ISBN 978-967-2110-70-5

CHAPTER 8

PREDICTION OF LONG TERM PAVEMENT PERFORMANCE

8.1 INTRODUCTION

The Whole Life Pavement Performance Model (WLPPM) studies have been performed since the 1980s [1].Such research has involved both analytical and mechanistic procedures. Comparing both methods, the analytical method is capable of calculating fundamental engineering parameters such as, stress, strain and deflection in a multi-layered system when subject to external loads, e.g. linear elastic analysis. Conversely, the mechanistic procedure is capable of translating an analytical calculation of pavement response into performance [1-8]. Ultimately, the concern is not with stresses and strains but with how these stresses and strains relate to field performance. Latest in NCHRP, The Mechanistic-Empirical Design Approach fully considers the change of temperature and moisture profile in the pavement structure and sub-grade over the design life of a pavement. The Enhanced Integrated Climatic Model (EICM) referred to simply as the Integrated Climatic Model, was developed for the Federal Highway Administration (FHWA) at Texas A&M University, Texas Transportation Institute in 1989 and is capable of generating realistic patterns of rainfall, solar radiation, cloud cover, wind speed and air temperature to simulate the upper boundary condition. It considers the lateral and vertical drainage of the base course in measuring the amount of water that enters the sub-grade by infiltration through the pavement surface and base course. It works by processing the input and feeds the computer output to the three major components of the Design Guide’s mechanistic-empirical design: framework materials, structural response and performance prediction. The most important output required from the EICM for pavement design is a set of adjustment factors for unbound material layers to account for the effects of environmental parameters and conditions such as, moisture content changes, freezing, thawing and recovery from thawing. EICM can compute in-situ temperature at the midpoints of each bound sub-layer as well as the temperature profiles within the AC layer for every hour and the average moisture content for each sub-layer in the pavement’s structure.

8.2 THEORY

The WLPPM (Figure 8.1) contains steps toward predicting primary response from loads, determining the stiffness modulus, examining the damage mechanisms and lastly, accumulating the level of pavement damage. This step is the final one when the failure mechanism is achieved; otherwise, it ends at the step of degrading the elastic modulus of the bituminous material. This WLPPM is capable of predicting longitudinal roughness, rutting and fatigue cracking of a pavement consisting of a bituminous layer, a granular sub-base layer and sub-grade. To simulate gradual deterioration over time, the WLPPM makes use of an incremental-recursive procedure; that is, the output from one time increment is used recursively as input for the next time increment.

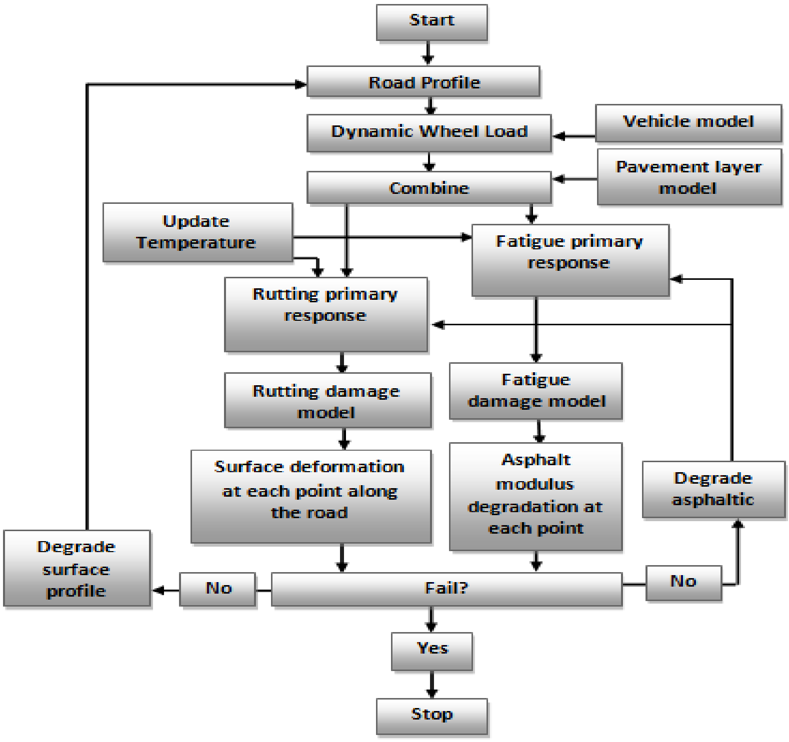


Figure 8.1: Whole Life Pavement Performance Model

8.3 LITERATURE REVIEW

The factors effecting bituminous aging include, characteristics of the bitumen and its content in the mix, nature of aggregate and particle size distribution, void content of the mix, production related factors, temperature and time. Short-term aging was included in the model by using typical bitumen properties recovered after mixing and laying. For long-term aging of the bitumen, it could be accounted for by increasing the recovered softening point temperature $T_{RB}^{(R)}$, with the age of the pavement according to the one-dimensional kinetic diffusion model as follows;

$$T_{RB}^{(R)}|_{t=t_1} = T_{RB}^{(R)}|_{t=0} + \sqrt{\Lambda t} \qquad (8.1)$$

Where, $T_{RB}^{(R)}|_{t=t_1}$ is the recovered 'Ring and Ball' temperature ($^\circ C$) at time $t = t_1$, $T_{RB}^{(R)}|_{t=0}$ is the initial Ring and Ball temperature $^\circ C$, at time $t = 0$, Λ is the reaction constant ($^\circ C^2/hour$) and t is the time (hours). A value of $\Lambda = 1.65 \times 10^{-3}\,^\circ C^2/hour$ can be used to model aging of the whole asphalt layer in a typical UK pavement [4]. An aging model of this type will affect both the elastic and viscous properties of the asphaltic material since they both depend on the properties of the bituminous binder

8.3.1 ASPHALTIC LAYER MODULUS DEGRADATION

The relationship between the elastic modulus of the asphaltic material and incurred fatigue damage is defined as [4]:

$$\frac{E_m}{E_m^0} = EXP\left\{log_e\left(\frac{E_m}{E_m^0}\right)_c D\right\} D \leq 1 \qquad (8.2)$$

$$\frac{E_m}{E_m^0} = \left(\frac{E_m}{E_m^0}\right)_c D > 1 \qquad (8.3)$$

Where, $\frac{E_m}{E_m^0}$ is the reduction in elastic modulus of the asphaltic material, D is the cumulative fatigue damage, $\left(\frac{E_m}{E_m^0}\right)_c$ is a constant, that is, the level of modulus reduction that corresponds to the point where the fatigue life of the asphalt has been reached (*D=1*). It may be equal to 0.2.

8.3.3 DAMAGE MODEL

Cracking of the asphaltic concrete layer caused by tensile strains generated in the pavement by not only traffic loading but also temperature variations and construction

ISBN 978-967-2110-70-5

practice. The general relationship defining the fatigue life based on crack initiation is as follows:

$$N_f = k_1(\varepsilon_t)^{-k_2} \qquad (8.6)$$

Where, N_f is number of applications of load to initiate fatigue cracking, ε_t is tensile strain at the bottom of the asphaltic layer and k_1 and k_2 are constants. The general relationship relating the rutting to the vertical strain on top of the subgrade is as the following equation:

$$N_r = k_4(\varepsilon_c)^{k_5} \qquad (8.7)$$

Where, $N_r$is an allowable number of vehicles to failure, ε_c is compression strain on top of the subgrade layer, k_4 and k_5 are constants. The values of $k_4$andk_5 can be calibrated to match the field observations. The value of k_5 has been found to vary considerably from 1.85 to 7.14 depending on the pavement design and the test condition. Ak_5 value equal to 3.57 has been found to be suitable for typical UK pavement [9].

8.3.4 DAMAGE ACCUMULATION

The pavement condition and material properties gradually change throughout the lifetime as the pavement is subjected to a succession of various magnitudes of load pulses and various time intervals between loading pulses. The statistical law can be applied irrespective of the pavement course or the distress mechanism involved, cracking or permanent deformation called Miner's Law [10]. The parameter D, referred to as accumulation of damage, varies between 0 and 1, where $D = 0$ for the undamaged material and $D = 1$ for failed material.

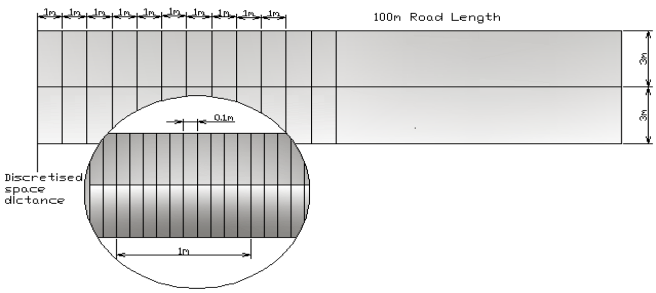
$$D = \sum_{i=1}^{j} \frac{N^{(i)}}{N_f^{(i)}} \qquad (8.6)$$

Where, $N^{(i)}$ is thenumber of cycles at a given strain level, $N_f^{(i)}$ is the number of cycles to failure at that strain level and j is the number of different strain levels.

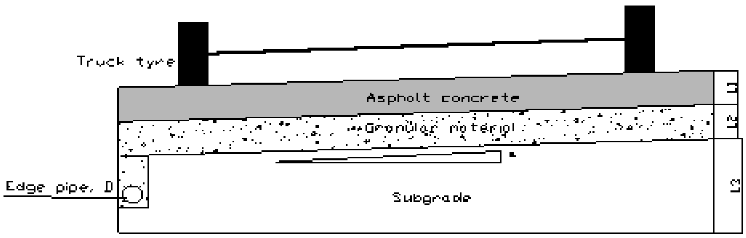
8.4 METHODOLOGY

The simulation works were found to follow the simulation flowchart as illustrated in Figure 8.1. As shown in the figures, the WLPPM makes use of an incremental-recursive procedure to simulate gradual deterioration over time. The output from each time increases recursively as the input in the next time increases. The incremental process is applied to individual points along the longitudinal road. The cycle is based on a time stepping algorithm that requires repeated application of force to the surface, updates in temperature, recalculating the critical response as well as, damage mechanism. Thus, the accumulation of damage is computed to degrade the asphaltic concrete stiffness modulus and road profile. This is applicable for all cases. For that purpose, a computer programme was developed using MATLAB for simulating the performance of the pavement from the beginning of trafficking until the roads fail.

Figure 8.2 shows the schematic figures illustrating the longitudinal road space distance and cross-sectional pavement structures as well as space cells for finite the difference method for WLPPM prediction.



a. Road Cross-sectional



b. Pavement structure

Figure 8.2: Schematic figures illustrating the longitudinal road space distance and cross-sectional pavement structures and space cells for FDM.

As shown in Figure 8.2 (a), 100m longitudinal road profiles were discretised into several block spaces with equal width. For each block, Figure 8.2 (b) shows the cross-section of each block that is, the structure of the pavement with a drainage pipe installed at the left edge. However, for predicting WLPPM without precipitation, this drainage pipe is omitted. The water flow was simulated using the finite difference method, thus, the cross-section of the pavement structure was discretised into several spaces distanced. The diameter of the loading area is derived from the tyres and was 0.3 m, which means that cells 3-4 and 17-18 are loaded and degrade throughout the time of simulation. The materials used in the pavement structure were based on the JKR/SPJ/2008, a Specification for Road Work in Malaysia [10] and Manual of Pavement Design (Technical Order (Road) 5/85 [Amendment 2013] [12].Table 8.1 gives the material properties that have been used in the pavement structure model. All the parameter values are constant throughout the simulation except the temperature which ranges from 27^{o}C to 30^{o}C; that is the monthly mean temperature from daily temperature data ranges of 21.7^{o}C to 34^{o}C. A linear ‘quarter-truck’ model has been used travelling over a 100m length of surface profile with varied levels of roughness. Detail of the quarter truck model was referring to previous work [13]. The road profiles as shown in Figure 8.3 are used. Power Spectral Density (PSD) of the profile height is used to characterize the amplitude and wavelength of roads where the road is considered a homogeneous, isotropic random process with a Gaussian distribution [14-15]. The vehicle speed as shown in Figure 1.4 has been used.

Table 8.1: Matrial Properties

	Parameters	Value
Mixture composition	Elastic modulus of the asphaltic concrete is based on the following values: • Volume of void, *Vv* • Volume of bitumen, *Vb* • Penetration of the bitumen, *Pi* • Temperature, *T*	5% 7.5% 60 Variation
	Resilient modulus of the base course is based on the following values: • CBR value CBR of sub-base layer and shall not be less than 30% • Optimum moisture content	60 8%
	The resilient modulus of the sub-grade soil is based on the following values: • CBR value • Optimum moisture content	5 12%

ISBN 978-967-2110-70-5

Pavement structure	Thickness is based on the mean standard thickness: • Surface (Asphalt concrete) & Poisson ratio • Base (asphalt concrete) &Poisson ratio • Sub-base (granular material) & Poisson ratio	0.2m & 0.35 0.2m & 0.4 0.2m & 0.4

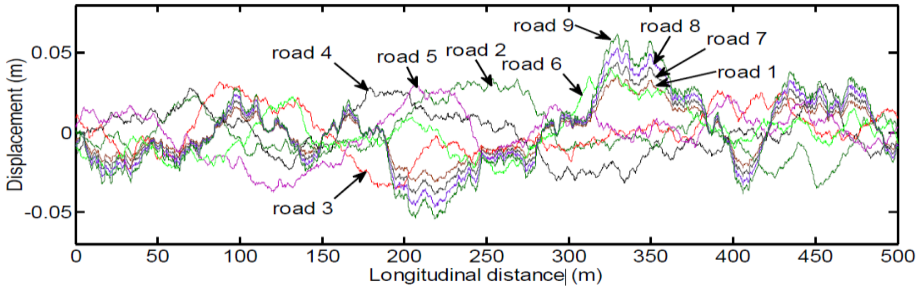


Figure 8.3: Road Profiles

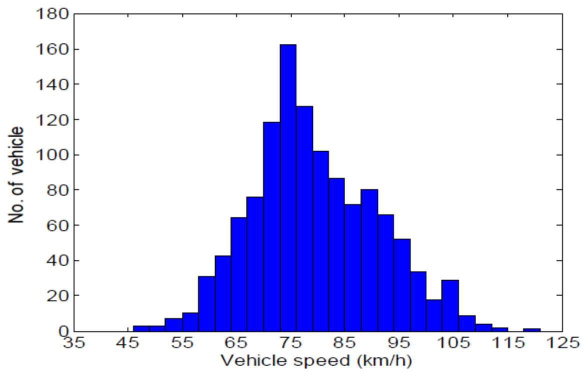


Figure 8.4: Daily number of vehicles versus speeds

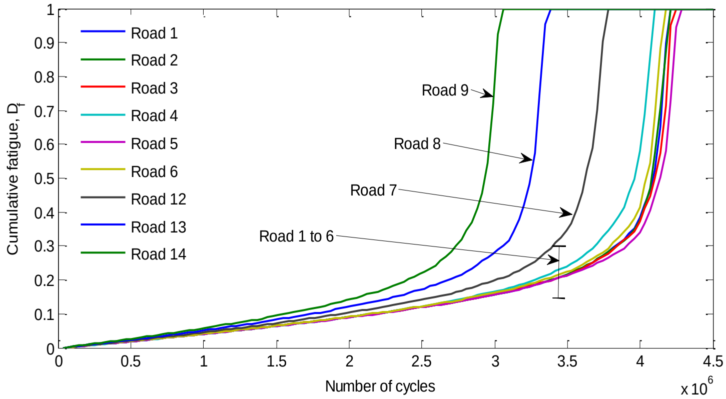
8.5 THE RESULTS OUTCOME

Figure 8.5 shows the Whole Life Pavement Performance of several roads. As shown in Figure 8.5, Road 1 to Road 6 are the road profiles generated with IRI=2 and the IRI for Road 7, Road 8 and Road 9 are 2.5, 3 and 3.5, respectively. The figure shows the cumulative road damage progression starting from zero defects up until the road’s failure. Dashed lines show the number of cycles where 5% of the total length of the road has a 20 mm rut and thence, automatic accelerated fatigue progression. Accordingly, every 36,000 cycles are equivalent to one month’s period of trafficking and, as outlined in Figure 8.6, four million cycles are equivalent to 9.3 years of trafficking. As shown in the figure, roads with lower IRI remain for more cycles than those with a higher IRI. As seen from the figure, the

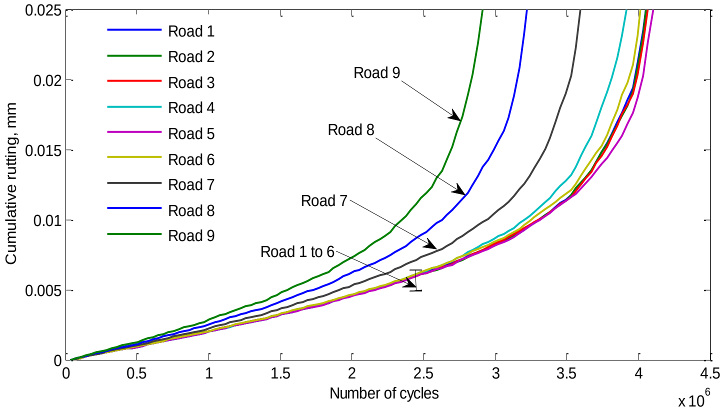
ISBN 978-967-2110-70-5

road with the IRI=3.5 endures for up to 8.36 years before it fails compared to roads that have an IRI= 2 which remain for approximately 11.6 to 12.1 years.

Also drawn from the figures, more fatigue occurs after a cumulative rutting of 0.02m. This is due to generated rutting on the pavement increasing the loading undulation on the surface in turn, increasing the response in the pavement (tensile strain at the bottom of asphaltic layer) and thus, accelerating pavement damage. It can be seen from the figure that for Roads 1 to 6 (IRI= 2) the pavement fails because of excessive rutting after an approximate range between 3.8x10^6 and 4.1x10^6load passes. However, for other roads, the pavement would take approximately 3.6x10^6, 3.2x$10^6$and 2.9x10^6load passes to fail. This is for Road7, Road8 and Road9, respectively.



(a)



(b)

Figure 8.5: Cumulative damages, (a) fatigue and (b) rutting

ISBN 978-967-2110-70-5

8.6 CONCLUSION AND DISCUSSION

In conclusion, the cumulative damage is significantly varied by different IRI of road profiles and a higher IRI value will result in more damage and vice versa. Roads with a different profile but the same initial IRI= 2 do not have any significant variation in predicted life. However, there is a rather linear decrease of the pavement's life when the initial IRI value is increased from 2 to 2.5. Thence, when the initial IRI increases to 3 and 3.5, the life will shorten significantly.

REFERENCES

[1] Ullidtz, P. and Larsen, B. K., 1983, "Mathematical model for predicting pavement performance", *TRB*, Vol. 949: pp. 45-55

[2] Brademeyer, B. D., Delatte, N. J. and Markow, M. J., 1986*, "Analysis of moving dynamic loads on highway pavements, Part II: Pavement response,"Int. Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, British Columbia, Canada*.

[3] Ullidtz, P., 1993, "Mathematical model of pavement performance under moving wheel load", *Presented at 72nd Annual Meeting of the TRB, Washington DC.*

[4] Collop, A. C., 1994, "Effect of traffic and temperature on flexible pavement wear", PhD thesis, Cambridge University Engineering Department, Cambridge UK.

[5] Papagiannakis, A. T., 1997, "Calibration of WIM Systems, through dynamic vehicle Simulation*", J. Of Testing and Evaluation*, JTEVA, Vol. 25, No. 2: pp. 197-204.

[6] Mattarocci, M., 2006, "Un modello di degrade empirico-meccanicistico per la valutazione della irregolarita longitudinal nelle sovrastrutture stradali flesibili", *PhD Thesis, Universita Degli Studi Di Napoli Federico.*

[7] NCHRP, 2004, "Guide for Mechanistic –Empirical design of new and rehabilitated pavement structures", *National Cooperative Highway Research Program.*

[8] Buhari R., Aman M.Y., Rohani M.M., Puteh S. (2016) Primary Response Of Pavement Variation With Construction Variables, *ARPN Journal of Engineering and Applied Sciences*, Asian Research Publishing Network , 11818, ISSN:18196608

[9] Brown, S. F. and Brunton, J. M., *1992,* "An introduction to the analytical design of bituminous pavements", 3rd ed., *Univ. Of Nottingham, Dept. of Civil Engineering*, Nottingham UK.

[10] Miner, M. A., 1945, "Cumulative damage in fatigue.''*Trans., Am. Soc. Mech. Eng*.,67, A159–A164.

[11] JKR/SPJ/2008-S4, 2008, "Standard specification for road works, Section 4: Flexible Pavement, *Malaysian Public Work Department,* Malaysia.

[12] JKR ATJ/5/8585 [Amendment 2013], *Malaysian Public Work Department,* Malaysia.

[13] Brown, S. F. and Brunton, J. M., *1992,* “An introduction to the analytical design of bituminous pavements”, 3rd ed., Univ. Of Nottingham, Dept. of Civil Engineering, Nottingham UK

[14] Buhari R., Abdullah M.e., Rohani M.M., "Predicting Truck Load Variation Using Q-Truck Model", *Applied Mechanics and Materials*, Vol. 534, pp. 105-110, 2014

[15] Dodds, C. J. and Robson, J. D., 1973, “The description of road surface roughness*”, J. Sound and vibration,* 31(2):pp. 175-183.

[16] Buhari R.**(**2015) Longitudinal Road Profile Model Generation Based on Measurement Data using Mathematical Approach, *Advanced Science Letters,* Vol: 21, 12, 3627-3651, ISSN:19366612