Pavement Performance Modeling: Literature Review and Research Agenda

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Introduction

Pavement performance modeling, as an essential part of pavement management system (PMS), aims at efficiently predicting the need for maintenance, rehabilitation, or reconstruction of the pavement. These models estimate the future conditions of pavement in order to optimize the maintenance treatments, and to determine the potential results of maintenance operations on the future pavement condition. Improving the prediction accuracy of the estimation methods would result in a more productive allocation of the financial resources, significant cost savings, and improving the systematic selection of different maintenance treatments. This study provides a comprehensive review of available approaches in pavement performance modeling and discusses the advantages and disadvantages of each approach.

Research Review

A wide variety of methodological approaches have been proposed for estimating pavement performance measures. These methods can be categorized into two major groups of deterministic and stochastic approaches. These approaches are significantly different from each other in terms of the model development concepts, model formulation, and output format of the models (Li et al. 1996).

The deterministic approach in pavement performance modeling include mechanistic models, mechanistic-empirical models, and regression models (George et al. 1989). The general form of deterministic models can be formulated as follows (Li et al. 1996):

$$PCS_t = f(P_0, ESAL_{st}, H_e \text{ or } SN, M_R, C, W, I)$$

where PCS_t is the generalized pavement condition state (PCS) at year t, P_0 is the initial pavement condition state, $ESAL_{st}$ is the accumulated equivalent single axle loads ($ESAL_s$) applications at age t, H_e is the total equivalent granular thickness of the pavement structure, SN is the structural number index of total pavement thickness, M_R is the subgrade soil resilient modulus, W is the set of climatic or environmental effects, I is the interaction effects of the preceding effects, and C is the set of construction effects.

The mechanistic models include the analysis of time-series pavement condition data, and consider parameters such as surface deflection, stress, or strain in the pavement performance model (Li et al. 1996). Several pavement performance measures such as fatigue cracking, thermal (transverse) cracking, and IRI, for flexible and rigid pavements are estimated using Mechanistic theories, and guides are presented in the Applied Research Associates Inc. (2004). For example, Saleh et al. (2000) proposed a mechanistic roughness model relating the surface roughness with the asphalt layer thickness, number of load repetitions, and axle load. The model is based on the finite element structural analysis and estimates the change of surface roughness for each load repetition. The model is formylated as follows (Saleh et al. 2000):

$$IRI = -1.415 + 2.923\sqrt{IRI_0} + 0.00129\sqrt{ESAL_S} + 0.000113T$$
$$-5.485 * 10^{-10}T\sqrt{ESAL_S} + 5.777 * 10^{-12}P^4\sqrt{ESAL_S}$$

In this model, IRI_0 represents the initial roughness, P is the axle load, T is the asphalt thickness, and $ESAL_S$ is the number of load repetitions.

The mechanistic-empirical models focus on the relationship between roughness, cracking, and traffic loading. For example, in a study of flexible pavement by Queiroz (1983), mechanistic-empirical models were developed based on linear elasticity as the basic constitutive relationship for the pavement materials. Their results showed horizontal tensile stress, strain, and strain energy at the bottom of the asphalt layer. Furthermore, George et al. (1989) developed empirical-mechanistic performance models for the highways in Mississippi based on the pavement condition data. The proposed performance models were evaluated based on the rational formulation, behavior of the models, and statistical parameters. The exponential and power functions of both concave and convex shapes were identified as the statistically significant functions (George et al., 1989)

Lastly, the regression models (including linear and non-linear models) consider the associations between performance parameters such as riding comfort index, and the predictive parameters such as pavement thickness, material properties, and traffic loading (Li et al. 1996). These models have been extensively used in the past to estimate factors affecting pavement condition parameters (such as PCI, PSI, etc.). In this line of research, AASHO (1962) developed a model for estimation of the number of equivalent single axle loads applications; the independent variables were subgrade strength, layer material properties, layer thicknesses, and environmental factors. Also, Watanada et al. (1987) developed models to estimate roughness and distress on flexible pavements (such as cracking and rutting) for The Highway Design and Maintenance Standards as a factor of subgrade strength, environmental factors, traffic load and time.

Nonlinear regression models (e.g., power function) have also been used in the literature for project design (Ferreira et al., 2003; LeClerc and Nelson, 1982). Chan et al. (1997) used data collected by North Carolina department of transportation and applied a regression model to estimate a power curve of the PCR based on the pavement age for each section of the roadway. Sebaaly et al. (1995 and 1996) developed nine flexible pavement performance models for the state of Nevada, which modeled PSI as a function of material properties, traffic load and environmental factors. Similarly, Mohammed et al. (1997) developed models for the State of Indiana to simultaneously predict performance change and maintenance occurrence (i.e., decision to perform maintenance) as a function of traffic and age among others. They also accounted for the endogeneity issue by using a two-stage modeling scheme.

Prozzi and Madanat (2004) used multivariate (joint) regression to estimate riding quality (calculated as a function of pavement roughness) based on data gathered from the field and experiments. In the similar context, Ramaswamy and Ben-Akiva (1991) simultaneously modeled PSI and three different maintenance parameters (i.e., sand seal maintenance, crack filling and chip sealing activities); in addition, they accounted for the endogeneity issue. Madanat et al. (1997) used probit models to predict bridge deck deterioration while accounting for panel data effect with random-effects model. They concluded that considering the heterogeneity resulting from the panel effect improves the estimation accuracy. Prozzi and Hong (2008) used seemingly unrelated regression estimation (SURE) model to estimate IRI and rutting depth of the pavement surface while accounting for the correlation between the two variables.

Some other types of regression-based models that have been used in pavement deterioration modeling are time series regression (Smith et al., 1997), stochastic duration models (Paterson and Chesher 1986; Nakat and Madanat 2008), joint discrete-continuous models (Madanat et al. 1995), and nonlinear mixed effects models (Archilla and Madanat 2001; Archilla 2006).

Although deterministic approaches have been extensively used in the literature, they have some limitations. For example, these models cannot explain (Li et al.1997):

a) Randomness of traffic loads and environmental conditions;
b) The difficulties in quantifying the factors that substantially affect pavement deterioration;
c) The measurement errors related to pavement condition, and the bias from subjective evaluations of pavement condition.

The second group of pavement performance models includes probability-based approaches (such as Markov probabilistic modeling approaches), which are alternatives to the deterministic models that do not provide probabilistic distributions of the existing values. These models have recently received considerable attentions from researchers. Typically, a stochastic model of pavement performance curve is represented by the Markov transition process (Li et al. 1997). With full information about the "before" state of pavement, the Markov process predicts the "after" state (George et al. 1989). This model, initially transforms the pavement condition ratings into discrete condition states. Then, it defines a transition-probability matrix (TPM) to determine the probabilities that a pavement remains in the current state or changes to another one in the future. In general, both historical data or engineering judgments can be used to estimate the transition probabilities. For example, Wang et al. (1994) developed the Markov transition-probability matrices for the Arizona DOT by using a comprehensive set of observed pavement performance historical data with several initial pavement condition states. The pavement probabilistic behavior is as follows (Wang et al. 1994):

$$P_{ij}^{(n)} = \sum_{k=0}^{M} P_{ik}^{(1)} P_{kj}^{(n-1)} \qquad \forall n \leq \nu$$

$$P_{ij}^{(n)} = \sum_{i=0}^{M} \sum_{k=0}^{M} (P_{ik}^{(\nu)} P_{kl}^{(1)a})\, P_{lj}^{(n-\nu-1)} \qquad \forall n > \nu$$

where $P_{ij}^{(n)}$ is the *n*-step transition probability from condition state i to j for the entire design period (N), $M+1$ is the total number of pavement condition states, ν is the period when the rehabilitation is applied; $P_{ik}^{(\nu)}$ is the ν-step transition probability from condition state i to k under the routine maintenance; $P_{kl}^{(1)a}$ is the one-step transition probability from condition k to l at period ν; and $P_{lj}^{(n-\nu-1)}$ is the (*n*-*v*-1) step transition probability from condition l to j under the routine maintenance (Wang et al. 1994).

Markov transition method is highly useful for the network level applications where historical databases and reliable regression equations are not available (see, for example, Finn et al., 1974; Haas et al., 1994). Markov models have the advantage of using different distributions for the expected value of the dependent variable, which indicate the future performance on different sections and changes in performance regardless of time. The main drawback is that there is no guidance to the physical causes for the pavement condition deterioration, and no consideration of pavement aging on transitional probabilities (Finn et al. 1974). The primary application of this approach is the maintenance, rehabilitation, and reconstruction (M-R-R) decision-making process at the network level. Some other examples of Markov chains and Bayesian statistics in determining pavement condition measures are Butt et al. (1987) and Hong and Prozzi (2006).

Other stochastic models use the Bayesian decision model, which uses a combination of prior knowledge and information from historical data to predict posterior estimates of pavement condition deterioration by exploring the statistical characteristic of the parameters. The model parameters in this approach are assumed to be random variables (Smith et al., 1979). An application of the Bayesian approach can be found in the Canadian Strategic Highway Research Program (SHRP) studies (Haas et al., 1994). The main advantage of this method over regression analysis is that a comprehensive historical database is not required for this type of analysis.

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