TRAFFIC CHARACTERISATION IN FLEXIBLE PAVEMENT DESIGN

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ABSTRACT

This paper investigates the way in which traffic data is used in flexible pavement design and analysis procedures. A deterministic Long Term Pavement Performance Model (LTPPM) is used to calculate flexible pavement damage caused by trafficking from three realistic fleets of commercial vehicles. The fleets have been modelled using seven axle group models representing steer axles, drive axles (single or tandem) and trailer axles (tandem or tridem) with either steel suspensions or air suspensions. Results are compared to the calculated flexible pavement damage caused by a fleet of 80kN standard axles and predictions from the currently used method of traffic characterisation for UK pavement design procedures. Results show that pavements that fail by rutting last longer when trafficked by the realistic vehicle fleets compared to the fleet of 80kN standard axles whereas the pavements that are predicted to fail by fatigue last longer when trafficked by the fleet of 80kN standard axles. Results also show that current UK pavement design procedures are more sensitive to differences in the vehicle fleet compared to LTPPM predictions.

INTRODUCTION

In current UK detailed pavement design procedures, the damage associated with different classes of commercial vehicles is characterised using Vehicle Wear Factors (*VWFs*). For a particular vehicle, *j*, the *VWF*, expressed in terms of an equivalent number of 80kN standard axles, is calculated using [1]:

$$VWF_j = \sum_{i=1}^{N_a} \left(\frac{P_i}{80} \right)^4 \tag{1}$$

where P_i is the static axle load (kN) on axle *i*, and N_a is the number of axles.
Average *VWFs* for the different classes of commercial vehicles (based on axle load measurements determined from static weighscales or, more recently, Weigh-in-Motion (WIM) systems [2]) are then used to calculate the design traffic using the following equation [1]:

$$T = 365 \times 10^{-6} Y \sum_{j=1}^{N_v} F_j \times G_j \times VWF_j \times Q_j \tag{2}$$

where T is the design traffic (million standard axles) Y is the design period (years), F_j is the present traffic flow (commercial vehicles per day) for vehicle class *j*, G_j is the annual growth factor for vehicle class *j*, Q_j is the proportion of vehicle class j using the left hand lane, and N_v is the number of vehicle classes.

Typically, the design traffic T is used in conjunction with an empirical design chart to determine the pavement construction that is required to carry the design traffic. It can be seen from Equation (1) that the damage associated with a particular vehicle is calculated using the static axle load raised to a fourth power. The power of four originates from full scale tests carried out in the late 1950s by the American Association of State Highway Officials (AASHO) [3]. Using a regression analysis it was found that the decrease in 'pavement serviceability' caused by a heavy vehicle axle could be related to its static load raised to a fourth power. Serviceability was rated by a panel of experts and expressed in terms of a 'present serviceability index' (PSI) ranging from 0 to 5 (perfect road). It was found that PSI could be correlated with cracking and patching, rutting, and surface roughness.

However, this approach has been found to be subject to a number of limitations [4], namely:

- The sensitivity of pavement damage to vehicle speed and the frequency of applied loads are not included;
- It does not account for the effects of dynamic tyre forces or tyre configuration;
- It does not account correctly for the mode of road failure (ie rutting, fatigue etc).

The validity of the 4th power law is also questionable because current axle group configurations, tyre sizes and pressures, pavement constructions, and traffic volumes are significantly different from the conditions of the AASHO road test.

In more analytical design procedures, the main difference is that a computer model of the pavement structure is used to calculate the response of the pavement to a standard 40kN load applied through dual tyres (or a single tyre), rather than using a design chart. Both of these procedures rely on *VWFs* for determination of the design traffic. Consequently, it can be seen that in both of these approaches, the effect of truck factors (eg axle spacing, load sharing, suspension type), tyre factors (eg contact area, contact pressure, tyre type etc) and pavement factors (eg surface roughness, variations in asphalt layer thickness) on pavement design cannot easily be incorporated. In the case of empirical design, these factors are implicitly included in the design charts for the vehicle fleets in operation when the empirical data was collected. However, subsequent changes in the vehicle fleet (eg super-single tyres, road-friendly suspensions) and associated changes in pavement performance cannot be predicted using empirical design charts.

The method to be investigated in this paper differs fundamentally from the standard *VWF* approach which is based on aggregating traffic. Realistic pavement damage models are used, and damage caused by different axle groups in the fleet are calculated and accumulated as the pavement is progressively trafficked. This can be thought of as an aggregate damage approach rather than an aggregate traffic approach. The model used is discussed in the following sections. The research described in this paper forms part of the Highways Agency's (HA's) research programme.

LONG-TERM PAVEMENT PERFORMANCE MODEL (LTPPM)

The model used to calculate long-term pavement performance in the presence of traffic and environmental loads. Areas of the model relating to the calculation of dynamic axle loads are described in the following section. Other details of the model and assumptions can be found in [5,6].

Referring to Figure 1, the initial inputs to the LTPPM are:

- The specification of the pavement being simulated (i.e. layer thicknesses, mixture specifications etc.);
- the time increment to be used in the simulation;
- The rate of traffic loading;
- The climatic conditions.

From this initial specification, the simulation process can be divided into the following steps.

1. A length of pavement surface profile is generated and divided into many equally spaced sub-sections of length 0.5m.
2. A time domain vehicle (or axle group) simulation is used to generate dynamic tyre forces for one vehicle (or more) as a function of distance along the pavement. The vehicle (or axle group) model parameters are chosen to best represent the traffic conditions for the type of pavement being simulated.
3. A set of primary response 'influence functions' is generated, for each pavement sub-section and each mode of damage. The modes of damage that are included in the LTPPM are permanent deformation (rutting) in both the asphaltic and lower pavement layers and fatigue damage to the asphaltic layers.
4. 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.

5. 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 the current time increment.
6. 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 dynamic tyre forces.
7. The calculated fatigue damage is used to reduce the elastic modulus of the asphaltic material for each sub-section. This mechanism reflects the effects of cumulative fatigue damage on the primary responses and hence subsequent pavement damage.
8. The above process is then repeated for the next time increment, and so on, until the pavement has reached the end of its serviceable life.

2.1. Axle Group Models

Due to the relatively large amount of computer time required to run the LTPPM [6] it was decided to represent a typical UK commercial vehicle fleet using a number of 2-dimensional axle group models rather than whole vehicle models. This assumes that the effect on dynamic tyre forces caused by interactions between axle groups is small compared to the dynamic tyre forces generated by the axle group itself. In total, seven models were chosen, to represent the axle groups found on a typical fleet of commercial vehicles (see Table 1). The steel spring suspension elements were based on a validated model developed by Fancher et. al. [7]. The parameters used in the models are largely based on results from validated articulated vehicle simulations developed by Cole and Cebon [8].

Single axle steel/air suspension

This axle group model was used to represent a tractor steer axle with steel suspension (STER) and a tractor drive axle with steel or air suspension (SINS, SINA). For all the axle group suspensions (except the steer axle) the first three letters denote the number of axles (ie SIN=single axle, DUA=dual axle, TRI=tri-axle) and the last letter indicates whether the suspension is steel sprung (S) or air sprung (A). The model is shown schematically in Figure 2. It can be seen from this Figure that this model has 2 degrees of freedom (Z_{u1} and Z_2). M_{s1} represents the sprung mass and M_{u1} represents the unsprung mass (axle mass etc). The force versus displacement characteristics of the suspension element joining the sprung and unsprung masses and the tyre element joining the unsprung mass to the pavement surface profile are shown in Figures 3(a) and 3(b) respectively [7].

It can be seen from Figure 3(a) that 6 parameters are required to characterise the force versus deflection characteristics for the suspension. k_u and k_l define the upper and lower stiffness envelopes for the model, β_u and β_l define the form of the exponential function used to join the envelopes, and F_f and C_s define the level of friction and hydraulic damping in the suspension. The values of these parameters for a typical air and steel suspension are given in Table 2. It can be seen from Table 2 that, for the drive axle suspensions, the suspension stiffness is lower for the air suspension; the air suspension has a higher level of hydraulic suspension damping; and there is no friction. The values of tyre stiffness and damping are typical for dual tyres [8]. The steer axle suspension has lower values of sprung and unsprung masses, lower suspension stiffness and a higher level of hydraulic suspension damping. The values of tyre stiffness and damping are typical for single tyres [8].

Tandem axle steel/air suspension

This axle group model was used to represent either a tractor drive axle with steel or air suspension or a trailer axle with steel or air suspension (DUAS, DUAA). The model is shown schematically in Figure 4.

It can be seen from this figure that this model has 6 degrees of freedom (Z_{u1}, Z_{u2}, Z_3, θ_{u1}, θ_{u2} and θ_l). As before M_{s1} represents the sprung mass and M_{u1} and M_{u2} represent the unsprung masses (axle mass etc). The force versus displacement characteristics of the suspension element joining the sprung and unsprung masses and the tyre element joining the unsprung mass to the pavement surface profile are shown in Figures 3(a) and 3(b). It can be seen from Figure 4 that the main difference between this model and the single axle model is the addition of a levelling beam between connecting the axles [9]. The force versus deflection characteristics of the levelling beam are shown in Figure 3(c). Values of the parameters used in the model are given in Table 2. It can be seen from

this table that, as before, the suspension stiffness is lower for the air suspension, the air suspension has a higher level of hydraulic suspension damping and there is no friction. The values of tyre stiffness and damping are typical for dual tyres [8]. It can also be seen from Table 2 that the levelling beam stiffness and damping are large for the air suspension compared to the steel suspension. This is because the axle of an air suspension work essentially independently whereas the axles on a steel suspension are typically coupled and do not behave independently of each other.

Tri-axle steel/air suspension

This axle group model was used to represent a trailer axle with steel or air suspension (TRIS, TRIA). The model is similar to the tandem axle suspension (Figure 4) with the addition of an additional axle station and is not shown for brevity.

This model has 9 degrees of freedom and, as before, M_{s1} represents the sprung mass and M_{u1}, M_{u2} and M_{u3} represent the unsprung masses (axle mass etc). The force versus displacement characteristics of the suspension element joining the sprung and unsprung masses and the tyre element joining the unsprung mass to the pavement surface profile are shown in Figures 3(a) and 3(b). The force versus deflection characteristics of the levelling beam are shown in Figure 3(c). Values of the parameters used in the model are given in Table 2.

Relative Axle Group Proportions

Detailed data from WIM measurements [10] were used to determine the relative proportions of the different commercial vehicles (and hence axle groups) for 3 classes of road (Motorway, Trunk Road, Principal Road). These data, in conjunction with results from Potter et. al. [11] were used to estimate the relative proportions of steel and air suspensions for each axle group model (see Table 3). The resulting axle group proportions for the 3 pavement classes (Motorway, Trunk Road, Principal Road) are denoted Fleet A, Fleet B and Fleet C in the rest of this paper.

Also shown in Table 3 are the *VWFs* for each of the axle group models calculated using Equation (1). In addition, a Fleet Vehicle Wear Factor (*FVWF*) has been calculated using the following equation:

$$FVWF = \sum_{i=1}^{N_g} VWF_i \times p_i \tag{3}$$

where VWF_i is the Vehicle Wear Factor for axle group i, N_g is the number of axle groups, and p_i is the proportion of axle group i.

The *FVWF* can be interpreted as the number of passes of a standard 80kN axle required to cause the same damage as one pass of the vehicle fleet according to the 4th power law. For example, if there were 38 passes of STER, 26 passes of SINS, 4 passes of SINA, 14 passes of DUAS, 4 passes of DUAA, 7 passes of TRIS and, 7 passes of TRIA this would be equivalent to approximately 185 passes of an 80kN standard axle.

To ensure that the dynamic force levels generated by the axle group models were realistic, simulations were performed where each axle was run over a typical Motorway pavement surface at 22m/s (50mph) and the Dynamic Load Coefficients (DLCs) were calculated for each axle. It was found that the DLCs were realistic and, as expected, the values for the steel sprung suspensions were greater than the values for the air sprung suspensions. For example, the DLCs for the tandem axle air suspension were found to be 5.5% and 5.1% compared to 10.3% and 10.2% for the tandem axle steel suspension.

LTPPM SIMULATIONS

LTPPM Input Parameters

The long-term response of the three classes of flexible pavement trafficked by four vehicle fleets (A, B, C and an 80kN standard fleet) have been calculated for typical UK climatic conditions using the LTPPM. It should be noted that Vehicle Fleets A, B and C were determined using traffic data measured from a Motorway, Trunk Road and

Principal Road respectively. In the LTPPM simulations these vehicle fleets have been applied to all three pavement classes (Motorway, Trunk Road and Principal Road) to investigate the sensitivity of long-term performance for each pavement class to changes in the vehicle fleet. Each of the pavements has been trafficked at the same rate (in terms of applied axle loads per month) for ease of comparison of the results and the speed of the axle group models were chosen to represent the average speed of heavy goods vehicles measured using WIM for the particular class of road (24.4m/s for a typical Motorway, 22.2m/s for a typical Trunk Road and 16.1m/s for a typical Principal Road). The only geometrical difference between the different classes is the thickness of the asphalt layer. This was taken to be 350mm for the Motorway, 250mm for the Trunk Road and 150mm for the Principal Road. The length of each simulated pavement section was 100m. A typical 50 pen Hot Rolled Asphalt (HRA) was used and the subgrade was assumed to have an elastic stiffness modulus of 40MPa. For a Motorway, an initial IRI roughness of 2 was used and for a Trunk Road and Principal Road initial IRI roughnesses of 3 were used. The variation in mean monthly air temperature for each type was assumed to be sinusoidal, with a mean temperature of 11°C and a temperature amplitude of 7°C. These are typical of UK climatic conditions [23]. The pavement surface profile was updated every 3 months, and the asphalt layer modulus was degraded in 10% steps to achieve a satisfactory trade-off between convergence of results and computational speed [6]. Two different exponents (1 and 4) were used in the lower layer rutting model to investigate the influence of the sensitivity of lower layer rutting to the level of dynamic load (see [5, 6] for further details).

For each of the pavements the performance for each of the Vehicle Fleets A, B and C has been quantified in relation to the pavement performance for the fleet of 80kN standard axle loads by use of a Pavement Life Reduction Factor (*PLRF*) defined as:

$$PLRF = \left(1 - \frac{N}{N_{std}}\right) \times 100\% \tag{4}$$

where N is the number of load passes required to produce failure conditions (defined as a 20mm rut or a cumulative level of fatigue damage equal to 1), N_{std} is the number of load applications of the fleet of standard 80kN axles required to produce failure conditions.

It can be seen from Equation (4) that the *PLRF* is a measure of the reduction in life of the pavement caused by trafficking by a particular vehicle fleet compared to the same pavement trafficked by a fleet of 80kN standard axles. For example, a *PLRF* of 50% would indicate that the life of the pavement trafficked by the realistic vehicle fleet is half of the life of the same pavement trafficked by a fleet of 80kN standard axles. However, it should be noted that the *PLRF* compares pavement damage in terms of the number of load passes required to achieve a certain level of pavement damage. Consequently, if the vehicle fleet has a different average static load compared to the standard fleet, this will be reflected in the *PLRF* as well as other differences between the vehicle fleet and the standard fleet that influence pavement damage such as dynamic loading and tyre type.

In addition to LTPPM simulations using axle group models operating under fully laden conditions, simulations have also been performed for axle group models operating under one-third and two-thirds of fully laden conditions (for Vehicle Fleet A) to enable *PLRFs* to be predicted for realistic axle load distributions which then can be directly compared with predictions from a standard traffic classification approach using *VWFs*.

Simulation Results (Fully Laden Vehicle Fleets)

A typical example of the output from the LTPPM is shown in Figure 5 where the pavement surface displacement profile at various loading stages is plotted as a function of distance along the pavement for the Motorway trafficked by Vehicle Fleet A using a subgrade rutting exponent of 1. It can be seen from this figure that the degradation in surface profile is relatively uniform, and the frequency content of the initial profile is largely preserved. This is because almost all of the rutting occurs in the upper bituminous material which is most sensitive to the level of static loading on the axle and relatively insensitive to the level of dynamic loading [22].

Figures 6 and 7 show the accumulation of average rut depth and 95th percentile fatigue damage as a function of the number of individual axle load passes for Vehicle Fleet A trafficking the Motorway. The 95th percentile level of fatigue damage has been used to reflect the more localised nature of fatigue damage, where pavement failure can occur when a relatively small proportion of the wheeltrack is extensively cracked [5]. It can be seen from Figures 6 and 7 that, as expected both forms of damage increase as the pavement is progressively trafficked. It can also be seen that the curves are not smooth. This is caused by seasonal variations in air temperature affecting the rate of damage accumulation. For example, rutting in the bituminous material occurs most rapidly in the Summer when the temperature is highest.

For the fleet of 80kN standard axles the average rut depth and the 95th percentile fatigue damage caused by static loads alone has also been plotted in Figures 6 and 7 respectively (dashed lines). The LTPPM simulation for this vehicle fleet did not include asphalt layer modulus degradation caused by cumulative fatigue damage. Therefore, the results for this fleet can be considered to be the "standard" case for comparison of the results with the more realistic vehicle fleets.

It can be seen from Figure 6 that, for the standard fleet, the average rut depth reaches failure conditions (defined as a 20mm rut depth) after approximately 47.5 million load applications. The corresponding life to failure for Vehicle Fleet A is approximately 32.3 million load applications giving a *PLRF* of approximately 32% (see Table 4). It can be seen from Figure 7 that the level of cumulative fatigue damage in this class of pavement is small (0.035 at 32.3 million load applications). This is consistent with recent observations from thick "long-life" flexible pavements where the long-term surface deflection was found to decrease [16] indicating little or no asphalt modulus degradation caused by cumulative fatigue damage. This will significantly increase with thinner pavement constructions where more fatigue damage is likely to occur. For this type of thick pavement where the failure mechanism is permanent deformation in the upper bituminous layers which is relatively insensitive to dynamic load [5], the *PLRF* primarily reflects differences in the average static load applied to the pavement by the 2 vehicle fleets. For example, for Vehicle Fleet A the rutting caused by static loads alone after 35 million load applications was 22.5mm which is almost identical to the average rut depth shown in Figure 6 at the same number of load passes.

Figures 8 and 9 show the corresponding results for the Principal Road trafficked by Vehicle Fleet A and the fleet of standard 80kN axles using a subgrade rutting exponent of 4. It can be seen from these figures that, for this type of pavement, the mode of failure is fatigue damage rather then rutting. This is caused by the pattern of dynamic loading applied by Vehicle Fleet A to the pavement surface causing an accumulation of fatigue damage in particular areas, thus reducing the effective stiffness of the asphaltic material in these areas which, in turn, leads to a more rapid accumulation of damage and, ultimately, failure. The *PLRF* for this case is approximately 89% (see Table 4). This is significantly greater than the corresponding value for the Motorway (32%) because this form of damage is more sensitive to the level of dynamic loading than permanent deformation in the upper bituminous layers which is relatively insensitive to dynamic loading [5]. In addition, this form of damage accelerates significantly as failure is approached owing to the modulus feedback mechanisms in the LTPPM methodology (see Figure 1).

It should also be noted from Figure 8 that the rate of rutting increases rapidly after the 95th percentile cumulative fatigue damage has reached failure. This is because as the level of fatigue damage approaches failure at certain locations on the pavement, the stiffness of the asphaltic material in these locations has decreased to 20% of its initial value and the vertical compressive strain transmitted to the subgrade has increased dramatically, thus increasing the rate of lower layer rutting. This is often observed in practice where extensive subgrade rutting can quickly follow after cracking in the bound bituminous material.

Results for the other combinations of pavement class and vehicle fleet are summarised (in terms of the resulting *PLRFs*) in Table 4. It can be seen from this table that, for all the vehicle fleets and both values of subgrade rutting exponent, the mode of failure for the Motorway is rutting, but fatigue for the Principal Road. The mode of failure for the Trunk Road was rutting for the 80kN fleet of standard axles, but fatigue for Vehicle Fleets A, B and C. It

can also be seen from this Table 4 that, for all 3 vehicle fleets, the *PLRFs* are relatively insensitive to the value of the subgrade rutting exponent and they are similar for all 3 fleets of vehicles.

Simulation Results (1/3 and 2/3 Laden Vehicle Fleets)

In addition to the results presented above, LTPPM simulations have also been performed for each of the three pavement classes trafficked by Vehicle Fleet A where the axle group models are nominally 1/3 laden and 2/3 laden (using a subgrade rutting exponent of 1). This was achieved by adjusting the sprung masses of the axle group models (see Table 2).

LTPPM simulations were performed with Vehicle Fleet A 1/3 and 2/3 laden at the same trafficking rate as in the fully laden case. It can be seen from Table 2 that the axle model representing the steer axle was not adjusted. This is because the steering axle load is not strongly dependent on whether the vehicle is fully laden or empty. Other combinations of vehicle fleet and subgrade rutting exponent were not considered because it was previously shown that the results (in terms of the *PLRF*) are relatively insensitive to these variables (see Table 4). In the cases where the pavement trafficked by the 1/3 or 2/3 laden fleet did not reach failure conditions after 20 years (ie it lasted longer than the same pavement trafficked by the fleet of 80kN standard axles) linear extrapolation was used to calculate the *PLRF*.

The results, in terms of *PLRFs*, are shown in Table 5. It can be seen by comparing the results with those in Table 4 that, for the Motorway, the 1/3 laden condition results in a *PLRF* of -10%. This means that under these loading conditions the life of the pavement is extended compared to the same pavement trafficked by the fleet of 80kN standard axles. The corresponding *PLRF* for the 2/3 laden condition is +16%. The situation for the Trunk Road is similar except that the extremes are greater. It should however be noted that the Trunk Road was predicted to fail by rutting for the 1/3 and 2/3 laden conditions whereas it was predicted to fail by fatigue for the fully laden condition. It can be seen from Table 9 that the situation for the Principal Road is different. In this case all three loading conditions result in positive *PLRFs* ranging from 76% to 89%. The reason for this is that all these pavements fail by fatigue which, as can be seen from Figure 9 occurs extremely rapidly because of modulus degradation. Consequently, although the static axle loads are reduced the peak loads (dynamic plus static) still cause relatively rapid pavement failure.

Realistic Axle Load Variations

The *PLRFs* calculated above are for cases where the fleet is assumed to be either one-third laden, two-thirds laden or fully laden. In reality each axle group in the vehicle fleet will contain a distribution of axle loads between unladen and fully laden. Consequently, the *PLRFs* calculated above have to be adjusted to take into account realistic axle load variations. To achieve this adjustment the measured axle load distribution for a typical UK motorway [3] was divided into three weight bands (1-4 tonnes, 4-7 tonnes and 7-10 tonnes). The proportions of axles in each weight band were estimated to be 0.52, 0.37 and 0.11 respectively. Using the data in Tables 3 and 5 the average axle weight was calculated for Vehicle Fleet A for the 1/3 laden, 2/3 laden and fully laden cases (4.5 tonnes, 6.4 tonnes and 8.4 tonnes respectively). Equivalent *PLRFs* were then calculated for each pavement class (Motorway, Trunk Road and Principal Road) corresponding to the mid-points of the 3 weight bands (2.5 tonnes, 5.5 tonnes and 8.5 tonnes) using cubic spline interpolation/extrapolation. These results were then combined with the relative proportions of axles in each weight band to estimate the overall *PLRFs* for each pavement class which are shown in Table 6.

It can be seen from Table 6 that the *PLRFs* predicted from the LTPPM are negative in all but one case (LTPPM, Principal Road) indicating that, as before, the realistic vehicle fleets are causing less pavement damage than the fleet of 80kN standard axles. It can also be seen from Table 6 that the *PLRFs* calculated from the LTPPM indicate an increase in pavement life of approximately 20% for the Motorway and Trunk Road trafficked by the realistic vehicle fleets compared to the fleet of 80kN standard axles. For the Principal Road the LTPPM predicts a decrease in pavement life of approximately 80% caused by trafficking by the realistic vehicle fleets.

COMPARISON WITH STANDARD *VWF* APPROACH

It can be seen from the above that the *PLRF* has been chosen as the performance measure for the different combinations of vehicle fleet and pavement structure. However, since the standard approach is in terms of *VWFs* a method is required to transform these into equivalent *PLRFs*.

For a single pass of a particular vehicle, the *VWF* can be considered to be the equivalent number of 80kN standard axles required to cause the same level of pavement damage. Consequently, assuming it takes x vehicle passes (and hence xN_a axle passes, where N_a is the number of axles per vehicle) to reach critical damage conditions it will take $xVWF$ passes of a standard 80kN axle load to reach the same damage conditions. Using Equation (4) an equivalent *PLRF* can be calculated to be:

$$PLRF = \left(1 - \frac{N_a}{VWF}\right) \times 100\% \tag{5}$$

For a vehicle fleet comprising a number of different vehicles the same approach can be used and Equation (5) can be generalised to give:

$$PLRF = \left(1 - \frac{\sum_{i=1}^{N_g} N_a^i \times p_i}{\sum_{i=1}^{N_g} VWF_i \times p_i}\right) \times 100\% = \left(1 - \frac{\sum_{i=1}^{N_g} N_a^i \times p_i}{FVWF}\right) \times 100\% \tag{6}$$

where N_a^i is the number of axles in axle group (or vehicle) i, VWF_i is the Vehicle Wear Factor for axle group (or vehicle) i, N_g is the number of axle groups (or vehicles), and p_i is the proportion of axle group (or vehicle) i.

The *PLRFs*, calculated using the *VWFs* currently used in HD 24/96 [1], the relative axle group proportions (Table 3) and Equation (7), are shown in Table 6 for the 3 vehicle fleets. It can be seen from this table that the *PLRFs* are negative indicating that the realistic vehicle fleets are causing significantly less pavement damage than the fleet of 80kN standard axles. It can also be seen from Table 6 that the *PLRFs* are sensitive to the different vehicle fleets. For example, the *PLRFs* predicted for Vehicle Fleet A show the pavement life to be increased by 74% for the realistic vehicle fleet compared to the fleet of standard 80kN axles whereas, for Vehicle Fleet C, the corresponding increase in pavement life is 170%.

CONCLUSIONS

- A recently developed model of Long-Term Flexible Pavement Performance (LTPPM) has been modified and used to calculate the damaging effect of different realistic vehicle fleets.
- The axle group models give realistic dynamic tyre force results as quantified by the Dynamic Load Coefficient (DLC).
- Three different vehicle fleets (A, B and C), and three different loading conditions for each fleet have been considered; fully laden, 2/3 laden and 1/3 laden.
- The effect of the different vehicle fleets (compared to a vehicle fleet of 80kN standard axles) on long-term flexible pavement performance has been assessed for three classes of pavement (Motorway, Trunk Road and Principal Road)
- Results from the LTPPM show that different failure mechanisms are predicted for different pavement classes. For example, a thick pavement construction (Motorway) is predicted to fail by rutting with negligible cumulative fatigue damage, whereas a much thinner pavement construction (Principal Road) is predicted to fail by fatigue damage and loss of stiffness in the asphaltic material.
- LTPPM predictions show that the results, in terms of a Pavement Life Reduction Factor (*PLRF*) are insensitive to the response of the lower pavement layers (sub-base and subgrade) to dynamic loads, and are relatively insensitive to differences in the vehicle fleet.
- Results from the 1/3 laden and 2/3 laden simulations have been used to adjust the *PLRFs* to account for realistic axle load variations within the vehicle fleet.

- The adjusted *PLRFs* calculated from the LTPPM are negative for those pavements that are predicted to fail by rutting indicating that the increase in pavement life caused by trafficking by the realistic vehicle fleets (compared to pavement life for the same pavements trafficked by a fleet of 80kN standard axles) is typically 20%.
- The corresponding *PLRFs* are positive for those pavements that are predicted to fail by fatigue indicating that the reduction in pavement life caused by trafficking by the realistic fully-laden vehicle fleets (compared to pavement life for the same pavements trafficked by a fleet of 80kN standard axles) is typically 78%.

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TABLES & FIGURES

Table 1: Axle Group Models.

Model Name	No. Axles	Axle Group	Suspension Type	Tyre Type	Axle Weight (Tonnes)
STER	1	Tractor (steer)	Steel (mono-leaf)	Single	7
SINS	1	Tractor (drive)	Steel (multi-leaf)	Dual	10
SINA	1	Tractor (drive)	Air + dampers	Dual	10
DUAS	2	Tractor (drive) Trailer	Steel (multi-leaf)	Dual	19
DUAA	2	Tractor (drive) Trailer	Air + dampers	Dual	19
TRIS	3	Trailer	Steel (multi-leaf)	S-single	22.5
TRIA	3	Trailer	Air + dampers	S-single	22.5

Table 2 Axle Group Model Parameters.

Parameter	STER	SINS	SINA	DUAS	DUAA	TRIS	TRIA
M_{s1} / kg (fully laden)	3100.0	4400.0	4400.0	8500.0	8500.0	10,050.0	10,050.0
(2/3 laden)	3100.0	2933.3	2933.3	5666.7	5666.7	6700.0	6700.0
(1/3 laden)	3100.0	1466.7	1466.7	2833.3	2833.3	3350.0	3350.0
M_{u1} / kg	400.0	600.0	600.0	500.0	500.0	400.0	400.0
M_{u2} / kg	-	-	-	500.0	500.0	400.0	400.0
M_{u3} / kg	-	-	-	-	-	400.0	400.0
I_{u2} / kgm^2	-	-	-	9.65	9.65	9.65	9.65
I_{u2} / kgm^2	-	-	-	9.65	9.65	9.65	9.65
I_{u3} / kgm^2	-	-	-	-	-	9.65	9.65
k_u / MN/m	0.23	0.86	0.5	0.9	0.2	0.9	0.2
k_l / MN/m	0.23	0.86	0.5	0.9	0.2	0.9	0.2
β_u / mm	2.5	2.5	2.5	1.5	1.5	1.5	1.5
β_l / mm	2.5	2.5	2.5	1.5	1.5	1.5	1.5
F_f / kN	5.0	8.0	0.0	4.5	0.0	4.5	0.0
C_S / kNs/m	1.5	6.5	13.0	1.0	8.0	1.0	8.0
k_p / kNm/rad	-	-	-	10.0	150.0	10.0	150.0
C_p / kNms/rad	-	-	-	0.1	2.0	0.1	2.0
k_T / MN/m	1.0	2.0	2.0	2.0	2.0	1.3	1.3
C_T / kNs/m	1.0	2.0	2.0	2.0	2.0	1.3	1.3
b_1 / m	-	-	-	0.495	0.495	0.495	0.495
b_2 / m	-	-	-	0.185	0.185	0.185	0.185

Table 3: Axle Group Model Proportions and Calculated *VWFs*.

Axle Group Model	*VWF*	Motorway (Fleet A)	Trunk Road (Fleet B)	Principal Road (Fleet C)
STER	0.54	0.38	0.43	0.45
SINS	2.26	0.26	0.34	0.37
SINA	2.26	0.04	0.06	0.06
DUAS	3.68	0.14	0.09	0.06
DUAA	3.68	0.04	0.02	0.02
TRIS	2.16	0.07	0.03	0.02
TRIA	2.16	0.07	0.03	0.02
FVWF	-	1.85	1.67	1.60

Table 4: *PLRFs* for Vehicle Fleets A, B and C (Fully Laden).

Road Type	Subgrade Rutting Exponent	Failure Mode	*PLRF* (A)	*PLRF* (B)	*PLRF* (C)
Motorway	1	Rutting	32%	32%	34%
	4	Rutting	34%	35%	35%
Trunk Road	1	Fatigue+	51%	56%	56%
	4	Fatigue+	56%	60%	60%
Principal Road	1	Fatigue	89%	90%	90%
	4	Fatigue	89%	90%	90%

Table 5: *PLRFs* for 1/3 and 2/3 Laden Conditions.

Road Type	Subgrade Rutting Exponent	Failure Mode	*PLRF* (Fleet A)		
			1/3 Laden	2/3 Laden	Fully Laden
Motorway	1	Rutting	-10%	16%	32%
Trunk Road	1	Rutting+	-22%	9%	51%
Principal Road	1	Fatigue	76%	80%	89%

Notes: + The mode of failure for the 1/3 and 2/3 laden conditions was rutting whereas the mode of failure for the fully laden condition was fatigue; -ve *PLRF* = Increase in life relative to fleet of 80kN standard axles; +ve *PLRF* = Decrease in life relative to fleet of 80kN standard axles.

Table 6: Predicted *PLRFs* Including Realistic Axle Load Variations.

Fleet	HD 24/96	LTPPM (L_2=1)		
		Motorway	Trunk	Principal
A	74%	-20%	-20%	+78%
B	136%	-	-	-
C	170%	-	-	-

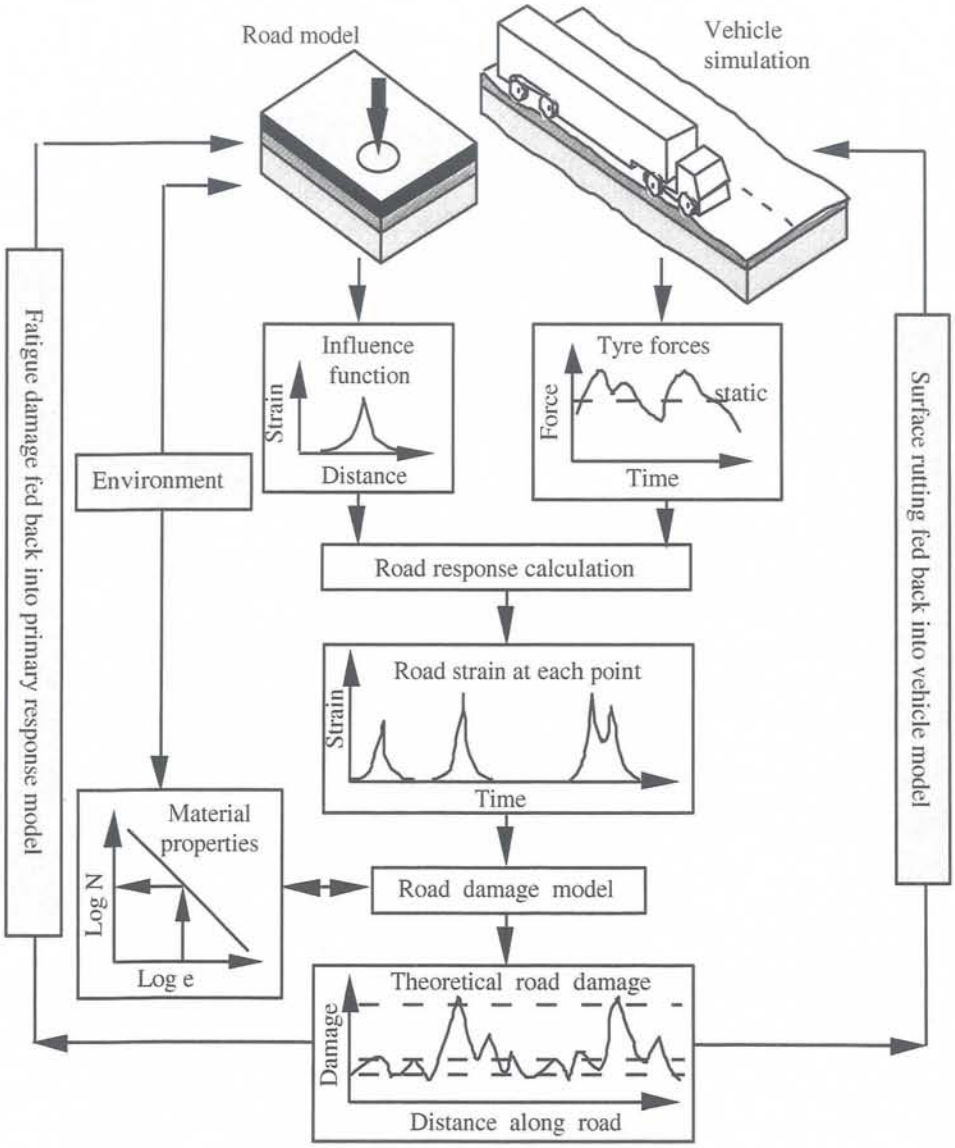

Figure 1: LTPPM Methodology.

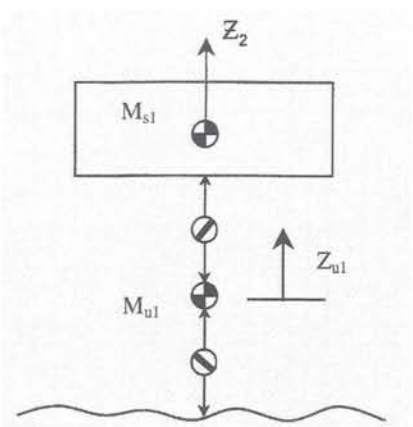

Figure 2: Single Axle Group Model.

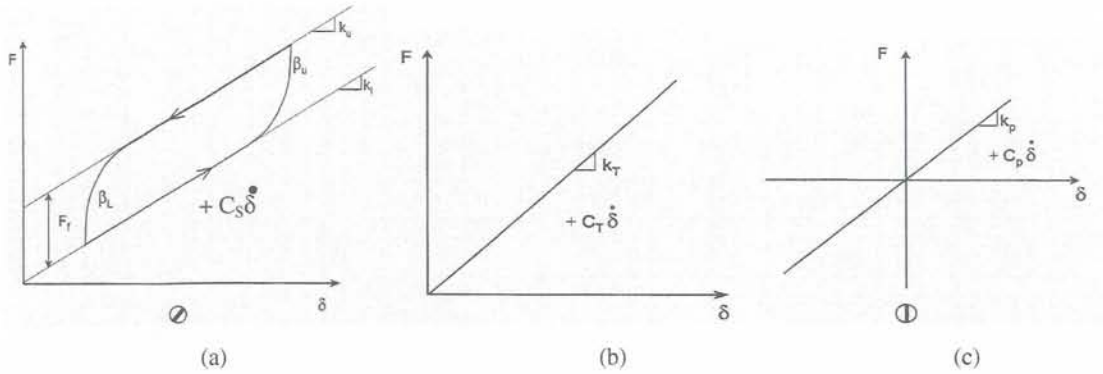

Figure 3: (a) Suspension Element, (b) Tyre Element, (c) Levelling Beam Element.

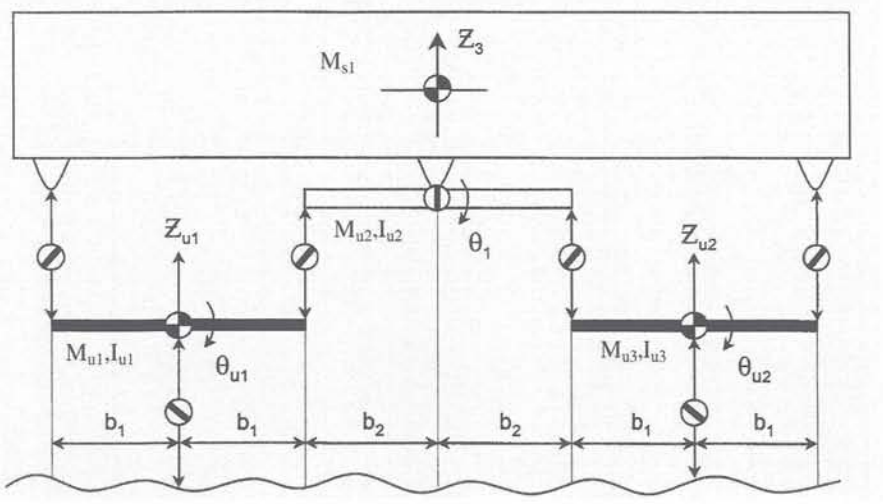

Figure 4: Tandem Axle Group Model.

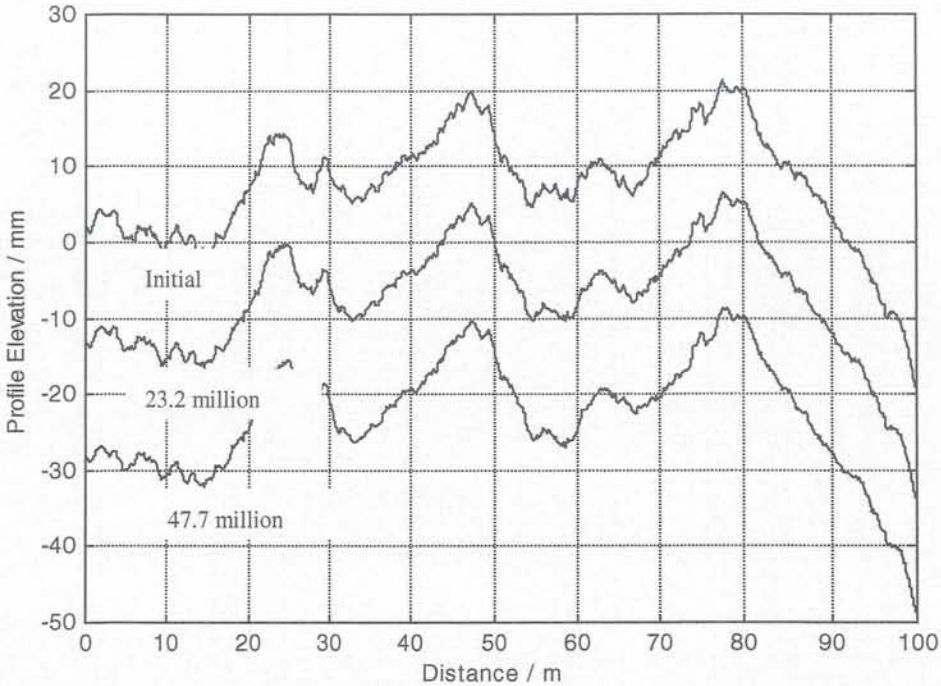

Figure 5: Surface Displacement Profiles for a Motorway Trafficked by Vehicle Fleet A (Subgrade Rutting Exponent=1).

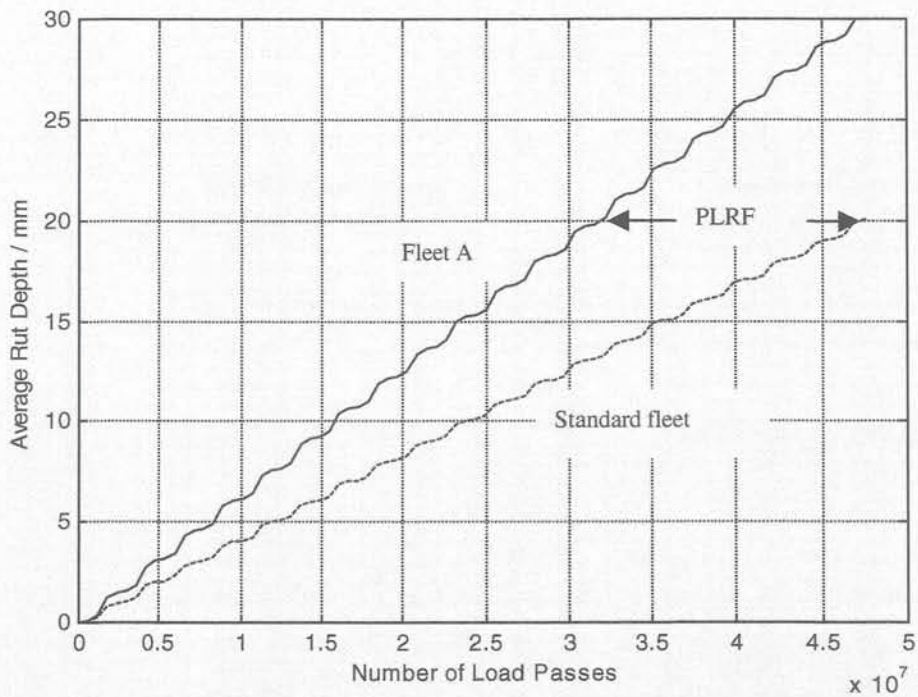

Figure 6: Accumulation of Rut Depth for a Motorway Trafficked by Vehicle Fleet A (Subgrade Rutting Exponent=1).

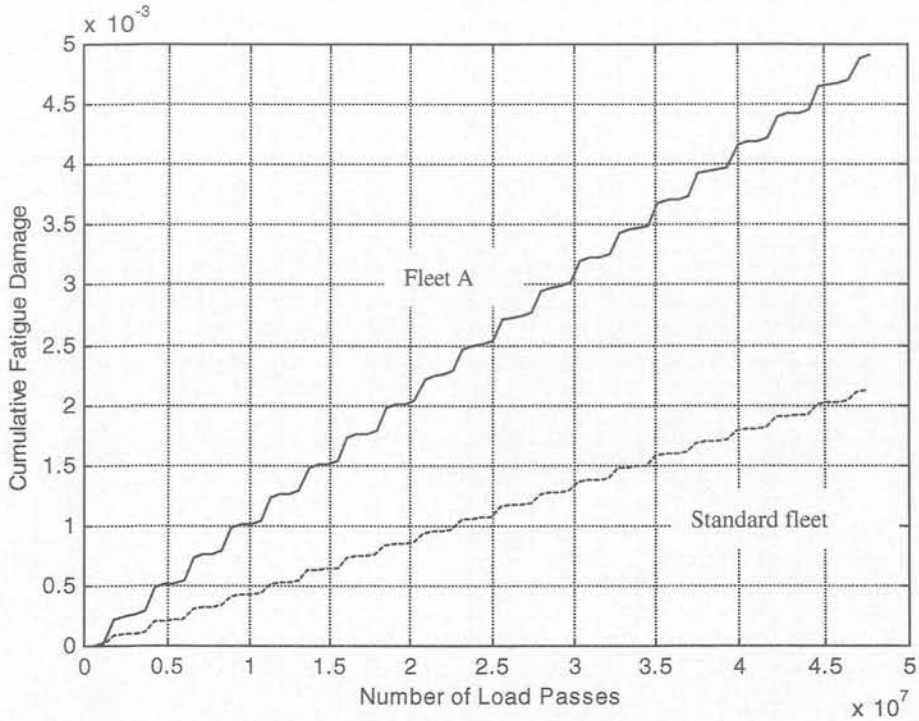

Figure 7: Accumulation of Fatigue Damage for a Motorway Trafficked by Vehicle Fleet A (Subgrade Rutting Exponent=1).

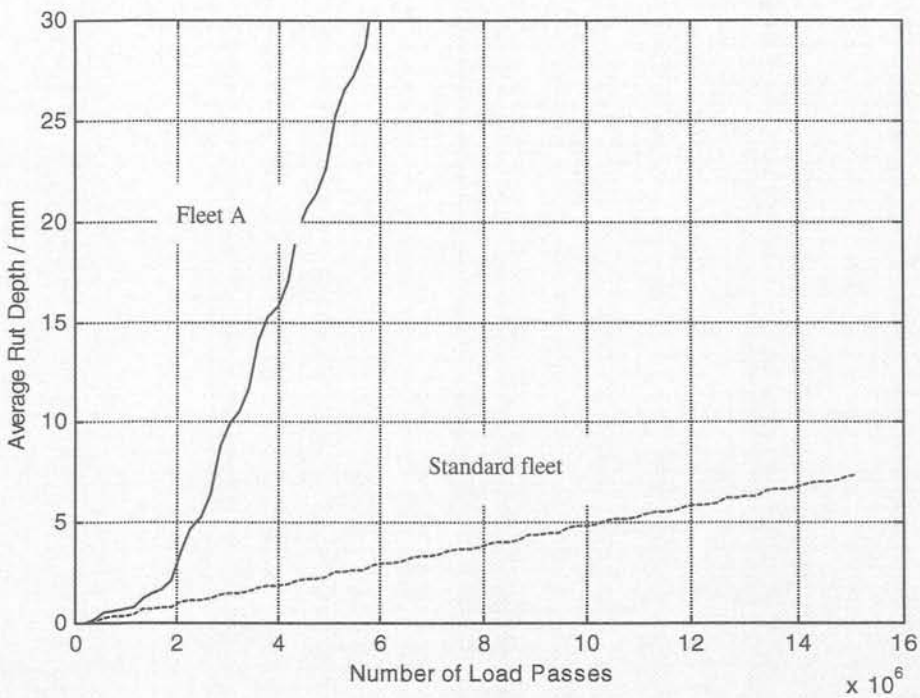

Figure 8: Accumulation of Rut Depth for a Principal Road Trafficked by Vehicle Fleet A (Subgrade Rutting Exponent=4).

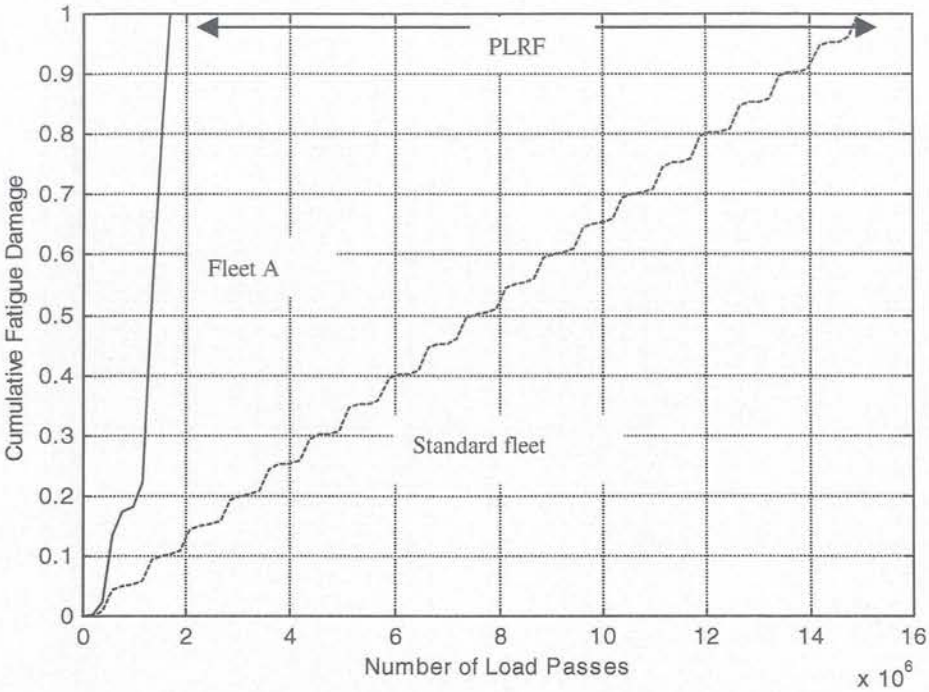

Figure 9: Accumulation of Fatigue Damage for a Principal Road Trafficked by Vehicle Fleet A (Subgrade Rutting Exponent=4).