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RESEARCH PAPER

Transition Probability Matrices for Flexible Pavement Deterioration Models with Half-Year Cycle Time

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Abstract Pavement performance models, a vital part of pavement management systems and life-cycle analysis, are generally divided into deterministic and probabilistic ones. Among probabilistic models, the Markov chains are attracting great attention. Transition probability matrices were developed for flexible pavement road network of the Republic of Moldova using the IRI values collected twice a year, in spring and in autumn, from 2013 to 2015. Consequently, a half-year cycle time was established. The aim of this paper is to demonstrate that it is feasible to develop transition probability matrices for an entire flexible pavement network using data from a short data collection period, and simultaneously carrying out maintenance and rehabilitation activities, if some assumptions are made. Results showed that road sections can drop two or three states in one cycle time, not only remaining in the same state or evolving to the next one, as it is usually assumed in pavement performance modeling. These models are proposed for countries in similar circumstances; a network with no new roads constructed in last decades, pavements maintained or rehabilitated in different moments during their service life, invalid or useless pavement condition data from previous years and unknown pavement structure in most of the sections.

Keywords Transition probability matrix · Markov chain · International Roughness Index · Probabilistic models · Pavement management · Pavement management system

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1 Introduction

As many other infrastructures, highway pavement deteriorates gradually, if no maintenance or rehabilitation actions are performed, due to different factors, such as, traffic loading, material aging, environmental agents, or construction deficiencies [1–3]. Since the total cost for pavement maintenance is usually greater than available funds, pavement management systems (PMS) are fundamental to identify strategies that optimize investments on the limited budgets [4–7]. The essential elements for a PMS are data collection, condition assessment, future condition prediction, and network-level and project-level maintenance and rehabilitation (M&R) planning [8, 9].

Present pavement condition can be evaluated by means of one or more indicators, measured directly from the road [10, 11]. These indicators evaluate a pavement characteristic and are expressed by a variety of indices [12, 13]. Many agencies have developed pavement performance models to forecast future road condition [7, 14]. Expected pavement characteristics over the whole life-cycle are used in life-cycle cost analysis, and M&R decisions are based on this foresight [4, 5, 15]. Consequently, a deterioration model is a key component of any advanced PMS [1, 16, 17].

The Pavement Management Guide [9] establishes four types of models that are usually employed to predict pavement conditions: deterministic, probabilistic, Bayesian and expert-based (or subjective) models. The first two models attract the greatest attention and they are broadly referred as the basic groups [11, 18, 19].

When historical condition data or sufficient survey results are available, deterministic models are used. They are obtained from a regression analysis after statistical relationships were established between two or more variables. The more independent variables introduced in the model, the more data inputs must be collected and the cost increases [20]. Nevertheless, the correlation between independent and dependent variables is not exact, determined by the best statistical fit used [14].

Unlike deterministic regression equations that predict a precise value for an index, probabilistic models estimate the probabilistic distribution of the expected value. While both models can develop the scope of predicting future condition, the probabilistic ones are able to incorporate uncertainty in pavement performance, which is assumed to be closer to reality [21]. Pavement performance is recognized to be probabilistic in nature, which requires assuming different levels of uncertainty [18, 22, 23]. Therefore, many authors over the last three decades have developed different forms of probability-based models to forecast future performance. Probably the most widely employed probabilistic model is the discrete time Markov chains, with examples in the PMS of different countries all over the world [7, 10, 24–27]. Further discussion about Markov model is provided in Sect. 2.

Pavement surface roughness is one of the most commonly used characteristic to evaluate users' level of satisfaction, assessing at the same time roadway conditions to road agencies [14, 28]. Various indices have been proposed to measure the longitudinal profile, such as Present Serviceability Rating (PSR) and Present Serviceability Index (PSI). To not depend on the longitudinal profile measurement device, the World Bank developed the International Roughness Index (IRI) using the results of the International Road Roughness Experiment performed in Brazil in 1982 [29]. Taking advantage of its stability over time and transferability throughout the world, the IRI has become a well-recognized standard for the measurement of road roughness. It applies the algorithm proposed by Sayers [30]. Normally employed units are mm/m or m/km.

Many agencies use IRI values as a measure of riding quality and it helps prioritizing M&R works [10, 14, 31, 32]. The Ministry of Transport and Road Infrastructure (MoTRI) of the Moldovan Government also has collected IRI values of main roads of the country for decades and it has been used as the only parameter to evaluate the condition of each road at project level and the global road situation of the entire system at network level.

The aim of this paper is to obtain transition probability matrices following the Markov models for the IRI values of flexible pavements of National Roads of the Republic of Moldova, making some assumptions, to be employed as a part of the National Pavement Management System to better allocation of limited budget in road preservation.

2 Probability Transition Matrices

The Markov prediction model is a stochastic process ruled by three restrictions [26]: the process is discrete in time, has a countable of finite state space and satisfies the 'Markov property' [33]. This property says that, given any past and present states, any future state of the process depends only on the present state, and it is independent on the past states [34]. It is widely assumed that the Markov property is fulfilled in pavement deterioration [35].

There are three main elements in a Markov process: the state probability vector, the cycle or step time and the transition matrix and they all are related to the number of condition states and the number of transitions.

The state probability vector, or condition probability vector, is a row vector that shows the current condition of the pavement via the proportions of pavement in each range of condition. Equation 1 represents a state vector with n states.

$$A = \{a_1, a_2, \ldots, a_i, \ldots, a_n\} \tag{1}$$

The vector must satisfy that the sum of all a_i should be equal to one, and all its elements should be nonnegative.

The step time is the time interval considered between two stages. As data collection is carried out on an annual basis due to seasonal climate change cycle, 1-year step has been usually adopted [26].

The transition probability matrix (TPM) represents the pavement deterioration with time and it is commonly denoted by P. It is a squared matrix, with n rows and n columns, where n indicates the number of states that are considered. The general form of P is given by:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}. \tag{2}$$

Each element p_{ij} expresses the probabilities of a section in condition i in stage t to shift to condition state j in stage $t + 1$ (Eq. 3).

$$p_{ij} = \mathrm{prob}[X(t+1) = j / X(t) = i] \tag{3}$$