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Mathematical programming framework for modeling and comparing network-level pavement maintenance strategies

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ABSTRACT

This study proposes a mathematical programming framework to model and quantitatively compare different maintenance strategies for network-level highway pavements. The study develops mixed-integer linear programming models for various maintenance strategies that are commonly adopted in practice and in the literature. In developing these models, traffic, pavement age, and maintenance actions with heterogeneous effects are considered. The strategies include optimization-based, worst-first, best-first, and threshold-based strategies. To demonstrate the flexibility of the framework and present a practical situation in which engineering judgment is sometimes incorporated in pavement maintenance strategies, we further develop a mixed strategy. A solution procedure combining the off-shelf mixed-integer programming solver, greedy algorithms, and Lagrangian relaxation algorithms is developed to efficiently solve the models. Finally, a numerical example of a hypothetical network is established. Different maintenance strategies are applied given different budget levels, traffic loadings, and initial pavement conditions. The results of the numerical example are reasonable, and they provide insights into the efficient implementation of maintenance strategies. Results also show that the framework has the potential to aid maintenance agencies in evaluating maintenance strategies before they are implemented, improving pavement conditions, and reducing the budget for transportation infrastructure.

1. Introduction

The condition of highway infrastructure is vital to the economic development and life quality of citizens. Under continuous wear by traffic and weather, highway pavements deteriorate and require maintenance. To improve the conditions of highway pavements over their lifespans, scholars have introduced the concept of life-cycle management to the decision-making process for pavement maintenance. The goal of life-cycle management is to minimize the life-cycle costs for maintenance and users under budgetary and other operational constraints. In practice, transportation agencies prefer maintenance strategies that are easy to implement and are intuitive over those that are complicated and difficult to understand (Task Force on Pavements and the AASHTO, 2001). The common pavement maintenance strategies that have been adopted in practice or studied in the literature include worst-first (WF), best-first (BF), threshold-based (THR), and optimization-based (OPT) strategies. They are defined, and the related studies are reviewed as follows. In the literature, maintenance strategies are also called maintenance policies.

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- OPT strategy: The OPT strategy is defined as using optimization methods to generate optimal or near-optimal maintenance plans for pavements. Numerous studies in the literature have adopted this strategy (Fwa et al., 1996; Lee and Madanat, 2015; Zhang et al., 2017). For example, Fwa et al. (1996) considered the strategy as a mathematical programming problem and solved the problem with a genetic algorithm. These optimization methods usually generate detailed plans of the types and magnitudes of maintenance actions for each pavement in each time period. The advantage of the strategy is that pavement conditions and the efficiency of budget utilization are optimized in theory. As discussed in Task Force on Pavements and the AASHTO (2001), detailed, pre-determined plans are not well accepted by transportation agencies because they are not robust, difficult to interpret, and incompatible with the workflow in practice.
- WF strategy: In the WF strategy, the pavement sections are sorted according to their conditions. The pavement sections in poor condition are maintained before the ones in good condition. The maintenance covers as many pavements as possible until the budget is exhausted. The advantage of the strategy is that it is intuitive and easy to implement. It might be the most commonly used strategy in practice (Zimmerman and Peshkin, 2003a; 2003b). Mijuskovic et al. (1995) and Abaza et al. (2004) both formulated the WF strategy within a discrete-state Markov chain framework. Vitillo et al. (2012) conducted a performance and economic analysis for the WF strategy.
- BF strategy: In the BF strategy, the pavement sections are also sorted according to their conditions. The pavement sections in good condition are maintained before the ones in poor condition. The maintenance covers as many pavement sections as possible until the budget is exhausted. The motivation of the strategy is to conduct preventive maintenance when pavements are in good condition and before they deteriorate to poor condition, which requires intensive maintenance actions. Zimmerman and Peshkin (2003a) and Zimmerman and Peshkin (2003b) stated that integrating preventive maintenance into pavement management could be beneficial in the long term. Mijuskovic et al. (1995) formulated the BF strategy with a Markov chain framework. Vitillo et al. (2012) evaluated the BF strategy using a performance and economic analysis.
- THR strategy: The strategy of threshold-based maintenance is that a pavement receives maintenance when its condition triggers given thresholds. In practice, the strategy fits the workflow of transportation agencies well and is thus also widely adopted. In the academic literature, it has been found that the optimal maintenance plans for a pavement actually follow a threshold structure under some conditions (Ouyang and Madanat, 2006). One of the drawbacks of the current practice of threshold-based pavement maintenance is that maintenance thresholds are often determined on the basis of engineering judgment (Khurshid et al., 2011). Without a systematic approach, the quality of these thresholds is difficult to evaluate and could be far from their optimal values. The threshold structure of the maintenance process has been studied in the literature for a single facility (Ouyang and Madanat, 2006; Gu et al., 2012; Hajibabai et al., 2014) and for multiple facilities (Sathaye and Madanat, 2011; 2012; Chu and Chen, 2012; Lee and Madanat, 2014; Lee et al., 2016).

This review indicates that WF, the most widely used strategy, and BF strategies are rarely studied. Among the studies related to WF and BF strategies, Mijuskovic et al. (1995) and Vitillo et al. (2012) compared the performance of the two strategies under different budget levels and initial pavement conditions. However, their conclusions are not fully comparable with those of the current study for the following reasons. First, their prediction of pavement conditions was performed using significantly different methodologies. A discrete-state Markov chain framework was adopted in Mijuskovic et al. (1995). Pavement conditions must be discretized in the discrete-state Markov framework, and this procedure leads to reduced accuracy of the inspection data. Moreover, the pavement deterioration mechanism and maintenance strategies considered in the Markov framework are usually limited. In Vitillo et al. (2012), pavement deterioration was predicted with a pavement condition index (PCI) versus age curve. Second, the available maintenance actions and their effectiveness differed in these previous studies. The comparison of WF and BF strategies in Vitillo et al. (2012) was inconclusive. Because the available maintenance actions and their effectiveness were not clearly defined, the reason BF and WF strategies exhibit a similar performance is unclear and thus the results of Vitillo et al. (2012) cannot be compared with those of other studies. According to Mijuskovic et al. (1995), the least-effective maintenance action applicable to pavements in good conditions is “surface treatment or thin layers.” Mijuskovic et al. (1995) concluded that the BF strategy is preferred over the WF strategy because the least-effective maintenance action is inexpensive and effective in improving pavement conditions. As indicated in Section 2.1, the least-effective maintenance action considered in this study was a fog seal; it only slows down deterioration but does not improve the pavement condition, a scenario that differs fundamentally from the assumption made in Mijuskovic et al. (1995). Thus, the results of the two studies are not directly comparable.

The optimization of pavement maintenance is frequently conducted under the OPT and THR strategies. In addition to the Markov chain, a variety of methodologies have been proposed for the OPT and THR strategies. The major categories of the assumptions adopted in these optimization models include facility- and network-level, continuous- and discrete-time, continuous- and discrete-state, Markovian- and non-Markovian deterioration, and the set of available maintenance actions. As the above maintenance strategies are studied individually under different assumptions, they have never been compared quantitatively. Another point that has often been overlooked in these studies is that although the maintenance can be optimized under a certain strategy, the resulting pavement conditions relative to the “optimal” condition that can be achieved without any form of strategy are still unknown. Without a comprehensive and rigorous comparison between available strategies, transportation agencies have no basis for choosing the appropriate maintenance strategy other than qualitative factors, such as the ease of implementation and interpretation. The above issues highlight the need for a framework for evaluating and comparing pavement maintenance strategies.