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<th>The Influence of Statistical Spatial Repeatability on Remaining Pavement Life</th>
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A road develops permanent deformation and fatigue damage because of the strains induced in its structure by surface loading and environmental change. A mechanistic-empirical approach is implemented here to simulate the deterioration of a pavement. A quarter car model is used to simulate pavement/vehicle dynamic interaction and a feedback mechanism is implemented after each run to update the pavement profile after the passage of each axle. In this way, the influence of Statistical Spatial Repeatability (SSR) is incorporated into the pavement damage model. The model is run for two sample profiles. The first is a simple step profile which demonstrates that the patterns of damage relate to the two natural frequencies of the quarter car. An initially random profile is also investigated. A complete history of the surface profile during its life demonstrates how the peaks and troughs migrate in response to the evolving pattern of SSR.

Keywords: Pavement, permanent deformation, spatial repeatability, dynamics, mechanistic-empirical.

1 Introduction

The traditional approach to pavement life assessment considers all axle weights that are anticipated and calculates the number of equivalent axles of standard weight. It does not calculate the effect of dynamic oscillation of axle forces about the static weight. More significantly, the traditional approach to pavement assessment does not account for ‘spatial repeatability’, the fact that the mean pattern of dynamic forces applied by a truck to a pavement, is repeatable. Many researchers (Cole & Cebon 1992, Collop 1994, Cole and Cebon 1992, Huhtala et al 1992) have presented evidence showing that for a given speed, the dynamic axle force time histories generated by a particular heavy vehicle are concentrated and repeated at specific locations along the road for repeated test runs. The mechanistic-empirical approach (De Pont & Pidwerbesky 1995, El Beheiry & Karnopp 1996, Sun & Kennedy 2002, Arnold et al. 2005, VanLoo and Visser 2005), illustrated in Figure 1, is used for assessing the remaining service life of a pavement. In the context of this paper, the significant elements are the dynamic vehicle simulation and the fact that it is updated in response to road damage.

A section of pavement is divided along its length into many equally spaced sub-sections. A time domain vehicle simulation is used to generate dynamic forces for axles at each point along its length.
Figure 1. Mechanistic-Empirical Framework

A simple pavement material model, based on the Method of Equivalent Thickness, is used here to calculate the peak strain corresponding to each passing axle. Two types of damage are evaluated after each pass:

- **Rutting** has the effect of changing the surface profile (permanent deformation).
- **Fatigue damage** reduces the modulus of elasticity. This has the effect of reducing the ability of the pavement to disperse the wheel load, resulting in greater strains for a given load.

Fatigue damage reduces the modulus of elasticity. After each axle pass, the pavement profile is updated to incorporate the permanent deformation and the modulus of elasticity is recalculated at each point to allow for the increased fatigue. The process is repeated for millions of axle passes until the pavement has reached the end of its serviceable life.

2 **Statistical Spatial Repeatability**

The concept of spatial repeatability is well established (Cole & Cebon 1996; O’Brien et al. 2004), i.e., as the same truck travels repeatedly over a given stretch of road, the pattern of dynamic forces is approximately the same for each run. “Statistical spatial repeatability” (SSR) (O’Connor et al. 2000) is the phenomenon that the statistical distribution of the pattern of dynamic force applied by a large group of axles to a given stretch of road is also repeatable, i.e., the same approximate distribution of patterns will apply for each group of axles.

The phenomenon is illustrated in Figure 2 which shows mean patterns of measured dynamic wheel forces on a section of road near Arnheim in the Netherlands.

Three patterns are illustrated, each representing the mean force applied by the third axle of one thousand 5-axle trucks. SSR has significant implications for pavement...
damage as some points (e.g., $x = 0$ in Figure 2) are subject to higher mean forces than others (e.g., $x = 19.5$). It can be inferred that the former point will be more damaged than the latter, unless/until the SSR pattern changes.

Wilson et al. (2006) use Bayesian Updating to back-calculate the dynamic properties of a fleet of axles from a database of axle forces measured at a multiple-sensor weigh-in-motion system. They go on to use the inferred fleet properties to successfully predict patterns of SSR. Their study demonstrates that it is possible to characterize a fleet of axles on a road or for a network of roads and to use those fleet properties in mechanistic-empirical calculations of remaining pavement life such as that described here.

3 Distribution of Forces at Various Points

The truck fleet model differs from a conventional truck dynamic model in that a force pattern is calculated for each of many passing axles (Türkay and Akçay 2005). Different combinations of vehicle properties are used in each run, reflecting variations between individual axles on the road. Such a model allows for statistical variation in the axle properties such as stiffness and mass. The outputs of repeated dynamic calculations are statistical distributions of dynamic force at each point along the road. For the truck fleet models described here, all the vehicle parameter properties are assumed to be Normally distributed. A quarter car model is used with the distribution properties given in Table 1 (Sun and Kennedy 2002, Grave 2001 and Cebon 1999).

Monte Carlo simulation is used to calculate the force patterns due to 1000 quarter cars from this fleet on an initially random road surface profile (Figure 3). The resulting distributions of applied force are illustrated in Figures 4 and 5. For this example, the most frequent force varies from as low as 48 kN (at $x = 30$ m) to as high as 50 kN (at $x = 25$). The standard deviations also vary with location though not to a great extent.

Table 1: Vehicle parameters of quarter car fleet model

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<th>No</th>
<th>Vehicle parameter</th>
<th>Mean</th>
<th>Std</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, $m_s$ (kg)</td>
<td>4535</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>Suspension stiffness, $K_s$ (N/m)</td>
<td>$1 \times 10^6$</td>
<td>$0.1 \times 10^6$</td>
</tr>
<tr>
<td>4</td>
<td>Suspension damping, $C_s$ (Ns/m)</td>
<td>$20 \times 10^3$</td>
<td>$2 \times 10^3$</td>
</tr>
<tr>
<td>5</td>
<td>Tire stiffness, $K_t$ (N/m)</td>
<td>$1.95 \times 10^6$</td>
<td>$0.2 \times 10^6$</td>
</tr>
<tr>
<td>6</td>
<td>Velocity, $v$ (m/s)</td>
<td>22.43</td>
<td>2.40</td>
</tr>
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</table>

Figure 3. Initial Road Profile
4. Examples of Application

Mechanistic-empirical design is complicated by the feedback loop in the road profile, i.e., the pattern of forces causes rutting which changes the initial profile which in turn changes the pattern of forces. While these changes are small, their influence accumulates and they should not be ignored. The road profile moduli of elasticity and climatic conditions are updated after each calculation and the process repeated until the pavement fails.

4.1 Step Road Profile

To illustrate the process of pavement damage evolution, a simple initial profile is considered that is perfectly smooth except for a 10 mm step change that is subjected to 18 million
passes of the quarter car. The step is at \( x = 4 \) m and rises 10 mm (Figure 6).

![Figure 6. Initial step profile](image)

The pavement has an asphalt thickness of 0.20 m. The Modulus of Elasticity of the asphalt layer is calculated assuming typical properties: monthly air temperature range \( 10^\circ\text{C} \) to \( 10^\circ\text{C} \), void content 10%, binder content 3.5%, Specific Gravity of binder 2700 kg/m\(^3\), Specific Gravity of aggregate 1020 kg/m\(^3\), proportion of binder 7.9% (Cebon 1999). The granular layer has a modulus of elasticity of 400 MPa and is 0.2 m thick. The subgrade layer is assumed to be infinitely thick with a modulus of 40 MPa (Collop 1994). The Poisson’s Ratio is taken to be 0.35 for all three layers (asphalt, granular and subgrade).

The permanent deformation of the profile, during its life and after 18 million axle passes, is illustrated in Figure 7. Two frequencies can be seen in the figure, corresponding to the two mean frequencies of the fleet of quarter cars.

![Figure 7. History of pavement profile during its life](image)
The high frequency tire hop causes greatest damage and has greatest influence immediately adjacent to the step (Figure 7(b)). The lower frequency corresponds to the suspension. It causes damage over a greater extent of road but of lesser magnitude. There are some locations (e.g., \( x = 10 \) m) where permanent deformation is less than for static loading alone, i.e., the axle dynamics actually reduces the damage.

The rate of damage increases progressively with time. This is partly due to a modest reduction in the material moduli of elasticity that comes from fatigue damage. It is also caused by ever increasing dynamic forces at certain points along the road (Figure 8). It can also be seen that locations of the peaks and troughs in the road profile move during its lifetime. For example, the slight trough at about \( x = 27 \) m in the early stages becomes a significant trough at \( x = 30 \) m later in the pavement’s life.

At around \( x = 17 \), there is a significant fall in elastic modulus combined with an increasing mean dynamic force. The rate of damage therefore increases in this area in the later stages of the pavement’s life, showing that the process is non-linear.

### 4.2 Artificially Generated Initial Road Profile

The fleet of quarter cars is also tested on the 50 m length of randomly generated initial road profile illustrated in Figure 3. The same pavement thickness and material properties and the same quarter car fleet properties are used as those described above.
Figure 9 shows the change in profile due to the 1st, 2nd, and 3rd group of 10 million axles. In general, the increment of damage tends to increase for each group of 10 million, as the elastic moduli are reducing and the profile is getting rougher. For example, at \( x = 35 \) to 40 m, the increment of permanent deformation can be seen to be increasing. There are other points where this is not the case. For example, at \( x = 45 \) m, the increments of permanent deformation are getting smaller. This is because the pattern of statistical spatial repeatability is changing and the peak in the mean force is progressively moving away from this point.

![Figure 9. Permanent deformation for randomly generated Class A initial](image)

5 Conclusions

The pattern of dynamic forces on a flexible pavement is a key factor in the calculation of its remaining life. The mechanistic-empirical method requires a prediction of the distribution of dynamic load caused by the fleet of axles that travel on that section of the road. The statistical distributions of the dynamic forces need to be recalculated periodically as pavement damage causes the road profile to change. This phenomenon is shown to be significant for pavement failure. The peaks and troughs in the road profile are shown to move as the pavement damage process progresses.

References


