TRANSPORTATION ASSET MANAGEMENT SYSTEMS: A RISK-ORIENTED DECISION MAKING APPROACH TO BRIDGE INVESTMENT

A Thesis
Presented to
The Academic Faculty

by

John Patrick O'Har

In Partial Fulfillment
of the Requirements for the Degree
Master's of Science of Civil Engineering in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
August 2011

TRANSPORTATION ASSET MANAGEMENT SYSTEMS: A RISK-ORIENTED DECISION MAKING APPROACH TO BRIDGE INVESTMENT

Approved by:

Dr. Michael D. Meyer, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Ajdo A. Amekudzi, Co-Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Frank Southworth
School of Civil and Environmental Engineering
Georgia Institute of Technology

Date Approved: July 5, 2011

DEDICATION

For Mom and Dad

ACKNOWLEDGEMENTS

Throughout my academic career, a number of family members, colleagues, faculty members, and friends helped me along the way with their support and guidance.

When I arrived at Georgia Tech I struggled to adjust to its academic rigor, but I quickly found a mentor and fellow Yankee fan in my civil engineering freshmen seminar, Dr. Larry Jacobs. His support and guidance not only helped me receive my undergraduate degree, but also encouraged me to study abroad in Australia and Spain for two consecutive terms, which was one of the most memorable experiences of my life.

Choosing to study here at Georgia Tech was one of the most important decisions in my life and one that I surely will never regret. This is truly a world-class university and it offers countless opportunities to its students. One of these opportunities is the five year B.S./M.S. degree program, to which I was accepted at the end of my sophomore year. Were it not for this program, I may never have attended graduate school.

With the support and guidance of Dr. Michael D. Meyer, I discovered my passion for the transportation profession. His transit systems course was the tip of the iceberg that has become my desire to learn more about transportation. He is truly a seminal figure in the transportation field. His leadership of the transportation program at Georgia Tech and his selfless dedication to its students has fostered one of the finest transportation programs in the world. I have had the pleasure of meeting and working with a phenomenal group of transportation scholars. Additionally, I have become close friends with many of my colleagues in this program. We have shared a memorable two years and I am confident there will be many more.

Particularly related to the analysis for this thesis, I must thank the Georgia Department of Transportation (GDOT) who sponsored much of the research in this thesis under the project "Best Practices in Selecting Performance Measures and Targets for Effective Asset Management". In particular, I would like to thank the Bridge Maintenance Unit and Kevin Schwartz, who provided thoughtful input and guidance. I must also thank Dr. Adjo Amekudzi. In addition to her support and guidance as my co-advisor, she was the principal investigator on the aforementioned GDOT project.

I must also thank the National Science Foundation Graduate Research Fellowship Program. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-0644493.

Last, but certainly not least, I must thank my parents. Their continuous love and support has afforded me countless opportunities throughout my life. In addition to all of the financial support they have provided me, they have always been there to give me that gentle encouragement when I need it.

Once again, to all of the people and organizations mentioned above, thank you. I know there are countless individuals that I have failed to mention here. I would like to say thank you to everyone who has helped me out along this journey, whether that help was small or large. My success has been largely dependent upon the help, love, support, dedication, time, kindness, and generosity of many individuals. To all of you I say a very special thank you.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASCII	American Standard Code for Information Interchange
BIMS	Bridge Information Management System
DOT	Department of Transportation
FHWA	Federal Highway Administration
GASB	Government Accounting Standards Board
GDOT	Georgia Department of Transportation
GIS	Geographic Information Systems
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
LaDOTD	Louisiana Department of Transportation and Development
LRFD	Load and Resistance Factor Design
MADM	Multi Attribute Decision Making
MAUT	Multi Attribute Utility Theory
NBI	National Bridge Inventory
TAM	Transportation Asset Management
TRB	Transportation Research Board

SUMMARY

Transportation Asset Management (TAM) systems are in use at a significant number of transportation agencies. These systems can be used to effectively allocate resources and continuously inventory and monitor the condition of transportation infrastructure assets. Risk-oriented decision making is becoming an increasingly important component of the management process at many organizations, including transportation agencies. TAM systems can be used to incorporate risk assessment and risk management techniques at transportation agencies.

To demonstrate the value of incorporating risk in TAM systems, an examination of the literature was performed, and a case study was conducted. This case study incorporated risk in bridge project prioritization through the utilization of data from the National Bridge Inventory (NBI), and application of Multi Attribute Decision Making (MADM) concepts to address uncertainty and prioritize selected bridges in the state of Georgia.

The case study examines the impacts of data aggregation and disaggregation, and the incorporation of uncertainty on bridge project prioritization. Results of this analysis show that when available, disaggregate data on bridge condition should be used. In addition, uncertainty, in terms of performance risk, should be incorporated when past bridge condition data is available. Furthermore, decision-maker input is an important component of the Multi Attribute Utility Theory (MAUT) prioritization methodology used in this analysis. Decision-makers determine the relative importance of certain attributes, which is one of the strengths of this type of prioritization effort.

CHAPTER 1

INTRODUCTION

Risk-oriented decision making is a term that is now used by managers in a variety of organizations (1). However, it is often unclear what a decision maker means when he or she states that risk-oriented decision making is an integral part of the management process. It is one thing to say that this sort of decision making is part of an organization's business process, but another to specify how exactly risk is a factor in everyday decision making. This thesis examines risk assessment and risk management at transportation agencies as it applies to Transportation Asset Management (TAM) systems and presents a case study that incorporates risk in bridge project prioritization. More specifically, this case study utilizes data from the National Bridge Inventory (NBI), applies Multi Attribute Decision Making (MADM) concepts to address uncertainty and prioritize selected bridges in the state of Georgia.

TAM systems are already in use at a significant number of transportation agencies, especially in larger agencies, such as state Departments of Transportation (DOTs). However, these agencies are at various stages of implementing TAM systems. Some agencies are quite advanced, particularly agencies in other countries that have been conducting transportation asset management for many years (2). For example, all of the international agencies examined in a 2005 Federal Highway Administration (FHWA) international scan of best practices incorporated some degree of risk assessment or risk management in selected areas of their TAM processes, particularly through the use of scenario analysis (2).

A 2006 scan tour in the United States, also on TAM systems, highlighted several state and local level agencies that were at various stages of implementation. The scan tour report identified best practices in TAM as found in the United States (3). As with the international experience, U.S. agencies often used scenario analysis as part of their risk assessment and risk management efforts. Typically, different funding scenarios were assumed leading to different condition or performance assessments of the transportation system. In particular, the scenarios often predicted pavement and bridge conditions with various levels of funding (3).

Perhaps the most common use of the term “risk” when applied to transportation infrastructure refers to the risk of failure of a transportation asset. However, such a use of risk of failure is not defined consistently given that performance measures for transportation infrastructure condition are often not standardized (4). Also, catastrophic and non-catastrophic, i.e. level of service, failures tend to be treated differently.

This thesis is organized in the following manner. Chapter 2 reviews TAM systems, and presents a basic overview of the concept of risk, risk assessment, and risk management. It then presents some examples of how risk can be used in TAM systems. Chapter 3 describes the methodology used in the case study, which focuses on bridge investment prioritization. Several prioritization scenarios are developed in Chapter 4, some using aggregate data while others use more disaggregate data. Some also incorporate uncertainty. Chapter 5 shows the results of data aggregation, disaggregation, and the incorporation of uncertainty into the prioritization scenarios. Finally, Chapter 6 discusses the impacts of the Chapter 5 results, identifies knowledge gaps, and presents future research needs.

CHAPTER 2

LITERATURE REVIEW

2.1 Transportation Asset Management Systems – A Historical Context

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), among other things, placed emphasis on the management of existing infrastructure as opposed to the construction of new facilities. ISTEA required state transportation agencies to have six infrastructure management systems for road pavement, bridges, safety, congestion, public transportation, and intermodal facilities (3). Congress, however, did not provide funding to the states to establish these infrastructure management systems and this mandate was repealed in 1995 after state DOTs argued that the infrastructure management systems represented unfunded mandates. However, in many cases, states had developed infrastructure management systems prior to ISTEA, such as pavement and bridge management systems, and continued to use them. In the case of congestion management systems, such systems were required for transportation management areas, defined as metropolitan areas over 200,000 population (this approach is now called the congestion management process.)

One of the distinguishing characteristics in the evolution of transportation asset management in the U.S. has been the use of conferences and workshops to develop and disseminate information on its application. A timeline of major conferences and workshops in the evolution of transportation asset management includes (two non-conference events are also included in the timeline because of their importance to the development of TAM):

- 1996: AASHTO and the FHWA co-sponsor a workshop in Washington D.C. entitled “Advancing the State of the Art into the 21st Century Through Public-Private Dialogue”. The workshop included representatives from Chrysler, Wal-Mart, GTE Conrail, and a number of public utilities. The underlying theme of the workshop was that principles and tools of good asset management in private organizations could also apply to public organizations (5).
- 1997: A workshop is held at the Center for Infrastructure and Transportation Studies at Rensselaer Polytechnic Institute further examining the practices, processes, and tools of asset management as they apply to state DOTs.
- 1998: Federal Highway Administration (FHWA) creates the Office of Asset Management (6).
- 1999: A national conference is held in Scottsdale, Arizona that serves as a peer exchange for state DOTs (7).
- 1999: The Government Accounting Standards Board (GASB) issues Statement No. 34. GASB 34 requires government agencies to report capital assets using a historical cost, a depreciation approach, or a modified approach for reporting on infrastructure assets. The modified approach requires government agencies to use some sort of asset management process (8).
- 2001: A national conference is held in Madison, Wisconsin with a theme of “Taking the Next Step” (7).
- 2003: National conferences are held in Atlanta and Seattle with the theme “Moving from Theory to Practice” (9).

- 2005: A national conference is held in Kansas City with the theme “Making Asset Management Work in Your Organization” (10).
- 2007: A national conference on transportation asset management is held in New Orleans with the theme “New Directions in Asset Management and Economic Analysis” (11).
- 2009: A national conference on Transportation Asset Management is held in Portland with the theme “Putting the Asset Management Pieces Together” (12).

These conferences and workshops occurred in parallel with an evolving literature on transportation applications in asset management that laid the foundation for today’s state of practice. For example, the FHWA, AASHTO, the TRB of the National Academies, and consultants from private industry have published various primers, reports, scans, and case studies regarding TAM (see (2) (3) (5) (6) (7) (8) (9) (10) (13) (14)).

2.2 Transportation Asset Management Systems- System Components

The term asset management means different things to different organizations, many of which practice some degree of asset management, but might not use that term. The AASHTO Subcommittee on Asset Management developed the following definition of asset management (13):

> “…a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and

utilization, with the objective of better decision making based upon quality information and well defined objectives."

Of importance to this thesis, NCHRP Report 551 identified the following core principles of a TAM system: policy-driven, performance-based, analysis of options and tradeoffs, decisions based on quality information, and monitoring to provide clear accountability and feedback (14).

For purposes of this thesis, the aforementioned AASHTO definition of a transportation asset management system (13) is used as a common point of departure. TAM systems are already in use in a large number of transportation agencies, especially in larger agencies, such as state DOTs. Most scans or other investigations of TAM systems show that implementation varies from one organization to another. Several international agencies, for example, have TAM systems that are quite advanced (2). Others are just beginning to understand how agency decisions could be informed by such a system. This being the case, not all agencies use the term asset management, and similarly there is no single asset management system or framework that has been adopted uniformly. However, the FHWA has attempted to identify key steps or elements in a transportation asset management process, including: goals and policies, asset inventory, condition assessment and performance monitoring, alternatives analysis and program optimization, short and long range plans, program implementation, and performance monitoring (6). (See Figure 1, which shows the generic components of an asset management system.)

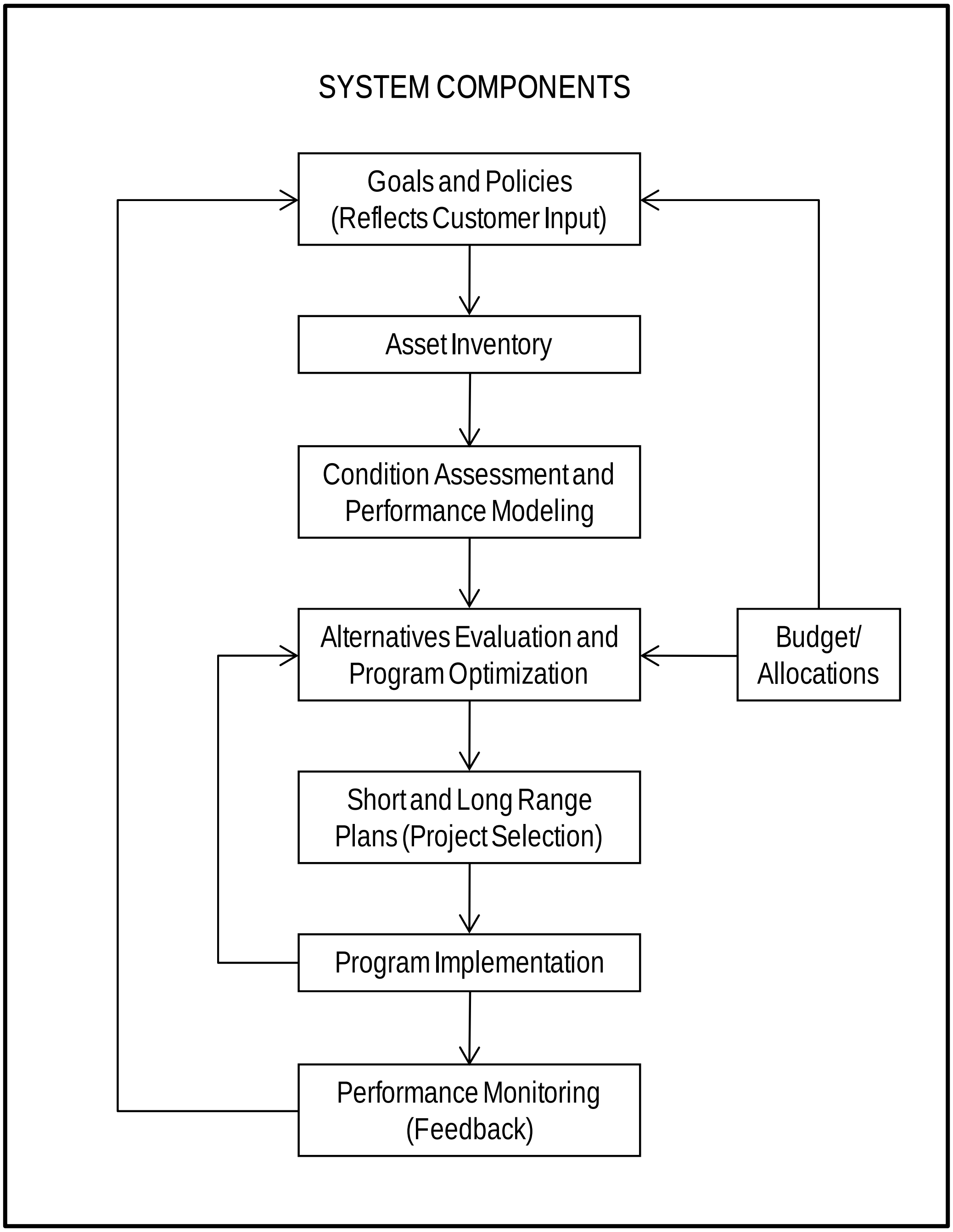

Figure 1. System components of a generic asset management system (6)

Some agencies enumerate specific goals and policies for their asset management systems before developing specific elements of a TAM system while other agencies may develop certain elements of a TAM system before defining goals and policies. TAM best practice includes clearly defined goals and policies that can be translated into specific performance measures and targets, which depends upon the resources available to an agency (7).

AASHTO's *Transportation Asset Management Guide* (7) was produced after the FHWA Asset Management Primer (6), and looked to build upon previous work. The AASHTO Guide also presented the basic elements of an example resource allocation and utilization process in a TAM system as shown in Figure 2. Although similar to the FHWA process, the AASHTO framework is intentionally broader, incorporating fewer elements. This is to serve the needs of different agencies better, so that agencies do not feel the need to overhaul every aspect of their TAM systems (14). Nonetheless, the basic elements of the FHWA process are also captured in the AASHTO process.

An updated and accurate inventory of assets is an essential component of an effective TAM system. Inventory data may contain a variety of data related to a specific asset and will likely vary depending upon the class of the asset, i.e., roads versus bridges. An important component of an asset inventory system is the location referencing system used. Agencies have used Geographic Information Systems (GIS), Global Positioning Systems (GPS), or imaging technologies as part of their inventory system process. Ideally, an asset inventory should be updated on a regular basis, so that it can provide information on changing conditions for both newer and older assets.

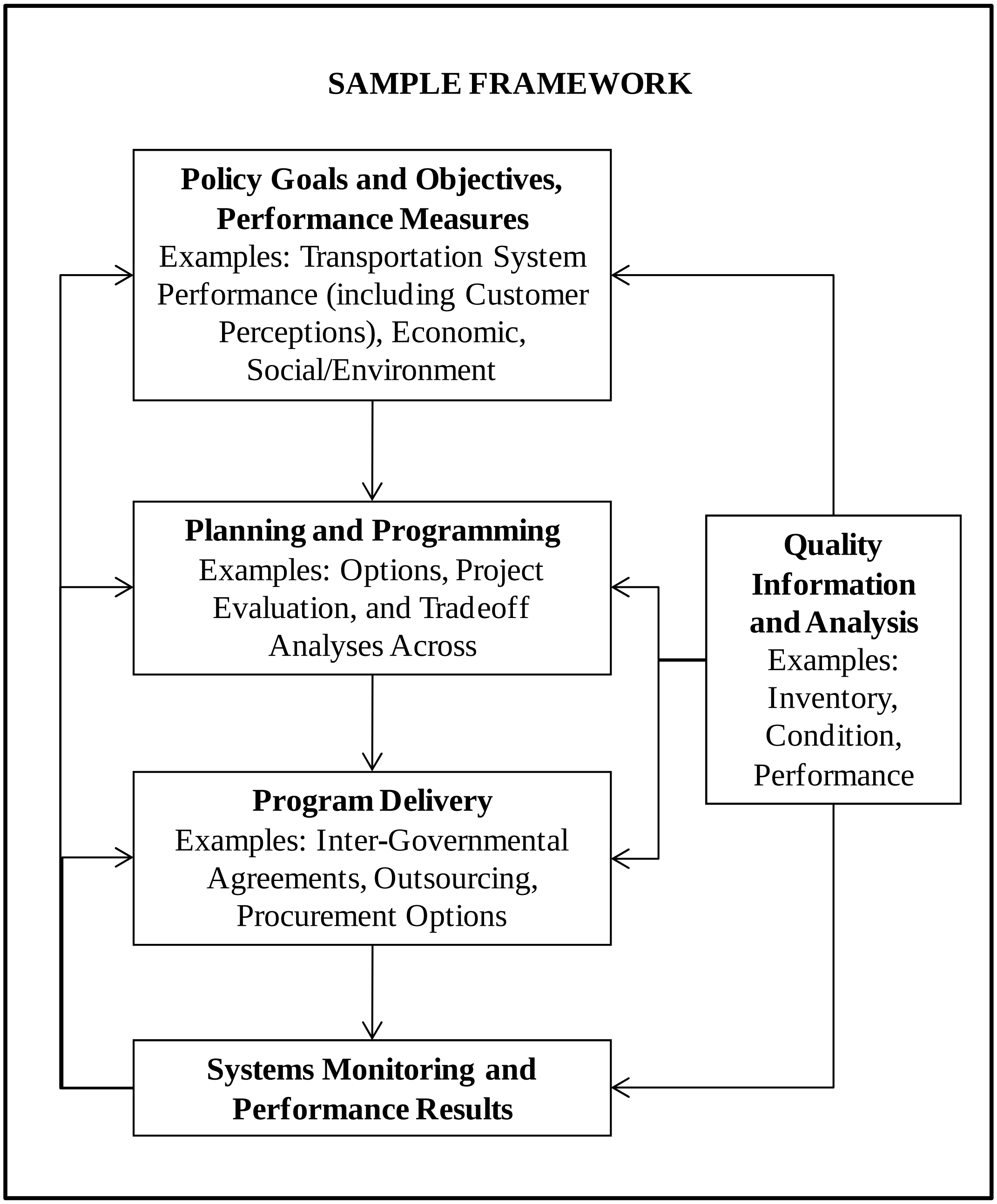

Figure 2. Sample resource allocation and utilization process in transportation asset management (7)

Condition assessment is another critical component of an effective asset management system. Not only is it important for transportation agencies to maintain data on current asset condition, but it is also critical to monitor trends in asset condition so as to identify how the transportation system is faring over time.

Performance modeling is a tool that allows transportation agencies to predict the future condition of assets. Oftentimes performance models depend upon the use of historic condition data to predict future asset condition. Many transportation agencies set a minimum defined condition level for their assets. For example, on a pavement condition scale of 0 to 100 an agency may set 85 as the minimally acceptable condition for interstate highways. In many instances, the level of funding directly impacts the condition of infrastructure assets.

Most TAM systems include some means of alternatives analysis and program optimization. Often an agency will develop a set of alternatives that meets its objectives given resource constraints. Program optimization can be used to identify the optimal set of alternatives that meet specified agency goals and objectives. However, there is not always an optimal alternative and as such, a decision maker selects one alternative based on his or her values and preferences. Sometimes agencies will evaluate various plans, programs, or project alternatives to assess tradeoffs involved in selecting one option over another. This implies that TAM systems should have procedures or processes for determining the relative value of one investment strategy versus another.

TAM systems are also significant components of many transportation organizations' short and long range plans in that TAM systems are used to both monitor current infrastructure asset condition and predict future asset condition. As part of their long-range planning efforts, several agencies with more advanced TAM systems have conducted scenario analysis to determine the effects of different funding levels on asset condition (3).

Plans lead to programs, documents that lay out the budget allocation and schedule of investment over time. Programs can focus on a range of investment categories such as regular maintenance, major rehabilitation or reconstruction. Programs perhaps are the most important part of a TAM in that this is where the ultimate decisions are made concerning where investment will be applied. Programs reflect an agency's priorities and overall strategy for keeping the transportation system in good condition and properly functioning.

Performance monitoring ensures that the asset management system is being provided some indication of whether the state of the transportation system is changing, and if so, in what direction. This is an important component of any TAM process as it ultimately relates to whether a transportation agency is meeting its stated goals and policies (assuming that transportation agency actions directly cause changes in performance). In order to ascertain the level of performance of transportation infrastructure, an agency needs to develop adequate performance measures.

2.3 Risk and Transportation Asset Management Systems

Risk assessment and risk management are important components of any asset management process (15). For example, risk is inherent to the transportation planning and development process. Transportation plans reflect political risks, such as the adverse reaction of a community to the impacts of a transportation project in the plan, potential changes in direction from newly elected officials, and uncertainty in the availability of funds. Risk can be considered in any part of the TAM process shown in Figure 1 or during any portion of the life cycle of an infrastructure asset. Often it is best to consider risk throughout the entire transportation planning and development process, but sometimes it is more appropriate to consider risk during the latter stages of the process (15).

As illustrated by the 2007 collapse of the I-35W bridge in Minneapolis, a more systematic and performance-based approach for evaluating infrastructure condition is necessary. The use of risk-based approaches to evaluate infrastructure condition can lead to investments that are targeted at higher risk assets. For example, a highly traveled interstate bridge could receive inspections with greater frequency. Additionally, in order to assess properly the risks associated with civil engineering infrastructure, a comprehensive approach towards defining infrastructure performance is needed.

The American Society of Civil Engineers (ASCE) has established a committee to develop a more complete definition of performance of engineered infrastructure. This committee has also investigated performance limit-states and performance-based design of infrastructure (4). It was recognized that although performance-based engineering is not a new concept in engineering (see for example the automotive, aerospace, and space industries, that are not driven by code-based designs), it is a relatively new concept in civil engineering. If the civil engineering profession establishes performance definitions and develops quantitative, measurable indices, the benefits could be substantial (4). For example, does it make sense to design a bridge in a low-risk seismic region to the same prescriptive code-based requirements as in a high-risk seismic region such as California?

Designs for modern bridges and buildings are based on limit states or load and resistance factor design (LRFD) concepts. Although these limit states are based on the basic LRFD concept of achieving predetermined reliability levels for typical limit states such as yielding, fracturing, and instability, limit state functions will vary for different building types such as bridges, tunnels, and dams (4). Table 1 shows the limit-states, limit-events, and expected performance goals recommended by the ASCE Committee on Performance-Based Design and Evaluation of Constructed Facilities. Standardization of limit-states, limit-events, and expected performance goals is an important step in the development of performance-based design guidelines. Performance-based design would consider risk of failure, which reflects both the probability of failure, i.e., the inability to meet stated performance objectives, and the consequences of failure (4).

Since the expected life of transportation infrastructure can be long, around one hundred years for bridges, it can become difficult to establish performance limit-states for various stages throughout the life of an infrastructure asset. Asset management systems provide an effective platform for monitoring the condition or performance of infrastructure assets throughout their life-cycle. As such, these TAM systems would be an effective platform for incorporating the risks associated with such infrastructure.

Table 1. Limit-states, Limit Events, and Expected Performance Goals of Constructed Facilities (4)

Limit state	Life-cycle utility, functionality, sustainability	Serviceability and durability	Life safety and stability of failure	Substantial safety at conditional limit states
Limit events	• Environmental impacts and sustainability • Societal impacts • Functionality throughout the life cycle • Financing mechanisms for initial *and* life-cycle costs • Operational capacity, safety, efficiency, flexibility, and security • Feasibility of construction, protection, and preservation aesthetics	• Excessive: displacements, deformations, shifts • Deterioration • Local damage • Vibrations • Lack of durability (Special limit state that should govern aspects of global design, detailing, materials, and construction)	• Excessive movements, settlements, geometry changes • Material failure • Fatigue • Local and member stability failure • Stability of failure(Incomplete and premature collapse mechanisms without adequate deformability and hardening) • Undesirable (sudden, brittle) failure mode(s)	• Lack of multiple escape routes in buildings • Lack of post-failure resiliency, leading to progressive collapse of buildings, bridges • Cascading failures of interconnected infrastructure systems • Failures of infrastructure elements critical for emergency response, medical, communication, water, energy, transportation, logistics, command, and control
Goals	• Constrained multi-objective function for integrated asset management (Functions relating to operations, security, and life-cycle cost)	• Constrained multi-objective function for integrated asset management (Functions relating to operations, security, and life-cycle cost)	• Multi-hazards risk management (Assurance of life safety and quick recovery of operations during days and months following an extreme event)	• Disaster response planning, and emergency management (protection of escape routes, evacuation, search and rescue needs, minimizing casualties, and economic recovery within years)

2.4 Risk Concepts

Risk is typically part of every individual's daily decision-making process. Risk-based decision making, however, suggests a different concept. This terminology, risk-based approaches to decision making, typically describes a systematic process that evaluates uncertainties, develops policies based on these uncertainties, and addresses the possible consequences of these policies (1). Risk-based decision making is not a simple undertaking. Risk is defined as the probability that a negative event occurs, along with the consequences of this negative event ((1) (16)).

Although closely related to risk, uncertainty carries a different meaning. Uncertainty is an inherent component of the decision-making process when choices are made based on incomplete knowledge (16). Decision makers often do not have complete knowledge of every facet of every decision; some level of uncertainty is present in nearly all decision making. This type of uncertainty is generally termed subjective uncertainty, contrasted with objective uncertainty arising from the randomness of systems, which is irreducible ((17) (18)).

In terms of infrastructure assets, uncertainty arises from both the randomness of events and sources of error. Three primary sources of error for infrastructure assets are data errors, forecasting errors, and modeling errors. Data errors are due to measurement error or simple human error. These types of errors can be measured through the use of statistical techniques and can be reduced by collecting more complete historical data. Forecasting errors relate to the uncertainty associated with future events. There are limitations on the ability to decrease forecasting errors since it is not possible to predict, with certainty, future events. Model errors are a result of the difference between observed or real-world values and model estimates. Since it is almost impossible to represent the complexity of actual conditions with one hundred percent accuracy in a mathematical model, there are also limitations on the extent to which model errors can be reduced (16). Various studies have shown forecasting uncertainties are relatively larger than model and other data uncertainties (see for example (19) (20)).

2.4.1 Risk Assessment and Risk Management

At first, risk assessment and risk management may appear to be similar, or maybe even interchangeable; but they are distinct. Risk assessment refers to the scientific process of measuring risks in a quantitative and empirical manner ((1) (16)). Risk management is a qualitative process that involves judging the acceptability of risks (1) within applicable legal, political, social, economic, environmental, and engineering considerations (16). The literature suggests that agencies, both public and private, that adequately address risk in their activities will be successful leaders in their respective fields (1).

Risk assessment and risk management are elements of nearly all engineered systems. For example, a building is designed to withstand greater than average wind loads, otherwise a building would topple each time there was a strong wind gust. It is rare that transportation infrastructure suddenly and unexpectedly fails; a testament to the civil engineering profession. The public trusts that the roads and bridges will not fail unexpectedly. However, there are catastrophes, such as the collapse of the Interstate 35W bridge in Minneapolis in 2007. Thirteen people were killed and over one hundred persons injured (21).

Most would consider this sort of catastrophic failure to be unacceptable. However, making sure that every possible failure contingency is incorporated into design is infeasible or possibly too costly. Decision makers must therefore determine an acceptable level of risk. This acceptable level of risk is often influenced by public perceptions of risk. Society perceives certain risks at different levels. For example, the risk of a traffic accident is far greater than the risk of an earthquake, but society is more willing to tolerate the risk of a traffic accident than the risk of a bridge failure due to natural events (20). This indicates the subjective nature of risk management. A risk assessment of the I-35W bridge at the time prior to its collapse could have quantitatively measured the risk of failure of the bridge; risk management actions would have determined appropriate actions to reduce or otherwise manage the existing risks. The failure of roadways and bridges in the Gulf Coast during Hurricane Katrina would be considered catastrophic by most. In anticipation of future storms and a rise in sea level, several bridges in the Gulf Coast area have already been reconstructed at higher elevations (22).

An FHWA hydraulic engineering circular highlighted the fact that 60,000 miles of highway nationwide lie within the Federal Emergency Management Agency's (FEMA) 100-year floodplain (23). This circular also points out that more than 1,000 bridges may be vulnerable to failure modes that have been associated with recent coastal storms such as Hurricane Katrina.

These examples are cited to illustrate some of the risks associated with transportation infrastructure. It is possible to mitigate some of these risks through the use of proper risk assessment and risk management techniques. Given that many transportation agencies have asset management systems, it seems that these systems would provide a strategic platform for incorporating a risk-oriented approach into the investment decision-making process. Figure 3 shows a proposed risk assessment framework for the investment decision-making process, with the last step of this framework being risk management, which is done by the decision maker.

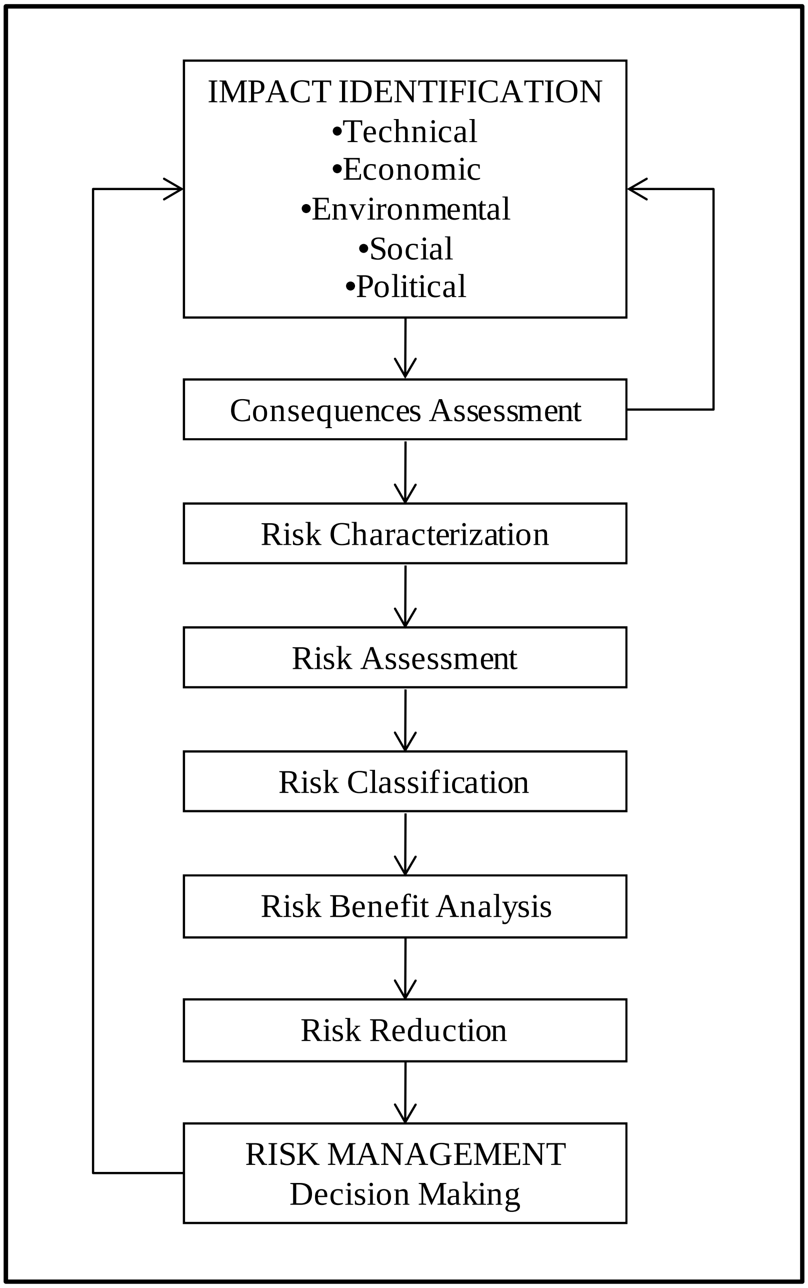

Figure 3. A framework for investment decision making under risk and uncertainty (16)

2.5 Risk Applications in Transportation Asset Management

The number of examples of risk applications in TAM is increasing in the literature. These applications use various methodologies to predict infrastructure asset performance while also addressing uncertainties. Several risk applications utilize methodologies for incorporating uncertainties in project prioritization, while other methodologies use risk as an investment decision-making criterion. The following sections describe a number of applications of risk in TAM systems.

2.5.1 Performance-Based Asset Management Framework

Atkan and Moon (20) emphasize the importance of performance monitoring in an effective asset management system. They present specific steps that are necessary for performance-based asset management. In their asset management framework, prioritization is driven by the risk of failure, or non-performance. The first step is to gather all relevant stakeholders so they can determine a definition for infrastructure performance that is based on societal, cultural, and technical values. (Technical values should be included since stakeholders developing societal and cultural values may not be able to articulate technical values. The technical agency should be responsible for developing these technical values, which are a critical component of infrastructure performance.)

Next, an organization should determine the geographic and organizational boundaries of the infrastructure assets in a system that are interconnected and interdependent. Performance requirements should then be established at the network, regional, and local levels for different infrastructure types. Performance requirements that are established at the network level can also be used at the regional and local levels. The funding that is available at the network, regional, and local levels should also be determined. Infrastructure should next be identified and documented (e.g. using geographic information system, or GIS tools) at least at the regional level.

Asset performance requirements should be specific to different groups or classes of assets. For example, roadway asset groups may include users, traffic flows, pavements, and bridges. However, the performance of different groups of assets should be related to one another, e.g., determining how bridge performance affects pavement performance (if the condition of a bridge requires that loads be restricted then the loads experienced on the roadways approaching the bridge will be affected). Organizational resources, such as knowledge, experience, core personnel, and buildings, can also be considered an asset group. Data related to the current condition and performance of assets in each asset group should be collected.

Once the preceding steps have been completed, the system should be tested in a way that allows for the identification of the most critical factors that affect system-wide performance. Once this has been done, resources can be strategically targeted at the identified critical factors. The final step involves considering the effects of the failure of one infrastructure asset on another, or the interdependencies among infrastructure assets (20). Ultimately, these steps will provide an asset management framework that identifies critical assets where the risk of non-performance of these assets is minimized.

2.5.2 Scenario Analysis, Sensitivity Analysis, and Uncertainty in TAMs

Scenario analyses, scenario planning methods, or scenario assessment represent a collection of tools that is used to evaluate risk and uncertainty ((15) (16)). One of the original applications was to identify plausible alternatives based on realistic future scenarios. This was done to develop and implement a plan that resulted in acceptable or superior conditions independent of which future scenario materialized, therefore accommodating prevailing uncertainties (24). Often, scenario analyses tools are used in the earlier stages of planning where transportation agencies consider several alternatives or scenarios and evaluate the possible outcomes of each alternative. First, alternative scenarios need to be defined and the different factors affecting each scenario, such as forecasted growth, congestion mitigation, economic development, and air quality impacts, need to be determined (15). Typically, some sort of scoring method is used to rank alternative scenarios. The alternative that provides the greatest benefit with minimal risk is usually the superior alternative. A scenario analysis serves as a means to evaluate different alternatives in project development. It is not a forecast, nor does it calculate the specific probability that a given event will occur (16). Scenario planning methods may prove to be the most useful for large-scale projects, given the potential for large negative consequences that may result from an alternative that is high-risk or worst-case (15).

A sensitivity analysis identifies the primary source of variability and can determine whether there are variables that contribute greater uncertainty to model results than others. Input parameters having the greatest impact on the variability of model results and that have insufficient data contribute significant uncertainty to model results. In 1983, the World Road Congress Committee on Economic and Finance examined approaches to a sensitivity analysis methodology. The Committee analyzed the uncertainties associated with data errors and with forecasting errors. Several input variables for a traffic model were considered and the range of possible values was determined for these variables. The Committee found that forecasting errors contributed significantly more to uncertainty than did data errors or model errors (16). This illustrates the fact that it is more difficult to predict accurately future events than to record data and develop models based on recorded historical data. While it would not be possible to eliminate uncertainty completely from forecasting, the input variables and model parameters that have the greatest impact on model outputs can be identified using sensitivity analysis.

A study by Amekudzi and McNeil (19) analyzed uncertainty in highway performance modeling at the federal level. Since 1968, the U.S. Congress has mandated that the FHWA produce a biennial highway investment needs estimate. The FHWA satisfies this mandate by producing a "Conditions and Performance" Report. Given the scope and scale of this effort, there is likely some uncertainty associated with the needs estimate, where this uncertainty can be grouped into two major categories, epistemic (non-variable phenomena in a real world system about which there is incomplete information) and aleatory (variable phenomena in a real world system).

This paper also examined the impacts of analysts' uncertainties about model inputs on model outputs through the use of Monte Carlo simulation techniques. The predominant source of model output variability in the Highway Economic Requirements System (HERS), the national highway investment model, was determined to be traffic forecasts. The approaches presented in this paper allow decision makers to determine changes in asset performance as a function of changes in input data (19). It is important for decision makers to be aware of which model inputs have the greatest uncertainty and the impact of these inputs on model outputs. A better understanding of uncertainty leads to better uses of the results of infrastructure performance models.

2.5.3 Project Prioritization, Project Programming, and Modeling

Program prioritization, also referred to as project optimization, is another component of the asset management process that typically incorporates some level of risk assessment. Prioritization techniques can be used at a number of different levels in the asset management process, ranging from a broader network level to a more specific project level. Project programming, or project selection, involves analyzing a range or combination of alternatives to determine which alternative(s) provide the best investment. This process usually involves scenario analysis, which presents decision makers with trade-offs among different alternatives (15).

There are different levels of project programming, with the most basic being simple subjective ranking based on judgment. More complex project programming processes use mathematical models to perform a comprehensive analysis, taking into account a variety of factors that influence project selection. Although these models are more complex and more difficult to develop and interpret, they provide a more optimal solution than more basic subjective project rankings (25).

The more effective project programming models will take into account user benefits, in addition to project costs. Using this methodology, and accounting for user benefits, allows for the most successful project optimization. These more advanced project programming models, however, are not in widespread use for the selection of new projects. More advanced project programming methods are widely used in a transportation agency’s maintenance activities (15). For example, an agency may monitor the condition of its pavement assets on a regular basis, and depending upon the condition and age of pavement, perform certain preventive maintenance activities, such as surface overlays.

Many transportation agencies have well-developed project programming techniques in place for maintenance activities, which include repair and rehabilitation efforts. Project programming methods for maintenance activities should answer the following three questions: what portions of a particular asset should be targeted for maintenance, repair, or rehabilitation? How can these areas be reconstructed or repaired, i.e. which particular alternatives apply to these areas? And when should these areas be reconstructed or maintained, i.e. what is the appropriate timing? (15). Given that there may be a large number of alternatives and that agencies often have different priorities for different projects, such as safety improvements or capacity expansion, it is often difficult to determine which is the best alternative or set of alternatives.

Comparing alternatives across different classes of assets, such as transit projects versus highway projects, is another area of interest for an alternatives analysis. Cross asset trade-off analysis presents additional challenges, such as standardizing the values of costs and benefits across asset classes (15). Focusing solely on comparing alternatives within the same asset class, such as roadway projects versus other roadway projects, can result in less-than-optimal resource allocation.

If uniform values can be established for roadway projects, bridge projects, and transit projects, then a more accurate cross-asset trade-off analysis can be performed. This would allow agencies to move away from dedicating funds specifically for highway improvements or bridge improvements, and permit agencies to determine what the optimal project is among a set of alternatives that encompasses multiple classes of assets. Where uniform values cannot be established, decision makers must consider the value tradeoffs that would occur from investing in different asset classes.

The aforementioned project programming methods typically incorporate some form of risk analysis. Several agencies, particularly those in other countries, use some form of risk assessment in their project prioritization methods ((2) (15) (26)).

Probabilistic models consider risk by taking uncertainty into account ((15) (16)). These models use statistical methods in which mathematical functions of decision-making factors are developed. Uncertainties of the model inputs are calculated using probability distributions and statistical parameters, such as coefficient of variation and mean. In order to conduct a probability-based risk assessment the uncertainties associated with the input variables, such as variation in user demand, need to be estimated.

Monte Carlo simulation techniques are one method to estimate model outputs. These simulations intend to capture the range of errors associated with each variable and typically result in a range of errors associated with the model outputs (16). Outputs of Monte Carlo simulations present decision makers with a range of possible outcomes, and the probabilities associated with each of these outcomes. Since the results of the simulation are presented in this manner, decision makers are made aware of the uncertainties associated with the outputs, and of which inputs have the greatest impact on model outputs.

Another method for predicting the future condition of infrastructure assets is the use of Markov models or Markov chains ((15) (27)). This method incorporates asset deterioration curves into its predictions. Markov models typically use historic data on asset condition, asset rehabilitation, asset repairs, and asset replacement. An asset element starts at its ideal condition, A if using an ordinal A to F rating system, such as the rating system using by the ASCE in its Report Card for America's Infrastructure (28). Through the course of its life an asset is likely to deteriorate from A to B and then B to C, and so on, with A representing an asset's optimal condition and F representing an asset's failed state. An asset will deteriorate from one condition state to another, for example, A to B, in a particular time-frame with some level of probability. This probability is referred to as a transition probability and can be obtained from a deterioration curve. Of course, over its lifetime the condition of an asset will continue to deteriorate, but various repair and rehabilitation policies can have a positive impact on asset condition. For example, a repair can move an asset from condition state C to condition state A. After a Markov model is developed based on historical condition state and repair and rehabilitation data, condition states of assets can be predicted at a given time period in the future (27).

An emerging risk assessment method called 'real options models' presents a new way of considering risk in the transportation analysis process (15). This approach accounts for the fact that while transportation projects are considered to have benefits, these predicted benefits are not always realized. In other cases, project results may be different from those that were predicted at the time when the investment decision was made. For this reason, it may be valuable to delay certain transportation investment decisions until additional information becomes available.

By doing this, decision makers may be able to decrease their risks. However, projects can lose value by waiting for new information to present itself. This potential lost value should be accounted for in calculations of project net present value. Since it may be more valuable to defer certain projects, it is useful when considering alternatives to consider those alternatives that can be phased in over time (29).

2.5.4 Risk Application Examples in TAMs

In AbouRizk and Siu's (27) work risk severity is defined as the probability of failure multiplied by the consequences of failure on the local community (27). This keeps with the traditional technical definition of risk as the probability of occurrence of a negative event and the severity of the consequences of this negative event (1). In order to determine accurately the probability of failure of a particular infrastructure asset, it is necessary to ascertain certain information about this asset. Some valuable pieces of information include the asset's replacement value, the physical attributes of the asset, such as age, dimensions, and quantity, and perhaps most importantly, the condition of the asset. The type and amount of information collected about infrastructure assets varies from agency to agency. For example, a transportation agency whose jurisdiction includes areas that are prone to rock slides will likely collect data about retaining walls, when rock-fall events occur, the severity of the rock-fall, etc.

The condition rating system used in the AbouRizk and Siu study is ASCE's ordinal scale for Infrastructure Report Cards: very good "A", good "B", fair "C", poor "D", or very poor "F" (27). In their study (27), these alphabetical grades are converted to a numerical rating from 1(F) to 5(A), with 5 being the best. Based on this system, estimates for expected failure of assets are determined by multiplying the elements of an asset in a certain condition by the probability of failure of the element, and summing the elements in each condition state. A sample equation is shown below (27):

$$E(L) = E(L_A) + E(L_B) + E(L_C) + E(L_D) + E(L_F)$$

where

$$E(L_j)=\text{Probability(asset failing while in condition j)x(\# of elements in condition j)}$$

This methodology has its limitations, as the ASCE condition rating system tends to be very subjective. The next step after determining the expected failure of an asset is determining the impact of failure of the asset, and the product of these two values is the risk severity of an asset. Determining the impact of asset failure is also somewhat subjective in nature, and will vary depending on what risk factors an agency considers to have most impact. AbouRizk and Siu (27) provide an example from the City of Edmonton that uses five areas to measure impact of failure and assigns the following weights (in parentheses) to each area: safety and public health (33%), growth (11%), environment (20%), monetary value required to replace an infrastructure element (20%), and services to people (16%). As these impact areas and their weights demonstrate, the impact of failure relates to the values of the communities that an agency serves.

Once the expected failure of an asset and the impact of failure are determined, the risk severity can be calculated as the product of the two values. AbouRizk and Siu (27) define risk severity zones as shown in Table 2. Once again, the specified risk severity zones show the subjective nature of both the expected failure of an asset and the impact of failure.

Table 2. Sample Risk Severity Zones (27)

Zone	Description
Acute	An *acute* level of severity is one in which both the expected failure and the impact of each unit of failure are intolerably high. At this level, there is the potential for loss of life if an asset fails combined with a high likelihood that an element asset will fail.
Critical	If the asset is deemed to be at a *critical* level of risk, then either the expected failure will be high and the impact substantial or the impact of an asset's failure will be devastating and the probability of failure still moderate.
Serious	Assets with a *serious* level of risk may have severe or substantial levels of impact; however, these tend to be combined with a low level of expected failure. As such, assets at this level of risk will require attention, yet their needs do not necessarily require immediate rehabilitation or repair.
Important	An asset considered to be at an *important* level of risk corresponds to a situation where the levels of expected failure and impact can be addressed in keeping with a municipality's strategic approach. An important level of risk has been anticipated for most elements.
Acceptable	The *acceptable* level of risk represents a situation in which the combined expected failure and level of impact are manageable.

In light of the 2007 collapse of the I-35W bridge in Minneapolis there has been increasing interest in incorporating risk into transportation asset management as these systems relate to bridge management. Cambridge Systematics, Inc., in collaboration with Lloyd's Register, a firm that specializes in risk management in the marine, oil, gas, and transportation sectors, developed a highway bridge risk model for 472,350 U.S. highway bridges, based on National Bridge Inventory (NBI) data (30).

The model developed in this paper used Lloyd's Register's Knowledge Based Asset Integrity (KBAI™) methodology, which was implemented in Lloyd's Register's asset management platform, Arivu™ (30). In this case, risk was defined as the product of failure multiplied by the consequence of failure. However, a failure was not defined as a catastrophic failure. Failure was defined as a bridge service interruption, which included emergency maintenance or repair, or some form of bridge use restriction. The model then predicted the mean time until a service interruption. A so-called highway bridge risk universe, as shown in Figure 4, can be visualized using the Arivu™ platform (30).

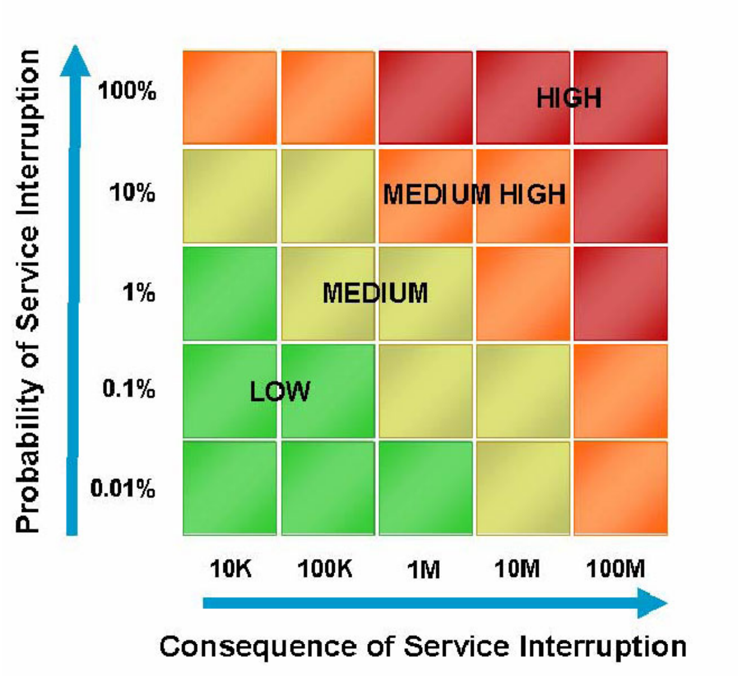

Figure 4. Highway bridge risk universe (30)

The probability of service interruption is calculated based on three risk units: deck, superstructure, and substructure. The probability that each one of these units would cause a service interruption is calculated, then these probabilities are added together to determine the overall probability that a bridge will experience a service interruption in the next year. Consequence of service interruption is determined using a number of bridge characteristics, such as ADT, percentage of trucks, detour distance, public perception, and facility served, that indicate the relative importance of the bridge to the network. It should be noted the consequence of service interruption is dimensionless and allows the user flexibility in that the characteristics used to determine the relative importance of the bridge can be modified (30). This model has a variety of potential applications. It can be used to prioritize bridge investments, to minimize risk, and prioritize bridge inspections.

An analysis of past NBI ratings to predict bridge system preservation needs was done for the Louisiana Department of Transportation and Development (LaDOTD) by Sun et al. (31). At the time, the LaDOTD was in the process of transitioning to the use of AASHTO's PONTIS bridge management software. PONTIS requires detailed element level bridge inspection data known as Commonly Recognized elements (CoRe). Collecting element level bridge inspection data takes years; so, an innovative approach was developed using readily available historic NBI data. Deterioration processes of three NBI elements were studied to develop element deterioration models. Bridge preservation plans and cost scenarios were developed using this readily available NBI data along with current LaDOTD practice and information (31). This illustrated that NBI data can be used to evaluate long-term performance of bridges under various budget scenarios.

For capital budgeting needs, decision makers often use rankings to prioritize investment in transportation projects. Several different methods can be used to prioritize bridge projects, including benefit cost ratio (BCR) analysis, the California Department of Transportation's Health Index (32), or the FHWA's Sufficiency Rating (SR) formula (33).

Dabous and Alkass (34) developed a method to rank bridge projects based on Multi-attribute Utility Theory (MAUT). Based on interviews with bridge engineers and transportation decision makers, the authors selected MAUT as the prioritization methodology since it allowed decision makers to include multiple and conflicting objectives, incorporating both qualitative and quantitative measurements. Utility functions were developed using the Analytical Hierarchy Process (AHP) and the Eigenvector approach. A case study was used to demonstrate the potential application of this method (34).

As mentioned earlier, many international agencies incorporate risk assessment into various components of their TAM processes. There are several local, state, and national level examples of risk applications in TAM systems. For example, the City of Edmonton places infrastructure assets, such as recreational facilities, buildings, parks, roads, drainage, traffic control devices, street lighting, and transit (27) into various risk severity zones.

As shown above, risk can be incorporated into TAM in various areas to achieve different objectives. For example, the framework developed by Cambridge Systematics can be used to prioritize bridge inspections or to minimize the risk of service interruption. Another feature of the frameworks highlighted above is that decision maker input is an important consideration. This is very important, because as mentioned in the international scan, risk assessment can be used as a way to inform and garner support from elected officials (2).

CHAPTER 3

METHODOLOGY

3.1 Background

The case study presented in this thesis utilizes data from the NBI for selected bridges in Georgia. Selected bridges are ranked based on utilities. This case study demonstrates the importance of using disaggregate versus aggregate data in prioritization where disaggregate data is available. In addition, the case study demonstrates the significance of incorporating uncertainty in cases where this data is available. Furthermore, this case study shows the impacts of data quality on investment prioritization, which highlights the importance of investing in the improvement of data collection techniques.

The NBI data is made available by the FHWA on its website in American Standard Code for Information Interchange (ASCII) format; this NBI data was available from 1992 through 2009 (35). Using the record format, which is also made available on the FHWA website (35), and the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges (33), this ASCII data was converted into Excel format using a script in the SPSS ® statistical analysis software.

The Georgia Department of Transportation (GDOT) uses an internally developed bridge prioritization formula as one of the inputs for allocating funds for bridge investment (36). This bridge prioritization formula is multi-criteria in nature and takes a range of factors of bridge condition and performance, as shown in Table 3, into consideration. GDOT assigns each bridge an overall score based on this formula. GDOT maintains a proprietary Bridge Information Management System (BIMS) that contains data elements for each state or locally owned bridge in Georgia. The data elements contained in the BIMS are identical to or based on the data elements in the NBI; each state is required to report NBI data elements annually to the FHWA.

Table 3. GDOT Bridge Prioritization Formula – Parameter Descriptions and Point Values (36)

Variable	Description	Point Values
HS	Inventory Rating	0, 13, 25, 35
ADT	Average Daily Traffic	1, 3, 6, 10, 15, 21, 27, 35
BYPASS	Bypass/detour length (Also accounts for posting, ADT, and % trucks)	0, 10, 18, 25
BRCOND	Bridge Condition – based on condition of deck, superstructure, and substructure	0, 10, 15, 20, 25, 30, 35, 40
Factor	Weighting Factor – based upon functional classification, i.e., interstate, defense, NHS	1.0, 1.3, 1.5, 1.8
TimbSUB	Timber Substructure	0, 2, 5 (state owned)
TimSUP	Timber Superstructure	0 or 2
TimbDECK	Timber Deck	0 or 2
POST	Bridge Posting	0 to 5
TEMP	Temporary Structure Designation	0 or 2
UND	Underclearance	0, 1, 2, 3, 4, 5, 6
FC	Fracture Critical	0 or 15
SC	Scour Critical	0, 1, 2, 3, 4, 5, 6
HMOD	Inventory Rating less than 15 tons for HMOD truck	0 or 5
Narrow	Based on number of travel lanes, shoulder width, length, and ADT	0 or 30

GDOT, similar to the LaDOTD, is in the process of collecting more detailed element level CoRe data (31). Without more detailed element level data, it is difficult to develop bridge deterioration models, especially at the project level. The analysis performed by Sun et. al. (31) developed deterioration matrices and used Markov chains to model bridge deterioration. Although this approach is feasible, it is more applicable at the network level. In their analysis, Sun et. al. (31) grouped bridges into four major categories: concrete, steel, pre-stressed concrete, and timber, and then developed deterioration matrices for each bridge group. Since individual bridges are being ranked using the GDOT data, rather than groups of bridges, it as deemed more appropriate to use a methodology that applies Multiple Criteria Decision Making (MCDM) principles, similar to that applied by Dabous and Alkass (34).

3.2 Prioritization Scenario Attributes

GDOT's bridge prioritization formula incorporates elements of MCDM. Certain variables or attributes are scored and weighted based upon their relative levels of importance. Four attributes in the formula are weighted. This indicates that these attributes, HS, ADT, BYPASS, and BRCOND, are likely considered more important to decision makers at GDOT than the rest of the attributes. Table 4 shows the attributes used in the prioritization scenarios and their associated NBI data items. Seven bridges were selected for analysis for the case study. The attributes in Table 4 were selected for analysis since the other attributes are relatively much less important or unimportant for the seven case study bridges, i.e., these attributes do not contribute to the scoring of a bridge.

Table 4. Attributes and Associated NBI Data Items

Attribute	NBI Data Item (s)
HS	66
ADT	29
BYPASS	19
BRCOND	58 (Deck) 59 (Superstructure) 60 (Substructure)
HISTORIC	Based on: 58, 59, 60
POST	70
TEMP	103
FC	92A
SC	113
Narrow	Based on: 28A (# of lanes) 29 (ADT) 49 (length) 51 (width)

HS (NBI item 66) represents the inventory rating of a bridge, also known as the capacity rating. This measures the live load that can safely utilize the bridge and is reported to the nearest tenth of a metric ton (33), which was then converted to short tons. ADT (NBI item 29) is the Average Daily Traffic. BYPASS is the bypass length reported in kilometers, which was converted to miles. BRCOND is comprised of deck (NBI item 58), superstructure (NBI item 59), and substructure (NBI item 60) condition ratings. These conditions ratings are coded from 0 to 9, with 0 being failed condition and 9 being excellent condition (33). Scenarios that used aggregate BRCOND data used the average of deck, superstructure, and substructure condition ratings whereas scenarios that used disaggregate BRCOND data did not average the 3 condition ratings.

HISTORIC is based on past bridge condition data (NBI items 58, 59, and 60). Past bridge condition data was available for the selected case study bridges from 1992 through 2009. Although 18 years of historic NBI bridge condition data is not enough to develop a detailed deterioration model, it is sufficient to identify bridges that are deteriorating at a more rapid rate than others. The slopes of the historic bridge condition data were calculated in Microsoft ® Excel based on the linear regression lines for the deck, superstructure, and substructure condition rating data plotted versus time. Average slope is simply the average of the slopes of the condition data plotted against time for the deck, superstructure, and substructure, respectively. Only bridges with negative average slopes, i.e., bridges that worsened in condition rating over time, received an attribute value. The attribute value of these bridges is the absolute value of the slope. The normalized attribute value is based on the largest negative slope from the deterioration gradients. Scenarios that used aggregate HISTORIC data averaged the slopes of the condition ratings for deck, superstructure, and substructure whereas scenarios that used disaggregate condition rating data did not average the slopes of the 3 condition ratings.

POST is based on a comparison of the maximum legal load in Georgia to loads permitted under a bridge's operating rating (NBI item 64). If the maximum legal load exceeds the operating rating then posting is required. The degree to which the operating rating is less than the maximum legal load determines how to code this data item from 0 to 5, with 5 meaning no posting is required and 0 meaning the operating rating is 39.9% or more below the maximum legal load (33).

'Narrow' is based on the number of travel lanes on the bridge (NBI item 28A), the bridge's ADT (NBI item 29), the bridge's length (NBI item 49), and the bridge's width (NBI item 51). The bridge's length and width are reported to the nearest tenth of a meter and were converted to feet (33). A bridge is considered narrow if its shoulders are less than 3 feet (assuming lanes are 12 feet wide), the total length of the bridge is greater than 400 feet, and the bridge's ADT is greater than 2000 (36).

TEMP (NBI item 103) is used when temporary structures or conditions exist. It is coded blank if not applicable and "T" if temporary structures or conditions exist (33). FC (NBI item 92A) is coded Y for the first digit if critical features, whose failure would likely cause the bridge or a portion of the bridge to collapse, need special inspections or special emphasis during inspections (33). SC (NBI item 113) identifies the current status of the bridge as it relates to its vulnerability to scour. This item is coded from 0 to 9, T, U, or N. However, only codes 0 to 4 indicate scour criticality, with 0 being the most severe, i.e., a bridge is scour critical and has failed (33).

3.3 Ranking Method

Similar to the method developed by Dabous and Alkass (22), the ranking method developed is based on four tiers of elements. The first level consists of the overall goal of cost-effective resource allocation. The second level consists of the objectives required to achieve that goal:

- Maximize condition preservation
- Minimize extent of disruption
- Minimize critical failures
- Minimize restrictions

The third level consists of the criteria or attributes used to evaluate the objectives:

- BRCOND
- HS
- ADT
- BYPASS
- FC
- SC
- TEMP
- Narrow
- Post

The last level consists of the alternatives or utilities for each bridge. Figure 5 shows the structure of the tiered approach used in this case study. Through the use of an MCDM scoring method that uses the simple additive weighting (SAW) method, each attribute is assigned a weight and a score. Both the weight and score of an attribute vary between 0 and 1. This is achieved by normalizing all scores and weights that are not normalized. The scoring method used for each attribute depends on whether the attribute is a benefit attribute, i.e., higher is better, or a cost attribute, i.e., lower is better. Table 5 shows whether an attribute is a cost attribute or a benefit attribute.

Table 5. Attribute Identification: Cost or Benefit

Attribute	NBI Data Item (s)
HS	Benefit
ADT	Cost
BYPASS	Cost
BRCOND	Benefit
HISTORIC	Cost
POST	Benefit
TEMP	Cost
FC	Cost
SC	Benefit
Narrow	Cost

Four prioritization scenarios are presented in this case study. The first scenario incorporates aggregate condition data and does not incorporate past bridge condition data. Scenario 2 incorporates disaggregate condition data without past bridge condition data. The third and fourth scenarios both incorporate uncertainty and performance risk by including past bridge condition. Scenario 3 incorporates aggregate past bridge condition in addition to aggregate snapshot, or current, bridge condition. The fourth scenario incorporates disaggregate snapshot bridge condition and disaggregate past bridge condition.

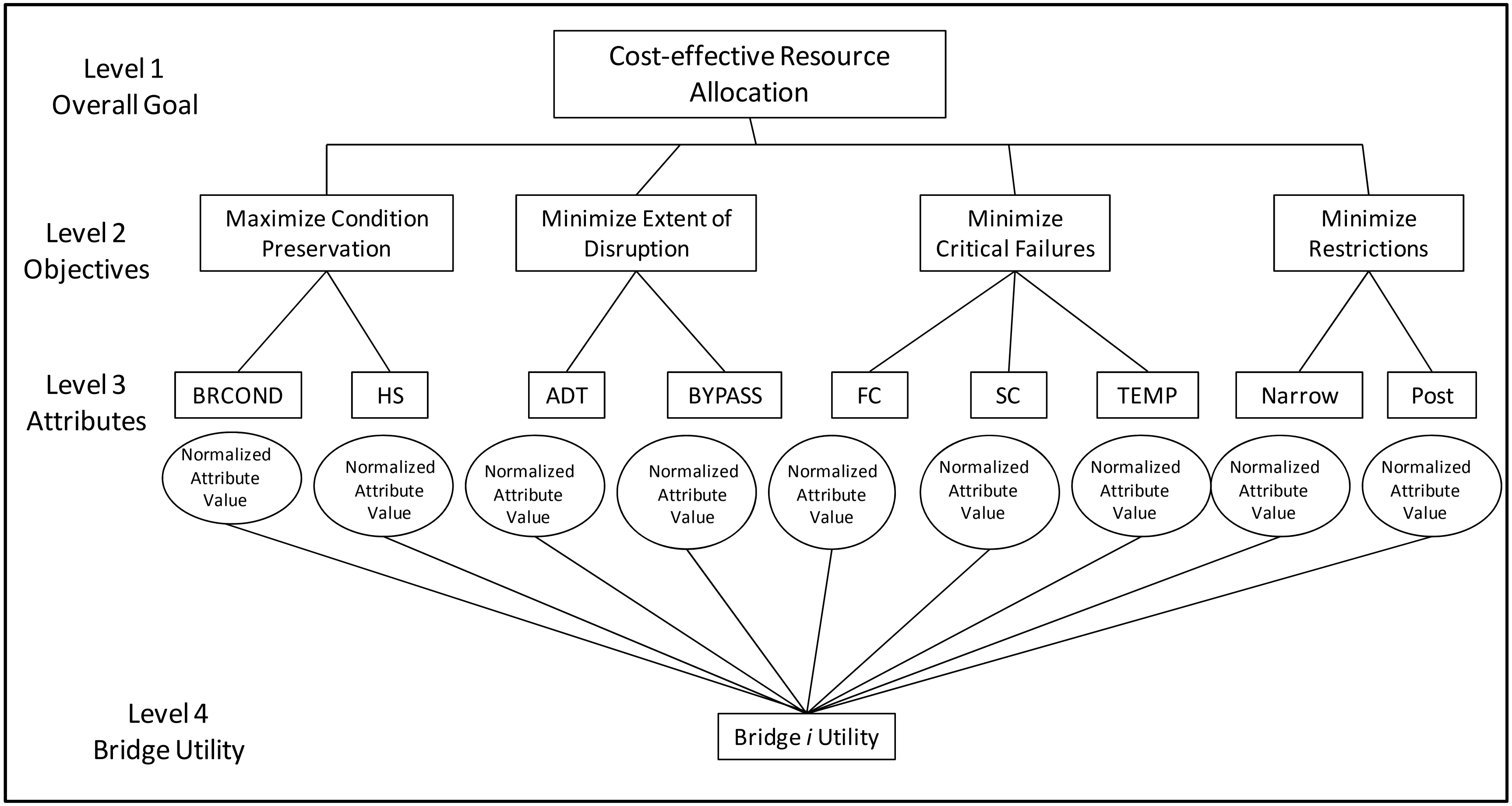

Figure 5. Structure of the hierarchy process used the prioritization method (31)

CHAPTER 4

ANALYSIS

4.1 Background

The weights assigned to each bridge in the ranking method are dependent upon the “Factor” assigned to each bridge in GDOT’s formula (36). There are four possible factors: 1.0, 1.3, 1.5, or 1.8. Table 6 shows how the weighting factor is determined for each bridge. Based on the factors, normalized attribute weights, i.e. on the scale of 0 to 1, were calculated for each scenario.

Table 6. Weighting Factor Descriptions

Factor	Description
1.8	Interstate routes
1.5	National Highway System and Defense Highway routes
1.3	Routes with ADT > 10,000
1.0	Routes not in the preceding 3 categories, i.e., factors of 1.8, 1.5, or 1.3

4.2 Scenario 1

The first scenario utilized aggregate data for bridge condition. As mentioned in Chapter 3, aggregate bridge condition data was estimated by averaging the condition ratings of the deck, superstructure, and substructure condition ratings. The weights used in scenario 1 are shown in Table 7. Table 8 shows the attribute values, their respective normalized values, and each bridge’s overall utility.

Table 7. Attribute Weights for Scenario 1

Factor of 1.8								
HS	ADT	BYPASS	BRCOND	POST	TEMP	FC	SC	Narrow
0.15	0.15	0.15	0.15	0.08	0.08	0.08	0.08	0.08
Factor of 1.5								
HS	ADT	BYPASS	BRCOND	POST	TEMP	FC	SC	Narrow
0.14	0.14	0.14	0.14	0.09	0.09	0.09	0.09	0.09
Factor of 1.3								
HS	ADT	BYPASS	BRCOND	POST	TEMP	FC	SC	Narrow
0.13	0.13	0.13	0.13	0.10	0.10	0.10	0.10	0.10
Factor of 1								
HS	ADT	BYPASS	BRCOND	POST	TEMP	FC	SC	Narrow
0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

Table 8. Scenario 1 Attributes, Normalized Attribute Values, and Bridge Utilities

Bridge ID	251-0026-0		117-0019-0		269-0020-0		255-0017-0		185-0010-0		021-0123-0		021-0124-0	
Criteria	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val
HS	12.90	0.5909	18.85	0.8636	12.90	0.5909	12.90	0.5909	12.90	0.5909	21.83	1.0000	21.83	1.0000
ADT	5200	0.4000	15960	0.1303	2080	1.0000	6590	0.3156	3170	0.6562	44430	0.0468	44430	0.0468
BYPASS	13.67	0.0455	6.835	0.0909	22.99	0.0270	9.942	0.0625	16.78	0.0370	0.6214	1.0000	0.6214	1.0000
BRCOND	5	0.6845	5.667	0.7738	4.667	0.6310	7	0.9524	5.667	0.7738	6	0.8214	6.3333	0.8690
POST	3	0.6000	4	0.8000	3	0.6000	3	0.6000	3	0.6000	5	1.0000	5	1.0000
TEMP	2	0.0000	0	1.0000	2	0.0000	2	0.0000	2	0.0000	0	1.0000	0	1.0000
FC	0	1.0000	0	1.0000	0	1.0000	0	1.0000	15	0.0000	0	1.0000	0	1.0000
SC	5	0.5556	9	1.0000	9	1.0000	9	1.0000	9	1.0000	3	0.3333	3	0.3333
Narrow	0	1.0000	30	0.0000	30	0.0000	0	1.0000	30	0.0000	30	0.0000	30	0.0000
Utility	0.52		0.61		0.54		0.59		0.41		0.70		0.70	

4.3 Scenario 2

Scenario 2 utilized disaggregate bridge condition data, i.e., bridge condition ratings for the deck, superstructure, and substructure were used individually. Instead of one attribute for bridge condition rating, there are now three, which altered the weights used in scenario 2. Table 9 shows the weights used in scenario 2 and Table 10 shows the attribute values, their respective normalized values and each bridge's overall utility.

Table 9. Attribute Weights for Scenario 2

Factor of 1.8										
			BRCOND							
HS	ADT	BYPASS	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.15	0.15	0.15	0.03	0.06	0.06	0.08	0.08	0.08	0.08	0.08
Factor of 1.5										
			BRCOND							
HS	ADT	BYPASS	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.14	0.14	0.14	0.03	0.05	0.05	0.09	0.09	0.09	0.09	0.09
Factor of 1.3										
			BRCOND							
HS	ADT	BYPASS	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.13	0.13	0.13	0.03	0.05	0.05	0.10	0.10	0.10	0.10	0.10
Factor of 1										
			BRCOND							
HS	ADT	BYPASS	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.11	0.11	0.11	0.02	0.04	0.04	0.11	0.11	0.11	0.11	0.11

Table 10. Scenario 2 Attributes, Normalized Attribute Values, and Bridge Utilities

Bridge ID	**251-0026-0**		**117-0019-0**		**269-0020-0**		**255-0017-0**		**185-0010-0**		**021-0123-0**		**021-0124-0**	
Criteria	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val
HS	12.90	0.5909	18.85	0.8636	12.90	0.5909	12.90	0.5909	12.90	0.5909	21.83	1.0000	21.83	1.0000
ADT	5200	0.4000	15960	0.1303	2080	1.0000	6590	0.3156	3170	0.6562	44430	0.0468	44430	0.0468
BYPASS	13.67	0.0455	6.835	0.0909	22.99	0.027	9.942	0.0625	16.78	0.0370	0.6214	1.0000	0.6214	1.0000
BRCOND - Deck	4	0.5714	5	0.7143	4	0.5714	6	0.8571	5	0.7143	6	0.8571	7	1.0000
BRCOND - Sup	5	0.6250	6	0.7500	6	0.7500	8	1.0000	6	0.7500	6	0.7500	6	0.7500
BRCOND - Sub	6	0.8571	6	0.8571	4	0.5714	7	1.0000	6	0.8571	6	0.8571	6	0.8571
POST	3	0.6	4	0.8	3	0.6	3	0.6	3	0.6	5	1	5	1
TEMP	2	0	0	1	2	0	2	0	2	0	0	1	0	1
FC	0	1	0	1	0	1	0	1	15	0	0	1	0	1
SC	5	0.5556	9	1	9	1	9	1	9	1	3	0.3333	3	0.3333
Narrow	0	1	30	0	30	0	0	1	30	0	30	0	30	0
Utility	0.52		0.61		0.54		0.59		0.41		0.70		0.70	

4.4 Scenario 3

The third scenario incorporated uncertainty, and performance risk is included as an attribute that accounts for past bridge condition, HISTORIC. The inclusion of an additional attribute altered the weights used, which are shown in Table 11. Scenario 2 utilized aggregate data for both snapshot (current) bridge condition and past bridge condition. As mentioned in Chapter 3, only bridges that worsened in condition rating over this time-period, i.e., bridges with negative average slopes, received an attribute value.

The attribute value of these bridges is the absolute value of the slope. The normalized attribute value is based on largest negative slope from the deterioration gradients. For the third scenario the average slope values, i.e., aggregate data, were used to determine the attribute values. The values of the slopes for each bridge are shown in Table 12. Table 13 shows the attribute values, their respective normalized values and each bridge's overall utility.

Table 11. Attribute Weights for Scenario 3

Factor of 1.8									
HS	ADT	BYPASS	BRCOND	HISTORIC	POST	TEMP	FC	SC	Narrow
0.13	0.13	0.13	0.13	0.13	0.07	0.07	0.07	0.07	0.07
Factor of 1.5									
HS	ADT	BYPASS	BRCOND	HISTORIC	POST	TEMP	FC	SC	Narrow
0.12	0.12	0.12	0.12	0.12	0.08	0.08	0.08	0.08	0.08
Factor of 1.3									
HS	ADT	BYPASS	BRCOND	HISTORIC	POST	TEMP	FC	SC	Narrow
0.11	0.11	0.11	0.11	0.11	0.09	0.09	0.09	0.09	0.09
Factor of 1									
HS	ADT	BYPASS	BRCOND	HISTORIC	POST	TEMP	FC	SC	Narrow
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Table 12. Slopes of Past Bridge Condition Ratings and HISTORIC Attribute Values and Normalized Attribute Values

Slopes											
Deck	Att	Norm Val	**Superstructure**	Att	Norm Val	**Substructure**	Att	Norm Val	**Average Slope**	Att	Norm Val
-0.17	0.1734	0.1154	**-0.04**	0.0361	0.5537	**-0.06**	0.0578	0.3461	**-0.27**	0.2673	0.0748
-0.04	0.0413	0.4845	**-0.06**	0.0578	0.3461	**0.00**	0.0000	1.0000	**-0.10**	0.0991	0.2019
-0.08	0.0846	0.2363	**-0.13**	0.1290	0.1550	**-0.19**	0.1930	0.1036	**-0.41**	0.4066	0.0492
0.00	0.0000	1.0000	**0.17**	0.0000	1.0000	**0.08**	0.0000	1.0000	**0.24**	0.0000	1.0000
0.00	0.0000	1.0000	**0.08**	0.0000	1.0000	**0.11**	0.0000	1.0000	**0.19**	0.0000	1.0000
-0.08	0.0795	0.2517	**0.00**	0.0000	1.0000	**-0.03**	0.0341	0.5873	**-0.11**	0.1135	0.1762
0.00	0.0000	1.0000	**-0.08**	0.0836	0.2393	**-0.02**	0.0200	1.0000	**-0.10**	0.1011	0.1978

Table 13. Scenario 3 Attributes, Normalized Attribute Values, and Bridge Utilities

Bridge ID	251-0026-0		117-0019-0		269-0020-0		255-0017-0		185-0010-0		021-0123-0		021-0124-0	
Criteria	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val
HS	12.90	0.591	18.85	0.864	12.90	0.591	12.90	0.591	12.90	0.591	21.83	1.000	21.83	1.000
ADT	5200	0.400	15960	0.130	2080	1.000	6590	0.316	3170	0.656	44430	0.047	44430	0.047
BYPASS	13.67	0.046	6.835	0.091	22.99	0.027	9.942	0.063	16.78	0.037	0.6214	1.000	0.6214	1.000
BRCOND	5	0.685	5.667	0.774	4.667	0.631	7	0.952	5.667	0.774	6	0.821	6.333	0.869
HISTORIC	0.267	0.075	0.0991	0.202	0.4066	0.049	0.0000	1.000	0.0000	1.000	0.1135	0.176	0.1011	0.198
POST	3	0.600	4	0.800	3	0.600	3	0.600	3	0.600	5	1.000	5	1.000
TEMP	2	0.000	0	1.000	2	0.000	2	0.000	2	0.000	0	1.000	0	1.000
FC	0	1.000	0	1.000	0	1.000	0	1.000	15	0.000	0	1.000	0	1.000
SC	5	0.556	9	1.000	9	1.000	9	1.000	9	1.000	3	0.333	3	0.333
Narrow	0	1.000	30	0.000	30	0.000	0	1.000	30	0.000	30	0.000	30	0.000
Utility	0.47		0.56		0.49		0.64		0.47		0.63		0.64	

4.5 Scenario 4

Scenario 4 utilized disaggregate data for snapshot (current) bridge condition rating and also for past bridge condition rating. Once again, disaggregate meant that instead of using the average of deck, superstructure, and substructure, individual attributes were used for deck, superstructure, and substructure. This altered the weights used in scenario 4 and these weights are shown in Table 14. In scenario 4 the individual deck, superstructure, and substructure slope values, i.e., disaggregate data, were used to determine the attribute values. The values of the slopes for each bridge are shown in Table 12. Table 15 shows the attribute values, their respective normalized values and each bridge's overall utility.

Table 14. Attribute Weights for Scenario 4

Factor of 1.8													
			DISAGGBRCOND			DISAGGHISTORIC							
HS	ADT	BYPASS	Deck	Sup	Sub	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.13	0.13	0.13	0.03	0.05	0.05	0.03	0.05	0.05	0.07	0.07	0.07	0.07	0.07
Factor of 1.5													
			DISAGGBRCOND			DISAGGHISTORIC							
HS	ADT	BYPASS	Deck	Sup	Sub	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.12	0.12	0.12	0.02	0.05	0.05	0.02	0.05	0.05	0.08	0.08	0.08	0.08	0.08
Factor of 1.3													
			DISAGGBRCOND			DISAGGHISTORIC							
HS	ADT	BYPASS	Deck	Sup	Sub	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.11	0.11	0.11	0.02	0.05	0.05	0.02	0.05	0.05	0.09	0.09	0.09	0.09	0.09
Factor of 1													
			DISAGGBRCOND			DISAGGHISTORIC							
HS	ADT	BYPASS	Deck	Sup	Sub	Deck	Sup	Sub	POST	TEMP	FC	SC	Narrow
0.10	0.10	0.10	0.02	0.04	0.04	0.02	0.04	0.04	0.10	0.10	0.10	0.10	0.10

Table 15. Scenario 4 Attributes, Normalized Attribute Values, and Bridge Utilities

Bridge ID	251-0026-0		117-0019-0		269-0020-0		255-0017-0		185-0010-0		021-0123-0		021-0124-0	
Criteria	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val	Att	Norm Val
HS	12.90	0.591	18.85	0.864	12.90	0.591	12.90	0.591	12.90	0.591	21.83	1.000	21.83	1.000
ADT	5200	0.400	15960	0.130	2080	1.000	6590	0.316	3170	0.656	44430	0.046	44430	0.047
BYPASS	13.67	0.046	6.835	0.091	22.99	0.027	9.942	0.063	16.78	0.037	0.6214	1.000	0.6214	1.000
BRCOND - Deck	4	0.571	5	0.714	4	0.571	6	0.857	5	0.714	6	0.857	7	1.000
BRCOND - Sup	5	0.625	6	0.750	6	0.750	8	1.000	6	0.750	6	0.750	6	0.750
BRCOND - Sub	6	0.857	6	0.857	4	0.571	7	1.000	6	0.857	6	0.857	6	0.857
HISTORIC - Deck	0.1734	0.115	0.0413	0.485	0.0846	0.236	0	1.000	0	1.000	0.0795	0.251	0	1.000
HISTORIC - Sup	0.0361	0.554	0.0578	0.346	0.129	0.155	0	1.000	0	1.000	0	1.000	0.0836	0.239
HISTORIC - Sub	0.0578	0.346	0	1.000	0.193	0.104	0	1.000	0	1.000	0.0341	0.587	0.02	1.000
POST	3	0.600	4	0.800	3	0.600	3	0.600	3	0.600	5	1.000	5	1.000
TEMP	2	0.000	0	1.000	2	0.000	2	0.000	2	0.000	0	1.000	0	1.000
FC	0	1.000	0	1.000	0	1.000	0	1.000	15	0.000	0	1.000	0	1.000
SC	5	0.556	9	1.000	9	1.000	9	1.000	9	1.000	3	0.333	3	0.333
Narrow	0	1.000	30	0.000	30	0.000	0	1.000	30	0.000	30	0.000	30	0.000
Utility	0.51		0.61		0.50		0.64		0.47		0.69		0.70	

CHAPTER 5

RESULTS

5.1 Background

As mentioned in Chapter 3, GDOT uses an internally developed prioritization formula as one of the inputs for ranking bridges for investment (36). This formula assigns a score to each bridge that the Department uses to allocate investments. For comparative purposes, Table 16 shows the Department's normalized rankings for the 7 bridges selected for this case study. It should be noted that GDOT assigns a point score to each bridge when developing its bridge rankings.

The Department's rankings are developed based on point scores, whereas the rankings developed for this case study utilized actual data from the NBI, with the exception of the TEMP and Narrow attributes, which are binary, i.e., the aforementioned conditions exist or do not exist. In the scenarios developed in this case study, actual data are used in the ranking criteria and as such, bridges with lower utility values rank higher, as opposed to scoring with points, in which case bridges with larger point values receive higher overall scores and priority.

Table 16. Normalized Rankings

Bridge ID	Normalized Score	Normalized Ranking	Factor Used
251-0026-0	0.52	3	1.5
117-0019-0	0.45	5	1.3
269-0020-0	0.61	2	1
255-0017-0	0.50	4	1.5
185-0010-0	0.67	1	1
021-0123-0	0.33	6	1.8
021-0124-0	0.33	6	1.8

5.2 Scenario 1 Results

As stated in Chapter 4, scenario 1 incorporates aggregate snapshot bridge condition data. The results of the rankings developed in the first scenario are shown below in Table 17. There is one difference between GDOT's normalized rankings and the rankings from the first scenario. The bridge that originally ranked third now ranks second, i.e., these two bridges switched places. These results suggest that using a point system, as opposed to actual data, does not always give the same results. Use of actual data can result in capturing more of the differences among the various alternatives for all the decision attributes being considered.

Table 17. Original Normalized Rankings Compared to Scenario 1 Rankings

Bridge ID	Normalized Score	Normalized Ranking	Factor Used	Scenario 1 Utility	New Ranking
251-0026-0	0.52	3	1.5	0.52	2
117-0019-0	0.45	5	1.3	0.61	5
269-0020-0	0.61	2	1	0.54	3
255-0017-0	0.50	4	1.5	0.59	4
185-0010-0	0.67	1	1	0.41	1
021-0123-0	0.33	6	1.8	0.70	6
021-0124-0	0.33	6	1.8	0.70	6

5.3 Scenario 2 Results

Scenario 2 incorporates disaggregate bridge condition data, i.e., bridge condition data for deck, superstructure, and substructure, as stated in Chapter 4. There are no differences in the utility values or rankings between scenarios 1 and 2. However, scenario 2 results in the same differences from the original ranking as scenario 1. Even though scenario 2 incorporates disaggregate (deck, superstructure, and substructure) data, the overall weight assigned to the three bridge condition attributes is the same as in scenario 1 (see Table 7 and Table 9), allowing for a comparison in the rankings between scenarios 1 and 2. The rankings developed in scenarios 1 and 2 are shown in Table 18.

This case study examines only seven bridges out of 17,000 listed in the NBI in Georgia in 2009 (35). This being the case, disaggregation of the bridge condition data into deck, superstructure, and substructure might well impact the overall rankings of many other bridges in the database, i.e. bridge rankings that are inclusive of all of the bridges in the NBI database in Georgia. Data aggregation can cause a loss of detail that can significantly impact the rankings. For example, a bridge with a very poor condition rating for its substructure may have a good condition rating for its deck and superstructure, resulting in a fair aggregate bridge condition rating. Decision-makers may find it useful to be aware of disaggregate condition data in terms of bridge project prioritization.

Table 18. Scenario 1 Rankings Compared with Scenario 2 Rankings

Bridge ID	Normalized Ranking	Factor Used	Scenario 1 Utility	Scenario 1 Ranking	Scenario 2 Utility	Scenario 2 Ranking
251-0026-0	3	1.5	0.52	2	0.52	2
117-0019-0	5	1.3	0.61	5	0.61	5
269-0020-0	2	1	0.54	3	0.54	3
255-0017-0	4	1.5	0.59	4	0.59	4
185-0010-0	1	1	0.41	1	0.41	1
021-0123-0	6	1.8	0.70	6	0.70	6
021-0124-0	6	1.8	0.70	6	0.70	6

5.4 Scenario 3 Results

The third scenario is the first of two scenarios, scenarios 3 and 4, that incorporated uncertainty and performance risk by accounting for past bridge condition. An additional attribute, HISTORIC, was included in scenario 3. Although this changed the weights assigned to each attribute (see Table 11), the factor used, i.e. the relative importance, of each attribute did not change, assuming that past bridge condition is equally as important as the HS, ADT, BYPASS, and BRCOND attributes. The rankings developed in scenarios 1 and 3 are shown in Table 19. These rankings demonstrate that incorporating past bridge condition, i.e., rate of bridge deterioration, can change the utility of a bridge and therefore change the prioritization of a bridge; all of the utilities and the rankings are different between scenarios 2 and 3.

Table 19 shows that accounting for uncertainty by incorporating bridge deterioration rather than simply treating bridge condition deterministically significantly changed the utilities and rankings for the case study bridges. It is also likely that incorporating this uncertainty on the overall bridge prioritization would result in a different outcome. The results of the prioritization outcomes are as good as the input data used for the exercise. Given that past condition data is easily obtainable, it can be incorporated into the prioritization exercise to refine the prioritization results.

Table 19. Scenario 2 Rankings Compared with Scenario 3 Rankings

Bridge ID	Normalized Ranking	Factor Used	Scenario 2 Utility	Scenario 2 Ranking	Scenario 3 Utility	Scenario 3 Ranking
251-0026-0	3	1.5	0.52	2	0.47	1
117-0019-0	5	1.3	0.61	5	0.56	3
269-0020-0	2	1	0.54	3	0.49	2
255-0017-0	4	1.5	0.59	4	0.64	5
185-0010-0	1	1	0.41	1	0.47	1
021-0123-0	6	1.8	0.70	6	0.63	4
021-0124-0	6	1.8	0.70	6	0.64	5

5.5 Scenario 4 Results

Scenario 4 also incorporated uncertainty and performance risk by incorporating past bridge condition. However, unlike scenario 3, which also incorporated past bridge condition, scenario 4 incorporated disaggregate snapshot (current) bridge condition as well as disaggregate past bridge condition. Although the weights for the attributes in scenario 4 are different from scenario 3 (see Table 11 and Table 14), the overall weights assigned to the snapshot bridge condition attributes and the past bridge condition attributes are the same as in scenario 3 so that meaningful comparisons can be made between scenarios 3 and 4.

Table 20 shows the rankings developed in scenarios 3 and 4. Disaggregation of both the snapshot and past bridge condition data significantly impacts the results of the rankings; all but one of the utilities are different between scenarios 3 and 4 and all but one of the rankings is different. This highlights the importance of incorporating disaggregate data where it is available. In addition, the result of data disaggregation between scenarios 3 and 4 has a more significant impact than data disaggregation between scenarios 1 and 2, in which there was no difference in utilities or rankings between the scenarios. This demonstrates the significance of incorporating both uncertainty in terms of bridge deterioration (versus deterministic, i.e., snapshot condition data) and disaggregate data. It is likely that incorporating uncertainty and disaggregate data would also alter the overall bridge prioritization.

Table 20. Scenario 3 Rankings Compared with Scenario 4 Rankings

Bridge ID	Normalized Ranking	Factor Used	Scenario 3 Utility	Scenario 3 Ranking	Scenario 4 Utility	Scenario 4 Ranking
251-0026-0	3	1.5	0.47	1	0.51	3
117-0019-0	5	1.3	0.56	3	0.61	4
269-0020-0	2	1	0.49	2	0.50	2
255-0017-0	4	1.5	0.64	5	0.64	5
185-0010-0	1	1	0.47	1	0.47	1
021-0123-0	6	1.8	0.63	4	0.69	6
021-0124-0	6	1.8	0.64	5	0.70	7

5.6 Deterioration Curves

As mentioned in Chapter 3, slopes were calculated for each of the case study bridges in Microsoft ® Excel based on the linear regression lines for the deck, superstructure, and substructure condition rating data plotted versus time. In order to demonstrate the importance of incorporating past bridge condition data using these slopes, Figure 6, Figure 7, and Figure 8 show plots of bridge condition ratings versus time for deck, superstructure, and substructure respectively for 3 selected bridges. These figures show that while it is likely typical for bridges to deteriorate slowly, this methodology can identify those bridges that are deteriorating more rapidly. In this case, bridge 269-0020-0 is deteriorating more rapidly than bridge 251-0026-0 and bridge 117-0019-0.

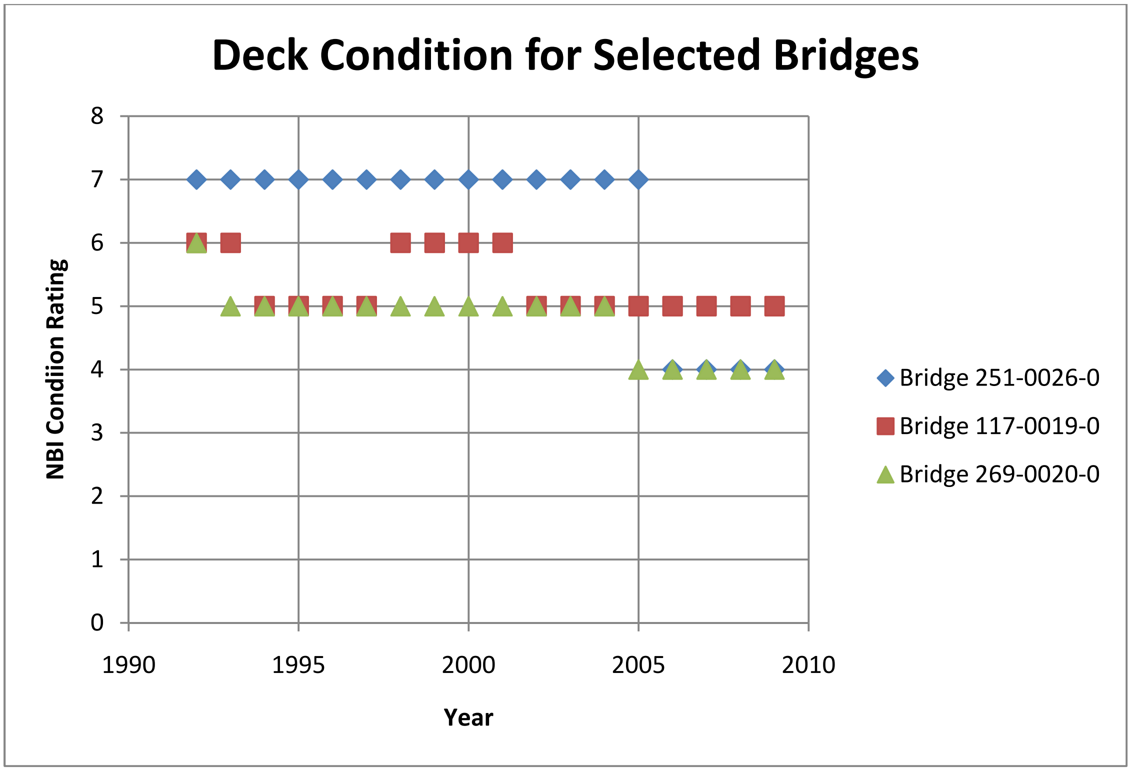

Figure 6. Deck condition rating versus time for 3 selected case study bridges

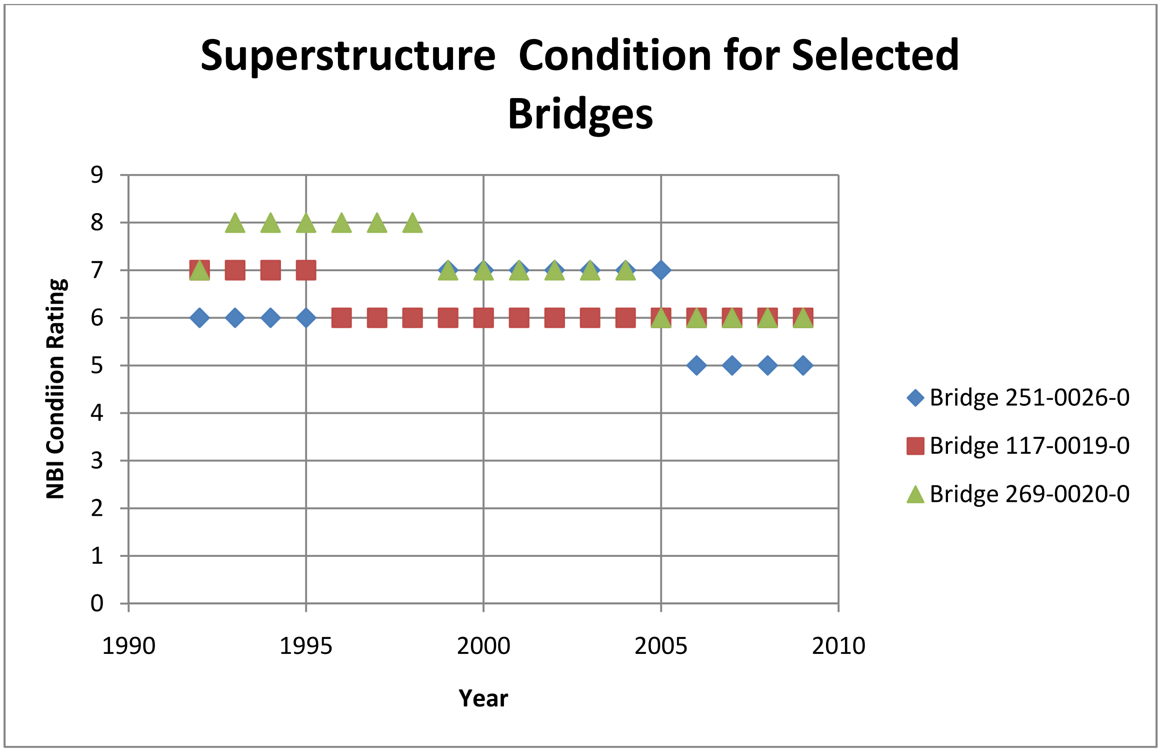

Figure 7. Superstructure condition rating versus time for 3 selected case study bridges

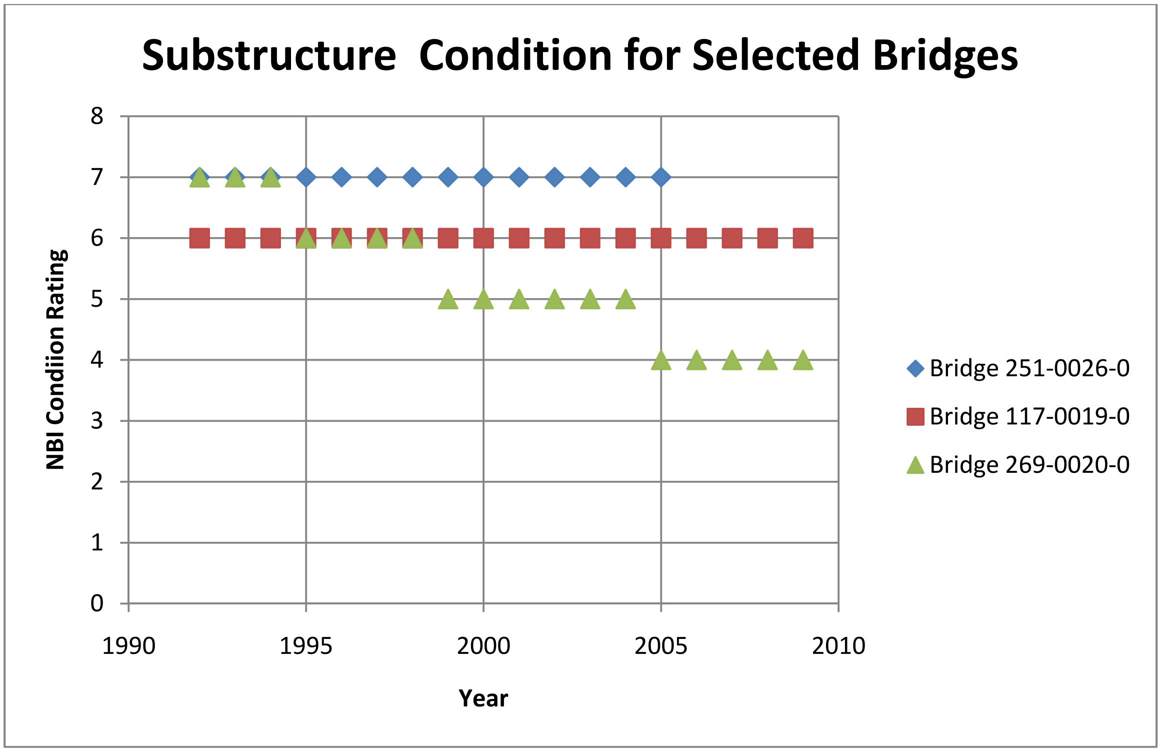

Figure 8. Substructure condition rating versus time for 3 selected case study bridges

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This thesis reviewed risk applications in transportation asset management (TAM) systems and developed a case study to prioritize selected bridges using the Multi Attribute Decision Making (MADM) technique, Multi Attribute Utility Theory (MAUT). The selected bridges were prioritized based on the following objectives:

- Maximize condition preservation
- Minimize extent of disruption
- Minimize critical failures
- Minimize restrictions

The attributes selected for this prioritization were: (see Table 4 and Chapter 3)

- BRCOND
- HS
- ADT
- BYPASS
- FC
- SC
- TEMP
- Narrow

Using data from the NBI, four prioritization scenarios were developed for seven selected bridges in Georgia.

6.1 Implications of Data Aggregation and Disaggregation

GDOT's internally developed bridge prioritization formula (36) utilized aggregate data in terms of bridge condition. The scenarios developed in this thesis, specifically scenario 4, demonstrate the importance of incorporating disaggregate data where it is available. Data disaggregation can impact the utilities and hence the rankings of bridges. In addition, disaggregate data can result in differences in overall bridge prioritization as well. This being the case, where it is available, disaggregate bridge condition data, i.e. data for deck, superstructure, and substructure, should be used in prioritization efforts.

6.2 Incorporating Uncertainty

Scenarios 3 and 4 incorporated uncertainty by including past condition data whereas the original GDOT formula does not (36). As opposed to incorporating bridge condition deterministically, i.e., only including current (snapshot) bridge condition data, scenarios 3 and 4 account for performance risk by including attribute(s) that are based on the slopes, i.e. linear regression, of bridge condition data. Incorporating uncertainty in scenarios 3 and 4 significantly altered the utilities and rankings of the selected case study bridges. This illustrates the importance of utilizing past condition data when available. In scenario 4 when disaggregate snapshot condition data was used in combination with disaggregate past condition data the impacts on the utilities and rankings were particularly significant.

6.3 Variation in Attribute Weights

An important component of the MAUT prioritization methodology used in this thesis is decision-maker input. Decision-makers determine the relative importance of certain attributes, influencing the weights of these attributes (see Table 7, Table 9, Table

11, and Table 14). A change in the relative importance of certain attributes, the "Factor" used in the case study in this thesis, results in a change in weight of these attributes. The number of attributes used also influences the weight since all attributes are weighted on a 0 to 1 scale. Although this appears to be subjective, it allows decision-makers flexibility in determining which attributes are more important than others. Given that the goals, objectives, and the criteria used to meet these goals and objectives vary from one transportation agency to another, giving the decision-maker the ability to adjust attribute weights in this type of prioritization effort is one of the strengths of this methodology.

6.4 Limitations

Only seven bridges were selected for the case study developed in this thesis. As mentioned in Chapter 5, there are over 17,000 bridges in the NBI database in Georgia (35). This being the case, without applying the methodology to all of the bridges in Georgia, it is difficult to determine the impact of approaches used in the four scenarios developed on the overall bridge prioritization in Georgia. Nonetheless, since there were notable changes in the rankings in several scenarios, particularly scenario 4, it is likely that there would be important changes on the overall bridge prioritization.

The past condition used in this analysis involved the use of past NBI condition ratings. Past element level bridge inspection data would allow for the development of more accurate deterioration models. The deterioration curves developed in this analysis were based on linear regression. However, many DOTs do not yet have the resources to collect the element level CoRe data that is necessary for more advanced deterioration and forecasting models such as AASHTO's PONTIS. Even so, NBI condition rating data is reported to the FHWA by DOTs on an annual basis, along with other useful data items such as ADT, bypass length, and inventory rating. Since these NBI data items are readily available to many transportation agencies, they can be used to develop prioritization frameworks.

6.5 Future Research

Although risk applications in transportation asset management (TAM) are common outside of the United States (2), a 2006 domestic scan tour indicated that generally, domestic transportation agencies were lagging in this area (3). This thesis presents several prioritization scenarios for bridge investment. Two of these incorporate performance risk, albeit a limited incorporation of uncertainty. However, as mentioned by Aktan, Ellingwood, and Kehoe (4), without standardized definitions of infrastructure performance, it is difficult to allocate investments based on risk-oriented approaches.

The traditional technical definition of risk is the probability of failure times the consequence of failure (1). However, without a standardized definition of infrastructure performance, it becomes difficult to calculate the probability of failure of an infrastructure asset. Pertaining specifically to bridges, is failure a catastrophic failure? i.e., the 2007 Minneapolis I-35-W bridge collapse, or a service interruption (as defined by Maconochie (30))? Standardized definitions of civil infrastructure are certainly an important area for future research.

A particularly promising area to incorporate risk into TAM systems is adapting to the potential impacts of climate change. The Transportation Research Board (TRB) of the National Academies released *Special Report 290* in 2008, which concluded that effective monitoring of climate change impacts on transportation infrastructure will be an important function of transportation agencies in the future (37). Since many transportation agencies already have TAM systems, these systems would provide a strategic platform for incorporating climate change considerations into the transportation investment decision-making process (38). And given the uncertainties in changing climatic conditions, a risk-oriented decision making approach can provide an effective means for transportation agencies to monitor and adapt to the potential impacts of climate change.

REFERENCES

1. Haimes, Yacov Y**.** *Risk Modeling, Assessment, and Management.* 2nd Edition. Hoboken, New Jersey : John Wiley & Sons, Inc., 2004.

2. FHWA**.** *Transportation Asset Management in Australia, Canada, England, and New Zealand.* Washington, D.C. : Transportation Research Board, 2005. Prepared for NCHRP Panel 20-36.

3. TRB**.** *U.S. Domestic Scan Program: Best Practices in Transportation Asset Management, SCAN-TOUR Report.* NCHRP 20-68. Washington, D.C. : s.n., 2007.

4. Aktan, A.E., Ellingwood, B.R. and Kehoe, B. *Performance-based Engineering of Constructed Systems.* s.l. : American Society of Civil Engineers, 2007, Journal of Structural Engineering, Vol. 133, pp. 311-323.

5. FHWA and AASHTO. *Asset Management: Advancing the State of the Art Into the 21st Century Through Public-Private Dialogue.* Washington, D.C. : US Department of Transportation, Federal Highway Administration, 1996. FHWA-RD-97-046.

6. FHWA**.** *Asset Management Primer.* Office of Asset Management. Washington, D.C. : s.n., 1999.

7. NCHRP**.** *Transportation Asset Management Guide.* Project 20-24(11) for AASHTO. Washington, D.C. : s.n., 2002.

8. PB Consult, Inc.; PricewaterhouseCoopers, LLP; Cambridge Systematics, Inc.; NuStats, Inc. *NCHRP Report 522 A Review of DOT Compliance with GASB 34 Requirements.* Washington, D.C. : Transportation Research Board, 2004.

9. Wittwer, Ernie, et al. *Key Findings from the 5th National Workshop on Transportation Asset Management.* Midwest Regional University Transportation Center. Madison, Wisconsin : s.n., 2004. Proceedings.

10. Zimmerman, Kathryn A. and Sweet, Leslie A. *6th National Conference on Transportation Asset Management.* Washington, D.C. : Transportation Research Board, 2006. Transportation Research Circular E-C093.

11. Transportation Research Board. TRB Final Program 7th National Conference on Transportation Asset Management: New Directions in Asset Management and Economic Analysis. [Online] 2007. [Cited: June 14, 2011.] http://onlinepubs.trb.org/onlinepubs/archive/conferences/2007/asset/program.pdf.

12. Transportation Research Board. TRB Final Program 8th National Conference on Transportation Asset Management: Putting the Asset Management Pieces Together. [Online] 2009. [Cited: June 14, 2011.] http://onlinepubs.trb.org/onlinepubs/conferences/2009/asset/assetmanagementfinal2009.pdf.

13. AASHTO**.** Motion to Amend the Definition to Advocate the Principles of Transportation Asset Management. [Online] 2006. http://www.transportation.org/amguide.pdf.

14. NCHRP**.** *Performance Measures and Targets for Transportation Asset Management.* Report 551. Washington, D.C. : s.n., 2006.

15. Amekudzi, Adjo**.** Asset Management. [book auth.] Institute of Transportation Engineers. *Transportation Planning Handbook.* 3rd Edition. Washington, D.C. : s.n., 2009, 8.

16. Piyatrapoomi, N, Kumar, A and Setunge, S. *Framework for Investment Decision-Making Under Risk and Uncertainty for Infrastructure Asset Management.* 2004, Research in Transportation Economics, Vol. 8, pp. 199-214.

17. Helton, J.C. and Burmaster. *Treatment of Aleatory and Epistemic Uncertainty in the Performance of Complex Systems.* 1996, Reliability Engineering and System Safety, Vol. 54, pp. 91-94.

18. Winkler, R.L. *Uncertainty in Probabilistic Risk Assessment.* 2-3, 1996, Reliability Engineering and System Safety, Vol. 54, pp. 91-94.

19. Amekudzi, A. and McNeil, S. *Capturing Data and Model Uncertainties in Highway Performance Estimation.* 6, s.l. : American Society of Civil Engineers, 2000, Journal of Transportation Engineering, Vol. 126, pp. 455-463.

20. Aktan, A.E. and Moon, F.L. *Mitigating Infrastructure Performance Failures Through Risk-based Asset Management.* Drexel Intelligent Infrastructure Institute, Drexel University. Philadelphia, PA : s.n., 2009.

21. National Transportation Safety Board. *Collapse of I-35W Highway Bridge: Minneapolis, Minnestota; August 1, 2007.* Washington, D.C. : s.n., 2008.

22. Meyer, M.D. *Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change.* Washington, D.C. : Transportation Research Board, 2008. Commissioned Paper.

23. Federal Highway Administration. *Highways in the Coastal Environment.* 2008. Hydraulic Engineering Circular No. 25.

24. Schwartz, P. *The Art of the Long View: Planning for the Future in an Uncertain World.* s.l. : Doubleday, 1996.

25. Haas, R. and Raymond, C. *Asset Management for Roads and Other Infrastructure.* Toronto, Ontario, Canada : Ontario Hot Mix Producers Association, 1999. Presented at the 8th Annual Fall Asphalt Seminar.

26. AASHTO. *Transportation Asset Management Guide Volume 2: A Focus on Implementation.* Washington, D.C. : Transportation Research Board, 2011.

27. AbouRizk, S.M. and Siu, K.L. *Standardized Risk Analysis for Infrastructure Assessment.* [ed.] A. Amekudzi and S. McNeil. 2008, Infrastructure Reporting and Asset Management: Best Practices and Opportunities, pp. 131-140.

28. American Society of Civil Engineers. *2009 Report Card for America's Infrastructure.* Reston, Virginia : ASCE, 2009.

29. Brand, D., Mehndiratta, S. and Parody, T. *The Options Approach to Risk Analysis in Transportation Planning.* Washington, D.C. : s.n., 2000, Transportation Research Record, Vol. 1706, pp. 54-63.

30. Maconochie, J.A. *U.S. Highway Bridge Risk Model - Development, Summary Results, and Applications for Federal and State Transportation Agencies.* Washington, D.C. : Transportation Research Board 89th Annual Meeting, 2010.

31. Sun, X, et al. *Analysis of Past National Bridge Inventory Ratings for Predicting Bridge System Preservation Needs.* Washington, D.C. : Transportation Research Board, 2004, Transportation Research Record, Vol. 1866, pp. 36-43.

32. Johnson, M.B. and Shephard, R.W. *California Bridge Health Index.* Washington, D.C. : Transportation Research Board, 1999. 8th International Bridge Management Conference.

33. FHWA. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges.* Washington, D.C. : s.n., 1995.

34. Dabous, S.A. and Alkass, S. *A Multi-attribute Method for Bridge Management.* 2010, Construction and Architectural Management, Vol. 17, pp. 282-291.

35. FHWA. NBI ASCII Files. *USDOT FHWA Bridge Programs.* [Online] April 6, 2011. [Cited: September 21, 2010.] http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm.

36. Georgia Department of Transportation. Bridge Prioritization Formula. s.l. : n.p., January 13, 2011.

37. TRB. *Special Report 290.* Washington, D.C. : Transportation Research Board, 2008.

38. Meyer, M.D., Amekudzi, A.A. and O'Har, J.P. *Transportation Asset Management and Climate Change: An Adaptive Systems Management Approach.* Washington, D.C. : Transportation Research Board, 2010, Transporation Research Record.