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Cross asset resource allocation framework for pavement and bridges in Iowa

by

Yazan Abukhalil

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Transportation Engineering)

Program of Study Committee:
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred

Iowa State University

Ames, Iowa

2019

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DEDICATION

If this work is to be dedicated, it will be to my parents, Basem and Ahlam; to my brother and life-long companion, Baraa; and to the one who taught me what fighting for life means, my sister Tala. Without all of you and your unlimited support, this thesis would not have been possible.

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ACKNOWLEDGMENTS

I would like to thank my committee chair, Omar Smadi, and my committee members Ahmad Alhasan, Basak Aldemir-Bektas, and Cameron Mackenzie, for their guidance and support throughout the course of this research. In addition, I would also like to thank my friends, colleagues, the department faculty and staff for making my time at Iowa State University a wonderful experience.

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ABSTRACT

With all the challenges facing U.S departments of transportation (US DOTs), especially the scarcity of resources and the deteriorating infrastructure systems, DOTs started to divert from separate assets decision making strategies to a more comprehensive resource allocation approach. This also resulted from the fact that the optimal allocation for each asset type separately is not the optimal allocation for all assets in the network. Specifically speaking about Iowa, about one quarter of Iowa's primary roadways fail to meet a sufficiency rating considered minimally acceptable, furthermore the rural Interstate system in Iowa was ranked 38th in the nation in 2010. The case in bridges is not better, where one of every five bridges in Iowa are rated as structurally deficient. By that, Iowa has the third worst state record in the nation. As a result of that, this research will focus on proposing a new simple and applicable cross asset resource allocation framework for pavements and bridges in Iowa, utilizing data from Pavement Management Information System (PMIS) and National Bridge Inventory (NBI). The objective function of this framework is to maximize the network monetary value by changing the proportions of total budget allocated to each asset type, while the resulting budgets are allocated in a need-based approach across importance groups and in a worst-first basis within each importance group. The final output of this research is a MATLAB simple tool that allocates five years of funding across interstate, U.S, and state pavements and bridges. This tool also provides a list of pavement mileage and bridge deck area that need to be treated by each maintenance action at each budget level. It also compares the impact of different pavement and bridge valuation definitions on the solution that

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maximizes the network monetary value. The results show that the proposed framework is not sensitive to the valuation approach. It also shows that at low budget levels, most of the budget is allocated to pavements. This condition is reversed at moderate budget levels, and equal allocation is achieved at very high total budget level, i.e. 1 billion dollars.

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CHAPTER 1. INTRODUCTION

This thesis is developed to suggest a cross asset resource allocation framework for pavements and bridges, and to apply it on a subset of the bridges and pavements network in the state of Iowa. This chapter will provide an introduction to the cross asset resource allocation topic by defining highway agencies problem and concerns, highlighting the impact of the study, describing the technical problem, defining research goals and objectives, and showing the significance of this research.

Highway Agency Problem

Transportation agencies make annual budget allocation decisions for different infrastructure assets in the network. These decisions impact the overall network performance, which affects people and goods movement, safety and comfort, as well as the national economy.

Highway Agency Concerns

Budget allocation decisions are supposed to support the economy, enhance the quality of life, and ease peoples' lives taking into consideration the need to minimize negative environmental impacts. This is not an easy task with the presence of limited resources that need to be distributed over multiple transportation assets that experience continuous aging. The costs for maintaining and improving public roads and highways in the U.S. exceed $100 billion annually (TRB 2013, Maggiore and Ford 2015).

The evolvement of advanced technologies such as advanced sensors, mobile computing, distributed databases, and spatial technologies enabled data collection and

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resulted in a very large amount of data. This data motivated the agencies to follow a more comprehensive and data-driven decision making strategies (Flintsch and Bryant 2006).

Impact of Study

Traditionally, transportation agencies manage their assets within individual silos, such as pavement and bridge management systems. To overcome the silo mentality, there is a need for unified performance measures and management systems capable of analyzing the transportation network as a one unit (Zimmerman *et al.* 2016). This way of managing assets does not result in the most effective use of resources, since the optimal allocation of funds for each individual asset category does not necessarily result in the optimal allocation for the entire network. Consequently, transportation agencies started to change their management practices towards enterprise management systems, known as cross-asset resource allocation. This approach forms the next generation of innovation that will improve transportation organizations' credibility, transparency and decision making. It will allow them to minimize life cycle costs associated with each asset category, maximize their long term return while managing the risk in decisions (AASHTO 2015).

Technical Problem

In June 2012, the US congress passed the Moving Ahead for Progress in the 21st Century Act (MAP-21), which required each state to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system to achieve both state's targets and national goals for assets' conditions and performance. This act gives priority to

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pavements and bridges and encourages the involvement of other infrastructure assets as well (AASHTO 2013). The subsequent legislation known as Fixing America's Surface Transportation (FAST) Act, which was passed in December 2015 supported the concept of managing assets in a performance-based manner.

Despite these efforts, 2017 infrastructure report card, shows that the nation’s infrastructure is in fair to poor condition with a cumulative GPA of D+, with elements approaching the end of their service life and having high risk of failure. Pavements and bridges are part of this poor infrastructure. One out of every five miles in the U.S. is in poor condition. Furthermore, 9.1% of nation’s bridges are structurally deficient. Economic studies show that the available funds in the U.S. covers only 50% of the needs. This will result in 3.9 trillion dollars lost in the U.S. GDP, 3.7 trillion dollars lost in business sales, and 2.5 million lost American jobs by 2025 (ASCE 2017).

Given the limited resources available; the current asset management practices, which focus on optimizing budget allocation for each asset class separately, will hold back the efforts to improve the network infrastructure. Furthermore, current practices do not provide a solid quantitative approach to decision making across assets. This makes it difficult to trace and compare the results of different asset management plans.

Research Goals and Objectives

The goal of this research is to improve the way transportation agencies allocate the funds acquired from tax revenue, user fees, federal funding, and credits on the network across pavement and bridge asset classes. This will help the agencies to achieve

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the best overall transportation network condition and insures the maximum revenue of each dollar spent.

The objectives of this research are to:

- Develop a simple and applicable cross-asset resource allocation framework for pavements and bridges.
- Apply the proposed framework to a subset of pavements and bridges in the state of Iowa within the U.S., Interstate and State highway systems based on data from the Pavement Management Information System (PMIS) and National Bridge Inventory (NBI).

Significance of the Research

Transportation agencies such as Departments of Transportation (DOTs), Metropolitan Planning Organizations (MPOs) and local agencies will benefit from the proposed simple cross asset framework to decide on how much budget need to be allocated to each asset category given a certain set of deterioration models, decision trees, treatment effectiveness models and valuation techniques for each asset category. This kind of trade-off analysis will help the agencies to get a sense of how each asset performance contribute to the entire network performance and which asset category needs more attention. Furthermore, they will be able to decide on which actions need to be taken within each asset category every year over a study period, given budgetary constraints. Being able to distribute funds within an asset group has been already addressed in pavement management systems (PMS) and bridge management systems (BMS). However, the imbalance in the overall network performance might limit the

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possible performance improvements given the limited budget. Cross-asset funds allocation can improve the overall network performance by optimizing the budget allocation.

Thesis Organization

This thesis consists of six chapters. Chapter 1 provides an introduction of the topic and highlights its importance. It provides a brief description of the highway agency problems and concerns, impact of study, technical problem, research goals, objectives, and significance. Chapter 2 is the topic background. It gives an extensive literature review about transportation asset management and the major two components, considered in this thesis, which are pavement and bridge management systems. It also covers the components of each management system including deterioration models, decision trees, treatment effectiveness and decision making approaches. It also introduces the cross asset resource allocation concept and reviews major studies and practices on the topic. Chapter 3 describes the data sources used in thesis. It provides an overview of the entire dataset, shows the interesting features of the data subset on which the proposed framework will be applied, and explains the data processing activities. Chapter 4 discusses the proposed cross asset resource allocation framework and gives a thorough explanation of each step. Chapter 5 provides the results of applying the proposed framework and justifies them. Chapter 6 states the conclusions drawn from this thesis, lists the limitations of the work and suggests possible future improvements

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CHAPTER 2: BACKGROUND

In this chapter, an extensive literature review about asset management, pavement management system, bridge management systems and their components will be presented. Furthermore, the limitations of the current asset management practices in transportation engineering will be highlighted with emphasis on the role of cross asset resource allocation in solving these limitations. Moreover, cross asset resource allocation research efforts will be reviewed.

Asset Management

Asset management in its general concept refers to “making financial investments decisions so that returns are maximized while satisfying risk tolerance and other investor requirements” (Mehairjan 2017). Originally, asset management is a business concept that started in private sector with an aim of maximizing return on financial investment. The concept of asset management in transportation engineering was initiated after the passage of the Government Performance and Results Act in 1993. This act identified accountability at all levels as a priority. Each agency became responsible for reporting the actions they took using public funds with a clear explanation of their decision making policy (FHWA 2007). For transportation agencies, this means all construction and maintenance actions performed on bridges, pavements, culverts, traffic signs, pavement marking and all other transportation assets need to be reported and justified. So, transportation asset management is “the strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle” (MnDOT). Transportation asset management goal is to manage resource allocation

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decisions to improve system performance, in a way that maximizes network value and user satisfaction. Transportation asset management is built on five core principles. The first principle is that asset management is policy-driven, where all decisions need to be defined with clear set of policy objectives. Since these policy objectives are based on the performance of the network, the second principle is that TAM is a performance-based process. In order to achieve the policy objectives, TAM decisions are based on quality information, which is the third core principle. Also, TAM decisions are done based analysis of options and tradeoffs, which is the forth core principle. This means decisions under asset management plans are based on comparing different options impact on achieving relevant policy objectives using credible and current data. To track the performance of the system, the last core principle of transportation asset management is monitoring results, which leads to clear accountability and feedback (FHWA 2007).

Pavement Management Systems

Pavement assets are a crucial component of the transportation network. They have a significant impact on the nation's economy due to the role they play in linking all states together and providing smooth transportation of freight. As pavement is part of the transportation network, pavement management system (PMS) is one of the major processes in transportation asset management. PMS is "a set of defined procedures for collecting, analyzing, maintaining, and reporting pavement data, to assist the decision makers in finding optimum strategies for maintaining pavements in serviceable condition over a given period of time for the least cost." In late 1950's and 1960's, most of the transportation agencies focused on the construction of new roads to provide the required linkage throughout the country. At that time, there were no electronic technologies for

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collecting the data. However, in mid to late 1970's, these agencies shifted towards maintaining current roads to insure acceptable level of service of the continually deteriorating roads. Along with the evolution of advanced database management systems and computers, the first PMS came to light during that period (MichiganTech 2008). In late 1980's, the leading associations in transportation engineering started to adopt PMS. The American Association of State Highway and Transportation Officials (AASHTO) published their first guidelines on pavement management in 1985 (AASHTO 1985). Furthermore, the Federal Highway Administration (FHWA) obligated the existence of a PMS for each state to manage their Primary Highway Systems in 1989 (Botelho 1994). In the following subsections; the different PMS components will be described thoroughly including deterioration models, decision trees, treatment effectiveness and decision making process.

Deterioration models

One of the main reasons behind the emergence of PMS is the need to maintain good performance of the continually deteriorating pavement network. Pavement deterioration is "the process by which distresses (defects) develop in the pavement under the combined effects of traffic loading and environmental conditions." It is caused by multiple reasons including traffic loading increase, temperature variation, poor shoulders, poor drainage, low quality foundation, and materials (Adlinge and Gupta 2013, Zumrawi 2015).

It is important to mention that deterioration depends on pavement type. Since the structure and the material composition of an asphalt cement concrete (ACC) pavement is

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different from that of Portland cement concrete (PCC), every type has its own deterioration mechanism and distresses, which are used to measure road surface deterioration. ACC pavement distresses have four main categories: cracking (alligator, longitudinal, transverse, Block), disintegration (potholes), surface deformation (rutting), and surface defects (raveling, bleeding, and polishing). On the other hand, PCC pavement distresses main categories are: cracking (corner, durability, longitudinal, and transverse), joint deficiencies (spalling, joint seal damage), surface defects (popouts, map cracking) and miscellaneous distresses (blowups, faulting of transverse joints and cracks, lane to shoulder drop-off, and separation) (Adlinge and Gupta 2013).

Regardless of the pavement type, pavement condition over time should be monitored to make sound decisions in the PMS. Pavement deterioration models are quantitative models to capture the change in condition over time and predict future pavement condition based on historical data, which supports and justifies decision making strategies. Deterioration models can be created based on deterministic or probabilistic approaches. Deterministic models are the simplest. They range from linear to exponential regression in complexity, and result in a single pavement condition value. Deterministic models include mechanistic, empirical, and mechanistic-empirical models. Mechanistic models are developed based on clear knowledge of the physical relationship between structural response and pavement condition; which is difficult to achieve in pavements due to the effect of traffic and climate, which are highly variable, on deterioration. Empirical models, are functions that link pavement condition indicator to independent variables through regression analysis. These independent variables include, but not limited to, traffic loading, climate variables and material characteristics. These

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models cannot predict pavement conditions beyond their calibration strata. The third type of deterministic deterioration models forms a combination of the previous two, which is the mechanistic-empirical models. These models are calibrated from the well-understood relationships between independent and dependent variables. They combine both the mechanistic responses such as stress and strain; with measured variables such as ESAL, freezing index, pavement age, and thickness in an empirical relation to forecast pavement performance. This type of models outmatched its precedents in the ability to accurately predict pavement condition (George *et al.* 1989, Raymond *et al.* 2003, Schram 2008, Abra Ens 2012).

The second type of deterioration models is the probabilistic models. As the name suggests, these models use input variables to predict the probability of getting a specific pavement condition at a specific point of time. Probabilistic modeling addresses deterministic modeling limitations such as failing to predict the uncertainty and dispersion in performance. The most common type of probabilistic deterioration models is the Markov model, which outputs the probability of pavement deterioration from its current condition to another based on historical data. The complexity of Markov models developed for pavement deterioration vary significantly. They can be homogeneous or non-homogeneous (Jiménez and Mrawira 2012, Surendrakumar *et al.* 2013, Abaza 2016, Saha *et al.* 2017). Other types of probabilistic deterioration models include the probabilistic regression models, which are used to find an estimate of future condition with its occurrence probability based on certain independent variables values (Lindsten *et al.* 2017).

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Decision trees

As mentioned above, these different deterioration models are developed to predict future pavement conditions to plan pavement treatment activities. These treatment activities cannot be assigned to pavement sections randomly. Each treatment is capable of fixing a specific distress or a combination of distresses. For instance, crack sealing is effective in fixing small transverse cracking but not alligator cracking, which needs placement of a hot mix asphalt (HMA) overlay in order to be fixed. The fact that pavement sections usually contain a combination of distresses, along with the presence of other factors affecting the selection of appropriate treatment, makes the choice more difficult. Factors impacting the selection of treatment strategies include (Johnson 2000):

- Existing pavement type and condition;
- Roadway class; level of traffic and its composition;
- Environmental factors,
- Cost of treatment;
- Pavement age and expected life;
- Last rehabilitation timing;
- Availability of qualified staff and contractors;
- Availability of good quality materials;
- Time of year of placement;
- Pavement noise; and
- Surface friction.

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In order to consider, as many factors as possible, decision trees and matrices are developed by DOTs and researchers. Decision trees, shown in Figure (1), are decision support tools that are used to assign appropriate treatments to pavement sections by comparing pavement condition indicators with predefined thresholds, and based on the other factors mentioned above. Since decision making factors vary among states, each state has its own treatment selection methodology. However, all of them agree on factors such as pavement type and quality, traffic condition and environmental factors, but the selection process varies. For instance, Michigan DOT (MDOT) sets certain thresholds for remaining service life (RSL), distress index (DI), international roughness index (IRI), riding quality index (RQI), and rut depth for each pavement type to select the appropriate treatment alternatives. Utah DOT uses a software to decide upon the treatment, in which roads are divided into three classes based on AADT. Treatments are chosen based on predefined condition indices and thresholds developed for different distresses. South Dakota DOT defines the severity and extent of the major distresses in the state. Then, treatments are selected based on a decision matrix for each distress based on different severity and extent levels. Illinois DOT (IDOT) has a more sophisticated selection strategy that goes beyond proposing several alternatives, to defining the most effective one (Abdelaty *et al.* 2015).

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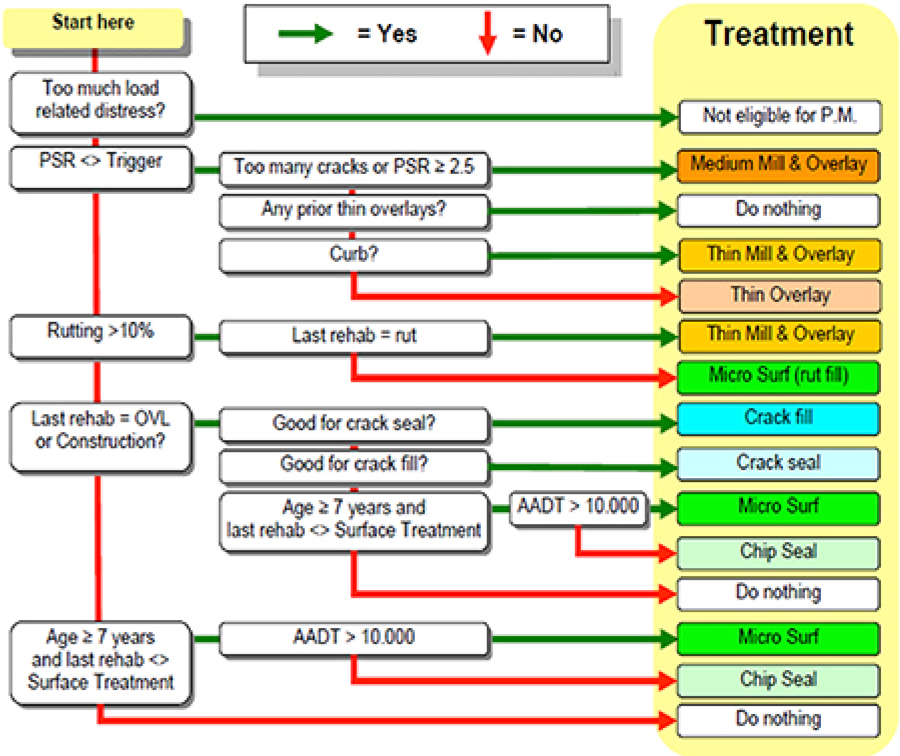

Figure 1: Pavement decision tree example (Kronick 2015)

Treatment effectiveness

In order to be able to select the most effective treatment, it is important to define treatment effectiveness, which is how long a treatment effect could last without the need to treat pavement again. The early understanding of treatment effectiveness was that, it is only the instantaneous improvement in pavement condition. However, as pavement deterioration behavior understanding improved, it was proven that treatments cause not only instantaneous improvement in the condition, but a decrease in the deterioration rate as well. As a result of that, other definitions, related to calculation procedure, for treatment effectiveness became available. These definitions include:

1- The extended life of pavement by the treatment

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2- The pavement performance instantaneous improvement on the deterioration curve due to the treatment.

3- The area between pretreatment and posttreatment curves along the pavement service life

4- Treatment service life, which can be defined in three ways as shown in Figure 2

   a. Time period between the end of the treatment and the beginning of the next one at the same road section

   b. Time period between the end of the treatment and point at which pavement performance reaches a predefined threshold value.

   c. Time period between the end of the treatment and point at which pavement performance reaches the pretreatment performance level (Dong *et al.* 2013, Ram and Peshkin 2013).

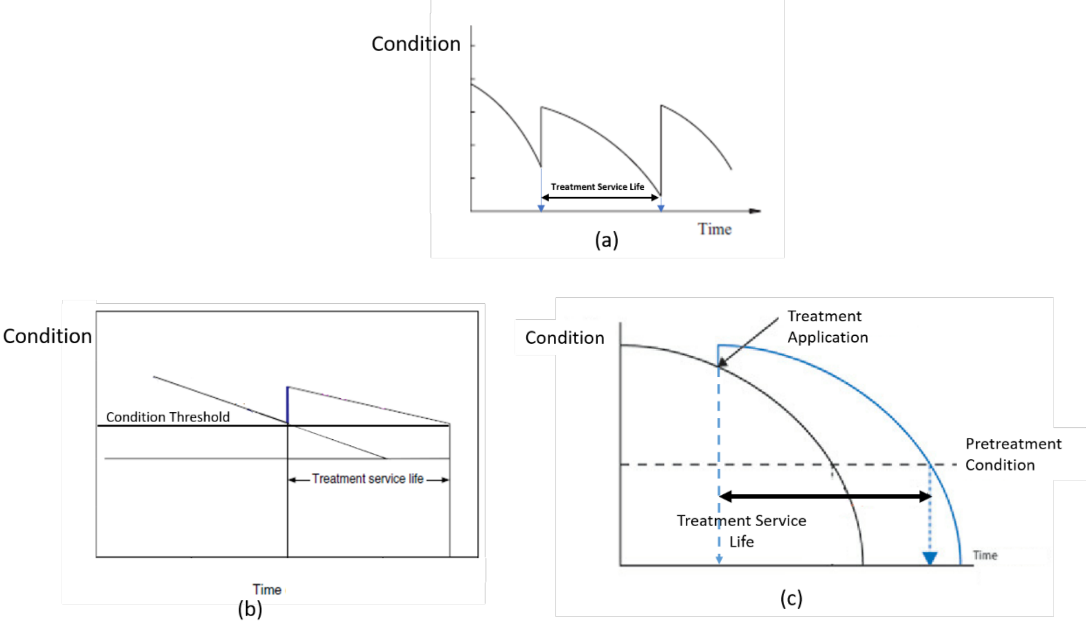

Figure 2: Treatment service life three definitions

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Different approaches were used to model treatment effectiveness including mechanistic-empirical pavement condition improvement models (Rajagopal and George 1991), probabilistic survival analysis in reference to control sections (Morian *et al.* 2011), and deterioration curves benefit area analysis (Ram and Peshkin 2013).

With all the differences in treatment effectiveness definitions and calculation process, researchers agree on its dependence on pavement condition, traffic condition, environmental condition, treatment thickness, and material. The worse the condition at which treatment is applied the lower the effectiveness of treatment. Furthermore, the application of a treatment on a section experiencing high traffic load or located in a harsh climate region will result in low treatment service life due to the high deterioration rate (Dong *et al.* 2013).

Decision making

All the previously described elements of PMS serve an ultimate goal of supporting the decision making process, which has two levels of decisions: network and project levels. The network level decisions are intended to "determine the optimum strategy for allocating pavement rehabilitation and maintenance funds over the entire network." In other words, it deals with setting maintenance priorities over an entire network to achieve the best network performance. On the other hand, project level decisions are related to determining the best strategy for maintenance or construction action of a specific pavement section (Horton 1990). These strategies involve the type of treatment and its time of application, which are highly related as shown in Figure (3).

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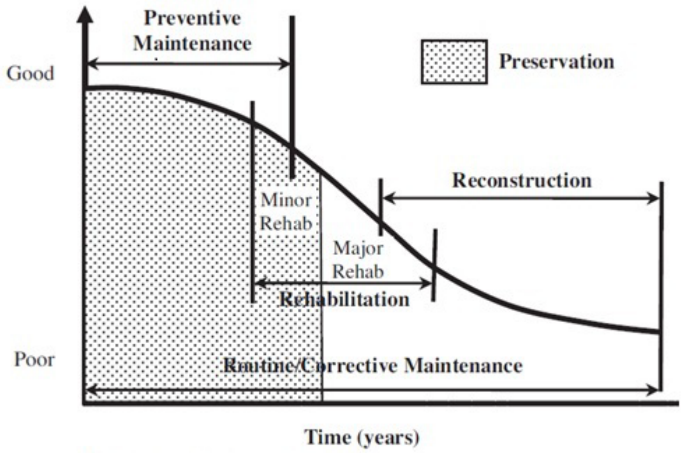

Figure 3: Pavement maintenance types and their application time (White 2012)

The way the two decision levels are linked in the decision making process can be a bottom-up or a top-down approach. In the bottom-up approach, life-cycle cost analysis techniques, such as benefit/cost ratio and cost effectiveness measures, provide the optimal maintenance, reconstruction and rehabilitation (MR&R) strategy for each individual project. Then, project prioritizing techniques, such as experts' judgment, worst-first, comprehensive optimization using mathematical models, heuristic approaches, weighting factors, and scoring are applied. These prioritization approaches have been addressed in many research studies (Dessouky *et al.* 2011, Dessouky and Papagiannakis 2016, Ahmed *et al.* 2017). The results of this process are a prioritized list of MR&R projects, fund needs estimations, single and multi-year MR&R strategies including cost, time and type of treatment. The second approach, i.e. top-down, relies on optimization models to analyze the network and find an optimally balanced MR&R program that maximizes network performance, maximizes user benefit or minimizes the total cost. Then, each individual project decision is made depending on its condition. It is

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not unlikely to get different decisions based on project and network levels due to the difference in the details level within each of them (MichiganTech 2008).

Bridge Management Systems

The second component of the transportation network that plays a vital role in connecting various parts of the country are bridges. As bridges are part of the transportation network, bridge management system (BMS) is one of the major processes of transportation asset management. BMS is defined as "a system designed to optimize the use of available resources for the inspection, maintenance, rehabilitation, and replacement of bridges" (AASHTO n.d.). In early 19th century, many states enacted laws to limit the speeds of carts moving over bridges. At that time, bridge maintenance was the responsibility of landowners. After automobiles were invented, states started to limit the weights of trucks on bridges and the management structure started to change. In 1911, a road law obligated the involvement of state authorities in managing public bridges and roads. All these events were important moves toward BMS development. One of the most critical events was the failure of the Silver Point Bridge in 1967. Congress responded to this terrible collapse by directing the US Secretary of Transportation to develop the National Bridge Inspection Standards (NBIS). The NBIS played an important role toward the establishment of BMS, since it was the first effort to record bridges' conditions over time. This motivated researchers to study bridges and transportation authorities to establish BMS-related programs (Hurt and Schrock 2016).

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Deterioration models

It is important to mention that bridges consist of three major components: deck, superstructure and substructure. Each of them consists of elements like beams, girders, piers, and joints. According to the NBIS, each bridge/culvert longer than 20 feet should be inspected by trained personnel once every 24 months period. Based on the inspection, each component is given a score ranging from 0, worst condition, to 9, best condition. If at least one component has condition less than 5, the bridge is called structurally deficient. Furthermore, if the bridge suffers from serviceability issues like insufficient lane width, shoulder width or vertical clearance, it is called functionally obsolete (Weseman 1995, Saadatmand *et al.* 2016).

In order to be able to use this data efficiently in decision making, future condition prediction is essential, which is achieved using bridge deterioration models. Each component deterioration is considered separately since deck is subjected to more wearing (Bulusu and Sinha 1997). But in all components, deterioration is considered as a stochastic process that depends on traffic load, climate, current condition, materials, and bridge design (Mauch and Madanat 2001). To simplify the representation of this process, national average deterioration rates were used in the past in states like Nebraska (Hatami and Morcous 2011). An example for that is the use of median time in condition state to govern the deterioration of bridge components. In this research, condition state means good, fair and poor states. However, condition rating is the NBI 0 to 9 scale. Deterioration models can be deterministic, which can be used to predict bridge future condition. These models are mainly based on simple regression. A major drawback in them is the failure to consider uncertainty and randomness. These models were used in

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the literature for different bridge types, such as reinforced concrete, prestressed concrete, steel, and timber bridges (West *et al.* 1989, Dunker and Rabbat 1993).

With the improvement of statistical analysis techniques and computational power, more sophisticated deterioration models were developed, such as the probabilistic deterioration models. In bridges, there are two types of these models. The first type is the time-based models, which output the probability distribution for time of transition from one condition state to another. The second type is the state-based models which output the probability that a bridge component will deteriorate from one condition state to another within a specific time period knowing the traffic, climate and maintenance schedule (Mauch and Madanat 2001). An example of these models is the Markov chain model, which takes into consideration the uncertainty and randomness in bridge deterioration (Li *et al.* 2014). The discrete condition indicator of bridges, unlike pavements, led to the wide spread of the discrete probabilistic deterioration models (Madanat *et al.* 1995, Mauch and Madanat 2001, Li *et al.* 2014). However, the biannual data collection makes it more difficult for bridges to develop this kind on models.

One of the major drawbacks of Markov chain process is the memoryless property, i.e. the future condition is only dependent on the current condition, but not the past (Kleywegt and Sinha 1994). To overcome this limitation, new technologies such as Artificial Neural Network (ANN) are used to model bridge deterioration. ANN is capable of modeling non-linear and complex relationships, as well as learning from the relationships of input variables to predict the unseen relationships in the data. The complexity of the developed ANN models ranges from using a small number of bridges,

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only 50, with only age variable to model deterioration (Sobanjo 1997) to the use of advanced back-propagation network on large number of bridges, 600 (Huang 2010).

Decision trees

As bridges deteriorate under the impact of traffic, climate, and aging; distresses start developing in bridges. These distresses develop in the different components of bridges such as spalling, deck fascia cracking, joint rust and corrosion. The solution for such problems ranges from cleaning to full replacement (MDOT 2016). These treatments are aggregated into four categories based on the FHWA preservation guide: routine maintenance, preservation, rehabilitation, and replacement. Table (1) provides definition and examples for each (FHWA 2018).

Table 1: Bridge treatment groups summary

Action Type	Definition	Examples
Routine maintenance	"Work that is performed in reaction to an event, season, or activities that are done for short-term operational need. They are not eligible for Federal funds."	Trash, snow, graffiti and hazardous material removal
Preservation, preventive maintenance (cyclic and condition-driven)	"Actions that prevent, or reduce deterioration of bridges or bridge elements. They keep bridges in good or fair condition; and extend their service life."	Deck/joint sealing, cathodic protection, protective coats, pile preservation and thin polymer epoxy overlay.
Rehabilitation	"major work required to restore the structural integrity of a bridge"	Partial/full deck replacement and

States have different groupings of their maintenance actions depending on their needs. The need for maintenance is derived either from bridge inspection reports directly or after deriving an index reflecting the overall condition. The way appropriate maintenance selection is made in bridges is different than that in pavements. In Delaware, the DOT relies on deficiency formula, which combines bridge condition with site

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condition, to identify candidates for preservation. It has a list of nine treatments and the corresponding conditions, at which each is applied to decide on treatments. Other states, such as Florida, rely on experts' judgment in treatment decisions. Ohio DOT uses inspectors' recommendations as their guide to decide on treatment needs. They have a list of twelve treatments from which they choose the most appropriate one. Michigan DOT utilizes a decision matrix that combines deck bottom and top surfaces conditions to get the appropriate action. For other components, generally, a component with NBI rating of less than 4 requires replacement. However, ones with NBI of 4 or 5 require rehabilitation, and all other conditions are eligible for preservation. These preservation actions are compared to those recommended by AASHTOWare Bridge Management software (Brm) preservation model, to check selection adequacy (Weykamp *et al.* 2009).

Treatment effectiveness

Bridge treatment effectiveness is usually expressed as the number of years added to bridge life. According to a survey created by Minnesota DOT in July 2016, only five DOTs answered the question related to the benefits of bridge maintenance and all of them rely on experts' judgment. These are California, Kansas, Michigan, New Jersey and North Carolina DOTs. Thus, more research efforts are being directed to this topic, such as the ongoing NCHRP project number 14-36 (MnDOT 2016).

Decision making

The previous components of BMSs collaborate to support agencies' decision making strategies. Similar to PMS, there are two levels of decisions in BMS. These two levels should be evaluated simultaneously to insure optimal decisions. Looking at the

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network level only while making decisions, neglects individual projects' needs and requires many assumptions. On the other hand, project level decisions are very specific and might lead to isolated analysis of the project from the network (Hegazy *et al.* 2004).

The main objective in network level analysis is to rank projects. This ranking can be done based on experts' judgment, worst-first approach, priority ranking techniques, mathematical optimization, and artificial intelligence (AI) approaches. Experts' judgment are useful on small scale networks only (Elbehairy 2007). On the other hand, the worst-first approach is a rational technique even on large networks, but does not maximize the benefit of MR&R strategies (Jiang 1990). Priority ranking approach uses benefit/cost (B/C) analysis, deficiency rating, level of service (LOS), or sufficiency rating to set MR&R priorities. One of the fundamental priority ranking approaches is the benefit/cost analysis, but it is difficult to implement, because of the difficulty in user benefit estimation (Elbehairy 2007). Mathematical optimization sets LOS, budget and minimum condition constraints to obtain the optimal set of ranked projects that maximizes the network performance or minimizes the cost. It forms one of the strongest and sophisticated decision making tools.

In the project level, the type, timing and cost of treatment are obtained in details using B/C analysis, life cycle cost (LCC) optimization, Multiple-criteria decision-making (MCDM) or AI techniques (Jiang 1990, Mohamed *et al.* 1995, Asadi *et al.* 2011). B/C analysis is more successful at this level due to the high level of details. On the other hand, LCC optimization obtains the minimum overall cost along the life cycle of the bridge under budget constraints and results in optimal MR&R strategy along bridge's life.

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However, these MR&R strategies might result in poor performance due to minimizing LCC. That's why MCDM was proposed to set multiple criteria when prioritizing projects. These criteria include minimum cost, maximum and minimum performance thresholds, in order to get the prioritized set of projects (Patidar *et al.* 2007). Finally, AI techniques have the ability to deal with multiple constraints efficiently to optimize maintenance schedules.

Current Asset Management Limitations

The previous sections described the components and strategies of traditional asset management practices, in which each asset type goals are independent of the others. However, there is significant interdependencies among transportation assets. Thus, these independent allocation approaches will result in a non-optimal utilization of resources. Furthermore, different asset management approaches can lead to contradictory results that are interpreted differently by different stakeholders, due to their different definition of success. Moreover, pavements and bridges are part of one network, and road users do not distinguish between them if they had an uncomfortable trip. They will have a bad impression about the entire network (Weninger-Vycudil *et al.* 2015).

These limitations motivated transportation agencies to evaluate their networks' performance as a whole not as independent pieces (Hudson *et al.* 2014). With the scarcity of resources and the continually aging transportation assets, these agencies might be required to transfer funds from one asset type to another to trade-off different levels of service against limited resources (CDOT 2010). Thus, it is important to develop a generic approach that considers multiple assets performance requirements and multiple

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stakeholders needs simultaneously. An approach that combines engineering and economic principles to serve transportation assets. This approach is the cross asset resource allocation.

Cross Asset Resource Allocation

Cross-Asset Allocation is “the decision making process by which resources to multiple programs or asset classes are distributed based on the simultaneous quantified prioritization of utility”(AASHTO 2015). It is not a new topic. Multiple researchers investigated this issue in the literature, but before discussing these studies, it is important to distinguish between three main concepts related to cross asset allocation. Cross asset allocations, cross asset trade-offs and cross asset optimization. In (2015), the American Association of State Highway Officials (AASTHO) published a discussion paper setting the definitions of these three concepts, which are as follows: (AASHTO 2015)

Cross-Asset Trade-Offs: The decision-making process by which resources from one asset class are transferred to another in order to maximize “perceived” utility.

Cross-Asset Optimization: A further refinement of cross-asset allocation where recursive mathematical computations are utilized to determine the maximum utility for a given set of investments

AASTHO discussion paper showed that cross asset resource allocation approaches are divided into three major categories, which are Benefit/Cost approach, Multi-Criteria Decision Analysis (MCDA), and Risk/Reward-Based Allocation, under which all the developed cross asset resource allocation frameworks fall.

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The NCHRP Report 545 used the available pavements' and bridges' data to evaluate the effect of different investment options within each asset and across different assets for both project and network level investments. It only showed different what if scenarios without considering resource allocation, handling life cycle cost and incorporating risk analysis (NCHRP 2005). Bai utilized MCDA in an eleven-step model among which two steps were extensively studied, which are scaling and amalgamation (Bai et al. 2008). These steps allow different assets to be compared through the use of dimensionless performance metrics. They also established a utility function that combines weighted functions of performance measures to evaluate projects. In 2009 they utilized MCDA as well to create a framework for selecting projects that satisfy multiple objective under certainty and uncertainty in projects outputs conditions. They utilized Monte Carlo simulation in the case of uncertainty and produced Pareto Frontier through genetic algorithms as solution to be used in the trade-off analysis between different projects, budgets or performance measures (Bai and Labi 2009). Hudson developed two approaches to the cross asset optimization, the first deals with the overall performance as linear combination of each asset performance, which requires users to have control over optimization process. The second approach is the derivative-free optimization, which considers each asset type problem as a black box (Hudson et al. 2014). Porras-Alvarado used fair division method to provide a framework for cross asset resource allocation, in which resources are allocated by giving a fair share to each asset based on a developed utility function (Porras-Alvarado et al. 2015).

The NCHRP Report 806 developed a framework for prioritizing projects based on their impact on multiple performance measures across assets using multi-objective

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decision analysis (MODA). Performance measures are weighted and then scaled based on preferences to create dimensionless metrics that are easy to compare across assets. Then, projects are scored based on their impact on the different performance measures (Maggiore and Ford 2015). The most recent FHWA report in cross asset resource allocation is the "Identification of Effective Next Generation Pavement Performance Measures and Asset Management Methodologies to Support MAP-21 Performance Management Requirements" (Zimmerman *et al.* 2016), which investigated available performance measures and suggested new ones to be used by state DOTs in the future. These next generation performance measures, which include backlog, asset sustainability index, RSL, etc. are used to identify candidate treatments, prioritize options, make tradeoff decisions and report outcomes. The developed cross-asset optimization framework requires three systems. Asset management system at program level to generate a list of possible treatment strategies over analysis period, which is known by multi-year multi-strategy analysis. A cross asset analysis tool that applies budget and performance constraints to determine the optimal strategy on multiple assets and an output interface that will include utility of each strategy and maximize this utility (Zimmerman *et al.* 2016).

From an international perspective, cross asset resource allocation is a popular concept as well. In Australia, the analytical hierarchy process was used for the optimization of cross-asset resource allocation under a constrained budget. This approach relied on dividing the allocation problem into levels, and established weights for each asset and each option based on decision makers' preference (Su and Hassan 2007). Furthermore, in New Zealand, asset value depreciation was used in resource allocation

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across assets, where assets with higher value depreciation rate were given higher priority (FNDC 2012).

In the U.S, DOTs started developing their cross asset tools with different levels of advancement. These tools are being developed in collaboration with asset management consultancy firms. By 2016, states that had developed cross-asset tools are Utah, North Carolina, North Dakota and Georgia. Utah developed cross-asset optimization for both system and project level on pavement, bridges and safety. North Dakota developed a trade-off hub tool to conduct cross asset optimization on pavement management and functional capacity. Furthermore, in Georgia, network-level trade-off analysis tool was developed to relate funding to performance for pavements, bridges, safety, capacity and operations (Zimmerman *et al.* 2016). On the other hand, Iowa DOT still utilizes separate asset management systems and decision tools. As a result of that, it is important to start developing a cross asset resource allocation framework utilizing the data and tools available in Iowa. This research will suggest a simple, applicable and rational cross asset resources framework for pavements and bridges only, with a goal of expanding that to other assets such as safety and mobility in the future.

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CHAPTER 3: DATA SOURCES

In this thesis, two major sources of data were used: Iowa Pavement Management Information System (PMIS) data and National Bridge Inventory (NBI) data. The following sections will give generic details about these data sources as well as specific description of the assets, bridges and pavements, on which the proposed cross asset framework is applied in this thesis.

PMIS Data

Iowa DOT is doing great effort in processing and reporting pavement data collected by a vendor at the network scale. The PMIS data covers all Iowa's Interstate and Primary road sections. PMIS data includes information about pavement structure such as the thickness of different layers. It also includes information related to road functionality such as AADT, AADTT, road location, functional class, width, and median details. The most important element in the PMIS data is the pavement condition information, which is collected utilizing automated collection methods on a two-year cycle. Condition data includes roughness and distresses, from which PCI is calculated. Roughness is expressed using the international roughness index (IRI). Furthermore, distresses data include the various severity levels of rutting, alligator cracking, transverse cracking, longitudinal cracking, joint spalling, faulting, and durability cracking. The major limitation in the PMIS data is the lack of maintenance records, which are essential in developing deterioration and treatment effectiveness models. The data reports resurfacing year only, which does not cover minor maintenance actions. For the purpose of this research, sections with full PMIS records between 2000 and 2017 were used.

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NBI Data

NBI database is a national effort for collecting bridges and culverts data across the states, and keeping them at one place for the use of decision makers and research studies. Based on the NBI regulations, each bridge and culvert longer than 20 ft. need to be inspected by qualified inspectors once every 24 months, while in some cases, such as fracture-critical bridges, inspections need to be done more frequently for safety purposes. Inspectors report structural information such as the structure type, material type and span length. They also report operational information including load posting, vertical clearance, width, AADT, detour length, functional classification and location. Condition ratings for bridge decks, superstructure, and substructure are available in the NBI data. The advantage of NBI database compared to PMIS is the availability of structural improvement recommendations. These recommendations include length of structural improvement, type of work, and proposed improvement cost. For the purpose of this research, NBI 2017 data was used.

Data Distributions

For the purpose of applying the proposed cross asset resource allocation framework, Interstate, U.S., and state routes in the state of Iowa were considered. These systems include 2,314 pavement sections with a total length of 11,084 miles and 2,826 bridges with various deck areas. These 2,826 bridges form around 12% of the total number of NBI bridges in the state of Iowa. Before processing the data, it is important to study the data carefully to obtain general patterns and distributions that will help in understanding the results of the decision tool. The following subsections will provide thorough description of the original pavements and bridges dtat in Iowa. Pavement

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sections distributions by section length, pavement type, age, AADT, and condition will be shown. On the other hand; AADT, detour length, components condition, and time-in-condition distributions will be shown for bridges.

Pavement data

The following provides a summary of the interesting features found in the PMIS database before processing:

- Pavement sections lengths in PMIS vary widely. They range from 0.05 to 18 miles with 34% of the sections less than 1 mile long. Only few of the segments, around 4%, are longer than 10 mile. Section length will have a large impact on the treatment cost and this wide variation available in the data motivates using mileage rather than section counts to get maintenance actions distributions in the analysis part of this research. Figure (4) shows the distribution of pavement sections based on their length.

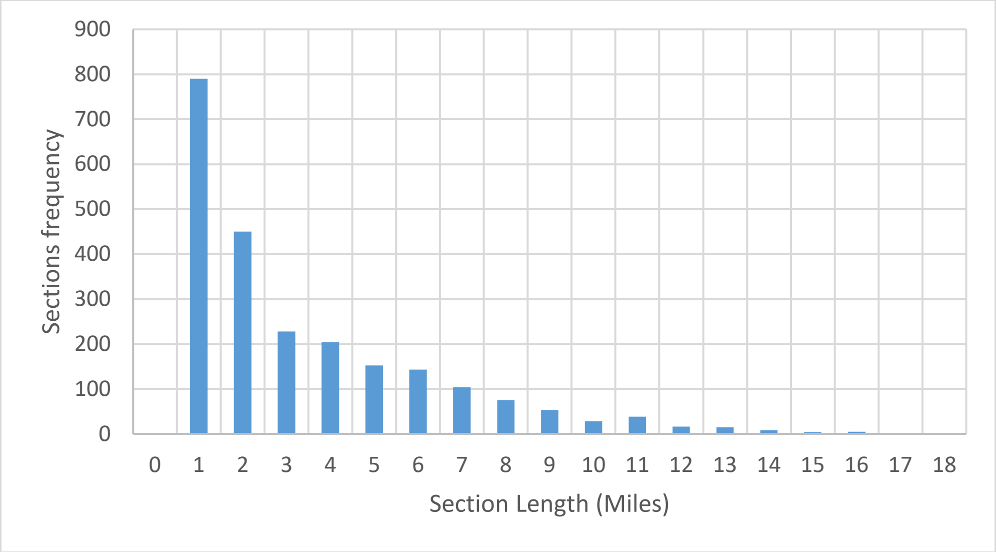

Figure 4: Pavement sections distribution by section length

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- Most of the pavements on the Interstate, U.S. and state road systems are composite. These pavements form 58% of the all pavements in the three systems, followed by jointed rigid pavement with a percentage of 23%. Figure (5) shows the distribution of pavement sections by pavement type.

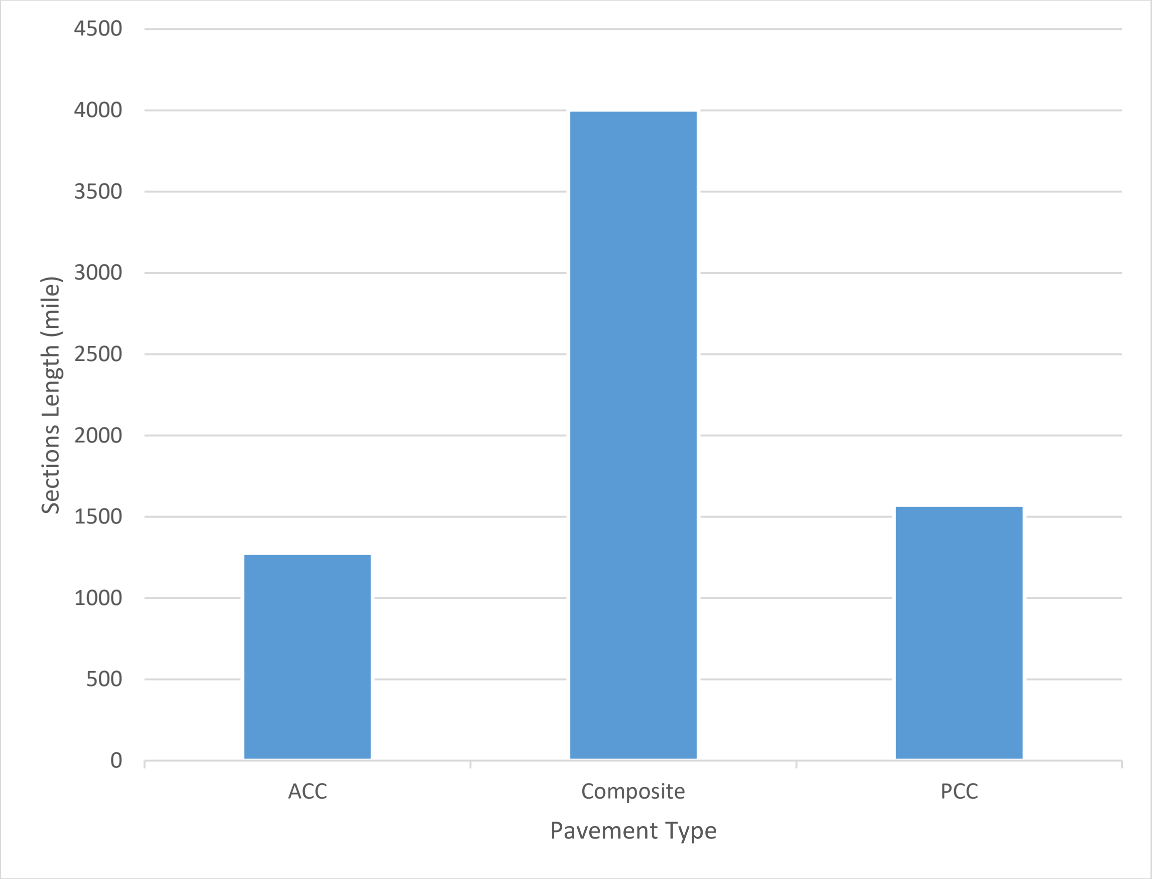

Figure 5: Pavement sections distribution by pavement type

- The distribution of pavement sections' ages from last reconstruction action, as indicated in the PMIS data, is positively skewed with the maximum length of sections having an age between 10 and 20 years, 2252 miles. There are 5.13 miles with an age between 70 and 100 years, which are obviously outliers. 171 miles

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have an age of zero, those that were resurfaced in 2017. Figure (6) shows the distribution of pavement sections based on age from the last resurfacing action.

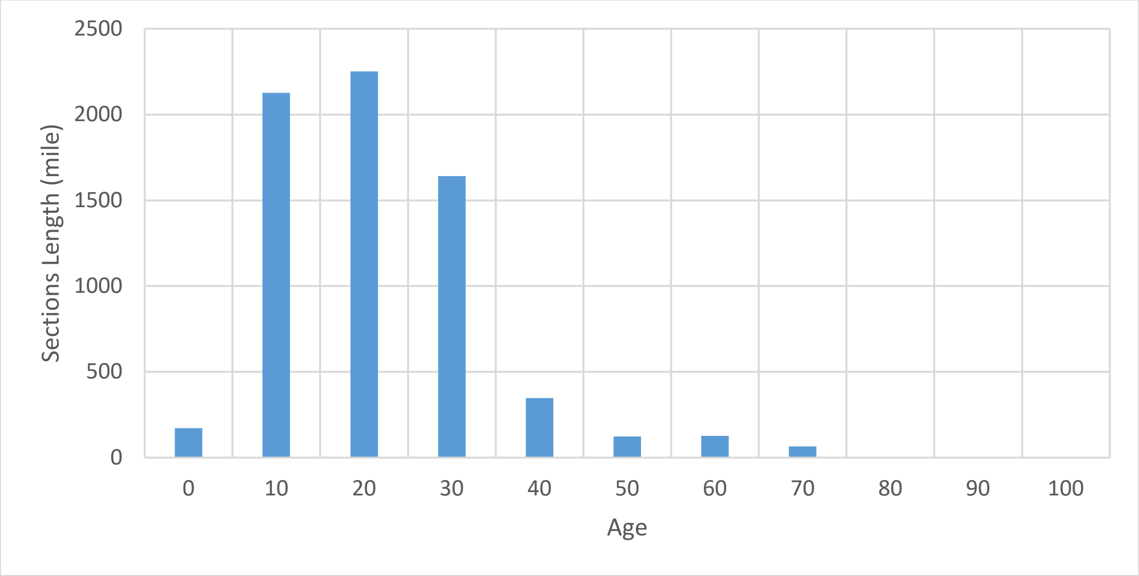

Figure 6: Pavement sections distribution by age from the latest resurfacing

- The distribution of pavement sections' average daily traffic is positively skewed. The reason behind this skew is the presence of sections with extremely high ADT records (> 20,000). 118 miles lie in this region. On the other hand, around 400 miles have AADT less than 1000. This indicate that the bulk of the sections lie between AADT values of 1,000 and 20,000. Figure (7) shows the distribution of pavement sections based on AADT.

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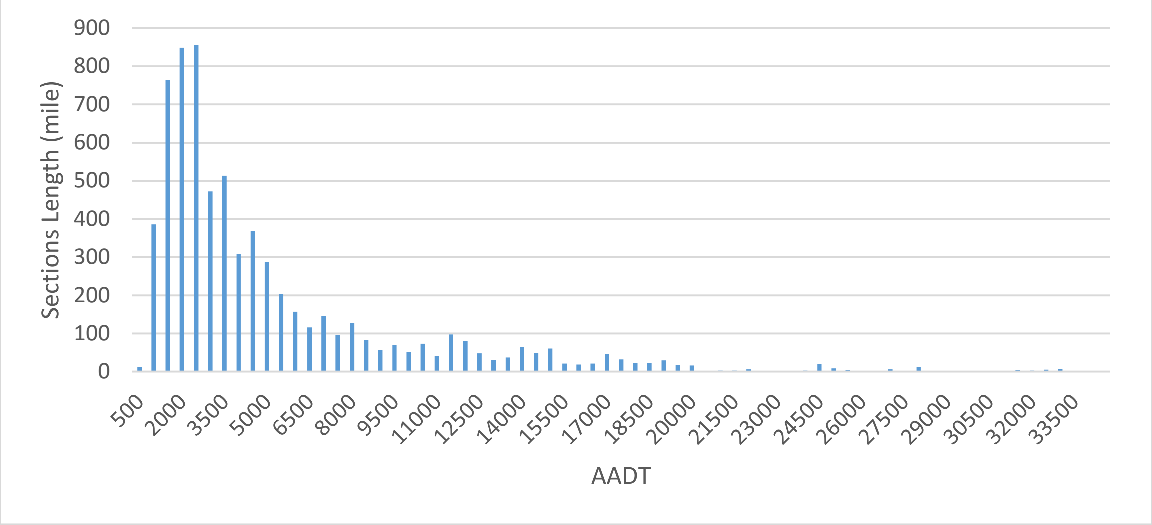

Figure 7: Pavement sections distribution by AADT

- The distribution of pavement sections' IRI is positively skewed, which indicate that most of the network falls within an acceptable range of roughness. 52% of the network falls within the good riding quality definition of the FHWA, i.e. has an IRI less than or equal to 1.5 m/km. Furthermore, 40% of the network has an IRI between 1.5 and 2.68, which is defined as acceptable as per the FHWA standards. The remaining 593 miles have bad riding quality and require treatment to get smooth surface. Figure (8) shows the distribution of pavement sections based on IRI.

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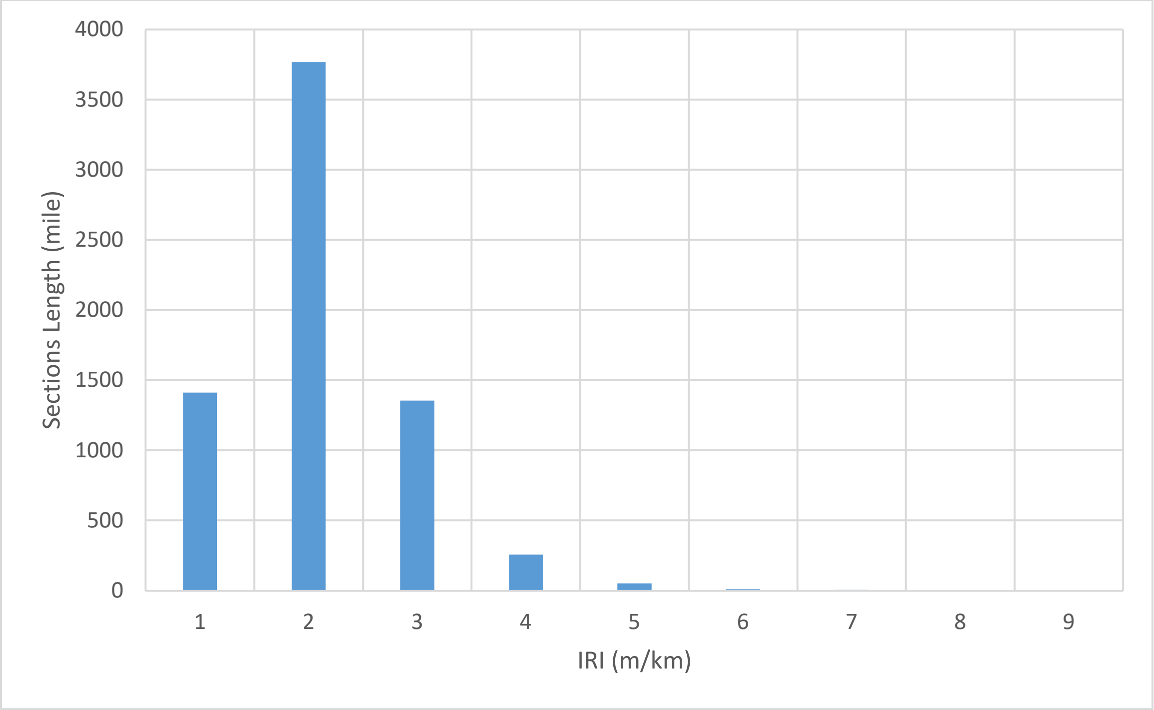

Figure 8: Pavement sections distribution by IRI

- The distribution of the pavement sections with IRI and age is concentrated at the low age low IRI region. However, there are some extreme IRI and ages. The distribution has a positive skew in the IRI for each age range that gets flatter as the age increases as shown in Figure (9). Also, the maximum frequency of sections shift toward higher IRI values at high ages.

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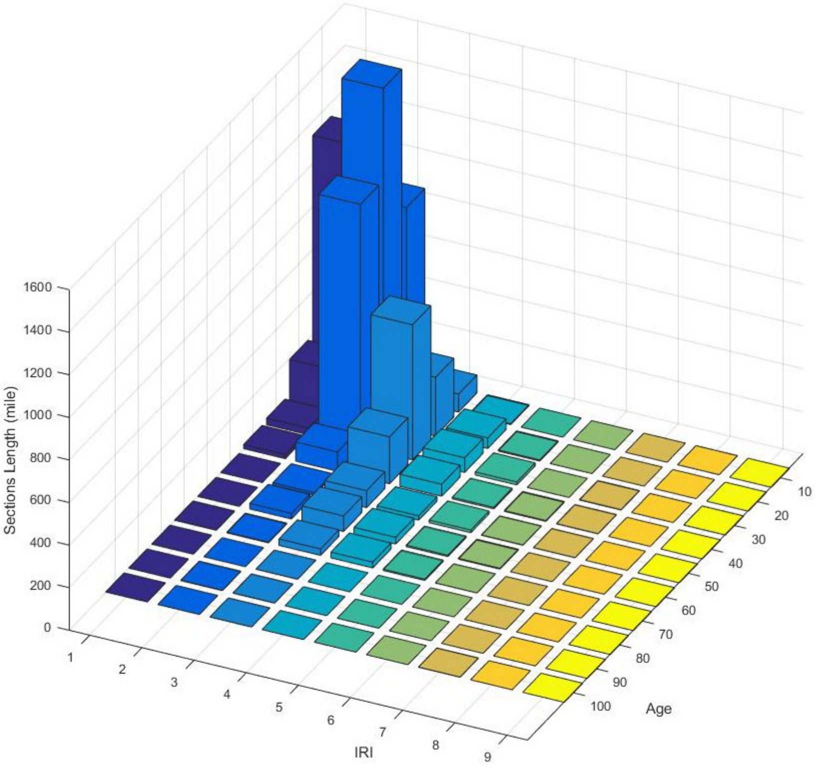

Figure 9: Pavement sections distribution by IRI and age

- On contrary, the distribution of pavement sections' PCI is negatively skewed. This indicated good network overall condition, since higher PCI values are associated with better conditions. The presence of few low PCI sections shifted the distribution to the left and created the skewness. Only 11.75 miles have a PCI of 20 or less. Those sections will require immediate replacement actions due to their extremely bad conditions. On the hand, 41% of the network, i.e. 2808 miles, have a PCI > 80. Those sections will require no action. Figure (10) shows the distribution of pavement sections based on PCI.

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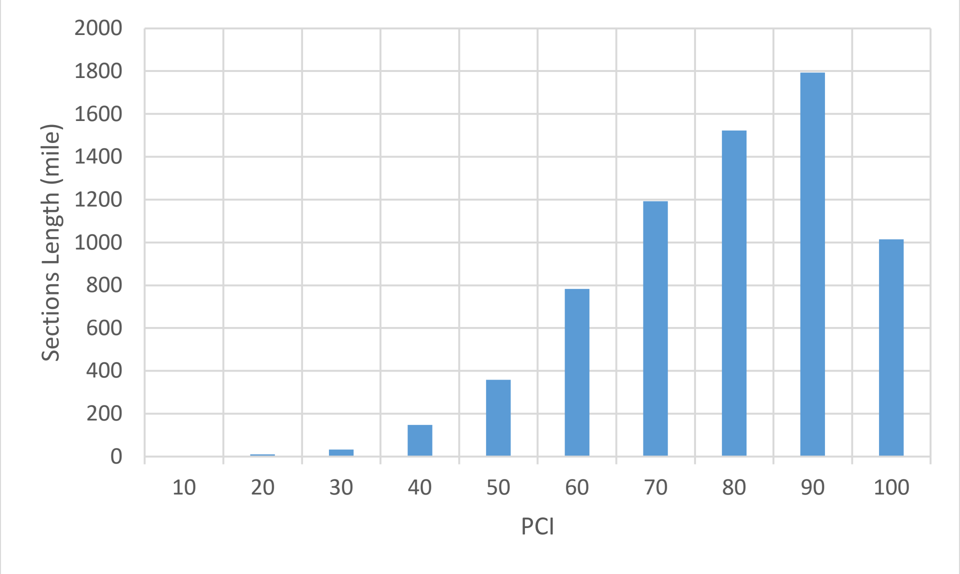

Figure 10: Pavement sections distribution by PCI

- For the distribution of pavement sections based on PCI and age, as the age increases, the distribution shifts toward lower PCI values, which reflects deterioration over time. However, some sections with ages between 40 and 60, from the last reported resurfacing action, have excellent PCI values, as shown in Figure (11). These are sections received unreported treatment actions or have miscoded PCI values. On the other hand, some sections are less than 10 years old and have a PCI less than 50, which mean they are within the range of structural maintenance need. These sections may be located in harsh climate or heavy traffic regions.

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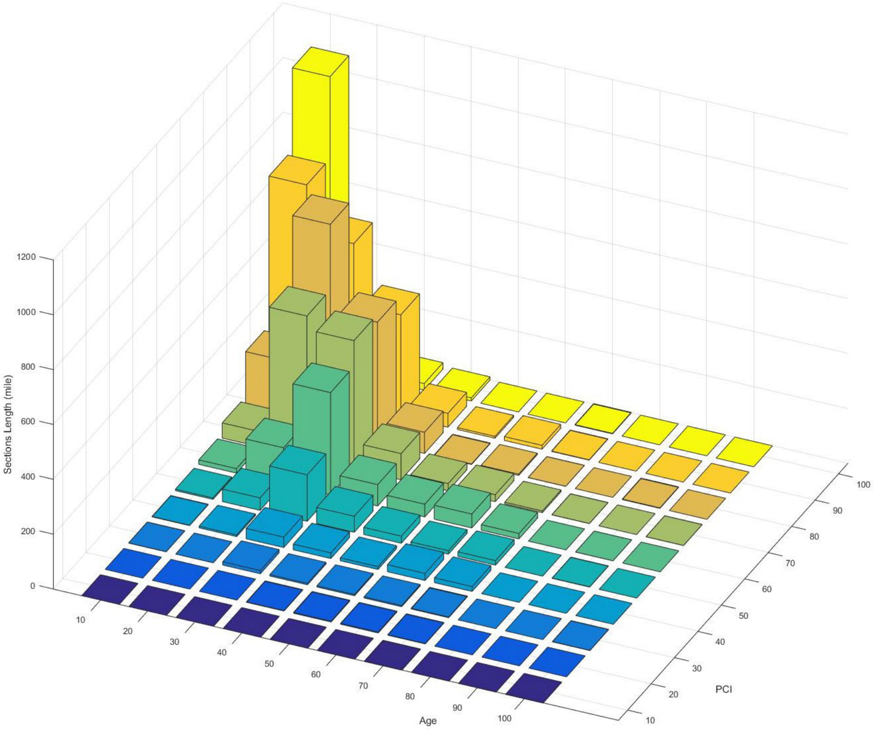

Figure 11: Pavement sections distribution by PCI and age

Bridge data

After limiting the NBI data to U.S, interstate and state bridges in Iowa, the following interesting features were found:

- As in the pavement sections, the distribution of ADT on bridges is positively skewed, but with larger number assets having an ADT less than 1,000 and greater than 20,000 as Figure (12) shows. The number of bridges within these ranges of ADT are 121 and 224 respectively.

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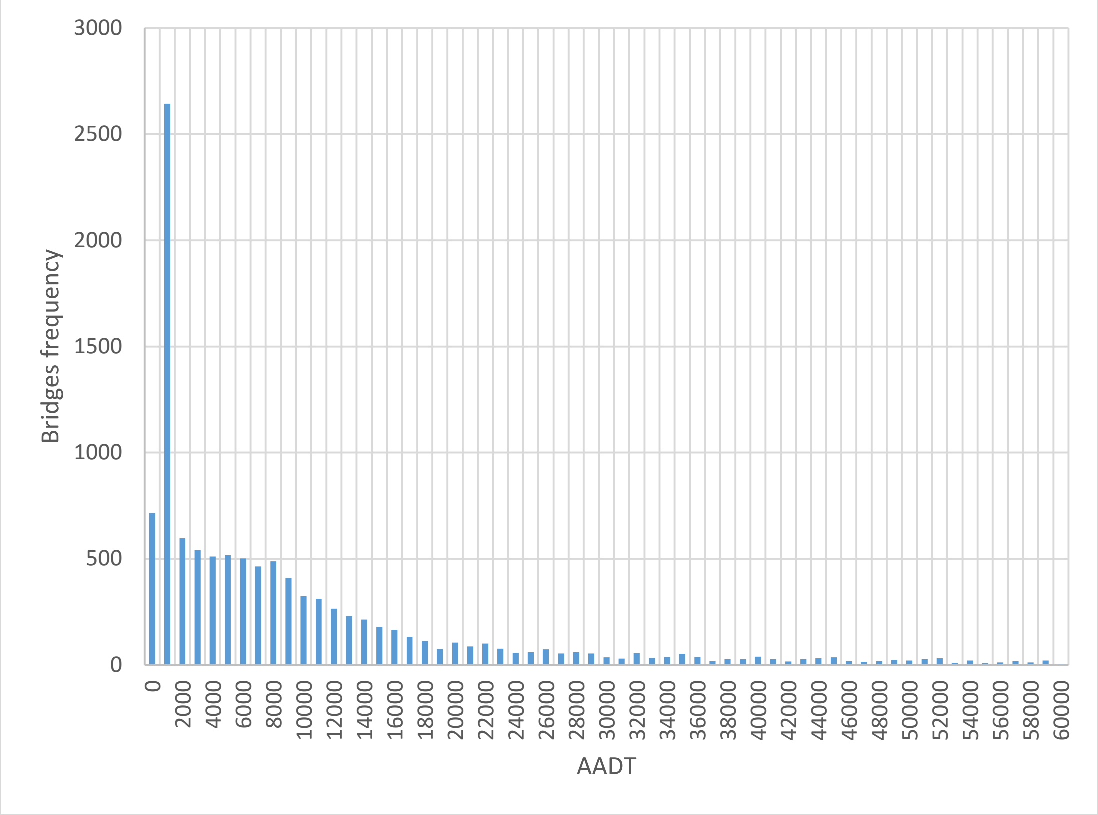

Figure 12: Bridges distribution by AADT

- As shown in Figure (13) the distribution of bridge detour lengths is positively skewed with 357 by-passable bridges, i.e. with zero detour length. On the other hand, 8 bridges have a detour length greater than 100 km. Furthermore, most of the bridges, 47%, have a detour length of 5 km which is relatively short. This indicates that major replacement and treatment works on large portion of the network will be manageable to some extent depending on the condition of the detours and their capacities.

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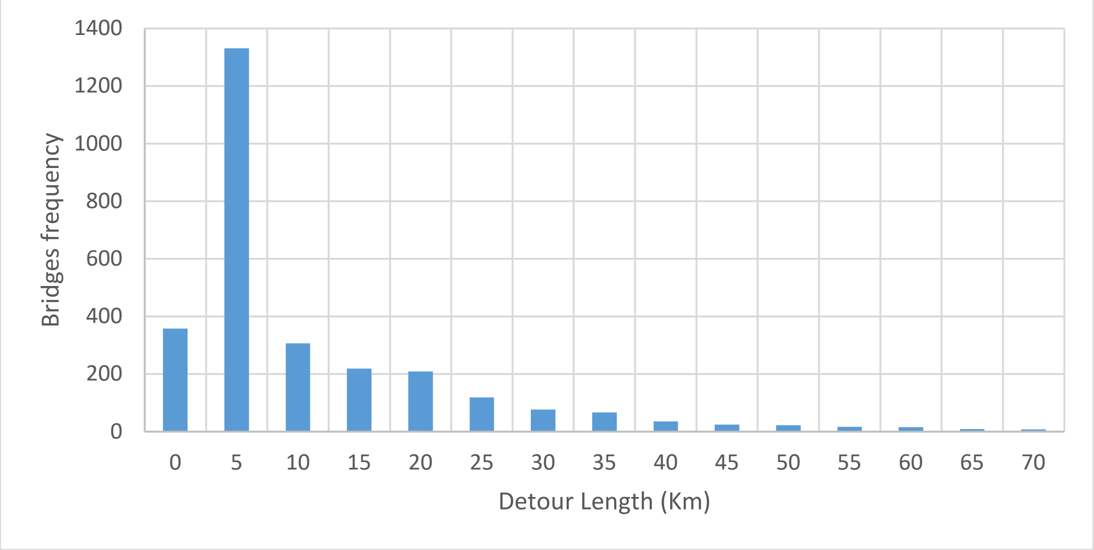

Figure 13: Bridges distribution by detour length

- The distribution of all bridge's components condition shown in Figure (14) is negatively skewed with more than 50% of the bridges having a condition better than the average network condition. However, there are few differences among the condition of the three components. First of all, there are two bridges with a superstructure of condition 3, while the minimum condition for decks and substructures is 4 in the network. The percentage of fair decks is around twice that of fair superstructures and substructures. However, the percentage of decks with condition greater than 7 is less than half that of superstructures and substructures within the same condition range, since decks are subjected to more wear and tear from traffic.

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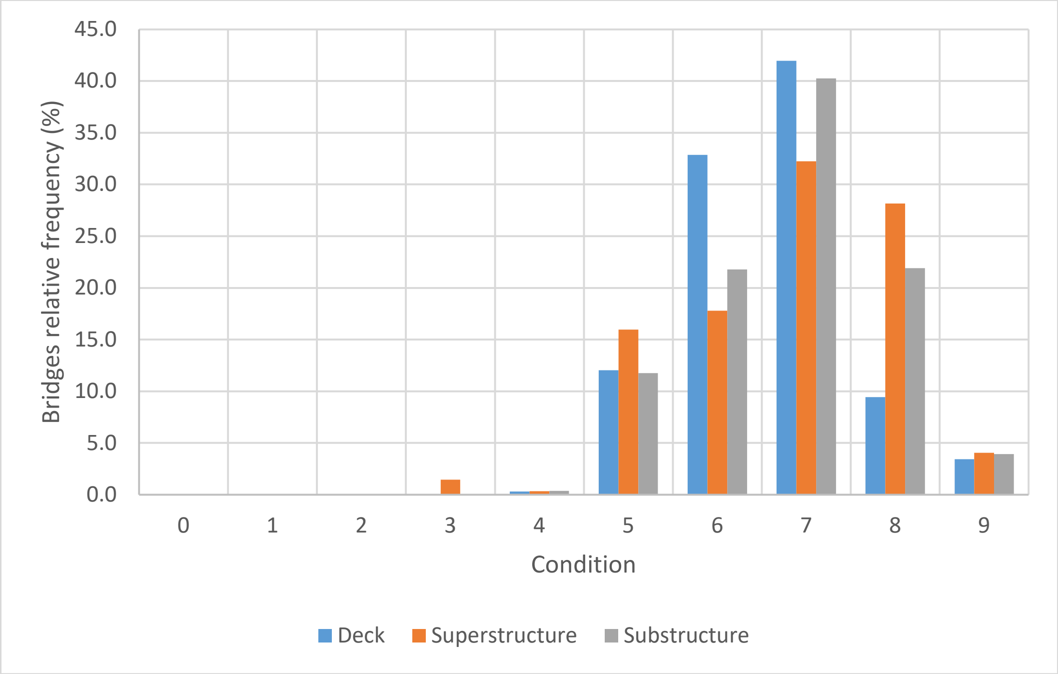

Figure 14: Bridge components distribution by condition

- For the distribution of bridges based on their components' condition of their elements, along with the time bridge component have stayed in that condition, the following observations were obtained from Figures (15) through (17):
    - The three bridge components follow fairly similar distributions based on condition and time in condition.
    - It is obvious that decks generally have lower time in condition because they are exposed to more wear and tear from traffic, thus it deteriorates from a condition state to another faster than other components. On the other hand, superstructures and substructures have greater number of bridges with large time in condition, especially those in fair condition. This might be because of the preservation actions that keep extending the life of these components.

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- The distribution is positively skewed along the time in condition due to the presence of bridges with extremely high time in condition. The highest number of bridges with extreme time in condition values are associated with condition 7. This could be because condition 7 has the highest median time in condition, between 14 and 15 years depending on the component. However, it is important to mention that more than 250 bridges have at least one component with condition of 7 and time in condition greater than 15. These bridges will immediately drop to the fair condition in the second year, if they are not main
- All bridge components with condition 9 have a time in condition less than 10 years. However, those with condition 4 have a time in condition between 5 and 15 years.

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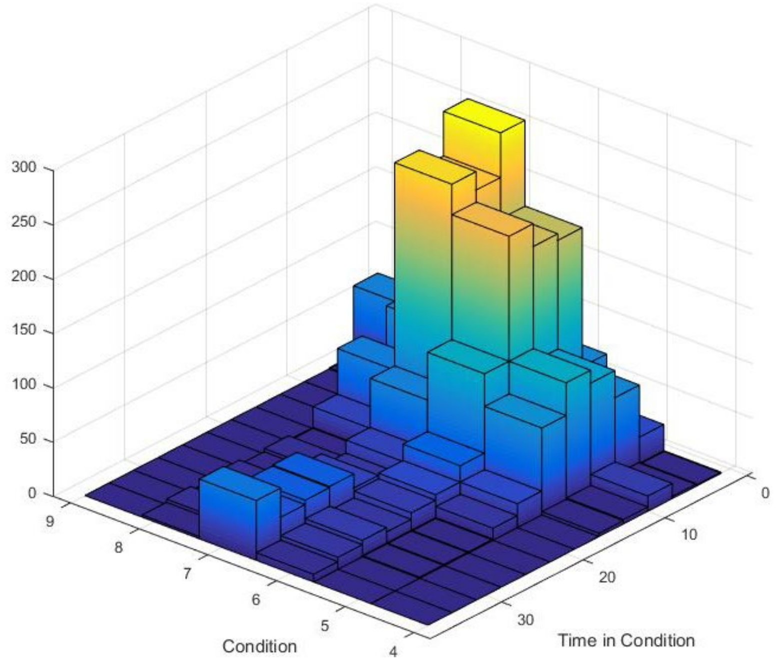

Figure 15: Bridge decks distribution by condition and time-in-condition

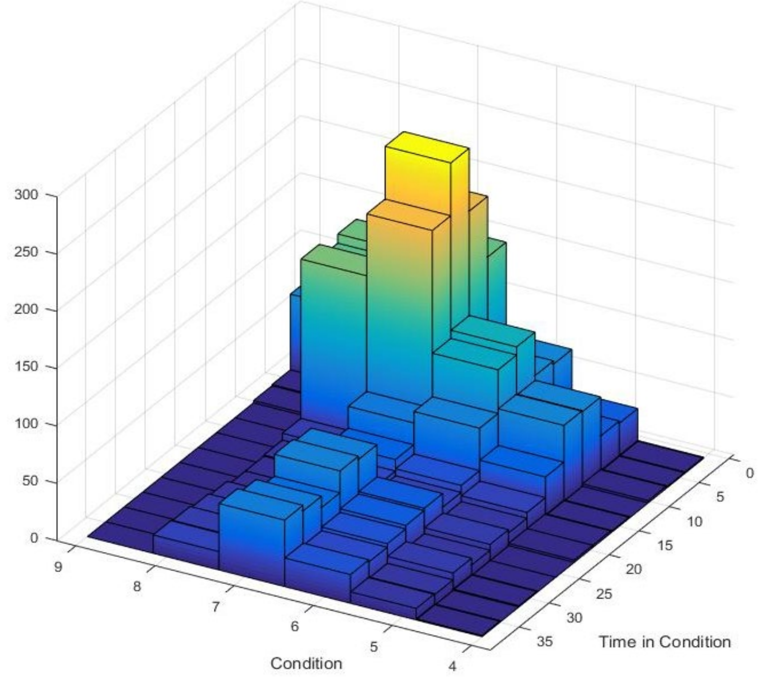

Figure 16: Bridge superstructure distribution by condition and time-in-condition

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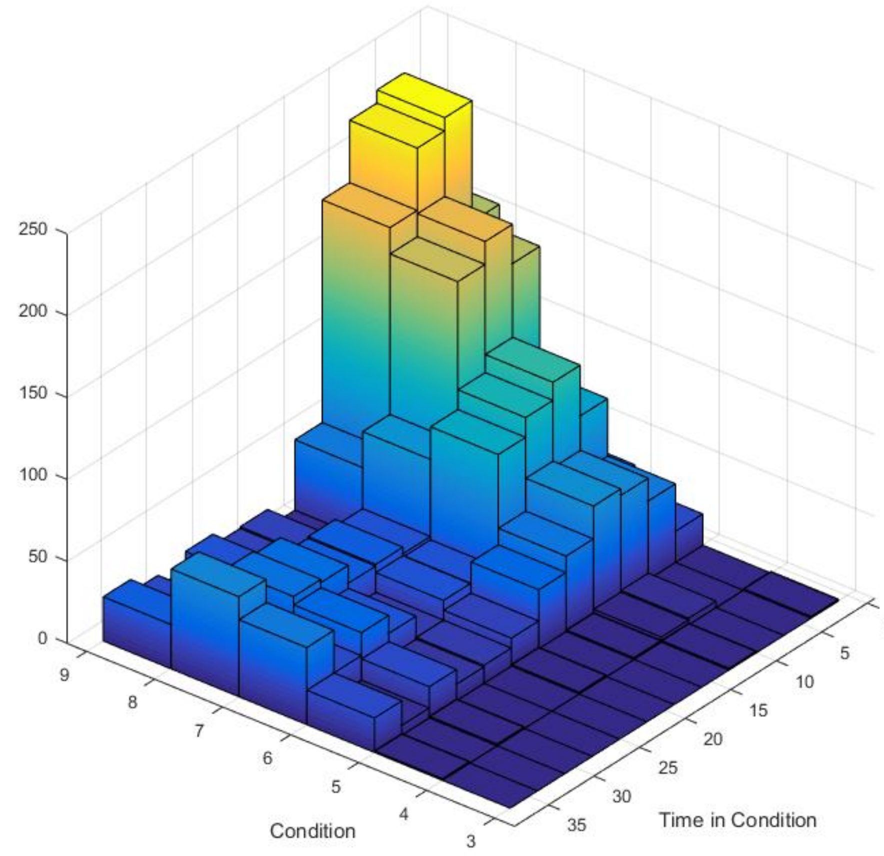

Figure 17: Bridge substructure distribution by condition and time-in-condition

Data Processing

As mentioned above, the used data contains obvious outliers that need to be removed in order to insure that all the assets included in this study exist. At the same time, it is not recommended to over process the data, which lead to excluding a large proportion of the network. Pavement and bridge data processing was done in different way due to the difference in the databases and the attributes of interest.

For pavements, 18 years of PMIS data were used, from 2000 to 2017. Only sections with continuous records during that period were considered for analysis, in order

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to be able to develop deterioration models. However, not all these records were considered in the analysis. Age was defined as the time since the last resurfacing record for sections with populated resurfacing year attribute and all condition records before that year were excluded. Those who do not have a resurfacing year record, their age was defined as the time since construction. It is not unlikely to have sections with increasing PCI values or decreasing IRI values without any reported maintenance action, and it is difficult to control this variability in the data. To reduce its impact, any pavement section older than 60 years was excluded from the data, because it is impossible for a pavement section to last 60 years without major rehabilitation or resurfacing actions.

For bridges, the latest NBI data was used, i.e. 2017, only because the deterioration approach used for bridges does not depend on previous years' data. Temporary bridges were excluded from the data. Moreover, components' conditions were translated into condition states (good, fair and poor), which reduced the number of possible conditions combinations from 729 to 27 possible condition states combinations. This will make the assignment of treatment actions easier and will decrease code's running time. Any component with condition greater than 6 is in good condition state, while anyone with condition less than 5 is in poor condition state, and those in between are in fair condition state. A tool was used to extract the time each bridge have stayed in its current condition. Then these times in condition were converted to time in condition state. The resulting TISs were compared with the median TISs. If the former exceeds the latter, then TIS is set to the median TIS because the median TIS will be used as bases for bridge deterioration.

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CHAPTER 4: METHODOLOGY

General Overview

The main objective of this thesis is to establish a simple and applicable cross-asset resource allocation framework for pavements and bridges utilizing part of the tools Iowa DOT uses in their PMS and BMS with some justified modifications. This chapter summarizes the methodology used to achieve this objective, starting with defining importance groups and ending with maximizing network monetary value. Between these two steps, total network budget is allocated to individual assets at three levels. The first level is to distribute total budget on asset types. The second level is the distribution of each asset type budget on importance groups using a need-based approach. The last level is the prioritization of assets within each importance group, which is achieved using a worst-first approach. Then, the deterioration and treatment effectiveness models are used to predict future asset condition, which is translated into network monetary value using different valuation methods. Maximizing network monetary value is achieved by developing a MATLAB code that repeats the entire process for different combinations of asset types' budget proportions. Figure (18) summarizes the general steps of the proposed framework. The below sections describe the methodology and explain the general steps to accomplish the research goals

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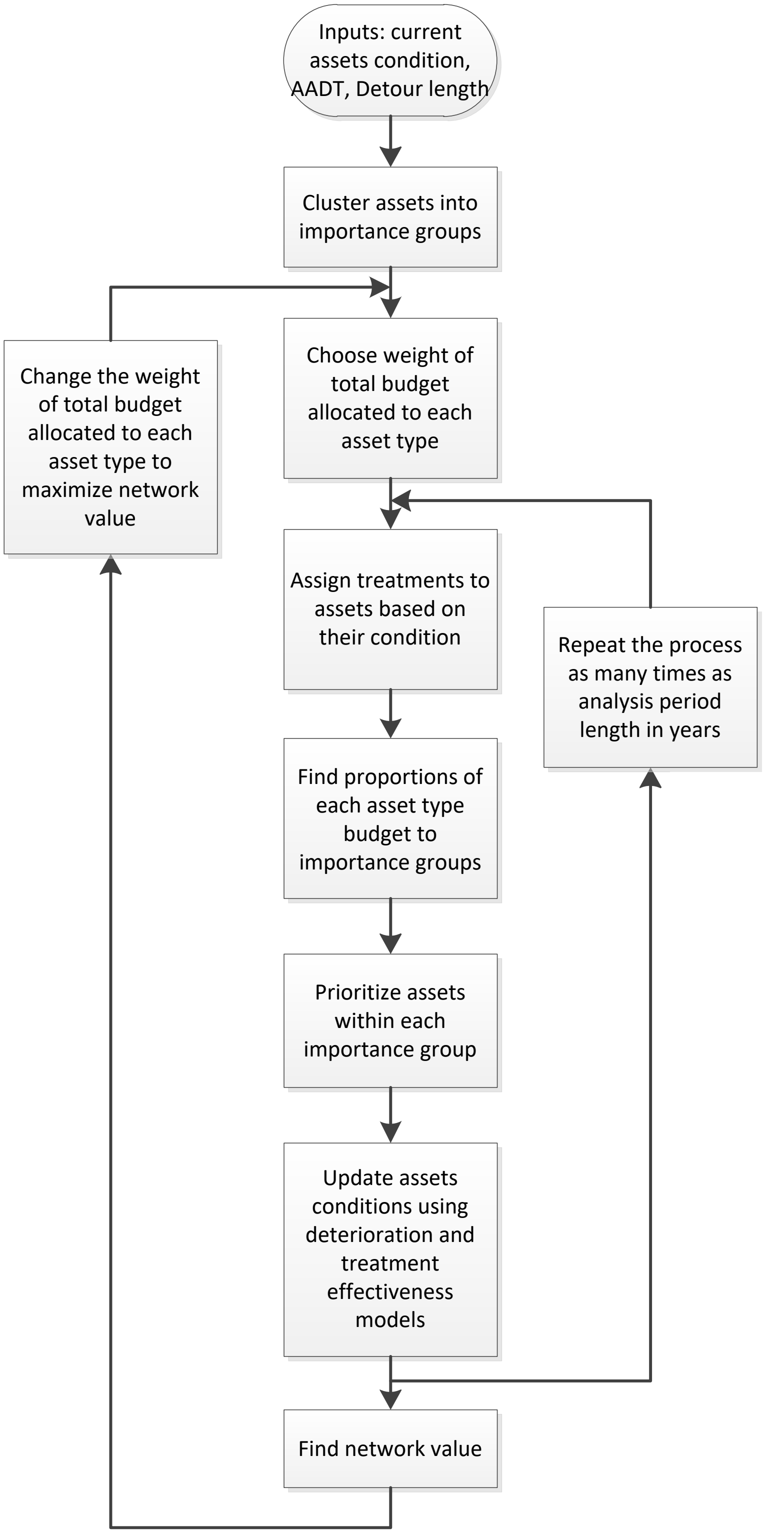

Figure 18: Proposed cross asset resource allocation framework

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Importance Groups

Assets importance groups are groups containing assets with similar characteristics and role in the network. Assets are grouped into importance groups to reduce the impact of excluding user benefit/cost; since, in this framework, user benefit/cost is not considered as part of the decision criteria. These groups will not impact the priorities of funds allocation, however, they will insure that when fund allocation strategy is applied within each importance group, assets will be at the same level of importance to the network and what matters after that is their condition only. The basis of forming the importance groups is different among pavements and bridges. The following subsections will provide the details for each asset type grouping.

Pavements

After reviewing the literature and the available data in Iowa PMS, pavement grouping factors include pavement type, average annual daily traffic (AADT), average annual daily truck traffic (AADTT), functional class, condition, location and age. AADT was selected to group pavements, since it reflects how many people will be affected by the bad performance of a specific pavement section, i.e. its importance. Furthermore, since Iowa DOT has separate decision trees for ACC and PCC, surface type was used to group pavements as well. Composite and ACC pavements were considered as one group, which was done previously by several DOTs, and specifically Iowa (Abdelaty *et al.* 2015).

Direct approach, based on percentiles, was used to divide pavements into importance groups, since only one continuous variable and one discrete variable were

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used to group pavements, which are AADT and pavement type respectively. Pavement sections were divided into three AADT groups based on the 33rd and 67th percentiles of AADT to insure equivalent distribution to importance groups. Each group is given an ID such that lower IDs represent higher AADT sections. Then, each AADT group is divided into two subgroups based on pavement type, and each of the resulting six groups is given an index (j) that will be used in the mathematical equations in the subsequent sections. Tables (2, 3) show the number of sections in each category and the categories IDs respectively.

Table 2: Pavement sections distribution by importance group

AADT Group	**Pavement type**		**Total**
	PCC	**ACC- Composite**	
1	321	452	773
2	215	556	771
3	88	682	770
Total	624	1690	2314

Table 3: Pavement importance groups IDs list

j	**Importance group**
1	High importance PCC pavement
2	Medium importance PCC pavement
3	Low importance PCC pavement
4	High importance ACC and Composite pavements
5	Medium importance ACC and Composite pavements
6	Low importance ACC and Composite pavements

Bridges

Factors used in categorizing bridges are similar to those used for pavements. However, structural type was not used for grouping bridges. But another factor appeared to be important, which is detour length. The higher the detour length, the more trouble

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bridge closure causes to road users. This means bridge importance has positive correlation with detour length.

Since there are two continuous variables impacting bridge grouping, two grouping approaches were tested and their results were compared. The first one is the k-means clustering, which is a method that finds the centroid of each cluster that minimizes data points' deviation from the cluster centroid. The major advantage of this methodology that it keeps the integrity of each variable, rather combining them in one index. However, it resulted in three groups that are difficult to rank based on importance. These groups, which are shown in Figure (19), are:

1- High AADT, low detour length group
2- Low AADT, high detour length group
3- Low AADT, low detour length group

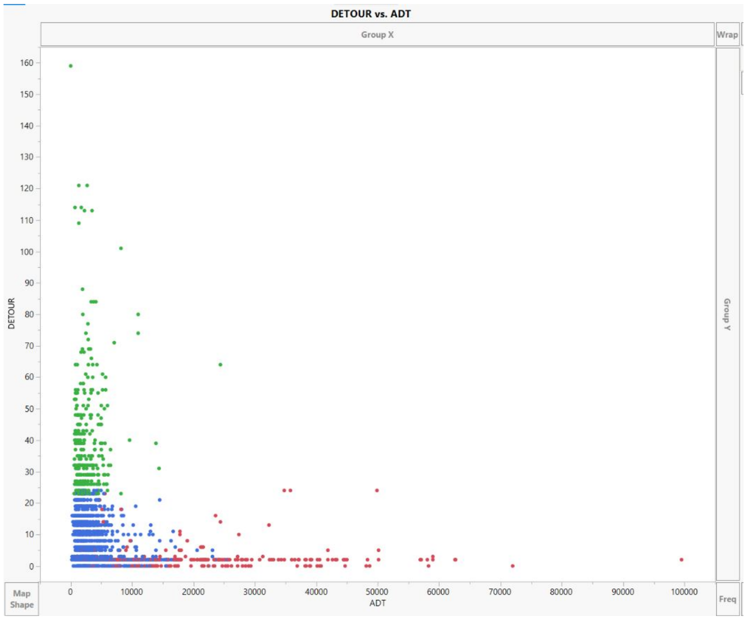

Figure 19: K-means clustering approach results

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The second approach of clustering bridges was done by defining an importance index as the multiplication of AADT and detour length. The higher the value of this index, the more important bridge is. The result of this clustering approach seemed more reasonable. As shown in Figure (20), importance groups have a diagonal orientation, and as a bridge location moves to the upper right corner of the AADT-detour length graph, it has higher AADT and detour length, thus higher importance.

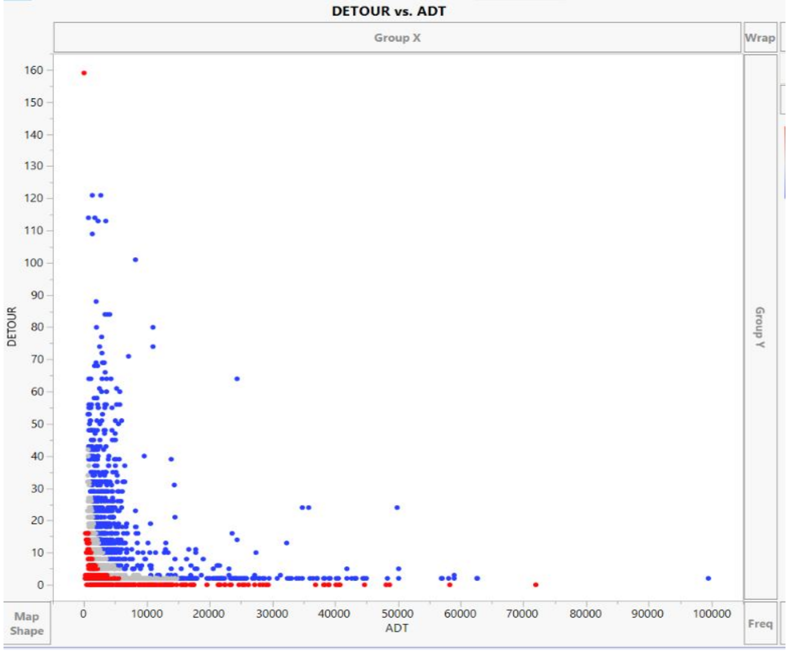

Figure 20: Importance index clustering approach results

Condition Description

In this step of the proposed framework, performance indicators that are needed to make decisions are defined. For pavements, both structural and functional performance are taken into consideration. Structural performance indicators are related to distresses developed due to traffic and environmental loading. These indicators are different for ACC, composite and PCC. Iowa DOT distresses used in selecting maintenance actions

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were used to express pavement condition. For ACC, alligator cracking and rutting are considered the as major distresses. But in PCC, faulting and joint spalling are the major distresses. Pavement condition index (PCI), which gives an overall condition rating, and IRI, which measure the functional performance of pavement, are used for both pavement types.

Bridges consist of multiple components which deteriorate at different rates. For that reason, each component condition is modeled separately. Based on the National Bridge Inventory (NBI); items 58, 59 and 60 represent deck, superstructure and substructure condition on a scale ranging from 0 to 9. These conditions are translated to condition states based on the FHWA preservation guide as shown in Table (4)

Table 4: FHWA bridge condition grouping criteria (FHWA 2018)

Condition State	NBI Rating Range (Condition)
Good	> 6
Fair	5 – 6
Poor	< 5

Treatment Assignment

In this step of the framework, each pavement section and bridge in the network is assigned a maintenance action, or no action if its condition is acceptable. This is achieved by adopting existing decision trees and matrices developed by the Iowa DOT. For pavements, Iowa DOT has a decision tree for each treatment action. These decision trees were modified to insure only one treatment is feasible for any condition. Then they were combined in one decision matrix for each pavement type. This was done to simplify the decision process, since in the absence of this condition, benefit/cost analysis must be done to pick the most suitable action. Each action is given an ID (k) that will be used in

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forming the mathematical equations. Figure (21) shows an example of the Iowa DOT decision trees and Tables (5, 6) show the final decision matrices for ACC, composite and PCC respectively.

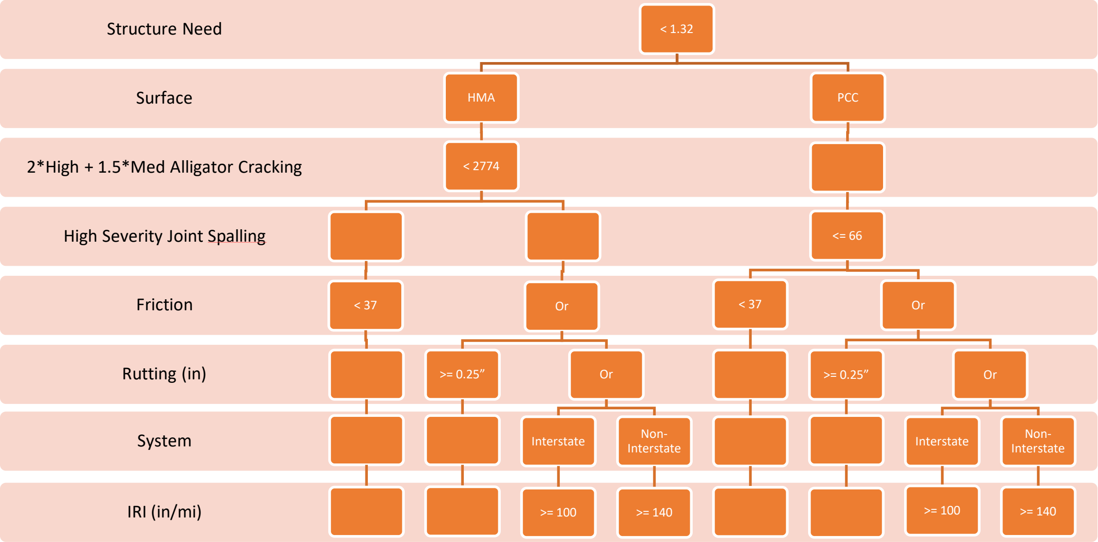

Figure 21: Iowa DOT pavement functional rehabilitation decision tree

Table 5: Refined Iowa DOT decision matrix for ACC and composite pavements

K	**PCI**	**2*High + 1.5* Med Alligator**	**IRI**	**Rutting**	**Treatment**
1	>50 and <80	< 2774	<= 140	<0.25”	Thin Surface treatment
2	>20 and <50	< 2774	>=100 (interstate) >=140 (non-interstate)		Functional rehabilitation
				>=0.25”	
3	>20 and <50	>= 2774	>140	<0.25’’	Minor Structural
4	>20 and <50	>= 2774		>=0.5	Major Structural
5	<20				Reconstruction
6	Otherwise				Do nothing

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Table 6: Refined Iowa DOT decision matrix for PCC pavements

K	PCI	High Severity Joint Spalling	IRI	Faulting	Treatment
1	>20	<66	>=100 (interstate) >=125 (non-interstate) and <140		Diamond Grinding
				>=0.12	
2	>20	<66	>=100 (interstate) >=140 (non-interstate) and <=170		Functional rehabilitation
3	>20	<66	> 170		Minor Structural
4	>20	>= 66			Major Structural
5	<=20				Reconstruction
6	Otherwise				Do nothing

For bridges, there are 27 possible combinations for components' states. Iowa DOT decision matrix covers 15 of them, which are the major works. These 15 cover bridge replacement, which is done when at least two components are in poor condition state or only the substructure is in poor condition state. Furthermore, low slump overlay is done when only the bridge deck is in poor condition state. Out of the remaining 12 combinations, 4 do not exist in the network, so they were neglected. Furthermore, when all components are in good condition state, there is no need to take an action. The remaining 7 combinations were assigned to preservation since they fail in the good-fair region, where preservation should be applied to avoid further bridge deterioration. Table (7) shows bridge decision matrix.

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Table 7: Refined Iowa DOT decision matrix for bridges

k	Deck	Super-structure	Sub-structure	Covered in Iowa DOT decision tree	Action
1	Poor	Poor	Poor	Yes	Replace bridge
	Poor	Poor	Fair	Yes	
	Poor	Poor	Good	Yes	
	Poor	Fair	Poor	Yes	
	Fair	Poor	Poor	Yes	
	Fair	Fair	Poor	Yes	
	Fair	Good	Poor	Yes	
	Good	Poor	Poor	Yes	
	Good	Fair	Poor	Yes	
	Poor	Good	Poor	Yes	
	Good	Good	Poor	Yes	
2	Poor	Fair	Fair	Yes	low slump concrete overlay
	Poor	Fair	Good	Yes	
	Poor	Good	Fair	Yes	
	Poor	Good	Good	Yes	
3	Fair	Fair	Fair	No	Preservation
	Fair	Fair	Good	No	
	Fair	Good	Fair	No	
	Fair	Good	Good	No	
	Good	Fair	Fair	No	
	Good	Fair	Good	No	
	Good	Good	Fair	No	
4	Good	Good	Good	No	Do nothing

Budget Allocation Process

This is the most important step in the proposed framework. Funds allocation is done at three levels, across asset types, across each importance groups and within each importance group. To allocate funds across asset types, each type will be given a proportion from the total budget. The sum of proportions will add up to 1. In the next steps, it will be clear that the objective of this framework is to find the proportions

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combination that results in the best network condition. The mathematical expression of this allocation level is shown in equations 1 and 2.

$$A_i = w_i * A \qquad (1)$$

$$\sum_{i=1}^{n} w_i = 1 \qquad (2)$$

Where A: the total budget available for all asset types

i: Indicator of asset type (i=1: pavement, i=2: bridges)

w_i: The proportion of total budget allocated to asset type i

A_i: The amount of budget allocated to asset type i

n: The total number of asset types considered in analysis, in this research n=2

The second allocation level is within each asset type, but across importance groups. In order to achieve it, a need-based allocation strategy is used. In this strategy, each importance group gets a proportion of asset type budget (A_i) that is proportional to the amount of budget needed to fix all poor assets within that importance group. Equations 3 through 7 describe the math behind this allocation level and Figure (22) provides an illustration of the higher two allocation levels.

$$p_{1j} = \frac{\sum_{k=3}^{5} C_{1jk}}{\sum_{j=1}^{6} \sum_{k=3}^{5} C_{1jk}} \qquad (3)$$

$$p_{2j} = \frac{\sum_{k=1}^{2} C_{2jk}}{\sum_{j=1}^{3} \sum_{k=1}^{2} C_{2jk}} \qquad (4)$$

$$C_{ijk} = c_{ik} * \sum_{l=1}^{X_{ijk}} U_{ijkl} \qquad (5)$$

$$\sum_{j=1}^{m_i} p_{ij} = 1 \qquad (6)$$

$$A_{ij} = A * w_i * p_{ij} \qquad (7)$$

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Where p_{ij}: proportion of asset type (i) budget allocated to importance group (j)

C_{ijk}: Total cost of fixing assets of type (i), within importance group (j) and assigned to treatment (k)

c_{ik}: Unit cost of the treatment (k) of asset type (i). These unit costs are summarized in Table (8)

U_{ijkl}: Unit measurement for asset (l) which is assigned to treatment (k), within importance category (j) and asset type (i). The unit measurement is mile-lane for pavements and square foot deck area for bridges.

m_i: Number of importance groups within asset type i ($m_1 = 6$ and $m_2 = 3$)

X_{ijk}: Number of assets of type (i), within importance group (j) and assigned to treatment (k)

A_{ij} : Budget allocated to importance group (j) within asset type (i)

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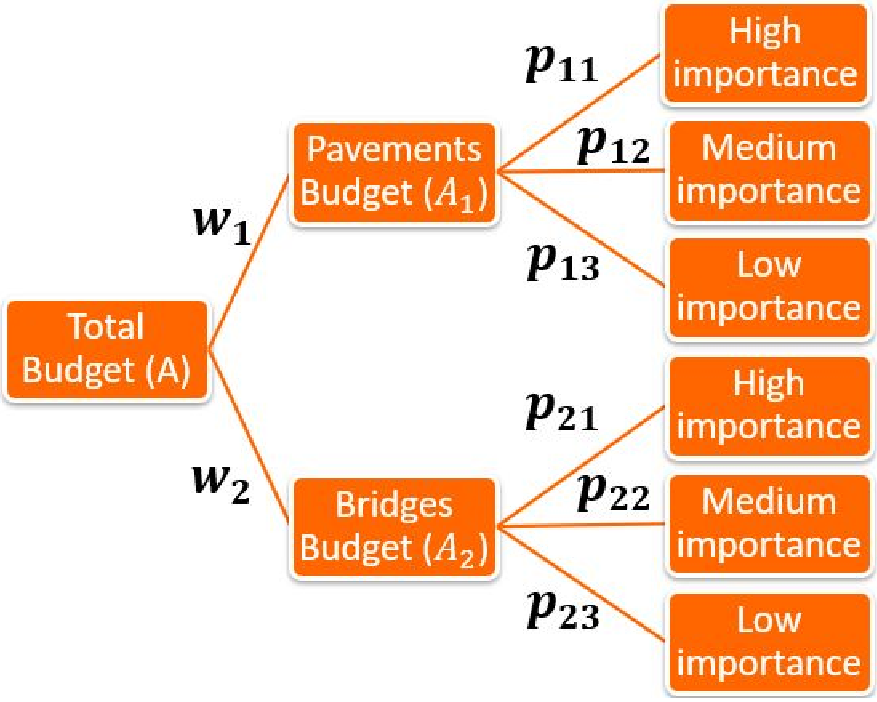

Figure 22: Upper two budget allocation levels summary

Table 8: Iowa DOT treatments unit costs

Asset type	Treatment	Unit cost
Pavement	Thin surface treatment	\$25,000/ mile-lane
	Diamond grinding	\$30,000/ mile-lane
	Functional rehabilitation	\$220,000/ mile-lane
	Minor structural	\$240,000/ mile-lane (Primary) \$380,000/ mile-lane (Interstate)
	Major structural	\$400,000/ mile-lane (Primary) \$550,000/ mile-lane (Interstate)
	Reconstruction	\$600,000/ mile-lane (Primary) \$750,000/ mile-lane (Interstate)
Bridges	Preservation	\$40/ deck square foot
	Low slump concrete overlay	\$50/ deck square foot
	Replacement	\$75/ deck square foot (Primary) \$80/ deck square foot (Interstate)

The last allocation level is the allocation of each importance group budget to assets within that importance group. This level involves prioritization of projects having the same importance level in the network. Worst-first approach was used to prioritize

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projects, since it is a good simplification approach to use for implementing the framework. It is less subjective than experts' judgment, and less complicated than LCC optimization and MCDM. For pavements, sections were ranked with an ascending PCI order so that sections with lower PCI will have higher priority of getting funds. On the other hand, prioritization in bridges is more complicated since they consist of three components, which might be in different condition states and have different time in condition state. Steps followed to prioritize bridges are illustrated in Figure (23) and prioritization rules are listed below:

- Bridges with higher number of poor components are given higher priority of getting funds
- When two bridges have the same number of poor components, the one with higher time in condition state is given priority of getting funds.
- When two bridges, each has one poor component and that component is the substructure in one of them. That bridge is given priority regardless to the time in condition state.
- The first two rules apply to bridges with fair components. But they will have lower priority than those having poor components.

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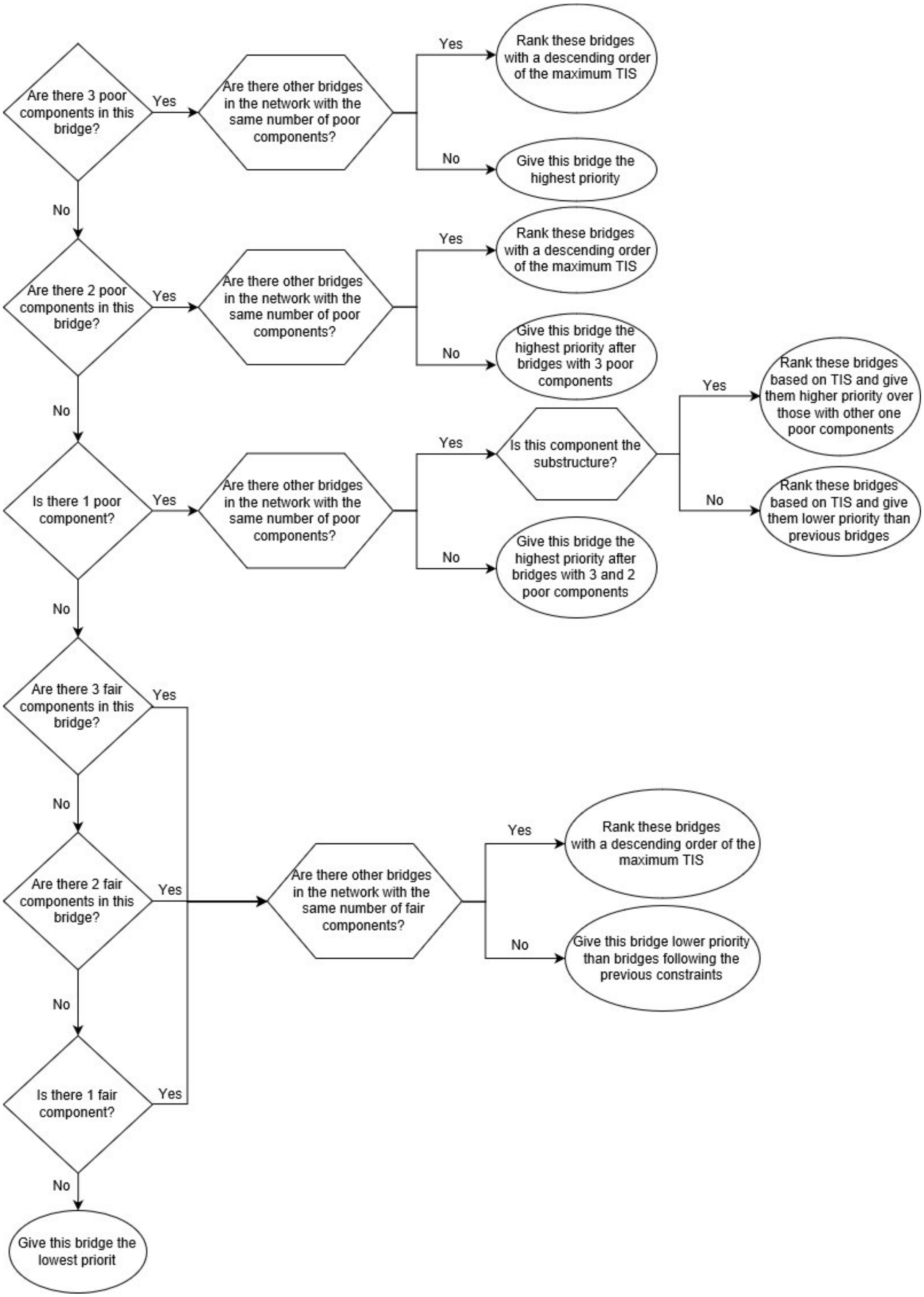

Figure 23: Bridge prioritization process

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Future Condition

After allocating the total network budget into projects, the next step is to predict next year assets' performance based on this allocation. This includes two types of assets, those who did not receive a treatment and those who did. Figure (24) shows the logic of obtaining assets' future performance.

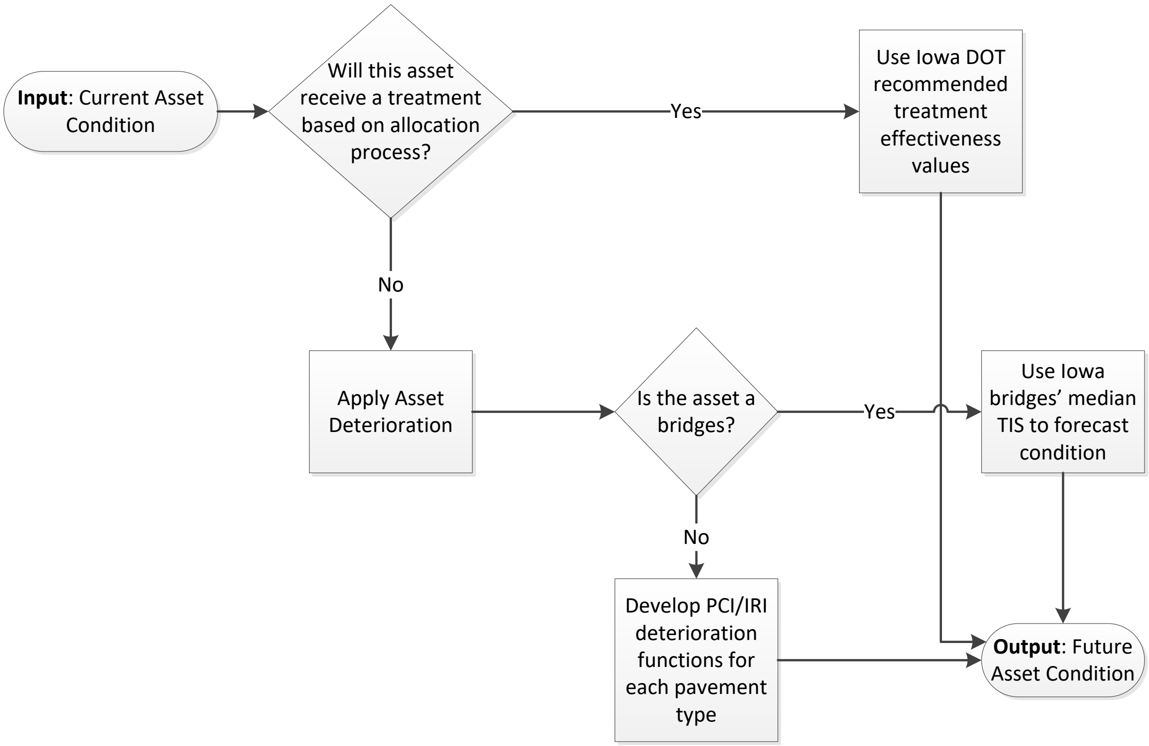

Figure 24: Assets' future performance determination process

Assets which did not get funded in the allocation step will continue their normal deterioration. This requires developing deterioration models or adopting deterioration approach to reflect aging, traffic and environment effects on assets. For pavements, individual distresses deterioration models were not developed due to lack of data and inconsistencies and high variability in distress-level data. Instead, network level deterioration models for PCI and IRI were developed for each pavement type separately.

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These models were simply done by developing an exponential relationship between IRI/PCI and age since resurfacing to get a master deterioration curve for each pavement type. Figures (25) through (30) show the developed deterioration models.

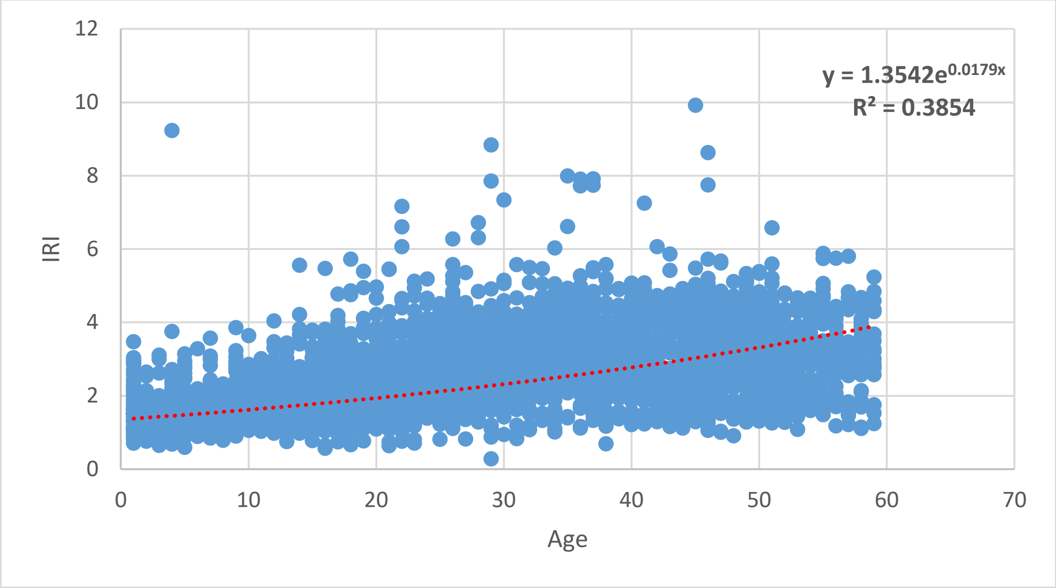

Figure 25: IRI Deterioration model for PCC

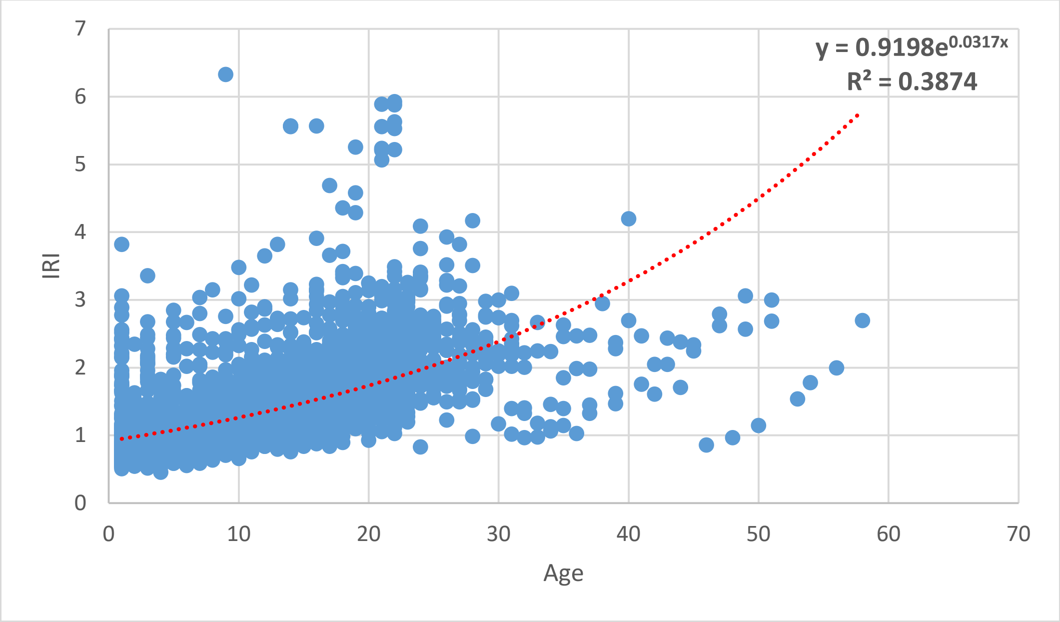

Figure 26: IRI Deterioration model for ACC

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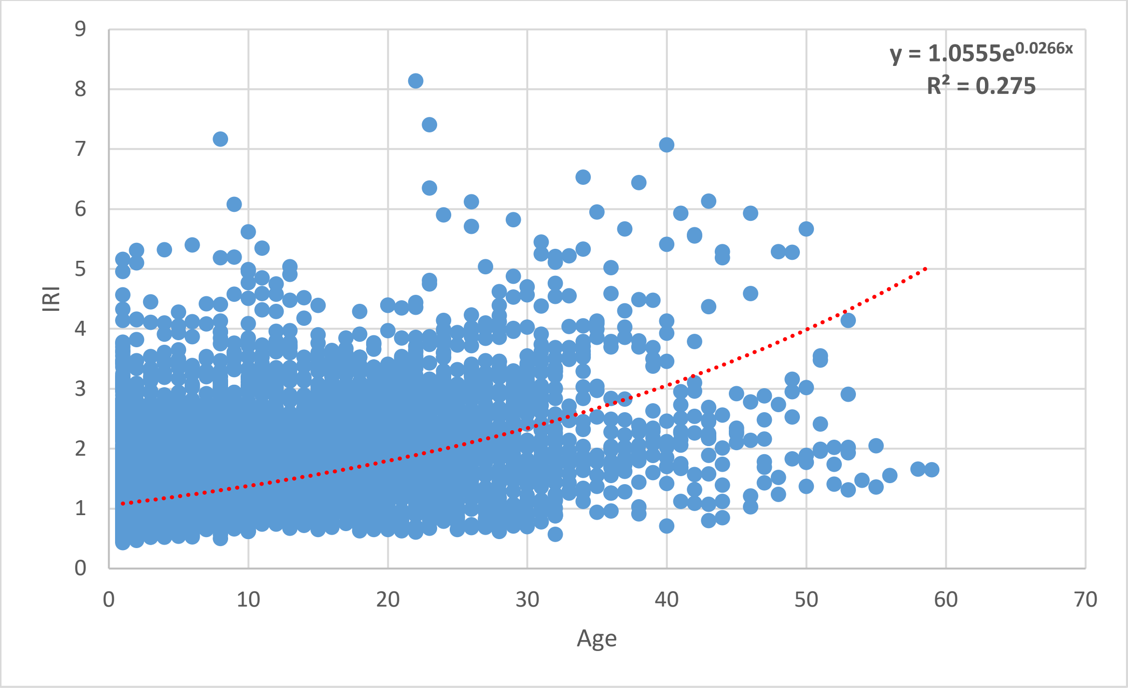

Figure 27: IRI Deterioration model for composite pavement

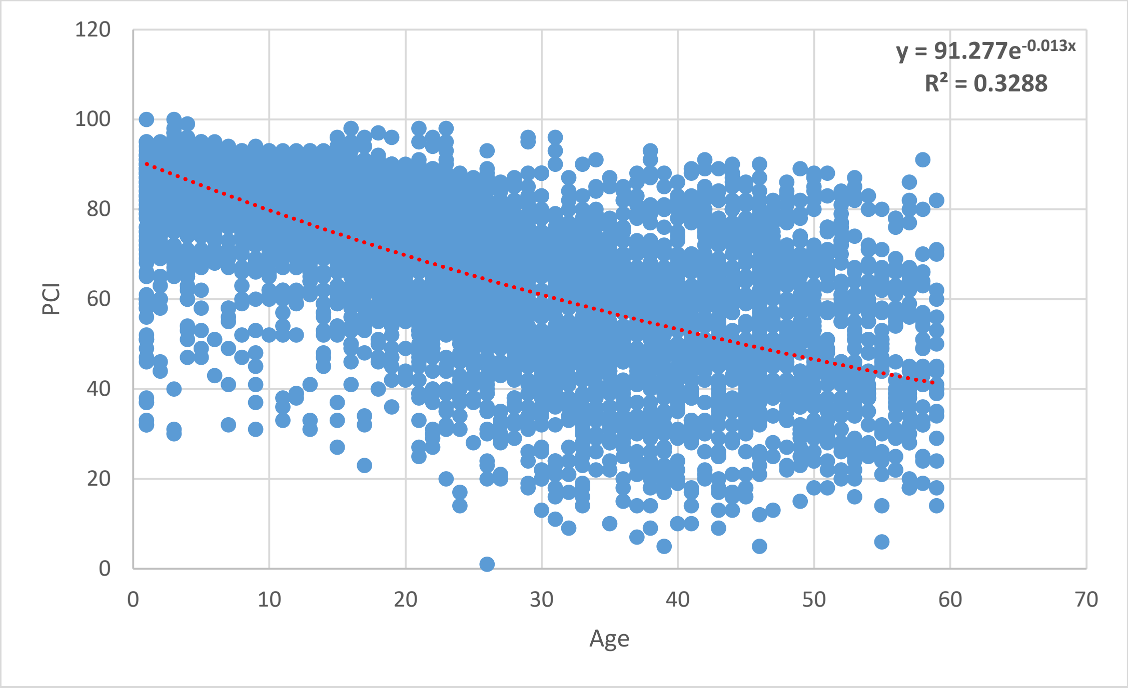

Figure 28: PCI Deterioration model for PCC

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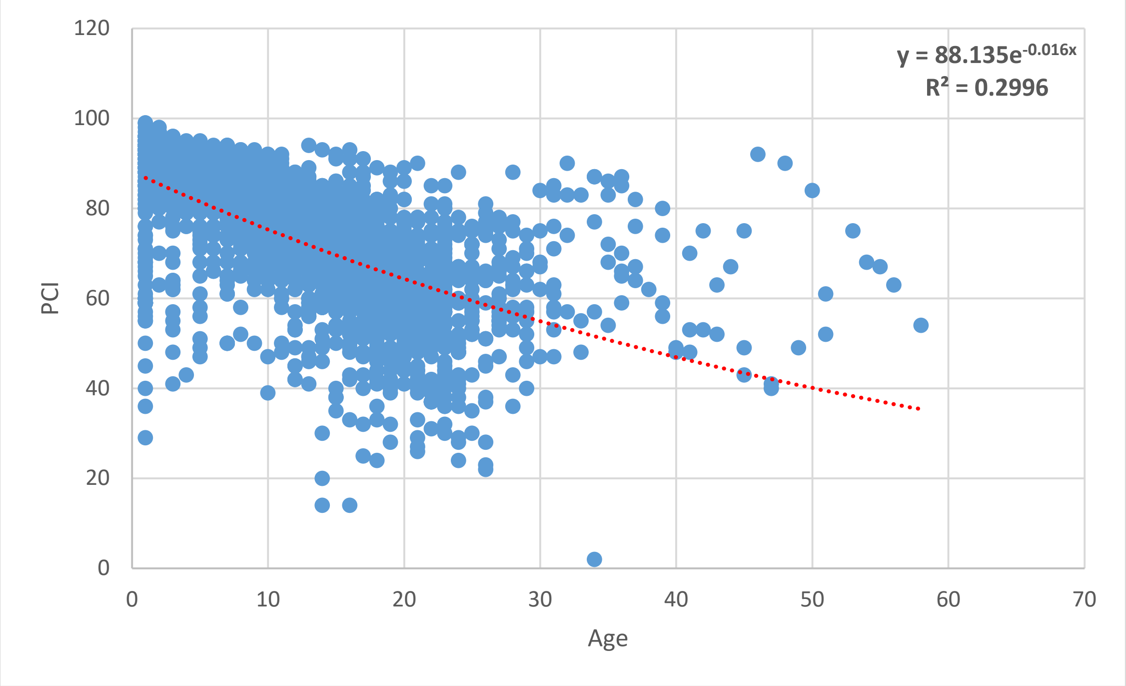

Figure 29: PCI Deterioration model for ACC

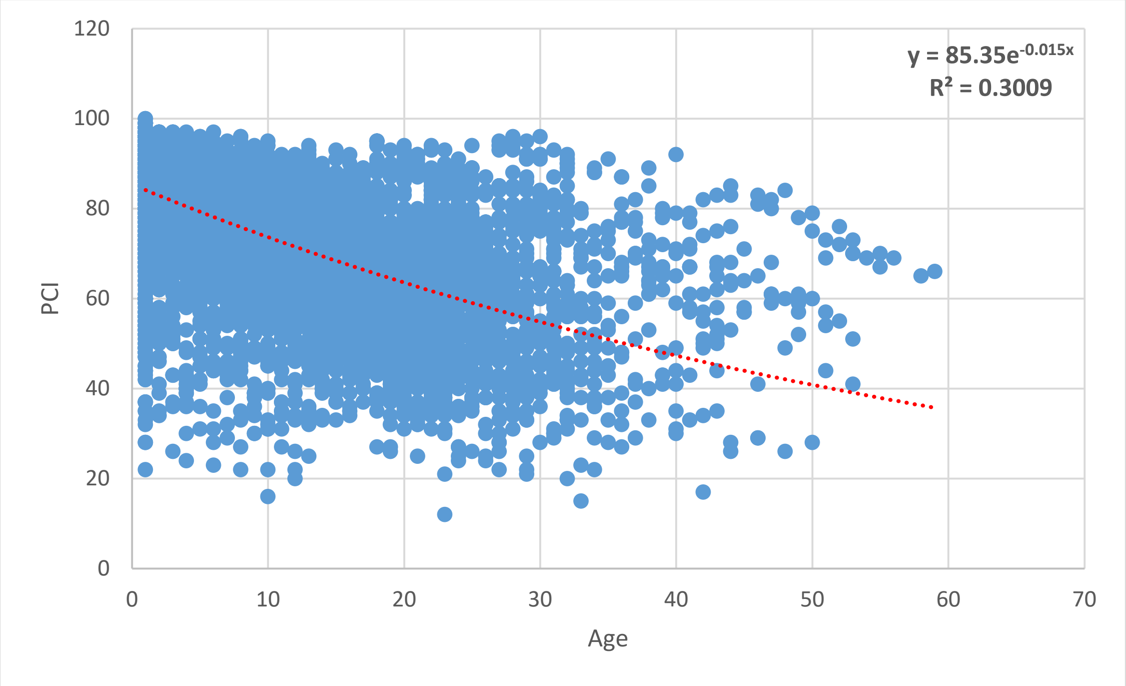

Figure 30: PCI Deterioration model for composite pavement

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Each individual pavement section condition is predicted by shifting the master curve to the current pavement's condition as shown in equation (8) and Figure (31).

$$X_t = X_{t_o} * e^{a(t-t_o)} \qquad (8)$$

Where X_t: pavement condition at any time (t)

X_{t_o}: Pavement condition at time t_o (current time)

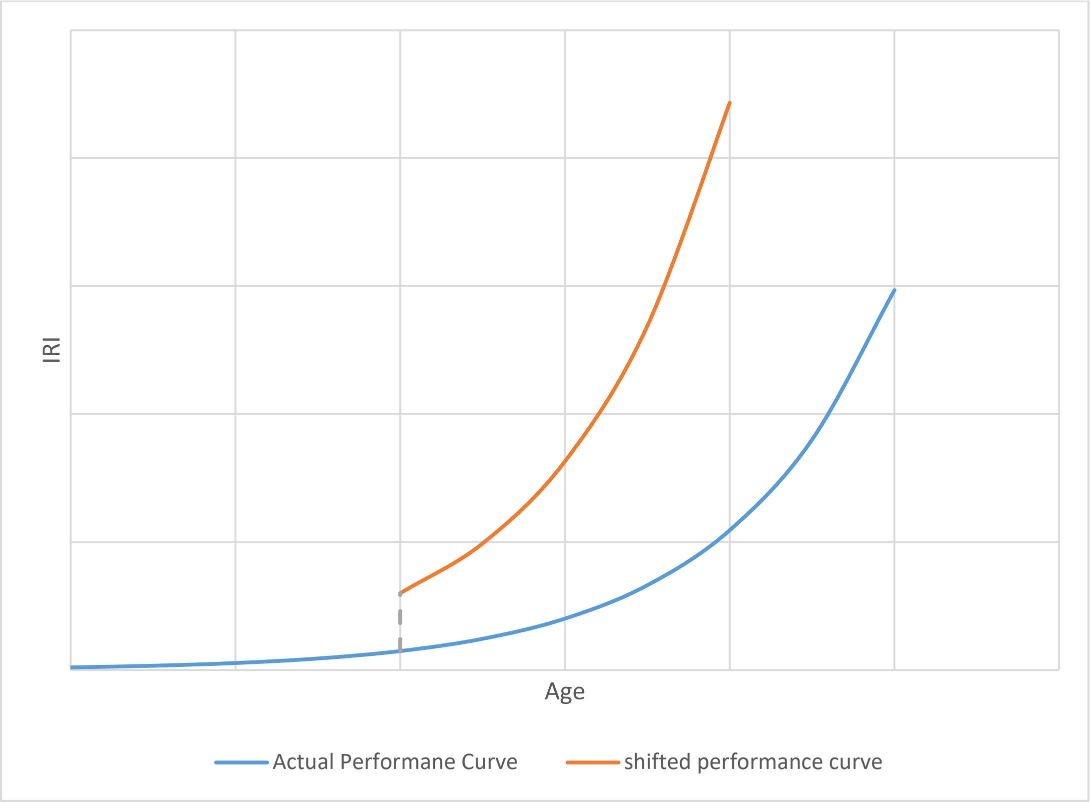

Figure 31: Master deterioration curve concept

For bridges, a simpler deterioration approach is adopted to represent each component's deterioration. This approach relies on adding one year to the current time in condition state (TIS) to obtain next year's TIS. Then, comparing the TIS for each component with the median TIS for all bridges in Iowa. If the median TIS is exceeded,

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the component moves to the next condition state. Otherwise, it stays in the same condition state. Equations (9, 10) summarize bridge deterioration concept and Table (9) shows median TIS for the three condition states of bridge components.

$$T_{ms(t+1)} = T_{ms(t)} + 1 \leq M_{ms} \rightarrow \; s_{m(t+1)} = s_{mt} \tag{9}$$

$$if \; T_{ms(t)} + 1 > M_{ms}, \; \rightarrow s_{m(t+1)} = s_{mt} + 1 \; and \; T_{m(s+1)(t+1)} = 0 \tag{10}$$

Where M_{ms}: median time in condition state (s) for component (m)

$T_{ms(t)}$: Current time in condition state (s) for component (m)

$T_{ms(t+1)}$: Future time in condition state (s) for component (m)

s_{mt}: Current condition state for component (m)

$s_{m(t+1)}$: Future condition state for component (m)

Table 9: Median time in condition state for bridge components

Condition State	**Component**		
	Deck	**Superstructure**	**Substructure**
Good	28.1	30.8	30.1
Fair	17.2	15.1	15.6
Poor	29.7	29.1	29.4

In case an asset receives a treatment, this treatment will have a positive impact that is reflected by the application of treatment effectiveness models. Due to the complexity of this topic and the large amount of historical records needed to develop an accurate model, Iowa DOT recommended effectiveness values were used. These values are summarized in Tables 10 through 12.

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Table 10: ACC and composite pavement treatments effectiveness

Treatment	IRI	PCI	Rutting	Cracking
Thin surface treatment	78% (improve)	+20 (improve)	-	Reset to 0
Functional rehab.	60 in/mile	80	Reset to 0	
Minor Structural		90		
Major Structural		95		
Reconstruction		100		

Table 11: PCC pavement treatments effectiveness

Treatment	IRI	PCI	Faulting	Joint Spalling
Diamond Grinding	45 in/mile	+20 (improve)	Reset to 0	-
Functional Rehab.	60 in/mile	80		Reset to 0
Minor Structural		90		-
Major Structural		95		-
Reconstruction		100		-

Table 12: Bridge treatments effectiveness

Treatment	Condition Improvement		
	Bridge Deck	**Superstructure**	**Substructure**
Preservation	Extends time in condition state by 4 years		
Low Slump Concrete Overlay	3 point increase with a maximum deck condition rating of 7	1 point improve with a maximum condition rating of 7	1 point with a maximum condition rating of 7
Bridge Replacement	New		

After repeating the previous steps for the entire analysis period, the result is each asset condition at the end of the analysis period expressed in PCI and NBI rating for pavements and bridges respectively.

Asset Valuation

The last step in the proposed framework is to obtain a metric to assess the entire network performance. Such a unified metric for bridges and pavements does not exist. Thus, asset monetary value is used to express different assets' conditions. In order to reduce the impact of subjectivity in monetization, condition-based monetization approach is used. This approach is characterized with value decay pattern and cutoff points, at

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which asset does not have a value. Different pavement and bridge value decay patterns and cutoff points impact on the solution that maximizes the network monetary value were examined. Linear and sigmoidal decay patterns were considered. Furthermore, 3 and 4 condition ratings were considered as possible cutoff points for bridges. On the other hand, 20 and 30 PCI cutoff values for pavements were examined. Table (13) summarizes all the valuation methods examined.

Table 13: Valuation methods used in analysis

Pavements	Bridges
Linear value decay with a cutoff point of 20	Linear value decay with a cutoff point of 3
Linear value decay with a cutoff point of 30	Linear value decay with a cutoff point of 4
Sigmoidal value decay without a cutoff point	Sigmoidal value decay with a cutoff point of 3
	Sigmoidal value decay with a cutoff point of 4

Equation (11) expresses the percentage of value remaining in the asset based on linear value decay. For sigmoidal value decay, equations (12, 13) were used for pavements and bridges respectively.

$$value\ percentage = \frac{Current\ condition - Cutoff\ point}{Best\ condition - Cutoff\ point} \qquad (11)$$

$$value\ percentage = \frac{1}{1+e^{\frac{50-PCI}{10}}} \qquad (12)$$

$$value\ percentage = 1 - \frac{1}{1+e^{(NBI-5)}},for\ NBI > cutoff\ point \qquad (13)$$

For pavements, value percentage is multiplied directly by pavement reconstruction cost to get current section value. However, in bridges, the percentage of remaining value is obtained for each component separately. Then, these percentages are averaged to get the overall percentage of bridge value, which is multiplied by bridge reconstruction cost to get bridge value. The sum of all assets' values in the network is

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used as a measure of network performance. The solution for the cross asset problem is the budget weight combination that maximizes the network monetary value. It was obtained by repeating the full allocation process with changing the weights from 0.05 to 0.95 with 0.05 increments. Furthermore, different budget levels were examined as well. Figure (32) shows a sample of how the solution of the cross asset resource allocation problem looks like.

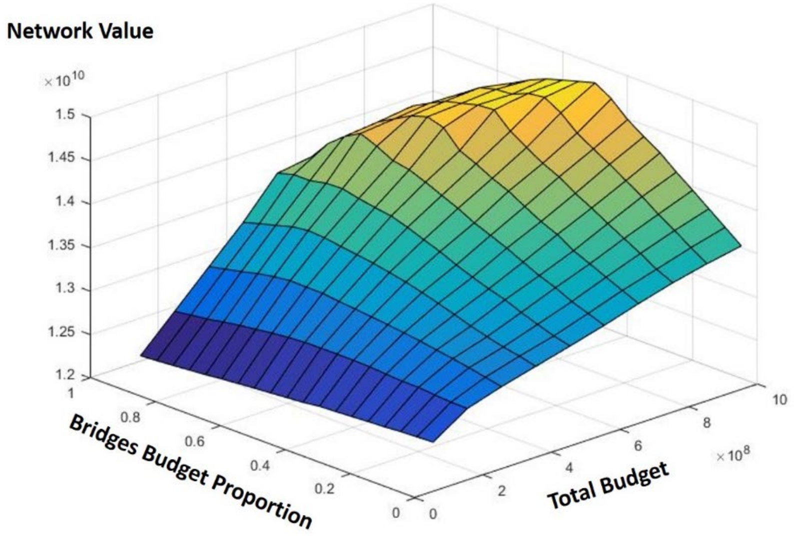

Figure 32: Sample cross asset problem solution

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CHAPTER 5: RESULTS AND DISCUSSION

This chapter introduces and discusses the results obtained from this research. Those results were obtained from a MATLAB code, which was created to perform the proposed cross asset resource allocation framework. This code was built in the form of a tool that calls functions. Each of these functions play a role in the allocation process such as assigning treatments to sections, predicting future condition, etc. Analysis period of five years was considered in running the code. The outputs of this process include the resource allocation for different budget levels and different valuation methods that will result in the highest network monetary value. It also provided the performance of the entire network as well as separate pavement and bridge network performance expressed in both monetary value and percentages of assets in each condition. Moreover, the tool was designed to output pavement mileage and bridge deck areas fixed by each maintenance type at every year for each budget level and budget allocation scenario. The following sections will show, discuss, and provide explanation for these results in details.

Solution at Different Budget Levels and Valuation Methods:

The following points summarize and discuss the impact of changing valuation methods and budget levels on the solution that maximizes the network monetary value.

- Figure (33) shows the change in the solution that maximizes the network monetary value with total budget level and different valuation methods. Table (14) explains the different valuation methods combinations Ids shown in the chart.
- It is clear that the general trend for the solution that maximizes the network monetary value based on the proposed methodology starts by allocating low

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percentage of total budget to bridges, 5% for annual budget of $100 million and 35% for annual budget of $200 million. Then, at moderate total budgets, the solution reverses in favor of bridge projects. At last, equal allocation for pavements and bridges is reached at very high total budgets.

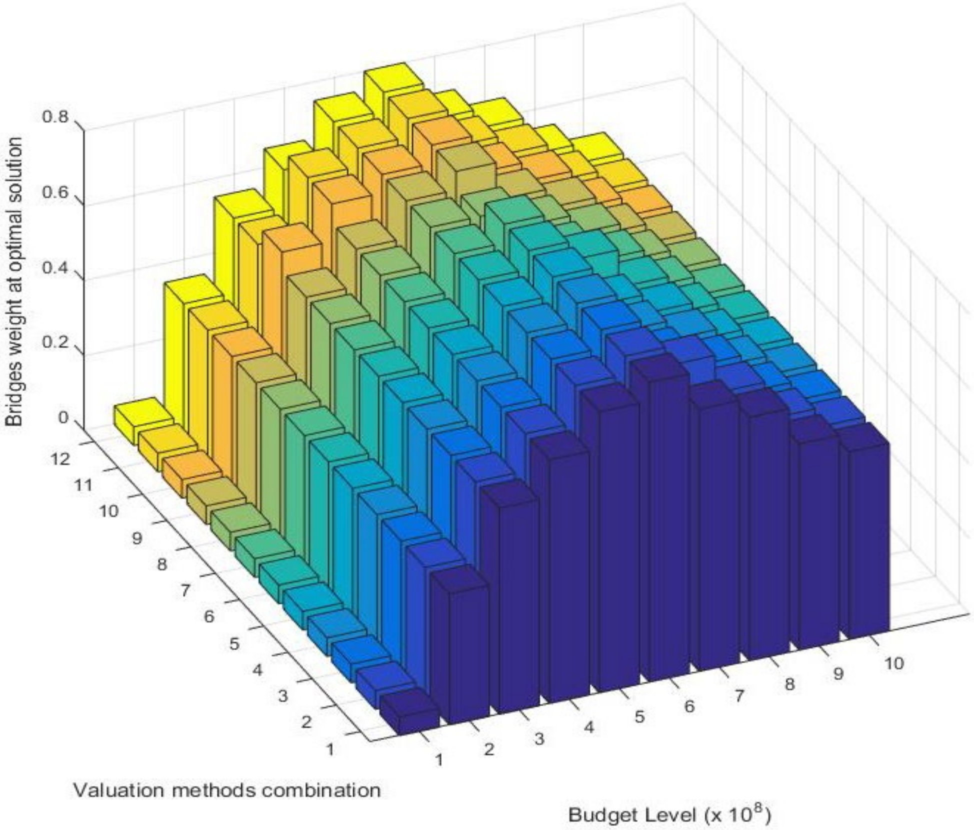

Figure 33: Solution change with total budget level and valuation method

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Table 14: Valuation methods combinations IDs definition

ID	Pavement valuation method	Bridge valuation method
1	Linear value decay with cutoff point of 20	Sigmoidal value decay with cutoff point of 3
2		Sigmoidal value decay with cutoff point of 4
3		Linear value decay with cutoff point of 4
4		Linear value decay with cutoff point of 3
5	Linear value decay with cutoff point of 30	Sigmoidal value decay with cutoff point of 3
6		Sigmoidal value decay with cutoff point of 4
7		Linear value decay with cutoff point of 4
8		Linear value decay with cutoff point of 3
9	Sigmoidal value decay without a cutoff point	Sigmoidal value decay with cutoff point of 3
10		Sigmoidal value decay with cutoff point of 4
11		Linear value decay with cutoff point of 4
12		Linear value decay with cutoff point of 3

- At low total budget levels, i.e. less than $300 million, all valuation methods favor pavement projects and give at least 65% of the total budget to pavements. This might result from the fact that bridge projects cost more than pavement projects and with this very small total budget, the impact of performing few bridge projects will be less than that of performing multiple pavement projects
- At budget levels greater than $200 million and less than 1 billion dollars, the solution that maximizes the network monetary value seems to be shifted toward bridges. This might be due to the fact that bridge value are higher than pavement value, thus improving their condition will have more impact on the network than improving pavements. Another reason is that at these budget levels, there will be sufficient budget to do major works on bridges, such as replacement. These major works will have huge impact on network monetary value compared to pavements. Also, it is important to mention that by giving most of the total budget to bridges at these budget levels, there will still be sufficient amount of budget to do pavement maintenance actions, which are limited based on the good condition of

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the network. This will have a positive impact on the overall network monetary value.

- At high total budget levels, i.e. 1 billion dollars, all valuation methods suggest fifty-fifty split, since the amount of total budget available will be sufficient to fix both pavements and bridges, and both of these projects will help improve the network monetary value.
- When comparing different valuation methods impact on the solution that maximize the network monetary value, it is negligible at all budget levels except 300, 400, 600 and 700 million dollars. However, even at these budget levels, only one or two valuation methods combinations provide a solution that is 0.05 more or less than all other valuation methods. The reason behind this consistency in valuation methods output might be the high maintenance needs in bridges compared to pavements, which will always shift the solution to bridges regardless of the valuation method, unless there is no enough budget to do major bridge maintenance actions.

The results discussed in the following sections are based on linear pavement valuation with 20 cutoff point and sigmoidal bridge valuation with 3 cutoff point.

Network Monetary Value, Bridge Value and Pavement Value

The following points discuss how total network monetary value, bridge value, and pavement value change with the change in budget allocation to each asset.

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- If no treatment is applied to the network in the next five years, its value will drop from around 15 billion dollars to around 13 billion dollars. This means the network will lose 13% of its value as shown in Figure (34).
- The network monetary value increases as the annual expenditures increase. However the increasing rate decreases with the increase in annual expenditure, which indicates a decrease in benefit/cost ratio of investment with the increase in annual expenditure.
- An annual total budget of around $500 million is required to return the network monetary value and overcome the impact of deterioration over a period of five years, which forms 3.3% of the total network monetary value.
- Above annual expenditure of $617 million, the network monetary value remains constant, which indicates reaching the maximum possible network monetary value.
- Based on Iowa DOT annual pavement and bridge expenditure, which is around $300 million, the proposed methodology suggests giving 35% of the total budget to bridges and 65% to the pavements in order to achieve the highest network monetary value.

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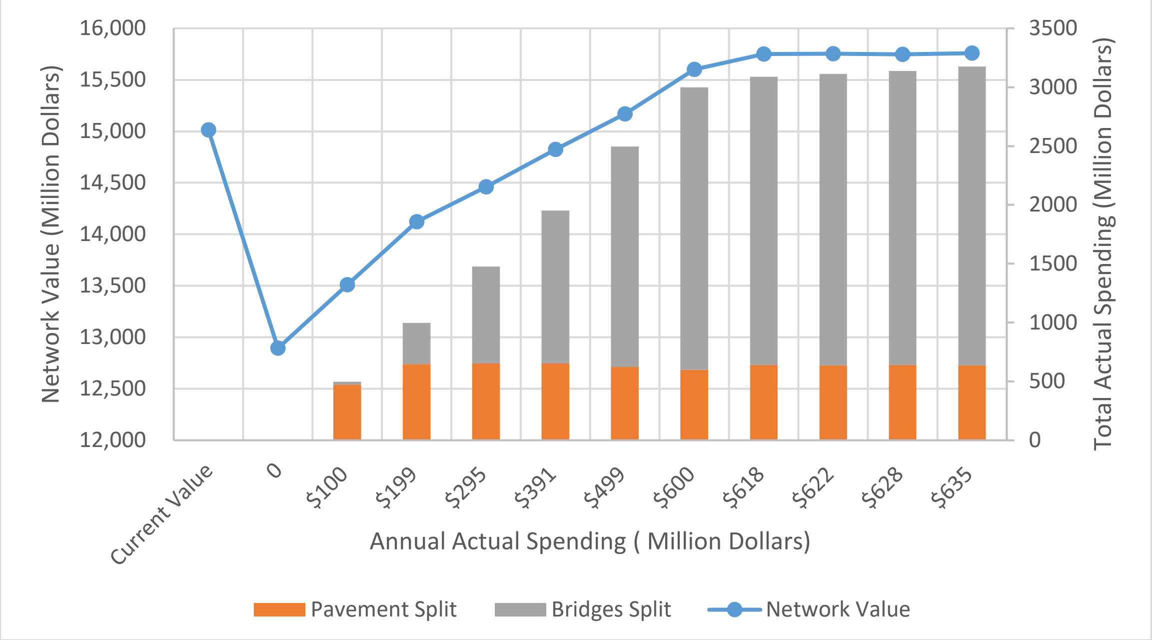

Figure 34: Total network monetary value trend with actual annual expenditure

- Figure (35) shows the network monetary value for different pavement-bridge tradeoff scenarios for a total annual budget of $100 million. The solution that results in the highest network monetary value, highlighted in red, does not correspond to the maximum amount of funds actually spent. However, it corresponds to the split of total budget that provides the maximum network monetary value, which is 5% of the total budget to bridges and 95% to pavements.

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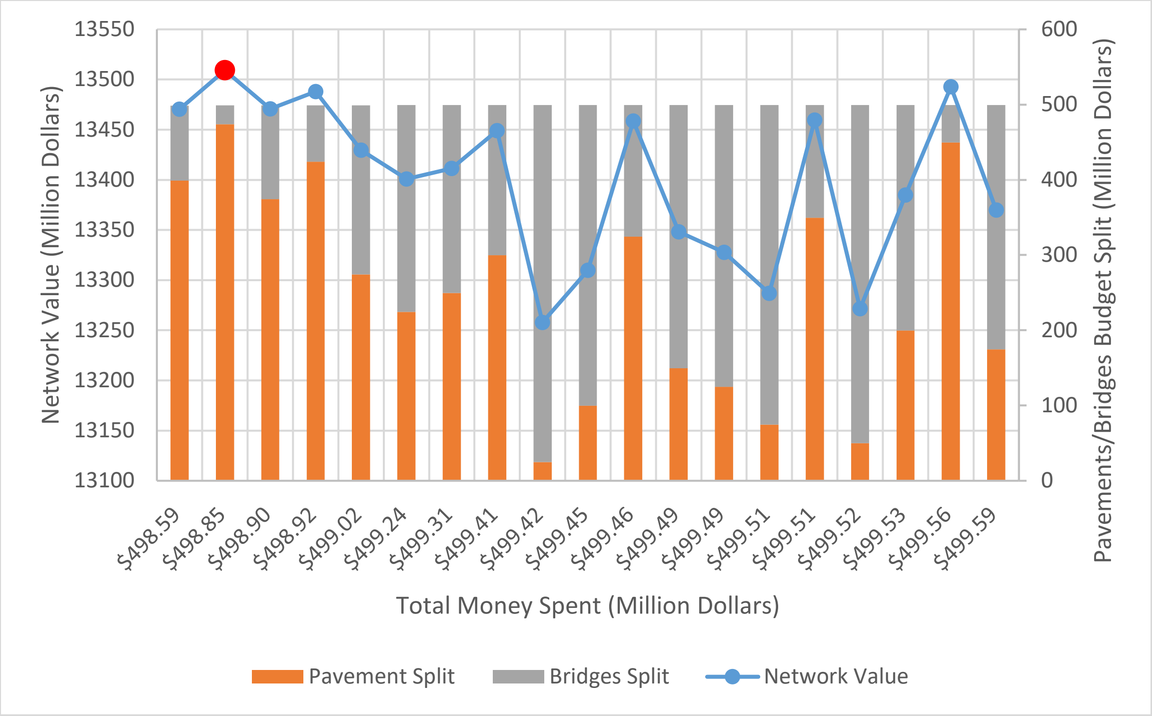

Figure 35: Total network monetary value with pavement-bridge split for $100 million total budget

- Figures 36 and 37 show the change in the added value and B/C ratio for both pavements and bridges with the change in expenditure at $300 million annual budget level. It is clear that as the amount of bridge expenditure increases, the value added to bridges and B/C ratio increases, which show high maintenance needs in the bridges side. However, the B/C ratio is less than 1 in all cases at this budget level, which indicates low benefit of bridge treatment compared to the expenditure level and maintenance cost. These low B/C ratio values might be due to the treatment effectiveness values used in the methodology.
- For pavements, there is less need for maintenance actions, which is shown by the flat added value trend after spending $635 million. Furthermore, B/C ratio is always above 1, which means investing in pavements provide high benefit to the

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network even at low expenditure levels. This supports the allocation of 95% and 65% of the total budget to pavements at total budget levels of $100 and $200 million annually.

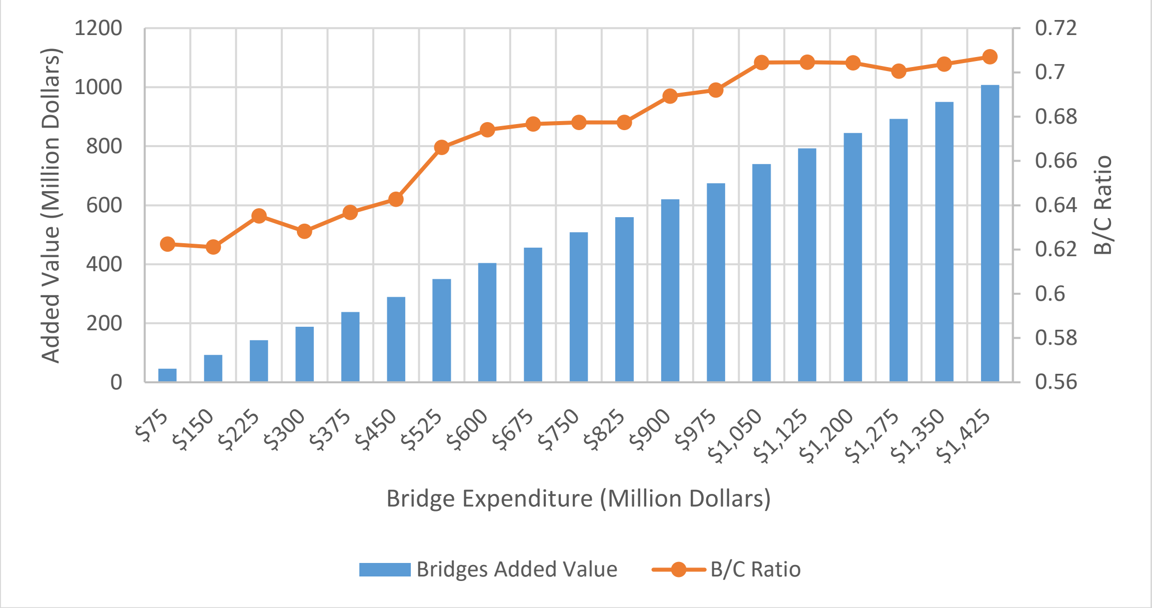

Figure 36: Bridge added value and B/C ratio by expenditure at $300 million annual budget level

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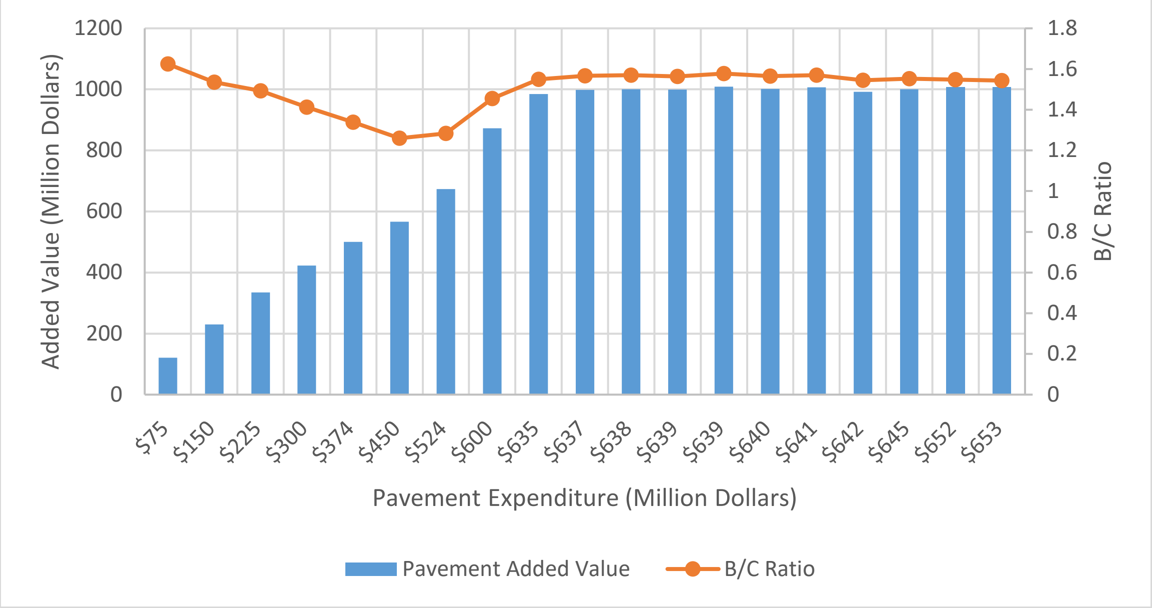

Figure 37: Pavement added value and B/C ratio by expenditure at $300 million annual budget level

- As the amount of budget allocated to bridges increases, the total value of bridges in the network increases as shown in Figure (38). However, there are two increasing trends above $1.5 billion spent on bridges. These trends show that at the same total expenditure, two different bridge monetary value can be achieved due to the difference in the maintenance strategy across the analysis period. After inspecting the total expenditure levels with two corresponding bridge monetary value, it was observed that the trend with the higher monetary value occur when higher total budget is allocated to bridges, which allows doing more preservation and low slump concrete overlays, rather than waiting for assets to drop to the poor condition and replacing them. This strategy of allocation improves the overall condition of bridges in the network, thus their value.

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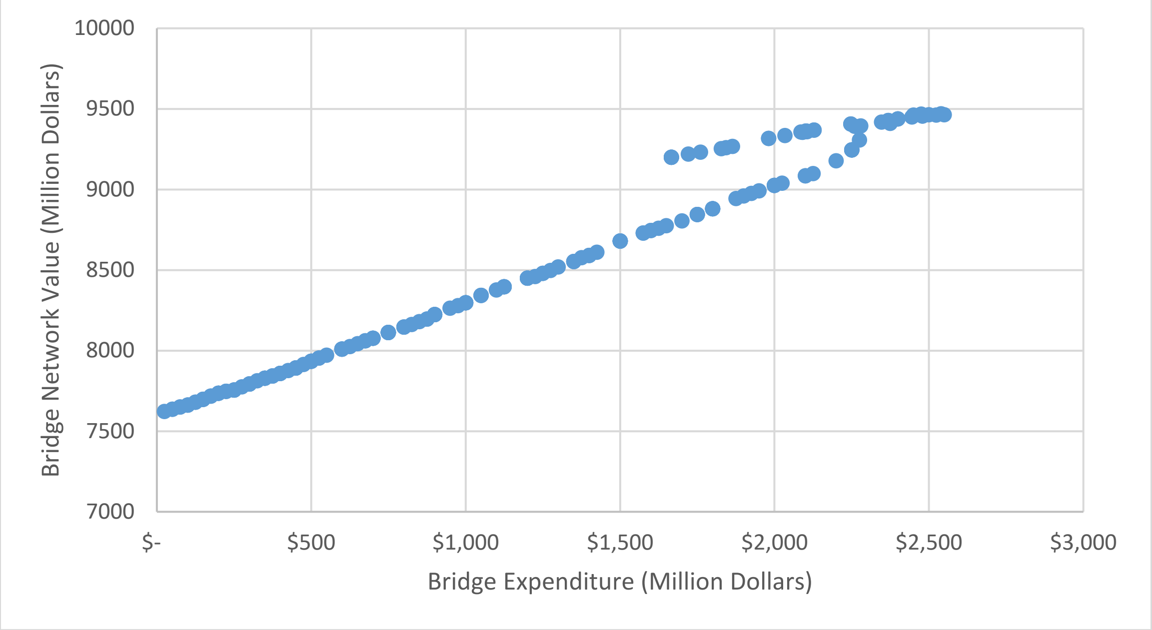

Figure 38: Bridge network monetary value trend with total bridge expenditure

- The trend of the total value of pavements in the network with budget allocation is similar to that of bridges as shown in Figure (39). Pavement value increases as pavement's budget increases, but the rate of increase varies with actual expenditure, with the highest increasing rate achieved at expenditure levels above $500 million.
- The total amount of budget needed to fix all pavements in the network is around $650 million, which is very low compared to bridges, which consume more than $2.5 billion to fix the entire network.
- Maintenance strategies impact on pavement network monetary value appears above total spending of $600 million. At this level, strategies with more preservation actions will result in higher network monetary value at the same expenditure level as in bridges.

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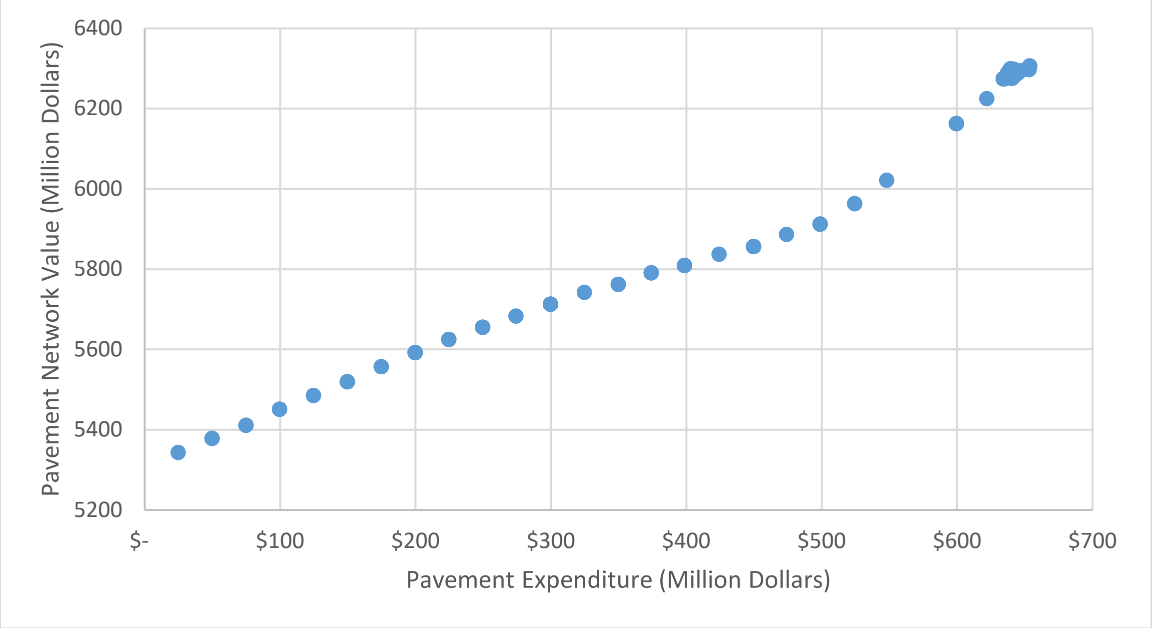

Figure 39: Pavement network monetary value trend with total pavement expenditure

Bridge and Pavement Condition with Allocation

In this section, the change in pavement network performance with total budget level and proportion of total budget allocated to pavements is discussed. Furthermore, the impact of bridge budget on the performance of bridge network is shown for each bridge component.

- As Figure (40) shows, as pavement expenditure increase, the mileage of pavements with PCI less than 50 decreases and the mileage with PCI greater than 80 increases, which indicates an improvement in the overall pavement network performance.

- At expenditure levels above $600 million, the mileage of pavements with PCI less than 50 remains constant. However, the mileage of pavements with PCI greater than 80 increases at different levels depending on the allocation strategy.

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Strategies that have more preservation actions will result in more mileage with PCI greater than 80, which supports the trend shown in pavement network monetary value.

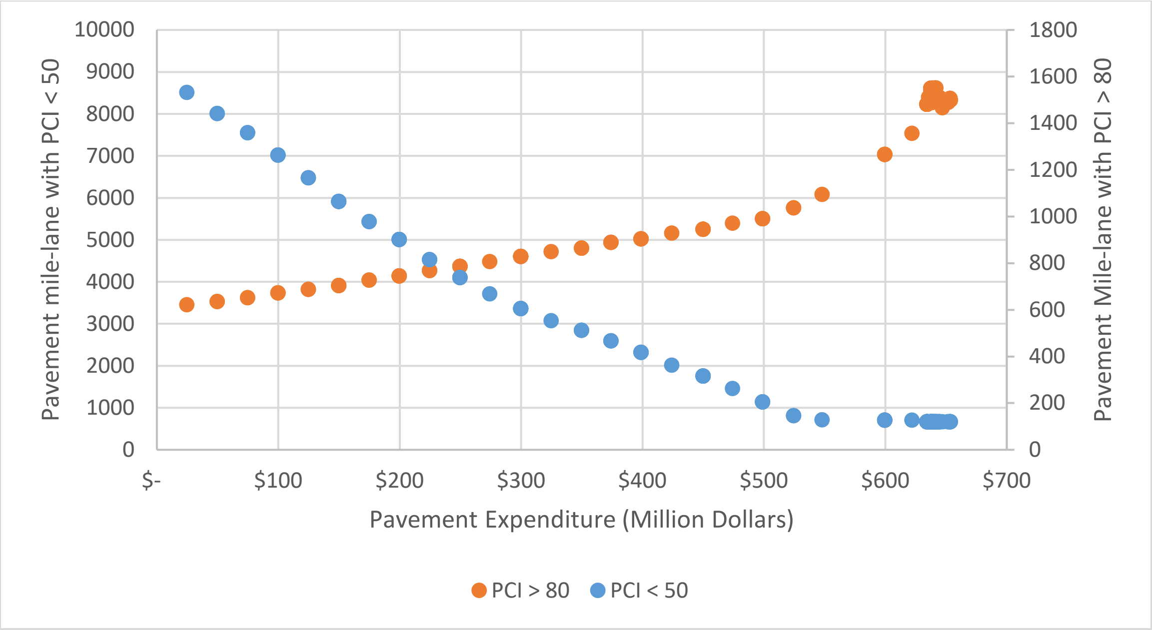

Figure 40: Change in pavement network condition within total pavement expenditure

- Figure (41) shows the trend of the three deck condition states with budget allocation.
- The overall trends of good and poor decks are increasing and decreasing, respectively. However, fair decks trend is more complicated. Fair decks area is constant for expenditure less than $500 million on bridges, then increases between $500 million and $1.5 billion. Then, it decreases between $1.5 billion and $2 billion, before continuing the increasing trend.
- The largest rate of increase in good bridge decks and decrease in poor bridge decks in the network occur between $2 and $2.5 billion total bridge expenditure.

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- It is obvious from the figure that there are two trends for each condition state. This means, at the same level of bridge expenditure, two different performance levels can be achieved. After inspecting each individual point in these trends, the reason behind the presence of these trends is the difference of allocation strategies over the years of the analysis period. The trend that gives higher good decks area and lower poor decks area is associated with more total budget allocated to bridges, but not fully utilized. In this case, more preservation actions and low slump concrete overlays are performed resulting in better condition of the network at the same amount of expenditure.
- Poor decks area dropped to zero after $1.65 and $2.4 billion bridge expenditures based on the two trends.

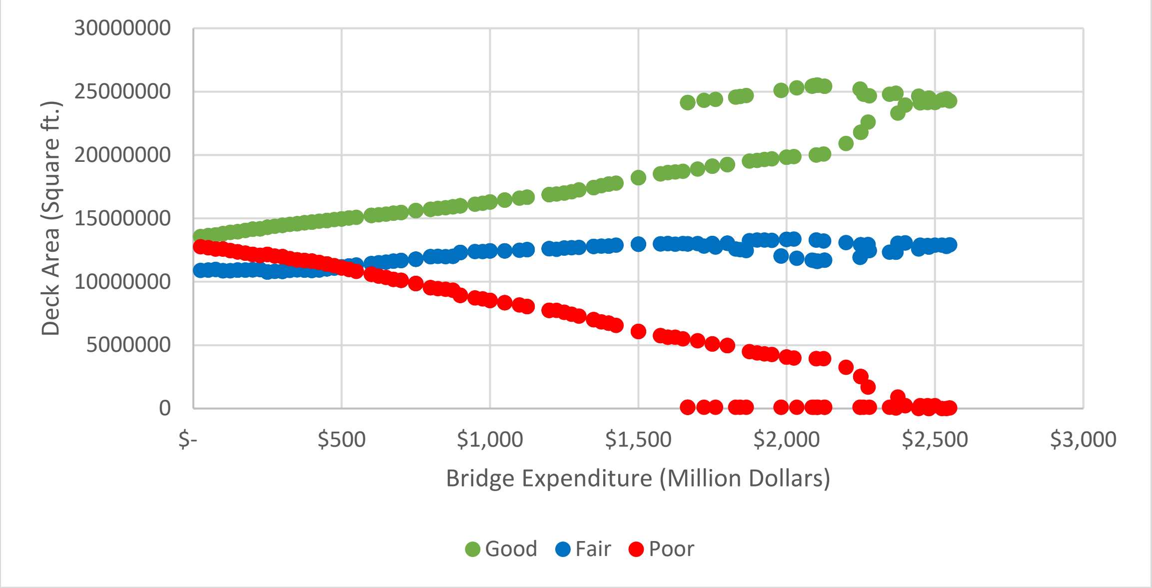

Figure 41: Deck condition states trend with bridge expenditure

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- The conditions of superstructures and substructures follow the similar trend as shown in Figures (42, 43). The only difference is the trend of fair superstructures and substructures, which is continuously increasing.

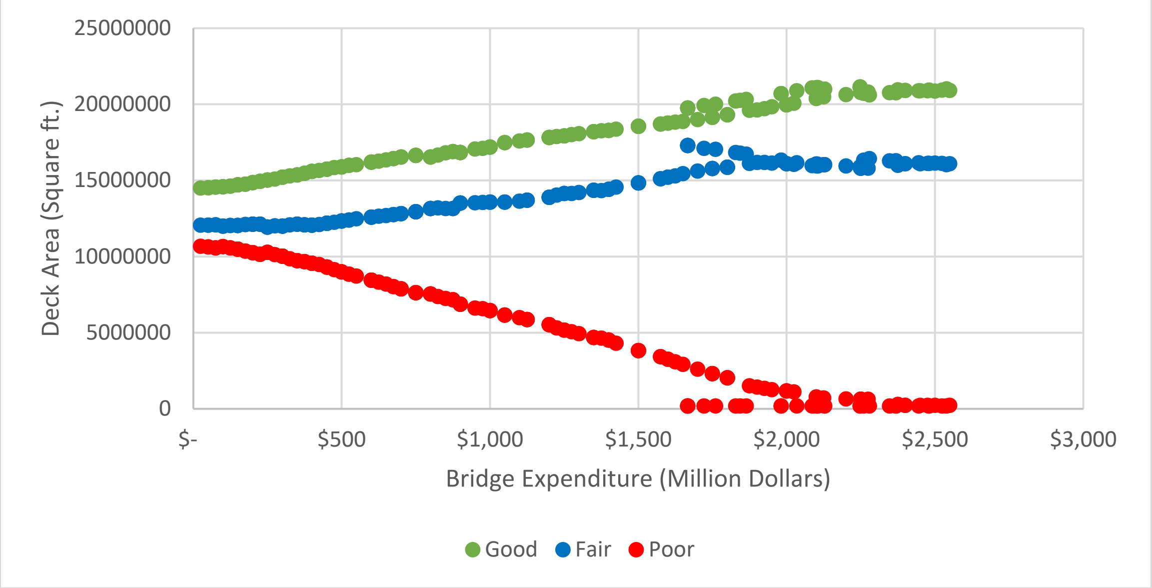

Figure 42: Superstructure condition states trend with bridge expenditure

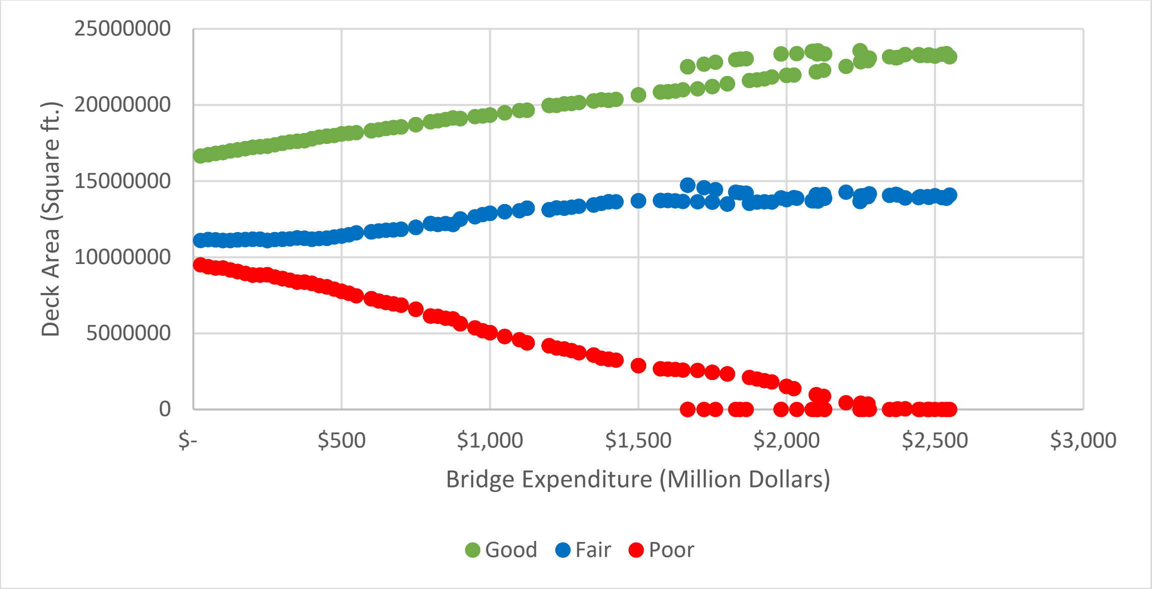

Figure 43: Substructure condition states trend with bridge expenditure

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Distribution of Bridge Actions over Years and Budget Allocations

Figures (44) through (46) illustrate the distribution of bridge replacement, preservation, and low slump concrete overlay applied annually for each budget level and bridge budget percentage combination. The following points summarize and explains the interesting features captured in the distributions.

- For low total budgets, as the percentage of budget allocated to bridges increases, the area of replaced decks increases. However, for high budgets, the total deck area replaced follows a bell shape curve, due to the increase in preservation actions. The impact of preservation is not obvious at low budget levels due to the worst first allocation strategy that gives priority to replacement under scarcity of resources. When sufficient resources are available, all bridges in fair condition will be preserved keeping them in fair condition. This will lead to reduce bridge replacement.
- On the other hand, it is obvious from the figures that for total budgets less than \$600 million, preservation actions are done in the first year only with an increasing trend with the percentage of bridge allocation. This can be attributed to the high percentage of bridges in fair condition, which need to be treated by preservation. Large part of these bridges have time in condition state exceeding their median time in condition state. These bridges drop to poor condition in the second year and require replacement. As mentioned above, based on the worst first allocation, these bridges will be given priority over those in fair condition

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with low time in condition state or those which dropped from good to fair condition due to deterioration

- In reference to the previous two points, the area of total bridge replacement in the first year is not affected by total budgets, because there is no deterioration effect in the first year, and poor bridges that need to be replaced are replaced even at low total budget levels, since they are given priority. What makes the real difference in the distribution of bridges replaced are the subsequent years. On the other hand, the amount of bridges preserved in the first year increases with the percentage of bridge allocation.
- For low slump concrete overlay, there are minor overlays applied at total budgets less than 500 million. While, the amount of overlays increases drastically at higher budget levels. This can be attributed to the availability of resources. In terms of the distribution over years, very few bridges were overlaid during the first year. On contrary, large proportion of them were overlaid during the third, fourth and fifth years. This is because 388 bridges have decks with condition of 5 and time in condition state of 5 years or more, which is 2 years less than the median time in condition state and fair/good substructure and superstructure conditions. These decks drop to poor leaving those bridges apt for overlays. It is important to mention that preservation have no impact on this trend in the presence of adequate budget since deck replacement has priority over preservation based on the worst first allocation strategy.

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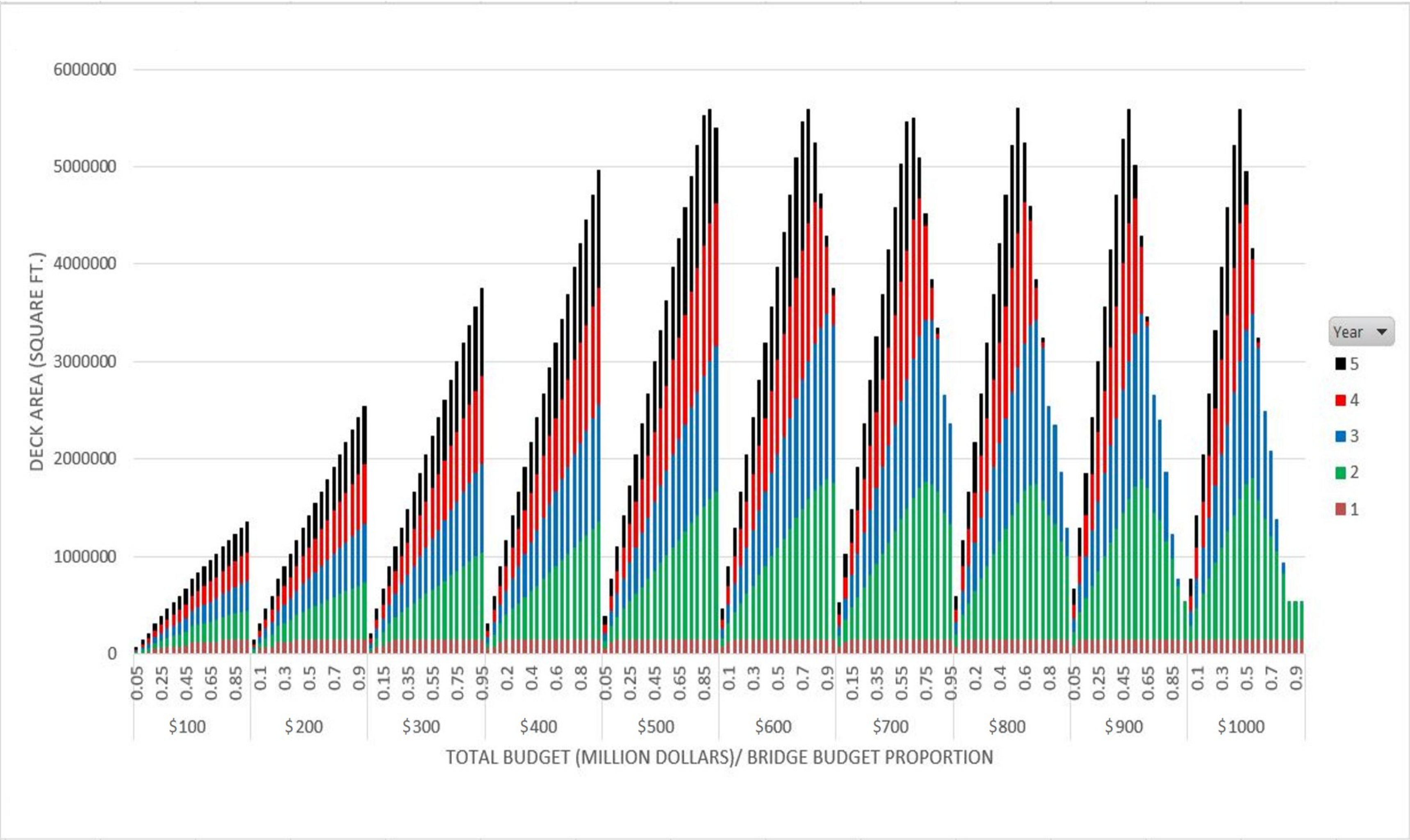

Figure 44: Distribution of bridge replacement over analysis years with allocation

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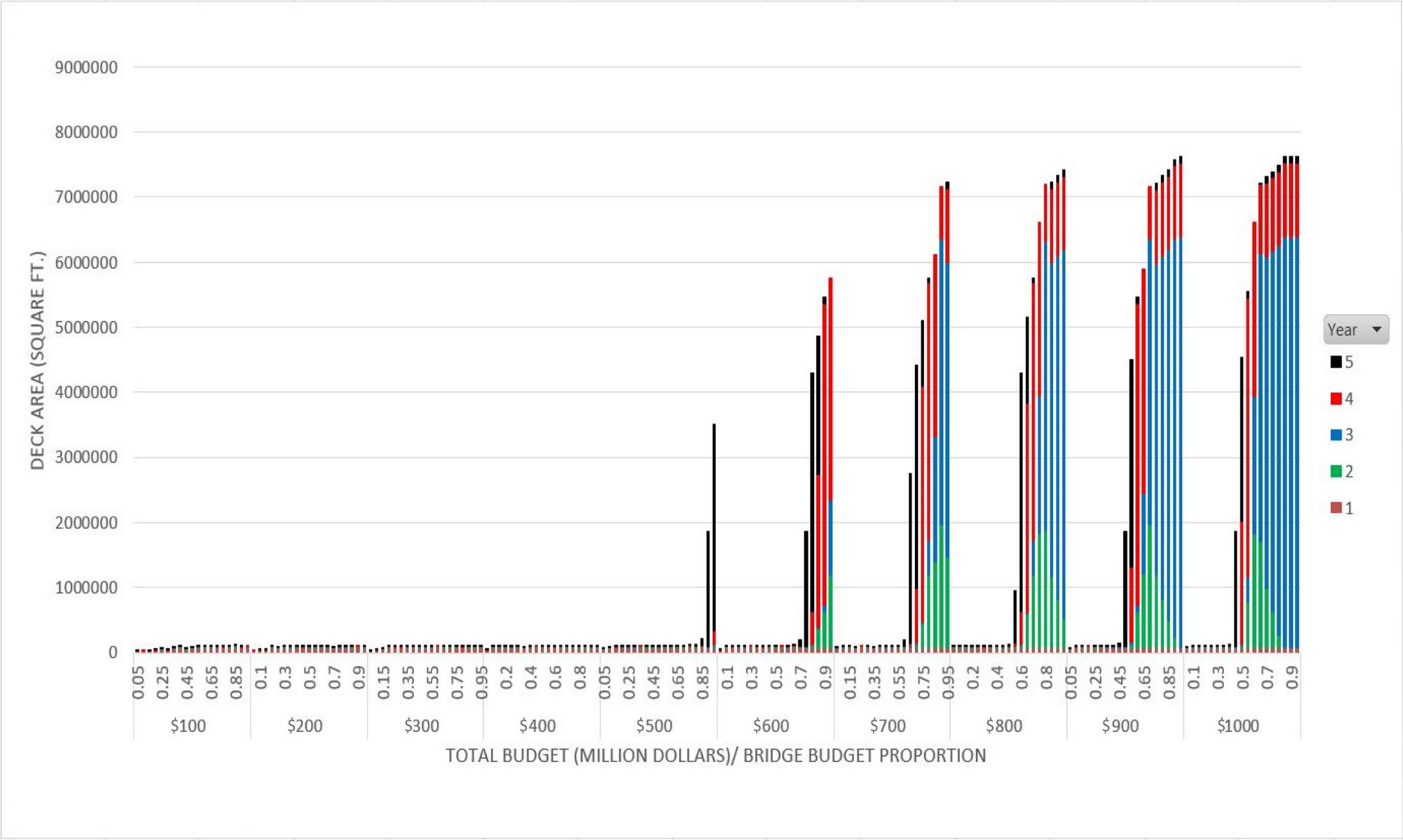

Figure 45: Distribution of bridge low slump concrete overlay over analysis years with allocation

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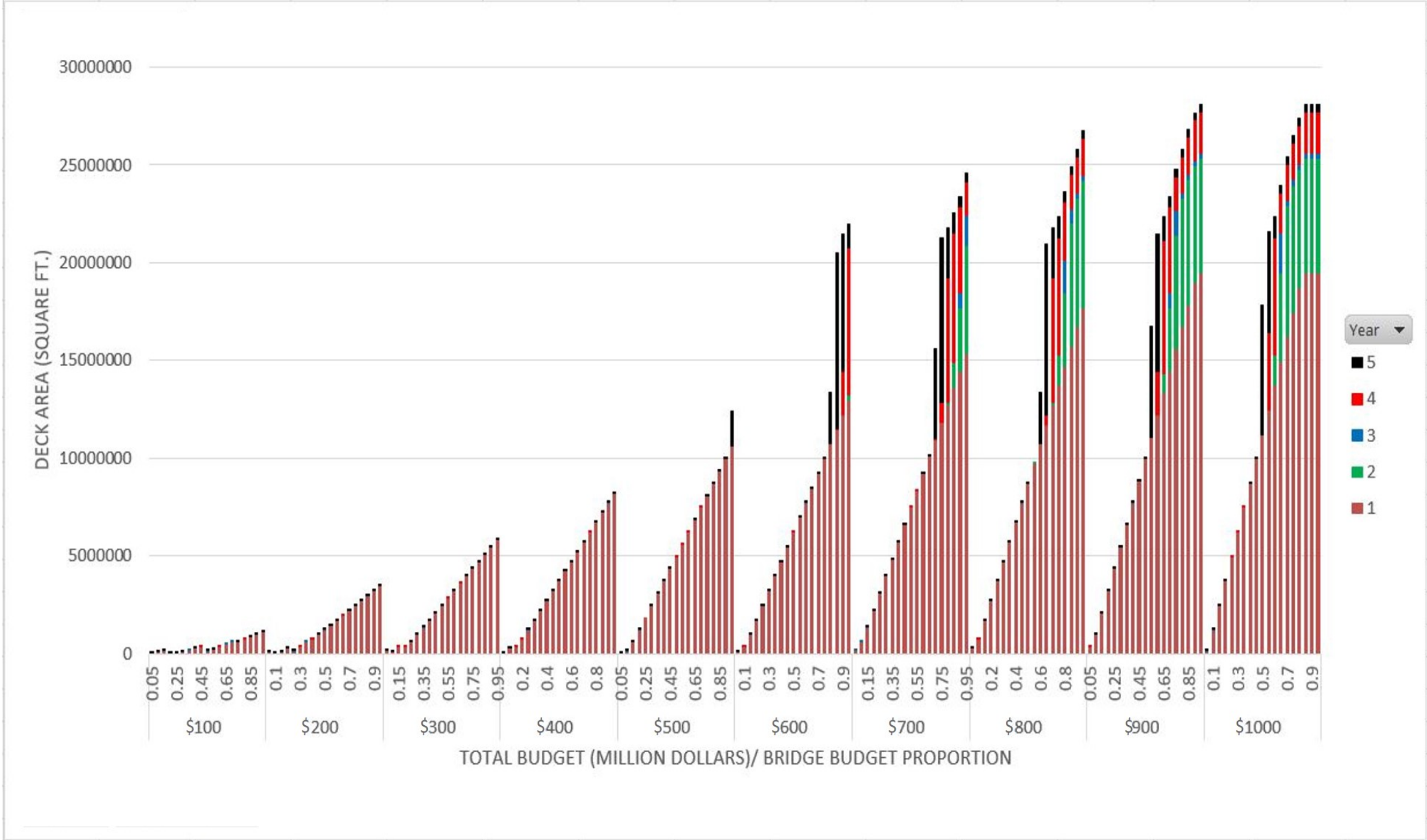

Figure 46: Distribution of bridge preservation over analysis years with allocation

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Distribution of Pavement Actions over Years and Budget Allocations

Figures (47) through (52) show the distribution of pavement treatment actions expressed as yearly treated mileages for each budget level and pavement budget percentage combination. Some interesting features were observed in these figures and summarized as follows:

- The distribution of actions for pavements is more complicated than that for bridges because bridge actions are dependent on components' overall condition, however, pavement actions depend on multiple condition factors such as PCI, IRI, cracking, rutting, faulting and joint spalling. No deterioration effects were applied to the last four factors, which makes predicting actions' distribution over time even harder.
- With all that being said, some trends can be justified. For instance, replacement actions are distributed over the analysis years at low budget levels due to the lack of funds. However, for large budget levels, all the replacement is done during the first year due to the availability of funds. Since the applied deterioration rates are relatively small and due to the application of major, minor structural actions along with other treatments because resources are available at these budget levels, no replacement actions will be required after the first year.
- Major structural treatment follows the same distribution of reconstruction actions
- For minor structural rehabilitation, there is an increasing trend at low total budget levels, due to the need in the network for this maintenance action. However, when more budget is allocated to pavement, the amount of segments treated by minor structural rehabilitation decreases until it reaches a steady region. The reason behind this decrease is the availability of funds to do functional rehabilitation and minor

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works such as thin surface treatment in ACC and diamond grinding in PCC, which will improve the network condition without the need to do major structural rehabilitation.

- Functional rehabilitation follows similar distribution to that of minor structural rehabilitation with most of the rehabilitation actions planned to be done in the first and the second year.
- Thin surface treatment for ACC and composite pavement increases with increase in budget because it has the lowest priority. When there is limited budget, this action is distributed over the analysis period, but when more budget is available, most of sections in need for thin surface treatment are treated in the first and second year.
- Although diamond grinding is given the lowest priority in PCC, the amount of sections treated by this action is high in the first and second year at relatively low budget. This could be due to the low cost of this action, which will allow multiple sections to be treated by diamond grinding using the money the remains after performing the major maintenance actions. The increase in fifth year diamond grinding action at high budget levels can be due to the deterioration of PCC segments treated by functional rehabilitation or minor structural rehabilitation, which are applied at early ages at these budget levels.

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Figure 47: Distribution of pavement replacement over analysis years with allocation

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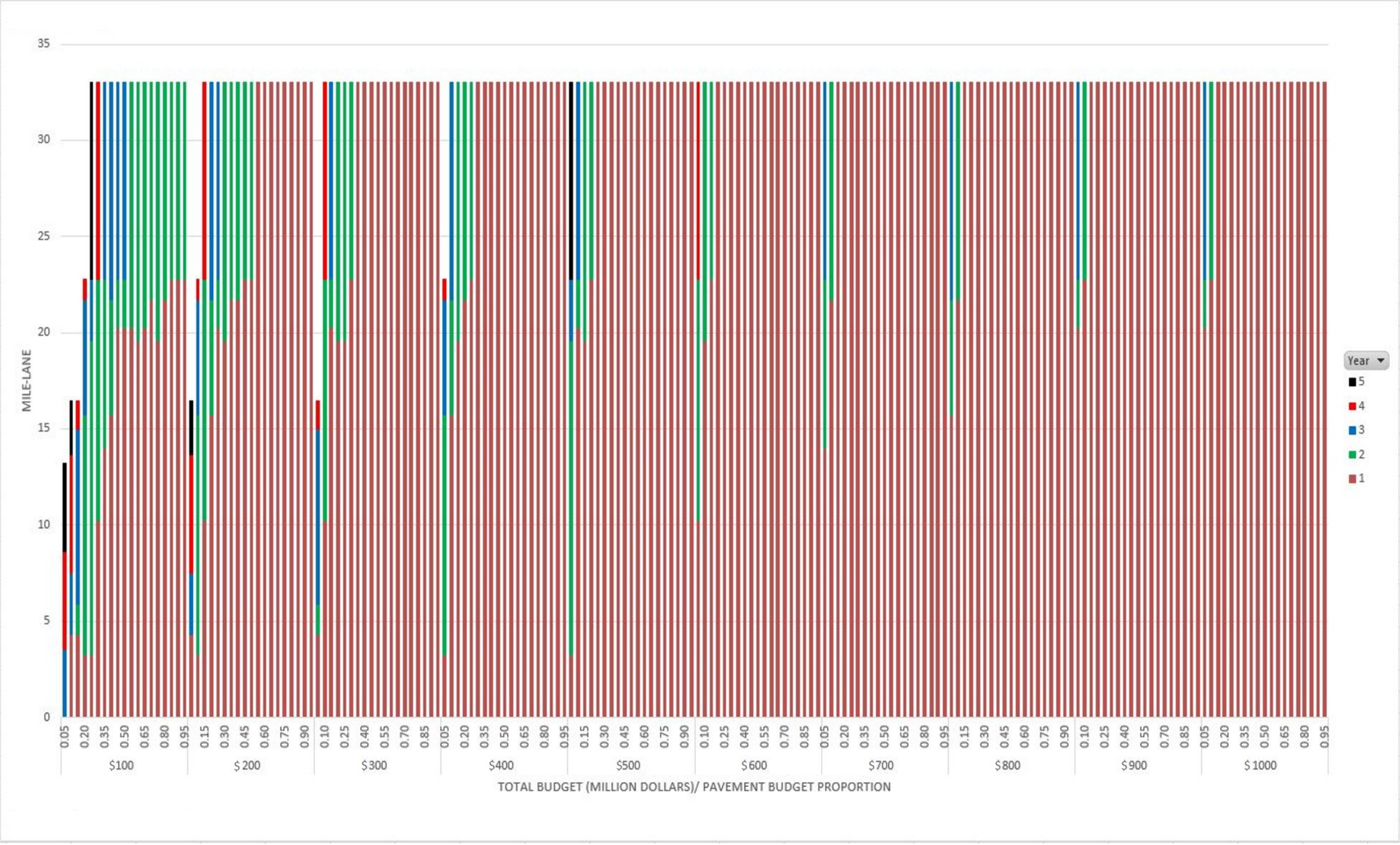

Figure 48: Distribution of major structural rehabilitation over analysis years with allocation

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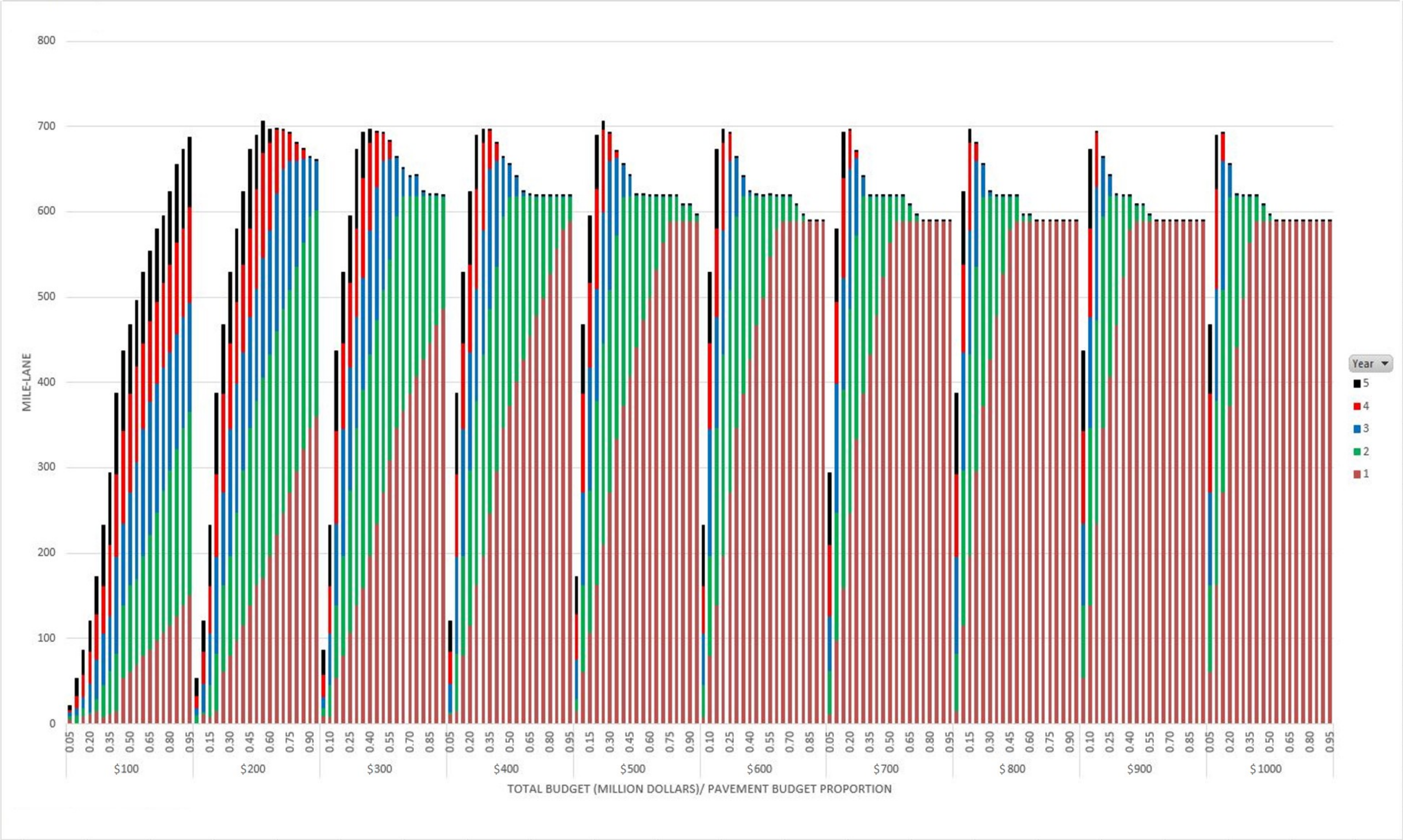

Figure 49: Distribution of minor structural rehabilitation over analysis years with allocation

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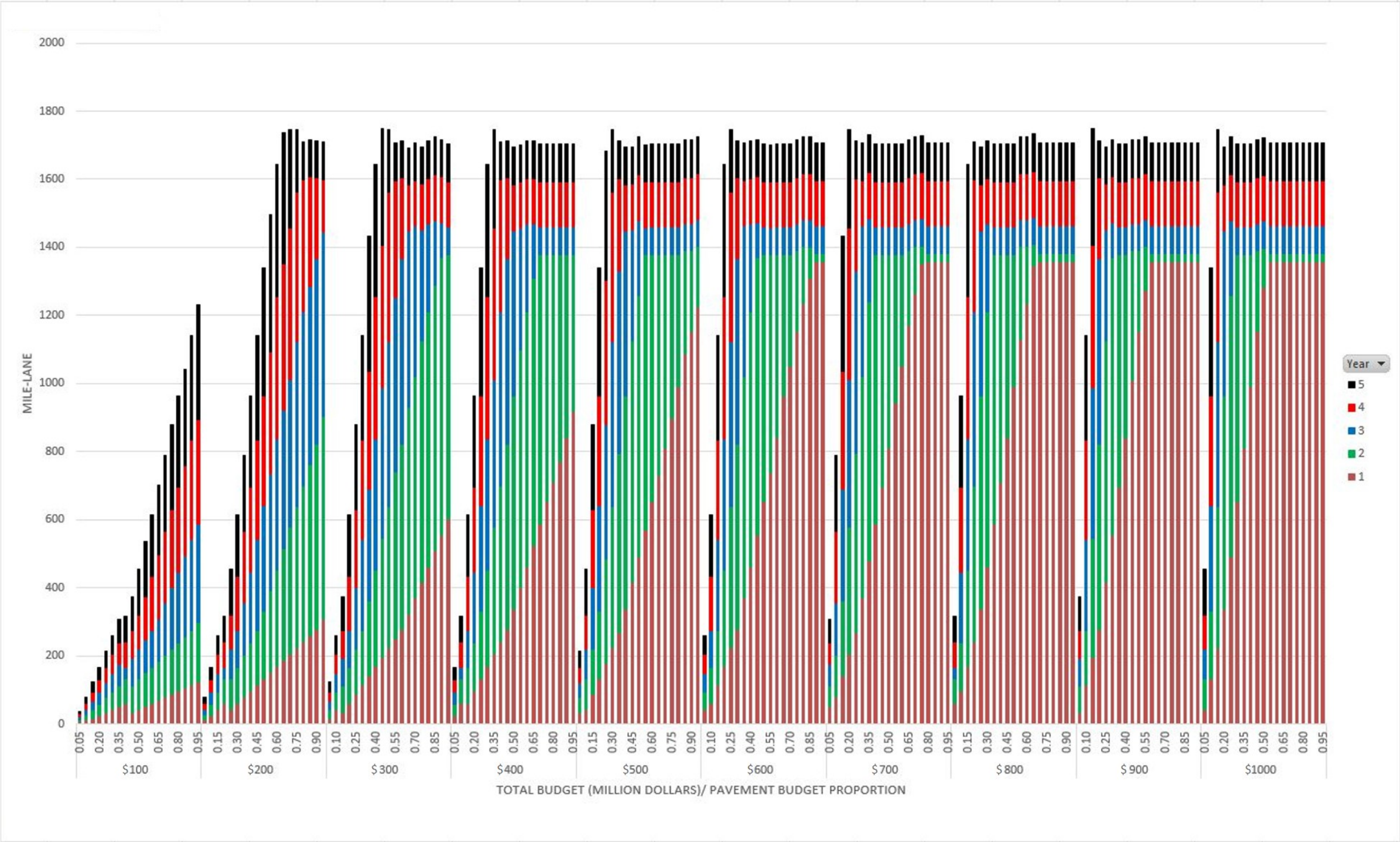

Figure 50: Distribution of functional rehabilitation over analysis years with allocation

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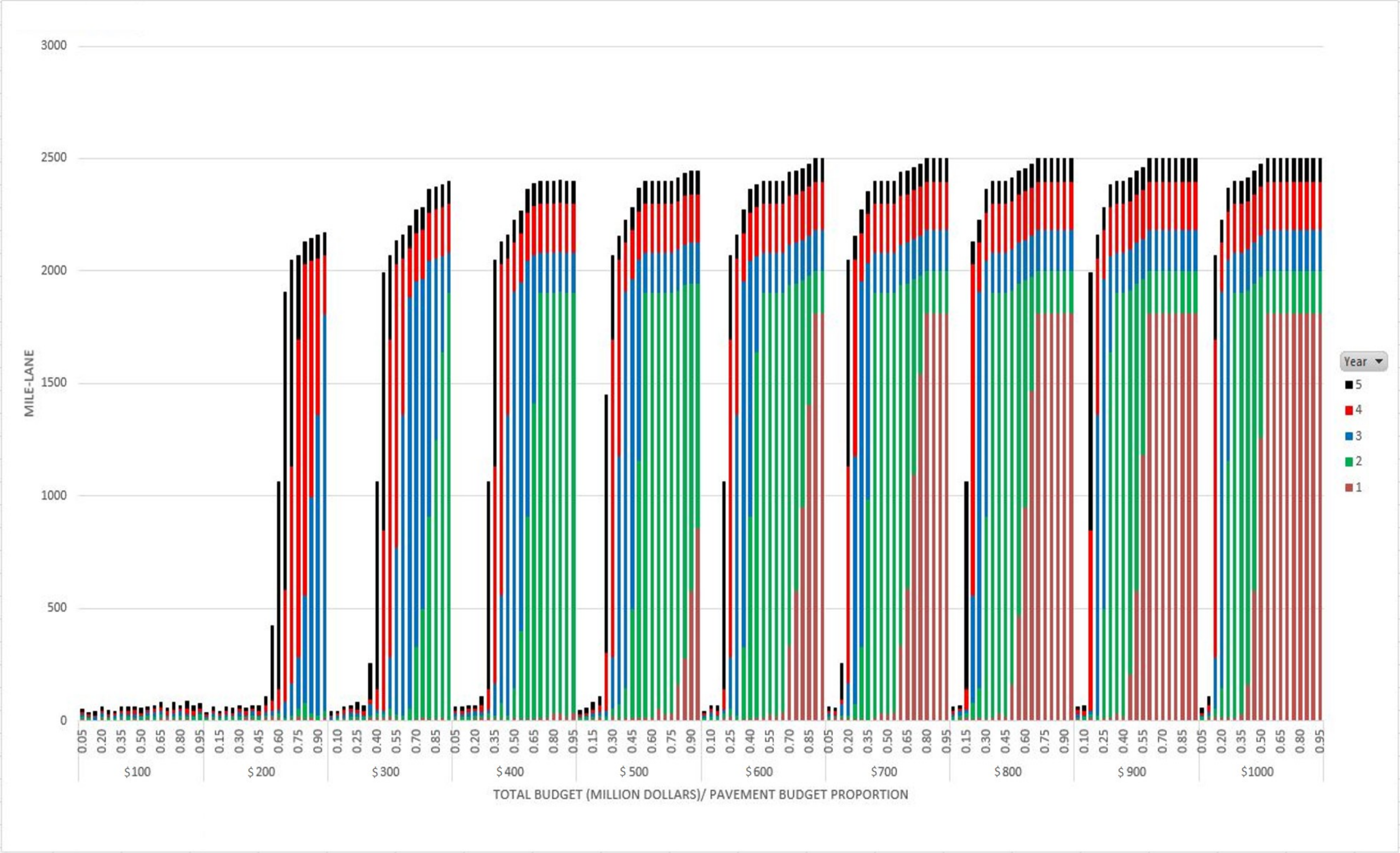

Figure 51: Distribution of thin surface treatment for ACC over analysis years with allocation

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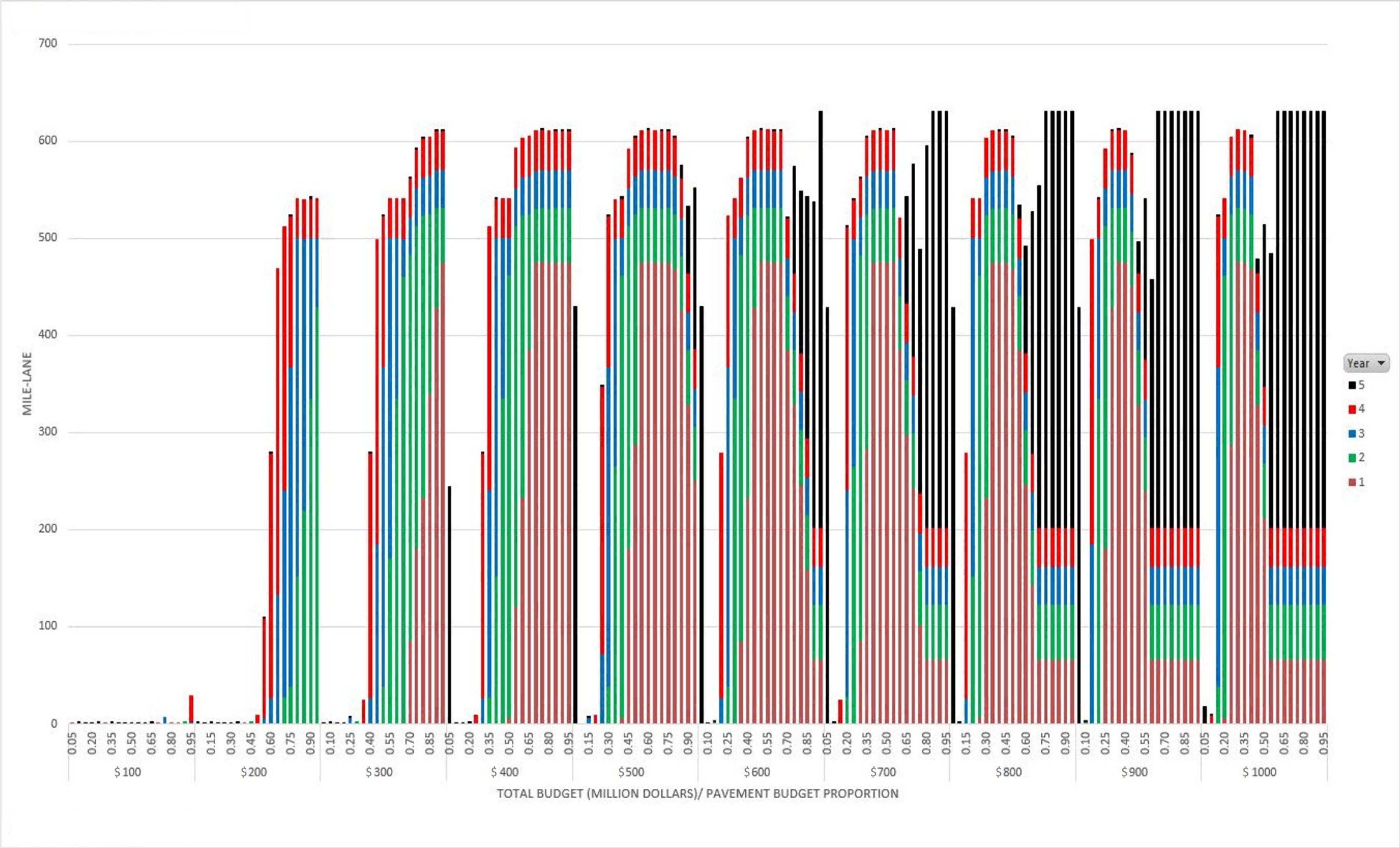

Figure 52: Distribution of diamond grinding treatment for PCC over analysis years with allocation

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CHAPTER 6: CONCLUSION

This chapter summarizes the conclusions of this research, highlights the major limitations in the used tools, and proposes future research work that will improve the results and overcome the limitations.

Conclusion

In conclusion, no one can deny the role of cross asset resource allocation in achieving comprehensive decision making strategies in transportation infrastructure. But the tools used within each asset type management system has a great impact on the solution of the cross asset problem. This was clear in the impact of worst-first allocation method on the distribution of maintenance actions at different budget levels. At low budget levels, there was no chance for applying preservation actions. The distribution of actions is also affected by the deterioration approach. The use of median time in condition state as the limiting condition for deterioration resulted in low preservation actions in all the years except the first year, due to the large number of bridges with TIS exceeding median TIS.

One of the advantages of the proposed framework is that the solution that maximizes the network monetary value is insensitive to valuation method based on the twelve different combinations tested. This framework favors pavements at low budget levels, bridges at moderate budget levels and reaches an equilibrium state at high budget levels. This consistency in valuation methods results from the high difference in maintenance needs between pavements and bridges, where bridge maintenance needs are four times that of pavements. Based on this method, increasing the amount of expenditure always improve the network monetary value, because more projects can be achieved at higher expenditure levels. However, different maintenance strategies across the analysis years result in different

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pavement and bridge network monetary values at the same total expenditure, with higher value for strategies using more preservation actions.

Limitations

The work done in this thesis had many limitations especially in the individual tools used in each step of the framework, since the purpose of this research is to establish a cross asset resource allocation framework and to prove its applicability on simple decision making tools, not to create all decision making tools. One of the major limitations is the worst-first allocation technique, which does not result in the optimal allocation within each importance group. However, it provides a rational allocation as research studies have proven. The second limitation is the lack of benefit/cost analysis in assigning maintenance actions to sections, which is a tool that insures the maximum benefit of each dollar spent and is considered one of the basis of asset management. This was overcome by insuring mutually exclusive maintenance actions that do not require benefit/cost analysis to choose. One of the reasons behind not using benefit/cost analysis is the lack of sophisticated treatment effectiveness modeling due to the missing maintenance records in the data. The inconsistency and high variability in individual pavement's distresses records impeded the development of individual distresses' deterioration models. This had a negative impact on pavement decisions, but this impact was not major since deterioration models were developed for IRI and PCI, which are the basic elements in decision matrices. In terms of bridge deterioration, the use of median time in condition state is a fairly good estimate of deterioration based on experts' judgment, however, the presence of bridges with TIS exceeding the median TIS at the current time is considered one of the limitations of this deterioration approach. The reason behind having these cases is the definition of the median, which means there is a 50%

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chance that a bridge will have a TIS greater than the median TIS. So it is not unlikely to see this case in bridges. Its effect was reduced by assuming that whenever the median TIS is exceeded, the bridge TIS is limited to the median TIS value.

Future Work

These limitations need to be resolved in future research by working on the individual pieces of the management systems. Probabilistic deterioration models, accurate maintenance actions' effectiveness models, benefit/cost analysis basis of assigning treatments and optimization-based allocation within importance groups will enhance the accuracy of the results and provide more realistic ones. After insuring each management system tools are built in sophisticated manner, this framework can be expanded to include other assets such as safety and mobility. This will insure comprehensive resource allocation approach at the network level.

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