Continuous Mechanistic Deterioration Modelling of Road Pavements

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ABSTRACT

The current flexible Australian pavement design approach is based on structural principles using layered elastic models considering standard axle loads to represent the entire traffic spectra. A more rational approach would be to directly consider the individual traffic axle loads and configurations. Another serious drawback in the current approach is that only one set of parameters is used to define material properties of the pavement layers. However, it is well established that pavement material properties significantly change with prevailing climate. For example, asphalt modulus is heavily dependant on the temperature and the modulus of unbound materials depends on the moisture content. This paper examines methods to incorporate climatic conditions in pavement design, where the pavement deterioration is modelled continuously taking into account the actual traffic load spectra. It is expected that these studies can lead to more rational design methodologies for pavement design.

Keywords: Climatic conditions, Load spectra, traffic loading, and pavement modulus

1.0 INTRODUCTION

The current Australian road pavement design approach (Austroads, 2004) is based on the mechanistic design method (linear elastic theory) that uses structural analysis of a multi-layered pavement system subjected to a standard axle loading. The design method assumes that the layers fail under specific stress modes under standard axle loading and involves determination of maximum strains at critical locations of the pavement. Subsequently, the critical maximum strain ε is used to determine the allowable number of standard axle load repetitions using an empirical fatigue relationship, like:

$$N = \left(\frac{k}{\varepsilon}\right)^{b} \tag{1}$$

where, N is the number of allowable standard axle repetitions (the standard axle is a single axle with dual tyres carrying 80 KN of axle load). The constants k and b are empirically derived for various pavement materials (*e.g.*, subgrade for its compression failure). The actual traffic spectrum is converted to equivalent standard axles for comparison with the allowable repetitions to determine the design pavement life. This conversion uses various power laws depending on the material.

This approach is too simplistic and does not take into account the complexities of the actual pavement performance. For instance, it does not allow for variation of traffic loading and axle configurations with time, failure of the pavement materials above a certain strain, existence of a fatigue limit below which no failure basically occur, and last but not least, the influence of environmental conditions on the pavement material properties. The last aspect is extremely important because some pavements experience significant damage even without much traffic loading at all. The current Austroads pavement design guide which was released in 2004 does not cover these issues in any detail. Another disadvantage of the current simplification is that the same pavement design approach cannot be used to examine the deterioration of pavements with time, which is of significant interest to infrastructure asset managers. In contrast, a myriad of empirical pavement deterioration models have emerged to fit the vast amount of deterioration data collected.

The present paper examines methods to incorporate climatic conditions in pavement design, where the pavement deterioration is modelled continuously taking into account the actual traffic load spectra. It is expected that these studies can lead to more rational design methodologies for pavement design.

2.0 CONTINUOUS TRAFFIC LOADING

Pavement damage appears to arise due to excessive strain applied to various pavement layers. This damage can arise in various modes such as rutting, fatigue cracking, shoving, block cracking (due to aging), transverse or longitudinal cracking and raveling. It is extremely difficult to cater for all these individual failure mechanisms in design. Therefore, in the current design approach, these failure modes are lumped into a fatigue failure mode in bound, semi-bound and subgrade materials. Unfortunately, deterioration of unbound materials is not yet catered for, and is only regarded as elastic materials that transmits load to the underlying layers.

In the approach considered in this paper, the fatigue failure mode is kept as the main failure mechanism. However, the traffic load spectra measured at existing Culway (weigh-in-motion) stations are directly considered in contrast to standard axle loading. In some instances, it is possible to consider artificially generated traffic spectra to simulate traffic growth, etc., while keeping the inherent statistical nature of the traffic data intact. Traffic volumes by vehicle class are forecasted for the design analysis period, and the load spectra developed for each class are used to estimate axle loads. Figure 1 shows an analysis of traffic load spectra obtained from VicRoads at a Culway site (Little River, Geelong, Victoria, Australia). The traffic load spectra are converted from weigh-in-motion (WIM) data. The WIM data are collected using devices that are able to measure the weights and dimensions of vehicles at highway speed and are the largest source of actual vehicle mass information available around the world. The flow chart for converting WIM data files into load spectra files in Excel is shown in Figure 1. The WIM "DCD" (Document Content Description) file is produced by the WIM logger (in Victoria this is usually a "Culway" WIM system). The Universal Traffic Converter (UTC) converts each DCD file into a load spectra CVS file, which is simply a text file of variable values separated by commas. This CVS file is then loaded into the supplied Access database and an Excel spreadsheet queries the database to obtain the required output.

In Figure 2, the WIM traffic data are analysed to obtain axle loads with corresponding percentages for years 2004 and 2005. Assuming that the light vehicle axle loads are less than 25 kN, the percentage of heavy vehicles can be computed. It is clear that there is a significant increase in the percentage of heavy vehicles from 20% in 2004 to 91% in 2005. This has a significant influence on the pavement performance because heavy vehicles induce much of the pavement damage. Figure 3 shows traffic load distributions for these two years broken down to individual axle categories (SAST – single axle with single tyres, SADT - single axle with dual tyres, TAST - tandem axle with single axle tyres, TADT - tandem axle with dual tyres, TRDT - triaxle with dual tyres, and QADT - quad-axle with dual tyres). It is interesting to note that the percentage of quad-axles has grown significantly from 2004 to 2005. This procedure was used to determine the passage of axle groups and loads for every hour of each day in each year. Figure 4 shows the distribution of traffic (for years 2004 and 2005) on the basis of axle types during various time periods during weekdays and weekend for the Little River (Slow Lane) site. The five time durations considered are; 12am to 6am, 6am to 10am, 10am to 4pm, 4pm to 8pm and 8pm to 12am. Figure 4 also indicates that the period 10am to 4pm has the greatest percentage of traffic and the night time periods from 8pm to 6am has the lowest percentage of traffic.

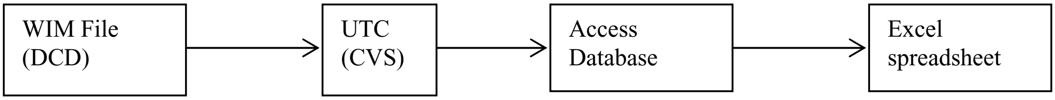


Figure 1: WIM data conversion procedure

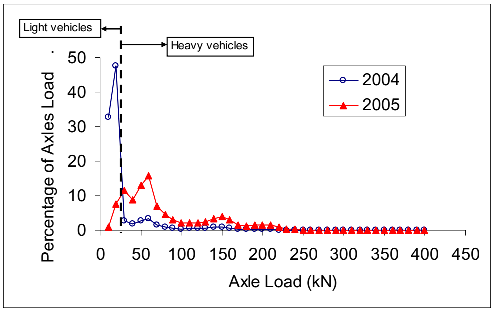
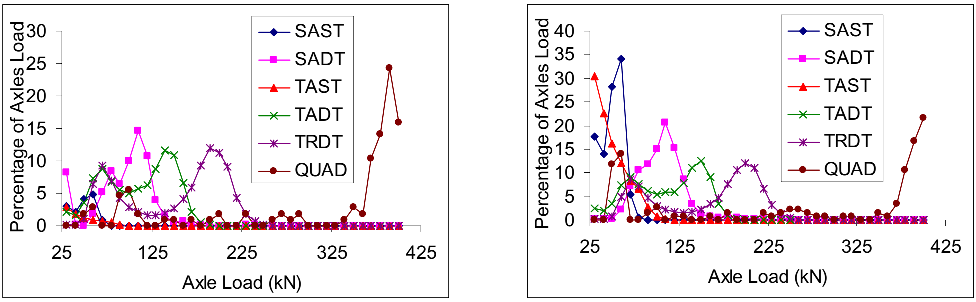


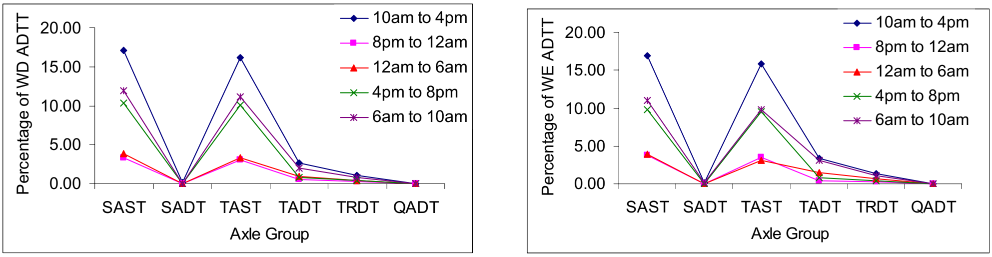
Figure 2: Annual normalized axle load distribution for Little River (Slow Lane)



(a)

(b)

Figure 3: Average annual axle load distribution for Little River (Slow Lane) for axle load greater than 25 kN: (a) traffic data for 2004; and (b) traffic data for 2005



(a)

(b)

Figure 4: Time of day normalized to axle group for Little River (Slow Lane) based on: (a) weekday traffic; and (b) weekend traffic

3.0 CLIMATE EFFECTS

It is considered that climate affects the pavement performance through temperature changes in the asphalt, moisture changes in unbound materials and subgrade, and moisture and temperature changes in cement treated bases. Rapid temperature and moisture (i.e., intensive rainfall) change may cause interface failure between pavement layer and subgrade material, and early pavement deformation. To take these effects into account, it is necessary to analyses temperature and moisture profiles within the pavement system with time. The measured temperature and moisture content data were used in an approximate way for the computer simulations.

3.1 ASPHALT CONCRETE (AC)

Generally the AC pavement is more sensitive to temperature changes than other pavement materials. The modulus of AC material decreases as the temperature increases, possibly leading to excessive deformation. Dickinson (1981) reported that AC pavement temperature rise can weaken it and underlying structural performance. He also indicated that rutting and shoving occur when heavy vehicles passing over the hot AC structure. Dickinson (1981) also found that low winter temperature can cause hardening binder films leading to premature cracking. Salem and Bayomy (2004) addressed the seasonal variation of the asphalt concrete (AC) modulus with the change in pavement temperature. They developed regression models that can be used by design engineers to assess the seasonal changes in AC modulus and an algorithm for calculating a seasonal adjustment factor.

3.2 UNBOUND PAVEMENT AND SUBGRADE

Moisture plays an important role in the response of unbound pavement and subgrade materials. It can have major influence on unbound pavement and subgrade modulus. Pavement moisture variation depends on environmental conditions (*e.g.* climate, seasonal variation and ground water table). Birgisson *et al* (2000) reported that unbound material strength decreases as the moisture content increases and that can induce significant pavement structure damage. Heath *et al* (2004) also indicated that moisture content has a major effect on granular pavement materials.

Figure 5 shows the variation of temperature and corresponding modulus for asphalt, unbound and subgrade layer on the basic of the data from Kwinana Freeway in Perth, Australia. Actual moduli measured at Kawinana Freeway were used to design the pattern of variety of the moduli about the mean values shown.

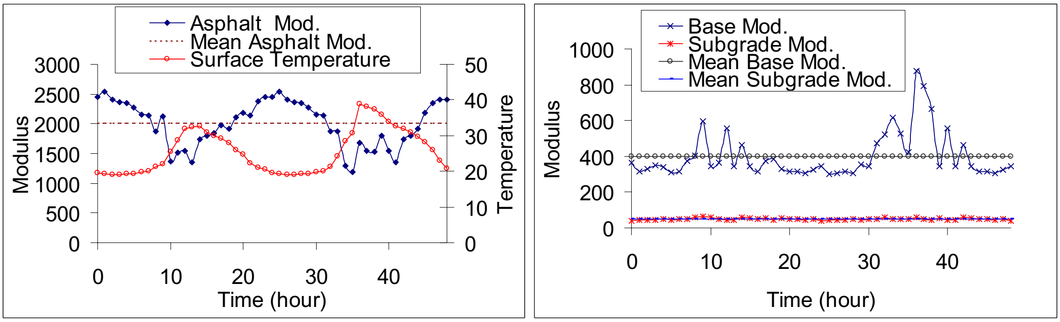


Figure 5: Temperature influence on pavement modulus

4.0 PAVEMENT DETERIORATION MODELLING

The stresses and strains generated from the structural models can be used to develop pavement deterioration with time. This is not a trivial task because the actual pavement deterioration occurs due to a range of mechanisms. These include fatigue cracking, thermal and shrinkage cracking, and rutting. Ultimately, the deterioration needs to be presented as an index of pavement roughness. Alternatively, it may be possible to present the damage accumulation on the basis of the above mechanisms separately. For example, the damage accumulation due to fatigue cracking may be presented using the Miner's rule. Use of Miner's hypothesis will allow the determination of the cumulative damage factor (CDF), where CDF is the summation of the damage factors (n_i) divided by the allowable repetitions (N_i) (Wardle *et al*. 2003).

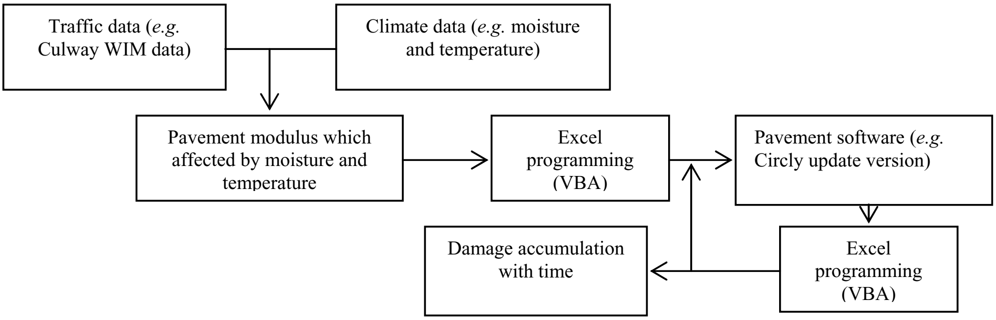
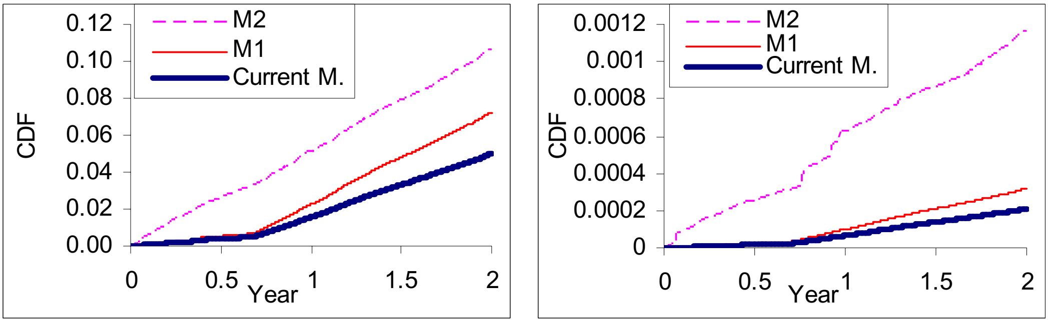


Figure 6: Proposed structure of pavement design approach

5.0 PRELIMINARY RESULTS



(a) (b)

Figure 7 Comparison of CDF for three different design methods: (a) Asphalt; (b) Subgrade

The pavement system considered in the present study consists of three layers; a 270mm thick asphalt surface overlaying a 100mm unbound granular and subgrade with CBR of 5%. Three methods were used to determine the pavement CDF. First, the current method (*i.e*. Austroads design guide, 2004) was used for the analysis. In this design method, 2000 MPa constant asphalt modulus, 400 MPa constant unbound granular modulus and 50 MPa constant subgrade modulus were used in the CIRCLY analysis. These moduli are shown in Figure 5, as the mean values of the modulus variation with time. The design life for this pavement is computed to be 40 years, i.e., CDF=1 (for asphalt), assuming no traffic growth after the first two years.

In this paper, two new methods are examined to incorporate climatic influence on pavement parameters. In both methods, hourly calculations are made to account for traffic and climatic variations. In each hour, the corresponding traffic and temperature and moisture data are considered. In method 1, the traffic data applicable to each hour is taken into account in the form of standard axles. The damage accumulation with time is computed by summing the CDF values for each hour over the calculation period. In method 2, hourly traffic data are considered in detailed form, accounting for various axle configurations (a total of six axle configurations were considered, as noted earlier). Therefore, CIRCLY calculations were performed for these axle configurations, inputting data for their specific geometries (as shown in Figures 3 and 4). The results for all three methods are shown in Figure 7. With the current method, the CDF plot should be a straight line with time provided that the traffic does not increase with time. The change in gradient is due to increase traffic, as shown. It can be clearly seen that the current design method can cause under estimation of pavement performance (lower rate of pavement deterioration is evident). Comparing the current method and method 1 indicates that the pavement may undergo significant pavement deterioration when the modulus variation is accounted for. However, the method 2 appears to produce the highest rate of pavement deterioration rate, giving half the pavement design life of that is obtained with the current method.

6.0 CONCLUSIONS

This paper examines a new methodology for continuous pavement deterioration modelling of Australian pavements. We highlight the deficiencies in the current approach, in particular the lack of consideration of the detailed traffic spectra and climate effects. It is also emphasized that pavements experience damage during times when the pavement is most vulnerable. Therefore, by undertaking a detailed analysis of the pavement performance considering the loading and the material behavior both in a time dependent manner, it may be possible to identify a relatively simplified method that could rationalize the current pavement design. This can lead to substantial cost savings to the community because currently over 9 billion dollars are spent on road pavements annually and this expenditure is expected to rise in future as the existing network approach its lifespan.

7.0 ACKNOWLEDGEMENTS

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