Structural Safety 67 (2017) 96–104

Contents lists available at ScienceDirect

Structural Safety

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

Bridge network maintenance prioritization under budget constraint

Weili Zhang[a], Naiyu Wang[b,*]

[a] Department of Industrial and Systems Engineering, University of Oklahoma, USA
[b] School of Civil Engineering and Environmental Science, University of Oklahoma, USA

ARTICLE INFO

Article history:
Received 28 March 2017
Accepted 1 May 2017

Keywords:
Transportation network
Travel time
Optimal maintenance scheduling
Prioritization
Optimization

ABSTRACT

This study develops a decision model to assist bridge authorities in determining a preferred maintenance prioritization schedule for a degraded bridge network in a community that optimizes the performance of transportation systems within budgetary constraints at a regional scale. The study utilizes network analysis methods, structural reliability principles and meta-heuristic optimization algorithms to integrate individual descriptive parameters such as bridge capacity rating, condition rating, traffic demand, and location of the bridge, into global objective functions that define the overall network performance and maintenance cost. The performance of the network is measured in terms of travel time between all possible origin-destination (O-D) pairs. In addition to the global budgetary constraint, the optimization is also conditioned on local constraints imposed on traffic flow by insufficient load carrying capacity of deficient bridges. Uncertainties in traffic demands, vehicle weights and maintenance costs are also considered in the problem formulation. Two project priority indices are introduced – the static priority index (SPI), defined as a function of the difference in network travel time between block running (with reduced load carrying capacity before repair) and smooth running (design-level load carrying capacity after repair) of a bridge, and the dynamic priority index (DPI) defined as the likelihood of a bridge being selected for repair when the budget is fixed and the uncertainties governing the performance of the transportation network are considered. Finally, this decision model is illustrated with a hypothetical network with 160 bridges.

1. Introduction

Highway bridges deteriorate in service as a result of a wide variety of events (e.g. floods, heavy truck traffic, aggressive environmental conditions, industrial action, and inadequate maintenance), making bridges the vulnerable links in transportation networks. According to the Federal Highway Administration's 2013 National Bridge Inventory Database (NBI), approximately 25 percent of the nation's bridges are either structurally deficient or functionally obsolete, causing significant social and economic impact to communities. Resources allocated to the maintenance of transportation networks in the United States (and societies worldwide) typically are limited, and seldom are sufficient to maintain in-service performance levels required for the infrastructure system. As stated in the 2013 ASCE Infrastructure Report Card, every year over $12 billion has been spent on the maintenance and rehabilitation of the nation's bridges, while the annual investment that would be necessary to improve the current condition of existing highway bridges has been estimated to be $20 billion. Bridge managers are facing ever-increasing challenges in prioritizing expenditures to maintain safety and functionality of deteriorating bridge systems. A decision-making framework that maximizes the functionality of a regional transportation system while ensuring that individual bridges conform to the minimum safety requirements stipulated by Association of State Highway and Transportation Officials (AASHTO) [2] is essential.

The study described in this paper is aimed at developing a decision model for bridge network management and project prioritization that enables the operational performance of a transportation system to be optimized, given the safety requirements mandated by AASHTO and the inevitable budgetary constraints imposed by limited resources. The study utilizes modern network analysis methods, structural reliability principles and meta-heuristic optimization algorithms to integrate individual descriptive parameters, such as bridge capacity rating, condition rating, traffic demand, and location of the bridge in the network, in global objective functions that define the network performance and maintenance cost. The network performance is measured in terms of travel time, computed based on the traffic demand within the network between all possible origin/destination (O-D) pairs. In addition to the overall network budgetary constraint, this optimization is also conditioned on the local traffic flow constraints due to insufficient load carrying capacity of structurally

---

* Corresponding author.
E-mail address: naiyu.wang@ou.edu (N. Wang).

http://dx.doi.org/10.1016/j.strusafe.2017.05.001
0167-4730/© 2017 Elsevier Ltd. All rights reserved.

deficient bridges that has been load posted. Uncertainties in traffic demands, vehicle weights and bridge maintenance costs are considered in the problem formulation.

The rest of the paper is organized as follows. Firstly, we review related literature and present the highlight of this study. Secondly, we summarize the bridge safety criteria (bridge condition rating and capacity rating) and introduce the bridge network efficiency measure (travel time) used in this study. A complete mathematical formulation of the decision optimization is then presented and two project prioritization mechanisms are introduced. The application of the overall developed methodology is illustrated using a hypothetical transportation network with 160 bridges, followed by concluding remarks.

2. Background

Finite resources for renewal/replacement of highway bridges within a transportation system must be distributed strategically among all bridges to optimize the performance of the system as a whole. Bridge maintenance programs in the past, however, usually have been developed to optimize the life-cycle cost (LCC) of individual bridges without considering the interaction between these bridges in making the transportation system as a whole functional. In reality, the condition of one bridge, e.g. deterioration, failure, maintenance priority and the timing of expenditure, may very well affect the performance and maintenance scheduling of neighboring bridges. Adopting a system perspective to assess the role of bridges serving a community will add an additional dimension to conventional bridge maintenance decisions by placing such decisions in the overall context of enhancing reliability and functionality of the entire transportation system.

In the past decade, several research studies have investigated bridge maintenance strategies considering bridges collectively as integral parts of a network. Frangopol and his co-researches have made number of important contributions to the bridge network maintenance planning. Liu and Frangopol [30–32] introduced a bridge reliability importance factor that relates individual bridge reliability to the reliability of the bridge network, and proposed a comprehensive mathematical model for evaluating the overall performance of a bridge network based on probabilistic analyses of network connectivity, user satisfaction, and structural reliability of the critical bridges in the network. Their later study [33] optimized bridge network maintenance based on a multi-objective approach using genetic algorithms. A thorough review of their work can be found in Frangopol [20]. Orcesi and Cremona [40] proposed a bridge network management approach using visual inspection data and Markov chains. These studies have based maintenance and project prioritization decisions on the LCC analysis over the projected service life of the bridges.

Although LCC analysis is the most mature and broadly understood decision method [19,35,10,4,17,47,39], problems exist in applying LCC analysis to bridge network maintenance. First, there are large uncertainties associated with LCC analysis due to a lack of supporting databases on cost estimation, especially when deterioration and natural hazards and their consequences are considered. Second, most decision makers for highway infrastructure are government officials, who are driven by public perceptions of their political performance and seldom have the motivation to make decisions based on the analysis that optimizes the outcome for a time span of 50–75 years [14]. Third, available budgets for bridge network maintenance vary from year to year, depending on social, economic and political factors, which often impose constraints on bridge maintenance-related decision making.

Rather than using LCC as a criterion for decision, several studies have attempted to obtain optimal bridge maintenance strategies by maximizing the operational performance of a transportation network. Current network performance indicators can be divided into two categories. The first one is network topology-based. Connectivity reliability (also known as reachability reliability) is defined as the probability that there exists at least one path between O-D pairs of interest and has been proved as a #P-complete problem [43]. Liu and Frangopol [30,33] applied genetic algorithm to maximize the connectivity reliability between a single O-D pair and simultaneously minimize associated maintenance cost. Bocchini and Frangopol [8] and Hu and Madanat [24] later expended the model to multiple O-D pairs. When a network is disrupted by extreme natural hazards (earthquakes, floods, etc.) and its links fail in unfavorable configurations, the network becomes disconnected and the connectivity reliability is often used to evaluate post-disaster network performance. Even when fully connected, however, a network may still fail to provide an adequate level of service to the local community. In such cases, the second type of performance metrics that is network functionality-based becomes more appropriate. Flow capacity reliability and travel time reliability often have been proposed to assess the efficiency of transportation network functionality. Chen et al. [11,12] defined the flow capacity reliability as the probability that the network can serve a certain travel demand using a user equilibrium model, and investigated its sensitivity to the capacity variations of individual links. Nojma [37] presented a prioritization method using maximum flow as the network performance metric to find Birnbaum's importance measure for each network component. Sanso and Milot [45] defined the transportation network performance in terms of its ability to transport passengers from their origins to destinations in a reasonable amount of time. Other previous studies on capacity reliability [15,26] and travel time reliability [6,7,5] provided useful tools to analyze network traffic equilibrium, but in these studies the links (bridges) of the network were modeled as either fully functional or completely closed. In reality, however, many structurally deficient bridges are in neither status; rather, they continue to operate with a reduced load (flow) capacity imposed by lane closures or load posting limits.

In this paper, our objective is to inform decision-making at point-in-time regarding project prioritization that maximizes the operational performance of a transportation system measured in terms of travel time under budgetary constraints. The major contributions of the paper include: (a) the formulation of the bridge maintenance optimization that integrates bridge safety, operation efficiency measured by network travel time, uncertainty of the network, maintenance cost and budgetary constraints; (b) the modeling of local constraints imposed by reduced load capacity of deficient bridges in a transportation system, realistically reflecting the operational status of degraded bridge networks; (c) the application of a metaheuristics method (binary particle swarm optimization algorithm) to provide solutions to the mixed integer optimizations problem formulated for large networks; and (d) the introduction and comparison of the two priority indices - static priority index (SPI) and dynamic priority index (DPI).

3. Bridge network safety and functionality

3.1. *Safety criteria for individual bridges – Bridge condition rating and capacity rating*

Safety is the first priority among all bridge performance objectives. In current engineering practice, bridge condition rating (on the scale of 0–9), assigned according to National Bridge Inspection Standard (NBIS) (summarized in Table 1), is widely used in bridge condition assessment in the US and is an overall measure of the physical condition of highway bridges. Bridge engineers assign condition ratings to existing bridges based on inspection data, traffic survey and highway types. The NBIS stipulates that a bridge