CTIPS Center for Transformative Infrastructure Preservation and Sustainability
USDOT Region 8 University Transportation Center

Maintenance Optimization System to Maximize Performance of Bridges within Available Budget

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University

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Research Needs

Effective maintenance planning for bridges is crucial for maintaining their performance, safety, and minimizing maintenance costs. Timely implementation of interventions can improve the performance of bridges and avoid the need for costly interventions. However, bridge maintenance is often delayed due to inadequate planning and/or budget allocation, as well as resource constraints such as funding. For example, the American Society of Civil Engineering issues a Report Card that evaluate the performance of infrastructure systems, providing a comprehensive metric of the condition and needs of the nation's critical infrastructure. In this Report Card, Bridges in Colorado received "C+" grade "Mediocre, requires attention", this is slightly higher than the national average of "C" grade for all bridges in the USA.

In this context, there is a pressing need to develop an optimization system to identify maintenance interventions for bridges to maximize their performance within the constraints of available budgets. Such a system would utilize advanced analytics and data-driven insights to prioritize maintenance tasks based on their urgency and impact, ensuring that limited resources are allocated in the most effective manner. For instance, in Colorado, the ASCE Report Card reveals that 5.4% of 8,786 bridges are rated structurally deficient (SD) (4.1% by deck area). By applying an optimization system, Colorado could strategically manage its bridge maintenance to enhance safety and efficiency, ultimately extending the lifespan of its infrastructure while complying with budgetary constraints.

In terms of existing literature and models, a number of studies focused on budgeting methods for bridge maintenance prioritization to support decision makers in planning and prioritizing maintenance and renovation activities (Amini et al., 2016; Contreras-Nieto et al., 2019; Das & Nakano, 2021; Echaveguren & Dechent, 2019; Fitriani et al., 2019; Gokasar et al., 2022; Hadjidemetriou et al., 2022; Kim et al., 2020; Valenzuela et al., 2010; Wakchaure & Jha, 2011). For example, Zhang et al. developed a bridge network model to prioritize maintenance interventions for a group of bridges while taking into account budget limitations. They created two performance indices: (1) Static Priority Index (SPI), which assesses the performance of networks based on travel time between all possible origin-destination pairs within the network, and (2) Dynamic Priority Index (DPI), which evaluates the performance of networks while considering the uncertainties affecting the performance of the transportation network. The findings of the case study indicated that the DPI is a more effective ranking system compared to the SPI (Zhang & Wang, 2017). Similarly, Contreras-Nieto et. al. developed a Multi-criteria Decision Making Model (MCDM) for prioritizing bridge maintenance tasks and budget allocation. They utilized Analytic Hierarchy Process (AHP) to rank the maintenance activities based on bridge experts' perceptions of the relative importance of maintenance interventions on the deck, substructure, superstructure, and score in terms of bridge resiliency, riding comfort, safety, and serviceability. The results of the case study indicated that bridge decks are the most critical component when considering safety, serviceability, and comfort, and that the substructure is of highest importance when considering the resiliency criterion (Contreras-Nieto et al., 2019). Similarly, Das et al. proposed a method for prioritizing bridge maintenance interventions using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The approach considered criteria such as bridge condition index, delay cost, and accessibility. The case study results indicated that the failure of higher priority bridges can result in higher social costs (Das & Nakano, 2021). Other research works considered maintenance and social costs as well as environmental impacts in order to prioritize bridge maintenance interventions. For example, Gokasar et al. developed a hybrid MCDM model to rank bridge maintenance projects based on various criteria such as cost effectiveness, physical condition, social impact for travelers, and CO2 emissions. They combined fuzzy weighted aggregated sum product assessment and TOPSIS to prioritize bridge maintenance projects. The case study results demonstrated that the environmental impacts of bridge maintenance projects can significantly influence the ranking of maintenance alternatives (Gokasar et al., 2022).

Although the aforementioned studies have significant contributions in presenting models for maintenance prioritization, they tend to focus on short-term bridge maintenance and therefore are not capable of generating long-term maintenance plans that optimize the performance of bridges within available budgets. In addition, several studies are limited to the performance of one bridge instead of focusing on bridges in a region to maximize their performance with available budget. Furthermore, the existing studies and systems do not consider prediction modes for bridge element deterioration and maintenance intervention costs in identifying and prioritizing maintenance interventions to maximize bridge performance within available budget.

Research Objectives

The primary objective of this research is to enhance the operational efficiency of bridges by developing a maintenance optimization system that will enable State DOTs to generate an optimal maintenance intervention schedule for bridges to maximize their performance within available budget constraints. The maintenance plans will specify repair, replacement, and preservation interventions to be performed within each year of a user-defined planning period (e.g., 4 years). The maintenance system can be used by decision makers to generate updated maintenance plans periodically such as annually. To achieve this goal, the maintenance optimization system will:

- Generate predictions of bridge conditions as well as bridge maintenance costs based on historical data of bridge conditions.
- Develop an optimal bridge maintenance schedule for a user-defined maintenance period and annual maintenance budget where overall performance of bridges is maximized.

Research Methods

To achieve the objectives of this research, our approach involves two primary phases:

*1) **Develop machine learning (ML) models for condition and cost forecasting***

Initially, the team will develop new ML models to predict the condition and costs associated with maintenance interventions for various bridge components. We will utilize advanced algorithms to analyze patterns from historical maintenance data to forecast condition and future costs. This phase involves an extensive collection of historical data on bridge conditions and maintenance interventions. The team will leverage available historical data such as the National Bridge Inventory (NBI) and National Bridge Elements (NBE) on bridge conditions to predict deterioration of bridge elements over time. After data collection, relevant features will be selected, and comprehensive preprocessing will be conducted to prepare the data for analysis. We will explore a range of ML algorithms—from basic regression models to more complex deep learning (DL) time series forecasting models. These models will be trained and fine-tuned using designated training and validation datasets. The effectiveness of these models will be assessed using precise metrics to ensure accuracy and reliability. Once validated, these models will serve as predictive tools to provide crucial insights into future maintenance costs, aiding in informed decision-making.

*2) **Optimize model for maintenance scheduling***

Following the predictive modeling, we will develop a novel optimization model to determine the most effective maintenance schedule based on the predicted conditions and maintenance costs of bridges. This will involve formulating the problem in mathematical terms, defining practical constraints, and establishing an objective function that reflects key performance indicators of bridge maintenance. An appropriate optimization algorithm will be selected to ensure that the maintenance schedule is optimized efficiently with minimal computational time and effort. The Principal Investigator (PI) will apply his substantial experience in developing optimization models for various challenges in transportation and infrastructure management, as evidenced by his previous work (Abdallah et al. 2019a; b, 2020; Abdallah and El-Rayes 2015, 2016a; b; Ghafoori et al. 2023, 2024a; b; Ghafoori and Abdallah 2021, 2022).

Relevance to Strategic Goals

This project directly aligns with the Transformation goal of transportation by designing forward-thinking, innovative solutions that address current challenges while paving the way for a future-ready transportation system. By developing advanced machine learning and optimization models, the project aims to modernize bridge maintenance management, a critical component of infrastructure. These models anticipate future maintenance needs and optimize interventions, ensuring that resources are allocated for maximum benefit. This proactive approach to maintenance not only enhances the current state of bridge infrastructure but also ensures that it remains robust and serviceable for future generations. The introduction of predictive tools and strategic planning methodologies is a purpose-driven innovation designed to adapt to and meet the evolving demands of a dynamic transportation landscape, ensuring it serves everyone effectively both today and in the future.

Furthermore, this research contributes to enhancing the safety of the transportation system. The accurate predictions of maintenance needs and optimizing the scheduling of maintenance interventions will improve performance of bridges and can indirectly reduce transportation-related injuries and fatalities. Bridges are vital components of the transportation network, and their failure can lead to catastrophic consequences. Through improved maintenance planning, this project ensures that bridges remain in the best performance condition based on available budgets, thus preventing accidents, and enhancing the safety of all users. This approach not only mitigates the immediate risks associated with poorly maintained infrastructure but also fosters a culture of safety that is essential for a future with reduced transportation-related injuries and fatalities.

Educational Benefits

In this project, a PhD student will be involved in developing the machine learning and optimization models, providing a rich educational and professional development opportunity. To this end, the student will gain hands-on experience in advanced data analytics, machine learning techniques, and optimization strategies, enhancing their expertise in computational modeling and data-driven decision-making. This practical experience is complemented by the theoretical knowledge they will acquire from the interdisciplinary collaboration with experts in maintenance management. Furthermore, the methodologies and insights derived from the project will be used as teaching materials in relevant university courses and training other PhD students in the program. This will not only broaden the educational impact of the project by incorporating real-world examples into the curriculum but also enable other students to learn about cutting-edge techniques in infrastructure management.

Outputs through Technology Transfer

The technology transfer plan for this project focuses on disseminating research findings primarily through academic channels to ensure a targeted and impactful distribution of knowledge. This approach will focus on the publication of one peer-reviewed journal article and one conference paper, in addition to the comprehensive final project report. The plan is detailed as follows:

Journal Article: A comprehensive peer-reviewed journal article will be prepared, detailing the methodologies, findings, and implications of the research. This article will target a high-impact journal within the fields of civil engineering and transportation infrastructure.

Conference Paper and Presentation: The research team will also develop a conference paper to be presented at a professional conference such as TRB. This presentation will provide an opportunity to discuss the research findings with peers, receive feedback, and engage with other professionals who can directly apply these insights into practice.

Final Project Report: The final report will integrate all aspects of the research development, including literature review, development of machine learning models and optimization model, research outcomes, and recommendations for future research.

Expected Outcomes and Impacts

The expected outcomes of this research are expected to advance both the theoretical and practical aspects of infrastructure management. Expected outcomes include the development of machine learning models capable of accurately forecasting conditions and maintenance costs for various bridge elements, which could revolutionize current maintenance planning processes. These models will provide a predictive tool that bridges the gap between reactive and proactive maintenance strategies, allowing for more efficient budget utilization and improved bridge safety. The optimization model developed will offer a systematic approach to schedule maintenance interventions effectively, minimizing costs while maximizing bridge performance and longevity. These advancements in modeling, practices, and procedures could set new standards for bridge maintenance management, potentially influencing future research to explore similar methodologies in other areas of infrastructure. The implications for future research are vast, as this project will generate a suite of new data and methodologies that could be applied to broader contexts, encouraging a shift towards more data-driven, predictive maintenance strategies across various sectors of infrastructure systems. Furthermore, the findings of this research work will be disseminated in leading journals and professional conferences in the field.

In addition to the project report and research articles, this project will produce a tangible product designed to extend its impact. A prototype software tool will be developed, integrating the machine learning and optimization models into an application that can be utilized by bridge maintenance practitioners. This tool will help in identifying maintenance needs and scheduling interventions, thereby directly enhancing the decision-making process in real-world scenarios.

Work Plan

The work plan is designed to progress through key tasks, ensuring systematic collection of the needed knowledge and development of the project models. The following section provides a detailed outline of the major tasks involved in the project:

Task 1: Perform literature review

This task involves a thorough investigation of existing scholarly articles, industry reports, and case studies related to the use of machine learning in infrastructure maintenance, optimization strategies for maintenance scheduling, and current practices in bridge maintenance management. The review will focus on identifying gaps in current methodologies and pinpointing opportunities where advanced analytics can enhance decision-making. The outcomes of this review will help shape the research approach by highlighting best practices and innovative methods that could be adapted in this project.

Task 2: Develop machine learning (ML) models

This task focuses on the development and training of machine learning models to predict the performance conditions and maintenance costs of bridges based on historical data. Data will be sourced from the National Bridge Inventory (NBI) and National Bridge Elements (NBE), focusing on metrics that indicate the deterioration of bridge elements over time. After collecting this data, relevant features that significantly influence maintenance needs and costs will be selected. Comprehensive data preprocessing will be conducted to enhance the quality and suitability of the data for analysis. A broad spectrum of machine learning algorithms, from basic regression models to more advanced deep learning (DL) and time series forecasting models, will be explored and implemented. These models will require training and fine-tuning using specifically designed training and validation datasets. These models will be evaluated using metrics to ensure their accuracy. Once validated, these models will serve as critical predictive tools, providing insights that will inform future maintenance planning and resource allocation as described in the following task.

Task 3: Develop optimization model for maintenance interventions

This task entails the development of an optimization model designed to schedule maintenance interventions efficiently, based on predictions from the ML models and considering constraints such as budget limits and resource availability. The development process will involve translating the scheduling problem into a series of mathematical models, defining constraints that ensure practical and feasible solutions, and formulating objective functions that maximize bridge performance through key performance indicators. Various optimization algorithms will be explored to find the most effective solution method. Initial runs of the model will be conducted to test its functionality and refine the model based on preliminary results.

Task 4: Perform case study

In this task, the developed machine learning and optimization models will be applied to a case study consisting of several bridges in a region to validate their practical utility and effectiveness. The case study will involve implementing the models on actual data from selected bridges, analyzing the outcomes, and refining the models based on the insights gained. This hands-on application will help identify any challenges and allow the research team to make necessary adjustments to enhance the models' accuracy and applicability in real-world settings. Furthermore, the case study will help demonstrate the new capabilities of the system and illustrate its use.

Task 5: Write final report

The final task involves compiling all findings, methodologies, and results from the project into a final report. This document will detail all aspects of the project, including literature review, model development processes, case study outcomes, and recommendations for future research.

The timeline for executing the project tasks is summarized in Table 1.

Table 1. Project Tasks and their Timeline

Project Tasks	Start (M)	Dur. (M)	Year 1												Year 2											
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1: Literature Review	1	4																								
Task 2: Machine Learning Models	4	8																								
Task 3: Optimization Model	10	8																								
Task 4: Case Study	17	6																								
Task 5: Final Report	22	3																								

Project Cost

Total Project Costs:	$120,000
CTIPS Funds Requested:	$ 60,000
Matching Funds:	$ 60,000
Source of Matching Funds:	University of Colorado Denver

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