Introduction References Biography Content

Pages 91-111

VALIDATING A WHOLE LIFE PAVEMENT PERFORMANCE MODEL

John de Pont, Transport Engineering Research New Zealand Limited
Kailash Thakur, Industrial Research Limited.
Bryan Pidwerbesky, Civil Engineering Department, Canterbury University
Bruce Steven, Civil Engineering Department, Canterbury University

ABSTRACT

Collop and Cebon (1995) presented a new “whole life” pavement performance modelling framework that takes into account realistic traffic and environmental effects. The model takes an initial pavement with known material properties, layer thicknesses, both of which may be variable, and surface profile. Vehicle simulation models are then subjected to this profile to calculate dynamic tyre forces. From these forces pavement primary responses (stress, strain and deflection) are calculated for each location along the pavement. These primary responses are then transformed into pavement damage. The surface profile and material properties are then updated based on the damage and environmental factors and a new iteration begins. The model is structured as a collection of sub-models that interact with each other. Thus it is relatively straightforward to replace sub-models with alternatives or even to add additional ones.

As part of the OECD DIVINE programme an accelerated pavement test was undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to investigate the influence of dynamic loading on pavement performance. During this test comprehensive measurements were taken a regular intervals. These measurements include material property tests, layer thicknesses and densities, longitudinal and transverse surface profiles, air and asphalt temperatures, structural capacity, asphalt, basecourse and sub-grade strains and deflections and dynamic wheel forces. The data from these measurements represent a unique opportunity for model validation.

This paper describes an implementation of the Collop-Cebon modelling framework and its validation using data from the OECD DIVINE accelerated pavement test. Each of the relevant sub-models is assessed for its fidelity in matching measured behaviour. Inadequacies are identified and quantified and modifications are proposed. Issues related to applying the framework to in-service roads are discussed.

1 INTRODUCTION

(Collop and Cebon 1995b) have developed a whole life pavement performance model (WLPPM) for flexible pavement structures. This model is a framework combining a set of linked sub-models. It attempts to predict pavement wear (roughness, fatigue cracking and rutting) deterministically by taking into account variations in pavement structure, dynamic loading effects and environmental factors. Essentially the framework can be dynamic loading effects and environmental factors. Essentially the framework can be divided into three areas: dynamic wheel force simulation, pavement primary response simulation and pavement damage simulation.

Between 1992 and 1996, the Organisation for Economic Co-operation and Development (OECD) undertook a substantial international co-ordinated research programme known as the Dynamic Interaction of Vehicle and Infrastructure Experiment (DIVINE). DIVINE consisted of six research elements addressing different aspects of the vehicle-infrastructure system with strong linkages between the elements. Element 1 in this programme was an accelerated pavement test conducted at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) in Christchurch, New Zealand. The aim of this research element was to answer the question: “How is the rate of progression of pavement distress (expressed as longitudinal profile, cracking, rutting and structural condition) affected by suspension type?” The test consisted of monitoring the performance of a test pavement with two independent wheel paths each being subjected to repeated load applications with the same static load magnitude but with different dynamic characteristics. This is effectively a physical WLPPM and is analogous in many respects to the computer-based model developed by Collop and Cebon.

Although a number of the sub-models comprising the Collop-Cebon model have been validated in isolation, the measurements undertaken for the DIVINE test at CAPTIF are very comprehensive and provide a unique opportunity to validate the Collop-Cebon modelling framework with actual data. In this paper we attempt to apply the Collop-Cebon framework to the DIVINE element 1 test at CAPTIF and by comparing the outputs with the measured results to determine the limitations of the current sub-models used.

2 THE COLLOP-CEBON WLPPM

The Collop-Cebon WLPPM has been described in detail in several publications ((Collop and Cebon 1995a; Collop 1994; Collop and Cebon 1995b)) and so the description presented here will be limited to the minimum level necessary. Basically the model consists of a collection of linked sub-models as illustrated by **figure 1**.

By using this modular approach the model can be developed and refined relatively easily. For example, in their sample applications, Collop and Cebon use a simple linear quarter car model for generating the dynamic wheel forces. This could easily be replaced by a whole vehicle model with non-linear suspension characteristics although at a significant penalty in computation time. Similarly if it is found that the any of the other sub-models do not adequately describe the observed behaviour, they can be modified or additional sub-models added.

3 THE DIVINE ACCELERATED PAVEMENT TEST AT CAPTIF

The results of the OECD DIVINE experiment at CAPTIF have been reported extensively elsewhere ((de Pont and Pidwerbesky 1995; de Pont et al. 1996; Kenis and Wang 1997b; OECD 1997; Steven and de Pont 1996)) so the description here will be limited to the minimum necessary.

CAPTIF consists of a 58 m long (on the centreline) 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. 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 laterally and can be used to have the two “vehicles” operating in independent wheel paths for comparative studies. This configuration was used for the DIVINE test. An elevation view is shown in figure 2.

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

For the DIVINE test one of the SLAVE units was fitted with a traditional multi-leaf steel spring suspension, which relies on inter-leaf friction for its damping while the other was fitted with an airbag suspension with a viscous damper. These represent the extremes in suspension type from a road-friendliness viewpoint. Wide-base single tyres were used to maximise the wheel path separation. Each SLAVE was loaded to a static load of 49 kN which corresponds to an axle load of 98 kN or 10 tonnes. Dynamic wheel forces were determined using accelerometers mounted on the SLAVEs. The test speed was set at 45 km/h.

The pavement design consisted of 85 mm of asphaltic concrete over a 200 mm crushed rock basecourse layer on a silty clay subgrade. With the 98 kN axle load this pavement had an expected design life of approximately 450,000 load applications. In fact, 1,700,000 load cycles were applied without achieving the pre-determined pavement failure criteria.

During construction the pavement was closely monitored and great care was taken to minimise the transverse variability across the pavement in order to minimise the difference between the two wheel paths. An eight metre long section of the track was extensively instrumented to measure pavement strains and deflections. In addition, measurement systems to measure the pavement structural capacity (falling weight deflectometer and a modified Benkelman beam device called the CAPTIF deflectometer) and surface profile (DIPStick, a laser profilometer, and a transverse profilometer) were used extensively. Before the load applications began an extensive set of measurements was undertaken to characterise the system as comprehensively as possible. Testing then proceeded with a number of load cycles being applied followed be a set of measurements. At the beginning of the test relatively few load cycles (10,000) were applied between measurements but this interval was increased as the test progressed so that for most of the test measurements were conducted every 100,000 load cycles.

4 APPLYING THE WLPPM TO THE CAPTIF TEST CONDITIONS

4.1 Asphalt Layer Thickness

In the Collop-Cebon (Collop and Cebon 1995a; Collop and Cebon 1995b) model, a sub-model is used to generate the asphalt layer thickness. This is done by an inverse Fast Fourier Transform (FFT) method applied to an equation for the thickness spectrum of the form:

$$S_h(\gamma) = \frac{F}{1 + \left(\gamma / \gamma_0 \right)^H}$$

where $S_h(\gamma)$ is the thickness spectrum

γ is the wavenumber

and F, H, γ_0 are constants

The constant values were obtained by fitting this equation to some measured data. Using the values of the fitted constants given in the two papers referenced does not generate the plotted curve also shown in these papers. It must be assumed that there are typographical errors in these values.

With the DIVINE test at CAPTIF the layer thicknesses were measured at each measurement station in each wheel path. The measurement stations are at one metre intervals on the centreline wheel path and thus the measurement spacing was 0.96 m on the inner wheel path and 1.04 m on the outer wheel path. As the circumference of the track is 58 m there are 58 thickness measurement values for the asphalt layer in each wheel path. This is rather too few for a detailed validation of the thickness sub-model. **Figure 4** shows the thickness spectra calculated for the two wheel paths together with a fitted equation of the same form (although with different constants) as that postulated by Collop and Cebon.

The magnitude of the spectra is somewhat lower than the example presented by Collop and Cebon which is to be expected as: firstly the pavement is relatively thin and thus should have less thickness variation than a thicker pavement and secondly it was constructed very carefully to have a high degree of uniformity. The spectra are relatively “noisy” because of the limited number of data points. However, they are consistent with the mathematical sub-model proposed.

The Collop-Cebon model does not consider variations in the thickness of the basecourse layer. For thicker asphalt layers the relative contribution of the basecourse to the overall stiffness of the pavement is small and thus small variations in its thickness would not have a significant effect. However, as the asphalt layer thickness decreases the contribution of the basecourse layer becomes more important.

The spectra of the basecourse layer thickness are shown in **figure 5**. Again because of the relatively small number of data points these are “noisy”. The magnitude is a little higher than that of the asphalt reflecting the higher mean layer thickness.

An interesting feature of the layer thicknesses measured at CAPTIF is that there was a reasonably strong negative correlation between the asphalt and basecourse layer thicknesses (-0.8 for the inner wheel path and –0.79 for the outer wheel path). This came about because of the efforts to keep the pavement surface as level and uniform as possible. The asphalt layer at CAPTIF was laid by hand because the size and geometry of the facility precludes the use of a paving machine.

4.2 Initial Surface Profile

The surface profiles measured at CAPTIF during the DIVINE experiment have been analysed extensively by (de Pont 1997). Measurements were made using a DIPStick profiler and thus data were obtained at 0.25 m spacing, which results in 232 data points around the centreline of the track. The power spectral density (PSD) functions of these profiles at the start of the test are shown in **figure 6**.

Collop and Cebon generate their initial surface profile using a spectrum of the form:

$$S_z(\gamma) = C\gamma^{-w}$$

where $S_z(\gamma)$ is the profile spectrum
γ is the wavenumber
and C, w are constants

On a log-log plot this would give a straight line which is consistent with figure 6. Collop and Cebon use a value for w = 2.5 while the ISO standard ((Anon. 1995)) for characterising road profiles uses w = 2. A regression fit on the spectra shown in figure 6 gives w = 1.4. The reason that the value obtained for the CAPTIF profiles is lower than the other two is that laying the asphalt by hand results in a relative increase in the amplitudes of the shorter wavelengths. For in-service pavements a higher value is more appropriate, although whether this should be 2 or 2.5 is still an issue for debate.

Collop and Cebon assumed no correlation between asphalt thickness and surface profile because they did not have any measurement data from which to deduce anything else. The values for the correlation between layer thickness and surface profile measured at CAPTIF are small, ranging from –0.2 to 0.4. There is also no obvious pattern. On one wheel path the correlation between basecourse thickness and profile is negative while on the other it is positive. Thus the CAPTIF test results do not provide any basis for assuming a correlation between profile and layer thickness.

4.3 Dynamic Wheel Forces

The SLAVE units at CAPTIF are designed to behave like quarter trucks with dynamic characteristics as close as possible to real heavy vehicles. In fact, the two degrees of freedom in the structure are rotations rather than displacements as shown in the schematic in **figure 7.**

The equations of motion of this system are as follows:

$$\begin{bmatrix} \mathrm{I}_{\mathrm{totalA}} & \mathrm{I}_{\mathrm{unsprungB}} + \mathrm{m}_{\mathrm{unsprung}}.\mathrm{L}.\mathrm{l}_{\mathrm{c}} \\ \mathrm{I}_{\mathrm{unsprungB}} + \mathrm{m}_{\mathrm{unsprung}}.\mathrm{L}.\mathrm{l}_{\mathrm{c}} & \mathrm{I}_{\mathrm{unsprung}} \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + \begin{bmatrix} \mathrm{L}+\mathrm{l} & 0 \\ \mathrm{l} & -\mathrm{l}_{\mathrm{s}} \end{bmatrix} \begin{bmatrix} \mathrm{F}_{\mathrm{t}} \\ \mathrm{F}_{\mathrm{s}} \end{bmatrix} = 0$$

where

$\mathrm{I}_{\mathrm{totalA}}$ = rotational moment of inertia of total system about A
$\mathrm{I}_{\mathrm{unsprungB}}$ = rotational moment of inertia of unsprung mass about B
F_{t} = tyre force
F_{s} = suspension force

The tyre and suspension forces depend on the model of tyre and suspension behaviour used. For this work the tyre was represented as a simple linear spring in parallel with a linear viscous damper. Two suspension models were used. One used the leaf spring model developed at the University of Michigan (Fancher et al. 1980; Winkler 1992) to simulate the SLAVE unit fitted with steel suspension. The other used a linear spring and a bi-modal viscous damper with different bump and rebound damping rates to simulate the SLAVE with air suspension.

As part of the DIVINE test static measurements of suspension and tyre stiffness were undertaken. In addition the damper was tested on damper testing machine, which cycles the damper at a constant rate through a fixed stroke and records the force-displacement history.

For both vehicles the mass and inertia terms were calculated used measured weights and dimensions for the various elements of the SLAVE units together with some assumptions regarding the mass distribution where this information was unknown. The tyre stiffness value used was determined from the static measurements. For the air-suspended the initial estimates of the suspension stiffness and damping were determined from the measured values. Some minor adjustments to these values were then applied to improve the match between the modelled and measured response. **Figure 8** shows a comparison between the measured and modelled suspension displacements using the measured profile data as input. The match is reasonably good.

For the steel leaf spring model, no data were available for the dynamic force deflection response of the steel leaf spring pack used on the CAPTIF rig. Consequently, some measured spring data for a similar spring were used as a starting point and the parameters were then adjusted to match the measured response. This was done on an ad hoc basis. **Figure 9** shows a comparison of the measured and modelling spring deflections using the same pavement profile for excitation as figure 8. The match is reasonably good for the underlying detail, though there are some discrepancies in the magnitude of the larger displacements. These average out over the length of signal shown, which represents a circuit of the track at CAPTIF. There is no obvious pattern to these differences and it difficult to see how adjusting the model parameters could improve the match.

4.4 Pavement Primary Response

Collop and Cebon used the VESYS IIIA pavement model to generate the pavement primary response influence functions. This model is also used here. As described in section 3 the pavement used for the DIVINE test at CAPTIF consisted of three layers. During construction the pavement was monitored very intensively and Falling Weight Deflectometer (FWD) tests were undertaken on each layer at each station in each wheel path after completion. (Kenis and Wang 1997a) applied the Boussinesq-Odemark method to the FWD deflections to calculate the moduli for each layer at each station in each wheel path using the measured layer thickness values for each location. This analysis showed quite large variations in modulus particularly for the asphalt and basecourse layers, with mean values somewhat lower than might be expected. For example, the mean asphalt modulus was approximately 1000 MPa where typically values of at least double this are used.

By applying the VESYS model to the section of the test rack which was extensively instrumented we can compare the calculated strains with measured values. At each station the actual layer thickness values and the calculated moduli were used. The measured contact patch size was used and the pressure was adjusted to give the correct wheel load. The initial analysis assumed a wheel force equal to static wheel loads and then the responses were adjusted to take into account the measured dynamic wheel loads at each location. Figures 10 - 15 show comparisons of the calculated pavement strains with the measured strains for each wheel path based on the start of the test. In each case, the calculated strains using the static wheel loads and those using the dynamic wheel loads are shown.

For the asphalt strains (**figures 10 and 11**) there are measurement data missing. The transducers at these stations for measuring these strains had failed by the time these measurements were made. (**Figures 12 - 15**)

As expected, the dynamic loading effects in the model are smaller for the inner wheel path where the air suspension was operating than on the outer wheel path where the steel suspension was used.

The measured asphalt strains are, in general, lower than those predicted by the models. This is offset by the subgrade strains, where the measured strains are somewhat higher than the modelled. There appears to be some correlation between the patterns of measured and modelled strains though it is far from perfect and there are relatively few data points for comparison. While it should be possible to obtain a better match between the measured and modelled strains by adjusting the moduli values, there is little justification for doing this. The moduli values used were already obtained by back-calculation from a measured response rather than by direct measurement of these properties.

It appears, therefore, that the linear elastic modelling approach used by VESYS has some limitations in predicting pavement strains for a relatively thin (by North American and European standards) asphalt pavement such as that used for the DIVINE test.

4.5 Pavement Damage Models

The pavement damage mechanisms included in the Collop-Cebon model consist of permanent deformation which leads to rutting and changes in the pavement profile and fatigue damage which leads to cracking in the asphalt surface layer. The permanent deformation consists of two components, viscous flow in the asphalt layer due to the visco-elastic nature of the material and permanent vertical deformation in the subgrade. Collop and Cebon adjusted the coefficients for their subgrade deformation model so that the contribution from the two components was approximately equal.

The post-mortem analysis of the DIVINE test at CAPTIF (Kenis and Wang 1997b) showed that by far the largest source of permanent deformation was compression of the crushed rock basecourse layer. There are two likely reasons for this. First, the asphalt layer is relatively thin and thus the crushed rock basecourse layer is a significant contributor to the overall pavement strength and second the subgrade used during the CAPTIF trial was relatively strong (CBR = 12%) and thus more resistant to permanent deformation. The issue of thinner surface layers is particularly relevant to the New Zealand and Australian situation where much of the network is constructed with pavements considerably thinner than that used at CAPTIF for the DIVINE test.

Analysis of the cracking present in the pavement at CAPTIF (Kenis and Wang 1997b) showed that the cracks mostly originated at the top surface of the asphalt layer and propagated towards the bottom. Although this does not fit with the classical fatigue theory, which is the basis of the fatigue damage model used by Collop and Cebon, it has been observed for many years that cracking does often initiate from the top of the asphalt layer down. However, cracking that initiates at the bottom of the layer is more critical, because such cracking is not visible until the crack reaches the top of the layer. Therefore, classical fatigue cracking theory assumes that cracking initiates at the bottom of the layer, in order to provide a conservative asphalt layer design thickness.

5 CONCLUSIONS

The Collop-Cebon framework for modelling whole life pavement performance is an exciting development that could lead to significant advances in our understanding of the behaviour and performance of pavement structures. The OECD DIVINE accelerated pavement test generated an extensive set of pavement performance data albeit under rather specialised and controlled conditions. This provides a unique opportunity to validate and develop the Collop-Cebon model.

In this paper we have evaluated a number of the sub-models comprising the WLPPM using the data from the DIVINE test. The sub-models for generating pavement layer thickness values and initial surface profile are consistent with the measurements undertaken for the DIVINE tests.

Vehicle dynamics models can be used to reproduce the behaviour of the SLAVE units at CAPTIF which apply the dynamic loads to the pavement. However, the performance of these models still depends on accurately characterising the vehicle suspension behaviour. This is consistent with the findings of the DIVINE research element 4 on computer simulation models ((OECD 1997)).

The match between the pavement strains predicted by VESYS and those measured is only fair. To an extent this is a function of the inherent errors in the measurements and the back-calculation process, which generated the moduli values used. As with the vehicle models characterising the system correctly is the key. Pavement materials are known to be non-linear and therefore modelling them as linear elastic is necessarily an approximation. The VESYS model was validated using thick asphalt pavements where the contribution of the basecourse and subgrade strains to the total deflection is relatively small and thus accuracy of the models for the behaviour of these materials is not so critical. For thinner surface pavements this is not the case. Further work is required to determine whether an improved method of estimating the material properties is sufficient to improve the model performance or whether a non-linear model is needed.

The observed pavement wear at CAPTIF did not fit in with the models of pavement deterioration used by Collop and Cebon. The models have not been tested yet to see whether they would have predicted wear, which was not observed. Further work is needed to extend the models of pavement deterioration to include the distress observed at CAPTIF.

The work described in this paper is in its early stages. Further validation testing is still to be done and development of some of the component sub-models to better match measured data is required.

Introduction Content

6 REFERENCES

Anon. (1995). Mechanical vibration - road surface profiles - reporting of measured data. *International standard. ISO 8608*, ISO [International Organisation for Standardization], Geneva.

Collop, A., and Cebon, D. (1995a). Modelling whole-life pavement performance. *Fourth International Symposium on Heavy Vehicle Weights and Dimensions*, Ann Arbor, USA, 201-212.

Collop, A. C. (1994). Effects of traffic and temperature on flexible pavement wear., Doctor of Philosophy, University of Cambridge., Cambridge.

Collop, A. C., and Cebon, D. (1995b). A model of whole-life flexible pavement performance. *IMechE J. Mech. Eng. Sci.*, Vol 209(No C6), pp 389-407.

de Pont, J. J. (1997). OECD DIVINE Project - Element 1. Longitudinal Pavement Profiles. *Research Report 708*, Industrial Research Limited, Auckland.

de Pont, J. J., and Pidwerbesky, B. (1995). The Impact of Vehicle Dynamics on Pavement Performance. *Fourth International Heavy Vehicle Weights and Dimensions Symposium*, Ann Arbor, Michigan, 323-332.

de Pont, J. J., Pidwerbesky, B. D., and Steven, B. D. (1996). The Influence of Vehicle Dynamics on Pavement Life. *Fourth Engineering Foundation Conference on Vehicle-Infrastructure Interaction*, San Diego.

Fancher, P. S., Ervin, R. D., MacAdam, C. C., and Winkler, C. B. (1980). Measurement and Representation of the mechanical properties of truck leaf springs. *SAE Technical Paper Series*(800905).

Kenis, W. J., and Wang, W. (1997a). Analysis of pavement structural variability. *Final report FHWA-RD-97-072*, Federal Highway Administration, McLean, Virginia.

Kenis, W. J., and Wang, W. (1997b). OECD DIVINE Element 1 final report. Accelerated pavement testing. *Final report* , FHWA, McLean.

OECD, R. T. R. P. (1997). *Dynamic interaction of heavy vehicles with roads and bridges*. *OECD Report Draft final report*, OECD, Paris.

Steven, B., and de Pont, J. (1996). Dynamic loading effects on pavement performance - The OECD DIVINE test at CAPTIF. *Proceedings Roads 96 Conference*, 93 - 108.

Winkler, C. B. (1992). UMTRI spring model. *Personal communication.*

Introduction Content

7 AUTHOR BIOGRAPHIES

John de Pont is the Director of Engineering Research at Transport Engineering Research New Zealand Limited (TERNZ). He was a member of the OECD Scientific Expert Group IR6, which conducted the DIVINE experiment and was the project manager for the accelerated pavement test conducted at CAPTIF.

Kailash Thakur is a Senior Research Scientist at Industrial Research Limited, Auckland. He has an extensive research background in solid state physics. His current research interests are in modelling.

Bryan Pidwerbesky was a Senior Lecturer in the Civil Engineering Department at Canterbury University from 1986-97 where he also managed the CAPTIF facility. He has recently joined the New Zealand Bitumen Contractors Association as Director and continues his interest in pavement engineering. He was a member of the OECD Scientific Expert Group IR6, which conducted the DIVINE experiment.

Bruce Steven is a graduate student in the Civil Engineering Department at Canterbury University and a research engineer at CAPTIF.

Introduction Content

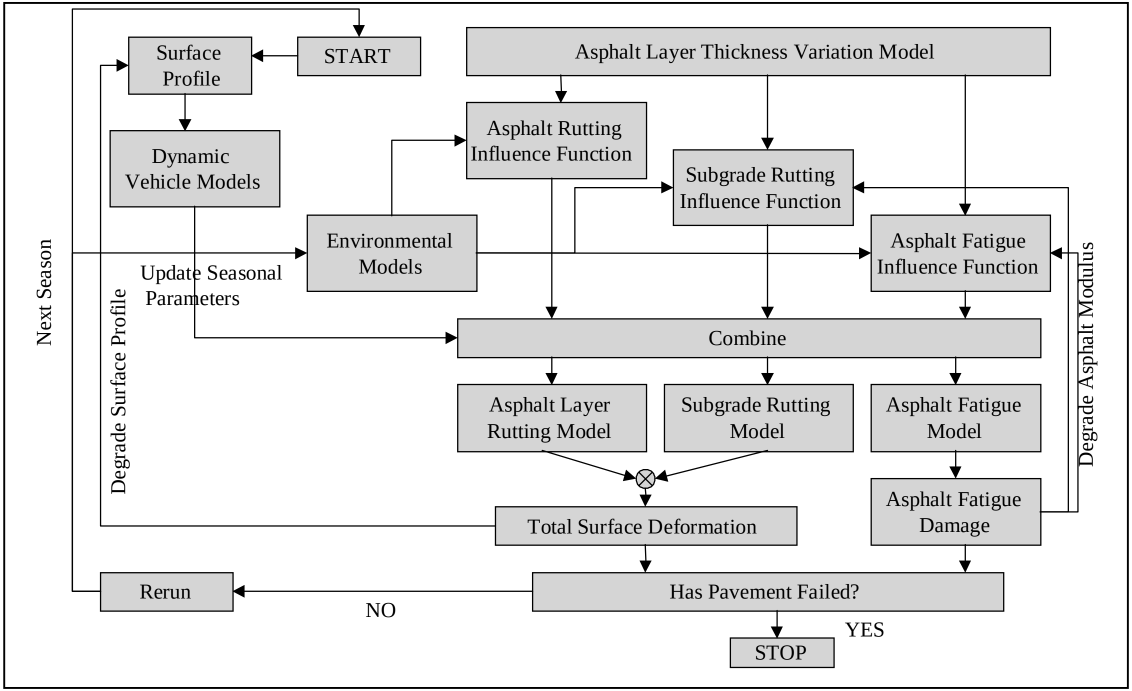

Figure 1. Collop-Cebon WLPPM framework.

Return to paper

Content

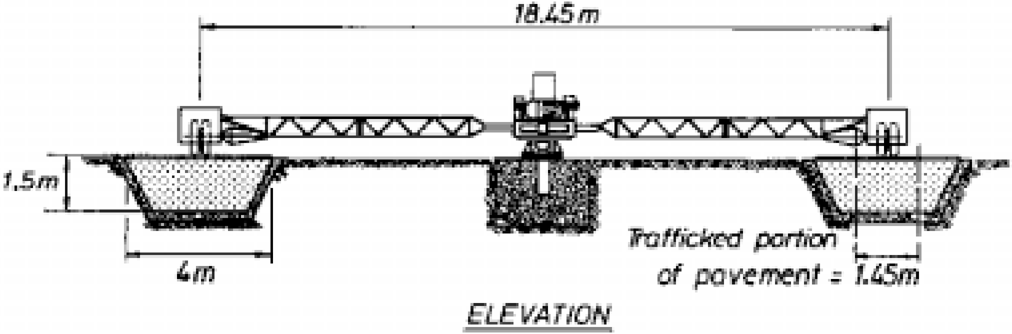

Figure 2. Elevation view of CAPTIF

Return to paper

Content

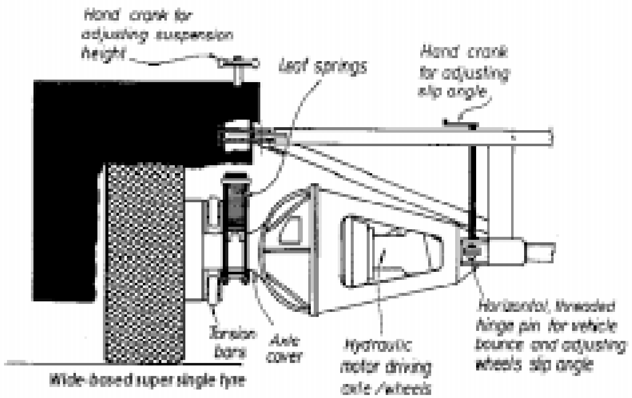

Figure 3. The CAPTIF SLAVE unit.

Return to paper

Content

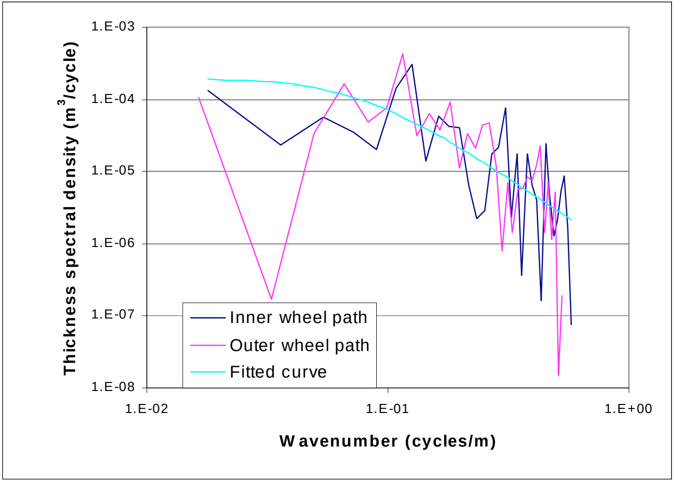

Figure 4. Asphalt layer thickness spectral density

Return to paper

Content

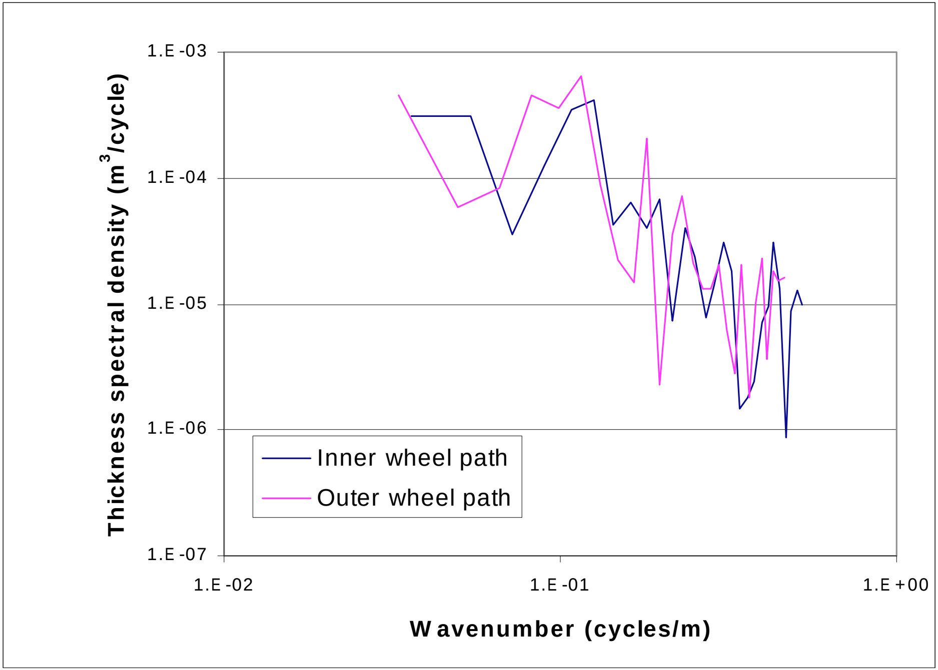

Figure 5. Bascourse layer thickness spectra.

Return to paper

Content

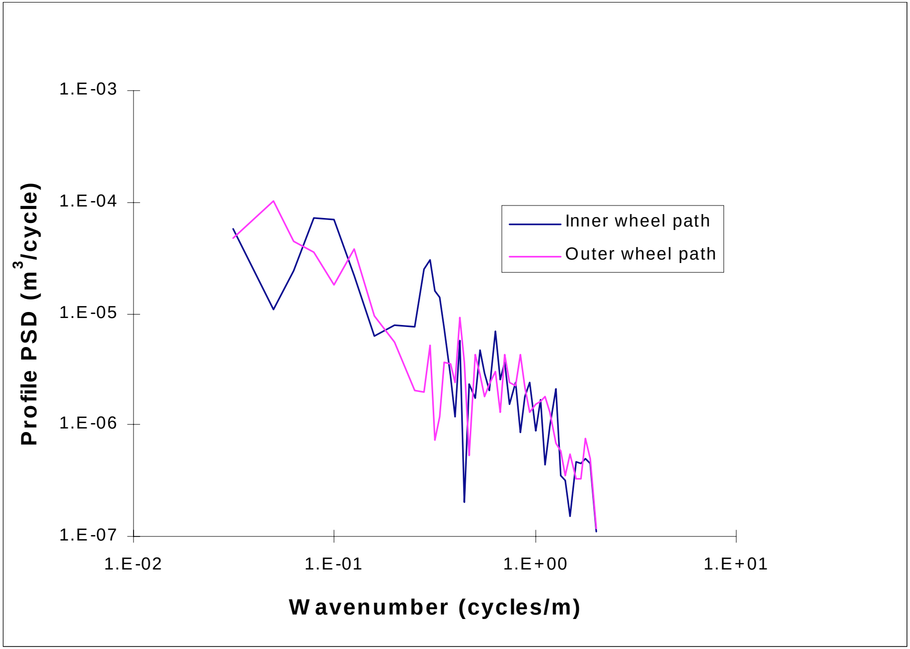

Figure 6. Initial surface profile spectra.

Return to paper

Content

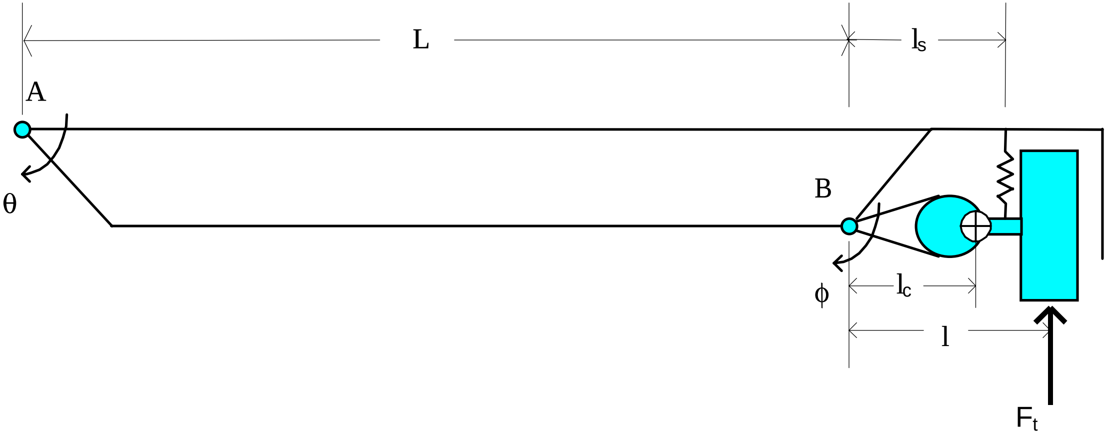

Figure 7. Schematic of CAPTIF vehicles.

Return to paper

Content

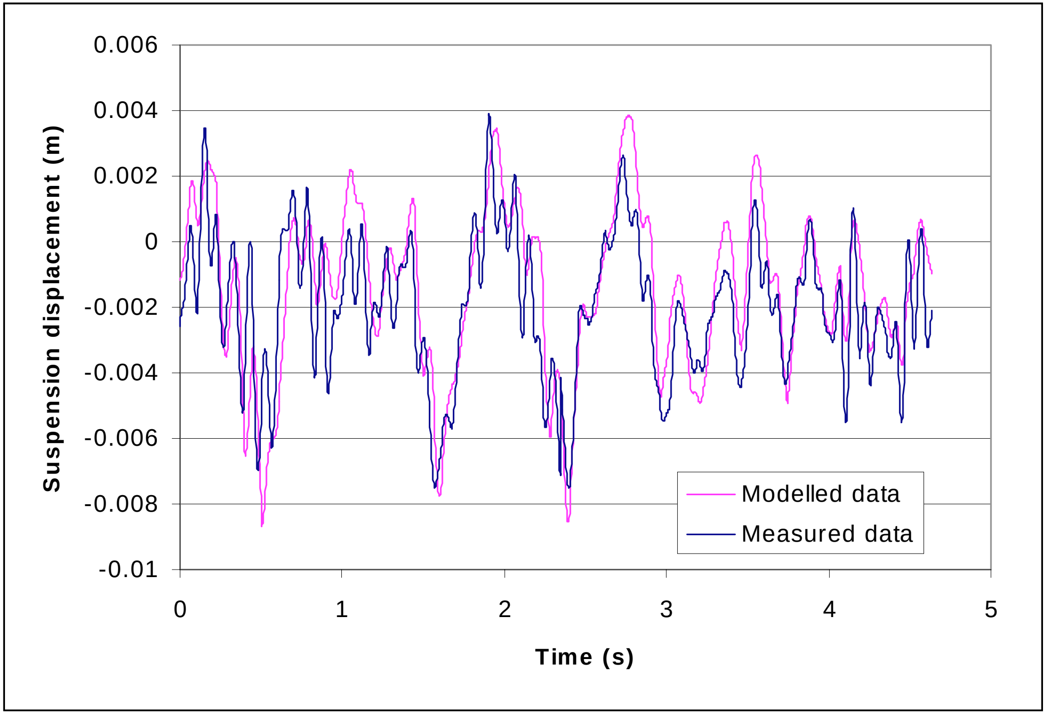

Figure 8. Comparison of measured and modelled deflection response for air suspension.

Return to paper

Content

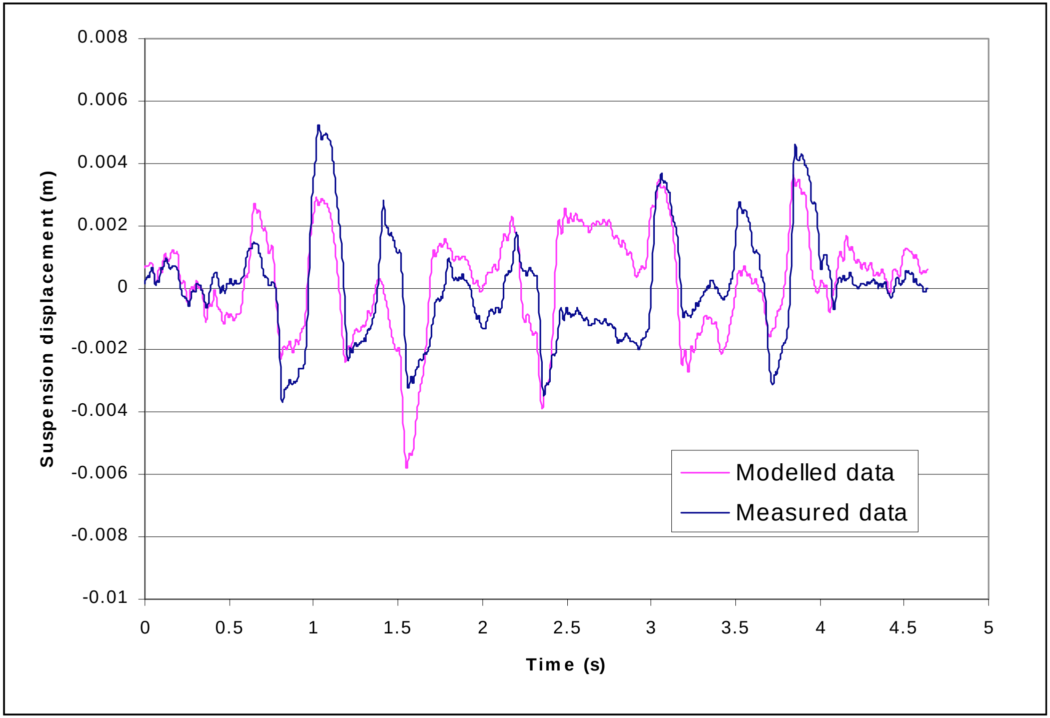

Figure 9. Comparison of measured and modelled deflection response for steel suspension

Return to paper

Content

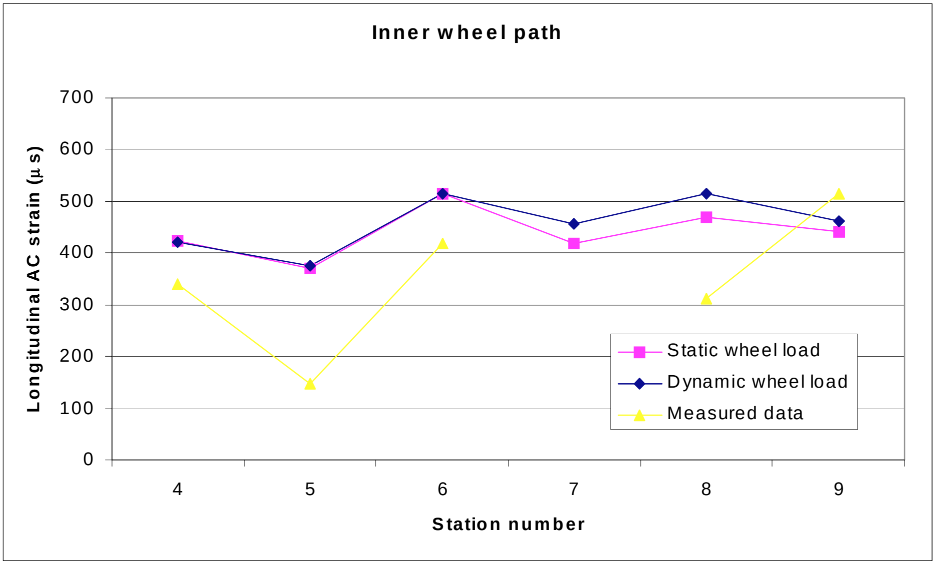

Figure 10. Longitudinal strain in asphalt layer on the inner wheel path.

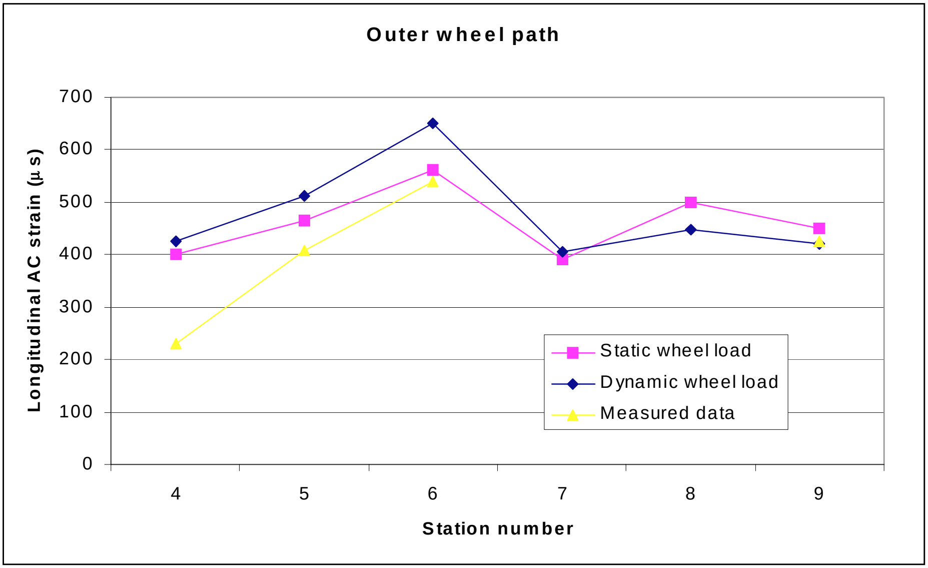

Figure 11. Longitudinal strain in asphalt layer on the outer wheel path.

Return to paper

Content

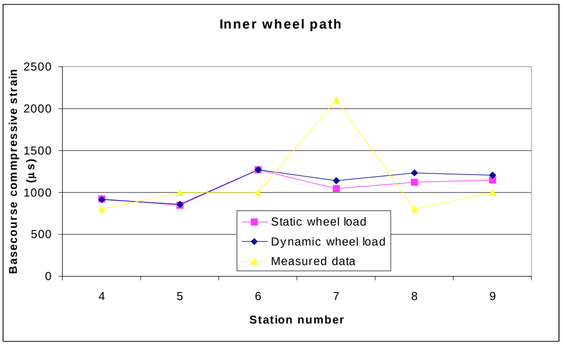

Figure 12. Vertical compressive strain in basecourse layer on the inner wheel path.

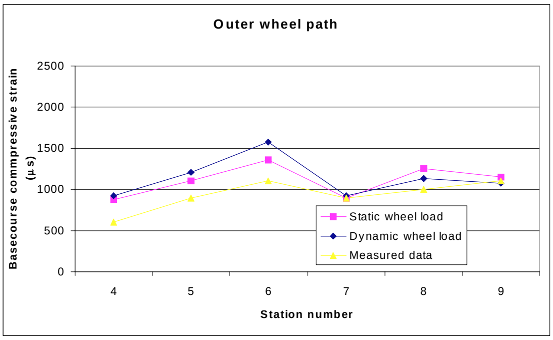

Figure 13. Vertical compressive strain in basecourse layer on the outer wheel path.

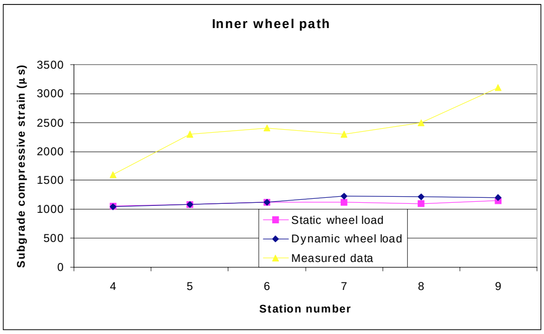

Figure 14. Vertical compressive strain in subgrade layer on the inner wheel path.

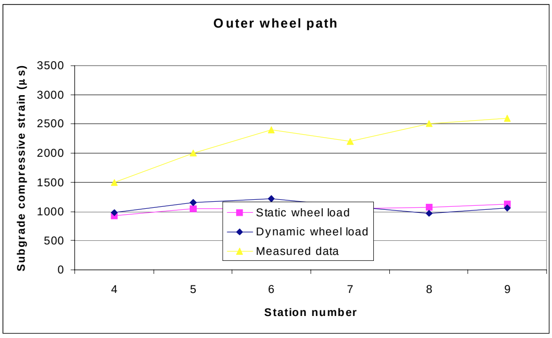

Figure 15. Vertical compressive strain in subgrade layer on the outer wheel path

Return to paper

Content