



Incorporating network considerations into pavement management systems: A case for approximate dynamic programming



Aditya Medury^{a,*}, Samer Madanat^b

^a Dept. of Civil and Environmental Engineering, Univ. of California, Berkeley, 116 McLaughlin Hall, Berkeley, CA 94720, United States

^b Dept. of Civil and Environmental Engineering, Univ. of California, Berkeley, 110 McLaughlin Hall, Berkeley, CA 94720, United States

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ABSTRACT

The objective of infrastructure management is to provide optimal maintenance, rehabilitation and replacement (MR&R) policies for a system of facilities over a planning horizon. While most approaches in the literature have studied the decision-making process as a finite resource allocation problem, the impact of construction activities on the road network is often not accounted for. The state-of-the-art Markov decision process (MDP)-based optimization approaches in infrastructure management, while optimal for solving budget allocation problems, become internally inconsistent upon introducing network constraints. In comparison, approximate dynamic programming (ADP) enables solving complex problem formulations by using simulation techniques and lower dimension value function approximations. In this paper, an ADP framework is proposed, wherein capacity losses due to construction activities are subjected to an agency-defined network capacity threshold. A parametric study is conducted on a stylized network configuration to infer the impact of network-based constraints on the decision-making process.

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1. Introduction

The objective of transportation infrastructure management is to provide optimal maintenance, rehabilitation and replacement (MR&R) policies for a system of facilities (roads, bridges, tunnels, etc.) over a planning horizon. While most approaches in the literature have studied it as a problem of optimal allocation of limited financial resources, the interdependence between facilities, as introduced by a unifying network configuration, is often not accounted for. The implementation of MR&R activities on road networks can result in significant delays to travelers due to loss in network capacity, detours, etc. According to one estimate, more than 60 million vehicles per hour per day of capacity were lost due to work zone activity on the National Highway System over a two week period in the United States in 2001 (Wunderlich and Hardesty, 2003). Given that the impact of scheduling work zones, especially in saturated traffic flow conditions, can be severe, it is important to systematically address and incorporate these user concerns within the decision-making process.

The recognition of an over-arching network configuration introduces several challenges, as well as opportunities, for system-level MR&R decision-making. In this paper, network-induced inter-facility interactions are examined in the context of structural interdependence among facilities, wherein MR&R activities on individual facilities leads to a cumulative effect on the capacity of the network.

* Corresponding author. Tel.: +1 510 529 8645.

E-mail addresses: amedury@berkeley.edu (A. Medury), madanat@ce.berkeley.edu (S. Madanat).

Existing system-level MR&R decision-making paradigms do not adequately account for the impacts of construction activities on the road traffic. Consequently, the measures taken by agencies to mitigate travel time increases occur at the project-level, i.e., once the MR&R activities have already been determined. However, in order to effectively address these user concerns at the system-level, the network configuration can provide insights into determining how each facility affects the system performance (such as the capacity or connectivity of the network).

For instance, consider a system comprising of four road segments. Without explicitly identifying the individual pavements within the network, it is impossible to gauge the impact of the proposed maintenance activities. However, it can be seen that if all the facilities in the system are arranged in series, as shown in Fig. 1a, then each facility is critical for the functioning of the network. As a result, a partial/complete road closure during peak hours of traffic will adversely affect the traffic. In comparison, if all the road segments are in parallel (Fig. 1b), the network exhibits a very high level of redundancy. Consequently, potential road closures can be accommodated by rerouting traffic through parallel routes. A more realistic network would perhaps comprise of links in both series and parallel, as shown in Fig. 1c. Hence, in order to better mitigate the impact of construction activities on road users, the identification of optimal system-level MR&R policies should capture the relation between the road segments in a systematic manner.

2. Literature review

System-level MR&R decision-making paradigms in the transportation infrastructure management literature can be differentiated on the basis of their underlying assumptions of continuous/discrete condition state variables, continuous/discrete time horizons and/or deterministic/stochastic rates of deterioration. Continuous-time methods are useful for providing high-level strategic policies, but are not well suited for a detailed, tactical planning of MR&R activities. For such analysis, discrete-time methods are more extensively used in the literature. For a more detailed discussion of continuous-time frameworks, readers are encouraged to refer to Ouyang and Madanat (2006) and Sathaye and Madanat (2011), among others.

Discrete-state, discrete-time Markov decision process (MDP)-based frameworks have been widely used in infrastructure management, especially in the context of uncertainty in the underlying facility performance models. One of the first instances of using MDP frameworks for infrastructure management was the development of the Arizona pavement management system (Golabi et al., 1982). The LP-based approach utilized *randomized* policies to effectively accommodate budget constraints within the MR&R decision-making problem. Randomized policies are probabilistic in nature, wherein the optimal policy for a facility in a given condition state is defined as a probability distribution function across two or more actions. The interpretation of randomized policies in a network setting relies on the assumption that all the facilities in the system deteriorate homogeneously. Consequently, such an approach can also be referred to as a *single-dimensional MDP* problem. Other applications of this framework include the bridge management system, Pontis (Golabi and Shepard, 1997), Smilowitz and Madanat (2000), Kuhn and Madanat (2005) and Madanat et al. (2006).

Randomized policies are shown to be optimal in a constrained MDP setting (Kallenberg, 1994). However, one of the limitations of the approach is that due to the probabilistic nature of the solution, randomized policies do not directly translate into facility-specific recommendations. In order to address this issue, Medury and Madanat (2013) extended the LP-based approach to provide facility-specific policies, while retaining the optimality of the original problem formulation.

Other MDP-based optimization frameworks have focussed on obtaining deterministic, facility-specific policies. Such approaches rely on decomposing the system-level MDP problem into two-stage (facility-level and system-level) problems

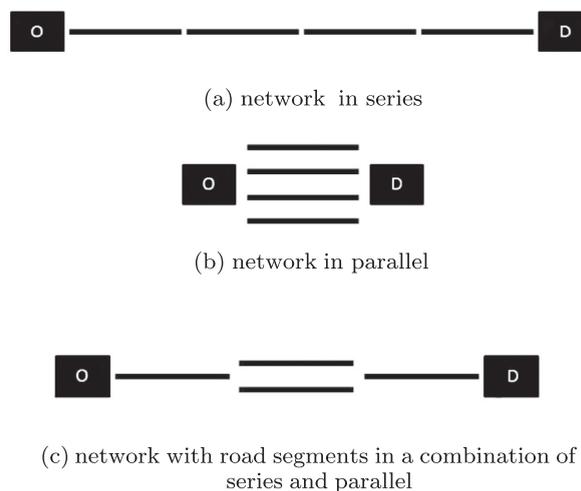


Fig. 1. Different types of network configurations.

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