

A time series analysis framework for transportation infrastructure management

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Abstract

We present an integrated framework to address performance prediction and maintenance optimization for transportation infrastructure facilities. The framework is based on formulating the underlying resource allocation problem as discrete-time, stochastic optimal control problem with linear dynamics and a quadratic criterion. Facility deterioration is represented as a time series which provides an attractive and rigorous approach to specify and estimate performance models. The state and decision variables in the framework are continuous which allows the framework to overcome important computational and statistical limitations that do not allow existing optimization models to address various problems that arise the management of transportation infrastructure. To illustrate the advantages of the proposed approach, we conduct a numerical study where we examine the case of multiple technologies being used simultaneously to collect condition data. Specifically, we illustrate how the framework can be used to quantify the effect of the capabilities of inspection technologies, i.e., precision, accuracy and relationships, on life-cycle costs. This information can be used to compute the operational value of combining technologies, and thus, to guide in their selection based on economic criteria.

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1. Introduction

Transportation infrastructure management refers to the process of making decisions concerning the allocation of resources for the preservation, i.e., maintenance and repair (M&R), of the facilities that comprise transportation systems, e.g., pavement and bridge networks. In developed countries, where much of the transportation infrastructure is mature and portions are nearing the end of their service lives and need to be replaced, M&R decisions are increasingly important. This is due to both the far-reaching and serious negative impacts of deficient infrastructure, as well as the magnitude of M&R expenditures. In the United States, for

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example, annual M&R expenditures are on the order of tens of billions of dollars.¹ M&R decisions trade off user costs, which depend on facility condition and correspond to a fraction of the costs associated with travel time, fuel consumption, vehicle depreciation and maintenance, with M&R costs. As facilities deteriorate, the rate at which user costs accrue increases. M&R costs are incurred to improve condition, and thus, reverse the effects of deterioration. Models to support infrastructure management evaluate both the short and long-term economic consequences associated with M&R decisions. This evaluation involves processing data related to current infrastructure condition and forecasting the effect of M&R decisions on future condition.² The economic consequences of M&R decisions are then estimated with a function that maps condition forecasts to costs.

The importance of transportation infrastructure management has, over the last 40 years, motivated a great deal of research to address both the development and estimation of statistical performance models to support condition forecasting, as well as the formulation and analysis of optimization models to support M&R decision-making. Optimization models to support M&R decisions have been developed from different perspectives to address numerous applications. Extensive surveys of M&R models and applications appear in Barlow et al. (1965), McCall (1965), Pierskalla and Voelker (1976), Sherif and Smith (1981), Valdez Flores and Feldman (1989) and Dekker (1996). With few exceptions, discrete-time M&R optimization models, consistent with the periodic review nature of infrastructure management, are formulated as finite (state and action) Markov decision processes (MDPs). Bellman (1955), Dreyfus (1960), Derman (1962) and Klein (1962) were first to propose the MDP formulations for M&R problems. Golabi et al. (1982) were first to adapt the methodology to the management of transportation infrastructure.

An important assumption in the MDP framework is that the state variables, representing facility condition or its proxies, are discrete. This seemingly innocuous assumption explains an important divergence in the infrastructure management literature. On one hand, there is the development and estimation of statistical models for condition forecasting (cf. Humplick (1992); Ben-Akiva and Ramaswamy (1993); Ben-Akiva and Gopinath (1995)). These models assume that facility condition is represented by continuous variables.³ On the other hand, there is the development and estimation of transition probabilities that are used for performance prediction in a manner consistent with the MDP framework, i.e., where condition or its proxies are represented by variables defined over discrete (and ordinal) sets (cf. Madanat et al. (1997) and Mishalani and Madanat (2002)). These sets are constructed by partitioning the variables' state-spaces into mutually exclusive and collectively exhaustive sets. The partitioning process introduces forecasting errors and uncertainty, and thus, explains why using continuous variables is not only intuitively appealing, but has also been shown in empirical studies to be superior.

In addition to introducing forecasting errors and uncertainty, the use of discrete state variables leads to computational and statistical limitations that make the MDP framework unattractive to support the management of transportation infrastructure. This is because both the number of parameters that require estimation to specify the transition probabilities for the model, and the computational effort to obtain optimal M&R policies increase exponentially with the number of variables in the model. These difficulties are well-known and referred to as "the curse of dimensionality". Moreover, these problems are statistically and practically significant because there are situations where having the flexibility to add variables to a model may be desirable, e.g., in cases where multiple technologies are used simultaneously to collect condition data, or to add explanatory variables to a facility deterioration model. The former is of practical importance as the use of multiple technologies (e.g., satellite imaging, video, radar, laser and sensors) to evaluate and measure distresses on transportation infrastructure is increasingly common. Relaxing the Markovian assumption (by add-

¹ Source: Federal Highway Administration, *Highway Statistics*, tables FA3, SF2, LGF2, SF4B for various years. In 2003, the most recent year for which statistics are available, federal, state and local maintenance expenditures on highways and roads exceeded \$30 billion.

² Data related to infrastructure condition are obtained by collecting distress measurements. Examples of distresses in pavement management include roughness, type and extent of cracking, rut depth and profile, and extent of surface patching. Condition forecasts are generated with a deterioration model which is a statistical expression that relates condition to a set of explanatory variables such as design characteristics, traffic loading, environmental factors, and history of M&R activities.

³ Condition is assumed to be continuous to reflect the fact that its degradation is caused by continuous physical and chemical processes that take place at the microscopic level. Examples of these processes include fatigue due to loadings, expansion and contraction due to temperature changes, and corrosion of reinforcing steel bars in reinforced concrete structures.

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