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Application of Markov Chains and Monte Carlo Simulations for Pavement Construction Engineering

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Abstract: Markov chains and Monte Carlo Simulation were applied to account for the probabilistic nature of pavement deterioration over time using data collected in the field. The primary purpose of this study was to evaluate pavement network performance of Western Australia (WA) by applying the existing pavement management tools relevant to WA road construction networks. Two approaches were used to analyze the pavement networks: evaluating current pavement performance data to assess WA State Road networks and predicting the future states using past and current pavement data. The Markov chains process and Monte Carlo Simulation methods were used to predicting future conditions. The results indicated that Markov chains and Monte Carlo Simulation prediction models perform well compared to pavement performance data from the last four decades. The results also revealed the impact of design, traffic demand, and climate and construction standards on urban pavement performance. This study recommends an appropriate and effective pavement engineering management system for proper pavement design and analysis, preliminary planning, future pavement maintenance and rehabilitation, service life, and sustainable pavement construction functionality.

Key words: markov chain; pavement performance, pavement management, probability model; construction engineering

1. INTRODUCTION

Pavements are an essential part of highway transportation infrastructure. A tremendous amount of time and money is spent each year on the construction of new pavements and the maintenances and rehabilitation (M&R) of the existing pavements [1]. A scientific approach that can maximize benefits and minimize overall costs is needed to design and manage pavements [2]. Pavement management systems (PMSs) provide consistent, objective, and routine procedures to determine priorities, schedule resources allocations, and budget for pavement M&R [3]. Pavement construction management is a decision-making action with fraught uncertainties. The resources necessary for pavement M&R are severely constrained; therefore, determining the best approach and timing is difficult and nearly overwhelming, and would be even if unlimited resources were available. Hard and soft technologies have emerged over the last seven decades that can offer stakeholders improved decision-making capabilities: microcomputers and decision support systems (DSSs), operation research methodologies, and artificial intelligence [1].

Pavement management systems based on the engineering uses the systems approach to unify pavement analysis and design, construction, maintenance, evaluation, and restoration [4]. Improving road safety through proper pavement engineering and care should be one of the primary pavement management system objectives [5]. A robust pavement engineering management system requires accurate and efficient pavement performance evaluations [5, 6] to develop prediction models based on the Pavement Condition Index and pavement age.

This study aims to evaluate Western Australia (WA) pavement network performance and apply existing pavement management tools relevant to WA road construction networks

2. PAVEMENT MANAGEMENT TOOLS AND REHABILITATION

Rehabilitating existing roads instead of building new section is a stakeholder's most critical decision. Pavement management includes planning, design, construction, maintenance, and pavement rehabilitation activities that are part of a public work program [16]. Pavement management systems include a set of methods that support decision makers as they determine the optimal strategies for road construction and maintenance over a time frame [17]. Operation research defines pavement management as a decision support system and nothing more research [18].

Several pavement management systems are described in the literature; however, these approaches fail when problem's exceptional circumstances are taken into account. Integral and integer goal programming problems cannot be solved on a microcomputer or problem of practical size, while linear and goal programming problems cannot handle duration constraints project since projects cannot last more than two consecutive years [18].

2.1. Pavement management systems overview

A pavement management system (PMS) is a decision support system that designed for use by pavement personnel to make cost-effective decisions concerning pavement maintenance and rehabilitation. These stakeholders are responsible for organizing the massive accounts of data that develop with a pavement network [19].

The basic elements of a network-pavement management system includes: an inventory, condition assessment, fund constrained project identification, and a method to determine the impact of funding decisions on future conditions. Pavement Analysis and design are complex engineering problems requiring a systematic approach to quantify and analyze the many variables that influence appropriate maintenance and rehabilitation techniques identification and selection that are needed [19].

2.2. Current system and shortcoming

The current pavement management system is computerized and has procedures for gathering data in, a database validation for data analysis and reporting and rehabilitation identification and prioritization; however, it does not take future pavement behavior into account [18]. Different roads characteristics must be taken into account to create a better schedule for maintenance and rehabilitation, and design models that forecast the pavement behavior such as ride comfort, crack formation, user costs, and routine maintenance and reaction to environmental conditions such as temperature and moisture.

3. PAVEMENT PERFORMANCE PREDICTING MODELS

Deterministic models are used to predicting a pavements' primary response, and structural, functional, and damage performance whereas probabilistic models include survivor curves, Markov and Semi-Markov transition process, and Monte Carlo Simulation [13, 14]. Lytton [13] emphasized the concepts of pavement performance prediction and modeling, including the limitations and use of the models. Network level models are necessarily less detailed; however, they are used in selecting optimal maintenance and rehabilitation strategies-, size and weight and cost allocation studies, and network-level trade-off analysis between pavement damage, maintenance, and other user costs. Well-developed performance models, resting on the twin pillars of statistics or experimental design and mechanics, can satisfy technical and economic requirements for managing pavement based on engineering [13]. Higher performing models development should be continuous task remains to clone.

Markov [15] suggested that load equivalent factors should be calculated based upon marginal damage concepts, with value the ranging from 0 to 1 based on pre-determined levels of distress or serviceability indices [13]. Load equivalent factors for the exact vehicle will change as the pavement becomes more distressed and will depend upon other types of distress and timely maintenance actions. Including these factors will make complicate load equivalence factors calculations for mixed traffic pavement design; however, the results will be more realistic. The allowable pavement and construction engineering treatments are listed in Table 1.

Table 1. Allowable pavement and construction engineering treatments

Measure of Goodness	Engineering Treatment Options				
	Do nothing	**Crack sealing**	**Thin overlay**	**Resurfacing**	**Reconstruction**
Excellent	Yes				
Good	Yes	Yes			
Fair	Yes		Yes		
Poor	Yes			Yes	
Very Poor	Yes				Yes

4. METHOD

4.1. Lao road design manual inventory

Pavement management data were collected from the Lao Road Design Manual (LRDM) inventory: ten roads categories from sixty-seven Western Australia roads network locations. Data included the past thirty years traffic roads surveys, including: surface type, construction, (M&R) year, average daily traffic (ADT), heavy vehicle in the road (HV, %), Thornwaite Moisture Index (TMI), and pavement cracking types.

4.2. Pavement network management tools

Linear and non-linear programming models are the principal algorithms researchers use to develop pavement management optimization models [1, 7]. Key assumptions for all functions including objective and constrain functions, are treated as linear when used in linear programming models. However, this assumptions does not accumulate in non-linear programming models [8]. Pavement condition prediction models are significant components of pavement optimization models. These are two types of prediction models: deterministic and probabilistic. Pavement deterioration rates are often “uncertain,” therefore, probabilistic models based on the Markov process approach and Monte Carlo Simulation are frequently used to evaluate and analyze pavement conditions performance [6, 9-11].

4.2.1. Model algorithms

Mathematical optimization models using Markov Chains and Monte Carlos Simulation can identify optimal effective and sustainable strategies for pavement maintenance, rehabilitation, and reconstruction. The linear (Equations 1 through 4) and non-linear (Equations 5 through 8) for pavement maintenance and rehabilitation optimization are formulated as [1, 7, 12]:

$$\sum_{t=1}^{T}\sum_{k`=1}^{K}\sum_{i=1}^{5}\sum_{k=0}^{K} Y_{tk`ik}\cdot C_{tk`ik} \tag{1}$$

$$\sum_{k=0}^{K} Y_{tk`jk} = \sum_{i=1}^{5}\sum_{k=1}^{K} Y_{(t-1)kik`}\cdot P_{k`ij} + \sum_{i=1}^{5} Y_{(t-1)k`io}\cdot DN_{k`ij}, \tag{2}$$

for all t = 2. . . T: k' = 1. . . K; j = 1. . . I

$Y_{tk'k} \geq 0$ for all t = 1. . . T; k' = 1. . . K; I = 1. . . I; k = 0. . . K

$$\sum_{t=1}^{K}\sum_{k`=1}^{5}\sum_{k=0}^{K} Y_{tk`jk} = 1\ for\ all\ t = 1,\ldots,T\ ; \tag{3}$$

$S_{Tj} \leq \varepsilon_{Tj}\ for\ selected\ j$

$$\sum_{t=1}^{T}\sum_{k`=1}^{K}\sum_{i=1}^{5}\sum_{k=0}^{K} Y_{tk`ik}\cdot C_{tk`ik}\cdot L \leq \beta_t\ \ for\ all\ t = 1,\ldots,T \tag{4}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{5} S_{tj}X_jLC_j \tag{5}$$

$$S_{tj} = \sum_{i=1}^{5} S_{t-1i}\{(1-X_i)DN_{ij} + X_iP_{ij})\} \tag{6}$$

for t = 2,…. T; J = 1, 2,…5:

$X_i \geq 0\ for\ i = 1\ldots.5$

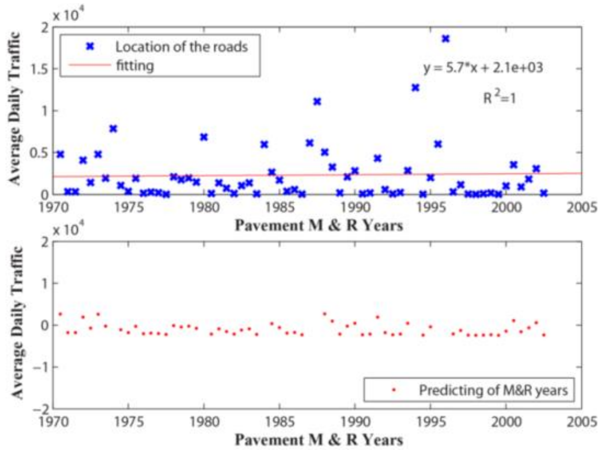
$$\sum_{k=0}^{4} X_{ik} = 1\ for\ i = 1\ldots.5 \tag{7}$$

$S_{Tj} \leq \varepsilon_{Tj}\ for\ selected\ j$

$$\sum_{j=1}^{5} S_{tj}X_j\ L\ C_j \leq B_t\ for\ t = 1\ \ldots.t \tag{8}$$

5. RESULTS

Average daily traffic (ADT) versus pavement rehabilitation over the past 30 years (1970 – 2002) is depicted in Figure 1. Western Australia (WA) ADT has been increasing by approximately 53.8% indicating that the use of full-depth asphalt pavement to construct and rehabilitate heavily loaded urban roads has grown rapidly over the past 20 years. Pavement M & R costs have also been increased from year to year. The average daily traffic in 1984, 1990, and 1994 was 5,971, 6,860, and 7,850, respectively. The measure of goodness correlation between construction and rehabilitation was (R^2=1).



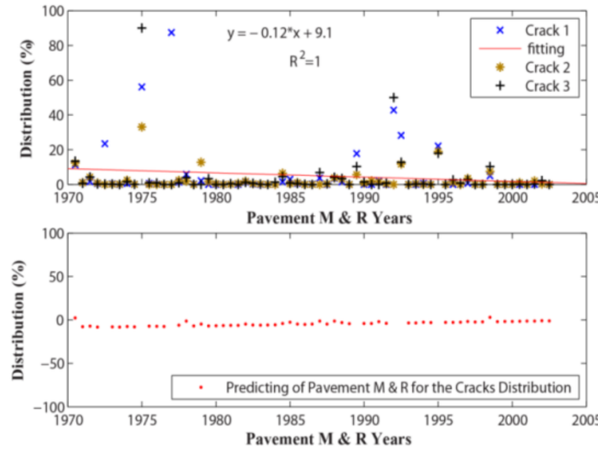
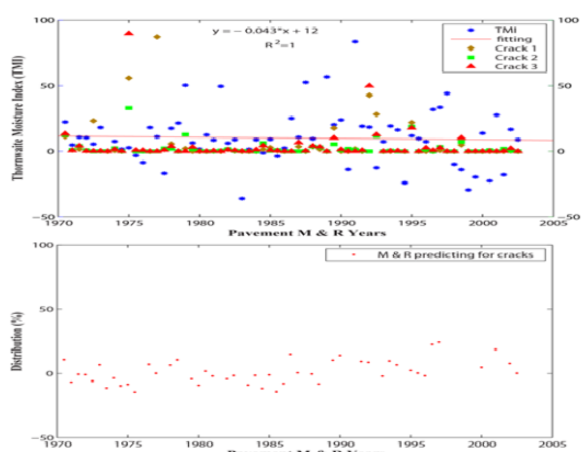


Figure 1. Average daily traffic versus pavement M&R years

Figure 2. Crack distribution versus pavement M&R years

Pavement crack distribution versus M&R years is illustrated in Figure 2. The crack distributions for type one and three were above 85% in all the areas during 1984 - 1986. The crack three types were also above 50% in 1999 indicating that the flexible asphalt pavement might have deteriorated and become damage due to traffic loading and environmental factors. Pavement construction and rehabilitation performance might not have been as effective and efficient. The measure of goodness correlation between crack types one, two, and three was (R^2=1) in terms of size distribution.

The Thornwaite Moisture Index (TMI) versus pavement cracks for the ten roads categories is depicted in Figure 3. The analyses indicated that the TMI for the granular sealed pavement was low approximately 50% from 1970-1990 then rapidly dropped below zero after 1990. This indicated that the sealed asphalt pavement roughness, rutting, and cracking were ubiquitous due to temperature, ages, and healing; therefore, pavement M & R actions were not effective and sustainable. The measure of goodness correlation between crack types one, two, and three was (R^2=1) in terms of size distribution.



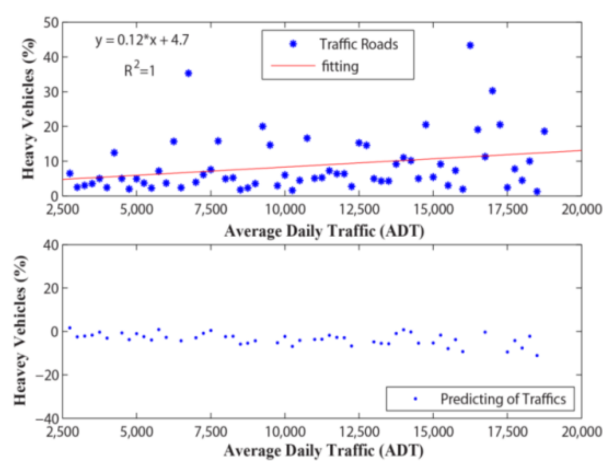


Figure 3. TMI versus pavement crack and Monte Carlo Simulation of pavement M&R for cracks

Figure 4. Average daily traffic versus heavy vehicles

Average daily traffic versus heavy vehicles for ten different types of roads categories from sixty-seven locations is illustrated in Figure 4. The heavy vehicle volume (HVV) increased from 30 to 40% since 1990 indicating that the heavy trucks wheel load of contributes to several forms of pavement distress. The measure of goodness correlation among the ten different road type categories was (R^2=1) in terms of pavement distress and fatigue.

The pavement construction years versus rehabilitation years for asphalt concrete surface types is displayed in Figure 5. Pavement crack rehabilitation has doubled year since 1990 indicating that the deterioration of flexible pavement increased by 50 percent more since the 1970s due to urban traffic loading and environmental factors. A very good correlation (R^2=1) between construction years and asphalt concrete rehabilitation years could be determine. Blankenship et al. [20] reported that it is common to see cracks reflect on a new pavement overlap in three to five years.

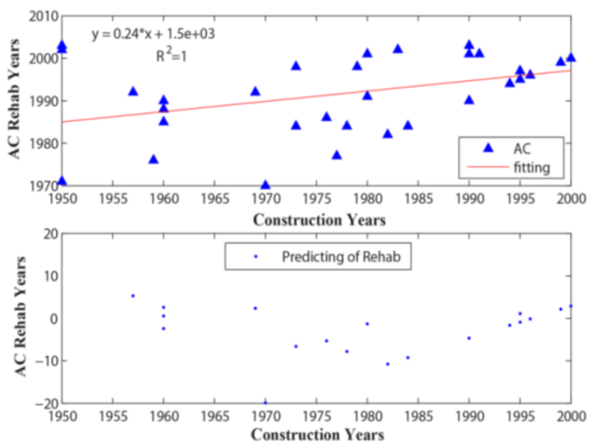


Figure 5. Asphalt concrete rehabilitation years versus construction years

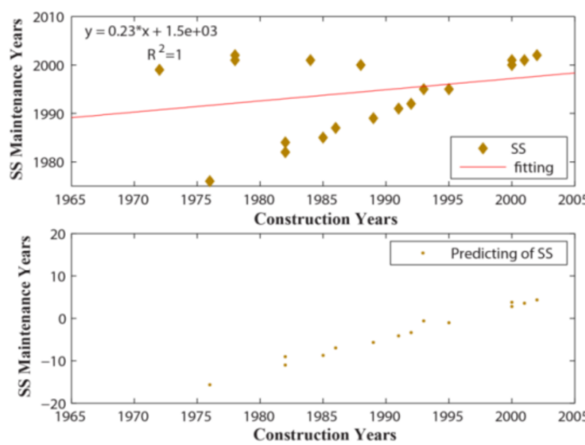


Figure 6. Slurry seals maintenance years versus construction years

Slurry Seals (SS) construction years versus maintenance years for different asphalt concrete is illustrated in Figure 6. The SS construction and rehabilitation years are somewhat consistent (R^2=1), which indicate the quality of flexible M&R pavement performance. Several rehabilitation strategies have been used in Western Australia; however, crack reflection through joint concrete pavement overlays has been a persistent problem.

6. CONCULSIONS

The use of full depth asphalt pavement to construct and rehabilitate heavily loaded urban roads has grown rapidly in Western Australia. The average daily traffic (ADT) has increased by 53.8% since 1994. The costs of pavement M & R has increased from year to year. The pavement crack distribution for crack types one, two, and three covered over 50% of area since 1999; however, the crack distribution for types one and three were above 85% during 1984 - 1986. The flexible asphalt pavement deterioration and damage have occurred due to the increased urban traffic loading and environmental factors.

The granular seal pavement Thomwaite Moisture Index (TMI) was low at approximately 50% during the past 20 years (1970-1990) then, rapidly decreased to below zero in 1990, indicating that the seal asphalt pavement's roughness, rutting, and cracking during these years was the result of temperature. Pavement crack construction and rehabilitation doubled each year since 1990, and flexible pavement deterioration increased by 50% since 1970. Several rehabilitation strategies have been used in Western Australia; however, crack through joint concrete pavement overlay has been a persistent problem.

The pavement predicting models using Markov Chains and Monte Carlo Simulation performed well in all categories; therefore, we recommended these methods determining probabilistic network of pavement engineering models.

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