of the findings require some further investigation.

- The power law model for permanent surface deformation used in this study was very simple, using only a snapshot of the pavement structure at the start of the test and the dynamic loads at mid-test. In fact, the pavement structure and dynamic loads change during the test. An incremental model taking into account these changes could give better results and this should be investigated.

- In-service pavements are loaded with a fleet of vehicles rather than a single vehicle. Further work is required to develop a model to predict the load distribution generated by the vehicle fleet.

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