Transportation Research Part B 105 (2017) 378–400

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

A general iterative approach for the system-level joint optimization of pavement maintenance, rehabilitation, and reconstruction planning

Le Zhang[a], Liangliang Fu[a], Weihua Gu[a,*], Yanfeng Ouyang[b], Yaohua Hu[c]

[a] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region
[b] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, USA
[c] College of Mathematics and Statistics, Shenzhen University, China

ARTICLE INFO

Article history:
Received 28 June 2017
Revised 19 September 2017
Accepted 20 September 2017

Keywords:
System-level MR&R planning
Budget constraints
Preventive maintenance model
Lagrange multiplier
Quasi-Newton methods

ABSTRACT

We formulate a general bottom-up model for the joint optimization of maintenance, rehabilitation, and reconstruction (MR&R) schedules for a system of heterogeneous pavement segments under budget constraints. The objective is to minimize the total costs incurred to both the highway users and the pavement management agency. We propose a Lagrange multiplier approach together with derivative-free quasi-Newton algorithms to solve the problem for two scenarios: i) with a combined budget constraint for all the treatments; and ii) with one budget constraint for each treatment. The system-level solution approach has the following merits: i) it can be applied to problems with any forms of segment-level models for user and agency costs, deterioration process, and treatment effectiveness, given that the solution to the segment-level problem is available; ii) under the combined budget constraint, it ensures that the optimality gap of the system-level solution is bounded by a term that depends upon the optimality gap of the segment-level solutions; and iii) it exhibits linear complexity with the number of segments.

At the segment level, a new maintenance effectiveness model fitted on empirical data is proposed and incorporated into the MR&R optimization program. A greedy heuristic algorithm is developed, which greatly reduces the computation time without compromising the solution quality. Combining the system- and segment-level models and solution algorithms, we examine a batch of numerical cases. The results show considerable cost savings from the incorporation of maintenance, and from jointly optimizing the use of a combined agency budget. A number of managerial insights stemmed from the numerical case studies are discussed, which can help highway agencies formulate more cost-efficient MR&R plans and budget allocation.

1. Introduction

1.1. Background

Surface roads constitute the world's largest transportation infrastructure network. For example, the United States alone has over 4 million miles of roads, which served over 3 trillion vehicle-miles in the year of 2015 (CBO, 2016; ASCE, 2017). The

* Corresponding author.
E-mail address: weihua.gu@polyu.edu.hk (W. Gu).

https://doi.org/10.1016/j.trb.2017.09.014

constantly increasing vehicle mileage creates ever-growing pavement deterioration and aging, and the deteriorated pavements in turn incur higher costs for vehicle repair, traffic congestion, and extra fuel consumption and emission, among others. This imposes a great challenge for highway agencies to optimally plan MR&R activities for the road pavements, especially given that a large portion of the pavements are already in poor conditions, and that the available budget rises consistently slower than the MR&R costs needed (ASCE, 2017).

Conventionally, a highway agency's long-term planning decision considered only rehabilitation and reconstruction activities. However, in recent decades many studies have reported the sizable effects of preventive maintenance activities (e.g. chip seal, microsurfacing) on slowing down the pavement's deterioration and extending its service life (Chong, 1989; Ponniah and Kennepohl, 1996; Labi and Sinha, 2003; Mamlouk and Dosa, 2014). These cheap maintenance treatments are particularly attractive for highway agencies under budget pressure. However, most highway agencies do not have well-established preventive maintenance planning mechanism (Peshkin et al., 2004). Hence, an optimization model for the joint planning of not only the rehabilitation and reconstruction activities, but also the preventive maintenance activities, is highly desired. Unfortunately such a model is missing in the literature to the best of our knowledge. We next examine the strength and deficiency of existing studies in the realm of MR&R planning optimization.

1.2. Literature review

Studies in this realm commenced by optimizing the rehabilitation planning of a single segment (Friesz and Fernandez, 1979; Fernandez and Friesz, 1981; Markow and Balta, 1985). A variety of segment-level optimization models have thenceforth been developed, which are characterized by the pavement deterioration process (memoryless or history-dependent), the number of treatments, and whether the time and/or pavement states are modeled by discrete or continuous variables. Table 1 summarizes the modeling features and solution approaches of select segment-level studies. Of note is that the table shows a general trend of evolution from simpler models (with memoryless deterioration process, single treatment, and discrete variables) to more complicated but realistic ones (with history-dependent deterioration process, multiple treatments, and continuous variables). This is partly thanks to the development of more sophisticated approaches for seeking global optimal solutions, e.g. calculus of variation (Ouyang and Madanat, 2006; Lee and Madanat, 2014b). The most complicated (and realistic) segment-level model so far seems to be Lee and Madanat (2014a), which optimized the planning of all the three treatments (maintenance, rehabilitation and reconstruction) with a history-dependent deterioration process. However, the solution relied on the technique of approximate dynamic programming, which requires high computation time and thus may not be suitable for large-scale systems of pavements. Another finding is that the solution approaches in Table 1 are usually problem-specific. This means a solution approach cannot be applied directly to solve a different version of the segment-level optimization model. Finally, the maintenance effectiveness models used in segment-level MR&R optimization are unrealistic. For example, the maintenance model used by Gu et al. (2012) and Lee and Madanat (2014a, b) was hypothesized with ungrounded parameter values. As a result, the optimal MR&R plan obtained by Lee and Madanat (2014a) showed that greater

Table 1
Select studies on segment-level optimization of MR&R planning.

Study	Deterioration process	Number of treatments	Discrete/Continuous time or pavement state	Solution approach
Golabi et al. (1982)	memoryless	1	discrete	linear programming
Carnahan et al. (1987)	memoryless	1	discrete	dynamic programming
Fwa et al. (1994)	memoryless	1	discrete	genetic algorithm
Durango-Cohen (2007)	memoryless	1	hybrid	dynamic programming
Friesz and Fernandez (1979)	memoryless	1	continuous	optimal control
Fernandez and Friesz (1981)	memoryless	1	continuous	optimal control
Tsunokawa and Schofer (1994)	memoryless	1	continuous	optimal control with trend curve approximation
Li and Madanat (2002)	memoryless	1	continuous	using the memoryless property
Ouyang and Madanat (2006)	memoryless	1	continuous	calculus of variation
Madanat (1993)	memoryless	3	discrete	dynamic programming
Madanat and Ben-Akiva (1994)	memoryless	3	discrete	dynamic programming
Gu et al. (2012)	memoryless	2	continuous	numerical method based on optimal conditions from Ouyang and Madanat (2006)
Rashid and Tsunokawa (2012)	memoryless	3	continuous	optimal control with trend curve approximation
Tsunokawa and Ul-Isalm (2002)	history-dependent	1	discrete	exhaustive search
Tsunokawa et al. (2006)	history-dependent	1	discrete	gradient search
Deshpande et al. (2010)	history-dependent	1	discrete	multi-objective genetic algorithm
Bai et al. (2015)	history-dependent	1	hybrid	dynamic programming
Miyamoto et al. (2000)	history-dependent	2	discrete	genetic algorithm
Lee and Madanat (2014a)	history-dependent	3	hybrid	dynamic programming
Lee and Madanat (2014b)	history-dependent	3	continuous	calculus of variation