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Safety-oriented pavement performance thresholds: Accounting for unobserved heterogeneity in a multi-objective optimization and goal programming approach

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ABSTRACT

The cornerstone of transportation infrastructure asset management is managing the physical infrastructure, with pavement preservation being one of the most critical and costly assets. Preserving pavements in an appropriate manner extends their service life, and most importantly improves motorists' safety and satisfaction while saving public tax dollars. To that end, this paper presents a methodology to estimate pavement performance thresholds that are cost-effective and safe for users. Using data from Indiana, the relationships of the three criteria, i.e., safety (accident rates), normalized treatment cost and pavement service life, with the pavement performance (roughness, rutting, overall rating, and surface deflection), road geometry, traffic characteristics and climate - are investigated and estimated. These relationships are utilized in a multi-objective optimization and goal-programming scheme to identify performance threshold values that trigger preservation treatments. These analytically determined threshold values are found to be comparable to historical thresholds and thresholds derived from experts' and users' opinions.

1. Introduction

Pavement performance measures, quantitative or qualitative, reflect the extent to which specific pavement performance objectives are met. Performance thresholds are values of the performance measures that separate the desired pavement state (or service level) from the undesired one. Appropriate thresholds are a necessary condition of reaching the desired pavement performance goals and objectives. The selection of performance thresholds will also affect the service life of the pavement and the time when it needs to be treated.

There has been an abundance of past research investigating pavement performance thresholds and their determination. The 1998 Federal Highway Administration (FHWA) strategic plan (FHWA, 1999) defined a qualitative pavement condition term: pavement serviceability rating (PSR) and the approximate corresponding quantitative term is international roughness index (IRI). As an alternate to PSR, based on the proposal of US Army Corps of Engineers, the American Society for Testing and Materials

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(ASTM) defined Pavement Condition Rating (PCR). PCR is a 0–100 numerical index system where 0 indicates extremely poor pavement condition and 100 indicates excellent pavement condition. PCR is based upon visual inspection of pavement distress by qualified and trained engineers. Rutting depth (RUT) is another measure of pavement condition which is defined as a depression or groove worn into the pavement by the travel of wheels or by erosion from flowing water. Finally, pavement surface deflection (FWD) is another pavement condition indicator which is a measure of the magnitude and the shape of the deflection and is a function of pavement structure, traffic (both type and volume), temperature and other factors. Among the several pavement performance indicators, IRI, PCR, RUT and FWD are considered in this paper. The reasons for using these pavement performance indicators are: a) they represent various aspects of pavement deterioration with respect to safety and, b) it is not well understood how the dimensions of rut depth, crack, deflection and roughness are individually responsible, especially in the context of their contributions to safety. Note that all of them are found to be significant in the analysis which clearly indicates that ignoring them would cause omitted variable bias in the models.

A number of studies used historical thresholds to develop design and preservation strategies or determine treatment effectiveness (Lamptey et al., 2005; Labi et al., 2005; Anastasopoulos et al., 2014; Warith et al., 2014, 2015). Other researchers have determined pavement performance thresholds based on users' or experts' opinion (Nair et al., 1985; Khattak et al., 1993; Ng et al., 1995; Kuemmel et al., 2001a, 2001b, 2001c; Shafizadeh et al., 2002; Shafizadeh and Mannering, 2003; Flintsch and Zaniewski, 1997). The FHWA (1999) recommended a threshold IRI value of 170 in/mi with respect to acceptable levels of road roughness by users. Shafizadeh and Mannering (2003) validated the FHWA's acceptable levels of road roughness as 170 in/mi. Hicks et al. (2000) used the average thresholds for IRI, PCR and rut depth as 108.6 in/mi, 61.2 and 0.47 in, whereas, Lamptey et al. (2005) used as 113.1 in/mi, 88.3, and 0.19 in respectively. Labi et al. (2005) reported different historical threshold values of IRI, PCR and rutting depth for interstate and non-interstate roads. However, the thresholds presented in the literature are mostly historical thresholds, or are solely based on experts' or users' opinions, or some cost factors. This paper offers analytically determined threshold values by using advanced statistical models and mathematical programming while considering safety, budget and other constraints. The models are suggestive of the need to consider safety in the evaluation of pavement performance thresholds, a perspective that is missing in the extant literature. In summary, the goal of this paper is to shed some light on the management related aspects of the various components of pavement deterioration with respect to not only budget and service life, but also to safety.

This paper develops a methodological framework for estimating specific safe and cost-effective threshold values with respect to pavement performance over time. Four pavement performance indicators are identified as crucial in determining trigger values for safety oriented pavement treatment initiation: the international roughness index (IRI), rutting, surface deflection, and pavement condition rating (PCR). The methodology is demonstrated using cost, pavement service life, and safety as the key threshold determinants, although other criteria can be easily accommodated in the proposed method.

2. Study framework

Provided that the measures of the pavement performance are appropriately determined (i.e., the performance indicators), the first step to identify the thresholds for each performance measure is to select well specified criteria. These may be utilized (in combination or not) to identify the threshold for each performance measure that initiates a pavement treatment. A starting point is to convert all performance criteria into directly comparable units, such as cost (user cost, operational cost, cost associated with environmental issues, etc.), or into dimensionless units. As such, the following three steps are proposed (Fig. 1). These steps can be generalized for any type of infrastructure asset..

First, pavement performance measures are identified. Such performance measures are considered to be appropriate when they best state the pavement condition in measurable terms. The thresholds of these measures can then be approximated based on the set of predetermined pavement performance goals and identified criteria. Second, pavement performance criteria and their relative importance are established. Example criteria considered for the approximation of the performance measure thresholds of a pavement treatment can be cost (preservation, operating, etc.), safety and security impacts, environmental and social impacts, or economic development. Finally, mathematical programming (multi-objective optimization and goal programming is used herein, as a possible approach; see Ragsdale (2007)) is used to approximate the pavement performance thresholds. As such, the decision variables are the pavement performance thresholds, the performance measures represent the objective functions, and the pavement performance criteria are the constraints.

3. Methodology

The proposed methodological framework is implemented to determine the performance thresholds that initiate pavement treatments for urban interstate flexible pavements in Indiana. Among the many indicators that measure the pavement performance, there are three that are typically used, roughness, pavement condition rating, and rut depth (Mannering et al., 2009; Sarwar and Anastasopoulos, 2016). In this study, surface deflection was also considered.

The IRI measures irregularities that can result from rutting, potholes, patching and other factors. In Indiana, the IRI is measured in inches/mile, with lower values indicating a smoother pavement (see Noyce and Bahia (2005), Shafizadeh and Mannering (2003, 2006), Anastasopoulos et al. (2011)).

Rut depth is defined as a depression worn into the pavement, in the longitudinal direction, by the traffic. It is measured as the differences in elevation on the pavement surface across the wheel path and is typically measured in inches. Excessive rutting can contribute to vehicle tracking and loss of control during maneuvering (NCHRP, 1997; Anastasopoulos et al., 2008).

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