Measuring road pavement maintenance effectiveness using Markov Chain analysis

This study assesses the effectiveness of road network pavement maintenance using Markov Chain analysis based on historical costs and road roughness progression data. The analysis is based on a database developed by the State of Victoria, Australia, consisting of 2,197 road sections. The analysis measures maintenance effectiveness using the criterion of whether road sections remain in the same condition state or move to the next worst state based on a predefined roughness value. Principal inputs for the stochastic models, such as the development of transition probability matrices and associated cost functions, are discussed. Results show that, within the current budget envelop and only undertaking routine maintenance, the probability of road sections remaining in the same condition state, which is a determinant of maintenance effectiveness, exhibits a declining tendency from good to worst condition states. This finding prompts the discussion on when to increase maintenance expenditure such that the whole of life outcome is optimized. The method discussed in this paper provides tools for road authorities to select the appropriate maintenance action for each condition state of pavements based on the comparison analysis of the results of Markov Chain for different types of maintenance actions.

Keywords: roads, maintenance, inspections, mathematical modeling, Markov Chain, roughness

1. Introduction

During its service life, a road section undergoes different types of maintenance, and these treatments change over time along with developments in technology. However, combining many types of maintenance alternatives increases the difficulty in predicting road performance (Butt, Shahin, Carpenter, & Carnahan, 1994; Li, Haas, & Xie, 1997; Abaza, Ashur, & Al-Khatib, 2004). Determining the effect of any single maintenance treatment on a specific road pavement becomes complex. Predicting the future condition of roads for specific maintenance treatments deterministically or probabilistically also becomes difficult. This complexity is particularly evident at the network-level assessment of maintenance effectiveness. The selection of appropriate maintenance actions is difficult for road authorities. Consequently, they rely heavily on engineering judgment.
This study develops a refined process for interpreting roughness as an input parameter to forecast this aspect of maintenance requirements. A new measurement for assessing the maintenance effectiveness of combined routine, periodic, and rehabilitation maintenance is proposed based on historic maintenance cost data and the International Roughness Index (IRI) progression using Markov Chain analysis.

The network-level effectiveness model is developed using the probability of the road network remaining in the same condition state that is defined by a certain IRI value or moving to next the worst condition state. The data used are obtained from Victorian road asset management systems for network-level analysis. Then, the effectiveness analysis results are converted to transition probability matrices as a determinant of the Markov Chain analysis.

2. Road pavement deterioration and performance criteria

Performance criteria of road pavements can be categorized into two broad types of evaluation, that is, user and functional evaluations (Uddin, 2006). User evaluation employs the pavement serviceability rating (PSR) or pavement condition rating (PCR) as the measurement criterion. This rating is subjective; panels of users are surveyed to grade the riding quality of the road under consideration (Baladi, Novak, & Kuo, 1992). Subsequently, a pavement serviceability index (PSI) can be developed by comparing and relating the value of PSR with quantifiable pavement distress (e.g., roughness, cracking, and rutting) (Uddin, 2006).

By contrast, the main criterion of functional assessment is longitudinal roughness or unevenness. Roughness is defined as “the variation in surface elevation that induces vibration in traversing vehicles” (Sayers, Gillespie, & Paterson, 1986). Roughness also refers to “the deviation of surface from a true planar surface with characteristic dimension that affect vehicle dynamics, ride quality, dynamic loads and
drainage” in ASTM specification E867-82A as cited in Paterson (1987). Thus, this indicator directly links any structural defect in terms of relative deviation from the longitudinal surface of pavement to the user perceptions of riding quality, dynamic vehicle loads or traffic, and safety. Roughness is measured through various standard units such as IRI in m/km or inches/mile (Sayers et al., 1986; Watanatada et al., 1987) and NAASRA Roughness Measure by Scala and Potter cited in McManus (2008). This measurement is considered adequate to represent the condition index of a pavement (Al-Suleiman, Sinha, & Anderson, 1988; Watanatada et al., 1987; Attoh-Okine, 2005).

User and functional evaluations may be related to each other to determine the performance of a road pavement. Various studies have been conducted to establish the correlations between PSR and functional evaluation criteria, such as roughness, rutting, and cracking. The most promising relationship is that between PSR and IRI, which has been broadly adopted. Equation 1 is the commonly accepted formula of the relationship between IRI and PSR for asphalt pavement suggested by Paterson (1987).

\[
IRI = 5.5 \log_e \left( \frac{5.0}{PSI} \right) \tag{1}
\]

Other common relationships were suggested by Al-Omari and Darter (1994). Equations 2 and 3 are for general flexible/asphalt pavement and asphalt concrete, respectively.

\[
PSR = 5 \exp(-0.26 \times IRI) \tag{2}
\]

\[
PSR = 5 \exp(-0.24 \times IRI) \tag{3}
\]

Various methods and studies aimed at determining the relationships between user evaluation (in terms of PSR/PCI) and functional evaluation (e.g., roughness, rutting, and cracking) as distress indices as a single determinant or a combination of determinants have been conducted. PSR/PCI is related to one factor or a combination of
factors through regression analysis. Hall and Munoz (1999) developed a model based on PSI road tests conducted by the American Association of State Highway Officials (AASHTO), which concluded that a more realistic correlation model can be obtained based on relationships between PSI and IRI. Hall and Munoz (1999) excluded other distress factors, such as cracking, rut depth, and percentage of patching, from the model. Their final model used only IRI to determine PSI, which is expressed as follows:

\[
PSI = 5 - 0.2397 \times x^4 + 1.771 \times x^3 - 1.4045 \times x^2 - 1.5803 \times x,
\]

(4)

where \( x = \log (1 + SV) \) and \( SV = 2.2704 \times IRI^2 \).

Labi, Lamptey, Konduri, and Sinha (2005) investigated the long-term effectiveness of thin hot mix asphalt (HMA) overlay as a preventive maintenance treatment and used three indicators of effectiveness, namely, IRI, PCR, and rutting (RUT). Different results were obtained. Moreover, the combined performance across indicators was not analyzed because of the differences in the dimensions of performance indicators. Irfan, Khurshid, and Labi (2009) also analyzed the long-term performance of HMA for the Indiana Department of Transport (DOT) and used three different indices, namely, IRI, PCR, and RUT. The indices use different threshold values. However, their study did not indicate which of these indices should be considered the trigger for intervention. Their results confirm the argument of Zimmerman and Peshkin (2004) that implementing a combination of different performance indicators is difficult. Therefore, road authorities should choose only one as the trigger for maintenance intervention and use the other performance indicators for project-level decisions.

Based on the aforementioned arguments and to be consistent with other studies and the experience of road authorities, this study adopts the IRI as the key indicator of road performance.
3. Road maintenance effectiveness

The most difficult aspect of maintenance management is the prediction of the long-term performance of specific maintenance treatments. For more than 30 years, many different maintenance effectiveness measurements have been suggested. However, these maintenance effectiveness measurements are mostly based on modeling approaches and less based on the actual performance in service data. Another important aspect is that local practices and conditions influence the effectiveness of treatments. It is recommended that specific road authorities develop a particular method of measuring maintenance effectiveness rather than simply adopt values obtained by different road authorities (Hajj, Loria, & Sebaaly, 2010).

In assessing the effectiveness of routine maintenance, Al-Suleiman et al. (1988) introduced the term “rate of change” in pavement roughness, which is expressed as follows:

\[
RRM = \frac{RN_j - RN_i}{RN_i},
\]

where \( RRM \) is the rate of change in pavement roughness (m/km), \( RN_i \) is the roughness in year \( i \) (m/km), and \( RN_j \) is the roughness in following year \( j \) (m/km).

The results showed that the effectiveness of routine maintenance is highly influenced by a regional factor in terms of climatic influences. When this factor is high, its influence is greater than the effect of different expenditure levels.

Modifying the method suggested by Al-Suleiman et al. (1988), Labi and Sinha (2003) assessed short-term maintenance effectiveness using three different types of relationships between maintenance and the timing of performance monitoring. Their findings indicated that the lag between maintenance intervention and the performance monitoring period is an important consideration. Based on the same principle, Abaza et
al. (2004) introduced relative performance when assessing the effectiveness of maintenance. In this case, PSI was used as the conditional criterion. The measurement is based on the relationships between PSI and 80 kN equivalent single axle load. However, their research relies only on the deterministic prediction curve based on AASHTO flexible design principle, not on the actual performance of the roads.

A recent approach was suggested by Hajj et al. (2010) in a study analyzing the performance of road pavement of the Nevada DOT. Hajj et al. (2010) developed an approach different from the previous models that relied heavily on modeling to measure effectiveness. Their approach to effectiveness was to assess whether the years of the remaining life of a road could be held/maintained or improved/extended via a specified condition after treatment service life based on the PSI value before and after maintenance. In their recommendation, although the PSI was used as the main criterion for performance, roughness (i.e., IRI) was observed to be the most influential factor in determining performance.

3.1 Recommended maintenance effectiveness measurement model

The outcomes of the previously presented measurement approaches and maintenance effectiveness models form the basis of the developed pavement maintenance effectiveness measurement adopted in the presented study. First, the performance of road pavements is revealed to be uncertain. Moreover, all of the road pavements requiring maintenance are in service, adding to the complexity of the measurement approach. Maintenance technology is also changing, making the prediction of the effect of specific maintenance treatments difficult under intensive maintenance. Second, in terms of performance criteria, various indices have been adopted, including using service life as a performance parameter. However, the most promising criterion thus far is the use of IRI as the sole parameter. This criterion is
currently widely accepted because it reflects the overall condition of roads and the perceptions of users.

Three main distinct foundations for measuring pavement maintenance effectiveness are recommended in the present study and explained in Subsections 3.1.1 to 3.1.3.

3.1.1 Effectiveness measured by change of roughness ($\Delta R$)

This approach modifies the method suggested by Al-Suleiman et al. (1988). The main idea of this analysis is to measure the maintenance effectiveness of a road network by observing whether road sections remain in the same condition state by using Equation 6. This measurement leads to the development of the transition probability matrix (TPM), as explained in Equations 7 and 8. The use of TPM is part of the main general idea of the study to use Markov Chain analysis. This approach is unique in developing TPM that directly relates to maintenance effectiveness. The formula measuring effectiveness is expressed as follows:

$$\Delta R = R_{\text{After}} - R_{\text{Before}},$$

where $\Delta R$ is the change of roughness IRI (m/km), $R_{\text{Before}}$ is the roughness before maintenance (m/km), and $R_{\text{After}}$ is the roughness after maintenance (m/km).

3.1.2 Effectiveness measured by whether a road remains in the same condition state or moves to the next condition state based on a predefined roughness value

This approach is similar in principle to the method suggested by Hajj et al. (2010). However, the present study uses the criterion of an inter-observation qualification of remaining in the same condition state or moving to the next condition state of pavements. Moreover, the model in this study uses a performance index that is directly applied in the analysis (i.e., roughness in IRI in this case).
The criteria for remaining in the same condition state or moving to the next condition state in terms of IRI are defined as follows:

- The road moves to the next condition state if $\Delta R \geq 0.2$ m/km (12.6 inches/mile).
- Otherwise, the road remains in the same condition state.

A preliminary analysis of the data has been conducted to define the criteria for moving to the next condition state or remaining in the same condition state. When the range of IRI used is 0.1 m/km (6.33 inches/mile), most of the roads tend to move to the next condition state within one observation period. If the value of 0.3 m/km (19.0 inches/mile) is used, then most of the roads remain in the same condition state because the roads rarely deteriorate at the gradation of 0.3 m/km. Therefore, the value of 0.2 m/km (12.67 inches/mile) is considered to be the marginal value of IRI transition and used as the criterion.

The total physical length of each condition state is calculated to obtain the probability of the road moving to another state/remaining in the same state on each condition state by dividing the length of roads remaining/moving to the condition state by the total length of the road in certain states before maintenance is conducted.

3.1.3 Introduction of “condition state” in favor of using time/year as dependent variables

The introduction of “condition state” is one of the distinct and unique ideas in this study. The maintenance intervention is driven by the condition of the road prior to that intervention, independent of the history of previous treatments and time (i.e., service life). This approach is different from the currently commonly used approach in which interventions depend on the service life of the road pavement. This approach is
consistent with the use of stochastic-based models for performance prediction using the first-order Markov Chain, which states that the future probability depends only on the current probability rather than the entire history.

4. Road pavement performance prediction model

Most conventional performance prediction models use deterministic methods via regression analysis, empirical estimation, and/or a combined mechanistic–empirical method. Although such methods are capable of predicting the future performance of roads, they are limited to specific projects or at the project level. Other factors influencing the accuracy of these simple predictive models are the unpredictability of traffic volume and loads, environmental changes, the complexity of the deterioration of specific pavements, the accuracy and consistency of parameters measured, and the span of time of the historical records using particular pavement condition ratings (Li et al., 1997; Hong & Wang, 2003).

In response to these limitations, probabilistic models are frequently developed to enhance the prediction of road pavement performance at the network level. Another advantage of probabilistic models is their capability of predicting performance under uncertainty, particularly when roads undergo intensive maintenance actions (Li et al., 1997; Abaza et al., 2004; Hong & Wang, 2003; Ortiz-Garcia, Costello, & Snaith, 2006). In the present study, Markov Chain analysis is used to develop the performance prediction model.

The most important step in using Markov Chain in analyzing the future performance of pavements is the development of the TPM. This approach was also proposed to handle the effects of reconstruction interventions by Wigan (1985). A TPM is developed to depict the future performance of roads, which is uncertain in nature and highly influenced by various factors during construction and maintenance (Li et al.,
In contrast to deterministic models that predict future conditions of roads exactly, probabilistic models, through a TPM using Markov Chain, represent the condition of road pavement in terms of the probability of condition states to be experienced in the future (Ortiz-Garcia et al., 2006).

The most common method for determining the TPM is based on historical data. An alternate method is based on the outcomes of interviews or questionnaires using a panel of experts to rate the probability of road pavement condition moving to state \( j \) from the given state \( i \). From the historical data, the probability of a portion of the road moving from state \( i \) to \( j \) is divided by the total length or portions of the road section being considered (Equation 7), as follows:

\[
p_{ji} = \frac{N_{ji}}{N_i},
\]

where \( p_{ji} \) is the probability that the condition of the road remains in state \( i \), \( N_{ji} \) is the total length of the roads remaining in state \( i \) (km), and \( N_i \) is the total length of the roads that are in state \( i \) prior to maintenance treatments in one observation period (km).

Different TPMs can be utilized for different road categories, such as geological conditions, traffic volume, and pavement structures. Another assumption used in this analysis (which is commonly adopted in pavement management) is that the condition state of the road can only deteriorate to a worse condition state and cannot move to a better condition state unless rehabilitation or reconstruction is conducted. Thus, estimating the probability that the roads will remain in the same condition state during one observation period is important. The other roads are assumed to move to the next condition state. Assuming that \( p_{ji} \geq 0 \), the prediction is expressed in Equation 8, as follows:
\[ p_0 = 1 - p_0. \] (8)

5. Methodology

5.1 Sample description

Samples are divided into two traffic criteria, that is, low-volume roads (LVRs) and high-volume roads. Consensus on the definition of LVRs has not been reached. A survey conducted by Swanson (1994) confirmed that no exact number is used to define the traffic volume of a LVR. The survey concluded that many different definitions exist. The traffic volume of an urban LVR ranged from 1,000 to 5,000 vehicles per day with an average of 3,200 vehicles per day. Extremely diverse numbers were observed for rural LVRs, ranging from 300 to 3,400 with an average of 1,700. For practical analysis and in consideration of the survey results of Swanson (1994), the definition of LVR used in this study is based on an average annual daily traffic (AADT) of less than 3,000 vehicles per day. Roads sampled in this analysis focus on roads that connect the main townships in the State of Victoria. Thus, the sample used 898 road sections of LVRs, and the other road sections were high-volume roads.

In Victoria, two common types of flexible asphalt surfacing exist, that is, Chip seal and asphalt mix. In other countries, Chip seal is used as a thin flexible pavement surfacing maintenance treatment. Therefore, two road pavement types (i.e., Chip seal and asphalt roads) are used in the present study based on the Victoria data.

5.2 Historical maintenance cost database development

This analysis uses historical maintenance costs from the Victoria maintenance data, a data set covering a 10 year observation period (1997–2008). The cost and treatments are divided into three types, namely, routine, periodic, and rehabilitation. Figure 1 describes the assumptions adopted for the analysis. Then, the cost of each
treatment is divided by the lane length of the road section. Thus, the cost pertains to the average cost for each type of treatment for each road section. This average is adopted because the performance of a road section is assessed by the average IRI of the total length of each road section.

A database is developed including the observation of maintenance measures for every year of road sections along with their respective performance in terms of IRI (m/km). IRI is monitored every two years for each road section. However, the annual maintenance measures on each road section may differ between the first and second years. Consequently, the entire road sample is grouped into eight sections (Table 1). The model intends to analyze the effectiveness of routine, periodic, and rehabilitation treatments and its combinations. The results are presented in four categories of actions representing maintenance measures in Table 1, and the corresponding TPMs are presented in Table 2. Then, the sample categories are sorted based on the IRI to obtain the data of each condition state to develop TPMs.

[Table 1 near here]

[Table 2 near here]

The description of each condition state is presented in Table 3. Road conditions are divided into 11 condition states. The IRI value range considered within different condition states is 0.2 m/km (12.6 inches/mile). This value also becomes the criterion for moving to the next condition state or remaining in the same condition state. The value based on the analyzed data is considered to be a marginal value of IRI wherein road conditions differ.

[Table 3 near here]
5.3 Maintenance effectiveness measurement

The theme of the study is to measure the maintenance effectiveness of a road network by observing whether road sections remain in the same condition state. This theme has been discussed in the section for recommended maintenance effectiveness measurement models. The effectiveness measurement used is defined in Equation 6, followed by the development of TPMs using Equations 7 and 8. The objective is to relate maintenance effectiveness measurement directly to the TPM (Table 2).

6. Results and discussion

6.1 Maintenance effectiveness results

The effectiveness of maintenance under a combination of routine, periodic, and rehabilitation treatments can be observed by considering the remaining or moving criteria in terms of IRI using Equations 6 to 8 and recapitulating the TPMs (Table 4). The results can be presented as a probability of roads remaining in the same condition state (Figures 2, 3, and 4) for low-volume Chip seal roads, high-volume Chip seal roads, and asphalt roads. Alternatively, the result can equally be presented as the percentage of roads moving to the next condition state. Figure 5 presents an illustrative result for low-volume Chip seal roads.

These results confirm the previous findings of Mamlouk and Zaniewski (1998) that periodic maintenance has a generally higher effectiveness than routine maintenance. The results (Figures 2 to 4) show that Action A, which consists of routine, no periodic, and no rehabilitation maintenance (i.e., undertaking only routine maintenance), generally has a low probability that roads will remain in the same condition state. This trend occurs particularly in the high condition states (worst
conditions). Action A also exhibits a descending trend. Alternatively, Figure 5, which presents the probability of low-volume Chip seal roads moving to the next worst condition state, also exhibits the same trend. In high condition states, intervention is required apart from routine maintenance.

These results are independent of the years/age of service life of roads. Effectiveness is measured between two performance monitoring observations, and only the treatment undertaken between these two performance measurements is considered. Effectiveness is also measured independent of the history of treatment. The findings provide a rationale for road authorities to conduct a high level of maintenance on the high states (worst states) and only use routine maintenance in the low state(s). Depending on the availability of funding, the choice of which state(s) to conduct intervention (i.e., periodic and rehabilitation treatments) can be decided strategically. An optimization model can be helpful in this case.

6.2 Cost functions: assumption, limitations, and results

Given the limited sample numbers, certain costs were unavailable, particularly for states 1, 2, and 11. Consequently, for further analysis planned in the future optimization phase for these states, the cost obtained were the same as those for the closed condition state. In several cases, the cost was considered to be unavailable or the same as that in other actions. In addition, certain costs are apparently high in several states, particularly for periodic and rehabilitation maintenance. This difference is probably because intensive maintenance is completed during a certain year for that specific condition state. This analysis applied purely the available cost data. The effect of this constraint is not discussed here. The cost function results are embedded in Figures 2 to 4.
6.2 TPM results

6.2.1 TPM assumptions and limitations

In a TPM, a state can only move to the next higher/worse condition state. The other states remain in the same condition state. A state can only move to a lower/better condition state when a full reconstruction is conducted, that is, the total length of the road section is in a new condition. Rehabilitation maintenance is conducted on the small in-depth part of the road section (Figure 1), but does not improve the overall condition of the road section. The only measure considered to improve a road to “as new” condition is a full reconstruction of a significant length of the road.

Limitations were observed during the analysis. First, given the limited number of samples, not all probabilities are available, particularly in states 1, 2, and 11. Thus, for further analysis planned in the future optimization phase in these states, the probability obtained is the same as that of the closed state. In several cases, the probability is considered to be unavailable or the same as that of other actions. Nevertheless, a limited number of samples were available in those states. A significant confidence level was observed in other states. Second, the analysis of asphalt roads was conducted for only high-volume roads because of the limited number of samples available for LVRs.

6.2.2 TPM results

The transition probabilities for Chip seal roads were divided into two categories, namely, LVRs and high-volume roads. TPMs for asphalt roads were represented by one TPM for each action because no analysis was conducted for the LVRs of asphalt pavements. One transition probability is evident for each type of action. Table 4 represents the output of a Markov Chain analysis in terms of TPMs.
7. Conclusions

Uncertainty in predicting the behavior of pavements is evident in this analysis. However, using broad criteria as to whether road sections remain in the same condition state or move to the next worse condition state, reasonable levels of confidence of trends were observed. Dividing road conditions into different condition states is proven to be an effective approach to assist road authorities in deciding an appropriate selection of maintenance strategies. In addition, general criteria for treatments (i.e., routine, periodic, and rehabilitation maintenance cases) can cope with the uncertainty related to technology changes in specific maintenance measure and cost fluctuation. An opportunity to apply informed engineering judgment in deciding specific maintenance treatments is presented, particularly at the project level.

Initiated by the idea of measuring maintenance effectiveness leading to the development of transition probability matrices as the main determinant of Markov Chain, the analysis presents the steps implemented in developing a stochastic-based performance prediction model. Details of the development of the cost function are also presented. Together, these data form inputs for utilizing the stochastic-based optimization problem. Other constraints (e.g., budgets and required performance thresholds) can be added to achieve optimum maintenance options.

Future research to link the TPM of Markov Chain with cost functions in an optimization model (e.g., using Markov Decision Processes) is proposed. However, certain aspects of the development of the cost function should be considered, such as the difficulty of measuring the effect of a specific maintenance treatment on specific road sections when those sections undergo different types of treatments during their service life, the effect of changes in government maintenance policy, and the effect of changing the maintenance technology.
An important requirement when using this analysis is the availability of data. This requirement is one of the limitations in using a Markovian model. Many variables are involved in the analysis, such as type of maintenance (i.e., routine, periodic, and rehabilitation treatments), AADT, types of road pavements, and different condition states. In an uncertain environment, the availability of a rigorous database determines the confidence level of the analysis.

Another limitation of this paper is that IRI is assumed to represent the overall effect of the aforementioned variables. Therefore, additional research is required to determine the characteristic behavior of pavements under different IRIs, the relationships of IRI with other variables, and the probability of the TPMs obtained from different variables to be significantly different. This research direction is important in deciding the criteria for maintenance effectiveness measurement.

However, the methodology presented provides results that can be easily interpreted by road authorities. A quantifiable effectiveness measure is another aspect that is attained by this assessment model. Future data using a similar 10 year observation period can be used for comparison to determine whether the TPM obtained is similar to the current TPM. Such data can also be compared with other methods of performance prediction.

References


