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<th>Prediction of Deterioration of Asphalt Pavements by Mechanistic-Empirical Methods</th>
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ABSTRACT

Cracking of an asphalt layer arises from repeated tensile strains, the maximum value of which typically occurs at the bottom of the layer (particularly for thinner asphalt layers). The crack, once initiated, propagates upwards causing gradual weakening of the structure. The development of a rut arises from the accumulation of permanent strains throughout the structure. A model of pavement damage accumulation, leading to a prediction of pavement life, is described. In addition to pavement damage, the model allows for the spatial repeatability of traffic loading and differences in the progression of damage at different points along the road.

The procedure is divided into four main areas: dynamic vehicle simulation; pavement primary response calculation; pavement damage calculation and damage feedback mechanism. The modes of damage that are included in the model are structural rutting and fatigue damage to the asphalt layers. These primary response influence functions are combined with the dynamic tyre forces, to give primary pavement response time histories at a large number of equally spaced discrete points along the pavement.

The primary responses are combined with the appropriate pavement damage models and the number of load applications, to predict damage (rutting and fatigue damage) as a function of distance along the pavement for each time increment. An updated surface profile is then generated by subtracting the calculated rutting in the wheel path from the initial profile used for that time increment. This mechanism accounts for the effects of changing surface roughness on the pattern of statistical spatial repeatability and hence the pattern of mean dynamic tyre force.

The calculated fatigue damage is used to reduce the stiffness of the asphaltic material for each subsection. This mechanism reflects the effects of cumulative fatigue damage on the primary responses and hence subsequent pavement damage. The above process is then repeated for many time increments until the pavement has reached the end of its serviceable life. The model gives many insights into the nature of the deterioration process and the changing pattern of spatial repeatability as the profile deforms.

Keywords: Mechanistic-Empirical, Dynamic, Load, Rutting, Fatigue, Pavement damage, Spatial Repeatability, Statistical.
1. INTRODUCTION

The AASHTO Guide for the design of pavement structures is commonly used to design pavements with traffic loadings greater than 50 million equivalent axle loads (ESALs) (Seeds 2002). It is assumed that each point is subjected to forces that are statistically similar to all other points and hence that the probability of deterioration is uniformly distributed along the pavement. This is clearly untrue given the phenomenon of statistical spatial repeatability (SSR) – it is known that some points on a road are subjected on average to greater forces than others. Data measured from a short stretch of road near Arnhem in the Netherlands (Belay et al. 2008) shows that the mean force applied by the third axle of one thousand 5-axle truck is repeatable, i.e., it confirms the phenomenon. Cole et al. (1996) found similar results by measuring dynamic force generated by 1500 heavy vehicles using a mat containing 144 capacitive strip sensors. O’Connor et al. (2000) report similar results from WIM data, demonstrating a pattern of spatial and statistical spatial repeatability of dynamic force. Ullidtz & Larsen (1983) and Collop & Cebon (1995) have shown that it is this dynamic force that should be used in the Mechanistic Empirical (ME) approach to predict the life of a flexible pavement. The clustering of high forces at particular points along a road pavement has important implications for the process of pavement deterioration.

2. STATISTICAL SPATIAL REPEATABILITY MODEL

The ME method requires a prediction of the actual distribution of dynamic load caused by the fleet of trucks (Collop & Cebon 1995). Furthermore, the predicted mean pattern of dynamic force needs to be recalculated periodically as pavement damage causes the road profile to change. The calculation scheme, illustrated schematically in Figure 1, is similar to that of Collop and Cebon (1995). It can be divided into four main areas: Dynamic Vehicle simulation; Pavement primary response calculation; Pavement damage calculation and Damage feedback mechanism.

DePont (2004) used dynamic vehicle models in an attempt to generate the mean patterns of dynamic force measured in the data of O’Connor et al. (2000). However, he used a stochastic road profile so it is not surprising that he did not get a good match to the measured mean patterns. Cole and Cebo (1992) also simulate patterns of spatial repeatability but for fixed vehicle dynamic properties. In an earlier study, Belay et al (2008) show that data from a multiple-sensor Weigh-in-Motion (WIM) system can be used to develop a simple truck fleet dynamic model. Such a model, when calibrated with field data, can predict patterns of spatial repeatability on a road with any specified profile. This in turn can be used to accurately predict the changing patterns of SSR as a pavement deforms in response to applied load.

3. PAVEMENT DETERIORATION MODEL

Odemark’s Method of Equivalent Thickness (MET) is used to transform a pavement consisting of multiple layers with different moduli into an equivalent system where all layers have the same modulus – equation 1 (Ullidtz & Larsen 1983):

\[ h_{en} = f \sum_{i=1}^{n} h_i \left( \frac{E_i}{E_n} \right)^{3/2} \quad \text{for} \quad v_1 = v_2 \]

where \( v \) is Poisson’s ratio, \( E_i \) is the elastic modulus of the layer to be transformed with respect to the modulus of layer \( n \) (\( E_n \)), \( h_{en} \) is the depth of the transformed section, \( h_i \) is depth of the section to be transformed, and \( f \) is the correction factor. This enables the use of Boussinesq’s plane strain
equations (Ullidtz & Larsen 1983). The concept of Odemark’s method is that stresses and strains below a layer depend only on the stiffness of that layer.

The vehicle fleet model properties are assumed to be Normally distributed. The model used here has the properties shown in Table 1 and are taken from a combination of references (Cebon 1999, Zhang et al (2001) and Engineering judgement. Monte Carlo simulation is used to generate quarter car dynamic model properties representative of the fleet. For each quarter car model (Belay et al 2008), the spatial pattern of wheel force is calculated. A typical distribution in the direction of travel is illustrated in Figure 2.

**Table 1 - Vehicle parameters of truck model**

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<th>Number</th>
<th>Vehicle parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
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<tr>
<td>1</td>
<td>Unsprung mass, ( m_u ) (kg)</td>
<td>420</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>Sprung mass, ( m_s ) (Tonnes)</td>
<td>4.45</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>Suspension stiffness, ( k_s ) (MN/m)</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>Suspension damping, ( k_s ) (kNs/m)</td>
<td>21.0</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>Tyre stiffness, ( k_t ) (MN/m)</td>
<td>1.95</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>Velocity, ( v ) (m/s)</td>
<td>22.43</td>
<td>2.4</td>
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For each point of application, the tyre pressure is assumed to be uniformly distributed over a circular contact area 300 mm in diameter (Ullidtz & Larsen 1983) (Figure 3). The disc is divided into small segments, each assigned a concentrated force proportional to its area and located at its geometric centre. These forces are substituted into Boussinesq’s equations. The vertical strain at the bottom of the granular layer and the horizontal strain at the base of the asphalt layer were calculated to determine the rutting and fatigue failure respectively for the multi-layer system.

The contributions of each concentrated point force are superimposed to find the resultant stress/strain at the point of interest. This is repeated for the whole length of the profile under consideration at intervals of 0.3m. The example was carried out for an asphalt thickness of 0.15m and Poisson’s Ratio was taken to be 0.35 for all layers. The stiffness of the asphalt layer is calculated from an initial binder penetration of 100 dmm, void content 10%, binder content 3.5%, specific gravity of binder 1020 kg/m³, specific gravity of aggregate 2700 kg/m³, proportion of binder by volume 7.9%. The thickness and stiffness of the granular layer were taken to be 200 mm and 300 MPa respectively. The modulus of the subgrade (soil) was taken to be 20 MPa (the thickness is infinite (Hildebrand 2002)). The temperature is assumed to vary cyclically through the year in the range of ±10°C. The pavement stiffnesses and surface profile affect the pattern of statistical spatial repeatability and are updated after each 3 months of traffic.
Figure 3: Subdivision of circular force into a number of small forces (Cebon 1999)

Sample strain distributions at the top of the subgrade and the bottom of the asphalt layer are illustrated in Figures 4(a) and (b) respectively as the vehicle travels past the point of interest.

Model for ageing of the asphalt layer, fatigue cracking, permanent deformation and asphalt modulus degradation are detailed in (Hildebrand 2002).

Figure 4: Sample strain distributions
4. RESULTS

Using the above formulation, a simulation of the complete process of pavement degradation has been developed. For alternative initial profiles, deformations at intervals of 1 million axle loads are calculated. A typical result is illustrated in Figure 5 for profile initially classified as smooth. A total of 24 observation points are assumed at 1.5 m intervals starting at 14 m.

There is clearly a cycle in the pavement degradation process of the road profile generating a pattern of Statistical Spatial Repeatability (SSR) which causes permanent deformation and hence a new profile. It can be seen in Figure 5 that the profile and the SSR patterns change during the pavement life. There is no clear trend in how the SSR pattern changes at first. Some points with high mean force change and become points with a low mean force. Other points have relatively high forces throughout the process.

As the pavement degrades, the deformations in response to mean force increase. As a result, the permanent deformations become more important and can cause relatively rapid changes in the pattern of SSR. However, the evidence is not one of ever more variability in the pattern of SSR. On the contrary, the pattern seems to converge in the later stages of degradation. It would appear that the initial pattern of SSR changes significantly through the stages and goes through several phases but eventually reaches a point where it 'locks in' to a pattern which is generating deformations which are enforcing that pattern, i.e., it appears that, regardless of the initial pattern, a final pattern of SSR emerges that is stable as it is generating deformations that strengthen the degree to which it is repeatable. It should be noted that the deformations and forces in later stages illustrated in Figure 5 are unrealistically large – in practice, the pavement would be repaired prior to the development of such excessive deformations.

Figure 5: Successive pavement deformations and mean patterns of applied force (each curve corresponds to the situation after 1 million axles)

Figure 6 provides a comparison of the initial road surface profile and the final road surface profile after 23 million dynamic axle load for four different profiles. The initial profiles are clearly
completely independent of one another – no relationship exists between them. The final profiles on
the other hand, have a similar frequency evident in all of them. The essential difference between
them is only one of phase. This is reasonable given that the pavement stiffness is constant
throughout the length considered, i.e., it is reasonable to assume that, if the initial profile is random,
then all points along the length are equally likely to be the point of eventual failure.

Figure 6: Comparison of initial and final road surface profiles for four different examples

Finally, it is noted that the lock-in frequency may be a strong indicator that the failure process has
commenced. This has considerable potential as an early indicator of the onset of the process of
failure and could be a useful tool to inform road maintenance programmes. From Figure 6, it can be
seen that profile 2 and 1 are the first and second to fail respectively.
4.1. LOCK IN EFFECTS

In order to find what all pavements deformation and mean dynamic axle force histories have in common, the frequency of the peaks in Figures 5 is identified, i.e., the inverse of the distance between the peaks for the mean maximum dynamic force and minimum depression point of the deformation (Figure 5). The frequency is recalculated, at two million axle load intervals, as the pavement progresses towards failure. In cases where it is difficult to know the forms of depression formed in the pavement profile, the measurement is only started where this pattern starts to clearly emerge. These plots are presented in figures 7. A similar plot was also perfumed for other three additional different types of pavements surface profiles. In all cases the pavement deformation and the mean dynamic axle force frequencies are converging to the same value. It is unsurprising that pavement deformation frequency converges to mean force frequency because, as the pavement approaches failure, the deformations due to mean force are large which deforms the profile in proportion to the force pattern. What is perhaps surprising is that the patterns converge in all four cases to approximately the same frequency of about 0.074 m\(^{-1}\).

![Figure 7: Frequency plot of profile for mean dynamic load and pavement profile deformation](image-url)
As is shown in figures 7a, 7b, 7c and 7d. In some cases in actual fact, they are not vanishing but rather it continues to seek to form a similar frequency. Some peaks shift beyond the fifty metre extent of the simulation while others adjust themselves to a similar frequency. This creates a lock in effect causing more damage to the road surface profile.

It is reasonable to conclude that there is a characteristic 'lock-in' frequency associated with the truck fleet and perhaps also the pavement properties. The exact point of failure will be a function of the initial profile but that is its only effect, i.e., the frequency of the failure pattern is independent of the initial profile. The number of axle loads to cause failure may be influenced by how quickly the lock-in occurs which is a function of the initial profile – it can be seen in the figure that, after the same number of axle loads, some pavements are much more deformed than others. This means that there is considerable random variation in the number of axles to failure, arising from the randomness of the initial profile.

4.2. EFFECT OF INCREASING THE PAVEMENT PROFILE

The effect of an extended profile beyond fifty metres is also studied. An 80m profile was used to see if there is a defined pattern of failure, an increasing pattern of deformation. It has been demonstrated that the deformation process is not continuously increasing with increase in profile length. For example, in Figure 8(a), the maximum deformation in the profile happens at approximately 50m. It is possible to say from these two graphs (Figure 8) that a study of the deterioration of an asphalt pavement is a complex process.

4.3. RELATIONSHIP BETWEEN MILLION AXLE FORCE, MAXIMUM DEFORMATION AND MAXIMUM AXLE FORCE

The maximum axle load and the maximum deformation was collected at each one million axle load increment. As seen in figure 8 the increase in the mean maximum dynamic force and the maximum deformation have a non linear relationship in this particular example. One can see that there is no increase in the maximum mean dynamic load and pavement deformation up to about 10 million axle loads. After 10 million axle loads, the increase in maximum mean dynamic force and maximum pavement deformation increases sharply in a non-linear manner. It can be seen from
(Figure 8) that there is a sharp increase in deformation after 12 million axle load. The timely intervention for maintenance can help to increase before major failure happens.

Figure 9: Relationship between mean one million axle dynamic force and pavement deformation at different stages of pavement life

5. CONCLUSION
A model is developed which helps to explain the nature of the process of pavement failure and which has the potential to assist with estimations of pavement life and provide early warning indicators of pavements that are starting to progress towards failure. The merit of this model is that it can be based on actual vehicle fleet population models. This makes possible the recalculation of the patterns of SSR as the profile changes in response to applied loading. It also shows the time at which the pavement starts to receive a higher magnitude of mean dynamic force from the same vehicle fleet population as deterioration progresses.

6. REFERENCES


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