



Smart Funding Strategies for Maintaining Interdependent Transportation Infrastructure Assets

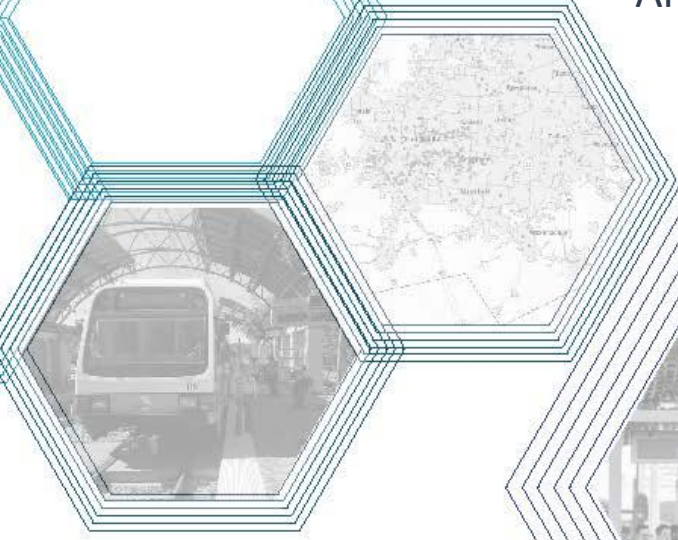
Zhaohua Wang

Mingshu Li

Lier Liu

Anirudh Houdhary

Ge Zhang



FINAL REPORT

SMART FUNDING STRATEGIES FOR MAINTAINING INTERDEPENDENT TRANSPORTATION INFRASTRUCTURE ASSETS

FINAL PROJECT REPORT

by

Zhaohua Wang
Mingshu Li
Lier Liu
Anirudh Houdhary
Ge Zhang

Georgia Institute of Technology

Sponsorship
(CTEDD and CSPAV)

for

Center for Transportation, Equity, Decisions and Dollars (**CTEDD**)
USDOT University Transportation Center
The University of Texas at Arlington
601 W.Nedderman Dr. Suite 103
Arlington TX 76019-0108 United States
Phone: 817-272-5138 | Email: C-Tedd@uta.edu

In cooperation with US Department of Transportation-Research and
Innovative Technology Administration (RITA)

Acknowledgment

This work was supported by a grant from the Center for Transportation Equity, Decisions and Dollars (CTEDD) funded by U.S. Department of Transportation Research and Innovative Technology Administration (OST-R) and housed at The University of Texas at Arlington.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The Center for Transportation, Equity, Decisions and Dollars (CTEDD), the U.S. Government and matching sponsor assume no liability for the contents or use thereof.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Smart Funding Strategies for Maintaining Interdependent Transportation Infrastructure Assets		5. Report Date December 14, 2019	
		6. Performing Organization Code	
7. Author(s) Zhaohua Wang, Mingshu Li, Lier Liu, Anirudh houdhary, Ge Zhang		8. Performing Organization Report No.	
9. Performing Organization Name and Address Center for Transportation, Equity, Decisions and Dollars (CTEDD) USDOT University Transportation Center The University of Texas at Arlington 601 W.Nedderman Dr. Suite 103 Arlington TX 76019-0108 United States		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. CTEDD 018-07	
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		13. Type of Report and Period Covered Final report; 8/15/2018 – 12/14/2019	
		14. Sponsoring Agency Code	
15. Supplementary Notes Report uploaded at www.ctedd.uta.edu			
16. Abstract <p>This research project aims to cost-effectively maintain entire road network that consists of different transportation infrastructure assets, such as pavements, bridges, signs, etc. A well-maintained road network is critically important to support the nation's mobility, conomy, and security. To address this need, this research project explored several aspects of smart funding strategies for optimally maintaining road network that consists of different, but interdependent, transportation infrastructure assets. First, a larger case study was conducted to demonstrate the benefit of maintenance programming by considering the interdependency between pavements and bridges. For this purpose, a general framework, consisting of pavements and bridges, was formulated as an interdependency-based optimization model by incorporating traffic capacity models, deterioration models, and treatment improvement models. In the meantime, for comparison purpose, a WSM-based optimization model was also developed by adopting the commonly used engineering-judgment-based MCDM method. The results demonstrated that WSM-based maintenance programming and the resulted performance relies on decision makers' preference. In contrast, the interdependency-based counterpart can achieve the best maintenance programming that maximizes the transportation efficiency of the road network without the need of decision makers' preference. More importantly, the maintenance programming based on engineering judgment cannot consider the spatial relationship and interdependency among different types of assets, which results in the difficulty of coordination in highway agencies' practice. Second, a new bridge deterioration modeling is developed to improve the objectivity and effectiveness of bridge maintenance action plan. Deterioration probability matrices of deck, substructure and superstructure, as three major components of a bridge, are used to determine their deterioration states instead of using substructure's matrix for a bridge as a whole. A new index is created to represent overall health of a bridge; it considers three components of a bridge, their area and unit maintenance costs, which can more subjectively define bridge condition. Third, traffic reassignment was explored to be integrated with pavement maintance programming. The open source traffic simulation software, SUMO, was adopted for this purpose. A case study taking a small fraction of road networks in Atlanta was used as input for computation. Integrating SUMO into this optimization problem formulation consumes excessive computation time than expected, yet the study shows promising results of such integration. Both objectivity and cost-effectiveness are improved in this attempt. Finally, conclusions and recommendations were offered.</p>			
17. Key Words Transportation Asset, Manament, Cross-asset, Genetic Algorithm, Traffic Reassignment		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 76	22. Price NA

Table of Content

Table of Figures	9
Table of Tables	10
Executive Summary	11
Chapter 1: Introduction	13
1. Background and Research Need	13
2. Research Approach and Focus	13
3. Report Organization.....	14
Chapter 2: Literature Review	15
1. Cross-Asset Management Modeling.....	15
2. Bridge Performance Measure	16
2.1 Bridge Inspection Tools.....	16
2.2 Bridge Performance Indicator	18
2.3 Bridge Cost.....	21
3. Bridge Deterioration Modeling.....	23
4. Traffic Simulation Modeling	24
4.1 Traffic Flow Models.....	24
4.2 Traffic Assignment Method.....	26
Chapter 3: A Large Case Study – Revisit of Cross-Asset Modeling.....	30
1. A General Framework.....	30
2. Implementation of General Framework.....	32
2.1 Transportation Network and Travel Time Computation	33
2.2 Traffic Capacity and Asset Condition	34
2.3 Asset Deterioration and Treatment Improvement	35
2.4 Interdependency-based Mathematical Optimization Model.....	36

3. Case Study	38
3.1 A WSM-based Optimization Model for Comparison.....	38
3.2 Objectivity vs. Subjectivity	39
3.3 Maintenance Strategy Comparison.....	40
4. Discussion	43
5. Summary	44
Chapter 4: Exploration of New Bridge Deterioration Modeling	46
1. Proposed Modifications on Bridge Deterioration Modeling	46
2. Improvements on Bridge Deterioration Modeling.....	46
2.1 Composite Rating of Bridge Condition	46
2.2 Deterioration Models of Different Bridge Elements	47
2.3 Bridge Maintenance Definition	48
3. Case Study brief and Results	49
3.1 Bridge Treatment Actions in Year 1.....	50
3.2 Bridge Condition Changes in Year 1.....	51
3.3 Yearwise Results from Genetic Algorithm	51
4. Summary	51
Chapter 5: Exploration of Traffic Reassignment in Pavement Maintenance Modeling	53
1. Proposed Framework	53
2. Implementation	55
2.1 DFROUTER Tool vs. Random Vehicle Trip Files Generation.....	55
2.2 SUMO Simulation	56
2.3 Pavement Deterioration and Conditions.....	56
3 Case Study	57
3.1 Map Filtering	57

3.2	Input Files Preparation for SUMO Simulation.....	58
3.3	NVI Computation and Edge Betweenness Centrality	59
3.4	Yearwise Genetic Algorithm on the Road Network.....	61
4	Summary	62
Chapter 6: Conclusions and Recommendations		64
1.	Conclusions.....	64
2.	Recommendations.....	65
References		66

Table of Figures

Figure 1.1 Road Network Consisting of Various Infrastructure Assets	14
Figure 2.1 Condition Assessment Tools for Bridge Performance Assessment (Omar et al., 2016)	16
Figure 3.1 A General Framework for Managing Interdependent Assets.....	32
Figure 3.2 Architecture for Managing Pavements and Bridges.....	33
Figure 3.3 A Local Road Network.....	38
Figure 3.4 Comparison of Maintenance Strategy of Selected Pavements and Bridges.....	42
Figure 4.1 A Local Road Network.....	50
Figure 5.1 Flow of SUMO Network.....	54
Figure 5.2 Filtered Atlanta Street Map	58
Figure 5.3 Simplified Atlanta Street Map.....	58
Figure 5.4 Colored Simplified Atlanta Street Map.....	58
Figure 5.5 Final Weights Map	60
Figure 5.6 Network Vulnerability-based Weights Map.....	60
Figure 5.7 Centrality-based Weights Map	61
Figure 5.8 Maintenance Actions, Costs, and Travel Time Results.....	62

Table of Tables

Table 2.1 Comparison of Performance Assessment Techniques for Bridges (Omar et al., 2016)	18
Table 2.2 Common Actions Based on National Bridge Inventory General Condition Ratings (FHWA, 2018)	19
Table 3.1 Bridge Condition and Traffic Capacity	35
Table 3.2 Treatment Criteria for Pavement	35
Table 3.3 Bridge Deterioration Probabilities	36
Table 3.4 Sensitivity Study of MCDM-based Optimization Model	40
Table 3.5 Comparison of Maintenance Strategy in First Year	41
Table 3.6 Comparison of T_g in Five-Year Programming	42
Table 4.1 Deck Deterioration Probabilities	48
Table 4.2 Substructure Deterioration Probabilities	48
Table 4.3 Substructure Deterioration Probabilities	48
Table 4.4 BQI and NBI Conversion and Actions	49
Table 4.5 BQI and NBI Conversion and Actions	50
Table 4.6 Bridge BQI and Maintenance Action in Year 1	51
Table 4.7 Yearwise Travel Time and Maintenance Costs Results	51

Executive Summary

This research project explored several aspects of smart funding strategies for optimally maintaining road network that consists of different, but interdependent, transportation infrastructure assets. Two major types of transportation infrastructure assets, pavements and bridges were utilized to demonstrate the effectiveness of the proposed methodology.

First, a larger case study was conducted to demonstrate the benefit of maintenance programming by considering the interdependency between pavements and bridges. The major formula followed the ones developed in previous project (Wang, et al., 2018). For this purpose, a general framework, consisting of pavements and bridges, was formulated as an interdependency-based optimization model by incorporating traffic capacity models, deterioration models, and treatment improvement models. In the meantime, for comparison purpose, a WSM-based optimization model was also developed by adopting the commonly used engineering-judgment-based MCDM method. The case study was conducted using a road network consisting 140 pavement segments and 29 bridges. The results demonstrated that WSM-based maintenance programming and the resulted performance relies on decision makers' preference. In contrast, the interdependency-based counterpart can achieve the best maintenance programming that maximizes the transportation efficiency of the road network without the need of decision makers' preference. More importantly, the maintenance programming based on engineering judgment cannot consider the spatial relationship and interdependency among different types of assets, which results in the difficulty of coordination in highway agencies' practice.

Second, assumption was made on bridge condition based on existing research of pavement and its condition measure, so the bridge deterioration model may need some modifications. In the previous study, deterioration probability matrix of substructure is used to represent the deterioration characteristics of a bridge as a whole for simplicity. Deck, superstructure, or substructure of a bridge deteriorate following various patterns and have different important levels to the bridge. Therefore, objective prioritization on maintenance actions is necessary to improve the effectiveness of bridge maintenance. An index representing bridge quality is developed, which derives the ratio of the current bridge value to the total bridge value as initially designed. This index uses NBI scores of all three components of a bridge; it can therefore improve the objectivity of bridge maintenance actions determination.

Finally, traffic reassignment was explored to be integrated with pavement maintenance programming. The open source traffic simulation software, SUMO, was adopted for this purpose. The objective fitness function was set to bring the network to a steady state and find the best road conditions, with constraints of annual budget and travel time reliability. Similar optimization model as the cross-asset modeling was used to determine the pavement maintenance programming. A case study taking a small fraction of road networks in Atlanta was

used as input for computation. Integrating SUMO into this optimization problem formulation consumes excessive computation time than expected, yet the study show promising results of such integration. Both objectivity and cost-effectiveness are improved in this attempt.

Due to the tremendous demand of computing power, the current models are still not proactical for computing a very large roadway network, especially when traffic reassignment is considered. Thus, parallel computing using GPU and/or computer cluster is needed to enhance the computing efficiency.

Chapter 1: Introduction

1. Background and Research Need

The proposed project aims to cost-effectively maintain entire road network that consists of different transportation infrastructure assets, such as pavements, bridges, signs, etc. A well-maintained road network is critically important to support the nation's mobility, economy, and security. Thus, the proposed project exactly aligns with C-TEDD's objectives to "improve economic development through more efficient, cost-effective use of the existing transportation system, and offers better access to jobs and opportunities."

The 2017 ASCE (The American Society of Civil Engineers) report card has rated America's roads a D, which are "chronically underfunded." According to the report, 21% of the nation's highways were in poor condition in 2015, which costs motorists \$120.5 billion per year in extra vehicle repairs and operating costs. Overall, there is a need of \$836 billion in repairs and capital investment for America's highway system. Therefore, how to cost-effectively maintain our road network under the stringent budget is the biggest challenge faced by highway agencies.

To address above need, the proposed project identifies the key systemic inefficiencies in state and local highway agencies in maintaining the road network, and proposes smart funding strategies to cost-effectively maintain the competing, interdependent transportation infrastructure assets using an objective means. The proposed project fills the gap between the use of transportation network and the maintenance of transportation infrastructure assets.

2. Research Approach and Focus

The objective of this research project is to develop smart funding strategies for optimally maintaining road network that consists of different, but interdependent, transportation infrastructure assets. Figure 1.1 illustrates various infrastructure assets in a road network that work together to provide mobility with desirable traffic safety to the public. Though dedicated asset management systems, e.g., pavement management system, have been employed in highway agencies to cost-effectively maintain individual types of infrastructure assets, the funding allocation on different assets remains a challenge to upper management or other decision makers. Recent years, researchers started to explore methodologies to tackle this issue, most of them resorted to multi-criteria decision-making processes, which inevitably resulted in significant subjectiveness, such as the determination of weighing factors of different objective functions.



Figure 1.1 Road Network Consisting of Various Infrastructure Assets

To address this problem, a new methodology will be proposed by analyzing the interdependency among different transportation infrastructure assets. For example, pavement and bridges form a road network that transports goods and provides accessibility to “jobs and opportunity.” In the meantime, signs and markings assist with traffic safety and ensure the mobility of a road network along with pavements and bridges. Based on the interdependency among different assets, new performance measures will be developed. These performance measures, e.g., average travel time of a road network, determine the interdependency of different assets. Thus, instead of maximizing the conditions of individual infrastructure assets, the proposed methodology seeks the optimal funding allocation in order to achieve the best performance of entire road network. The following are the major steps in the proposed new methodology, which aim to objectively integrate different assets together under the framework of a network-level resource allocation.

3. Report Organization

This report is organized into six chapters. Chapter 1 summarizes the research background, need, and approaches; Chapter 2 presents a comprehensive literature review. Chapter 3 explores a larger case study to demonstrate the benefit of maintenance programming and funding allocation by integrating pavements and bridges in terms of their interdependency. Chapter 4 explores a new bridge deterioration modeling. Chapter 5 studies the integration of traffic reassignment in a pavement maintenance programming. Chapter 6 summarizes the conclusions and makes recommendations for future research.

Chapter 2: Literature Review

1. Cross-Asset Management Modeling

For convenience of management, decision makers in highway agencies tend to break down a big asset into smaller units and manage them in individual “silos,” e.g., pavements, bridges, signs, etc. It is well-known that the silo-based management results in sub-optimal maintenance decisions due to the difficulty of communication and coordination among different management units (Maze, et al., 2008). For example, a safety-improvement project with surface treatment might need immediate major rehabilitation. Without proper communication or coordination, the investment on surface treatment could be wasted when the major rehabilitation is scheduled after that. To overcome the inefficiency of silo-based management, cross-asset management has been recognized as the next generation of innovation for highway agencies to improve their decision making on managing multiple transportation assets (Proctor & Zimmerman, 2016). Proctor and Zimmerman (Proctor & Zimmerman, 2016) summarized and formally defined all the major methods for cross-asset management, such as tradeoff, cross-asset allocation, and cross-asset optimization.

Due to the involvement of multiple types of assets, different decision-making techniques need to be applied to normalize and compare the benefit obtained from maintaining them (Maggiore & Ford, 2015). Some literatures focused on the modeling and solution of multiobjective asset management and left the final decisions to users (Chen, et al., 2015; Shoghli & Garza, 2017). However, there exist infinite sets of solutions to optimize various conflicting objectives, which is called Pareto frontier. Nevertheless, a decision maker still needs to use subjective preference to evaluate different objectives and/or criteria in order to achieve a single solution. This process is called multi-criteria decision-making (MCDM). Kabir, et al. (2014) has done a comprehensive literature review by summarizing the MCDM-related literatures published from January 1980 to October 2012. Weighted sum model (WSM) and analytical hierarchy process (AHP) are two commonly used methods for transportation asset management (Ziara, et al., 2002; Ahmed, et al., 2017; Farhan & Fwa, 2014). The above MCDM methods provide systematic approaches for decision makers to deal with conflicting objectives and/or selection criteria. However, their subjective preference on the objectives and/or criteria is still needed, which makes it difficult to objectively justify the superiority of a solution over another.

Due to the complexity of decision-making process for maintaining multiple types of transportation assets, a certain level of subjectivity is unavoidable. Zhang, et al. (2002) developed an integrated asset management system for pavements and bridges, in which priority indexes were used to combine the different objectives. Sadek, et al. (2003) used the weighted sum of the condition of six types of assets, including pavements and bridges, as utility function in the optimization modeling. The weighting factors indicate the relative importance of different assets. Dehghani, et al. (2013) used a more complex trade-off analysis to come up with a single

quality measure for the entire transportation network by considering structure, function, safety, and environment for pavements, bridges, and other safety features. Weninger-Vycudil, et al. (2015) used a weighted benefit-cost ratio as a utility function to allocate resources for pavement and bridge maintenance projects. The selection of weighting factors among different assets largely rely on decision makers' preference.

The use of WSM, AHP or other MCDM methods for cross-asset management is reasonable due to the difficulty to objectively measure the entire network's performance given conflicting objectives and/or criteria. However, is there any room to enhance the objectivity in the above cross-asset decision making process since we need to "be objective wherever possible" in a decision-making process (Buchanan, et al., 1998)? To answer this question, this project explored a general framework for managing multiple types of transportation assets by integrating their interdependency. Thus, a more objective performance measure could be developed in terms of the level of service (LoS), e.g., transportation and safety, of the entire road network.

2. Bridge Performance Measure

In previous project (Wang, et a., 2018), the performance measure for bridge was drastically simplified. To make the following case study more realistic, a more complicated bridge deterioration model and performance measure were explored. In this subsection, the commonly used bridge performance measure was reviewed.

2.1 Bridge Inspection Tools

Commonly used tools for bridge condition assessments are visual inspection, nondestructive testing and structural health monitoring, as shown in Figure 2.1

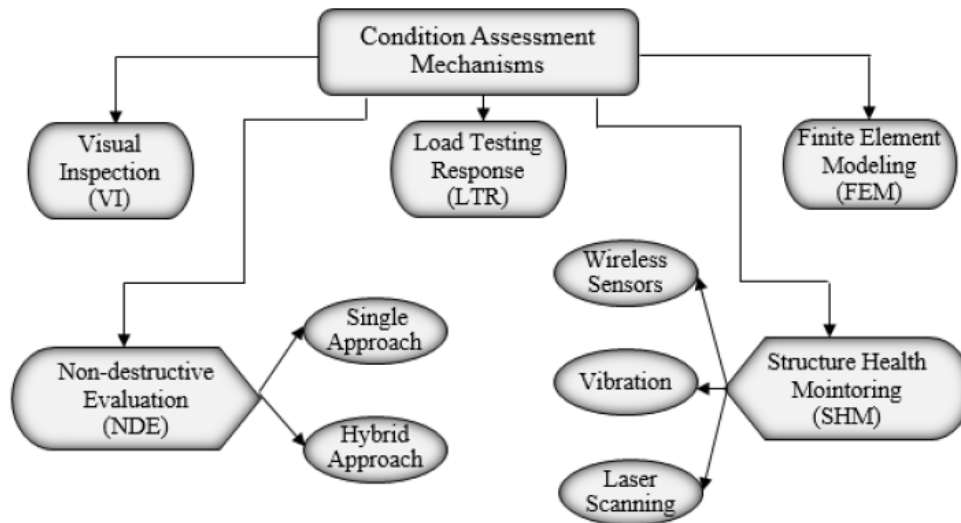


Figure 2.1 Condition Assessment Tools for Bridge Performance Assessment (Omar et al., 2016)

Visual inspection

Traditional bridge condition assessment is conducted by visual inspection. Experienced experts carry out inspection at component level and combine individual rating into overall bridge condition. However, Perception is an individual and situation-related category, and is hence not an objective photographic copy of reality but rather the subjective experience and interpretation of the observer (Tenzeral et al., 2012). The result might contain large variation depending on inspectors' experience, judgment and environmental factors, etc.. Moreover, many damages are invisible or hard to be detected at the beginning, for instance, bridge deck deterioration often takes place below the surface where it cannot be evaluated by visual means (Gucunski et al., 2013). As Purvis et al. mentioned, the flaw is often very small, the inspector has to be close, to know where to look, and to recognize the crack when it first becomes visible.

Nondestructive testing

Nondestructive testing is another popular tool for bridge condition assessment. The advantage is that non-destructive testing can provide information that cannot be obtained through simple visual examination, such as steel corrosion. Nondestructive testing (NDT) techniques have the potential of providing the needed information about the under-the-surface deteriorated condition of the deck (Gucunski et al., 2013). The only limitation is that they are usually more expensive and time consuming. The most often used techniques include ground penetrating radar, impact echo, infrared thermography and other automatized solutions.

Load testing response

The reliability bridge evaluation rating process described in the AASHTO's manual is based on load testing response. Load testing is a procedure to determine the safe loading levels of a bridge, leading to a load rating which provides the capacity level of a bridge (Omar et al., 2016). Through static and dynamic loading test under different combination, bridge structural response can be collected, and loading capacities can be thus determined. Other properties such as bridge structural integrity and safety level can also be evaluated through component response.

Structural health monitoring

Structural health monitoring is a more advanced assessment tool to examine reliability and safety level against static and dynamic loading. Information is acquired through multiple sensors embedded in structure to monitor structure response and evaluate bridge health conditions. Most SHM systems have similar fundamental elements: (1) measurements by sensors and instrumentation, (2) structural assessment (e.g. peak strains or modal analysis), and (3) condition assessment to support MR&R related decision-making (Omar et al., 2016).

Finite element modeling

Finite element modeling is widely used in bridge performance assessment in terms of mechanical characteristics. For instance, fragility analysis is developed to analyze structure response of

individual bridge under seismic loading and corresponding reliability level. The results can thus be utilized to facilitate maintenance arrangement under extreme events at network level. (Padgett et al., 2008)

Table 2.1 Comparison of Performance Assessment Techniques for Bridges (Omar et al., 2016)

Technique	Description	Advantages & Limitations	
		Advantages	Limitations
Visual Inspection (VI)	Trained engineers have to recognize, register, and evaluate the physical condition of different bridge elements using inspection manuals and defined codes.	BMSs, rely primarily on VI to record components condition ratings, which are quantified and standardized through a priority-ranking procedure. It is the most cost-effective method	Subjective evaluation, results greatly depend on the qualification of persons conducting inspections. Considers only the observed physical health of the bridge.
Non-Destructive Evaluation (NDE)	Each NDE method uses a unique physical principal of the bridge materials to identify locations flaws or deterioration without damaging the elements.	Objectify the inspection process and make it more fast and reliable to provide effective, and accurate condition assessment.	No single NDT technology is capable of identifying all of the various deterioration phenomena. It requires trained persons for data collection, and interpretation.
Structure Health Monitoring (SHM)	Encompasses a range of methods and practices designed to capture structural response, and detect anomalous behavior.	Reliable and potentially real-time bridge assessment. Wireless sensors alleviated the cost associated with cabled monitoring systems. More meaningful than using loading response data.	Requires routine, on-site maintenance. Wireless sensors often rely on battery power. The complexity and size of the bridge could result in complex SHM system.

2.2 Bridge Performance Indicator

Developing a clear performance goal and indicator for transportation infrastructure asset is crucial in that it helps agencies better evaluate the asset’s current condition and apply appropriate treatment. Usually performance indicators are defined to reflect specific aspect of asset’s functionality. General goals are system preservation, user/agency cost, and safety/reliability.

System preservation

Most commonly used bridge performance indicator by transportation agencies for large network management is condition rating. Usually a numerical value assigned during a visual inspection. The most popular highway bridge management system in the United States, PONTIS, is adopting such condition rating system to facilitate maintenance planning.

NBI condition rating

The NBI rating is a numerical scale ranging from 0 (poorest condition) ~ 9 (ideal condition), that is used to describe the existing, in-place bridge or culvert as compared to the as-built condition (FHWA, 2018). Major components including deck, super-structure, sub-structure and culvert,

etc. are rated separately and then combined to reflect overall condition of the bridge. Table below provides recommended treatments corresponding to different condition categories.

Table 2.2 Common Actions Based on National Bridge Inventory General Condition Ratings (FHWA, 2018)

Code	Description	Common Actions
9	EXCELLENT CONDITION	Preservation/Cyclic Maintenance
8	VERY GOOD CONDITION—No problems noted.	
7	GOOD CONDITION—Some minor problems.	
6	SATISFACTORY CONDITION—Structural elements show some minor deterioration.	Preservation/Condition-Based Maintenance
5	FAIR CONDITION—All primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour.	
4	POOR CONDITION—Advanced section loss, deterioration, spalling, or scour.	Rehabilitation or Replacement
3	SERIOUS CONDITION—Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.	
2	CRITICAL CONDITION—Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present, or scour may have removed substructure support. Unless closely monitored, the bridge may have to be closed until corrective action is taken.	
1	IMMINENT FAILURE CONDITION—Major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic, but corrective action may put it back in light service.	
0	FAILED CONDITION—Out of service. Bridge is beyond corrective action.	

Sufficiency rating

Sufficiency ratings is a numerical value ranging from 0 ~ 100 which is intended to indicate a measure of the ability of a bridge to remain in service, the following four factors are taken into consideration.

- 1) Structural Adequacy and Safety (most heavily weighted factor, 55% at most)
- 2) Serviceability and Functional Obsolescence (second most weighted factor, 30% at most)
- 3) Essentiality for Public Use
- 4) Special Reductions

The four weighted factors are added together to determine the sufficiency rating (SR).

Health index

Bridge health index is defined as a numerical rating ranging from 0 (poorest condition) ~ 100 (ideal condition). The Health Index differs from the Federal Highway Administration's Sufficiency Rating in that it provides an insight to the structural condition of a bridge irrespective of its functional adequacy (Shepard et al., 1999). Below is the formulation of the index.

$$HI = \left(\frac{\sum_e CEV}{\sum_e TEV} \right) \times 100\%$$

$$TEV = TEQ \times W_e$$

$$CEV = W_e \times \sum_i (QCS_i \times WF_i)$$

Where

CEV = current element value

TEV = total element value

TEQ = total element quantity

QCS_i = quantity in condition state i, and

WF_i = weighting factor for the condition state i.

The weight of an element e, W_e , represents the element failure cost or some other reasonable indication of importance of each element.

2.3 Bridge Cost

Agency cost

Agency costs consist of routine maintenance, element rehabilitation, and bridge replacement costs (Hawk, 2003). A common strategy for most agencies is to extract cost information from historical bid records. For example, the preservation and functional improvement and replacement unit cost inputs in Pontis bridge management software package are derived based on a weighting scheme where expert's estimates and historical element-level data are included. Pontis then applies optimal maintenance, repair and rehabilitation actions to each bridge according to the estimated unit costs. (Sobanjo et al., 2001)

User cost

Generally, user cost can be divided into three categories, that is, travel delay, vehicle operation cost and crash cost. Quantitative performance measure most used for evaluating impact of maintenance activity on user benefits is travel time. For example, the benefits of functional improvements in Pontis are assessed in terms of user cost savings. When a bridge has insufficient load capacity rating due to deterioration, certain trucks are not permitted to pass through a bridge. Detour and extra travel time are inevitable. Other considerations include vertical clearance, narrow bridge width and crash rates etc. (Thompson et al. 1999)

$$B_r = \frac{W_c}{100} \times V_{ry}(BW_r + BR_r + BS_r)$$

Where

W_c is the weight given to user cost benefits, in percent

V_{ry} is the forecast average daily traffic volume for the program year

BW_r is the annual benefit of widening per unit average daily traffic

BR_r is the annual benefit of raising per unit average daily traffic

BS_r is the annual benefit of strengthening per unit average daily traffic

Vehicle operation cost is often associated with deck surface characteristics (roughness, geometry, etc.), vehicle characteristics (weight, age, brand, etc.), and other factors. For example, when traveling through narrow bridges or bridges with poor deck surface condition, travel speed is less than that at ideal conditions (Sinha et al. 2009). Other factors like vertical clearance and load limit etc. can all incur extra vehicle operation cost.

Traffic time and delay is relevant to complicate factors. When related to user cost, monetary value of unit time is multiplied to travel time and is differentiated by different trip purposes. Hu et al. proposed a reliability-based bridge network management system by

minimizing total user costs in terms of extra travel distance under budget constraints. In Liu et al.'s bridge maintenance model, where the objective is to minimize maintenance cost, bridge failure cost and user cost based on time-dependent bridge structural reliability prediction, user cost is determined as the difference between cumulative travel expenses and that associated with the fully operational network.

Besides degraded network efficiency caused by bridge deterioration, there are extra user costs result from bridge maintenance activities which is temporary but worth considering. Orcesi et al. compared user costs in terms of travel time when adequate level of service is provided and when inadequate level of service is available due to both bridge partial closure due to maintenance and failure event. Step functions were used to quantify impact on maintenance activity and structure deficiency on traffic capacity.

In addition to vehicle operation cost and travel time, crash costs can also be counted as user costs. Crash costs can be predicted given crash rate and unit crash cost. Crash rate is closely related to bridge attributes, such as appropriate deck geometry, sufficient vertical clearance and inventory rating (Sinha et al. 2009). Appropriate and timely treatment such as bridge widening reduces user costs in terms of decreasing accident rate.

Safety

Sometimes crash cost is considered under safety/reliability category instead of user cost. Traffic safety can be evaluated through traffic safety features, inventory rating, geometric rating, deck geometric rating, etc.

Traffic safety features

Reflected in NBI item 36, the following features are taken into consideration related to traffic safety:

- Bridge railings
- Transitions
- Approach guardrail
- Approach guardrail ends

Whether the bridge meets the currently acceptable standards is recorded by binary values.

Inventory rating and capacity rating

The inventory rating which reflects the capacity level of a bridge is used to evaluate a load level which can safely utilize an existing structure for an indefinite period of time. While the capacity rating/operating rating is the absolute maximum permissible load level to which the structure may be subjected.

Deck geometry

The evaluation of deck geometry includes the curb-to-curb or face-to-face of rail bridge width and the minimum vertical clearance over the bridge roadway. It's a numeric value ranging from 0~9 to reflect deck geometry feature.

Reliability

Bridges are vulnerable under extreme events, such as earthquake, flooding, explosion, etc.. thus, performance indicator to quantify the ability of a structure to survive during unexpected attack is defined. Saydam et al. proposed a framework to compute time-dependent indicators of bridges including reliability, vulnerability, robustness and redundancy. Encouraged by the reliability related performance measure, maintenance strategies based on bridge network reliability are also developed. Zonta et al. proposed a reliability-based bridge management concept, where maintenance priority is given to actions that minimize the risk of unacceptable event at network level.

“Performance measures deal with abstract measurement of the condition of assets, making them directly incomparable between asset categories (e.g., the International Roughness Index as a measure of condition for roads and a health index for bridges).” Maze, Thomas H., et al. Use of Functional Silos to Optimize Agency Decision Making. No. MRUTC 05-05. 2008.

3. Bridge Deterioration Modeling

For the performance indicators introduced in the previous section, there are a variety deterioration models developed, and they can mainly be divided into two categories: deterministic.

Deterministic models usually employ linear regression or non-linear regression to model the relationship between the dependent variable (performance indicator) and the independent variables (bridge attributes, age, traffic condition, and other factors). Different forms have been adopted to simulate bridge deterioration such as linear, exponential and higher order polynomial. West et al. developed a nonlinear deterioration model to explore the relationship between condition rating and age utilizing exponential decay function. However, deterministic models are incapable of capturing the embedded uncertainty in the deterioration process.

Bridge deterioration is more of a stochastic process rather than a deterministic one because of the complicated mechanics nature in a bridge structure. Deterministic models give absolute value as result which ignores the random nature in the deterioration process. The most widely used stochastic model is the Markov process. Uncertainty can be accounted for by using a transition probability matrix where elements represent the probability of current bridge condition transits the next state in a time cycle. The most popular bridge management system used among the state DOTs, Pontis adopts Markov Chain as the core part of deterioration prediction (Fu et al., 2008). The Indiana bridge management system utilizes deterioration models developed using

two alternative approaches: a continuous regression model and a discrete probability Markov chain model (Sinha et al., 2009).

4. Traffic Simulation Modeling

4.1 Traffic Flow Models

Traffic flow models are primarily categorized into 2 categories: Macroscopic Flow and Microscopic Flow models. Microscopic flow models focus on modeling the individual behavior of a vehicle based on the traffic environment conditions. The model captures the interaction among vehicles and might also take into consideration the interaction between the driver and the vehicle. Car-following model is an example of microscopic traffic flow model. Three major classes of car-following models are safe-distance models, stimulus-response models and optimal velocity models. Safe distance methods try to model the dynamics of a vehicle with respect to its predecessor such that a minimum safe distance is maintained. Pipes (1966) developed the first car-following model based on the assumption that driver would keep a safe distance dependent on the speed on the vehicle. Godunov (1959) proposed the first model of collision avoidance collision by transcribing the trajectory of a vehicle according to a minimal safe distance. Gipps, (1981) extended their approach to include a safe speed for keeping a minimum distance between the cars given their acceleration and speeds. He also extended the model to multiple lanes and consider lane changing behavior. Hodas and Jagota (2003) used a combination of microscopic behavior models which incorporate car-following, lane-changing and other individual driver behavior models to simulate multi-lane traffic flow dynamics.

Optimal velocity model defines driver's actions based on the difference between the driver's desired velocity and current velocity. The model is simple and can describe various complex traffic phenomena. Optimal velocity model was proposed by Bando et al. (1995) to describe many properties of real traffic flows like traffic flow instability, the evolution of traffic congestion, and the formation of stop-and-go waves. Helbing and Tilch (1998) extended the optimal velocity model by proposing a generalized force model incorporating a new term representing the impact of negative velocity i.e. the condition that the velocity of the front vehicle is lower than that of the follower. However, both optimal velocity and generalized force models cannot account for the event that even though the headway distance between two consecutive vehicles is smaller than safety distance, the following vehicle may not decelerate if the leading vehicle is much faster. Jiang et al.(2001) extended the generalized force model to solve this problem and developed full velocity difference model (FVD). Nagatani (1999) developed an extended optimal velocity model by considering the impact of vehicle's headway, Ge et al.(2004) proposed an extended optimal velocity model with multi-headways; Zhao and Gao (2005) proposed a model considering leading vehicle's acceleration given that the FVD model may produce collision under some specific conditions; Wang et al. (2006) constructed an extended FVD model with consideration of multi-velocity differences.

Psycho-physical models also known as action point models consider the driver behavior and perception while modeling the flow and applies a threshold to the relative speed and distance between two vehicles beyond which the drivers change their behaviour. Wiedemann (1974) developed the first psychophysical car-following model in 1974. His model has different parameters to account for all the different driving behaviors that can be used for the driving functions. These functions are delimited by thresholds that define different types of interactions and regimes like Following, closing-in, free-driving etc. Wiedemann and Rieter (1992) published an updated model in 1992 to support calibration parameters for freeways. The model has been incorporated in VISSIM, which is a popular microsimulation software used for traffic flow analysis.

Macroscopic models study the aggregate behavior of a set of vehicles based on fluid flow principles. These models are easier to validate compared to microscopic models because of lower computational cost and the difficulty in getting appropriate data to model the behavior of drivers in real traffic. Macroscopic models do not distinguish their component flows by origin-destination pair and hence, assign fixed turning ratios for traffic stream. Lighthill and Whitham and Richards (1955) provided the most used flow-dynamic model termed as the LWR model, which is based on first-order differential equations modeling the relationship between flow and velocity, considering mass flow conservation. It treats traffic flow as compressible fluid and studies the properties induced by interaction of a group of vehicles while ignoring the details of individual vehicles. Daganzo (1994) proposed a discretized version of LWR model known as cell transmission model (CTM). CTM uses Godunov scheme to simulate traffic flow by dividing a lane into homogeneous sections and can be used to reproduce kinematic waves and the formation and dissipation of a queue in both congested and uncongested regimes. However, Godunov scheme (1959) relies on a computational grid and generates an approximate solution of the PDE. Mazare, Dehwah, Claudel and Bayen (2018) formulated a computationally efficient method which uses cumulative number of vehicles function as an integral form of density function and uses ‘Lax-Hopf’ method. It entails lesser computational cost given that it doesn’t need to grid the space and generates exact solution numerically instead of approximating PDE derivatives by finite differences.

Higher order models incorporating momentum equation on top of mass flow conservation have been developed to improve LWR model. Two models are widely accepted: Payne-Whitham (PW) model (1971) and Aw-Rascle (2000) model. PW model has been proposed to improve the explanation given by LWR model near shocks. It considers traffic as compressible fluid and applies conservation of mass and momentum. However, a key difference between a car and fluid particle is that the car mostly responds to frontal stimuli only. Also, the PW model sometimes predicts negative velocities by smoothing out discontinuities. To improve over the assumptions of PW model, Aw-Rascle model suggests using a convective derivative rather than a space derivative to fix the problem of negative velocities. Papageorgiou and Yuan (1990) added extra functions to consider on and off ramp flow which results in additional parameters for calibration.

Most of research on LWR model is based on the traditional Eulerian coordinate system based on time and space. However, researchers have investigated the use of Lagrangian coordinates for modeling cumulative traffic flow. Newell (1993, 1995) proposed the first approach based on conservation law in Lagrangian coordinates from gas dynamics which was improved by Daganzo using variation theory. Brockfeld et al. (2004) validated the LWR model in Lagrangian coordinates empirically. Macroscopic traffic flow models have been used in the past to incorporate probe vehicle data and provide real-time traffic information. Kang-Ching Chu (2016) relies on formulating a stochastic Lagrangian macroscopic traffic flow model to incorporate probing data into the LWR model. They convert the LWR model into Lagrangian coordinates with a forcing function and use Unscented Kalman filter to update the prediction of model parameters and traffic state in real-time. However, Lagrangian formulation requires mobile sensor data and our formulation currently has access to fixed sensor data, hence using Lagrangian formulation is currently out of scope.

Due to the stochastic nature and uncertainty of the traffic, researchers have introduced stochasticity to traffic flow model. However, the variance of stochastic models which can be interpreted as the confidence level of the prediction is generally missing from the discussion.

4.2 Traffic Assignment Method

The challenge is to find a model which achieves an efficient routing and assignment of traffic flows whenever the capacity of a link reduces. The research on traffic assignment has focused on the following models:

Static Traffic Assignment

Traditional models have focused on modeling the equilibrium in a situation when traffic demand and supply are consistent with each other. The governing solution is derived using Wardrop's first and second principle (Wardrop, 1952). The first principle is user equilibrium optimum, which states that "the journey time on all the routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route". The second principle is system optimum, which states that "the average journey is minimum". The two principles have been studied extensively in the literatures. One of the most commonly used solution approaches which has been quite popular over the last decade has been the Frank-Wolfe algorithm (1956) with path-based approach. Lo and Chen (2000) converted the traffic assignment problem into an unconstrained optimization problem, which makes it possible to model traffic assignment with a general route-cost structure. Bar-Gera[29] presented an origin-based algorithm (OBA) for the traffic assignment problem wherein a projected quasi-Newton search method is used to shift flows between paths. Bar-Gera (2010) later proposed a paired alternative segment algorithm that constructs a 'user equilibrium' solution from pairs of alternative segments but the algorithmic design makes it difficult to directly exclude paths for road users. Chen et al. (1998) evaluated the performance of two popular path-based algorithms for traffic assignment problems in realistic networks: the disaggregate simplicial decomposition algorithm and the gradient projection

algorithm. Dial (2006) developed a path-based, user-equilibrium traffic assignment algorithm that repeatedly moves flows from the costliest paths to the cheapest paths until the cost of all the paths used are within the tolerance range of the cheapest path.

The static traffic assignment models have primarily focused on traffic assignment considering a static snapshot of the network at a single point in time. Hence, they are unable to consider traffic demand changes over time and thus the impact of traffic flow changes over vulnerability. Also, researchers have pointed out that while the user equilibrium should satisfy the drivers, it does not necessarily minimize the total travel time of the system (Jahn and Mohring, 2006). Roughgarden and Tardos (2002) investigate the relation between the system optimum and the user equilibrium. The system optimum expects to minimize the total travel time; however, it may route some drivers on unacceptable routes in order to obtain the whole system benefits. So, neither user equilibrium optimum nor system optimum is practical for the routing problem.

Stochastic Traffic Assignment

In most studies, road users are assumed to have perfect network information and make rational route decisions. The assumption of perfect knowledge of travel costs greatly reduces the practicability of traffic assignment and/or degrade the accuracy of predicted flow patterns. Stochastic traffic assignment (SUE) has been proposed to solve this problem. The core of stochastic traffic assignment model is probabilistic route choice model in which drivers are assumed to minimize their perceived costs given a set of routes. Daganzo and Sheffi (1977) defined the concept of SUE. At SUE, no driver can improve his/her perceived travel time by changing routes unilaterally. SUE generally evaluates the probability of each path being chosen and distributes road users among all the potential paths according to probabilities calculated from road users' utility functions. Prashker and Bekhor (2004) reviewed various route choice models including Probit model with structured covariance, MNL model and its modifications like C-logit and PSL, various GEV models and LK model. In state of the practice models, the MNL or modified versions like C-logit and PSL are implemented. They found that for congested networks, the difference between the route choice models became small. However, for moderate congestion, the route choice models exhibited different patterns and GEV models tend to give superior results compared to MNL models. However, the existing paradigms found in the literature on SUE do not explicitly account for the size of the road users' choice/path set. . Shao et al. (2008) proposed a reliability-based stochastic user equilibrium (RSUE) which is extended from risk user equilibrium using perceived travel time budget. Risk user equilibrium proposed by Bell and Cassir (2002) is based on a Nash game framework in which travelers aim to minimize the expected travel time while demons aim to maximize the total travel time of travelers.

Dynamic Traffic Assignment

Dynamic Traffic Assignment (DTA) is the most prevalent method currently being utilized for traffic assignment. Unlike static traffic assignment, dynamic traffic assignment (DTA) considers

the time-varying nature of network congestion. DTA methods can be leveraged for more realistic vulnerability assessment by modeling traffic demand as function of time and including large scale events like sports events. This means that the criticality of a link can be studied as a function of time. DTA comprises of 2 key components: travel choice and traffic flow. The traffic flow component depicts the velocity/density of traffic movement within the network and governs the performance of link in terms of travel time. The travel choice component is dependent on user decision making and determines the traffic flow level on each link. DTA solves for the flow pattern which satisfies the two components simultaneously. DTA extends static traffic assignment by considering the departure time of travelers, even if the time is fixed. Studies focused on choice of departure time have been conducted but it is currently out of scope of our solution formulation.

Dynamic extensions of travel choice used in static traffic assignment are dynamic user equilibrium (DUE) route choice, dynamic user equilibrium time choice principle and dynamic system optimal principle. Dynamic user equilibrium (DUE) route choice principle, which is the simplest extension of Wardrop's first principle, states that for travelers departing at the same time and for every O/D pair, the routes chosen must have equal and minimal travel time. The time choice principle considers departure time instead of route choice but is out of scope of our current formulation. Stochastic dynamic user equilibrium route choice principle proposed by Ran and Boyce(2012) is the stochastic extension of DUE route choice and considers perceived travel time instead of actual travel time. Many extensions of dynamic equilibrium concepts consider both perception error and uncertain travel time Ran and Boyce (2001) who considered the dynamic extension of the generalized traffic equilibrium. Szeto et al. (2011) proposed the reliability-based stochastic dynamic user equilibrium route choice principle which considers the risk attitudes of travelers towards late arrivals due to uncertain travel times, in addition to variations in their perception of the travel times. Travelers are assumed to select routes with the lowest perceived effective travel times. However, the reliability-based user equilibrium has not been verified empirically.

The pure route choice model can be further classified into reactive DTA model and predictive DTA model. Reactive DTA model allows drivers to change their routes during their trips given updated traffic information while predictive DTA assumes that choices do not change during trips and travelers select routes based on pre-trip information and predicted travel times. DTA models can be either simulation based or analytical-based. Simulation based DTA models emphasize microscopic traffic characteristics like lane changing and strict adherence to Wardrop's principle is not a primary requirement. They can find a solution quickly but it's difficult to prove that the solution has achieved optimality. Analytical-based approaches consider macroscopic traffic behavior and have well defined optimality condition adhering to Wardrop's principle. However, the key difficulty is adding traffic dynamics like queue spillback since the formulations are already complicated.

Many simulators have been developed which allow users to simulate traffic using micro/macro/mesoscopic traffic flow equations and include various options for route choice modeling. SUMO (Krajzewicz, 2010) and Smith et al. (1995) are the most used open source micro-simulators and they allow traffic to be modeled using stochastic user equilibrium as well as agent-based simulations. They support the complete process of transportation modeling and simulation from population synthesis, through activity generation to traffic microsimulation

TRANSIMS (TRansportation ANalysis and SIMulation System) is a microscopic traffic flow simulation system that is based on cellular automata (CA) theory and uses the basic Nagel-Schreckenberg car following model. The process is usually run iteratively to obtain system equilibrium according to the first Wardrop's principle. One key drawback of TRANSIMS is that it does not contain the tool for traffic generation based on turning ratios.

SUMO (Simulation for Urban MObility) is a microscopic traffic flow simulation system developed by German Aerospace Center (DLR) that facilitates modeling of multiple vehicle types. SUMO uses Krajzewicz model of lane change and the safe distance car following Krauss model by default, which is simple and has proved to be valid within a set of performed car-following model comparisons (Pipes, 1996; Gipps, 1981; Hdas, 2003). Its shortcomings include conservative gap size and inability to scale well when the time step length is changed. Other models included in SUMO are the intelligent driver model, Kerner's three-phase model, and the Wiedemann model. SUMO supports space-continuous time-discrete approach along with various intersections with or without traffic signals, for large networks. SUMO provides two route choices algorithm based on whether past probability of choosing a route is considered to calculate the new probability (Gawron's model) or not (Logit model). SUMO provides traffic generation procedure using JTRROUTER that facilitates route generation based on turning ratios and incoming flows.

Empirical analysis by Maciejewski points to similar effects in traffic flow propagation (i.e. network bottlenecks and gridlocks) observed in both TRANSIMS and SUMO. However, the performance of TRANSIMS is found to be slightly slower compared to SUMO, particularly for larger networks, as highlighted by Allan and Farid (2015).

Chapter 3: A Large Case Study – Revisit of Cross-Asset Modeling

In previous project (Wang, et al., 2018), a small road network consisting of pavements and bridges was explored to assess the cross-asset modeling, in which the benefit of cross-asset modeling is not significant. In the chapter, a larger case study was conducted with the similar mathematical modeling. To make this report a self-contained one, the formula were also included though they are similar to the ones in the previous final report (Wang, et al., 2018).

1. A General Framework

Each type of transportation asset is an integral part of a road network. They work together to provide sufficient transportation and safety to the road users, and thus, are interdependent. However, in a silo-based management, a statistical performance measure, without the consideration of assets' spatial interdependency, is often used, e.g., average structural and/or functional condition rating, which essentially assumes that individual assets are independent of each other. Some researchers also considered the spatial relationship of individual pavement projects and tried to cluster them in order to minimize the construction management and logistical cost (15, 16), which still dealt with a single type of asset and used the performance measure that is not related to the performance of service of a road network.

Using statistical performance measure, decision-makers' preference is often needed when resource is allocated among multiple types of assets. In contrast, if a performance measure, e.g., transportation and/or safety of the entire road network, inherently integrates different spatially interdependent assets, resource can be more objectively allocated for maintenance in terms of their structural and/or functional performance. Before that, the link between performance measure and asset conditions need to be determined.

Figure 3.1 illustrates a general framework for managing and maintaining multiple types of asset by integrating their interdependency. The flowchart looks similar to a silo-based decision-making process for a single type of asset, which includes the key components of condition evaluation, treatment selection, condition prediction, performance measurement, and an optimization mechanism. However, the general framework takes the entire road network as the input, in which different assets, e.g., pavements, bridges, signs, and culverts, are not in silos. Instead, each individual asset forms a building block of the entire road network. In addition, the performance measure is not a weighted sum of different assets' condition ratings, which relies on decision makers' preference. In the framework, the performance measure should take the entire road network as the input and take into the consideration of transportation and/or safety. Thus, the interdependency among different assets can be integrated.

To implement the general framework, the following models need to be determined.

- 1) Transportation network model. To integrate all transportation assets of different types, a network model is needed, which is usually a directed graph.
- 2) Performance measure. A road network provides users with transportation and safety. Thus, their performance can be a direct health indicator of the combination of all different transportation assets. In transportation planning, there are many performance measures defined for transportation (e.g., traffic, mobility, and accessibility) and/or safety (e.g., number of run-of-road fatalities, number of speeding-related fatalities, etc.). However, in the context of maintenance programming, the performance measure should be directly related to asset conditions.
- 3) Relationship between asset condition and performance measure. For example, if traffic time is selected as a performance measure, the relationship between pavement/bridge condition and traffic capacity needs to be determined. Thus, the benefit of asset maintenance can be reflected in the improvement of traffic time.
- 4) Asset condition deterioration model. Asset deterioration model tells how its condition drops over time without any treatment. The accuracy of deterioration model affects how well the network-level asset condition can be predicted and the maintenance programming can be planned over a given time horizon, e.g., 5 or 10 years.
- 5) Treatment cost, performance and selection criteria. The final decision of an asset management system is when, where, and how to treat an asset. Thus, the knowledge about treatments and cost is very crucial. Local market and economy are factors of treatment cost. Its prediction needs economic analysis. The performance of a treatment determines the preference of selecting a candidate treatment. The candidate treatments are normally determined in terms of an asset's condition. Thus, the treatment selection criteria are needed.
- 6) Mathematical optimization. To acquire the optimal treatment solution that maximizes the network performance, a mathematical optimization model is needed. Because the solution is to determine when, where, and how to treat an asset, an integer programming is often employed.

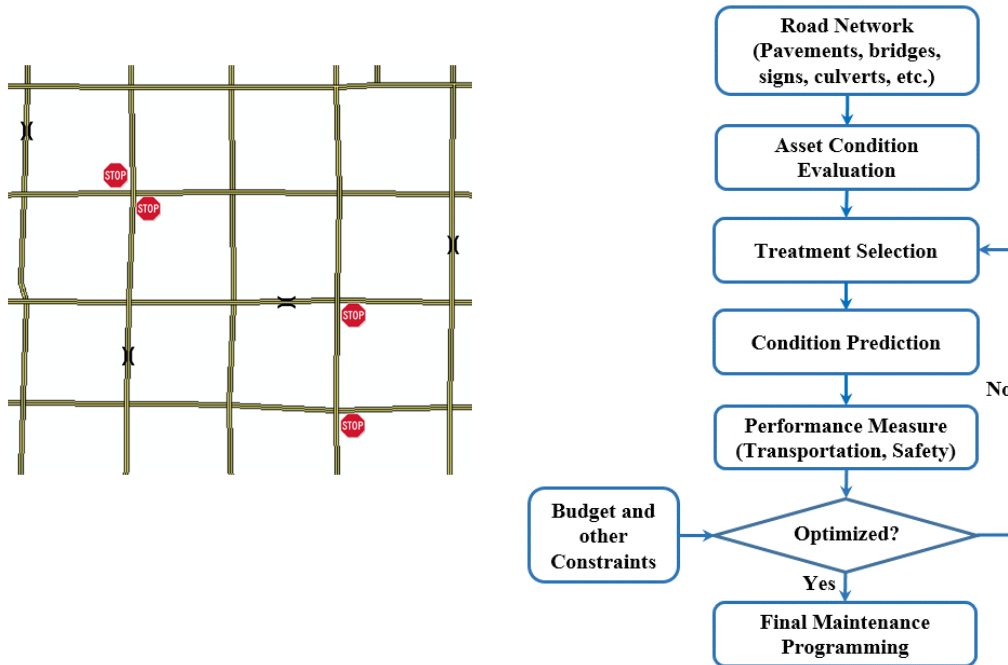


Figure 3.1 A General Framework for Managing Interdependent Assets

2. Implementation of General Framework

To demonstrate the advantages of the general framework, the following illustrates an implementation using a road network consisting of pavements and bridges that are two biggest transportation assets. To explicitly consider the interdependency between pavements and bridges, the average travel time of the road network is used as the performance measure.

Figure 3.2 shows the system architecture that is an instantiation of the general framework discussed above. Because pavements and bridges work together to provide transportation, there is no need of decision makers' preference on each of these two types of assets when maintenance programming is being planned. The performance measure and objective are defined in terms of the transportation provided by the road network, which is to minimize the network travel time, while the decisions are made in the area of pavement/bridge engineering, which are the maintenance programming for both pavements and bridges. The relationship between the pavement/bridge conditions and their traffic capacity bridges these two areas.

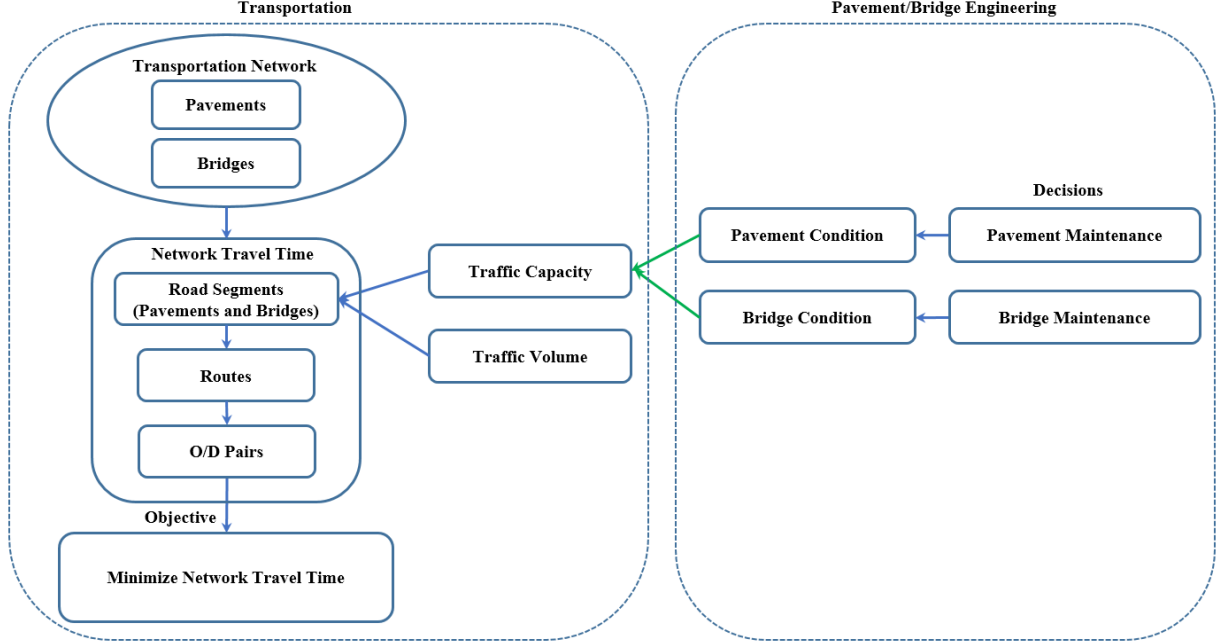


Figure 3.2 Architecture for Managing Pavements and Bridges

2.1 Transportation Network and Travel Time Computation

A transportation network can be modeled as a directed graph $G = (V, E)$, where V is the set of all nodes and E is the set of all arcs (i.e. road segments). For convenience, bridges can be associated with pavements instead of being midpoints. A normal node has no limitation on traffic capacity. Use bp_j to indicate the pavement id where bridge j is associated as shown in Eq. (1).

$$bp_j = i, \text{ where } i \in (1, 2, \dots, N^p), j = 1, 2, \dots, N^b \quad (1)$$

Where N^p is the total number of pavement segments and N^b is the total number of bridges. When a pavement segment i consists of one or more bridges, its traffic capacity C_i^p is equal to the minimum value of pavement and bridges as shown in Eq. (2).

$$C_i^p = \min(C_i^p, (C_{bp_1}^b, C_{bp_2}^b, \dots, C_{bp_j}^b, \dots, C_{bp_{N^b}}^b; \text{ where } bp_j = i)) \quad (2)$$

The interdependent pavements and bridges provide the mobility of the entire transportation network. In traffic engineering, transportation network mobility refers to the required travel time and costs. Normally, the average travel time and reliability are used as the measure of mobility. In this implementation, the mobility measure developed by Leng, et al. (2017) is used, as shown in Eq. (3).

$$T_{gi} = \eta \left(\frac{T_i}{t_i} \right) + (1 - \eta)r_i, i = 1, 2, \dots, N^p \quad (3)$$

where T_{gi} is the generalized travel time. It consists of two parts: the first part is the ratio of actual travel time T_i to the free-flow traffic t_i ; the second part is the probability that a road segment doesn't meet the reliability requirement. These two parts are summed using two weighting factors, η and $1-\eta$, which can be determined by Stated Preference (SP) survey. The

detailed computation of T_{gi} can be referred to the work done by Leng, et al. (2017), in which T_i is a function of traffic volume, TV_i , and traffic capacity, C_i^p .

Eq. (3) only measures the mobility of one pavement segment, i . To measure the mobility of the entire transportation network, the average travel time for each origin-destination (OD) pair is first defined. Then, the travel time for the entire network can be evaluated based on the mobility of all OD pairs.

The shortest path (st) for each OD pair from node s to t is used to compute the travel time, $T_{g,st}$, which is a weighted average travel time of all pavement segments on this path. TV_i on each segment is used as the weighting factor.

$$T_{g,st} = \frac{\sum_{i=1}^{N^p} \delta_{i,st} \cdot TV_i \cdot T_{gi}}{\sum_{i=1}^{N^p} \delta_{i,st} \cdot TV_i} \quad (4)$$

Where

$$\delta_{i,st} = \begin{cases} 1, & \text{pavement segment, } i \in (st) \\ 0, & \text{pavement segment } i \notin (st) \end{cases} \quad (5)$$

The travel time of the entire network, T_g , is then defined as the weighted average of all possible OD pairs. The length, l_{st} , of each OD pair is used as the weighting factor.

$$T_g = \frac{\sum_{s \in V, t \in V, s \neq t} l_{st} \cdot T_{g,st}}{\sum_{s \in V, t \in V, s \neq t} l_{st}} \quad (6)$$

T_g also measures the accessibility of the road network. If an OD pair is inaccessible, the entire road network has an infinite travel time, and therefore, is not connected.

2.2 Traffic Capacity and Asset Condition

As shown in Figure 3.2, the relationship between traffic capacity and pavement/bridge condition links traffic engineering and pavement/bridge engineering. Normally, a pavement or bridge's traffic capacity will decrease when its condition degrades. Condition improvement due to maintenance will increase its traffic capacity.

To the best of our knowledge, there is not much research in this interdisciplinary area in literature. Chandra (2004) has studied the two-lane roads in India by correlating road traffic capacity to pavement roughness, which is measured by the international roughness index (IRI).

$$C_i^p = 93,312 - 113.3 \cdot IRI \quad (7)$$

In Eq. (7), the unit of C_i^p is passenger car unit per day (PCU)/d and the one for IRI is inch per mile (in/mi). This is an empirical equation, in which 93,312 is the design capacity. In the following case study, this equation is modified to fit in with the test road network.

Pertaining to bridges, no relative research was found in the literature to correlate bridge capacity to its condition. For demonstration purpose, a step function is assumed based on the definition of the National Bridge Inventory (NBI) score as shown in Table 3.1. Given the design traffic capacity, a bridge's capacity is discounted by the NBI score. For example, when NBI is 5 in fair condition, the capacity is 85% of the design value. When NBI is in critical or imminent failure, its capacity is 0 because the bridge needs to be closed for corrective action.

2.3 Asset Deterioration and Treatment Improvement

The deterioration model is a key component in an asset management system. When a pavement or bridge deteriorates, its traffic capacity will also decrease. Ouyang & Madanat (2004) proposed a deterministic deterioration model. It is a simplification based on the model developed by Paterson (1990).

$$s(t + 1) = (s(t) + f^*) \cdot \exp(\beta), \quad t = 0, 1, 2, \dots, T \quad (8)$$

Where t is the discretized time starting from 0. According to the pavement survey interval, time is normally discretized as years. T is the total analysis horizon. f^* is a constant representing the average deterioration trend and β is a small constant. Pavement condition, $s(t)$ is measured by roughness, i.e., IRI.

Table 3.1 Bridge Condition and Traffic Capacity

NBI	Percentage of Design Capacity (%)	Description (FHWA, 2018)
9, 8	99	Excellent or very good condition
7	95	Good condition: some minor problems
6	90	Satisfactory condition: minor structural element deterioration
5	85	Fair condition: minor section loss, cracking, spalling or scour
4	50	Poor condition: advanced section loss, deterioration, spalling or scour
3	40	Serious condition: loss of section, deterioration, spalling or scour affects primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present
2, 1	0	Critical or imminent failure condition: bridge should be closed for corrective action

When pavement maintenance is applied, pavement condition will be improved. For simplicity, three categories of treatments, including “do nothing”, “minor preventive maintenance”, and “major rehabilitation” are used as shown in Table 3.2.

Table 3.2 Treatment Criteria for Pavement

Pavement Condition (IRI)	Do Nothing	Minor Preventive Maintenance	Major Rehabilitation
Good (IRI < 95 in/mi)	X		
Acceptable (95 < IRI < 170 in/mi)	X	X	
Poor (IRI > 170 in/mi)	X		X

As shown in Table 3.2, pavement condition is categorized as good, acceptable, and poor based on a different range of IRI. Minor preventive maintenance, e.g., microsurfacing, can only be applied to “acceptable” pavement; and major rehabilitation, e.g., milling and overlay, can only be applied to “poor” pavement. The effectiveness of each treatment is defined as follows:

- Do nothing: no condition improvement
- Minor Preventive Maintenance: pavement condition remains the same for the next 2 years
- Major rehabilitation: pavement condition becomes good ($IRI < 95\text{in/mi}$)

For bridges, a Markov transition probability matrix (TPM) is used as shown in Table 3.3 (Morcouc & Hatami, 2011). Though different components, e.g. deck, superstructure, or substructure, of a bridge has different deterioration characteristics, for simplicity, only the one for substructure is used in this implementation.

Table 3.3 Bridge Deterioration Probabilities

NBI	9	8	7	6	5	4	3	2	1
9	0.85	0.15	0	0	0	0	0	0	0
8	0	0.95	0.05	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.91	0.09	0	0
3	0	0	0	0	0	0	0.89	0.11	0
2	0	0	0	0	0	0	0	0.94	0.06
1	0	0	0	0	0	0	0	0	1.0

Similarly, for treatment purpose, bridge condition is categorized as excellent, good, fair, and poor based on a different range of NBI scores. Minor preventive maintenance can only be applied to “good” or “fair” bridges, and major rehabilitation can only be applied to “poor” bridges. The effectiveness of each treatment is defined as follows:

- Do nothing: no condition improvement
- Minor Preventive Maintenance: bridge condition remains the same for the next 2 years
- Major rehabilitation: pavement condition becomes excellent ($NBI = 9$)

Please note that the above models, treatment selection criteria, and treatment performance are only used for demonstrating an implementation of the proposed framework. For real-world applications, these models and criteria need to be modified or refined according to the actual pavement and bridge characteristics and treatments.

2.4 Interdependency-based Mathematical Optimization Model

With the above models established, the mathematical optimization can be developed. Without loss of generality, let U^p and U^b be the interdependent sets of all pavement segments and bridges,

respectively. $x_{i,t,k}$ is the decision variable for pavement segment i taking treatment k in year t . Similarly, $y_{i,t,k}$ is the decision variable for bridge i taking treatment k in year t . $x_{i,t,k}$ and $y_{i,t,k}$ are two 0-1 variables as follows.

$$x_{i,t,k} = \begin{cases} 1, & \text{if treatment } k \text{ is applied to pavement } i \text{ in year } t \\ 0, & \text{if treatment } k \text{ is not applied to pavement } i \text{ in year } t \end{cases} \quad (8)$$

$$y_{i,t,k} = \begin{cases} 1, & \text{if treatment } k \text{ is applied to bridge } i \text{ in year } t \\ 0, & \text{if treatment } k \text{ is not applied to bridge } i \text{ in year } t \end{cases} \quad (9)$$

The objective is to minimize the network travel time in all analysis years, which is equivalent to maximize the network mobility.

$$\text{Objective: minimize } \sum_{t=1}^T T_{gt} \quad (10)$$

where T_{gt} is the generalized travel time for the entire transportation network in year t , which is the function of the transportation network, and the traffic volume and traffic capacity of each pavement segment and bridge as introduced in the above subsection.

The following constraints are applied.

- Annual budget, B_t .

$$\sum_{i \in U^p} \sum_{k=0}^{K^p} (1+d)^t \cdot c_{i,k}^p \cdot x_{i,t,k} + \sum_{i \in U^b} \sum_{k=0}^{K^b} (1+d)^t \cdot c_{i,k}^b \cdot y_{i,t,k} \leq B_t \quad (11)$$

where K^p and K^b are the numbers of available treatments (including “do nothing”) for pavements and bridges, respectively. $c_{i,k}^p$ and $c_{i,k}^b$ are the cost if treatment k is applied for i^{th} pavement segment and bridge, respectively. d is the discount rate, which is assumed to be a constant.

- Intrinsic constraints: one and only one treatment should be applied to a pavement segment or a bridge in one year.

$$\sum_{k=0}^{K^p} x_{i,t,k} = 1, \forall t \in \{1, 2, \dots, T\}, i \in U^p \quad (12)$$

$$\sum_{k=0}^{K^b} y_{i,t,k} = 1, \forall t \in \{1, 2, \dots, T\}, i \in U^b \quad (13)$$

- Functions to relate pavement/bridge condition to traffic capacity (see Eq. 7 and Table 3.1)
- Deterioration functions (see Eq. 8 and Table 3.3)

The above optimization model is an integer programming. For a large transportation network, the exact solution is hard to be found. Thus, a heuristic method is often needed. In the following case study, a genetic algorithm (GA) is applied.

3. Case Study

A case study is performed using a local road network shown in **Figure 3** to demonstrate applicability and effectiveness of the general framework. The selected network contains 169 utilities, i.e., 140 pavement segments and 29 bridges. The pavement ID is marked on each segment and corresponding bridge ID is in the brackets. The AADT of each road segment was extracted from the traffic count data in Georgia Department of Transportation. The initial utility conditions, IRIs for pavements and NBIs for bridges, were assigned purposely to facilitate the case study.

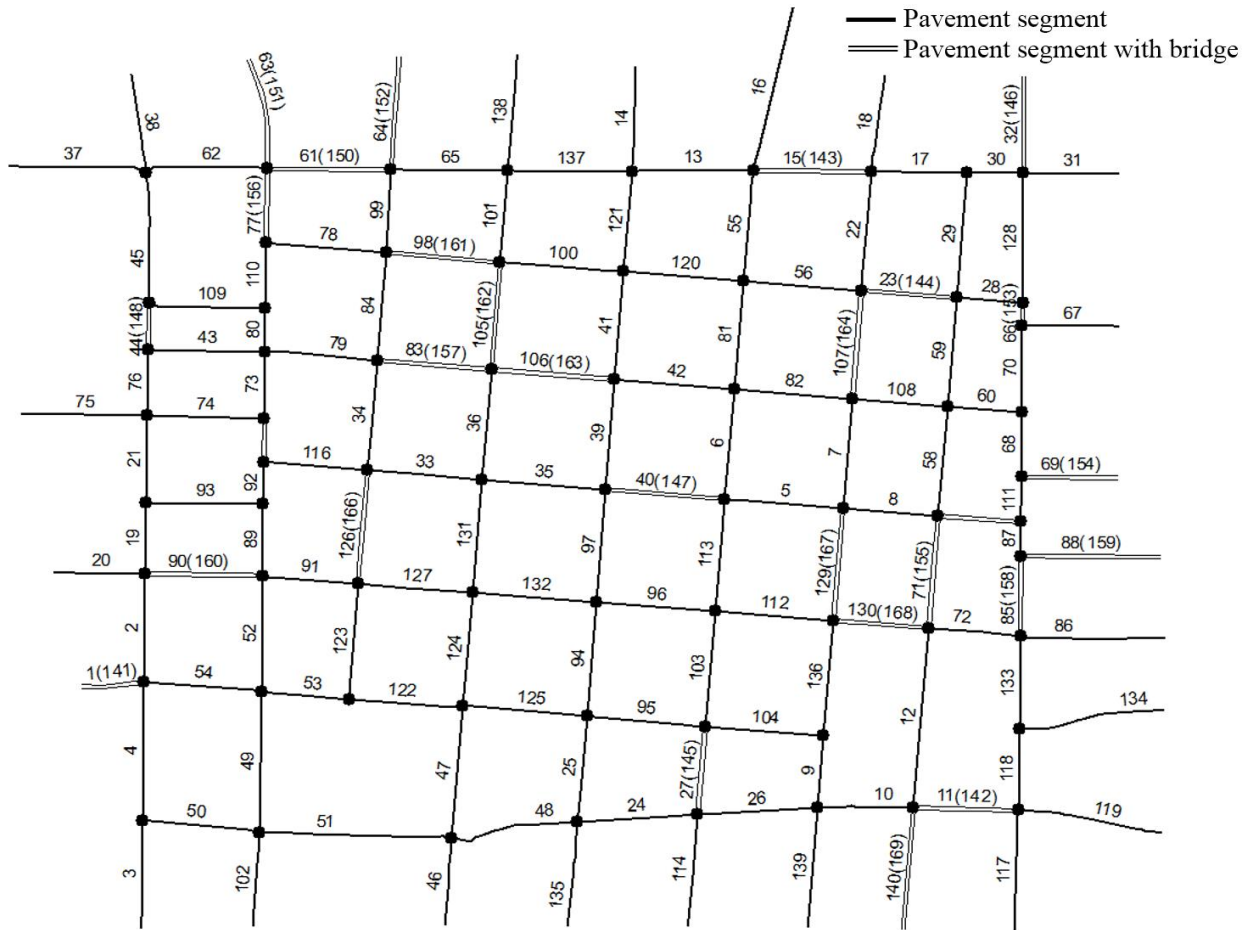


Figure 3.3 A Local Road Network

3.1 A WSM-based Optimization Model for Comparison

To assess the effectiveness of interdependency-based asset management, a weighed-sum-model (WSM)-based optimization model is also developed. In a normal WSM framework, pavements and bridges are considered as two independent assets. When decision makers allocate funds between these two assets, a common strategy is to use a multiobjective optimization model, i.e., to maximize the overall conditions of pavements and bridges with given constraints. The overall

condition of pavements can be the length-weighted roughness; the one for bridges can be traffic-volume-weighted NBI scores. To make a decision based on these two conflicting objectives, WSM is the most commonly used method, by which a multiobjective optimization can be converted to a single-objective counterpart. Before that, the rating for pavements and bridges need to be scaled for a fair comparison. Assuming the range for pavement IRI is (90, 240), Eq. (14) converts pavement roughness to a score, PR , ranging between 0 and 100 (0 indicates the roughest pavement; 100 indicates the smoothest one). Similarly, Eq. (15) convert bridge NBI score to another score, BR , ranging between 0 and 100, too.

$$PR = \frac{240-IRI}{240-90} \times 100 \quad (14)$$

$$BR = \frac{NBI-1}{9-1} \times 100 \quad (15)$$

When a WSM method is used, the above two objectives are converted to maximizing the composition rating, CR , that is the weighted sum of PR and BR , where w is the weighting factor for pavements and l_i is the linear length of i^{th} pavement segment.

$$\text{maximize: } CR = w \cdot \frac{\sum_{i=1}^{N^p} PR_i \cdot l_i}{\sum_{i=1}^{N^p} l_i} + (1 - w) \cdot \frac{\sum_{j=1}^{N^b} BR_j \cdot TV_j}{\sum_{j=1}^{N^b} TV_j} \quad (16)$$

For a fair comparison, the constraints for this WSM-based optimization model are exactly same with the ones of interdependency-based counterpart.

3.2 Objectivity vs. Subjectivity

Buchanan, et Al. (1998) had a comprehensive discussion about the distinction between objectivity and subjectivity. “The rule is: subjective pertains to elements which belong to the mind; elements that are outside the mind and which can be shared by other people are objective.” Based on this definition, all “elements” in the interdependency-based optimization model are “outside the mind”, and “can be shared by other people”. On the other hand, the weighting factor, w , in the WSM-based optimization model is purely a decision maker’s preference. This preference belongs to the mind, and cannot be shared.

To quantify the impact of the subjectivity, a sensitivity study is conducted by changing the weighting factor, w , from 0 to 1. Table 3.4 lists the generalized network travel time, T_g , and composite rating, CR along with different weighting factors after the first year’s treatments.

Table 3.4 Sensitivity Study of MCDM-based Optimization Model

w	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
T_g	7.603	7.371	4.600	4.600	5.213	4.600	4.600	4.600	5.213	4.600	4.600
CR	66.41	65.41	67.55	71.43	74.30	76.56	80.02	82.89	85.69	88.56	91.45

Because of the use of decision makers’ preference, the CR s in different cases are not comparable. However, the measurement of travel time, i.e., T_g , can be used for comparison because it is more objective. From Table 3.4, neither apparent correlation between w and T_g nor the one between CR and T_g can be observed, which means the preference-based decisions on maintenance are not related to the transportation-based performance measure. Though T_g is the best (4.600) under several weighting factors, it is only applicable in this specific case study.

The above sensitivity study shows that the WSM-based maintenance programming is subjective, and relies on decision makers’ preference. The resulting benefit for network travel time might not be optimal in terms of the benefit in transportation.

3.3 Maintenance Strategy Comparison

Table 3.5 summarizes the different maintenance strategies for the first year using the above two optimization models. w is chosen as 0.7 based on the above sensitivity study, which yields the best performance in terms of travel time. A five-year programming is presented in this case study with a yearly \$6 million budget.

Due to the limited budget, only one bridge in poor condition can be rehabilitated. As shown in Table 3.5, the interdependency-based model selected bridge #153 (initial NBI = 3) that is located on pavement segment #66 (initial IRI = 200), which is rehabilitated at the same time. However, WSM-based model didn’t allocate any funding for major rehabilitation on any bridge in the first year. Instead, large amount of funding is used for minor preventive maintenance on pavement in order to achieve the highest composite rating, which doesn’t contribute to improving transportation efficiency.

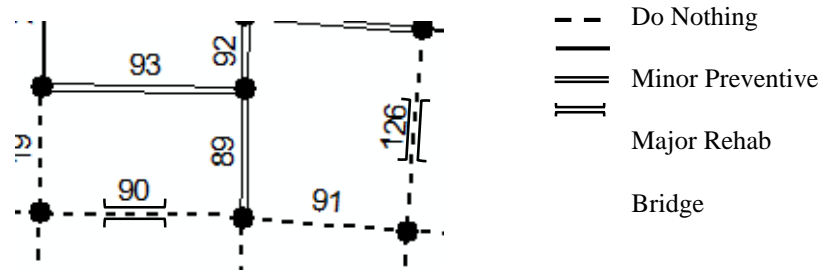
Figure 3.4 compares the maintenance programming in a small subset of the road network. Different line styles illustrate different pavement treatment methods, i.e., “Do Nothing,” “Minor Preventive,” and “Major Rehab” for the first year. Two bridges under poor condition (NBI values are 1, and 2, respectively) are located on pavement segment #90 and #126 (pavement IRIs are both 200). Due to the limited budget, either of these two bridges cannot be treated at this time. Thus, the interdependency-based model chose Do Nothing on these two pavement segments, too, as shown in Figure 3.4 (a). This is because repairing pavement only doesn’t improve transportation efficiency if either bridge cannot be treated in the meantime. In contrast, the WSM-based model applied major rehabilitation to the two pavement segments as shown in Figure 3.4 (b), which is a futile attempt since bridge is the key utility to control transportation in

this case. In real-world scenario, this would cause a maintenance conflict that needs the coordination between pavement and bridge maintenance units. However, this coordination might not be needed when the interdependency-based model is used because it could potentially solve this issue systematically by considering the spatial interdependency between pavements and bridges.

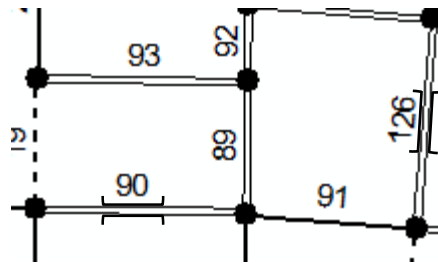
Table 3.5 Comparison of Maintenance Strategy in First Year

		Minor Preventive Maintenance (Utility ID(s))	Major Rehabilitation (Utility ID(s))	Total Cost (Million Dollar)
Interdependency-based model $T_g = 2.448$ $CR = 62.76$	Pavement	5,8,21,30,36,50,58,60,74,85,99,102,119,135	6,10,11,13,16,17,18,23,28,46,61,64,66,70,71,73,76,78,80,88,89,92,93,111,113,114,116,118	5.72
	Bridge	142,150,155,156,168,169	153	
WSM-based Model $T_g = 4.600$ $CR = 82.89$	Pavement	2,3,5,8,20,21,30,36,49,50,52,55,56,58,60,62,69,74,81,85,91,95,99,102,103,117,119,135	6,9,10,11,13,14,16,17,18,23,25,26,28,33,34,39,42,43,46,47,48,51,53,54,57,61,64,66,70,71,72,73,76,78,79,80,83,84,88,89,90,92,93,94,105,106,108,111,112,113,114,116,118,122,124,125,126,127,129,132,138,139,140	5.92
	Bridge	144,146,150	None	

The above case demonstrates the benefit of adopting an interdependency-based model because it considers different types of assets as integral parts of the entire road network. In contrast, the WSM-based model only pursues the highest rating, in which the spatial relationship among different assets cannot be considered.



(a) Interdependency-based model



(b) WSM-based model

Figure 3.4 Comparison of Maintenance Strategy of Selected Pavements and Bridges

Table 5 lists the five-year performance of two models. The interdependency-based model significantly improves the transportation performance. Ten-times' difference is observed at second and third year. Since user costs represent the monetary value of travel delays, if translated to user costs, that would imply a big savings.

Table 3.6 Comparison of T_g in Five-Year Programming

Model	Year 1	Year 2	Year 3	Year 4	Year 5
Interdependency	2.448	0.556	0.459	0.460	0.458
WSM	4.600	5.205	5.210	1.207	1.062

In summary, the interdependency-based model has much more optimal yearly transportation performance because the priority is always given first to the key utility. In contrast, WSM-based model tends to randomly select candidate utilities ignoring their inherent spatial interdependency.

4. Discussion

From the proposed framework and the case study, it can be seen that the selection of a proper network-level performance measure is the first key component to establish the spatial interdependency among different types of assets. The performance measure should be directly linked to the service provided by a road network, e.g., transportation and/or safety. The commonly used statistical measure based on utilities' structural or functional conditions assumes they are independent of each other. Though the weighted sum of the structural or functional conditions of different assets are more or less related to the service of entire road network, the maintenance programming is normally irrelevant to the spatial interdependency among different types of assets, and thus, cannot guarantee the most cost effectiveness in terms of the service of entire road network. In addition, the maintenance confliction cannot be avoided as shown in the case study.

The second key component is the relationship between asset condition and road network performance measure. To the best of our knowledge, the relative research is rare. The study of asset condition and corresponding treatments falls in the pavement/bridge engineering; the study of road network performance measure is often found in transportation planning. Theoretically speaking, the condition of transportation assets, e.g., pavements, bridges, and others, impact the LoS of entire road network, e.g., transportation and safety, though it is not the single factor. However, in the context of maintenance programming, other factors can be considered fixed. Thus, there does exist a relationship between asset condition and road network performance measure. After all, the purpose of maintaining asset condition at an acceptable level is to provide the sufficient LoS to road users.

For purpose of demonstration, the weighted average travel time of all possible OD pairs was adopted as a road network performance measure in this study. It could be used to reflect the LoS in terms of transportation efficiency of a road network. Its relationship with pavement condition was established based on an existing study on IRI and traffic capacity. For bridge, there is no relative research found in literature. Thus, an assumption was made in this study. Intuitively, asset condition could affect traffic capacity when its condition is bad. For example, when pavement rutting or raveling is very severe, drivers have to slow down their speeds. Thus, the free flow speed will be lowered accordingly. Similarly, when a bridge is structurally deficient, traffic would be affected. On the other hand, when asset condition is not so bad that driving safety is not a concern, traffic capacity should not be affected. Therefore, the relationship models used in the case study might not be accurate.

Nevertheless, the findings from the case study are still valid given the assumption on the relationship models. First, the integration of spatial interdependency of different types of assets makes it possible for a maintenance programming to identify the key utilities in the sense of road network instead of the weighted sum of asset ratings. According to the 2017 ASCE Infrastructure Report Card, 20% of highway pavement in U.S. is in poor condition; and 9.1% of

all bridges were structurally deficient in 2016. Given the situation of severe backlog of asset repair, the impact of the deteriorated asset conditions on road network performance needs to be studied. Thus, the maintenance funding can be more cost-effectively used to improve the LoS of entire road network. Second, the interdependency-based model treats different types of assets as building blocks of the entire road network. The maintenance programming is determined based on their contribution to the road network performance. Thus, the maintenance confliction between different assets can be avoided.

As a first endeavor, this study attempts to demonstrate the importance and effectiveness of integrating the spatial interdependency of different types of assets in maintenance programming. As a continuous research, there is a need to develop a dedicated performance measure that can better describe the spatial interdependency and be correlated to assets' structural and/or functional condition.

5. Summary

Cross-asset maintenance programming in highway agencies often adopts MCDMs that involve subjective engineering judgment. To enhance the objectivity and improve the cost-effectiveness, a general framework for cross-asset maintenance programming was explored. Under this framework, the interdependency among different types of assets can be explicitly considered. Thus, the maintenance programming can be more objectively determined.

To demonstrate the effectiveness of the general framework, the maintenance programming for a road network consisting of pavements and bridges, the two biggest transportation assets, was formulated as an interdependency-based optimization model by incorporating traffic capacity models, deterioration models, and treatment improvement models. In the meantime, for comparison purpose, a WSM-based optimization model was also developed by adopting the commonly used engineering-judgment-based MCDM method.

A case study was conducted using a road network consisting 140 pavement segments and 29 bridges. The results demonstrated that WSM-based maintenance programming and the resulted performance relies on decision makers' preference. In contrast, the interdependency-based counterpart can achieve the best maintenance programming that maximizes the transportation efficiency of the road network without the need of decision makers' preference. More importantly, the maintenance programming based on engineering judgment cannot consider the spatial relationship and interdependency among different types of assets, which results in the difficulty of coordination in highway agencies' practice.

The research showed promising results of integrating interdependency in cross-asset maintenance programming to enhance the objectivity in multi-criteria decision making and improve the cost-effectiveness. For a more practical application, further research is still needed. First, a new performance measure is needed to integrate different types assets. In this paper, the

performance measure is only related to the transportation efficiency of a road network. If safety is considered, other safety-related assets can also be integrated in the general framework. Second, the relationship between asset conditions and performance measure needs further study. To demonstrate the effectiveness of the general framework, significant simplification was made on the related models. For a practical application, these models need further study. Third, the models for asset deterioration and treatment improvement need to be developed for a highway agency using its historical asset condition and maintenance data. Finally, for a large road network, the computing efficiency needs to be improved by parallelizing the GA algorithms using GPU and/or computer cluster.

Chapter 4: Exploration of New Bridge Deterioration Modeling

1. Proposed Modifications on Bridge Deterioration Modeling

In the previous stage, assumption on bridge condition was made based on existing research of pavement and its condition measure. Very few references could be drawn from literatures implying bridge condition assessment, bridge capacity and corresponding treatment improvement. The bridge deterioration model may also need some refinements.

For bridges, a Markov transition probability matrix (TPM) is used to compute the deterioration matrix. Unlike a pure deterioration model, matrices below are calibrated that during the inspection period bridge components may experience maintenance actions plus deterioration (Sun et al., 2004). Such matrices could assist in predicting bridges' future performance with different maintenance actions in the following years. In the previous study, only the one for substructure is used in the implementation for different components, e.g. deck, superstructure, or substructure for simplicity, yet these three components of a bridge has different deterioration characteristics. Deck, superstructure, or substructure deteriorate following different patterns. Additionally, they serve various functions to a bridge, and their maintenance actions are supposed to be prioritized by certain criteria. The overall health of a bridge is determined by all three elements.

2. Improvements on Bridge Deterioration Modeling

The National Bridge Inventory (NBI) is previously used in our study, in which capacity is expressed in percentages. NBI scores of 8 or 9 suggest capacity of 99% of the value originally designed, and NBI scores of 1 or 2 correlate to capacity of 0. NBI scores of 3,4,5,6 and 7 are respectively linked with bridge capacity of 40%, 50%, 85%, 90%, and 95%.

2.1 Composite Rating of Bridge Condition

Quality of decks, substructure and superstructure, as major components of a bridge, all account for the overall bridge health condition. A single component defect could undermine bridge health and traffic capacity. California Bridge health index (BHI) equals to the ratio of the current element value to the total element value, taking variables including weighting factors of each condition state, failure costs, quantities or areas of each element (Thompson and Shepard, 2000). Based on the logic of California BHI, a Bridge Quality Index (BQI) could be developed as follows, which gives the ratio of the current bridge value to the total bridge value as initially designed.

$$CBV = \sum NBI_i * Area_i * UC_i$$

$$TBV = NBI_{ini} * \sum Area_i * UC_i$$

$$BQI = \frac{CBV}{TBV} * 100\%$$

Where

i = component categories d, b, p, representing deck, substructure, superstructure of a bridge

NBI_i = NBI of each bridge component

$Area_i$ = Area of each bridge component (in ft²)

UC_i = Predicted replacement cost of each component (in \$/ft²)

$NBI_{ini} = 9$, original/excellent condition of bridge component

CBV = Current bridge value

TBV = Total bridge value, i.e. remaining value at year 0.

BQI generates composite rating scores for a bridge, taking NBI rating scores, areas and unit costs of 3 bridge components, decks, substructure and superstructure. Integrating areas and unit costs of each component can partly avoid subjectivity in determining composite scores with three input NBI scores. The unit cost of a component corresponds to its economic value for decks, substructure and superstructure are \$90, \$1200, and \$210 per square feet defined by Louisiana Department of Transportation (Sun et al., 2004). Area of each component used in calculation was estimated and computed based on the measurements of concrete bridges design samples published on U.S. Federal Highway Administration website (FHWA, 2017). Sample area used for testing were 34,188, 76,998, and 1,609 for decks, substructure and superstructure respectively (Wassef et al., 2003). Detailed measurements of three components of each bridge will be needed for further study.

2.2 Deterioration Models of Different Bridge Elements

For bridges, a Markov transition probability matrix (TPM) is used as shown in Table 4.1, Table 4.2, and Table 4.3 (Morcouc & Hatami, 2011). Major component, e.g. deck, superstructure, or substructure, of a bridge has different deterioration characteristics for which different transition matrix table is used for calculation. Tables of bridge deterioration probabilities matrix for three components are shown below. For instance, deck element of a bridge is rated as a NBI of 9 this year, and the probability that its NBI deteriorates to 8 is 23% and there is 67% possibility that it remains at the same condition as this year.

Table 4.1 Deck Deterioration Probabilities

NBI	9	8	7	6	5	4	3	2	1
9	0.67	0.23	0	0	0	0	0	0	0
8	0	0.89	0.11	0	0	0	0	0	0
7	0	0	0.91	0.09	0	0	0	0	0
6	0	0	0	0.89	0.11	0	0	0	0
5	0	0	0	0	0.93	0.07	0	0	0
4	0	0	0	0	0	0.70	0.30	0	0
3	0	0	0	0	0	0	0.90	0.10	0
2	0	0	0	0	0	0	0	0.99	0.01
1	0	0	0	0	0	0	0	0	1.0

Table 4.2 Substructure Deterioration Probabilities

NBI	9	8	7	6	5	4	3	2	1
9	0.85	0.15	0	0	0	0	0	0	0
8	0	0.95	0.05	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.91	0.09	0	0
3	0	0	0	0	0	0	0.89	0.11	0
2	0	0	0	0	0	0	0	0.94	0.06
1	0	0	0	0	0	0	0	0	1.0

Table 4.3 Substructure Deterioration Probabilities

NBI	9	8	7	6	5	4	3	2	1
9	0.92	0.08	0	0	0	0	0	0	0
8	0	0.95	0.05	0	0	0	0	0	0
7	0	0	0.94	0.06	0	0	0	0	0
6	0	0	0	0.87	0.13	0	0	0	0
5	0	0	0	0	0.94	0.06	0	0	0
4	0	0	0	0	0	0.91	0.09	0	0
3	0	0	0	0	0	0	0.89	0.11	0
2	0	0	0	0	0	0	0	0.94	0.06
1	0	0	0	0	0	0	0	0	1.0

2.3 Bridge Maintenance Definition

For treatment purpose, BQI scores are divided into 4 ranges to fit into common actions applied to NBI scores defined by FHWA (FHWA, 2018). Thresholds of each range are defined based on the discounting percentages of NBI scores mentioned in the previous section of the paper.

Minor preventive maintenance can only be applied to good or fair bridges; major rehabilitation is needed for bridges in serious or poor conditions; component replacement should

be applied to bridges in failure conditions. Bridges with NBI scores above 7 (BQI above 95%) are grouped and currently need no action. Major and minor maintenance costs could be considered as a fraction of replacement costs. Conversion between NBI and BQI is shown in Table 4.4. The effectiveness and unit cost of each treatment is defined as follows:

- Do nothing: no condition improvement
- Minor Preventive Maintenance: bridge condition remains the same for next 2 years,
- Major rehabilitation: bridge condition becomes excellent (BQI above 95%)
- Replacement: replacement of elements and bridge condition becomes excellent

Table 4.4 BQI and NBI Conversion and Actions

NBI Code	FHWA Description	BQI Scores	Common Actions
9	Excellent Condition	100%~95%	Do Nothing
8	Very Good Condition		
7	Good Condition		
6	Satisfactory Condition	85%~95%	Minor Maintenance
5	Fair Condition		
4	Poor Condition		
3	Serious Condition	40%~85%	Major Rehabilitation
2	Critical Condition		
1	Imminent Failure Condition		
0	Failed Condition	0~40%	Replacement

Please note that the above models, treatment selection criteria, and treatment performance are only used for demonstrating an implementation of the general framework. For real-world applications, these models and criteria need to be modified or refined according to the actual pavement and bridge characteristics and treatments.

3. Case Study brief and Results

A case study is performed using the same local road network shown in Figure 4.1 similar to the previous study to demonstrate effectiveness and improvements of the general framework. The selected network contains 169 utilities, i.e., 140 pavement segments and 29 bridges. Each segment is marked by its pavement ID and corresponding bridge ID is in the brackets. The annual average daily traffic of each road segment was extracted from the traffic count data in Georgia Department of Transportation. The initial utility conditions and IRIs for pavements

were assigned the same as the previous study for comparison purposes. NBIs of deck, substructure and superstructure components were assumed to be the same for each bridge.

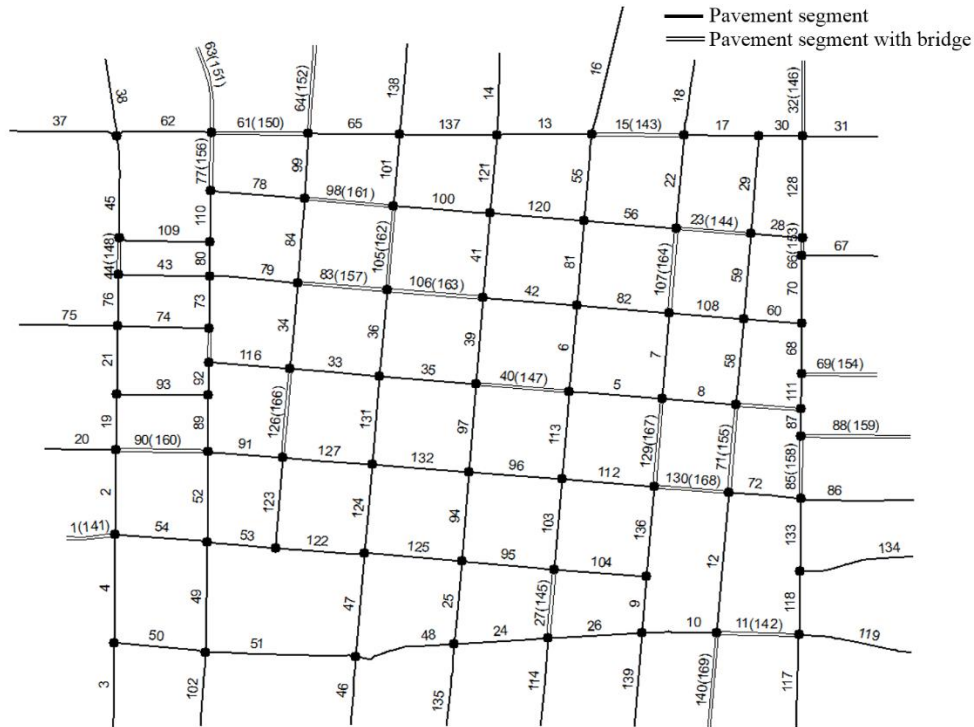


Figure 4.1 A Local Road Network

3.1 Bridge Treatment Actions in Year 1

For demonstration purposes, only results of the first year are presented in the following sections. Based on results from Genetic Algorithm codes and bridge components’ BQI values in the current year, maintenance actions are further divided into 4 categories, as shown in Table 4.5.

Table 4.5 BQI and NBI Conversion and Actions

	No Action	Minor Preventive Maintenance	Major Rehabilitation	Replacement
Bridge IDs	143, 144, 146, 147, 150, 152, 153, 154, 155, 156, 157, 158, 159, 161, 162, 163, 165, 168	168, 169	145, 148, 149, 151, 167, 169	160, 164, 166

3.2 Bridge Condition Changes in Year 1

To provide a clearer view of how individual bridge maintenance actions improve overall health of the bridge, Table 4.6 shows the BQI changes from the current year (year 0) to year 1.

Table 4.6 Bridge BQI and Maintenance Action in Year 1

	Year 0	Year 1			Year 0	Year 1	
Bridge Num	BQI	Maintenance Procedure	BQI	Bridge Num	BQI	Maintenance Procedure	BQI
143	22.2	No Action	22	158	88.9	No Action	89
144	88.9	No action	89	159	100	No Action	100
145	44.4	Major Rehabilitation	95	160	66.7	No Action	67
146	88.9	No Action	89	161	11.1	Replacement	100
147	100	No Action	100	162	88.9	No Action	89
148	66.7	Major Rehabilitation	95	163	100	No Action	100
149	66.7	Major Rehabilitation	95	164	55.6	No Action	56
150	77.8	No Action	78	165	22.2	Replacement	100
151	77.8	Major Rehabilitation	95	166	100	No Action	100
152	100	No Action	100	167	22.2	Replacement	100
153	100	No Action	100	168	55.6	Major Rehabilit	95
154	100	No Action	100	169	77.8	No Action	78
155	66.7	No Action	67				

3.3 Yearwise Results from Genetic Algorithm

Table 4.7 delivers an overview of results from running a 5-year Genetic Algorithm codes. The population size and the number of generation are kept the same as the previous study, being 400 and 50. Annual budget of maintenance of \$600,000 is a constraint of the objective function.

Table 4.7 Yearwise Travel Time and Maintenance Costs Results

	Year 1	Year 2	Year 3	Year 4	Year 5
Travel Time	2.935811E+22	2.935744E+22	2.935744E+22	2.935744E+22	2.935744E+22
Maintenance Costs	10813652.46	8186351.262	954160.9226	427630.0258	451889.9167
Total Cost	20833684.59				

4. Summary

Since assumption was made on bridge condition based on existing research of pavement and its condition measure. The bridge deterioration model may need some modifications.

A Markov transition probability matrix is applied to calculate the deterioration matrix. The matrices could help with bridges' future performance prediction with different maintenance actions in the following years. In the previous study, only the deterioration probability matrix of

substructure is used in the implementation for different components, e.g. deck, superstructure, or substructure for simplicity, though they probably have different deterioration characteristics. Deck, superstructure, or substructure deteriorate following different patterns and have different important levels to the bridge as a whole. Therefore, objective prioritization on maintenance actions should be made based on certain criteria to improve the overall health of a bridge.

Similar to the logic of California Bridge health index, a Bridge Quality Index is developed, which computes the ratio of the current bridge value to the total bridge value as initially designed. BQI gives composite rating scores for a bridge, using NBI scores, areas and unit costs of 3 bridge components. Integration of areas and unit costs of each component can improve objectivity in determining composite scores with three input NBI scores. The use of BQI can therefore improve the overall objectivity of bridge maintenance actions determination.

Possible improvements can be made on the programming of Genetic Algorithm. For a transportation network of 169 infrastructure assets, the computation time to run a 5-year duration test takes more than expected. For future larger road networks, the computation time needs to be shortened for efficiency purposes. This can possibly be achieved through parallelizing GA algorithms using computer cluster and/or GPU.

Chapter 5: Exploration of Traffic Reassignment in Pavement Maintenance Modeling

This chapter introduces the infrastructure assets optimization using genetic algorithm and traffic simulation based on simulation of urban mobility (SUMO). This project aims to optimize conditions of individual infrastructure assets considering their spatial interdependency, to achieve best performance of the road network. This model is established to reduce the subjectivity in resource allocation during the decision-making process. In our study, the optimization is constrained with assigned budget and travel time reliability. Genetic algorithm is applied to optimize maintenance actions over the whole network. A supporting case study is later presented using a small fraction of highway network around Atlanta, Georgia, to demonstrate role of SUMO based traffic simulation.

1. Proposed Framework

This framework utilizes similar methodology as the cross-asset modeling project to reduce the subjectivity in allocating resources among different interdependent transportation assets. The model's objectivity is improved accordingly. Note that pavement assets serve as an example to demonstrate the advantages of the proposed method.

To consider the interdependency among pavements, the mobility of the whole transportation network can be used as the performance measure. The framework for managing interdependent pavement assets is similar to the one used in cross-asset project. Pavements in the entire transportation network work collectively such that decision makers' preference on each individual asset is unnecessary when maintenance programming is being formulated. The performance measure, travel time, is settled similarly in the discipline of traffic engineering, yet the decision-making of maintenance programming is set in the discipline of pavement engineering. The correlation between pavement conditions and corresponding traffic capacity connects such two disciplines. The objective in this case is to perform iterations of simulation to achieve a steady state of network and find best action sequence. The number of iterations is dependent upon transportation network's complexity.

SUMO is the core concept in this project, which refers to a microscopic open source traffic simulator designed to assess traffic models or traffic management plans. Beyond a traffic simulation, SUMO is also a suite packed with applications and tools used to generate input files and perform traffic simulation (Behrisch 2011). It is capable of addressing large transportation networks, in which multiple transportation assets can be handled including public transportation, pedestrian, and vehicles. With the open platform, research groups working on traffic simulation topics can integrate tools into their related algorithms. Through SUMO applications, significant missions such as best routes seeking, traffic visualization and vehicular pollutant emissions prediction.

Major SUMO applications used in this project include NETCONVERT, DEROUTER, and DUAROUTER. NETCONVERT serves to import digital road network maps and perform road network files conversion for other uses of SUMO tools (Behrisch 2011). Multiple formats of road networks can be input of NETCONVERT tool, including OpenStreetMap and SUMO network files. NETCONVERT is coded to deal with edges, junctions, nodes and pedestrian on the input networks. After road networks are created by NETCONVERT, DFROUTER takes values generated from induction loops and derives routes and flow data of vehicles. Another useful application DUAROUTER is used for computing routes for further uses and adopts shortest path calculation (Behrisch 2011). Routes of vehicles are established based on certain user-defined demand.

TraCI stands for Traffic Control Interface and works together with SUMO to assist users with accessing data of a running traffic simulation and controlling elements being simulated. TraCI can be imported as a Python library, of which many commands could be used in the script for traffic simulation operation, shutdown, and reloading.

Figure 5.1 illustrates the flow of programming and explain the role of SUMO in the project. SUMO requires road network and routes files to perform traffic simulation. Input files are generated through steps below.

Figure 5.1

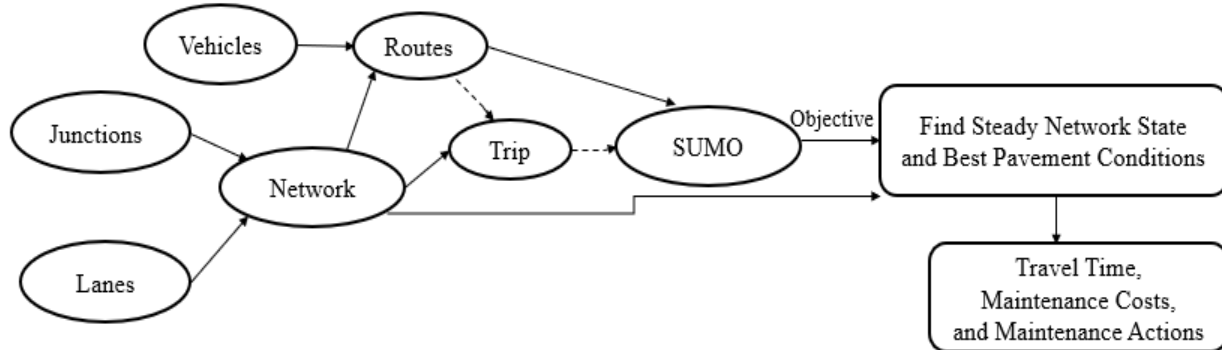


Figure 5.1 Flow of SUMO Network

To implement the above flow, the following applications of SUMO and models need to be determined:

- A map is simplified and converted to a SUMO network file. Vehicle trips are later created through actual measured traffic counts from the detectors.
- Routes and flow data are generated DFROUTER, and output data include information related to routes, origin and destination for different vehicles.
- Routes file are subsequently used for creating vehicle trips using shortest path calculation.

- A configuration file is also required to perform SUMO traffic simulation. Then, TRACI is used to run and access different output information related to edges, lanes, vehicles, and simulation state.
- The Network Vulnerability Index (NVI) and final weights for individual edges is also calculated to be used in the objective function.
- The fitness objective function takes in weighted combination of network mobility, travel time reliability and unmet demand.
- Three major results are generated, being travel time, maintenance actions and maintenance costs.

2. Implementation

To test the application of traffic simulation on transportation infrastructure optimization, the following sections illustrates an implementation on the basis of the knowledge from reasonable assumptions and/or existing literature.

2.1 DFROUTER Tool vs. Random Vehicle Trip Files Generation

An OpenStreetMap map is simplified and converted to a text-based SUMO network file using NETCONVERT tool embedded in the SUMO suite. The induction loop detectors are later placed on the network file, and vehicle trips can later be generated using actual measured traffic counts from the detectors. Then, route and flow xml data used for traffic simulation is created by DFROUTER. When the road network is partially or completely covered by induction loops and generates routes with all the OD pairs, DFROUTER will be employed. The output data are about routes, origin, and destination of different vehicles.

DFROUTER needs a network containing a list of induction loop detectors, with their positions and corresponding vehicle counts. The main requirement of DFROUTER is that the road network must contain at least one induction loop detector on each main road segment; secondary streets without induction loops are nevertheless taken into consideration for route calculation. Other sources of traffic flow information that differ from standard induction loops are not supported. This means that DFROUTER needs a network containing a list of induction loop detectors, including their position and associated vehicle counts. Detailed steps are shown as follows.

- Importing the road network, including the detector positions and associated measurements.
- Applying the detector classification for the following categories: source detectors (starting points of routes), in-between detectors and sink detectors (ending points of routes).
- Calculate the vehicle flow between consecutive detectors.

- Compute the route usage probabilities. Usually, measurements are provided on a per-lane basis, and they need to be summarized for each cross-section.

Another option is to use random trip generation for a defined time-period. A time period of 3600 seconds is used. This leads to faster simulation since vehicles are loaded uniformly and well distributed, however, it might not be aligned with the real-world traffic scenario. For testing purpose, the simplified setting is used.

The following step is to generate vehicle trips using the routes file generated in the previous step. DUAROUTER is used to generate an initial trip file using the shortest path assignment. Subsequently, route assignment is improved through iterations based on Gawron's route-choice algorithm (Dynamic User Assignment) for 10 iterations. The final route file generated is taken as input for subsequent traffic simulation.

2.2 SUMO Simulation

SUMO requires a configuration file to perform traffic simulation. This file is used to pass the various parameters required by the SUMO executable file, which is located under SUMO's parent directory. SUMO GUI file can also be used if we intend to visualize and control the simulation manually using GUI. In Python environment, TraCI provides functions to access edgewise travel time, departed vehicle count and currently running vehicle count. It is applied to run simulation and access various output values related to edges, lanes, vehicles, and simulation state.

An initial simulation with 1,000 iterations is performed to bring the network to a steady state, and the number of iterations could vary depending on complexity of the selected network. The state is then used to perform subsequent simulations on a modified network, and an optimal maintenance action choice can be made. 400 steps are performed for a simple road network. Edge betweenness centrality is computed as the amount of shortest paths that pass through an edge in a transportation network. Vulnerability analysis is conducted for each road link using NVI. Edge betweenness centrality calculated previously is multiplied by NVI, and final weights for each edge used for the objective function can be determined.

A weighted combination of mobility (travel time), travel time reliability and unmet demand is used for the fitness function. Unmet demand is measured by performing a simulation for 400 steps on original and modified network and measuring the difference in departed vehicle counts. Travel time reliability is measured using standard deviation of travel time and travelling vehicle count for the network during 400 steps.

2.3 Pavement Deterioration and Conditions

Deterioration functions of pavement follow the Markov transition probability matrix applied in the cross-asset modeling project. IRI values are discretized into 3 categories. Basis this, the multiplying factor is computed for reducing the edge capacity. There are 2 ways to modify the edge capacity, being blocking certain lanes within the edge, and reducing maximum lane speed.

Then, maximum speed parameter is modified for all edges to reduce the maximum speed for all lanes in that edge as follows:

- Good state: All lanes in an edge have maximum speed which is present in OSM data. IRI values are less than 95.
- Medium state: maximum speed = $0.5 * \text{best case maximum speed}$. IRI values are between 95 to 170.
- Worst state: maximum speed = $0.25 * \text{best case maximum speed}$. IRI values are greater than 170.

3 Case Study

A small segment of road networks of Atlanta is used as input for computation. The input data of this case study is a street map of Atlanta, Georgia is downloaded from OpenStreetMap (OSM) website using the place search query. Unlike traditional geographic information system data which consist of points, lines and polygons, XML files generated in the OSM format save data in nodes, ways and relations forms. Each element in the Atlanta OSM file contain multiple descriptive tags including motorways, highways, sidewalks, street names, and traffic signals.

3.1 Map Filtering

The Atlanta map downloaded from OpenStreetMap contains various regions or components which are not necessarily relevant to this project such as railways and buildings. Highways particularly motorways are the target objects in this study and OSMFilter is utilized to filter out the desired regions. The filtered map displayed in OpenStreetMap software is shown in Figure 5.2. Further details on highways can be found on OpenStreetMap's highways webpage. At the maximum, transportation assets such as motorway, trunk and primary highways with motorway links, trunk links and highway links are supposed to be included, since all other roads are between small towns. The link roads are important to include, otherwise different types of highways could be disconnected.

The simplification module built in the OSMnx package is used to simplified the transportation network for further analysis. The OSMnx tool is capable of converting OpenStreetMap file to network graph object and removing isolated edges to straighten road links of the entire network. The extracted Atlanta street map is taken in and simplified shown in Figure 5.3. Edge betweenness centrality refers to the number of shortest paths that pass through an edge in the transportation network, and after the betweenness centrality is computed, the origianl graph is colored with closeness centralities in the line graph. The output graph is display as Figure 5.4.

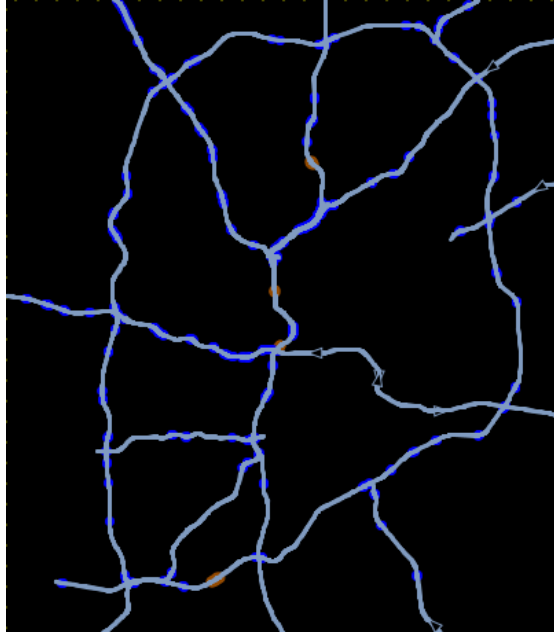


Figure 5.2 Filtered Atlanta Street Map



Figure 5.3 Simplified Atlanta Street Map

Figure 5.4 Colored Simplified Atlanta Street Map

3.2 Input Files Preparation for SUMO Simulation

Since SUMO needs road network and routes files to perform traffic simulation, NETCONVERT and DFROUTER tools are applied to prepare input files for simulation. Detectors data are extracted from an xml file to look for the lane corresponding to various induction loop detectors.

Detector are later placed on the network map using latitude and longitude data. Any without incoming edges will be marked as a source; any edge without outgoing edges will be marked as a sink; any edge that is neither source or sink is labeled as in-between. The following step is to generate route files using DFROUTER tool or the random trip generator. The DFROUTER tool takes induction loop annual average daily traffic data to create vehicle trips. The other option is to randomly assign vehicle trips to the transportation network, instead of using induction loop data, to the network during given time duration. The generated file only contains trip routes with no vehicle type definitions and no vehicles present. Source and sink detectors are used to generate vehicles; therefore, generated file contains individual vehicles which are assigned routes from the output routes file. The final route file generated is prepared as input to preform subsequent traffic simulation.

3.3 NVI Computation and Edge Betweenness Centrality

It takes approximately 10 seconds to run an initial simulation with 1,000 iterations to bring the network to a steady state, and the round of iterations greatly varies depending on the complexity of the target network. The state is save to perform subsequent traffic simulations on a modified network, and a desired maintenance action choice can therefore be made. 400 simulation steps are performed for a simple road network. Edge betweenness centrality is calculated as the amount of shortest paths that pass through an edge in a transportation network. Then, network vulnerability analysis is performed for each road link using NVI. Edge betweenness centrality calculated is multiplied by NVI, and final weights for each edge used for the objective function can be determined. The output of final weights map is shown in Figure 5.5. Figure 5.6 display the results of network vulnerability based weights on the simplified Atlanta street map. Centrality based weights street map is shown in Figure 5.7.

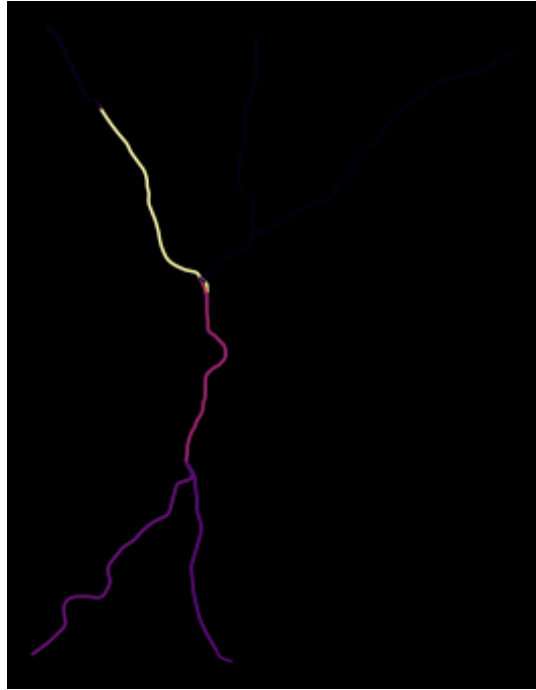


Figure 5.5 Final Weights Map



Figure 5.6 Network Vulnerability-based Weights Map

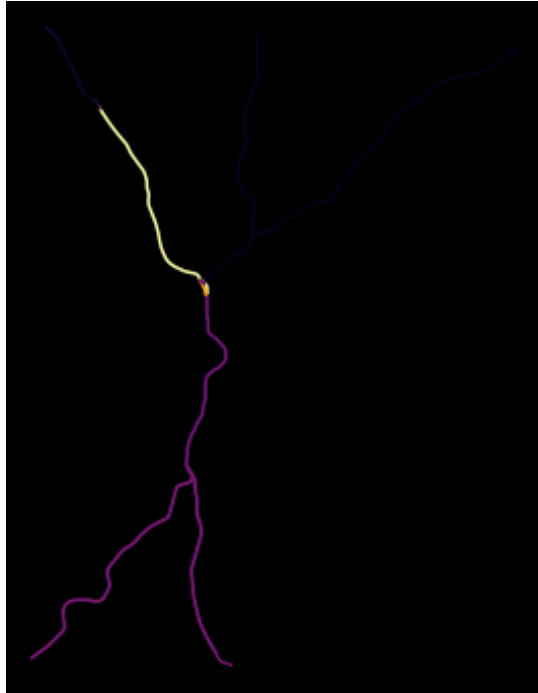


Figure 5.7 Centrality-based Weights Map

A weighted combination of travel time, travel time reliability and unmet traffic demand is taken into the fitness function. Unmet demand is computed by performing a simulation for 400 steps on original and modified network and measuring the difference in departed vehicle counts. The departed vehicle count is computed in a condition that all roads are in their best states. Travel time reliability is measured using standard deviation of travel time and travelling vehicle count for the network during 400 steps. In this case, 294 vehicles depart in 400 simulation steps with a constraint that all roads are in their best conditions.

3.4 Yearwise Genetic Algorithm on the Road Network

A five-year programming is presented in this case study with a yearly \$6 million budget. Multiple tests prove that integrating SUMO into calculation of travel time and maintenance costs consumes more time than expected. Population size and the number of generation is set to be 80 and 15, lower than normal genetic algorithm programming to avoid excessive computing time.

Deterioration of pavement follows the Markov transition probability matrix applied in the cross-asset modeling project. IRI values are discretized into 3 categories and in this case, IRI values are automatically generated among 90, 130, and 200 for demonstration purposes. With annual budget and travel time reliability constraints, optimized maintenance actions plans for each year in the 5-year duration are determined on the simplified Atlanta network. Results of yearly maintenance costs and actions, and travel time are shown in Figure 5.8 below.

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Budget	6000000	6000000	6000000	6000000	6000000	6000000
Population Size	80	80	80	80	80	80
Number of Generations	15	15	15	15	15	15
Maintenance Actions	0000000000 0000000000	1000000010 1000000000	001010000000 101000000001	000010000000 101000000011	001010000000 101000000001	000010000000 101000000011
Travel Time	N/A	17.03041707	17.03041707	17.03041707	17.03041707	17.03041707
Maintenance Costs	N/A	4280894.411	4488946.610	4630215.394	4855244.653	5008040.971
Total travel Time	85.15208534					
Total Cost	23263342.038					

Figure 5.8 Maintenance Actions, Costs, and Travel Time Results

4 Summary

This project is designed to optimize infrastructure assets' conditions at network level, considering their interdependency. The goal is to achieve the best performance of the road network. Subjectivity in resource allocation during the decision-making process in this model is reduced. The case study, using a small fraction of highway network around Atlanta, Georgia, demonstrates role of SUMO-based traffic reassignment.

The objective fitness function is set to bring the network to a steady state and find best road conditions, with constraints of annual budget and travel time reliability. Similar optimization model as the cross-asset modeling is used in this project to determine pavement maintenance programming.

A case study taking a small fraction of road networks in Atlanta is used as input for computation. A street map of Atlanta, Georgia, as the input map, is downloaded from OpenStreetMap website using the place search query. The input map is first extracted and filtered, and for demonstration purposes, the map is simplified. SUMO applications such as DFROUTER and NETCONVERT are used to prepare files to perform SUMO traffic simulation. 400 steps are completed for a very simple network to determine the best action sequences.

Before running the Genetic Algorithm codes, the vulnerability analysis is conducted and the results are multiplied by edge betweenness centrality in order to derive weights of each edge of the network, to be used in the objective function. For the objective function, mobility, travel time reliability and unmet demand, weighted in combination, are used. These factors are measured by departed vehicle count, standard deviation of travel time, and travelling vehicle count respectively. The pavement deterioration functions in use similar to the previous MATLAB implementation. However, we discretize IRI into 3 categories (less than 95 is good; 95 to 170 is medium, and greater than 170 is worst condition).

Integrating SUMO into this optimization problem formulation consumes excessive computation time than expected, yet the study show promising results of such integration. Both

objectivity and cost-effectiveness are improved in this attempt. Two suggestions for future related research could be made on the constraint definition and objective function. Instead of the network based betweenness centrality calculated using shortest path, the use of shortest time based betweenness centrality by assigning travel time based weights to graph edges could be more convincing and centrality can be subsequently computed. In the objective function, the weights for combining mobility, reliability and unmet demand are currently set by us. It should be ideally determined basis the probability of the link moving to bad condition. Finally, improvements could be made on Genetic Algorithm to avoid extra computation time.

Chapter 6: Conclusions and Recommendations

This research project explored several aspects of smart funding strategies for optimally maintaining road network that consists of different, but interdependent, transportation infrastructure assets. Two major types of transportation infrastructure assets, pavements and bridges were utilized to demonstrate the effectiveness of the proposed methodology. The following summarize the major findings and offer some recommendations for future study.

1. Conclusions

First, a larger case study was conducted to demonstrate the benefit of maintenance programming by considering the interdependency between pavements and bridges. The major formula followed the ones developed in previous project (Wang, et al., 2018). For this purpose, a general framework, consisting of pavements and bridges, was formulated as an interdependency-based optimization model by incorporating traffic capacity models, deterioration models, and treatment improvement models. In the meantime, for comparison purpose, a WSM-based optimization model was also developed by adopting the commonly used engineering-judgment-based MCDM method. The case study was conducted using a road network consisting 140 pavement segments and 29 bridges. The results demonstrated that WSM-based maintenance programming and the resulted performance relies on decision makers' preference. In contrast, the interdependency-based counterpart can achieve the best maintenance programming that maximizes the transportation efficiency of the road network without the need of decision makers' preference. More importantly, the maintenance programming based on engineering judgment cannot consider the spatial relationship and interdependency among different types of assets, which results in the difficulty of coordination in highway agencies' practice.

Second, the references drawn from existing literatures implying evaluation of bridge condition, capacity and maintenance action are very limited. Simplification was made previously assumed on the bridge deterioration modeling, improvements are made on the model. Deterioration probability matrix of substructure is used to represent the bridge deterioration patterns; nevertheless, bridge components deck, substructure, and superstructure deteriorate with different trends. A Bridge Quality Index (BQI) could be defined, on the basis of the logic of California Bridge Health Index, which computes the ratio of the current bridge value to the total bridge value as initially designed. BQI integrates deterioration rates of 3 major components of a bridge, unit costs of their maintenance, and area. Another improvement is the categorization of bridge treatment actions of 4 groups, being no action, minor and major rehabilitation, and replacement. Above modifications made on bridge deterioration modeling can partly avoid subjectivity in determining a bridge's condition.

Finally, traffic reassignment was explored to be integrated with pavement maintenance programming. The open source traffic simulation software, SUMO, was adopted for this purpose. The objective fitness function was set to bring the network to a steady state and find

the best road conditions, with constraints of annual budget and travel time reliability. Similar optimization model as the cross-asset modeling was used to determine the pavement maintenance programming. A case study taking a small fraction of road networks in Atlanta was used as input for computation. Integrating SUMO into this optimization problem formulation consumes excessive computation time than expected, yet the study show promising results of such integration. Both objectivity and cost-effectiveness are improved in this attempt.

2. Recommendations

The following are some areas where further research and studies can be done:

- The large case study showed promising results of integrating interdependency in cross-asset maintenance programming to enhance the objectivity in multi-criteria decision making and improve the cost-effectiveness. For a more practical application, further research is still needed.
 - A new performance measure is needed to integrate different types assets. In this project, the performance measure is only related to the transportation efficiency of a road network. If safety is considered, other safety-related assets can also be integrated in the general framework.
 - The relationship between asset conditions and performance measure needs further study. To demonstrate the effectiveness of the general framework, significant simplification was made on the related models. For a practical application, these models need further study.
 - The models for asset deterioration and treatment improvement need to be developed for a highway agency using its historical asset condition and maintenance data.
- For the model used for traffic reassignment, instead of the network based betweenness centrality calculated using shortest path, the use of shortest time based betweenness centrality by assigning travel time based weights to graph edges could be more convincing and centrality can be subsequently computed. In the objective function, the weights for combining mobility, reliability and unmet demand are currently set by us. It should be ideally determined based on the probability of the link moving to bad condition.
- For a large road network, the computing efficiency needs to be improved by parallelizing the GA algorithms using GPU and/or computer cluster.

References

- AASHTO (2013). "AASHTO Transportation Asset Management Guide: A Focus on Implementation", Publication No. FHWA-HIF-13-047.
- Ahmed, S., Vedagiri, P. & Krishna Rao, V.K. (2017). "Prioritization of Pavement Maintenance Sections using Objective based Analytic Hierarchy Process."
- Allan, D. F., & Farid, A. M. (2015, September). A benchmark analysis of open source transportation-electrification simulation tools. In 2015 IEEE 18th International Conference on Intelligent Transportation Systems (pp. 1202-1208). IEEE.
- ASTM (2018). "Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys, ASTM D6433 – 16, 2016" DOI: 10.1520/D6433-18.
- Atlanta Regional Commission (2017). "The Atlanta Region's Plan Finances."
- Aw, A., and M. Rascole (2000), Resurrection of "second order" models of traffic flow, SIAM journal on applied mathematics, 60 (3), 916–938
- Bando, M & Hasebe, K & Nakayama, A & Shibata, Akihiro & Sugiyama, Y. (1995). Dynamic model of traffic congestion and numerical simulation. Physical review. E, Statistical physics, plasmas, fluids, and related interdisciplinary topics. 51. 1035-1042. 10.1103/PhysRevE.51.1035.
- Bar-Gera, H. (2002). Origin-based algorithm for the traffic assignment problem. Transportation Science, 36(4):398–417
- Bar-Gera, H. (2010). Traffic assignment by paired alternative segments. Transportation Research Part B: Methodological, 44(8-9), 1022-1046.
- Behrisch, Michael, Laura Bieker, Jakob Erdmann, and Daniel Krajzewicz. "SUMO—simulation of urban mobility: an overview." In Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind, 2011.
- Bell MGH, Cassir C, (2002). Risk-averse user equilibrium traffic assignment: an application of game theory, Transportation Research Part B: Methodological, Vol: 36, Pages: 671-681, ISSN: 0191-2615
- Bernardin, V. & Durango-Cohen, P. (2006). "Transportation Asset Management for Local Government Agencies: Threshold Levels and Best Practice Guide", Midwest Regional University Transportation Center, Report 05-01.
- Brockfeld, E., Kühne, R. D., & Wagner, P. (2004). Calibration and validation of microscopic traffic flow models. Transportation Research Record, 1876(1), 62-70.

- Boyce, D., Lee, D. H., & Ran, B. (2001). Analytical models of the dynamic traffic assignment problem. *Networks and Spatial Economics*, 1(3-4), 377-390.
- Buchanan, J. T., Henig, E. J., & Henig, M. I. (1998). Objectivity and subjectivity in the decision making process. *Annals of Operations Research*, 80, 333-345.
- Cambridge Systematics, Inc. (2006). "Asset Management Guide for Local Agencies in Michigan."
- Chandra, S. (2004). "Effect of Road Roughness on Capacity of Two-lane Roads.", *Journal of Transportation Engineering*, 130(3): 360-364.
- Chen, A., & Lee, D. (1998). Path-Based Algorithms for a Large-scale Traffic Equilibrium Problem: A Comparison of the Disaggregate Simplicial Decomposition and Gradient Projection Algorithms (No. UCI-ITS-WP-98-13).
- Chen, L., T. F. P., Henning, A. Raith, & Shamseldin, A. (2015). "Multiobjective Optimization for Maintenance Decision Making in Infrastructure Asset Management", *ASCE: Journal of Management in Engineering*, 31(6): 04015015.
- Chu, K. C. (2016). Modeling and Probing Strategy for Intelligent Transportation System Utilizing Lagrangian Traffic Data (Doctoral dissertation).
- Daganzo, C. F. (1994), The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory, 28 (4), 269–287
- Daganzo, C.F., Sheffi, Y., (1977). On stochastic models of traffic assignment. *Transportation Science*, 11 (3), 351-372.
- Dehghani et al. (2013). "Cross-Asset Resource Allocation Framework for Achieving Performance Sustainability", *Transportation Research Record: Journal of the Transportation Research Board*, DOI: 10.3141/2361-03.
- Dial, R. B. (2006). A path-based user-equilibrium traffic assignment algorithm that obviates path storage and enumeration. *Transportation Research Part B: Methodological*, 40(10), 917-936.
- Edelhoff, T., Schilling, H., Balmer, M., Möhring, R. H., & Nagel, K. (2006). Optimal route assignment in large scale micro-simulations. *Arbeitsbericht Verkehrs-und Raumplanung*, 409.
- FHWA (1995). "Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridge", Office of Engineering Bridge Division, Report No. FHWA-PD-96-001.

- FHWA (2007). “Asset Management Overview”, FHWA Office of Asset Management, Report No. FHWA-IF-08-008.
- FHWA (2012a). “Asset Management Questions & Answers, MAP-21”, <https://www.fhwa.dot.gov/map21/qandas/qaassetmgmt.cfm>
- FHWA (2012b). “Moving Ahead for Progress in the 21st Century Act (MAP-21): A Summary of Highway Provisions.”
- FHWA (2013a). “Generic Work Plan for Developing TAMP.”
- FHWA (2013b). “Practical Guide for Quality Management of Pavement Condition Data Collection”, Applied Pavement Technology, Inc.
- FHWA (2015). “Financial Planning for Transportation Asset Management: An Overview”, June 2015, Report No. 2.
- FHWA (2016). “National Highway Performance Program (NHPP) Implementation Guidance”, <https://www.fhwa.dot.gov/specialfunding/nhpp/160309.cfm>
- FHWA (2017). “Transportation Asset Management Case Studies CMS Case Study Minnesota”, https://www.fhwa.dot.gov/infrastructure/asstmgmt/tamcs_cms04.cfm
- FHWA (2017). “LRFD Steel Girder SuperStructure Design Example. Pier Design Example Design Step 8”, https://www.fhwa.dot.gov/bridge/lrfd/us_ds8.cfm
- FHWA (2018). “Bridge Preservation Guide – Maintaining a Resilient Infrastructure to Preserve Mobility.” Publication No. FHWA-HIF-18-022.
- Fitzpatrick, C. (2016). “Implementing Data-Driven Decision for Asset Management in Local Communities”, University of Missouri-Columbia.
- Fwa, T.F. & Farhan, J. (2012). “Optimal Multi-Asset Maintenance Budget Allocation in Highway Asset Management”, ASCE, Journal of Transportation Engineering, 138(10): 1179-1187.
- Farhan, J. & Fwa, T.F. (2014). “Use of Analytic Hierarchy Process to Prioritize Network-Level Maintenance of Pavement Segments with Multiple Distresses”, Transportation Research Record: Journal of the Transportation Research Board, DOI: 10.3141/2225-02.
- Flintsch, G. & Bryant, J.W. (2006). “Asset Management Data Collection for Supporting Decision Processes”, Virginia Polytechnic Institute and State University.
- Frank, M., & Wolfe, P. (1956). An algorithm for quadratic programming. Naval research logistics quarterly, 3(1 - 2), 95-110.

- Georgia Department of Transportation (GDOT) (2005). "Pavement Design Manual."
- GDOT (2011). "Transportation Asset Management: The Strategic Direction of Georgia Department of Transportation."
- GDOT (2014). "2014-2018 Transportation Asset Management Plan."
- GDOT (2017). "Local Maintenance and Improvement Grant (LMIG)."
- GDOT (2018). "Transportation Asset Management Plan: Fiscal Years 2018-2027."
- Ge, H. X., Dai, S. Q., Dong, L. Y., & Xue, Y. (2004). Stabilization effect of traffic flow in an extended car-following model based on an intelligent transportation system application. *Physical Review E*, 70(6), 066134.
- Gipps, P. G. (1981). A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological*, 15(2), 105-111.
- Governmental Accounting Standards Board (1999). "Summary of Statement No. 34 Basic Financial Statements and Management's Discussion and Analysis for State and Local Governments", <http://www.gasb.org/st/summary/gstsm34.html>
- Gwinnett County Government. Asset Management Website Section, <https://www.gwinnettcounty.com/portal/gwinnett/Departments/PublicUtilities/Operations/Infrastructure/AssetManagement>
- Hodas, N. O., & Jagota, A. (2003). Microscopic modeling of multi-lane highway traffic flow. *American Journal of Physics*, 71(12), 1247-1256.
- Helbing, D., Tilch, B. (1998) Generalized force model of traffic dynamics. *Physical Review E*. 58, pp. 133-138. DOI: 10.1103/physreve.58.133
- Jiang, R., Wu, Q., Zhu, Z. (2001) Full velocity difference model for a car following theory. *Physical Review E*. 64(1). DOI: 10.1103/physreve.64.017101
- Kabir, G., Sadiq, R. & Tesfamariam, S. (2014). "A Review of Multi-Criteria Decision-making Methods for Infrastructure Management", *Structure and Infrastructure Engineering Journal*, Vol. 10, No. 9, 1176–1210.
- Krajzewicz, D. (2010). Traffic simulation with SUMO—simulation of urban mobility. In *Fundamentals of traffic simulation* (pp. 269-293). Springer, New York, NY.
- Leng, J. Q., Yang, L. H., Liu, W. Y. & Zhao, L. (2017). "Measuring Road Network Vulnerability with Sensitivity Analysis.", *PLoS One*, 12 (1), 2017, pp. 1-17.

- Lighthill, M., and G. Whitham (1955), On kinematic waves. II. A theory of traffic flow on long crowded roads, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, pp. 317–345.
- Li, Z. & Sinha, K. (2004). “Multicriteria Highway Programming Incorporating Risk and Uncertainty: A Methodology for Highway Asset Management System”, Purdue University Publication No. FHWA/IN/JTRP-2003/21.
- Lo, H. K., and Chen, A. (2000) Traffic Equilibrium Problem with Route-Specific Costs: Formulation and Algorithms, Journal of Transportation Research Part B, Vol. 34, 493-513.
- Maggiore, M. & Ford, K.M. (2015). “NCHRP Report 806: Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance.”
- Maze, T. H., O. G. Smadi, N. Burke and C. I. MacGillivray. Use of Functional Silos to Optimize Agency Decision Making. Final Report MRUTC 05-05. 2008.
- Morcous, G. and Hatami, A. (2011). “Developing Deterioration Models for Nebraska Bridges.”, Report Number SPR-P1(11) M302, Nebraska Transportation Center.
- Nagatani, T. (1999). Stabilization and enhancement of traffic flow by the next-nearest-neighbor interaction. Physical Review E, 60(6), 6395.
- National Cooperative Highway Research Program (NCHRP) (2006). “Performance Measures and Targets for Transportation Asset Management”, Report 551, Transportation Research Board.
- Newell, G. F. (1993). A simplified theory of kinematic waves in highway traffic, part I: General theory. Transportation Research Part B: Methodological, 27(4), 281-287.
- Newell, G. F. (1993). A simplified theory of kinematic waves in highway traffic, part II: Queueing at freeway bottlenecks. Transportation Research Part B: Methodological, 27(4), 289-303.
- Newell, G. F. (1993). A simplified theory of kinematic waves in highway traffic, part III: Multi-destination flows. Transportation Research Part B: Methodological, 27(4), 305-313.
- Newell, G. F. (1995). Theory of highway traffic flow: 1945 to 1965.
- Omar, T. & Nehdi, M. (2016). “Condition Assessment and Deterioration Prediction Tools for Concrete Bridges: A New Look”, CSCE Conference London 2016, MAT-714.

- Ouyang, Y. and Madanat, S. (2004). "Optimal Scheduling of Rehabilitation Activities for Multiple Pavement Facilities: Exact and Approximate Solutions." *Transportation Research Part A*, 38, 2004, pp. 347-365.
- Pantelias, A. (2005). "Asset Management Data Collection for Supporting Decision Processes", Virginia Polytechnic Institute and State University.
- Papageorgiou, M., J.-M. Blosseville, and H. Hadj-Salem (1990), Modelling and real-time control of traffic flow on the southern part of Boulevard Peripherique in Paris: Part II: Coordinated on-ramp metering
- Paterson, W. D. O. (1990). "Quantifying the Effectiveness of Pavement Maintenance and Rehabilitation.", Proceedings at the 6th REAAA Conference, Kuala Lumpur, Malaysia.
- Payne, H. J. (1971), Models of freeway traffic and control., *Mathematical models of public systems*
- Pipes, L. A. (1966). Car following models and the fundamental diagram of road traffic. *Transportation Research/UK/*.
- Porras-Alvarado et Al. (2016). "Fairness and Efficiency Considerations in Performance-Based, Cross-Asset Resource Allocation", *Transportation Research Record: Journal of the Transportation Research Board*, DOI: 10.3141/2596-03.
- Prashker, Joseph & Bekhor, Shlomo. (2004). Route Choice Models Used in the Stochastic User Equilibrium Problem: A Review. *Transport Reviews*. 24. 437-463. 10.1080/0144164042000181707.
- Proctor, G. & Zimmerman, K. (2016). "Defining Cross-Asset Decision Making. A discussion paper from the Transportation Asset Management Expert Task Group (TAM ETG)", <https://www.tam-portal.com/wp-content/uploads/2016/01/Cross-Asset-Allocation.pdf>
- Ran, B., & Boyce, D. (2012). *Modeling dynamic transportation networks: an intelligent transportation system oriented approach*. Springer Science & Business Media.
- Sadek et Al. (2003). "Integrated Infrastructure Management Systems: Small Urban Area's Experience", *ASCE Journal of Infrastructure Systems*, 9(3): 98-106.
- Shao, H., Lam, W. H., Tam, M. L., & Yuan, X. M. (2008). Modelling rain effects on risk - taking behaviours of multi - user classes in road networks with uncertainty. *Journal of Advanced Transportation*, 42(3), 265-290.
- Shoghli, O. and de la Garza, J. M. (2017). "Multi-Asset Optimization of Roadways Asset Maintenance", *ASCE International Workshop on Computing in Civil Engineering*, pp. 297-305.

- Simoni, M., & Claudel, C. (2018). A Fast Lax-Hopf formula to solve the Lighthill-Whitham-Richards traffic flow model on networks. arXiv preprint arXiv:1802.05391.
- Smith, G. J. (2013). "Road Transportation Asset Management Guidelines", AECOM Report.
- Smith, L., Beckman, R., Baggerly, K., Anson, D., & Williams, M. (1995). Overview of TRANSIMS, the TRansportation ANalysis and SIMulation System. Los Alamos National Laboratory.
- Sun, X., Zhang, Z., Wang, R., and Wang, X. "Analysis of past national bridge inventory ratings for predicting bridge system preservation needs." Transportation Research Record 1866, Transportation Research Board, Washington, DC, 36–43. 2004.
- Szeto, W. Y., Jiang, Y., & Sumalee, A. (2011). A cell - based model for multi - class doubly stochastic dynamic traffic assignment. Computer - Aided Civil and Infrastructure Engineering, 26(8), 595-611.
- Thompson, Paul D., and Richard W. Shepard. "AASHTO Commonly-recognized bridge elements." In Materials for National Workshop on Commonly Recognized Measures for Maintenance, Scottsdale, Arizona. 2000.
- TRB (2008). "Transportation Asset Management: Strategic Workshop for Department of Transportation Executives", Report No. E-C131.
- TRB (2015). "Transportation Asset Management from Plans to Practice: A Workshop for State Practitioners", Report No. E-C200.
- Walker, D. (2002). "Pavement Surface Evaluation and Rating Asphalt PASER Manual", Wisconsin Transportation Information Center
- Wang, S. (2014). "Optimization Models for Network-level Transportation Asset Preservation Strategies", University of Toledo.
- Wang, Tao, Zi-You Gao, and Xiao-Mei Zhao. "Multiple velocity difference model and its stability analysis." (2006): 634-640.
- Wardrop, J. G. (1952). Some theoretical aspects of road traffic research. Proceedings of the Institution of Civil Engineers, Volume 1, Part II, 325–378.
- Wassef, W. G., Smith, C., Clancy, C. M., & Smith, M. J. (2003). Comprehensive Design Example for Prestressed Concrete (PSC) Girder Superstructure Bridge with Commentary (in US Customary Units) (No. FHWA NHI-04-043).

- Weninger-Vycudil, A., Hanley, C., Deix, S., O'connor, A., & Pakrashi, V. (2015). "Cross-asset Management for Road Infrastructure Network", Institute of Civil Engineers, Transport Volume 168 Issue TR5, pp. 442–456.
- Wiedemann, Rainer. (1974). "Simulation des Strassenverkehrsflusses."
- Wiedemann, R. and Reiter, U. (1992). Microscopic traffic simulation: the simulation system MISSION, background and actual state. Project ICARUS (V1052) Final Report. Brussels, CEC. 2: Appendix A.
- Wittwer, et. al. (2003). "Key Findings from the Fifth National Workshop on Transportation Asset Management", Midwest Regional University Transportation Center, University of Wisconsin.
- World Bank (2007). "Data Collection Technologies for Road Management", East Asia Pacific Transport Unit, Report Version 2.0
- Zhang et Al. (2002). "Developing an Integrated Management System for the Urban Transportation Infrastructure", Center for Transportation Research, University of Texas at Austin, Report No. 167511-1.
- Zhao, X. M., & Gao, Z. Y. (2005). A new car-following model: full velocity and acceleration difference model. The European Physical Journal B-Condensed Matter and Complex Systems, 47(1), 145-150.
- Ziara, M., K. Nigim, Enshassi, A. & Ayyub, B.M. (2002). "Strategic Implementation of Infrastructure Priority Projects: Case Study in Palestine", ASCE Journal of Infrastructure Systems, DOI: 10.1061.

