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A competing Markov model for cracking prediction on civil structures

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ABSTRACT

Cracks on the surface of civil structures (e.g. pavement sections, concrete structures) progress in several formations and under different deterioration mechanisms. In monitoring practice, it is often that cracking type with its worst damage level is selected as a representative condition state, while other cracking types and their damage levels are neglected in records, remaining as hidden information. Therefore, the practice in monitoring has a potential to conceal with a bias selection process, which possibly result in not optimal intervention strategies. In overcoming these problems, our paper presents a non-homogeneous Markov hazard model, with competing hazard rates. Cracking condition states are classified in three types (longitudinal crack, horizontal crack, and alligator crack), with three respective damage levels. The dynamic selection of cracking condition states are undergone a competing process of cracking types and damage levels. We apply a numerical solution using Bayesian estimation and Markov Chain Monte Carlo method to solve the problem of high-order integration of complete likelihood function. An empirical study on a data-set of Japanese pavement system is presented to demonstrate the applicability and contribution of the model.

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1. Introduction

Modeling deterioration of civil infrastructures with statistical approach has been significantly documented in the past decades. One of the advantages of statistical deterioration forecasting models is the consideration of uncertainties. Uncertainties in deterioration processes of civil infrastructures can be reduced by making use of historical monitoring data (Golabi et al., 1982; Madanat and Ibrahim, 1995; Madanat et al., 1995; Golabi and Shepard, 1997; Madanat et al., 1997). Among statistical modeling models used in infrastructure asset management field, models with Markov chain have been widely applied both in research (Tsuda et al., 2006; Robelin and Madanat, 2007; Kobayashi et al., 2012b) and in practice (Thompson et al., 1998; AASHTO, 2004). In Markov deterioration forecasting models, the deterioration process of civil infrastructures is described by the transition probability among discrete condition states, which are deducted values or composite values from performance indicators of civil infrastructures (e.g. pavement service indicator (PSI) is a composite condition state, which is evaluated using performance indicators such as cracking, roughness, etc. (Shahin, 2005).

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In pavement management systems (PMSs), quality of a road surface is generally valuated by its riding quality and the skid resistance. The riding quality and skid resistance are reflected and quantified by evaluating pavement performance indicators such as cracking, rutting, and longitudinal profile (Fukuhara et al., 1990). Measured values of those indicators are monitoring data, which are stored in the data bank of the PMS. Monitoring data are used for the evaluation of pavement condition, deterioration forecasting, and supporting decision makers to select optimal intervention strategies (OISs). If monitoring data appears to possess measurement errors or bias selection of data, it is likely that accurate deterioration forecasting is flaw, as a results, decision makers would end up with intervention strategies (ISs), which are not optimal and considerable amount of benefits incurred to stakeholders (e.g. owner, users, and the public) reduced (Kobayashi et al., 2012b).

The deterioration of pavement is a complex process and therefore a single performance indicator would not be possible to perfectly capture the process (Dore and Zubeck, 2009; Kenneth, 2010) (e.g. riding quality of pavement is measured not only by cracking, but also by rutting, and longitudinal profile). Even when considering a single performance indicator alone, its deterioration mechanism and progress could be complicated. One of the typical examples that shows a complex deterioration process, which concerns one performance indicator, is the mechanism and development of cracks.

Cracking is one of the popular deterioration phenomena in the PMSs, especially in the cold regions (Dore and Zubeck, 2009). Cracks appear on the road surface in different patterns and directions. Cracks are progressed and observed in horizontal direction, longitudinal direction, or the combination of the twos. Reasons for crack initiation can be numerous (e.g. rain water infiltrated directly into pavement structures and causes the reduction in the cohesion of materials, or contraction and expansion of materials due to high fluctuation of ambient temperature). If a small crack initiated on a particular location of a pavement section, the overall deterioration process of that road section would significantly advanced with a greater speed.

In practices, when percentage of cracks on a pavement section reaches to a certain alarming level (level at which riding quality, skid resistance, and greater negative impact is anticipated, or the alarming level specified as technical standard and requirement for interventions, etc.), interventions (e.g. crack sealing and crack filling) should be implemented to prevent cracking from further advancement and also to ensure the riding quality in acceptable standards for users. However, as earlier mentioned, cracking is a complex deterioration process. Cracks progress in various directions and possibly with different levels of damages (Kaito et al., 2007). Mechanism of horizontal cracking could be different from that of longitudinal cracking. Moreover, treatments for different cracking types are not always the same. Therefore, it is important to understand the deterioration process of each crack types. This paper focuses on deterioration prediction of cracking, which is a good representation of complex pavement performance indicators, with multiple types.

Thanks to the development of high-tech inspection and measurement devices for civil infrastructures in the past decades, especially the application of high definition cameras and image processing techniques (Kawashima et al., 1984; Fukuhara et al., 1990; Mohajeri and Manning, 1991; Wang and Smadi, 2011), a small crack, even with 1 mm width, can be detected (Fukuhara et al., 1990). Basically, cracks are classified into three types: horizontal crack (or transverse crack), longitudinal crack, and alligator crack (Kaito et al., 2007; Nakat and Madanat, 2008). Despite the fact that there are different types of cracks that can be recorded and stored in the data bank of the PMS, the use of crack is often referred and represented to its general name as ‘‘crack’’ without much attention of the actual type of crack itself. In many practical cases, the percentage of crack on a road section is the representation of the percentage of a type of crack at its worst deterioration condition. The representative crack and its corresponding deterioration condition is used directly for deterioration prediction using Markov model with single dimension of condition states (e.g. a single dimension Markov model is formulated using only a vector of condition states).

There is a problem in practice that selection of representative crack to be used in Markov models is, in many cases, driven by the bias or default assumption on which cracking types and their corresponding levels of deterioration. For example, during the courses of inspections, engineers often select the cracking type with its worst deterioration condition among other cracking types to be the representative of crack for the examined road section. Under this situation, there is a bias in the selection of crack for use in the Markov deterioration model with single dimension of condition states. The practice of selecting the typical cracking type with its worst deterioration condition among other cracking types is not only considered as bias selection process, but also a competitive selection process as well. For example, in the first inspection time, horizontal crack is selected to be representative crack of the investigated road section. However, in the second inspection time on the same road section (or other inspection on different road section), longitudinal crack is selected to be the representative one.

To overcome the limitation of using Markov models with single dimension of condition states, in this paper, we proposes a multiple dimension condition states model based on the earlier research works of Tsuda et al. (2006), Kobayashi et al. (2012a), i.e. in the new model, cracks are classified into three types: horizontal crack, longitudinal crack, and alligator crack. The deterioration of each cracking type is expressed as Markov transition probabilities (m.t.p) among its damage levels. Based on cracking types and their corresponding damage levels, a multi-dimension discrete condition states are defined (Table 1).

Another important feature of the new model is that it enables the consideration of selection bias in monitoring data. Furthermore, in the new model, an efficient algorithm has been developed using Bayesian estimation approach and Markov Chain Monte Carlo simulation to derive the models parameters based on historical data.

Following section gives a brief review of the selection bias existing in monitoring and management practices. Section 3 summaries important formulation of the multi-stage exponential Markov model, which is considered as the core of the new model in this paper. Section 4 includes the mathematical formulation of the new model. Numerical solution as estimation

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