TOWARD A RISK FRAMEWORK FOR PRIORITIZING ANCILLARY TRANSPORTATION ASSETS FOR MANAGEMENT

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TOWARD A RISK FRAMEWORK FOR PRIORITIZING ANCILLARY TRANSPORTATION ASSETS FOR MANAGEMENT

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To Hirut, Ronia, and Jozy

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LIST OF SYMBOLS AND ABBREVIATIONS

ſ	Average Failure Rate
TAM	Transportation Asset Management
AASHTO	American Association of State Highway and Transportation Officials
GIS	Geographic Information System
FHWA	Federal Highway Administration
FY	Fiscal Year
CAMG	City Asset Managers Group
ODOT	Oregon Department of Transportation
DfT	Department for Transport
ERS	Earth Retaining Structure
IHS	Interstate Highway System
HAAFM	Highways Agency's Adaptation Framework Model
NCHRP	National Cooperative Highway Research Program
DOT	Departments of Transportation
IT	Information Technology
GPS	Global Positioning System
EAM	Enterprise Asset Management
GPS	Global Positioning System
BADCS	Buckeye Asset Data Collection System
SHA	State Highway Administration
FMEA	Failure Mode and Effects Analysis
PRA	Probabilistic Risk Analysis

SUMMARY

A growing number of transportation agencies have begun to manage selected ancillary transportation assets systematically—culverts, guardrails, pavement markings, sidewalks and curbs, street lighting, traffic signals, traffic signs, utilities and manholes, earth retaining structures, and environmental mitigation features. Given budget limitations, several agencies are interested in prioritizing these assets for inclusion in their existing management systems. To provide decision-support capabilities for this task, this study reviews information technology and analytical tools in asset management practices, the basics of risk theory, and examines risk applications in transportation asset management, water mains management, and storm water management. In addition, the study identifies the basic risk elements of a risk-benefit-cost framework for prioritizing ancillary transportation assets for management. These elements can be used as a basis for developing a decision analysis framework to properly make a business case for the formal management of ancillary transportation assets and to prioritize them for inclusion in existing transportation asset management programs. Using these elements, a risk ranking model was developed that can be used by transportation officials to prioritize their ancillary asset classes for management. A demonstration of the model is presented to illustrate its effectiveness. The study concludes that in order to obtain useful data for the model, the different types of ancillary transportation assets failing on our roadways have to be monitored and data collected on asset failures and their consequences. Therefore, this study recommends that agencies commit the necessary time and resources to gather information (e.g., asset failures and their consequences) and establish an

integrated database that would support appropriate risk analysis. Tracking and documenting the failures of ancillary transportation assets would also help in identifying trends/probability of failure as well as quantifying the consequences associated with these failures. This tracked and documented information could be used to estimate appropriate risk factors (i.e., the risk of failure) and used in prioritizing individual asset classes for inclusion in existing management systems.

CHAPTER 1

INTRODUCTION

1.1 Background

A useful analytical tool in business practice over the past several decades, transportation asset management (TAM) has been applied to transportation investment decision making over the lifecycles of infrastructure facilities and systems [1, 2]. The American Association of State Highway and Transportation Officials (AASHTO) defines TAM as "a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle [3]." In the initial years of TAM, agencies tended to focus on pavement and bridge management [2]. Recently, however, various agencies have increasingly expanded their asset management activities to include the management of ancillary transportation assets such as pavement markings, sidewalks and curbs, street lighting, traffic signals, traffic signs, utilities and manholes, and earth retaining structures [4-6], with utilities and manholes being predominantly managed at the local level.

Such expansion of TAM activities requires additional funds for gathering and managing data, and in some cases developing analytical tools. Given that agencies usually have limited funds, ancillary assets will compete for formalized asset management programs or activities. Making a business case for managing various assets can help agencies prioritize the management of the assets that yield the highest returns and minimize risks in the levels of service provided to system users (i.e., both in performance and catastrophic failures). To help agencies prioritize the competing assets for formal management, this study reviews geographic information system (GIS) and risk applications in TAM and then discusses the critical elements of a risk-benefit-cost framework. Finally, the study proposes a risk model that assesses the rates and consequences of failure and prioritizes these assets for formal management.

In recent years, the concept of risk, defined as the probability of failure and its consequence, [9] has been introduced into TAM [1, 7, 8]. Over the years, risk has been used as a basis for decision making in the nuclear power, environment, and food industries. However, in the past several years, risk had been increasingly incorporated in the systematic management of transportation assets. In fact, the concept is being applied more broadly as a way to make better use of limited resources in providing adequate levels of service to the general public while showing accountability for the use of taxpayer dollars. An international and a domestic assessment of transportation asset management sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) in 2005 and 2007, respectively, identified a number of international agencies that have adopted some degree of risk assessment or risk management in some areas of their transportation asset management systems [7]. Both scans ascertained that risk assessment or risk management is most often used in scenario analysis processes [7, 10].

The literature shows that different agencies assess and manage risks using different methods [10]. For example, in FY 2008-09, the Financial Planning Department of the City of Portland requested that the City Asset Managers Group (CAMG) incorporate a risk-based approach to address existing capital assets. Consequently, the City's repair and renewal projects were prioritized based on their risk levels. Projects that had higher risk levels were given more attention in funding allocation [11]. A review of the literature also reveals that risk has been applied to roadway maintenance and slope management. The Oregon Department of Transportation's (ODOT) unstable slope management process uses a numeric score to categorize the risks associated with potential landslide locations [10]. High-risk locations are given priority and any risky situations are addressed. That is, the system manages and mitigates road conditions (e.g., landslides and rock falls) that contributed to 382 crashes between 1993 and 2003, resulting in 154 injuries and 23 deaths [10]. The England Department for Transport (DfT) uses a scoring matrix approach to rank and prioritize roadway maintenance projects. The agency reviews the scoring process through management workshops involving stakeholders. In addition, it employs a software package known as SWEEP to perform a life-cycle treatment analysis over a 60-year time horizon [7]. These are a few of several applications of risk in decision making being used by various transportation agencies in the U.S. and internationally.

1.2 Ancillary Transportation Assets

In order to establish a risk management system, it is critical that an agency identify all their ancillary transportation assets. Such assets include culverts, pavement markings, earth retaining structures (ERS), sidewalks, mitigation features, guardrails, traffic signals, utilities, and manholes. State agencies tend to manage all of these assets with the exception of utilities and manholes, which tend to be managed at the local level. All these transportation assets work collectively to ensure the safe and efficient operation of a transportation network. Generally, most of these assets are referred to as roadway safety hardware. Therefore, it is logical to expect that managing these assets in a systematic manner will improve safety conditions and functional characteristics. One way of improving these conditions and preserving this valuable stock of transportation infrastructure is to efficiently allocate limited resources. Indeed, identifying high-risk ancillary transportation assets and determining the appropriate mitigation strategies are ways of managing transportation infrastructure cost effectively. Examples of ancillary transportation assets —guardrail, lighting, pavement marking, signs, and traffic signals—are illustrated in the following Figures 1.1 through 1.5.

Figure 1.1 Guardrail Assets [16]

Figure 1.2 Pavement Marking Asset [16]

Figure 1.3 Sign Asset [16]

Figure 1.4 Lighting Assets [16]

Figure 1.5 Traffic Signal Asset

According to the Federal Highway Administration (FHWA), over 160 million sq. ft. of permanent earth retaining structures (ERSs) are constructed in the United States each year, and hundreds of millions of dollars are spent installing, repairing, upgrading, and replacing ancillary assets (safety hardware). The FHWA estimates that about 40 percent of these ERSs are on public projects [12]. However, these critical components of the surface transportation network are given less attention when it comes to their management despite the important role they play in the geometric design of highway and bridge construction. In addition, other research has identified that most state departments of transportation allocate their safety hardware management program budgets according to expert opinion [4]. However, at the time of increasing highway travel demand, aging infrastructure, and declining/insufficient transportation funds, more systematic approaches to managing ancillary transportation assets is crucial. Therefore, resource allocation for the management of ancillary structures must be aligned with the asset condition data, the asset risk of failure, and the agency's management objectives.

1.3 Study Objectives and Outline

Making a business case for managing competing or complementary asset classes involves understanding the overall and marginal costs and benefits associated with introducing more formal management programs relative to the status quo of decision making. That is, we must understand the relative costs and benefits to be incurred and gained, respectively, by gathering data and introducing formal analytical methods that support decision making. Because of subjective uncertainty associated with limited knowledge of the assets and objective uncertainty associated with randomness in the facilities and systems, a framework for properly making a good business case has to include the consideration of uncertainty. For example, in a set (X=1 ... n) -- where X is used to refer to distinctive asset classes and takes integer values from 1 to n, -- of n competing or cooperating discrete asset classes, the critical question to be answered in making a business case is which asset classes have the highest marginal benefit-cost ratio when data collection and other asset management functions such as performance prediction and project prioritization are introduced. Figure 1.6 illustrates how the benefit-to-resource ratio can be computed in a deterministic scenario, as presented by Yeddanapudi [13].

Since deterministic scenario analysis does not account for uncertainty, a non-deterministic scenario analysis (i.e., scenario involving uncertainty) would have to be incorporated if this question is expanded to include the consideration of risk with the intent of identifying the asset classes that will result in the most significant risk reduction to the general public, when formal asset management activities are introduced. In order to address this consideration, this study reviews relevant literature on information technology (IT) and analytical tools in asset management practices, the basics of risk theory, and also examines risk applications in transportation asset management, water mains management, and storm water management. In addition, the study identifies the basic risk elements of a risk-benefit-cost framework for prioritizing ancillary transportation assets for management. Transportation management and water management systems are presented here because they have a range of characteristics (e.g., lack of condition data, lack of resources for maintenance and rehabilitation, and a structure of network of elements) pertinent to the issue being considered. Subsequently, a decision-support tool was developed using a risk matrix that can help decision makers prioritize alternatives based on their risk differentials. Finally, we demonstrate the model to validate its effectiveness and limitations and recommend steps necessary to improve the decision support capabilities of the proposed model.

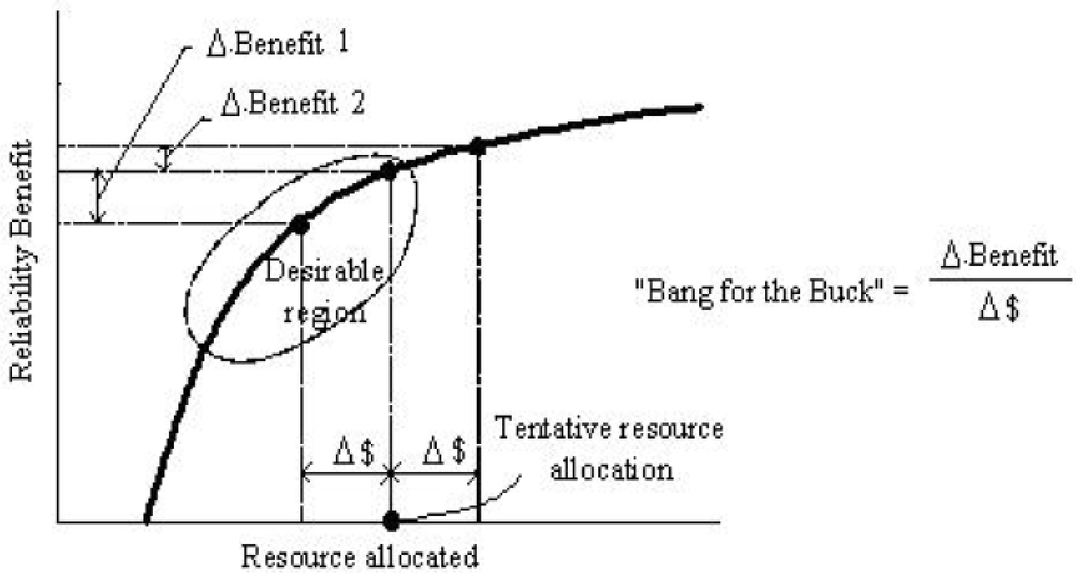

Figure 1.6 Benefits Obtained From Various Resource-Allocation Levels [13]

1.4 Research Benefits

Agencies adopting the risk model proposed by this research as a decision-support tool for managing their transportation infrastructure systems would benefit in several ways. For one, this research can help transportation agencies effectively improve and monitor the performance of the transportation network based on their management objectives by identifying high-risk assets and mitigating the risks by prioritizing the identified assets for inclusion in existing asset management systems. In addition, the research can help transportation agencies reduce their potential risk of liability (i.e., social, environmental, financial, and political risks) by proactively identifying high-risk assets and mitigating the risks. The model proposed also offers a systematic procedure for ranking the risk posed by each asset, and aligning the consequence of failure with the agency's short- and long-term objectives. Finally, the research provides an alternative effective approach for transportation agencies to allocate and utilize limited transportation resources in a cost-effective manner.

1.5 Thesis Organization

The remainder of this thesis is organized into the following chapters:

- Chapter 2 presents the literature review, providing an overview of the application of risk in decision making, describing where the present effort is focused in risk decision making. The chapter also reviews transportation asset management with an overview of the different phases involved, some information technology systems available, and some analytical tools being used in decision making. In addition, this chapter reviews the basic concepts of risk and finally concludes with risk decision making for infrastructure systems.
- Chapter 3 outlines two frameworks (i.e., a risk framework and a risk-benefit-cost framework), details all the components making up the frameworks, and discusses agency's responsibilities in implementing the risk framework.
- Chapter 4 reviews the proposed model, which is based on a risk matrix and discusses the procedure and practical issues in implementing the model. The model is demonstrated in this chapter to demonstrate its potential effectiveness.
- Chapter 5 presents the summary and conclusion of the research effort. Discussion of the research limitations and prospects for future research are also presented. Finally, recommendations are provided for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Risk analysis has been employed over the years as a decision aid. Risk applications for resource allocation and other functions can be found in transportation management, waste water management, and water mains management. In fact, several transportation agencies in the United States and around the world have acknowledged the merits of incorporating risk in their decision-making processes of budget allocation and project prioritization [12]. In addition, more and more transportation agencies are considering risk applications to enhance their TAM programs [7].

2.2 Scope of Previous Studies

The literature shows that risk analysis has been employed in various capacities for making decisions in transportation planning and transportation investment. For example, an earlier study developed a Leontief-based infrastructure input-output model to help account for the intraconnectedness within each critical infrastructure as well as the interconnectedness among them. The study generalized the linear input/output model into a generic risk model with the former as the first-order approximation (Haimes and Jaing 2001). A review of the literature also reveals another study (Cambridge Systematics et al. 2009) that outlines a proposed approach that augments transportation agencies' existing risk management activities with a process that helps assess risks resulting from the failure of interstate highway system (IHS) assets. The approach helps owners of the IHS to perform risk assessment for their IHS assets and any other assets they define to be on their highest priority network. This risk assessment approach yields a set of priorities for risk mitigation.

In addition to these studies, Salgado et al. (2010) reviewed some approaches to developing a model based on expert opinion for critical infrastructure risks assessment and vulnerability analysis. The researchers addressed the challenges (i.e., obtaining estimates for the probabilities of the initiating events as well as obtaining values for the associated consequences) in performing quantitative risk assessment of very rare events by reviewing Dempster-Shafer and Fuzzy approaches to elicit expert opinions.

Furthermore, Parsons Brinckerhoff et al. (2009) developed the Highway Agency's Adaptation Framework Model (HAAFM), which provides a seven-stage process that identifies activities that will be affected by a changing climate, determines associated risks and opportunities, and identifies preferred options in mitigating them. The researchers identified over 80 highway agency activities or vulnerabilities that may be affected by climate change. The study also found that over 60 percent of the risks associated with these vulnerabilities are expected to be materially affected by current predicted levels of climate change within their relevant asset life or activity time horizon. Another finding of the study by Parsons Brinckerhoff et al. is that the risk appraisal enabled vulnerabilities to be prioritized for attention based upon several criteria including their potential to disrupt the operation of the strategic road network.

FHWA (2005) outlines how Queensland, Australia assesses the risk (product of the probability of failure and the consequence of failure) posed by a bridge, using a program called Whichbridge. The program assigns numerical scores to bridges based on factors such as condition of bridge components, environmental impacts, component materials, design standards and traffic volumes.

Li et al. (2009) also proposed an uncertainty-based methodology that incorporates certainty, risk, and uncertainty inherent in input factors such as highway agency cost, traffic growth rates, and discount rates used in the computation of highway project-level lifecycle benefit or cost. The methodology, therefore, addresses a limitation that existing project-level lifecycle cost analysis approaches encounter. The study found significant differences between scenarios with and without uncertainty considerations. As a result of the large data requirements, the application of the methodology could be limited to only state and large-scale local transportation agencies because of the amount and level of historical data they maintain.

Dicdican and Haimes' (2004) study on highway infrastructure develops a systematic risk-based asset management methodology to manage the maintenance of highway infrastructure systems [38]. The decision-making methodology developed could enable the harmonization and coordination of actions of different units and levels in a hierarchical organization. The framework uses a multiobjective decision tree for analysis to validate the tradeoffs between long-term and short-term costs, applying the concept of remaining life to distinguish actions in the present from those in the future. The systemic methodology also enables organizations to prioritize assets for maintenance while addressing the potential for extreme events. The costs, benefits, and risks of maintenance and inspection policies are balanced by the methodology and applied to the various types of assets. The methodology suggested by this paper adopts three objective functions in the options and strategies evaluation process: minimizing short-term cost, minimizing long-term cost, and maximizing the remaining service life of highway assets. The researchers used a constraint function, which enables the method to eliminate infeasible options by coordinating the remaining service life across assets. The methodology is not only applicable to highway infrastructure systems, but it can also be applied to the management of large-scale dynamic systems that exhibit similar characteristics as those of highway systems.

Other studies have also shown that risk has been used as a decision-support tool for investment planning for infrastructure management other than transportation assets. One example of such studies is in the storm water management in which Kannapiran used risk to consider infrastructure decision making. Kannapiran points out in his study on the strategic management of storm water assets that a statistical or conventional mathematical modeling approach has been found impractical for assessment of deteriorating infrastructure [39]. The study suggests the use of fuzzy-based risk models because they are more suitable as they link engineering judgment, experience and scarce field data of the deteriorating assets. Kannapiran draws a representative network of a buried storm water system's data and derives a pipe condition index by linking the field data and reasoning using a fuzzy approach. The result of the study implies that the fuzzy approach can be useful and relevant for asset maintenance and development projects.

In addition, in water main management, Fares and Zayed use a hierarchical fuzzy expert system to assess the risk of failure of water mains. This paper states that there are 700 water main breaks per day in Canada and the United States, costing more than CAD 6 billion since 2000 [30]. It defines risk of failure as the combination of probability and impact severity of a particular circumstance that negatively impacts the ability of infrastructure assets to meet municipal objectives. The study proposes a framework to evaluate the risk associated with the failure of a water main using a hierarchical fuzzy expert system (HFES). The model considers 16 risk-of-failure factors within four main categories which represent both the probability and the negative consequences of failure. It establishes a strong correlation between pipe age and risk of failure followed by pipe material and breakage rate. The study also shows that the surroundings suffered the most negative consequence of a failure event. Finally, a pilot project was implemented to examine the methodology. This project suggested that a percentage (~8%) of the network's pipelines is risky and requires mitigation actions in the short term.

The review of the literature found a significant number of studies that show a vertical (i.e., within a group of assets) risk optimization process. In fact, very little research was found in which risk management was employed as a horizontal (i.e., across different asset classes) decision-support tool for asset prioritization.

In essence, the literature review revealed that some degree of risk management is being used in infrastructure decision making to prioritize risky alternatives. However, most of the studies have focused on a project-level analysis of risk in decision making, rather than a program-level addressing tradeoffs across different asset classes and decision-making objectives.

2.2 Asset Management

Asset management concepts are adopted by asset managers to minimize the total cost of designing, acquiring, operating, maintaining, replacing, and disposing capital transportation assets over their useful lives while accomplishing the desired levels of service. The main impetuses to the development of formal asset management programs are demand for increased financial accountability for the publicly-owned assets, aging infrastructure, and growing need for better utilization of limited or declining transportation resources. The AASHTO definition of TAM focuses on a Department of Transportation business process for resource allocation and utilization with the objective of better decision making based upon quality information and well-defined objectives [2]. Figure 2.1 illustrates the FHWA overview of transportation asset management as outlined in the “Asset Management Primer” report. Another framework shown in Figure 2.2 is adopted from Volume 1 of the AASHTO Transportation Asset Management Guide (NCHRP, 2002). The framework illustrates resource allocation and utilization process in asset management. The flexibility of the framework presented in Figure 2.1 allows for modifications that meet the needs of organizations with dissimilar policy, institutional, organizational, technological, and financial settings [2].

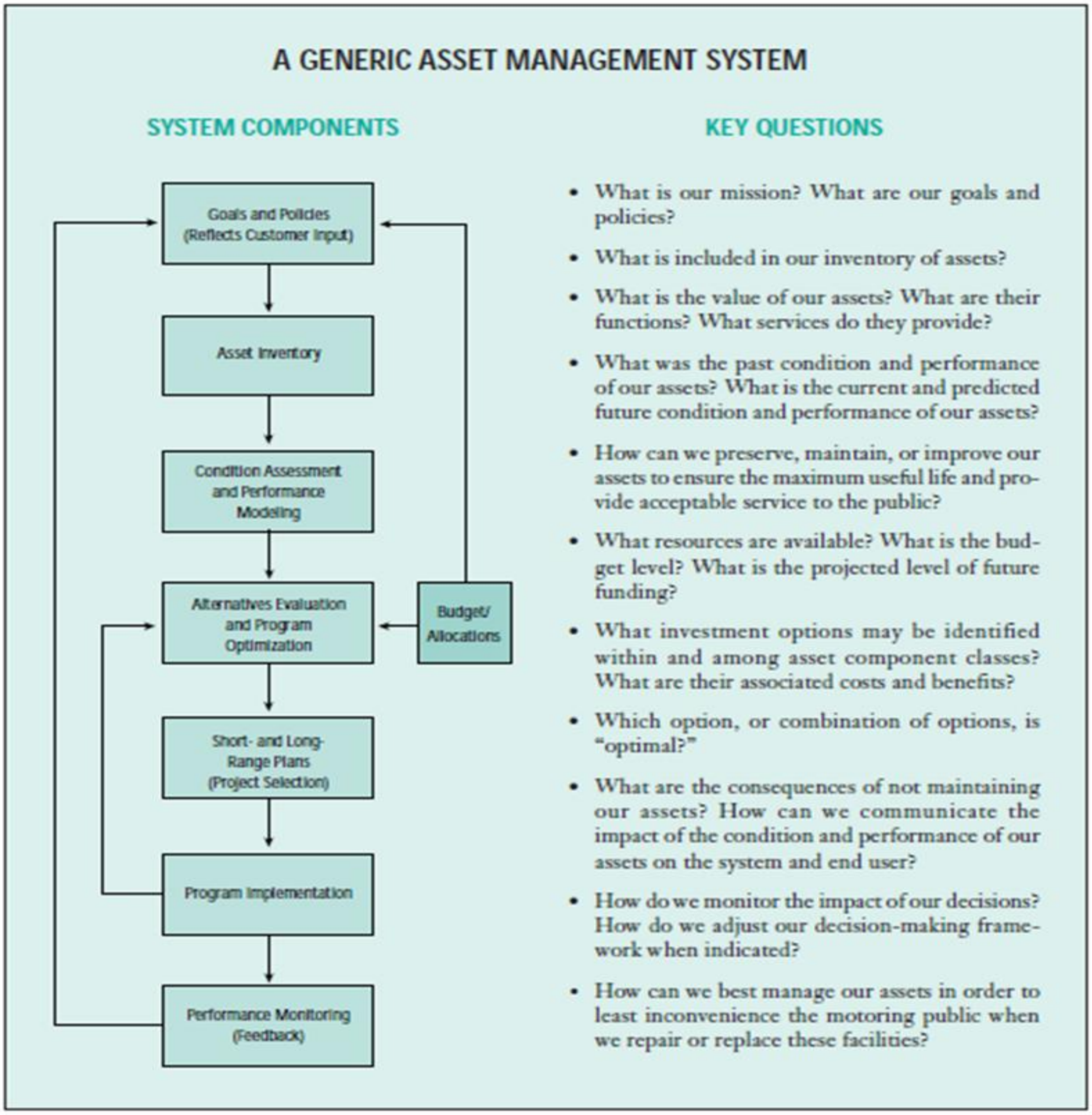

Figure 2.1 FHWA Overview of an Asset Management System [15]

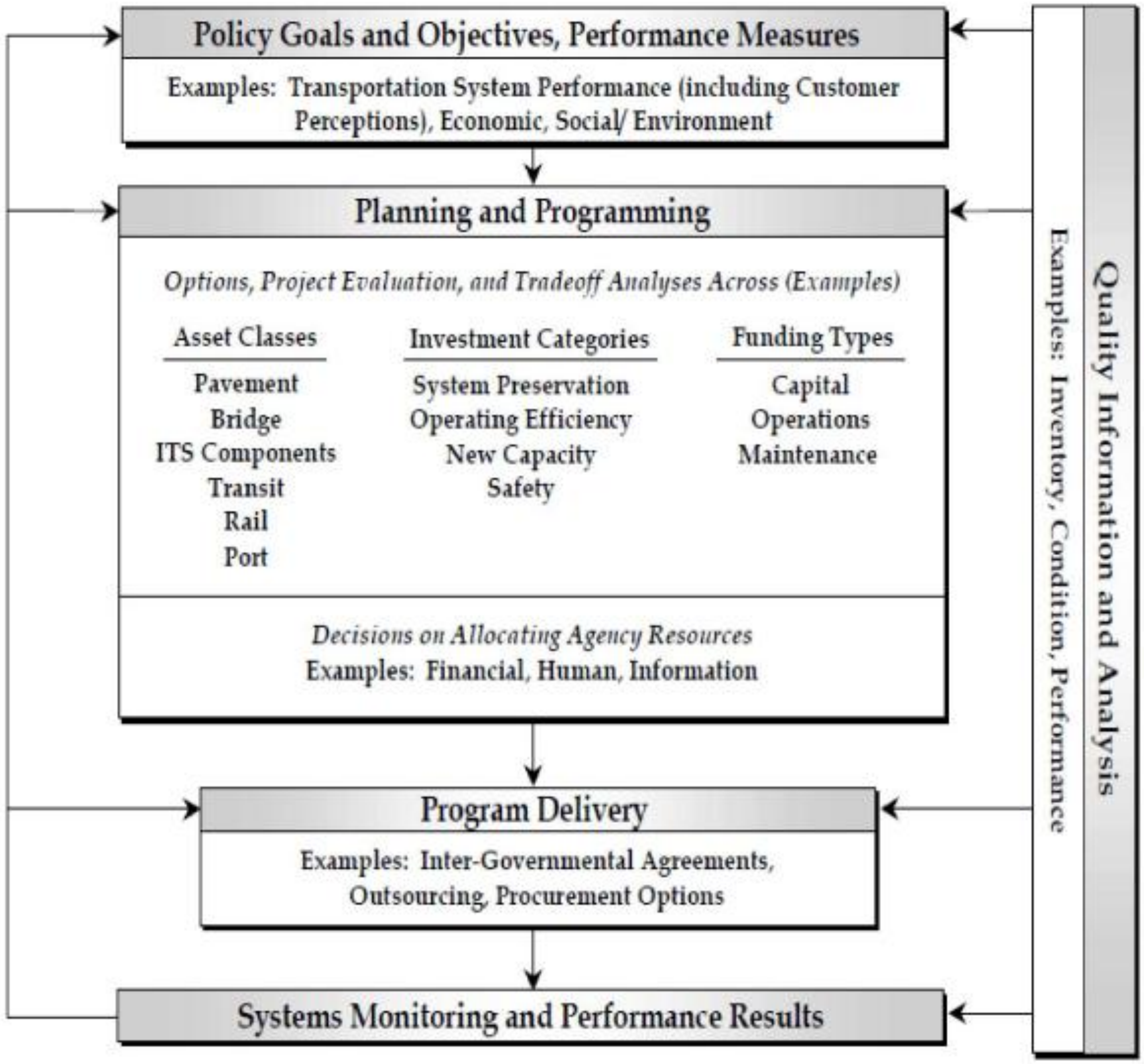

Figure 2.2 Transportation Asset Management: Resource Allocation and Utilization [2]

With factors such as aging infrastructures, increasing maintenance and replacement costs, and limited funds, transportation agencies are seeking more proactive and efficient ways to manage their assets. Asset management, therefore, presents a tool that facilitates an agency's decisions in resource allocation and utilization in managing its transportation infrastructure [2]. Indeed, an asset management tool allows an agency to base its decision methods and criteria on current policy guidelines. In addition, asset management tools enable asset managers to consider a range of alternatives while they focus on the outcomes of decisions and applying more objective information to decisions. Several examples of asset management tools were identified by the international review performed by United States transportation professionals in Sweden, Australia, New Zealand, and the United Kingdom in 2005 [7]. Asset management, which is a system-based decision-support tool, is also identified as a way of doing business through the incorporation into every aspect of the transportation agency, including planning, engineering, finance, programming, construction, maintenance, and information systems [2]. Therefore, at a time of declining/insufficient resources, these system-based management practices can help agencies make informed decisions and also provide the federal, state and local governments and the general public with convenient, safe, and a reliable transportation network.

An effective asset management system entails three main principles [2]. For one, it is strategic, focusing on asset performance and cost and aligning with the policy goals and objectives of an agency. This principle cuts across the other two principles of asset management; analysis and decision-making. Asset management requires complete, current, and accurate information on the transportation infrastructure and strong analytical capabilities, suggesting that asset managers should employ the suitable level of information collection capabilities. Finally, as a business process, asset management entails tradeoff analyses across competing alternatives together with organizational goals, policies, budget, and asset performance. Thus, through the elicitation of expert knowledge and engineering judgment, all levels of the organization contribute to effective communication that addresses the needs of asset management. In addition, with this information in hand, asset managers could make resource allocation decisions while monitoring and evaluating the system in order to make adjustments or changes with the aim of attaining set performance targets and achieving organizational goals. These processes facilitate an effective asset management program that enables transportation agencies to build, preserve, operate, and improve the performance of their facilities more cost-effectively, make the best use of limited resources, enhance their credibility and accountability, and contribute to the long-term economic vitality of the nation.

2.3 Analytical Tools

The literature reveals that diverse analytical tools have been used by transportation agencies to improve highway network preservation and investment planning, as approaches, in enhancing the decision-making process in asset management. Figure 2.3 summarizes the findings of a survey of ten DOTs, conducted in 2002, under the auspices of the National Cooperative Highway Research Program (NCHRP) [15]. The Figure illustrates the predominate use of pavement management tool among the ten states. Following the pavement management analysis tool are benefit-cost and safety analysis tools. In addition, lifecycle cost analysis is the least used tool among the surveyed agencies. Many of these model-based tools for asset management focus on cost-effectiveness analyses, prioritization, and optimization methods. Others also focus on the selection of rehabilitation strategies, prediction models, and performance measures. However, little research has been done on the development of optimization tools for prioritizing different categories of ancillary transportation assets for inclusion in existing transportation asset management systems. In addition, the existing analytical tools are not being utilized to their full potential. These limitations may have hindered transportation agencies wishing to improve their asset management systems.

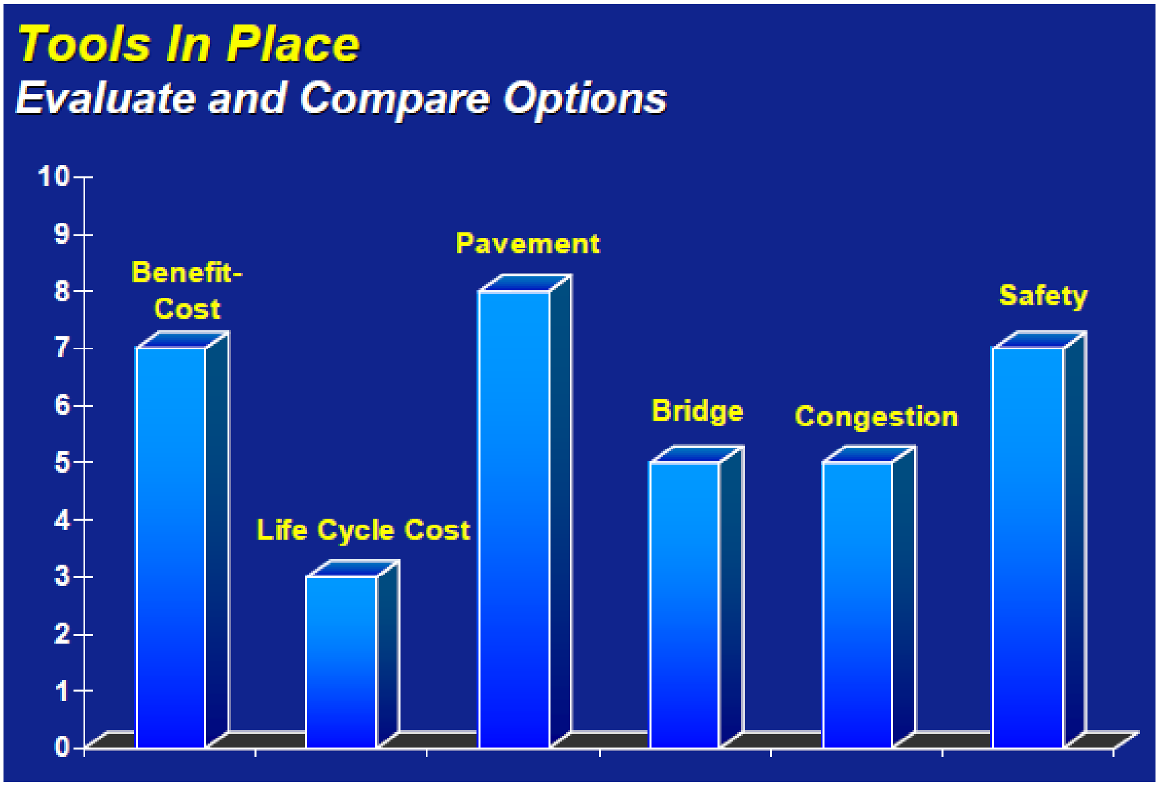

Figure 2.3 Summary of findings of Analytical tools used to Evaluate and Compare Options [15]

To help state DOTs and other transportation agencies identify, evaluate, and recommend investment decisions for managing their infrastructure assets, NCHRP 20-57 proposed two field-tested analytical tools: AssetManager NT and AssetManager PT [16]. AssetManager NT analyzes investments and their associated performance (i.e., tradeoff analyses) across infrastructure categories in the highway mode over a 10- to 20-year horizon. AssetManager PT focuses on the impact of investment choices on a short-term program of projects.

2.4 Information Technology

Among the myriad challenges to implementing asset management within an organization is gathering and managing the required data (i.e., gathering and organizing detailed inventory and attribute data on assets). Implementing an integrated information and systems framework based on industry best practices and standards is an effective way to support the exchange and the integration of information across business units within a transportation organization. Increasing the efficiency of automated data processing and data reporting by employing information technology (IT) complements an agency process of making decisions in asset management. Over the years, various sophisticated analytical tools, techniques, and IT systems that support a comprehensive, fully integrated asset management system have been developed with the advent of more powerful computer systems [17]. These technologies enable transportation officials to effectively communicate with decision makers through "what if" queries (i.e., officials can analyze the effect of varying budget levels on system condition and performance, and on users) [17].

IT plays two major roles in asset management: collection, storage, and the analysis of data; and the presentation and communication of the analysis results to decision makers inside and outside the agency [17]. Figure 2.4 illustrates how IT integrates the essential elements of strategic asset management. In recent years, IT usage has enhanced the rate of data collection with higher quality and spatial accuracy. The development of powerful data servers and software such as geographic information systems (GIS) and global positioning systems (GPS) facilitate data storage, data retrieval, and data analysis. The second major role of IT in asset management is accomplished through a network of computers within the transportation agency and those of all other stakeholders. Computer networking helps with the distribution of information and the results of any analyses undertaken by analysts. These results are then graphically presented to the decision makers using advanced multimedia capabilities.

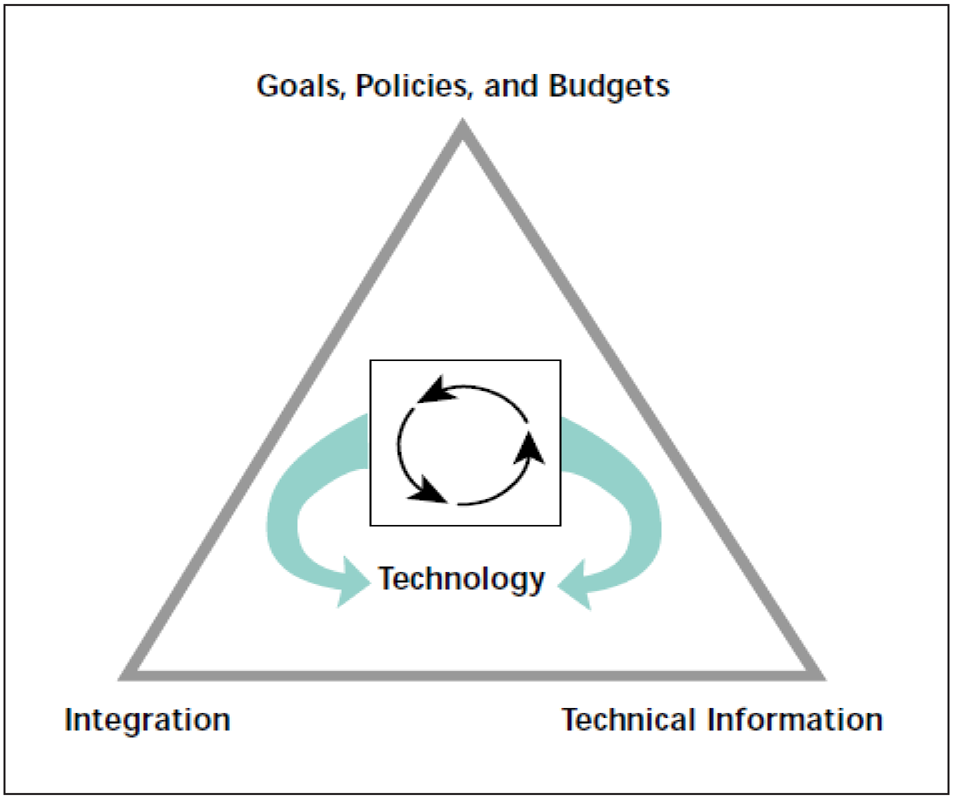

Figure 2 .4 Integration of Essential Elements of Strategic Asset Management by the use of Information Technology [17]

Figure 2.5 illustrates a proposed IT interaction model in an advanced high-quantity, low-cost, or ancillary transportation asset management system developed by Rasdorf et al. [18]. In their model, the source of data is field data collection, automated sensors, and existing data (examples of existing data are legacy and historical data). These data sources are primarily used to populate either inventory and/or condition assessment databases. The paper also identified several IT challenges that arise with respect to collecting, managing, and analyzing asset data. The challenges include asset identification, asset location, data availability, data fragmentation, and unsuccessful data collection automation. Their model is regarded as an advanced asset management system because it is capable of modeling system performance [18]. In addition to the challenges outlined by the authors, another challenge that should be managed or addressed is the likelihood of data errors. The significance of data error in asset management contributes to the effectiveness of recommendations suggested by an analytical tool.

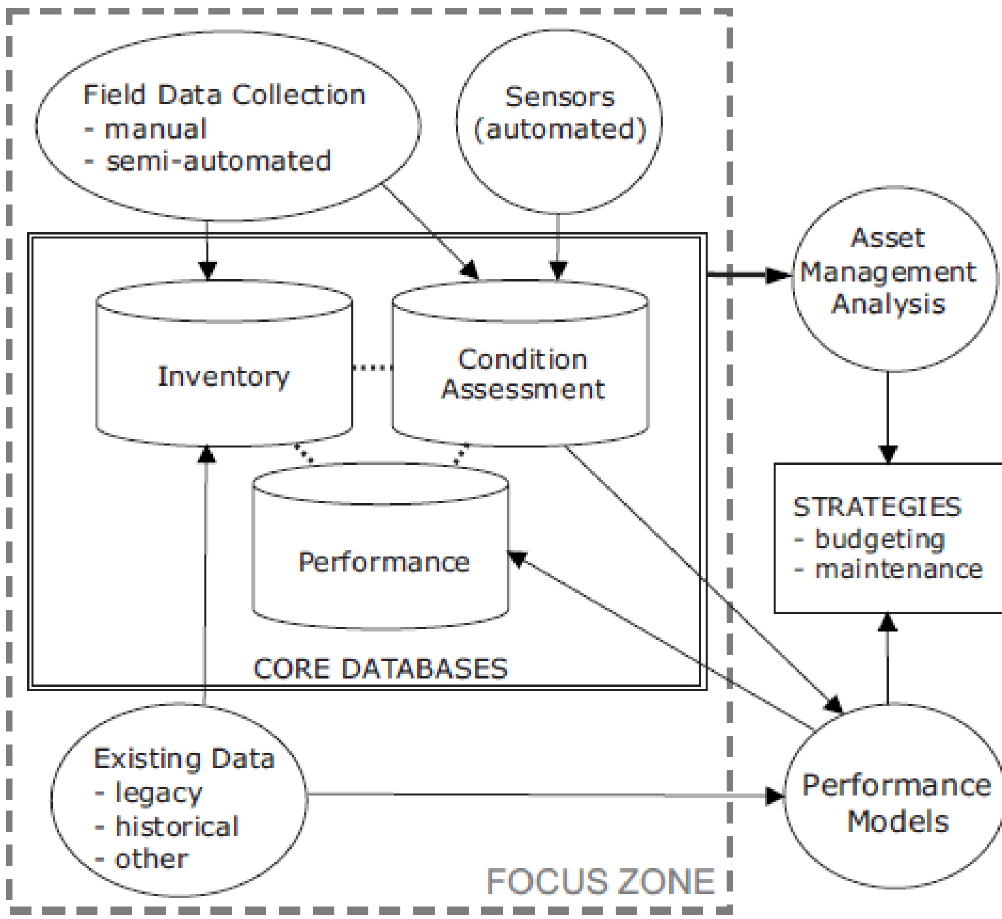

Figure 2.5 IT Interactions Model in an Advanced Ancillary Transportation Asset Management System [18]

2.5 Geographic Information System

Another system that complements the asset management process is a geographic information system (GIS). The GIS is capable of integrating hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. Figure 2.6 illustrates a complete GIS for organizing roadway maintenance proposed by the Environmental Systems Research Institute (ESRI). Transportation agencies can track, locate, and manage the transportation assets through the use of a GIS-based enterprise asset management (EAM), which offers a user-friendly environment. Through the use of GIS technology, transportation asset managers can view, query, and understand data in many ways.

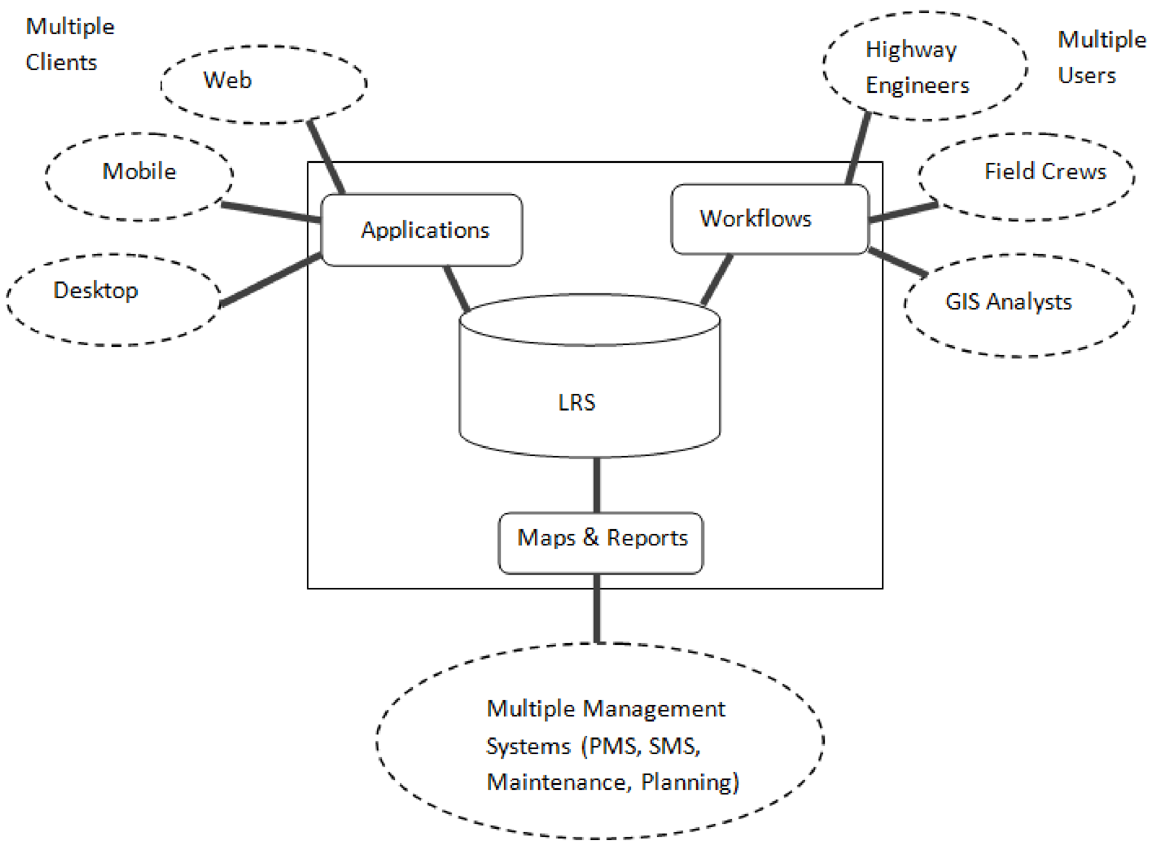

Figure 2.6 Complete Systems for Roadway Maintenance Organization [49]

Using GIS as a tool in managing transportation infrastructure assets offers numerous benefits. For one, the processes of making informed decisions and prioritizing projects are enhanced by the visualization of competing assets and the surrounding environment. Another benefit is the unique ability of GIS to integrate with a wide gamut of technologies facilitating data integration and decision making. In addition, a GIS-based asset management system can efficiently schedule activities (e.g., asset upgrade or repair) and track work tasks, personnel, equipment, and material usage. In reality, most DOTs report only limited success in both using good asset management practices and incorporating GIS into their asset management practices [19]. However, other DOTs have made positive advances in the use of GIS for asset management. For example, the Ohio Department of Transportation (ODOT) has developed several state-of-the-art GIS standards and geospatial applications to help allocate resources [20]. One such application developed by the ODOT is the Buckeye Asset Data Collection System (BADCS), a web-based video application capable of collecting large-scale asset inventories on ODOT roadways more efficiently.

The BADCS also includes a mobile asset management application capable of operating on any Windows mobile device with GPS capability, ensuring that data is updated as it is being changed in the field. The combination of all these systems has aided ODOT to achieve and surpass its business goals. In fact, the agency was able to collect data on tens of thousands of assets valued at millions of dollars in less than three months [20]. Figure 2.7 illustrates screenshots from a mobile device. The BADCS is currently being utilized by ODOT Districts 1 and 2.

Figure 2.7 Screenshot from ODOT's BADCS Mobile Devices [20]

Another DOT that has effectively utilized GIS in their asset management process is the Maryland State Highway Administration (SHA). The SHA uses GIS to accurately track and efficiently manage sidewalks along all state routes and highways to ensure that they comply with the Americans with Disability Act (ADA) [21]. The system has improved SHA business processes by making fast and accurate sidewalk data available to decision makers. Indeed, over a period of eight months, the SHA collected data on sidewalks along state routes and highways (nearly 900 miles) [21]. The application system has not only enabled SHA to measure its performance in improving facilities, but also guided the sidewalk improvement program so that it focuses on improvements in which the need is most significant and uses funding for the greatest benefit. For example, the GIS-based system helped SHA identify areas with high pedestrian traffic. Data on pedestrian volumes and pedestrian accidents are utilized in the GIS and this improves the prioritization of sidewalk improvement projects. The interactive nature of the GIS enables users to view SHA videos of sections of roadways and to assess the condition of sidewalks and their attributes, whether the sidewalks are ADA compliant or not. Figure 2.8 shows a screenshot of a roadway section of the SHA system.

Figure 2.8 Screenshot of a Roadway Section of the SHA System [21]

2.6 Risk and Uncertainty

All these technological systems can be made more useful in asset management if they incorporate the risk and uncertainty pertaining to the physical assets. The potential for negative events and consequences constitute opportunities for risk. In the context of safety, risk is viewed as a negative consequence. Thus, the focus of risk management is to mitigate the negative consequences. Risk can be defined in various ways depending on context. Despite the variations in all the definitions, they all acknowledge two main characteristics related to uncertainty and consequences. The *Webster's Collegiate Dictionary* defines risk as the chance of loss, the degree of probability of loss, the amount of possible loss, or the type of loss that an insurance policy covers [13]. In the literature, the definition of risk usually makes reference to an uncertain cause that results in some sort of damage to an existing entity. This uncertain cause is usually referred to as a risk event. In the context of technical risk event analysis, a numerical value is assigned to the risk [9]. This value is obtained by multiplying the probability of the risk event by the consequence of the event. However, the formulation of risk in this form for decision making fails to incorporate the societal dimensions of risk (i.e., the political and ethical dimension of risk are not taken into account) [9]. In the decision-making process, risk assessment is defined as a systematic process that incorporates the evaluation of uncertainties, the development of policies, and the possible consequences of such policies [14].

Uncertainty rises as a result of sparse data availability and incomplete knowledge in the decision-making process [15]. Uncertainty also exists as a result of the inherent randomness associated with systems and events [16]. Uncertainty can, therefore, be attributed to three different types of errors in risk-based decision making for infrastructure: data errors, modeling errors, and forecasting errors. Amekudzi and McNeil, for example, demonstrate the impact of data and model uncertainties associated with highway investment needs analysis [17]. That is, how do these uncertainties impact the optimal solution? Other studies have also shown how optimal maintenance programs can be impacted significantly with small adjustment to their input parameters [18]. In fact, the level of confidence in the decisions made from the use of these outputs depends on how accurate the input data is. Although these errors could be reduced through the use of statistical models, it must be noted that the extent of reduction of these errors is limited [15]. Pate-Cornell discusses when and why a full uncertainty analysis is justified because of the complexity and cost involved [19]. However, the process of reducing uncertainty helps to represent risks with increasing levels of confidence.

2.7 Likelihoods and Consequences

As mentioned above, risk is measured in terms of likelihoods and consequences. The probability of occurrence of some future event can sometimes be calculated precisely with no uncertainty. Other rare future events, however, are forecasted or predicted with a considerable amount of uncertainty. This level of uncertainty inherent in the forecasting process gives rise to risk. Kaplan and Garrick define risk to be a set of scenarios, s_i, each with probability p_i and consequence x_i. If the scenarios are ordered in terms of the increasing severity of the consequences, then a risk curve can be plotted [20]. Another refined notion of risk by Kaplan and Garrick talks about the frequency with which an event might take place instead of using the probability of occurrence of the event. In this context, they introduce the notion of an uncertainty about the frequency with which the event will occur (i.e., the "probability of a frequency") [20].

One challenging factor in measuring risk is the inability to precisely quantify all resulting consequences. Despite the fact that the cost of replacement or repair, or the maintenance cost of some assets may be easily quantified and incorporated in the consequences quantification process, other costs such as societal costs may be very difficult to estimate. To help agencies understand the consequences associated with the failures as they occur, agencies need to accurately track asset failures. Again, accurate tracking would also enable agencies to quantify the likelihoods/probabilities of failure of these assets. Both of these factors would facilitate the risk categorization process. An agency that tracks the condition of its ancillary assets and implements strategic management actions is likely to benefit from the reduction/elimination of unexpected failure of these assets as well as saving on emergency repairs resulting from the unexpected failures.

2.8 Types of Risks

The consequence of a risk occurrence differs depending on the type of failure an asset experiences. Ancillary transportation assets are subjected to numerous types of failure that can be grouped under various categories. The two types of failure under consideration in this paper are catastrophic and non-catastrophic (performance) failures, which result in two types of risk. One is catastrophic risk, which results when a catastrophic failure occurs. Catastrophic failures are failures that are caused by the occurrence of extreme events which are defined as having a low likelihood of occurrence, but with catastrophic results [27]. Examples of such events are earthquakes, hurricanes, and floods. Therefore, the probability of occurrence and the consequences of such failures are termed catastrophic risk. An example of a catastrophic failure is the collapse of a section of the retaining wall in hilly northern Manhattan onto the Henry Hudson Parkway in 2005, sending tons of dirt, rocks, and trees onto the roadway, stopping traffic for miles around, and leading to the evacuation of nearby buildings [28]. The other type of risk is non-catastrophic risk, which results from the occurrence of non-catastrophic or performance failures. This type of failure is caused by the inability of an asset to properly offer the service for which it was built. Any reduction in operational performance below the minimal level of service is referred to as a performance failure. Thus, the probability of occurrence and the consequence of such failures can be termed non-catastrophic or performance risks.

2.9 Risk Assessment and Risk Management

The risks associated with the failure of ancillary transportation assets can be managed effectively only if they are assessed correctly. The meaning of the term management may vary in many ways depending on the discipline and/or context in which it is being used [41]. Risk assessment and risk management, which remain essential components of any asset management process [34], are two distinctive processes; however, the term risk management is sometimes used to describe both the risk assessment and risk management processes [42]. Risk assessment refers to the scientific process of measuring risks in a quantitative and practical manner. Kaplan and Garrick describe the risk assessment process as an attempt to answer a set of three questions: What can go wrong, what is the likelihood that it would go wrong, and what are the consequences? [29]. Through these three questions, the inherent risks are identified, measured, quantified, and evaluated, and subsequently, their consequences and impacts established. Effectively, the risk assessment process objectively accomplishes an assessment to foresee negative effects or risks so that adverse consequences can be minimized [24]. The assessment process identifies a single event or a sequence of events that can lead to these adverse consequences. These single events or sequences of events are called scenarios. Examples of such events could be the failure of a traffic signal, the failure of a pavement marking, the failure of a sign, or the failure of a culvert. Any of these events could lead to consequences: higher costs of repair, reduction in network mobility, or delay in travel time. The risk assessment process is dependent on the views, the knowledge, and the experience of individuals or experts.

Unlike risk assessment, risk management is a qualitative process that involves the selection and implementation of a risk mitigation strategy that alleviates or accepts the specific risk under consideration [23]. Risk management, which focuses on addressing uncertainties in a proactive manner in order to minimize threats, maximize opportunities, and optimize achievement of objectives, is a proper platform for solving critical infrastructure preservation tasks. In addition, the risk management process also attempts to answer three main questions [42]: What are the available options, what are the associated trade-offs, and what are the impacts of current decisions on future options? These questions build up from the risk assessment process. The last question, which evaluates the impacts of current decisions on future options, is the most critical of all the three questions for managerial decision making [41]. In order to believe that the decision made is optimal or reflects the desired tradeoffs of decision makers and their stakeholders, policy makers would have to ascertain that they have reasonably optimized the benefits of current decisions with respect to future options. This is achieved by weighing the negative and the positive effects of current decisions on future decisions. In the context of transportation asset management, AASHTO defines risk management as "a process of identifying sources of risk, evaluating them, and integrating mitigation actions and strategies into routine business functions of the agency" [1].

2.10 Risk Modeling

The risk inherent in any situation can effectively be managed if it is better understood. Risk modeling can follow two approaches: quantitative and qualitative assessments. The quantitative risk assessment approach quantifies the likelihood (probability) and outcomes (consequences) of a future negative event (e.g., the failure of a transportation asset) and multiplies them to obtain the risk of the event. As an illustration, consider n potential consequences resulting from n potential likelihoods of future events. Then, risk can be defined quantitatively as a collection of n pairs.

$$\text{Risk}= \{(Li,O1),\ldots\ldots\ldots\ldots\ldots\ldots\ldots, (Ln,On)\},$$

where Oi and Li denote the consequences (i.e., outcomes) of i and its likelihood, respectively.

An example of an analysis tool used in quantitative risk analysis is Monte Carlo Simulation. Other methods such as fault tree analysis, Bayesian inference, and fuzzy arithmetic can also be used to quantify risk.

In contrast to quantitative risk analysis, qualitative risk analysis employs a set of standard parameters: severity, impact, and mitigation. In this approach, the probability of an event may be unknown, not agreed upon, or not recognized to have any consequence [30]. Examples of such approaches used in qualitative risk analysis are fuzzy theory, failure mode and effects analysis (FMEA), and preliminary risk/hazard analysis [31]. In fact, a list of examples of risk assessments methods is presented in Table 2.1. Qualitative risk assessment also assigns relative values for measures of risk based on ranking or separation into descriptive categories such as low, medium, high; not important, important, and very important; or other ordinal scales such as a scale from 1 to 10. Three types of risk models for risk assessment—matrix, probabilistic, and index models—are outlined by Muhlbauer [32]. Another model enjoying increased applications is the Real Options model. These models are discussed in some detail below.

Table 2.1: Risk Assessment Methods [48]

Method	Scope
Safety/Review Audit	Identifies equipment conditions or operating procedures that could lead to a casualty or results in property damage or environmental impacts.
Checklist	Ensures that organizations are complying with standard practices.
What-If	Identifies hazards, hazardous situations, or specific accident events that could result in undesirable consequences.
Hazard and Operability Study (HAZOP)	Identifies system deviations and their causes that can lead to undesirable consequences and determine recommendation actions to reduce the frequency and/or consequences of the deviations
Preliminary Hazard Analysis (PrHA)	Identifies and prioritizes hazards leading to undesirable consequences early in the life of a system. It determines recommended actions to reduce the frequency and/or consequences of the prioritized hazards. This is an inductive modeling approach.
Probabilistic Risk Analysis (PRA)	Quantifies risk, and was developed by the nuclear engineering community for risk assessment. This comprehensive process may use a combination of risk assessment methods.
Failure Modes and Effects Analysis (FMEA)	Identifies the equipment failure modes and the impacts on the surrounding components and the system. This is an inductive modeling approach.
Fault Tree Analysis (FTA)	Identifies combinations of equipment failures and human errors that can result in an accident. This is a deductive modeling approach.
Event Tree Analysis (ETA)	Identifies various sequences of events, both failures and successes that can lead to an accident. This is an inductive modeling approach.
The Delphi Technique	Assists experts to reach consensus on a subject such as project risk while maintaining anonymity by soliciting ideas about the important project risk that are collected and circulated to the experts for further comments. Consensus on the main project risks may be reached in a few rounds of this process.
Interviewing	Identifies risk events by interviews of experienced project managers or subject-matter experts. The interviewees identify risk events based experience and project information.
Experienced-Based Identification	Identifies risk events based on experience including implicit assumptions.
Brain Storming	Identifies risk events using facilitated sessions with stakeholders, project team members, and infrastructure support staff.

2.10.1 Matrix Models

One of the simplest modeling methods used in risk assessment is the matrix model. The matrix model, as the name suggests, assess risk categories using a risk matrix, which is a two-dimensional presentation of likelihood and consequences using qualitative metrics for both dimensions, with each (probability and consequence) assessed as low, medium, or high. A matrix model can sometimes rank a risk event by assigning simple numerical scales to the likelihood and consequences of the event (e.g., the scale of zero to five mapped to "not likely" to "most likely," respectively). This approach of risk ranking requires the elicitation of expert opinions. Figure 2.9 illustrates a sample risk matrix defining the various risk severity zones depending on the likelihood and consequence of the event.

	CONSEQUENCES				
LIKELIHOOD	Insignificant	Minor	Moderate	Major	Extreme
Rare	Low	Low	Low	Low	Low
Unlikely	Low	Low	Low	Moderate	Moderate
Possible	Low	Low	Moderate	Moderate	Moderate
Likely	Low	Moderate	Moderate	High	High
Almost Certain	Low	Mderate	Moderate	High	Extreme

Figure 2.9 Sample Risk Matrix

2.10.2 Probabilistic Risk Models

Another modeling approach usually employed in risk assessment is probabilistic risk analysis (PRA) through which an initiating event is transformed into a risk profile by adopting a systematic approach [33]. PRA exhibits a superior predictive ability amongst all the other risk models. This superior characteristic is attributed to the fact that this model relies heavily on historic failure data and event/fault-tree analysis, making it highly data driven [32].

2.10.3 Indexed-Based Risk Models

The indexed-based risk model is also used in risk assessment. The indexing method of modeling depends on either statistical or engineering judgment. This method assigns relative weights to the individual components of the asset that contribute to the risk event, depending on how much influence the components have on the failure of the asset. In this case, the risk of failure of an asset is based on the probability, or likelihood, of failure of the individual components that contribute to the overall probability of failure [32].

2.10.4 Real Options Models

Risk assessment methodologies have evolved over the years, giving rise to the emergence of one assessment tool known as the real options model, which has been applied to analyze risk in the transportation management process [34]. The Real Options approach is one that captures the investor's flexibility to optimize the timing of his or her investment. Real Options methodology considers investments in assets as options (i.e., permits with different values at different time periods to undertake some business decision). The Real Options model offers a nuanced approach to strategic investment that considers the value of opened options for budget decision makers [35]. The approach involves developing estimates of the benefits from an investment project and discounting them to their present value at the discount rate that reflects the market price of the risky project.

2.11 Benefits of Risk Management

Adopting risk as a management decision-support tool for transportation infrastructure systems offers several benefits. For one, prioritizing the inclusion of ancillary transportation assets into existing asset management systems by using risk management enables transportation agencies to better balance limited funds to provide adequate levels of service for their customers. In addition, risk management facilitates the efficient allocation of limited transportation resources. Resources are often directed to the highest-risk assets after the agency evaluates their associated risks. That is, within an asset class, risk management can be used to optimize the "return-on-investment" of competing assets for a single objective analysis. However, in the case of multi-objective analysis, it is challenging for agencies to achieve this goal. In situations in which different objectives are under consideration, one may have to perform trade-off analyses and not focus solely on optimizing the "return-on-investment." The effective mitigation of such risk leads to the reduction of the likelihood of risk events. Reduction of event likelihood in turn translates into reduced failures. In addition, effective risk mitigation strategies also lessen the consequences associated with the failure of an asset.

Another benefit of risk management is that it can enable asset managers make a better case to decision makers for resources. By quantifying or assessing the probability of failure and consequence of failure of an asset, that is, estimating the risk of failure, asset managers are able to justify why more resources should be made available to manage such failing assets. In addition, responses to situations are made quicker in the event of a failure. Knowing the magnitude of the risks associated with the failure of an asset, agencies are able to put in place strategic response procedures for any envisioned failure. This benefit is much more critical for catastrophic failures. This is because the probabilities of such failures are difficult to quantify, and if they occur, they should be managed proactively as opposed to being addressed reactively.

2.12 Failure of Ancillary Transportation Assets

Before the risk of failure of an ancillary transportation asset is addressed, it is essential to understand why and how these assets fail. There are many ways in which a transportation asset can fail. All else being equal, transportation assets usually fail as a result of lack of effective and timely maintenance, repair, or rehabilitation. Undertaking these activities to preserve and to prolong the service life of the transportation system assets is a complex, large-scale activity that is not only affected, but is also influenced, by many elements [29]. As noted earlier, the failures experienced by ancillary transportation assets can be classified into two main categories: catastrophic failure and non-catastrophic or performance failure. While catastrophic failures tend to be rare, performance failures, in contrast, are very common. There are many causes of performance failure for any given class of assets. Table 2.2 shows some examples of elements that should be rated to assess the performance of an ancillary transportation asset. In fact, Table 2.3 illustrates the FHWA and the National Park Services (NPS) checklist of elements for the performance of ERSs in their Retaining Wall Inventory Field Guide (WIFG) based on the wall structural type.

Many ancillary transportation assets have experienced various types of catastrophic failures. In 2006, Perrin conducted a study to review some examples of failed culverts in the United States [46]. Parts of the survey questionnaire sent to transportation agencies in the United State queried for documentation on any failures during the past 10 years, and the agencies' current procedure for documenting culvert failures. The study further obtained more specific information from agencies that had documented failures within their jurisdiction within the past 10 years. Examples of such specific information includes: location, duration of repair, and culvert details and the costs involved in repairing or replacing the culvert. The study also presented a few examples of culvert failures, as illustrated by Figures 2.10 to 2.12. In addition to the failed culverts, Figures 2.13 and 2.14 illustrate some examples of failed signs, and Figure 2.15 is an illustration of a failed ERS.

Table 2.2: Sample of Factors Affecting Performance of Assets

Asset	Category	ID	Year Built	Static Data (Long/Lat)	LOCATION	Condition Element
Culvert	Corrugated Pipe				Across Freeway	Cracking
						Corrosion
						Infiltration
						Distortion or Deflection
						Surface Settlement
Lighting	Steel Support				Arterial	Pole Condition
						Lens Condition
						Bulb Condition
Pavement Marking	Tape					Retro Reflectivity
	Solvent Base					Cracking
	Epoflex					Night Visibility
						Day Visibility
						Marking Thickness
						Bead Density
						Uniformity
Traffic Signals						Corrosion
						Truss Seat
						Base Plate
						Anchor Rod
						Pole to Base Plate Connection
						Mast Arm to Pole Connection
						Luminaries
ERS						Deformation
						Settlements
						Panel Condition
						Drainage
						Reinforcement Metal Loss
Guardrail						Splice Connections Condition
						Post Condition
						Rail Condition
						Blockout Condition

Table 2.3 Wall Elements Rated to Assess the Performance of Retaining Walls [5]

WALL TYPE	PRIMARY ELEMENTS	Piles and Shafts	Lagging	Anchor Heads	Wire/Geosyn. Facing Elements	Bin or Crib	Concrete	Shotcrete	Mortar	Manufactured Block/Brick	Placed Stone	Stone Masonry	Wall Foundation Material	Other Primary Element	SECONDARY ELEMENTS	Wall Drains	Architectural Facing	Traffic Barrier/Fence	Road/Sidewalk/Shoulder	Upslope	Downslope	Lateral Slope	Vegetation	Culvert	Curb/Berm/Ditch	Other Secondary Element	WALL PERFORMANCE	Performance
[AH] Anchor, Tieback H-Pile		●	●	●									●			●			○	○	○	●						●
[AM] Anchor Micropile		●		●									●			●			○	○	○	●						●
[AS] Anchor, Tieback Sheet Pile		●		●									●			●			○	○	○	●						●
[BC] Bin, Concrete						●							●			●			○	○	○	●						●
[BM] Bin, Metal						●							●			●			○	○	○	●						●
[CL] Cantilever, Concrete							●						●			●			○	○	○	●						●
[CP] Cantilever, Soldier Pile		●	●										●			●			○	○	○	●						●
[CS] Cantilever, Sheet Pile		●											●			●			○	○	○	●						●
[CC] Crib, Concrete						●							●			●			○	○	○	●						●
[CM] Crib, Metal						●							●			●			○	○	○	●						●
[CT] Crib, Timber						●							●			●			○	○	○	●						●
[GB] Gravity, Concrete Block/Brick									●	●			●			●			○	○	○	●						●
[GC] Gravity, Mass Concrete							●						●			●			○	○	○	●						●
[GD] Gravity, Dry Stone											○	○	●			●			○	○	○	●						●
[GG] Gravity, Gabion					●								●			●			○	○	○	●						●
[GM] Gravity, Mortared Stone									●		○	○	●			●			○	○	○	●						●
[MG] MSE, Geosyn. Wrapped Face					●								●			●			○	○	○	●						●
[MP] MSE, Precast Panel							●						●			●			○	○	○	●						●
[MS] MSE, Segmental Block										●			●			●			○	○	○	●						●
[MW] MSE, Welded Wire Face					●								●			●			○	○	○	●						●
[SN] Soil Nail								●					●			●			○	○	○	●						●
[TP] Tangent/Secant Pile		●											●			●			○	○	○	●						●
[OT] Other, User Defined													●			●			○	○	○	●						●

● Wall elements that should always be rated for the given wall type (others may also apply).

○ 1 of 2 primary wall elements required depending on material observed.
2 of 3 secondary wall elements required depending on wall location relative to roadway.

Road/Sidewalk/Shoulder: Rate only when these elements lie within the influence of the wall. The shoulder is generally defined as extending no greater than 5 ft horizontally from the roadway/sidewalk, and less than -5 ft vertical offset.

Upslope: Rate the upslope condition for all walls above roadway grade, regardless of slope ratio. Rate the upslope condition for all walls below roadway grade, regardless of slope ratio, when the vertical offset to the wall from the roadway/shoulder is greater than 5 ft (otherwise evaluate the condition of the upslope under the "Road/Sidewalk/Shoulder" element).

Downslope: Rate the downslope condition for all walls below roadway grade, regardless of slope ratio. Rate the downslope condition for all walls above roadway grade, regardless of slope ratio, when the vertical offset to the wall from the roadway/shoulder is greater than 5 ft (otherwise evaluate the condition of the downslope under the "Road/Sidewalk/Shoulder" element).

Figure 2.10 Bakersfield, California Sinkhole [46]

Figure 2.11 Owings Mills Mall Sinkhole in Baltimore, Maryland [46]

Figure 2.12 Highway-40 Failure in 2005 between Montreal and Quebec City [46]

Figure 2.13 Example of a Failing Road Sign

Figure 2.14 A Failed Cantilever Sign Structure [40]

Figure 2.15 Failed Earth Returning Structure along Riverside Drive near Manhattan in New York [37]

Figure 2.16 Damaged Guardrails [50]

2.13 Consequences of Failure

Consequences arise as a result of the failure of ancillary transportation asset. The consequences of failure of ancillary transportation assets may be defined as any negative loss or impact, directly or indirectly, experienced as a result of the failure of the asset. Two main categories of consequences can be classified: agency consequences and user consequences. User consequences are classified as the losses experienced by the system users, while the loss of failure experienced by the agency is said to be the agency's experienced consequence. Again, the consequences of failure can be classified as direct or indirect consequences. Direct consequences resulting from the failure of an asset include replacement cost, repair cost, environmental degradation cost, and remediation costs of which are considered consequences associated with the agency, and fatalities, bodily injuries, delay, and property damages are considered consequences associated with the user. In contrast, litigation, political reactions, dissatisfaction of customers, fines, and penalties constitute indirect consequences [32]. As an illustration, the 2006 study by Perrin mentioned above outlines some consequences of failure surrounding culverts [46]. Table 2.4 outlines a few catastrophic failures of culverts within the United States and their associated consequences as documented by Perrin. The study concludes that most of these failing culverts were corrugated metal pipes, which had reached their life expectancy age, but with no systematic replacement plan in place to replace them [46]. Other consequences resulting from the failure of ancillary transportation assets have also been documented in the literature. For one, the Palm Beach Post in Lake Worth, FL, reported that one person died while three other people sustained various degrees of injuries in 2010, after they were in a traffic accident that involved 3 vehicles at an intersection with a malfunctioning/failed traffic light [52]. In addition, the County of Camden, New Jersey was found liable for a car accident in which a driver crashed through a guardrail that county officials knew was faulty. The teen driver ended up having his left leg amputated and a jury awarded him a record $31 million in damages [53].

Table 2.4: Examples of Culverts Failures and Consequences in the United States [46]

Location	I-70-CO	I-480-OH	SR 79-OH	5400 S-UT	I-70 -CO Eisenhower	Prudenville-MI	Milton-ON
Pipe Size / Type	66" CMP	60" CMP	30" CMP	72" CMP	60" CMP	73"x55" ellipse, CMP	30" CMP
Costs of Replacement ($)	4,200,000	384,000	NA	48,000	45,000	95,000	
Length (ft)	85-100'		50'	50'	40'	50'	40'
Days	49	8	6	5	7	6	1
Impacted AADT	20950	16760	4920	19338	1257	5100	45000
Delay	120 min	60 min	20 min.	20 min.	30 min	20 min	240 min
User Cost ($)	4,046,000	3,079,000	290,000	693,000	220,000	249,000	5,033,000
Total Costs ($)	8,246,000	3,463,000		741,000	265,000	344,000	
Age (yrs)	35-60	60	30+	20	30	30	25
% Construction	51	11		6	17	28	
% User cost	49	89		94	83	72	
Normal Replacement cost	$18,000-50yr $30,000 - 100 yr	$15,000 - 50 yr $28,000-100yr	NA	$7,200 -20 yr$13,400-100 yr	NA	NA	NA
Total Emergency Replacement Cost	4,200,000	384,000	NA	47,800	45,000	95,000	NA
ERF	140	14	NA	4	NA		
Number of Replacements	1	1	3	4	2	2	3
Emergency Replacement Installation Costs (2003 $)	4,200,000	384,000	NA	192,000	90,000	190,000	NA
User Delay Costs for all Replacements (2003 $)	4,046,000	3,079,000	870,000	2,772,000	440,000	498,000	15,099,000
Total Costs for 100 yr Horizon (2003 $)	8,046,000	3,463,000	NA	2,964,000	530,000	688,000	NA
Estimated Cost to change to 100 year pipe (2003 $)	12,000	13,000	NA	6,200	4,500	6,200	NA
Benefit/ Cost Ratio	671	266	NA	478	118	111	NA

All cost rounded to nearest $1,000

CHAPTER 3

RISK-BENEFIT-COST ANALYSIS TO PRIORITIZE ANCILLARY TRANSPORTATION ASSETS FOR MANAGEMENT: CRITICAL ELEMENTS

3.1 Risk Framework

In light of the literature reviewed for this study, this section discusses basic elements of a risk-based cost-benefit framework that can help asset managers and decision makers to rank and prioritize ancillary transportation assets for inclusion in existing asset management programs. The section discusses seven basic risk elements and three basic cost-benefit elements that can form the basis of a conceptual framework to properly make a business case for complementary or competing assets to prioritize them for inclusion in an existing formal asset management program. These elements are common in various risk and cost-benefit management processes. Figures 3.1 and 3.2 show the conceptual frameworks proposed.

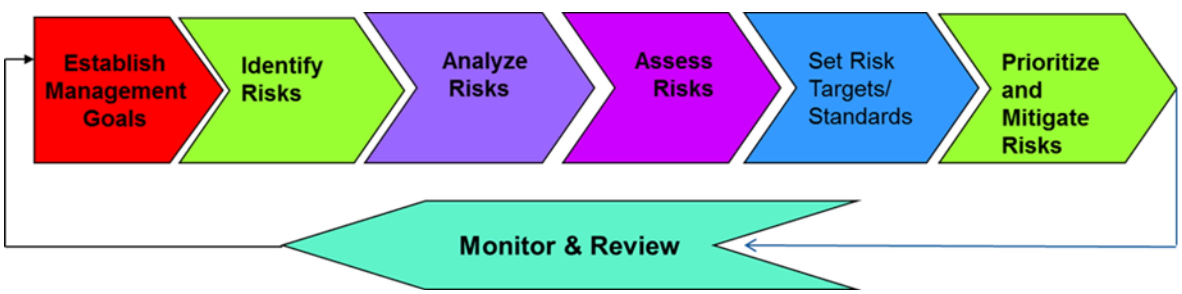

Figure 3.1 Conceptual Risk Framework for Decision Making [1]

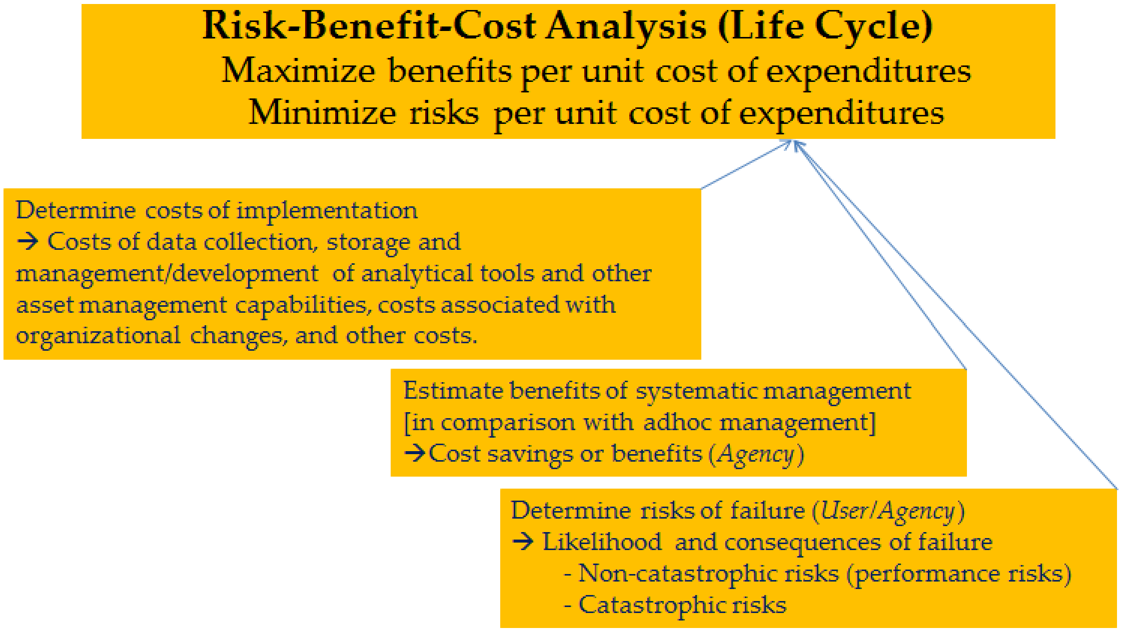

Figure 3.2 Conceptual Risk-Benefit-Cost Framework for Decision Making

3.2 Elements of Risk Framework

3.2.1 Identify Management Goals

Identifying management goals is one of the most important steps in the risk management process because objectives must exist before management can identify potential actions to achieve these objectives. Within the context of the agency's established mission or vision, strategic objectives and written policies must be aligned. The focus of the agency then becomes working towards the achievement of these objectives.

3.2.2 Identify Risks

The next step after identifying management goals is identifying risks. The objective of the risk identification process is to identify all the assets foreseen to be at risk with respect to the agency's strategic short- and long-term goals. The identified assets are examined to identify any failure scenarios (i.e., identifying what can happen to the asset of interest). The causes of such scenarios are also identified. The risk identification process exposes and records all foreseeable risks that could affect objectives.

3.2.3 Analyze Risks

After risk identification is risk analysis. The risk analysis process accomplishes two objectives: determining the likelihood and consequence of failure. That is, the risk analysis process is a comprehensive and systematic process of breaking down risk into its underlying elements. This process presents a few challenges due to the limited availability of condition or historic data for many ancillary assets. This limitation makes the determination of probabilities and consequences very much subjective. However, elicitation of expert knowledge and engineering judgment can aid the decision making process.

3.2.4 Assess Risks

After analyzing the risk, likelihoods and consequences are then converted into risk numbers. Depending on the risk modeling approach adopted in the analysis process, the resultant risk of each asset is ascertained. This process basically quantifies and categorizes the risks so that they can be ranked. The ranking identifies which asset is of extreme, high, moderate or low priority. Indeed, the risk assessment process can require as well as provide both qualitative and quantitative data to decision makers for use in risk management. Table 3.1 illustrates four categories of risk zones as identified by Najafi and Salem for culvert management [43], and Table 3.2 also illustrates different categories of risk effects that result as a consequence of non-maintenance of highway assets [38].

TABLE 3.1: Sample Risk Categories [43]

General Appraisal	Risk Zone
9,8	Routine maintenance sufficient, no repair required
7,6	Culvert needs repair
5	Culverts needs several repairs or renewal
4,3,2,1,0	Culverts needs to be renewed or replaced

Table 3.2: Categories of Risk Effects and Most Likely Consequences Resulting from Non-Maintenance of Assets [38]

Risk Effect	Examples
Critical	Multiple fatalities Multiple injuries Complete loss of service Loss of military mobility Total area inaccessibility Major traffic disruption
Moderate	Partial loss of services Partial lane closure Moderate number of fatalities Moderate number of injuries
Minor	Slight increase in maintenance costs Temporary traffic disruption

3.2.5 Select Risk Targets/Standards

Once the risk is assessed, the agency will have to define the thresholds for acceptable risk. This is normally dependent on the agency's and public's attitude toward risk. Risk can be perceived differently by the society or different segments of the society. Aktan and Moon explain how society is more willing to tolerate the risk of a traffic accident than the risk of a bridge failure due to natural events. The risk of a traffic accident, however, is far greater than the risk of an earthquake [44]. Starr also suggests that the degree of voluntariness affects the trade-off between risk and benefit [45].

3.2.6 Adopt a Mitigation Strategy

For a given set of risks and their ranking from the risk assessment step, the next phase of the risk management process is to select a comprehensive strategy for mitigating the risks in a cost-effective manner. In essence, the objective of this step is to make the best use of limited resources to maximize the benefits of investment while minimizing the risks to the general public using the assets under consideration, taking into consideration the risk attitude of the user of the system. Any suggested mitigation activities must take into account cost, time to implement, likelihood of success, and impact over the entire life-cycle of the asset. A risk mitigation strategy must be constrained by management's short- and long-term goals. The strategy must also directly identify monitoring procedures that can be used to demonstrate that risks have been properly mitigated.

3.2.7 Performance Measurement

The risk management process is not a unidirectional process. The process is a continuous feedback loop. Each phase of the risk management process should be reviewed against and aligned to the objectives of the organization. Management objectives/goals are used as guidance to monitor the performance of the process. This process answers a fundamental question: did you meet management goals? If not, the whole process starts over again. This check turns the risk management process into a cyclic event to meet management objectives. The cyclic characteristic of the risk management process helps the decision-making process to improve. In order to achieve this process, the risk framework requires interaction or collaboration and exchange of information and opinions among stakeholders (e.g., surveying the road users to ascertain their level of satisfaction with network performance). It often involves multiple messages about the nature of risk or expressing concerns, opinions, or reactions to risk managers or to legal and institutional stakeholders for risk management. Risk communication is a great way to define the risk acceptance levels of an agency (including the system users' risk acceptance levels) and helps define the acceptance criteria to achieve the agency's transportation network objectives.

3.3 Elements of Benefit-Cost Framework

Inasmuch as transportation agencies make efforts to manage the risk of failure of their ancillary transportation assets, it is essential to minimize the cost, or to achieve this effort with maximum cost savings (i.e., for a given set of asset classes, how does an asset manager select the alternative with the highest benefits) while minimizing the risk and the cost of implementation. To accomplish this objective, agencies and asset managers must invest significant efforts to maximize their benefits per unit cost of expenditure over the lifecycle of their assets. In order for transportation agencies to achieve this objective, they must first determine the costs involved in establishing, implementing, and maintaining a formal management system over the life cycle of individual assets. For example, the asset manager should determine costs such as: data collection, management, and storage costs, any anticipated costs for the development of analytical tools and all other costs associated with the establishment of the system. Whereas data collection costs involve all costs/expenditures associated with gathering raw data (i.e., both inventory and attribute data) on individual assets from the field, other costs involve but are not limited to costs of maintaining the system (i.e., acquisition of IT hardware and IT personnel, if necessary). Although the cost of gathering data is contingent on the type of asset (e.g., usage, location, complexity), today, with the advent of new technologies, data gathering, data storing, and data analysis could be accomplished in a fast and efficient manner. The objective of the asset manager is to select the technology that yields the highest return per unit cost of expenditure when the system is finally implemented.

In addition to determining the cost of implementation of the management system, another indispensable element of the benefit-cost framework that asset managers need to consider is estimating the benefits (i.e., both the dollar and nondollar benefits after program implementation) associated with the systematic management of ancillary transportation assets. Despite the challenges involved in the estimation of benefits that accrue from instituting asset management systems, it is critical that the asset manager quantify the benefits that such a system would yield, as opposed to the adhoc form of management. In this way, the asset manager would be in a better position to properly make a business case for why an asset category should be prioritized for inclusion in existing management systems.

While this thesis focuses primarily on risk factors, it should be mentioned here that risk factors should be combined with other benefit and cost factors to evaluate formal programs for asset management more comprehensively. Relevant cost and benefit factors include standardized operation and maintenance, repair and rehabilitation costs, user costs, salvage value, and other costs associated with providing the required level(s) of service for system users. Standardized costs for operating and maintaining the systems under consideration before and after program implementation provide an indicator of the value of adopting formalized asset management procedures. Equation 3.1 below captures key costs and benefits factors that would help assess the benefits of a formal asset management program in terms of the reduction in agency costs in operating the system at desired level(s) of service and the reduction of the costs of the system users after implementation of formal asset management program.

$TAWOMC_{x,n} = [\sum ((CC_{x,t} + MO_{x,t} + UC_{x,t}) * PWF_{x,t}) – RSW_{x,n} * PWF_{x,n}] * AWF$ … Eqn. 3.1

Where:

$TAWOMC_{x,n}$ = Total Annual Worth of Operating and Maintenance Costs for asset x for analysis period of n years$(ICC)_{x,}$ = Initial Capital Costs of establishing a system for asset x

$(CC)_{x,t}$ = Capital Cost of Replacing the System After t years, where $t<n$

$(MO)_{x,t}$ = Maintenance and Operating Costs for Asset x at time t

$(UC)_{x,t}$ = User Cost at Time t

RSW = Remaining Service Worth (Salvage value)

PWF = Present Worth Factor

AWF = Annual Worth Factor

$TAWOMC_{x,n}$ (Before Implementation) - $TAWOMC_{x,n}$ (After Implementation) will give an indication of the net benefits of system implementation. Combined with the risk factors, the asset classes that have the highest risks with the highest potential net benefits after asset management implementation will be the highest priority assets for formal management programs.

Over the years, other studies have been conducted to make a business case for formal asset management by employing multi-criteria decision-making (MCDM) methodologies that measure the benefits of a highway project using a utility function. Using the base scenario (i.e., adhoc form of management), the same procedures could be employed by asset managers to quantify the benefits that could accrue over the life cycle of the asset when a systematic asset management is implemented. Given that asset management systems can be developed to various levels of sophistication, it is important that the asset manager identify the type of management system that is necessary to achieve management goals, and does a good job estimating the benefits and costs associated with such a system in the timeframe considered. Estimates can be based on historic data for the adoption of formal asset management procedures for similar ancillary assets, expert opinion, or a combination of both.

CHAPTER 4

APPLICATION OF RISK FRAMEWORK

4.1 Background

The purpose of the risk-based categorization process is to rank asset classes based on their risk differentiation. We have employed the risk matrix modeling approach to differentiate the risk level of each asset category. The risk level of each asset category is differentiated based on the strategic objectives of the agency and considering a set of identified performance measures. Table 4.1 illustrates the risk matrix used to analyze a selected performance measure (i.e., safety risk) associated with an asset class.

Table 4.1: Risk Matrix

Risk Level of Performanace Measure		Safety		
		CONSEQUENCE		
		LOW	MEDIUM	HIGH
PROBABILITY	LOW	LOW	LOW	MEDIUM
	MEDIUM	LOW	MEDIUM	HIGH
	HIGH	MEDIUM	HIGH	HIGH

This generic risk matrix could be used for all of the performance measures identified by an agency. For a specific performance measure and a given asset class, the risk is estimated by mapping the probability of failure with the consequence of failure. The probability of failure could be dependent on several factors such as: asset age, maintenance practices, failure modes, and operating environment. With the experts understanding of these factors, the likelihood/rate of failure of the asset can be estimated reasonably though subjectively. In our illustration, the probability of failure is dependent on the average age and the average expected useful life of the asset class as illustrated in equation 4.1. Tables 4.2 to 4.5 illustrate the definition of the probability and consequence scales used in the risk matrix. The consequence scales were developed using guidelines from the consequences of failure factors identified by the FHWA wall inventory program [5]. These factors are outlined below:

- Low or Minor. No loss of roadway, no to low public risk, no impact to traffic during wall repair/replacement.
- Moderate or Significant. Hourly- to short-term closure of roadway, low-to-moderate public risk, multiple alternate routes available.
- High or Severe. Seasonal- to long-term loss of roadway, substantial loss-of-life risk, no alternate routes available.

Each of the identified asset classes is evaluated to estimate how much risk it poses for each of the identified performance measures.

Average Failure Rate (ʃ) = Average Age of Asset Class/Average Expected Useful life…Eq. 4.1

Table 4.2: Probability Scale [5]

Scale	Description	PROBABILITY
3	LOW	If failure rate ʃ < 0.5
2	MEDIUM	If failure rate 0.5 ≤ ʃ < 1
1	HIGH	If failure rate ʃ ≥ 1

Table 4.3: Safety Risk Consequences Scale [5]

Scale	Description	CONSEQUENCES
3	LOW	No injuries or death in 10yrs
2	MEDIUM	Property loss or body injuries in 10yrs
1	HIGH	Body injuries and death in 10yrs

Table 4.4: Mobility Risk Consequences Scale [5]

Scale	Description	CONSEQUENCES
3	LOW	lane(s) closure/delays experienced for a period (within hours, no detour required) in 10yrs
2	MEDIUM	lane(s) closure/delays experienced for a day or more (no detour required) in 10yrs
1	HIGH	Road closure for a day or more (detour required) in 10yrs

Table 4.5: Maintenance Risk Consequences Scale [5]

Scale	Description	CONSEQUENCES
3	LOW	Impacting less than 5000 ADT
2	MEDIUM	Impacting between 5000 and 25000 ADT
1	HIGH	Impacting over 25000 ADT

4.2 Evaluation of Asset Classes against Selected Performance Measures

As mentioned earlier, based on agency strategic goals, the agency identifies a set of performance measures. In this evaluation, three performance measures were identified (i.e., safety, mobility, and maintenance). Each asset class was evaluated against each performance measure to establish a risk factor by considering the probability and the consequence of failure of the asset. The probability, consequence, and risk factors were all measured on a scale of 1, 2, and 3, representing high, medium, and low, respectively. In the evaluation, the scale measures were used to assess the risk differentials using hypothetical data to represent three categories of assets: fairly new assets, medium aged assets, fairly old assets. The data presented in Table 4.6 is not at all to say that traffic signals do not fail and cause injuries or deaths throughout the year, but if agencies are documenting these failures and consequences, they would achieve better results using the proposed framework. Table 4.6 contains data representative of three categories of assets (culverts, guardrail, and traffic signals) representing fairly new, medium and old assets. The culvert has a low probability of failure, a high safety consequence, a high mobility consequence, and a medium maintenance consequence. The, culvert therefore possesses a medium safety risk (ranked as 2), a medium mobility risk (ranked as 2), and a low maintenance risk (ranked as 3). In addition, guardrail and traffic signals were categorized using the same procedure and the results in Table 4.7 were achieved.

Table 4.6: Evaluation Data

Asset Class	Culvert	Guardrail	Traffic Signal
PROBABILITY			
Average age of asset base	35	50	70
Expected useful life of asset	100	100	100
Average failure rate of asset	0.35	0.5	0.7
CONSEQUENCES (10yr analysis period) - Yes/No			
Safety			
Bodily injury to involved party	YES	NO	NO
Property loss/damage	YES	YES	NO
Death/fatality	YES	NO	NO
Mobility			
Lane closure/delay resolved in hours	NO	YES	YES
Lane closure/delay resolved in days with no detours	NO	YES	NO
Lane closure/delay resolved in days with detours	YES	NO	NO
Maintenance			
Failure on roadway with ADT <5000	YES	NO	YES
Failure on roadway with ADT 5000 - 25000	YES	YES	YES
Failure on roadway with ADT >25000	NO	YES	NO

Table 4.7: Risk Factor Description Scale

Scale	Risk Description
3	LOW
2	MEDIUM
1	HIGH

4.3 Risk-Based Asset Prioritization

Assuming that all the identified performance measures carry the same weight, the results from the risk categorization of each alternative (asset class) are put into another selection matrix as shown in Table 4.8. In this illustration, the risk factors in Table 4.8 for each performance measure were deduced using the probability and consequence scales above. The linear sum of the risk factors for each performance measure is termed the total score, and used as the alternative selection criterion. Using the total score, Table 4.9, and the agency's risk target/standard, a wish list of qualifying alternatives, can be established and used as a point of departure for decision makers. As an illustration, the computational selection and the alternative ranking matrices (i.e., Tables 4.8 and Table 4.9, respectively) indicate that traffic signals are a low risk alternative, culverts are a medium risk alternative, and guardrails are a high risk alternative.

Table 4.8: Computational selection matrix

ALTERNATIVES PRIORITIZATION				
ALTERNATIVES	SAFETY	MOBILITY	EFFICIENT MANAGEMENT	TOTAL SCORE
Culverts	2	2	3	7
Guardrail	2	2	1	5
Traffic Signals	3	3	2	8

Table 4.9: Alternatives Ranking Matrix

High Risk Alternative	Action Required if Total Score is <=5 (i.e., at least 1 high risk and 2 medium risks)
Medium Risk Alternative	Total Score is Either 6 or 7
Low Risk Alternative	Total Score >7

Each alternative is ranked using Table 4.7 and Table 4.8, and the highest risk alternatives are short-listed for further evaluation and consideration (i.e., cost of implementation, other costs, and benefits) and prioritized for inclusion in the existing asset management system. The main objective in using the selection matrix to further evaluate and consider the alternatives is to help decision makers identify second best alternatives, or even third best based on the potential for risk reduction as well as the cost-benefit ratio. These analyses and evaluation procedures are undertaken to select the most critical alternatives for prioritization.

4.4 Data Availability

Availability of quality information is critical for any risk-based asset management system. Data is necessary for setting agency objectives, assisting with the decision-making process and with project delivery, and monitoring progress toward the objectives. Data availability affects every step in the asset management process. That is, the accuracy of a model, and the effectiveness of a final decision are very much contingent on the amount and accuracy of information available to an agency during the decision-making process. In transportation asset management, accurate data is one of the driving forces that make decisions in resource allocation and utilization more effective.

Information about each class of asset—age, condition data, historical failure rates, and maintenance activities as well as consequences of failure to the user (user cost), the agency (agency cost), and the environment (external cost) — are very critical to a risk modeling process. However, information regarding ancillary transportation assets is not always available, or is not always in a suitable format. In fact, depending on the asset class under consideration, most of this data is not available, or is not in the appropriate disaggregate format pertinent to the problem at hand. For example, highway fatality statistics exist for various states, but often, they are not stratified to show the causes of the fatalities -- that is, how many of these fatalities resulted from the collapse or failure of a culvert, guardrail, retaining wall, pavement marking, traffic sign, or highway sign. Because the proposed model does not only address fatality issues, it is imperative that the other types of consequences — bodily injuries, extent of property damage, duration of closure of lanes — are also properly documented.

With this shortcoming (i.e., lack of the proper form of data), ancillary transportation asset management development can make use of other databases (e.g., police accident reports) complemented with expert evaluations and estimations; these would be very vital in the risk modeling and categorization process. Over the long-term, agencies must find ways to gather and incorporate such data regarding ancillary transportation assets in order to improve data available for risk modeling. Agencies must also establish well-defined processes for gathering and documenting failures within their transportation network. A starting point is to develop a simple survey that acquires simple information from other management systems in their departments, (e.g., culvert management system, safety management system, congestion management system, sign management system, traffic management system, and mobility management system) and then amalgamate this data into a single database. A sample survey is shown in appendix A.

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Conclusion

This study presents basic concepts of risk theory, risk assessment, and risk management that can be applied when making a business case for the formal management of ancillary transportation assets. While transportation asset management has been steadily developed for the past several decades, more agencies have focused on the development of pavement management systems and bridge management systems than the development of formal management systems for ancillary transportation assets such as pavement markings, sidewalks and curbs, street lighting, traffic signals, traffic signs, utilities and manholes, and earth retaining structures.

This study identifies a number of common elements and approaches to risk assessment and management and discusses basic elements for a risk framework for assessing and prioritizing ancillary transportation assets for inclusion in formal transportation asset management programs. It discusses seven risk elements commonly present in recognized risk approaches to asset management. The framework elements are based on a review of good practice in transportation asset management, storm water management, and water main management, domestically and internationally. These framework elements are used to develop a risk model that provides a means for optimizing the return-on-investment within particular asset classes and also capable of evaluating the tradeoffs across different asset classes. The approach covers the lifecycle of the asset while linking this to the wider strategic objectives of the transportation agency and its stakeholders.

The proposed framework draws and builds on a number of established risk-based management systems that have been developed over several years. Although this provision exists, there is little evidence that agencies have actually employed risk-based benefit-cost approaches to prioritize their ancillary assets for inclusion into existing asset management systems. Additionally, the majority of risk methods that are in use, currently, by transportation agencies have large elements of subjectivity. A framework that includes risk profiles for different asset classes, developed by combining engineering judgment with quantitative data, can be tailored to capture the local knowledge in agencies while making the best use of the quantitative data that is available. Furthermore, the study illustrates with an example how the proposed model could be implemented.

The study concludes that tracking and documentation of ancillary transportation asset failures would help agencies better understand the risks associated with failure because assessing the probability and consequences of failure of transportation assets requires considerable knowledge about historical trends of failure. Tracking and documenting the failures of ancillary transportation assets would, therefore, help in identifying the trends/probability of failure as well as in quantifying the consequences associated with these failures. Based on the tracked and documented information, a risk prioritization factor could also be estimated and used in prioritizing individual asset classes for inclusion in existing transportation asset management systems, in combination with other benefit/cost factors. The accuracy of the risk factor computed would, consequently, affect the accuracy of the model. Establishing the accuracy of a model requires a more complete dataset, which requires agencies to eventually devote extra time and funding to collect data. However, some existing management systems (e.g., safety management system, culvert management system, and pavement management system) are already collecting some valuable data, and would only require minimal effort to include some specific data (i.e., detailed information as attached in appendix A) that are essential to risk modeling.

5.2 Recommendation

The literature reviewed shows that there has been very little effort made by agencies to gather condition data and document failures caused by ancillary transportation assets. Although a few of such failures have occurred, agencies have very little detailed information documented that pertains to these failures. In addition, the information that exists is found in decentralized databases, which are not readily available to decision makers. Therefore, this study recommends the commitment of time and other resources to gather information (e.g., asset failures and their consequences) and establish an integrated database that would facilitate risk modeling. In the absence of such a system, it would be challenging for decision makers to objectively determine the risks associated with each asset class. On the other hand, establishing such a system would provide valuable information that would help agencies understand the trends and consequences of failure of these ancillary transportation assets.

5.3 Direction for Future Research

The current model proposed by this research is limited in one capacity. This limitation must be addressed by future research to develop a more robust model in prioritizing ancillary transportation assets. The limitation is the inability of the model to incorporate the effect of asset failures resulting from external conditions: random human events such as failures resulting from a driver running into traffic signal or sign, or failures resulting from natural phenomena such as storm damage or earthquakes. No matter what the asset manager does to reduce risk, these events will always exist. However, evaluating the effects of such failures (i.e., by building an event tree using data from selected potential random occurrences), and incorporating them in the risk ranking process would provide asset managers with additional information to make better decisions that would be beneficial from the standpoint of the overall reliability and performance of the model and the transportation network system, respectively.

APPENDIX A

SAMPLE SURVEY TO TRACK FAILURE DATA [46]

Department Contact: ________________

Type of Asset: ________________________

Location(s) of Asset Failure - Road: __________ Milepost:___________

Asset Identification Number: ________________________

Date of Asset Failure: ________________________

Number of Lanes Damaged/Closed: ______________

Date of Initial Re-opening: ____________

Number of Lanes Temporarily Opened: _________

Date of Final Repair: ____________

Length of Detour: ____________________

Average Daily Traffic (ADT) on Highway Impacted by Asset Failure:

____

Percentage Heavy Vehicles on Highway Impacted by Asset Failure:

____

Average Time to Travel Detour (while asset was down and traffic was congested):_________

Average Truck Time to Travel Detour (if different than for normal traffic):

____

Detour Route (Describe and attach a map if possible): ____________________________

Describe the likely cause of Failure: ____

Average Age of Asset: ____________________________________

Failure Costs

Initial Cost of Asset Installation: ____________________

Cost of Traffic Control: ____________________

Number of Accidents Caused by Failure: Property Damage: _______ Injury: _____Fatality:_____

Other Indirect Costs (Business Loss, etc.,):____________________________

Total Cost: _______________________

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