

Final Report

FHWA/IN/JTRP-2003/21

**MULTICRITERIA HIGHWAY PROGRAMMING INCORPORATING
RISK AND UNCERTAINTY: A METHODOLOGY FOR HIGHWAY ASSET
MANAGEMENT SYSTEM**

by

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Joint Transportation Research Program
Project No.: C-36-78G
File No.3-10-7
SPR-2384

Prepared in Cooperation with the
Indiana Department of Transportation and
The U.S. Department of Transportation
Federal Highway Administration

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Purdue University
West Lafayette, Indiana 47907
November 2004

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2003/21	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Multicriteria Highway Programming Incorporating Risk and Uncertainty: A Methodology for Highway Asset Management System		5. Report Date November 2004	
		6. Performing Organization Code	
7. Author(s) Zongzhi Li and Kumares C. Sinha		8. Performing Organization Report No. FHWA/IN/JTRP-2003/21	
9. Performing Organization Name and Address Joint Transportation Research Program 1284 Civil Engineering Building Purdue University West Lafayette, IN 47907-1284		10. Work Unit No.	
		11. Contract or Grant No. SPR-2384	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.			
16. Abstract Highway asset management is a systematic process that aims to preserve, expand, and operate highway assets in the most cost-effective manner. It is an analytical tool that facilitates organized, logical, and integrated decision-making in asset management practice. This study proposes a methodology for the development of a highway asset management system that addresses asset valuation, performance modeling, marginal benefit analysis, and multicriteria decision-making, including tradeoff analysis as well as project selection and programming. While most existing management systems deal with individual physical highway assets or system usage only under certainty or risk, this research focuses on the management of an entire highway network that also incorporates tradeoff decisions involving uncertainty. Systemwide multiattribute utility functions and standardized focus gain-over-loss ratio functions based on utility theory and Shackle's model, respectively, are calibrated using data collected through a series of questionnaire surveys. A system optimization model, along with a solution algorithm, is formulated to facilitate project selection and programming. A Highway Asset Management System software program is developed and utilized in a case study for systemwide project selection based on information for candidate projects proposed for state highway programming in Indiana during 1998-2001. For all given years and regardless of the tradeoff decision under certainty, risk, or uncertainty, the software outputs match with the results of actual highway programming at least 85 percent of the time. The case study results validate the proposed methodology and research findings and also reveal the advantages of using the algorithm for overall highway asset management practice.			
17. Key Words Multicriteria, Highway Programming, Risk, Uncertainty, Asset Management		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 272	22. Price

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance provided by Mrs. Jill Faulkenberg and Messrs. Bill Flora, David Glenn, Jaffar Golkhajeh, Tony Hedge, David Holtz, Roger Manning, John Nagle, Samy Nouredin, and Barry Partridge (INDOT); Mike Byers (ACPA); and Jay DuMontelle (FHWA) who served on the Study Advisory Committee. The authors are particularly thankful to Professors Jon D. Fricker, Fred L. Mannering, and Frederick T. Sparrow, as well as Thomas L. Morin, who all were very supportive to the study in diverse ways. Special thanks also go to Dr. Samuel Labi, Mrs. Karen S. Hatke, and Ms. Jackie G. Whiteley for their support in various stages of this study.

IMPLEMENTATION REPORT

A methodology has been developed for a systematic management of the state highway assets in Indiana. The methodology focuses on asset valuation, performance modeling, marginal benefit analysis, and multicriteria decision-making, including trade-off analysis as well as projection selection and programming. A comparison with the historical programming practice in the Indiana Department of Transportation (INDOT) indicated that the use of the methodology gave a high total number of contracts, regardless of the type of decision-making, certainty, risk, or uncertainty. On the other hand, irrespective of budget scenarios, a lower number of projects was selected under certainty as compared to the number of projects selected under risk and uncertainty. As such, risk and uncertainty should be incorporated into the overall asset management decision-making process. The current study results also revealed, as can be expected, that project selection was sensitive to the budget level for a given analysis period. However, the relative weights of the agency and user decision groups appeared to be not as significant, which suggested that the agency and the user maintained consistent perceptions on asset management system goals. The findings demonstrated that the proposed methodology provided reliable results and it could indeed be used for state highway programming and management.

The methodology developed in the study can be used by the INDOT Program Development Division to evaluate the programming decisions made by traditional procedures. The methodology and study findings can also be adopted by other transportation agencies for highway asset management practice. However, additional research will be necessary for implementation of the methodology. The implementation project would provide specific procedures and guidelines, including readily usable software.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytical Hierarchy Process
ANOVA	Analysis of Variance
APWA	American Public Works Association
ARME	Annual Routine Maintenance Expenditure
ASPA	American Society for Public Administration
BMS	Bridge Management System
CBP	Capital Budgeting Problem
CBR	California Bearing Ratio
CMS	Congestion Management System
CPI	Consumer Price Index
CRC	Continuously Reinforced Concrete
DEA	Data Envelopment Analysis
DM	Dummy Variable
DOT	Department of Transportation
EHA	English Highway Agency
ELECTRE	Elimination and (et) Choice Translating Algorithm
ESAL	Equivalent Single Axle Load
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration

GA	Genetic Algorithms
GASB	Governmental Accounting Standards Board
HAMS	Highway Asset Management System
HC	Highway Classification
HDM	Highway Development and Management System
HERS	Highway Economic Requirements System
HPMS	Highway Performance and Monitoring System
IBMS	Indiana Bridge Management System
INDOT	Indiana Department of Transportation
IRI	International Roughness Index
IS	Interstate Highways
ISOHDM	International Study of Highway Development and Management
ITS	Intelligent Transportation System
JCP	Joint Concrete Pavements
JTRP	Joint Transportation Research Program
KDOT	Kansas Department of Transportation
LTPP	Long-Term Pavement Performance
MCKP	Multi-Choice Knapsack Problem
MCMDKP	Multi-Choice Multidimensional Knapsack Problem
MDKP	Multidimensional Knapsack Problem
MMS	Maintenance Management System
MTC	Metropolitan Transportation Commission
MUT	Multiple Unit Truck
NAPA	National Academy of Public Administration
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System

NHTSA	National Highway Traffic Safety Administration
OECD	Organization for Economic Cooperation and Development
OLS	Ordinary Least Squares
PMG	Program Management Groups
PMS	Pavement Management System
PPI	Producer Price Index
PSI	Present Serviceability Index
RI	Rehabilitation Interval
ROW	Right-of-Way
SHRP	Strategic Highway Research Program
SMS	Safety Management System
STEM	Step Method
SUT	Single Unit Truck
TAC	Transportation Association of Canada
TRB	Transportation Research Board
TSP	Total Suspended Particles
TTI	Texas Transportation Institute
VMT	Vehicle Mile of Travel
VC	Vehicle Class
VOC	Vehicle Operating Cost
WIM	Weigh-in-Motion
WSI	Weather Severity Index

CHAPTER 1 INTRODUCTION

Transportation facilities constitute one of the most valuable public assets and account for a major share of public sector expenditure worldwide. These investments serve to build, operate, and preserve infrastructure that supports movements of people and goods by various modes. Efficient, economical, and safe transportation is critical to a society in meeting its goals toward economic progress, social welfare, and emergency preparedness. Given the ever-increasing personal and commercial travel demands vis-à-vis limited resources, changes in public expectations, and extraordinary advances in technology, the task of providing transportation services becomes more critical than ever. Most recently, transportation agencies throughout the world are increasingly adopting a strategic approach, referred to as transportation asset management, to make investment decisions for system preservation, expansion, and operation, based on comprehensive information and in a holistic and proactive way. Defined as a systematic process of maintaining, upgrading, and operating physical assets cost-effectively, highway asset management combines engineering principles with sound business practices and economic theory, and provides a tool to facilitate an organized, logical, and integrated approach to highway investment decision-making [FHWA, 1999].

1.1 Current Highway Asset Management Practice

1.1.1 Highway Asset Management Worldwide

A study to address the current practice in highway asset management was conducted by the Organization for Economic Cooperation and Development's (OECD) expert group of engineers, economists, and road administrators [OECD, 2000]. The study defined asset management as a

systematic process supported by procedures of data collection, storage, management, and analysis; asset valuation and depreciation methods; and the use of performance indicators. The benefits of implementing an asset management system, according to this study, included improved internal and external agency communication, the condition and levels of service of the asset inventory, road network performance, asset management tools, budget process, and staff development.

Australia and New Zealand have national legislation requiring government agencies to utilize asset management systems. AUSTROADS, a cooperative association formed to provide strategic direction for the integrated development, management, and operation of Australian and New Zealand highways, published documents on asset management guidelines and strategies that defined the composition of road assets and pointed out that asset management decisions were generally made at the collective level for local, regional, or national road system [AUSTROADS, 1997]. The strategies identified a programmed set of management actions that directed physical treatments to assets, or controls on the use of assets, so as to affect their physical or operational performance, consequent levels of service provided to the highway user and benefit to the community, including accessibility, economic development, social justice, security, and environment.

The Transportation Association of Canada (TAC) published an asset management primer that characterized asset management as a comprehensive process that employed people, information, and technology to allocate funds effectively and efficiently among competing asset needs [TAC, 1999]. The principal components of an asset management system classified in the primer included asset inventory, performance prediction models, project-specific analytical tools, and decision-aid tools. The primer further stated the key steps for asset management implementation, including definition of objectives, review of current process and gap analysis, framework scoping, benefit-cost analysis, internal expertise assessment, management changes, and assessment of functional performance and investment strategies. Subsequently, a detailed study was conducted focusing on the calculation of highway asset value using performance indicators to assess facility condition and performance, and

effectively communicating the implications of performance indicators to external audiences [TAC, 2000].

The English Highways Agency (EHA) was mandated by legislation emanating from the United Kingdom to adopt an asset management-oriented approach to infrastructure development and maintenance. The agency is currently making efforts to develop a geographically referenced database to support an online pavement management system. This system will serve as the basis of a comprehensive asset management system to be developed in the future [Cambridge Systematics *et al.*, 2002].

1.1.2 Highway Asset Management in the United States

The public road system in the United States has nearly four million miles of highways and streets and over 550,000 bridges. Constituting the largest government-owned assets in the country, highways are associated with annual investment levels exceeding one trillion dollars nationwide [FHWA and AASHTO, 1996]. Recognizing the growing importance of asset management to transportation agencies, a task force formed by the American Association of State Highway and Transportation Officials (AASHTO) in 1997 developed a 10-year strategic plan outlining goals, strategies, and tasks needed to implement transportation asset management within the United States.

The American Public Works Association (APWA) also commissioned a task force for asset management. In August 1998, the task force delivered a report titled “Asset Management for the Public Works Manager: Challenges and Strategies” to the APWA Board of Directors [Danylo and Lemer, 1998].

In February 1999, the Federal Highway Administration (FHWA) created an Office of Asset Management within the Office of Infrastructure and developed an asset management primer to build a foundation for discussion throughout the FHWA and among other interested parties regarding asset management [FHWA, 1999]. The Office of Asset Management has key responsibilities that include

providing national leadership in asset management principles for highway programming, developing asset management policies for system preservation, and cooperating with AASHTO, other FHWA offices, and others to conduct nationwide programs.

While transportation asset management is still a growing discipline, some state transportation agencies have taken a proactive approach to asset management as an overall departmental initiative. For instance, the New York Department of Transportation (DOT) has had an active asset management program focusing on system preservation since 1998. Michigan DOT has pursued several business process and information technology advances for asset management since the mid-1990s. Arizona DOT, Indiana DOT (INDOT), and Pennsylvania DOT are currently developing asset management plans and strategies and in the past have undertaken programs that conform to good asset management practice [Neumann, 1997].

1.2 Recent Trends in Highway Financial Management

In June 1999, the Governmental Accounting Standards Board (GASB) approved Statement No. 34 (GASB34) titled “Basic Financial Statements and Management's Discussion and Analysis for State and Local Governments,” which updated standards for state and local agencies in preparing reports of their financial condition. According to GASB34, governmental agencies need to determine infrastructure asset categories for asset valuation and reporting. There are two approaches to asset valuation and reporting. The first is a depreciation approach, with which the historical cost of an asset is adjusted in accordance with accepted depreciation methods. The second is a modified approach, an alternative to depreciation, which requires maintaining an inventory of current assets, establishing the minimum acceptable condition levels, periodically conducting asset condition assessments, and comparing the expected and actual maintenance and preservation expenditure [GASB, 1999]. The key elements of infrastructure reporting are an inventory of assets in terms of type and extent and a valuation of assets. [Dornan, 2000].

1.3 Dimensions of Highway Asset Management

Sinha and Fwa [1989] defined the concept of a comprehensive highway asset management as a three-dimensional matrix structure, with dimensions representing highway facilities, system goals, and operational functions, as shown in Figure 1.

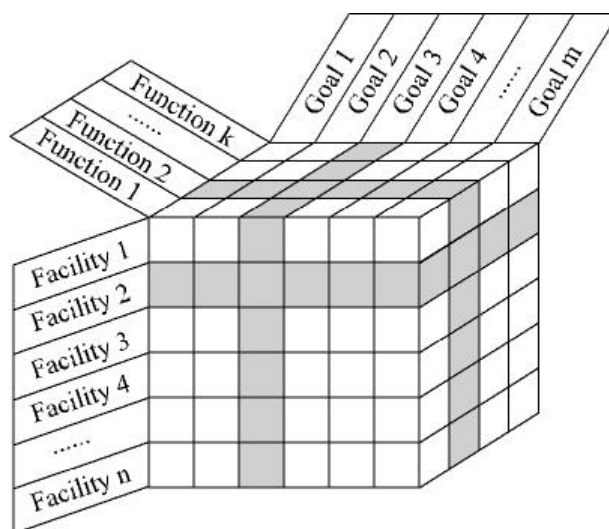


Figure 1: Dimensions of Highway Asset Management

A highway system includes a number of physical facilities such as pavements, bridges, drainage systems, traffic control devices, and roadside furniture. Each facility plays a unique role in the delivery of transportation services. For instance, pavements and bridges carry traffic; drainage ensures drivability and safeguards water quality; traffic control devices foster smooth traffic flow; and roadside furniture enhance convenience, aesthetics, and safety. Each physical highway facility is associated with one or more component management system of highway asset management. The overall effectiveness of a highway system depends on the levels of service provided by individual facilities.

System goals are specified levels of selected performance measures relating to the condition or usage of physical highway facilities. Such goals may include preservation of facility condition at or above a desired level, minimization of agency and user cost, energy use, and environmental impacts, and maximization of safety and socio-economic benefits. To facilitate the task of highway programming and management, system goals may be assessed quantitatively by means of highway performance indicators that provide indications of the degree of fulfillment of system goals.

An operational function is an activity carried out on highway facilities in order to achieve a system goal, which may include planning, design, construction, system evaluation, maintenance, and rehabilitation. Each operational function is related to one or more component management systems of highway asset management. The planning phase involves the preparation of capital expenditure programs for highways based on overall needs, demand analysis, and estimation of facility needs. The design phase generates, analyzes, and evaluates alternative facility configurations. The construction phase involves quality, progress, and cost control to transform designs into physical realities. Operational functions of system evaluation and facility maintenance and rehabilitation are currently the main focus of most facility management systems.

A highway asset management system explicitly considers its three dimensions in order to select projects that can maximize the attainment of system goals. For example, the operational function of maintenance activities is carried out on pavement facilities to achieve the goal of condition preservation. For this task to be carried out properly, it is necessary to determine any tradeoff relationships that may exist between various operational functions, for a given facility or across facility types, to yield maximum system benefits. An example of such analysis is the tradeoff between routine maintenance level and rehabilitation interval [Labi, 2001].

1.4 Current Component Management Systems

In order to enhance the ability to diagnose existing and potential problems throughout a highway network and evaluate and prioritize alternative strategies, most state transportation agencies have developed various highway-related management systems, which mainly deal with pavements, bridges, congestion, and safety. In addition, many states have developed systems for maintenance management to aid in planning and evaluation of maintenance work on pavements, bridges, drainage systems and roadside furniture. Systems for the management of pavements, bridges, and maintenance activities are oriented towards the physical state of highway assets, as their primary purpose is to inventory, track, and address the condition of various components of the highway network and to assist in establishing cost-effective strategies to sustain an acceptable condition of such facilities. On the other hand, systems dealing with congestion and safety are mainly focused on the operation and performance of the transportation network. The various management systems are briefly described in the following sections.

1.4.1 Pavement Management System

A Pavement Management System (PMS) is a set of tools to find optimal strategies for preserving pavements in a serviceable condition over a given period of time [AASHTO, 1990]. In its broad sense, pavement management includes all activities involved in planning and programming, design, construction, maintenance, and rehabilitation of highway pavements. There are three principal components in a PMS: data collection and management, analysis, and feedback and updates [FHWA, 1991]. At the network level, agency-wide pavement programs for new construction, maintenance, or rehabilitation are developed such that overall cost-effectiveness is maximized over a given analysis period. At the project level, detailed consideration is typically given to alternative design, construction, maintenance, or rehabilitation activities for a particular pavement section or project within the overall program that will provide the desired benefits or service levels at the least total cost over the analysis period.

1.4.2 Bridge Management System

A Bridge Management System (BMS) is a systematic approach to assist in making decisions regarding cost-effective maintenance, rehabilitation, and replacement plans for bridges [FHWA, 1987]. Such a system seeks to identify current and future deficiencies, estimate the backlog of investment requirements, and project future requirements. A BMS also helps to identify the optimal program of bridge investments over time periods, given particular funding levels. A BMS generally includes four basic components: a database, cost and deterioration models, project selection and programming, and updating functions. The database component contains information from regular field inspections. Deterioration models predict the future condition of bridge elements. Agency cost models are associated with maintenance and improvements of bridge components, while user cost models relate more directly to bridge safety and serviceability. Using results from cost and deterioration modeling, an optimization model can help determine the least-cost strategies for bridge elements.

1.4.3 Maintenance Management System

Maintenance activities carried out in-house by highway agencies are associated with significant levels of resources. A Maintenance Management System (MMS) seeks to utilize limited resources for in-house maintenance cost-effectively and improve the coordination of maintenance and rehabilitation programs so that tradeoffs between maintenance and rehabilitation activities can be evaluated. A MMS incorporates a number of features, including a maintenance activity definition and list, an asset inventory, performance standards, work programs, a performance budget, a work calendar, resource requirements, scheduling, work reporting, and management reports; and typically

includes components of database development, maintenance needs assessment, resource needs assessment, cost analysis, optimal programming, scheduling, and budgeting [Markow *et al.*, 1994].

1.4.4 Congestion Management System

Traffic congestion has become a major concern on existing highways and the situation is deteriorating at an alarming rate. Detrimental consequences of traffic congestion include longer travel time, higher fuel consumption, and increased air pollution. The proposed Indiana Congestion Management System (CMS) is an example of a statewide system that provides information on transportation system performance and alternative strategies to alleviate congestion and to enhance mobility of people and goods in a state highway network [Choocharukul and Sinha, 2000]. Congestion management implies a direct customer orientation to planning and investment and can be tailored to provide a mechanism to measure the economic and environmental consequences of current system performance and to propose future investments.

1.4.5 Safety Management System

High rates of highway vehicle collisions make it necessary to identify highway facility problematic areas so that necessary safety improvement investments can be carried out. A Safety Management System (SMS) integrates vehicle, driver, and roadway elements with the goal of reducing the number and severity of vehicle collisions by ensuring that all opportunities to improve highway safety are identified, considered, implemented, and evaluated in all phases of highway planning, design, construction, maintenance, and operation, and by providing information for selecting and implementing effective highway safety strategies and projects [Farooq *et al.*, 1994]. A SMS generally consists of the following elements: identification of hazardous locations, development and

evaluation of safety enhancing measures, estimation of costs and benefits, implementation of safety improvement projects, and review of the safety management system on a continuing basis.

1.5 Need for an Analytical Tool for Overall Highway Asset Management

Since the early 1990s, transportation agencies in the United States have shifted their focus from major construction and expansion to preservation and operation of the existing system. At the same time, public sentiment has grown about government accountability, as well as expectations regarding levels of service. In response to these challenges, transportation agencies are making efforts to improve efficiency and productivity and to increase the value of their services and products to the highway user. In this environment new tools and procedures are needed that can assist in making overall highway investment decisions; considering changing system demands, budget constraints, accountability requirements, integrated programming needs, and coordination of planning, programming, and budgeting [FHWA, 1999].

As procedures for data gathering and analysis of system inventory and needs for preservation and new capacities become increasingly automated, integration of information generated from the existing management systems to an overall asset management framework for programming and financial management becomes not only possible and but also necessary. There are three primary functions that can be viewed as common to all state and local transportation agencies: long-range planning and programming. Deployment of an asset management system enables coordination among the three functions. However, an overall highway asset management system shall not be considered as the replacement of the existing component management systems. The highway asset management system will, however, make use of information generated from individual management systems and assist in overall investment decision-making to achieve maximum benefits for an entire highway system.

1.6 Problem Definition

1.6.1 Highway Asset Management System Components

A framework for highway asset management is presented in Figure 2. The components of a highway asset management system generally cover system goals, asset inventory, asset valuation, performance modeling, marginal benefit analysis, multicriteria decision-making, implementation and feedback [FHWA, 1999].

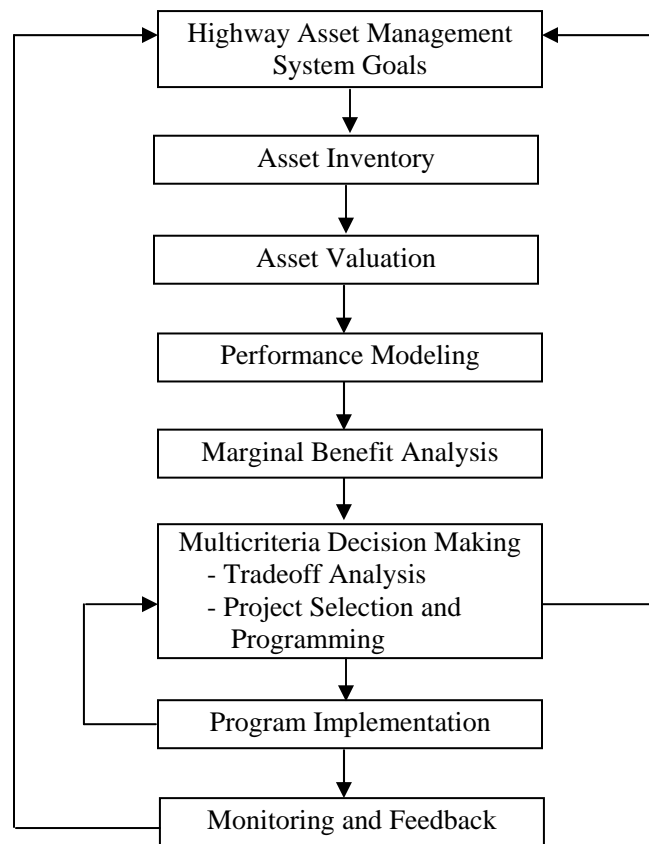


Figure 2: Key Components of a Highway Asset Management System

System goals are general statements that define priority areas and reflect a holistic, long-term view of asset performance and cost. Policy formulation allows the agency latitude in arriving at performance-driven decisions on resource allocation. An integrated system data inventory allows

displaying and analyzing multiple program requirements. As program implementation is a continuous process, monitoring of system performance must be done periodically. The resulting information is used to inform and to update other stages of the overall asset management process. One of the key functions of a highway asset management system is to conduct tradeoff analysis. Tradeoff decisions can be made either within or across various asset management programs that serve the purpose of managing various physical highway assets and system usage. Based on tradeoff analysis, decisions can be made on recommended capital projects and levels of service for maintenance and operational activities. In addition, risk and uncertainty can be incorporated into the tradeoff decision process. Highway asset management is an evolutionary process that is expected to be responsive to the needs of the highway agency and the user. It is important that highway asset management systems be made flexible to keep abreast of the changing needs of highway transportation, yet robust enough to be applicable in a wide variety of areas related to asset management.

1.6.2 Development of Highway Agency and User Goals and Objectives

1.6.2.1 Categories of Goals and Objectives

A goal is a general statement of a desired state or ideal function of a highway transportation system. An objective is a concrete step towards achieving a goal, stated in measurable terms. Goals and objectives are related to system performance in that they reflect different perceptions of what the transportation system should achieve and are often developed through extensive public outreach efforts. As such, goals and objectives incorporate a broad user perspective on what elements of system performance are important. Understanding different goals and objectives is critical to identifying the different types of performance indicators that might be included in a highway asset management system.

1.6.3 Highway Asset Management Programs

Highway asset management programs are a set of general programs for the preservation and expansion of physical highway assets and sustaining levels of service of a highway network. For a typical highway system, general programs may cover those for the preservation of pavements and bridges, safety and roadside improvements, major or new construction, and so forth. It is practical to divide each of those program categories into more detailed subcategories.

1.6.4 Establishment of Highway Performance Indicators

Performance is defined as the execution of a required function. Performance indicators are quantitative or qualitative measures that directly or indirectly reflect the degree to which results meet expectations or goals [Poister, 1997]. The impetus to link government agencies with performance indicators results from two aspects. Externally, the need for meaningful performance indicators in government has been underscored by resolutions made by professional organizations, such as GASB [1989], the National Academy of Public Administration (NAPA) [1991], and the American Society for Public Administration (ASPA) [1992]. The U.S. Congress also passed two pieces of legislation, Public Law 101-576 and Public Law 103-62, to build performance measurement into federal management processes. Internally, strategic management or total quality management processes within a governmental agency is impossible without the development and use of performance indicators to track progress in achieving strategic goals or to evaluate the success of continuous process improvement activities.

1.7 Scope and Objectives of the Research

Similar to the traditional highway planning process, a highway asset management system is goal-driven. It focuses on the performance of physical highway assets, as well as system usage, and provides an analytical tool for systemwide highway project selection and programming. The primary beneficiary of highway asset management is the highway agency, as the agency aims at extending asset service lives at the minimum cost. The highway user also stands to benefit directly as the user receives improved riding quality, mobility, and safety.

The present study will focus on proposing a methodology for the development of a highway asset management system that will assist in system-wide highway programming. To assist in tradeoff decisions under certainty, risk, and uncertainty, models will be calibrated on the basis of the proposed methodology using field data. A system optimization model, along with a solution algorithm, will also be formulated. The key research issues that will be investigated include the following:

- Network-level highway user cost computation and modeling
- Pavement and bridge performance modeling
- Establishment of highway asset management system goals and their relative weights
- Models for tradeoff decisions incorporating risk and uncertainty
- System optimization model along with solution algorithm for systemwide highway project selection and programming
- Development of a highway asset management system software using the study findings

1.8 Dissertation Organization

The dissertation is comprised of 10 chapters. Chapter 1 discusses the increasing need for a new analytical tool for overall highway asset management and the main components of a highway asset management system, as well as the scope and objectives of the research. Chapter 2 provides

background information on methods for asset valuation, highway asset management system goals and performance indicators, performance modeling, life-cycle cost analysis, and multiple criteria decision-making. Chapter 3 elaborates on the study design and proposed methodology, and Chapter 4 concentrates on network-level highway user cost computation and models. Chapter 5 focuses on modeling the performance of physical pavements and bridges. Using the information from the calibrated models, Chapter 6 establishes the marginal effects of different types of projects in achieving various highway asset management system goals. Chapter 7 focuses on the tradeoffs of different types of projects involving certainty, risk, or uncertainty, and a system optimization model along with a solution algorithm is provided in Chapter 8. Chapter 9 begins with a brief introduction to a highway asset management system software, and a case study using the software package then follows to validate the proposed methodology and study findings. Finally, Chapter 10 provides a summary of the study findings and discusses areas for future research.

CHAPTER 2 BACKGROUND INFORMATION

This chapter provides a review of the existing literature on highway asset management in the following areas: highway asset valuation, highway system goals and performance indicators, performance modeling, life-cycle cost analysis, and multicriteria decision-making. These topics are discussed sequentially in the following sections.

2.1 Highway Asset Valuation

Highway facilities constitute an interconnected system that has crucial impacts on the economy, the environment, and the quality of life in general. As these facilities are a public asset, managers of such assets have a stewardship role to play in ensuring that maximum benefits are produced from public expenditure through the use of cost-effective practices. In order to provide more comprehensive cost information upon which to make informed judgments about the ability of governments to repay their debts and properly manage physical assets, GASB34 requires that physical assets must be included in the governmentwide annual financial statements [Dornan, 2000]. More specifically, the cost of existing major physical assets acquired, removed, restored, or improved in the fiscal year ending after June 30, 1980 must be reported retrospectively, while physical assets acquired, renovated, restored, or improved after the effective date of implementing GASB34 must be reported on a prospective basis [GASB, 1999]. State transportation agencies are among those governmental agencies required to report on the cost of physical assets within their jurisdiction. However, highway asset management should not only focus on the management of physical highway assets, but also on the management of asset usage. Toward this end, highway user cost information is also needed to further support a transportation agency's service obligations. As such, highway asset valuation in the

current study covers valuation of physical highway assets and network-level highway user cost computation.

2.1.1 Approaches for the Valuation of Physical Highway Assets

GASB defines infrastructure assets as long-lived capital assets associated with governmental activities that normally are stationary in nature and can be preserved for a significant number of years [GASB, 1999]. Two approaches are applicable for the valuation of highway assets: the depreciation approach and the modified approach. The depreciation approach assumes gradual deterioration of an asset over its service life and consequently reduces the recorded value of the asset on the balance sheet, using appropriate methods for depreciation. The commonly used depreciation approaches include net book value, replacement cost, perpetual inventory, and discounted value approaches [Lemer and McCarthy, 1997]. The common methods for depreciation include straight line, declining balance, sum-of-years digits, and sinking fund methods [Canada *et al.*, 1996]. The modified approach assumes that the asset is preserved at or above prescribed condition standards through timely maintenance and rehabilitation. Agencies that use this approach do not have to account for depreciation if, however, they can demonstrate that the asset is being properly preserved by maintaining up-to-date records of asset inventory, condition, and expenditure to preserve the asset [GASB, 1999].

2.1.2 Previous Studies on Highway User Cost Computation

A number of studies developed project level models for highway user cost estimation. One of the most widely accepted is the “1977 AASHTO Manual on User Benefit Analysis and Bus-Transit Improvements” [AASHTO, 1977]. This manual provides cost factors, nomographs, and guidelines for economic analysis of most types of highway and bus transit improvements, including curve

elimination, widening or added travel lanes, reducing gradients, new construction, intersection improvements, and deciding bus lanes. A number of physical and cost data on highway capacity, traffic condition, transit patronage, vehicle travel, and traveling speed are required to conduct benefit-cost analysis and economic assessment.

Based on the concept of economic analysis using the techniques of benefit-cost ratio, net present value, and internal rate of return, the Texas Transportation Institute (TTI) developed the MicroBENCOST software for user benefit-cost analysis on highway projects, such as intersection improvements, roadway upgrading, new constructions, and safety improvements [TTI, 1993]. A number of input data, including characteristics of existing, proposed, and alternative facilities, cost, and traffic are needed for the analysis. The program can compute average speed, congestion and delays, accidents, air pollution, and reduction in user cost as project benefits.

StratBENCOST, the sister tool of MicroBENCOST, was developed by HLB Decision Economics [2001] to assist in comparing large numbers of project options. It forecasts the benefits of candidate highway investments in terms of highway user cost and the environmental effects and compares the benefits with the capital and ongoing cost in terms of their net present value the agency will incur in constructing, maintaining, and operating the project. StratBENCOST is also capable of conducting risk analysis, which provides both the median estimates for variables relevant to highway user cost estimation and a probability range for the variables resulting from different methods and data sources.

The Highway Development and Management System (HDM-4) is a software program for highway investment decisions produced by the International Study of Highway Development and Management (ISOHDM) [2000]. The system is capable of conducting strategic planning on a highway network and economic assessments at the project level. The strategic planning application involves an analysis of network level cost estimation, together with pavement performance prediction and user effects, for highway development and maintenance under various budgetary and economic scenarios.

The Highway Economic Requirements System (HERS) software was developed by FHWA in the mid-1990s. The software simulates the effects of future highway improvements by comparing the relative benefit and cost associated with alternative improvement options on the basis of information about existing highways [FHWA, 2000]. It begins by assessing the current condition of highway segments and then projects the future condition and performance in terms of congestion of the highway segments based on expected changes in traffic, pavement condition, and average speed. For each segment identified as deficient according to FHWA deficiency criteria, the model assesses the relative benefit and cost associated with improvement options to determine whether improving the segment is economically justified. The cost calculated includes improvement expenditure, and the benefit is computed as reductions in vehicle operating cost, travel time, and accidents over the service life of the improvement.

Ozbay *et al.* [2001] described a methodology for estimating full marginal highway transportation cost. The full marginal highway transportation cost for each origin-destination pairs was defined as a function of the average highway transportation cost and the congestion-related cost imposed by an additional trip to the rest of the traffic. For the marginal cost estimations, the authors first classified highway transportation cost as user cost, infrastructure cost, and environmental cost. User cost was further broken down into vehicle operating, accident and congestion costs. Infrastructure cost covered all long-term expenditures of facility construction, material, labor, and administration, as well as right-of-way (ROW) costs. Environmental cost included air pollution and noise costs. Regression analysis was then conducted to develop the cost functions for each cost category, and the marginal cost functions were determined simply by taking the first order derivative of the respective cost functions. The one-route marginal cost was generalized as the sum of individual marginal costs.

2.1.2.1 Critiques

The AASHTO Manual was used extensively in the 1980s and a large part of the estimated parameters have become obsolete. Both the MicroBENCOST and the StratBENCOST are very comprehensive programs, but a large amount of input data is required. The HDM-4 system also uses a large default data set, and was designed for use at project level. The major strength of the HERS model is its application of benefit-cost analysis in estimating investment options at network level. However, the lifetime benefits associated with a given improvement is computed only for the first five-year period, and an estimate of an improvement's construction cost is used as a proxy for its remaining future benefits. The Ozbay model was calibrated for each origin-destination pair, which may not be transferable for use at network-level. It is therefore desirable to explore an alternative approach to estimate aggregated network-level highway user cost without having to carry out user cost estimation for the individual highway segments that comprise such a network.

2.2 Highway Asset Management System Goals and Performance Indicators

2.2.1 General Highway Asset Management System Goals

The goals of an asset management system are related to highway system performance in that they reflect different perceptions of what the highway system should achieve. Understanding different goals is critical to identifying different types of highway performance indicators that need to be included into the management process. Table 1 summarizes an example set of goals and objectives identified by Cambridge Systematics [2000] that were found to provide a solid and broad basis for the highway asset management process.

Table 1: Example Goals and Objectives by Category

Category	Goal	Objective
System Preservation	Preserve highway infrastructure cost-effectively to protect the public investment	Improve construction techniques and materials to minimize construction delays and improve service lives of highway assets
Operational Efficiency	Develop strategies that improve the transfer of people and goods by reducing delays and minimizing discomforts	Utilize economies of scale by providing for joint use of inter-modal facilities
Accessibility	Ensure reasonable accessibility for all residences	Maintain access to population that can reach specified services
Mobility	Ensure basic mobility for all residences by providing safe, efficient, and economical access to employment, educational opportunities, and essential services	Make public transportation travel time competitive with automobiles
Economic Development	Address anticipated demand from increase in trade	Improve access to passenger and freight facilities to serve trade
Quality of Life	Ensure that highway investments are cost-effective, protect the environment, promote energy efficiency	Provide opportunity for safe, enjoyable, and low environmental impact recreation
Safety	Ensure high standards of safety in the transportation system	Reduce motor vehicle-related fatalities, injuries, and property damages
Resource and Environment	Develop projects that are environmentally acceptable	Improve air quality through transportation measures

2.2.2 Performance Indicators under System Goals

The purpose of establishing performance indicators is to enable transportation agencies to assess the degree to which the selected investment program has been successful in terms of improved system benefits. Setting clear performance indicators and using the results of this evaluation to inform future investment choices and management decisions are essential to ensure that an agency's investment is producing intended outcomes. Table 2 summarizes highway performance indicators currently used by state transportation agencies [Poister, 1997].

Table 2: Highway Performance Indicators Utilized by State Transportation Agencies

Category		Performance Indicator	State	
System Preservation	Pavement	Percent highway miles built to target design	OR	
		Average roughness or overall pavement index value for state highway, by functional class	CT, FL, IN, MN, NC, NY, PA, RI, VA	
		Percent of highways rated good to excellent	IN, MN, NY	
		Percent roads with score of 80 or higher on overall highway maintenance rating scale	FL, IN, MN, OR	
		Percent of total lane miles rated fair or better	OR	
		Miles of highway that need to be reconstructed	MN, NY, WA	
	Bridge	Percent of highway bridges rated good or better	IN	
		Percent of highway mainline bridges rated poor	IN, WA	
		Number of bridges that need to be rebuilt	FL, IN, WA	
Operational Efficiency	Construction, maintenance, and operation	Cost per lane-mile of highway constructed	AL, GA, FL	
		Cost per unit of highway maintenance work completed; labor cost per unit completed	AZ, NC, MN, PA, WA	
	Cost-effectiveness	Cost per percentage point increase in lane miles rated fair or better on pavement condition	CA, VA	
		Cost per accident avoided by safety projects	CA, VA	
Accessibility	Automobile/roadway	Percent of population residing within 10 minutes or 5 miles of state aided public roads	MN, OR	
	Roadway	Percent of bridges with weight restrictions	AZ	
		Miles of bicycle compatible highway rated as good or fair	IN	
Mobility	Travel speed	Average speed versus peak-hour speed	MN	
		Hours of delay	MN, NY	
	Delay, congestion	Percent of limited access highways in urban areas not heavily congested during peak hours	IN, OR, NY	
		Amount of travel	Vehicle miles of travel on state highways	PA
			Percent VMT on roads with high v/c ratios	AZ, NJ, PA
Economic Development	Support of economy by transportation	Percent PMT in private vehicles and public transit buses on roads with high v/c ratios	NJ	
		Percent of wholesale and retail sales occurring in significant economic centers served by unrestricted market artery routes	MN	
Quality of Life	Accessibility, mobility related	Percent motorists indicating they are satisfied with travel times for work and other trips	IN, MN, PA	

Table 2: Highway Performance Indicators Utilized by State Transportation Agencies (Continued)

Safety	Number of vehicle collisions	Vehicular accidents per million VMT	CA, IN, KS
		Fatalities or injury per 100 vehicle miles of travel	CA, IN, KS, OR
		Accidents involving injuries per 1,000 residents	KS
		Accidents involving pedestrians or bicyclists	IN
		Number of pedestrians killed on state highways	IN
	Roadway condition related	Percent change in miles in high accident locations	PA
		Percent accident reduction due to highway construction or reconstruction projects	CA, OR, VA
		Reduction in highway accidents by safety improvement projects	IL
		Number of railroad crossing accidents	CA, IN
		Percent of motorists satisfying with snow and ice removal, or roadside appearance	MN
	Construction related	Number of accidents in highway workzones	IN, NC
Resource and Environment	Fuel usage	Highway vehicle miles of travel per gallon of fuel	IN

Note: VMT- vehicle mile of travel; PMT- person mile of travel.

2.2.3 Discussions on Highway Performance Indicators

State transportation agencies, as can be seen from the above table, tend to maintain a variety of performance indicators for a number of goals ranging from system preservation, agency cost, operational efficiency, mobility, and safety, to the environment. In the present study, we will look into the details of performance indicators identified, refine the content, and also consider the data collection efforts needed to establish a final set of performance indicators under the study framework.

2.3 Modeling of Physical Highway Asset Performance

2.3.1 Introduction

System performance refers to the manner in which the assets of a highway system deteriorate after cumulative use. Pavements and bridges are the primary physical assets in a highway network,

and over the years, state transportation agencies responsible for the preservation of a highway network have committed significant amounts towards collecting and analyzing data on condition of pavements and bridges. One of the purposes of this effort is to determine historical trends and to develop models for forecasting future performance so that the information can be used to identify maintenance and rehabilitation strategies for these highway assets. The present section mainly focuses on a review of performance modeling of pavements and bridges based on deterministic and probabilistic models.

2.3.2 Review of Studies Using Deterministic Models

2.3.2.1 Regression Models

Over the past two decades, regression analysis has been used for pavement performance modeling in a number of studies. For instance, Sharaf *et al.* [1998] used regression analysis to model pavement condition trends at selected U.S. Army installations. New York DOT also used regression analysis to model pavement condition over a period of time [Gepffrey and Shufon, 1992]. Twelve years of data were used to develop pavement performance curves in Ontario, Canada, using regression analysis [Ponniah, 1992]. Statistical regression was used in a Strategic Highway Research Program (SHRP) study to obtain predictive pavement performance models for various pavement types, traffic levels, and environmental conditions, among others [Daleiden *et al.*, 1993]. Al-Mansour and Sinha [1994] used regression to obtain a relationship between pavement performance in terms of PSI and pavement age. A study conducted by Geoffroy *et al.* [1996] suggested that the actual pavement performance curve could be determined by performing a regression analysis of time-condition data. Ullidtz [1999] presented a number of mechanistic-empirical deterioration models for managing flexible pavements, in which a simple mechanistic method using the critical stresses and strains in pavement materials was combined with deterioration models to predict pavement deterioration in terms of roughness, rutting, and cracking, respectively, as a function of traffic loading, climate, and age.

Regression models are often used in model development because they are fairly easy to develop with commonly available analysis packages. The results are also easy to interpret. There are, however, limitations with regression analysis. The use of regression techniques assumes that the errors are normally distributed and their variance is homogeneous, which does not systematically vary with the variation of the predicted value of the dependent variable. The underlying assumptions for the use of regression must be verified with the data before such an analysis can be used [Mouaket and Sinha, 1990]. Furthermore, the accuracy of regression models can be adversely affected by any correlated independent variables. For example, a model that has pavement age and cumulative Equivalent Single Axle Loads (ESALs), without correcting for biases, could suffer because the greater the age of a pavement, the greater the likelihood of a high cumulative ESALs.

2.3.2.2 Econometric Models

The past decade has seen a rise in the use of econometric analysis for pavement and bridge performance modeling. Most of such studies have generally been limited to research purposes, but the results they provide have been shown to be more consistent with actual observation, compared to those offered by regression analysis. Using econometric models, the multicollinearity between explanatory variables, heteroscedasticity of the error variances, selectivity bias including simultaneity and endogeneity biases from sample selection procedures can be adequately addressed.

Econometric analysis commonly uses single equation and mixed equation approaches. In the single equation approach, an underlying assumption is that past maintenance has a unilateral and exogenous effect on performance. For example, the pavement condition may currently be acceptable but may become unacceptable in the future if no action is taken. To forestall pavement deterioration to an unacceptable level, a decision may be made to perform a work activity. The effect of the work activity on performance can be modeled using the single equation approach. Examples of the single equation approach were found in the work of Ramaswamy and Ben-Akiva [1997], who developed

simultaneous models to represent the interaction of pavement performance and maintenance; and of Madanat *et al.* [1997], who developed a random effect probit model with state dependence for bridge deck deterioration modeling. The mixed equation approach is applicable to situations where discrete choices are involved in the investment process and performance modeling needs to be carried out as a result of a given investment decision. An example of the mixed equation approach is contained in the study by Mohamad *et al.* [1997] who investigated the relationship between maintenance and performance. In that study, a discrete model was developed to examine the impact of pavement performance levels on the decision to perform maintenance on pavement segments. A continuous model was then formulated to investigate the effect of maintenance on the level of pavement performance. It was found that the mixed logit approach produced much better results than the single equation method in specifying the models in terms of coefficient signs and their significances.

2.3.2.3 Heuristic Optimization Approach

Deterioration models may also be categorized as linear or nonlinear. Linear models generally have simple equation forms and are relatively easy to use, but such models may have their own disadvantages of not being able to serve many purposes. In recent years, researchers also started to develop nonlinear models through optimization techniques as a solution. One example is the work of Shekharan [2000], who used genetic algorithms as a tool for the development of nonlinear deterioration models.

2.3.3 Review of Studies Using Probabilistic Models

Probabilistic models include Markovian process models, Bayesian decision models, and survivor curves. Markov theory assumes that a change in condition from one state to another is only dependent on its current state. Bayesian theory allows for combining both subjective and objective

data to develop predictive models using regression analysis [Butt, 1991]. Survivor curves represent the percent of highways that remain in service as a function of time [McNeil *et al.*, 1992].

2.3.3.1 Markovian Process Models

Markovian process models are developed from estimates of probability that a given condition state will either stay the same or move to another state. The probability of each of these events is estimated based on historical field data or the experience of agency personnel. For instance, Washington DOT started to use Markov transition probabilities of pavement condition states in the early 1970s; INDOT used the Markov chain for bridge performance prediction for bridge management in 1980s [Jiang *et al.*, 1988]; Arizona DOT used the Markovian process for pavement performance prediction in the 1980s and improved the transition probability matrices by introducing the concept of pavement probabilistic behavior curves [Wang *et al.*, 1994]; and Ohio DOT developed Markovian deterioration models using Monte Carlo simulation for pavement performance analysis [Tack and Chou, 2001]. Pavement or bridge conditions can be predicted at any point in the future as long as the initial condition state and transition matrix are known. Using the probability transition matrices, an agency can also develop pavement performance models by calculating plotted points based on matrix multiplication. Markovian process assumes time homogeneity of the transition probabilities, which may not be realistic for pavement or bridge performance. One remedying measure to this limitation is to incorporate the use of zones within which the transition process is stationary [FHWA, 1987].

2.3.3.2 Bayesian Regression Analysis

In Bayesian regression analysis, both subjective and objective data are used to develop prediction models. An example of this approach was provided in a research project in the State of Washington [Kay *et al.*, 1993]. By using both the subjective opinions of experienced personnel and

objective data obtained from mechanistic models, new models were developed to relate pavement fatigue life as a function of asphalt consistency, asphalt content, asphalt concrete proportion, and base course density. Using Bayesian regression analysis, the model parameters were found to be random variables with associated probability distributions.

2.3.4 Summary of Review on Modeling of Physical Asset Performance

Over the past several decades, deterministic models, especially regression models, have served performance prediction needs reasonably well. In recent years there is a trend to explore other methods of performance modeling in order to achieve an improved level of accuracy. An example of these efforts is the use of econometric models. Although econometrics involve mathematical rigor, with increasingly available econometric modeling software packages, it is possible to adopt these techniques for predicting the performance of physical highway assets such as pavements and bridges.

Probabilistic models are also gaining attention, as they facilitate the prediction of pavement condition on a network level. Significant progress has been made in probabilistic modeling of pavement and bridge performance. The relationship between deterministic and probabilistic models was investigated by Li *et al.* [1997]. The successful use of probabilistic models largely depends on establishing transition probability matrices and incorporating pavement and bridge history into the model development, which is a difficult task.

2.4 Modeling of Asset Usage Performance

In a highway network, asset usage performance is represented by highway user cost. User cost savings are considered benefits when conducting economic analysis. Therefore, the determination of highway user cost is one of the most important issues in highway programming and management. Extensive user cost studies have been carried out throughout the world in recent years to establish user

cost models as a function of road condition. For instance, Du Plessis and Schutte [1991] developed vehicle operating cost as a function of PSI separately for different vehicle types. Models of highway user cost including vehicle operating cost, crash-related cost, and user delay cost during maintenance and rehabilitation operations at workzones were established by Vadakpat *et al.* [2000]. The existing user cost models are mainly for use at the project level. As a highway asset management system is to be used to assist in systemwide highway investment decisions, network level user cost models are needed.

2.5 Life-Cycle Cost Analysis

Life-cycle cost analysis for highway assets such as pavements and bridges is a process that evaluates the total economic worth of the initial cost and the discounted future cost of maintenance, rehabilitation, and reconstruction associated with the assets. Many state transportation agencies have started to use life-cycle cost analysis for asset management in recent years [FHWA, 1991]. FHWA has made a concerted effort for the use of life-cycle cost analysis in highway design [FHWA, 1998]. A life-cycle cost analysis can use a deterministic approach by incorporating a single point value or a probabilistic approach, which includes mean, variance, and probability distribution for the concerning variables used. Tighe [2001] conducted probabilistic life-cycle cost analysis for highways and concluded that typical construction variables, such as thickness and cost, follow a lognormal distribution rather than a normal distribution. Ignoring the lognormal nature of these variables can introduce significant biases in the overall life-cycle cost estimation. As highway asset management involves various physical assets that have different service lives, life-cycle costing needs to be carried out to allow comparison of investments on the assumption of an equal basis.

2.6 Multicriteria Decision-Making

2.6.1 Tradeoff Analysis

Highway asset management entails a comprehensive view across a range of physical highway assets and their usage. The management process encourages developing the most cost-effective mix of projects under various program categories and examining the implications of shifting funds between different program categories. Insufficient attention has been given in the past to explicit program evaluation and examination of tradeoffs between program categories within a mode, between modes, and between jurisdiction levels [Cambridge Systematics, 2001]. Through tradeoff analysis, the economic benefit and cost of shifting funds from one program category to another can be assessed. In addition, the service level possible at different program funding levels can also be defined.

A highway asset management system involves multiple system goals, including system preservation, agency and user cost, mobility, safety, and the environment. These goals have non-commensurable measurement units. For instance, system preservation could be reflected in terms of the remaining service life in years, cost could be represented in dollars, and environmental impacts could be shown by vehicle emission quantities in tons. To validate the tradeoff decision process involving multiple, non-commensurable goals, relative weights between the system goals must first be established; then the non-commensurable units under individual goals can be scaled into dimensionless values. The dimensionless values under individual system goals can finally be combined into a systemwide dimensionless value. The above three steps are commonly termed as weighting, scaling, and amalgamation. The following sections present a review of techniques currently available for dealing with these issues encountered in the tradeoff decision process.

2.6.1.1 Methods of Weighting

Because the values of relative weights can make a large difference in the resulting ranks of alternative projects, the determination of weights should be approached carefully. The common weighting methods include equal weights, observer-derived weights, direct weighting, Analytical Hierarchy Process, and the gamble method. These are briefly discussed below.

The use of equal weights is simple and straightforward and easy to implement, but it does not capture the preference among different attributes. Observer-derived weights [Hobbs and Meier, 2000] estimate relative weights of multiple goals by analyzing unaided subjective evaluations of alternatives using regression analysis. For each of the given alternatives, the decision-maker is asked to assign scores to benefits under individual goals and a total score on a scale of 0 to 100. A functional relationship is then established using the total score as a response variable and the scores assigned under individual goals as explanatory variables through regression analysis. The calibrated coefficients of the model thus become the relative weights of the multiple goals. Psychologists and pollsters prefer this method because it yields the weights that best predict unaided opinions.

Direct weighting methods [Dodgson *et al.*, 2001] ask the decision-maker to specify numerical values directly for individual goals between 1 and 10 on an interval scale. There are two ways of scaling. One possibility is global scaling, which is to assign a score of 1 to represent the worst level of performance that is likely to be encountered and 10 to represent the best level. Another option is called local scaling, which associates 1 with the performance level of the alternative in the currently considered set of alternatives that performs least well and 10 with that which performs best. The global scaling more easily accommodates new alternatives at a later stage if their performances lie outside those of the original set. However, it requires additional judgments in defining the extremes of the scale, and is less easily used than local scaling to construct relative weights for the different goals.

The Analytic Hierarchy Process (AHP) can consider both objective and subjective factors in assigning weights to multiple goals [Saaty, 1977]. The AHP technique is based on three principles:

decomposition, comparative judgments, and synthesis of priorities. The relative weights of individual decision-makers that reflect their importance are first established, and then the relative weights of individual decision-makers for the multiple goals are assessed. The local priorities of the goals with respect to each decision-maker are finally synthesized to arrive at the global priorities of the goals. One criticism to this technique is the rank reversal of goals when an extra goal is introduced.

The gamble method [Keeney and Raiffa, 1993] chooses a weight for one goal at a time by asking the decision-maker to compare a “sure thing” and a “gamble”. The first step is to determine which goal is most important to move from its worst to its best possible level. Then, two situations must be considered. First, the most important goal is set at its best level and other goals are at their least desirable levels. Second, the chance of all goals being at their most desirable levels is set to p , and chance of $(1-p)$ for all goals is at their worst values. If the two situations are equally desirable, the weight for the most important goal will be precisely p . The same approach is repeated to derive the weights for remaining goals with decreasing relative importance. The hypothetical probabilities for all goals in their best or worst cases will likely vary with different assessors.

2.6.1.2 Methods of Scaling

For tradeoff analysis with multiple, non-commensurable goals, the decision-maker must scale the attributes. Value scaling can be viewed as a value function that translates a social, economic, or environmental attribute into an indicator of worth or desirability. A value function usually describes a decision-maker’s preferences regarding different levels of an attribute under certainty, with which the most preferred outcome is assigned a value of one and the worst outcome a value of zero. As a more specific type of the value function, a utility function reflects both the innate value of different levels of the attributes as well as the decision-maker’s attitudes toward risk, i.e., risk prone, risk neutral, and risk averse. The utility function is often applied in three steps: create a single attribute utility function for an attribute; characterize the probability distribution of the attribute for each alternative; and

calculate the expected utility of the attribute for each alternative. The alternative with a higher expected utility value is the more preferred by the decision-maker.

The assessment of a utility function can be carried out by the following five steps: prepare for assessment, identify relevant qualitative characteristics, specify quantitative restrictions, choose a utility function, and check for consistency [Keeney and Raiffa, 1993]. At the early stage of the assessment, it is needed to determine whether the utility function is monotonic and whether the utility function is risk prone, risk neutral, or risk averse. After identifying the relative shape of the utility function, quantitative utility values corresponding to some attribute values, normally on five points, need to be assessed. This can be done by first choosing attribute values at their lowest, first quarter, half, third quarter, and highest levels, and then finding the corresponding utility values. The calibration can also be conducted by fixing utility values at zero, one quarter, half, three quarters, and one, and then determining the attribute values associated with these utility values. Before finishing the whole evaluation process, some simple consistency checks need to be conducted. For instance, the decision-maker's certainty equivalent can be assessed using three consecutive points in a five-point assessment procedure.

2.6.1.3 Methods of Amalgamation

Amalgamation is a process applied to yield a single value index for an alternative that involves multiple goals, which allows the alternatives to be ranked. Amalgamation methods can be categorized as no-preference, prior, posterior, interactive, and evolutionary methods. The classical methods with no-preference include the ϵ -constraint method [Goicoechea et al., 1982] and weighted sum and weighted Tchebycheff method [Steuer, 1989]. Prior methods can be either continuous or discrete with prior articulation of preferences and mainly include goal programming [Charnes and Cooper, 1961], the multiattribute utility function method [Keeney and Raiffa, 1993], the surrogate worth tradeoff method [Haimes and Hall, 1974], and the outranking method [Benayoun *et al.*, 1966;

and Roy and Bertier, 1971]. The method based on posterior articulation of preferences includes data envelopment analysis [Charnes *et al.*, 1978]. Interactive methods are used for situations where minimum knowledge is needed for a prior, and are often termed as methods of progressive articulation of preferences. Popular interactive methods include the step method [Benayoun and Tergny, 1969] and compromise programming [Zeleny, 1973]. Evolutionary algorithms mimic natural evolutionary principles to constitute optimization processes. These algorithms are well suited for situations where nonlinearities and complex interactions among problem variables are present. The most commonly used evolutionary algorithms are genetic algorithms [Holland, 1975]. The following section briefly discusses each of these methods.

The ε -constraint methods [Goicoechea *et al.*, 1982] allow the user to arbitrarily select an objective function for maximization and at the same time specify bounds on the remaining objectives, which alleviates the difficulties faced by the weighted sum method in solving problems having non-convex solution space. Motivation for specifying bounds on the objective functions is often provided by the formulation requirements of the problem. As the solution technique is used to solve for one objective function at a time, this method only leads to an intermediate non-dominated solution, and the global non-dominated solution can only be obtained under some specific conditions.

The weighted sum method is the most widely used procedure that scales multiple objectives into a single objective by multiplying a weight to each objective. Setting relative weights for individual objectives becomes a central issue in applying this method. It should be noted that setting up a weight vector for the multiple objectives depends highly on the magnitude of each objective function, and it is desirable to normalize them so that each has more or less the same scale of magnitude. Instead of using a simple weighted sum of the multiple objectives, the weighted Tchebycheff method [Steuer, 1989] uses distance metrics for the amalgamation process:

$$l_p = \left[\sum_{m=1}^M \left(w_m * |f_m(x) - z_m^*|^p \right) \right]^{1/p}, \text{ where } f_m(x) \text{ is the single objective function, } z_m^* \text{ is the ideal solution for}$$

$f_m(x)$, $m = 1, 2, \dots, M$ for number of objectives, and p is the metric parameter that takes values between 1 and ∞ . This is the basic idea of goal programming, which will be discussed below.

Goal programming [Charnes and Cooper, 1961] is an approach to solve multicriteria optimization problems when the relationship between multiple conflicting goals and decision variables can be expressed mathematically. This method requires the decision-maker to provide relative weights for the conflicting goals and the target level of each goal to be achieved. Alternatives are then ranked according to the weighted deviation from the goal, i.e., the smaller the deviation, the more preferred the alternative. The idea is to choose an alternative closest to the goals by minimizing a distance measure. A variation of goal programming is compromise programming [Zeleny, 1973], which identifies solutions closest to the ideal solution as determined by some measure of distance. The solutions identified are called compromise solutions and constitute the compromise set. If the compromise set is small enough to allow the decision-maker to choose a satisfactory solution, then the process is terminated. Otherwise, the ideal solution is redefined and the whole process is repeated.

Multiattribute utility functions [Keeney and Raiffa, 1993] capture a decision-maker's preferences regarding levels of attributes and also the attitude towards risk for several attributes simultaneously. This is accomplished by weighting and synthesizing single attribute utility functions to a multiattribute utility function, either in additive or multiplicative form. The expected values of the multiattribute utility function are then used to rank the alternatives, and the alternative with the maximum expected utility value is then chosen. Two assumptions are made for the multiattribute utility functions: utility independence and preference independence. Utility independence means that each attribute's utility function does not depend on the levels of other attributes. Preference independence assumes if the tradeoffs between two attributes do not depend on the levels of other attributes.

The surrogate worth tradeoff method [Haimes and Hall, 1974] assumes that the decision-maker maintains a multiattribute utility function with continuous variables and twice differentiable. The method is applied systematically and compares two objectives at a time. Application of the

method is facilitated by the following: (i) generate a representative subset of non-dominated solutions; (ii) obtain relevant tradeoff information for each generated solution; (iii) construct surrogate worth tradeoff functions by assessing each time the decision-maker's own marginal rate of substitution for a pair of non-dominated solutions; and (iv) use optimal tradeoffs relative to the decision-maker's preferences to identify the best compromise solution.

Outranking methods are a class of multicriteria decision-making techniques that provide an ordinal ranking (sometimes only a partial ordering) of the alternatives. The Elimination and (et) Choice Translating Algorithm (ELECTRE) method [Benayoun *et al.*, 1966; and Roy and Bertier, 1971] falls into the category of outranking methods, and its purpose is to establish a set of outranking relationships among alternatives using the following procedure. One alternative is found to outrank another only if two conditions are satisfied. First, the sum of normalized weights in which the first alternative is better, i.e., concordance index, exceeds a predetermined threshold value. Second, the number of attributes in which the second alternative is better by an amount greater than a tolerable threshold value, i.e., discordance index, is zero. An extension of the ELECTRE method by incorporating uncertainty was provided by Mahmassani [1981].

The Data Envelopment Analysis (DEA) method [Charnes *et al.*, 1978] is used to analyze the relative efficiency of each of a set of alternatives by constructing the efficiency frontier. The most commonly used DEA models are based on a linear programming formulation that uses a pair of primal and dual linear programming models. Given the input and output for a set of alternatives, the primal and dual pairs are solved. When the optimal objective functions for both the primal and dual reach zero, then the corresponding alternative is on the efficient frontier. The values of the dual variables for efficient alternatives provide the rates of substitution of the input for the output along the efficiency frontier.

The Step Method (STEM) [Benayoun and Tergny, 1969] was the first interactive method introduced to solve for linear and nonlinear problems. The method assumes that the best compromising solution has the minimum combined deviation from the ideal point, and the decision-

maker has a pessimistic view of the worst component of all individual deviations from the ideal point. The technique essentially consists of two steps. First, a non-dominated solution in the minimax sense to the ideal point for each objective function is sought, and a payoff table is constructed to obtain the ideal criterion vector. The decision-maker then compares the solution vector with the ideal vector of a payoff table by modifying a constraint set and the relative weights of objective functions. The process terminates when the decision-maker is satisfied with the current solution.

Over the last decade, Genetic Algorithms (GA) [Holland, 1975] have been widely used as analytical tools to handle optimization problems with heuristic solutions. In principle, a genetic algorithm begins a search with a random set of solutions. Once a random population of solutions is created, the solutions are evaluated by calculating the objective function values and constraint violations, by which a metric is defined to assign relative merits, called fitness, corresponding to the solutions. The population of the solutions is updated through operations of reproduction, crossover, and mutation to maintain and combine good binary strings, as well as to create a better string. A better population of random solutions may be created with additional iterations. The algorithm stops when the termination criterion is met.

2.6.1.4 Incorporation of Risk and Uncertainty into the Tradeoff Decision Process

The concept of risk comes from the inability to know what the future will bring in response to a given action today. Risk can be subjective or objective. Subjective risk is based on personal perception that may be related to the consequences of the failure as well as the ability or inability to control the situation. Objective risk is based on theory, experiment, or observation [FHWA, 1998]. In the case of risk, the decision-maker is ignorant of possible outcomes but the range and distribution of possible outcomes are known. For uncertainty, on the other hand, either the range or distribution of possible outcomes, or both, are not known.

Most existing decision-making tools for highway asset management treat input variables as discrete fixed values, i.e., the values are certain. In fact, the majority of input variables inherit a certain amount of uncertainty. For instance, uncertainties are involved in conducting a life-cycle cost analysis and quantifying the benefits of investments. In addition, a wide range of factors are also likely to change over time, some of which are beyond the control of state transportation agencies. For example, changes in project cost and scheduling and changes in federal and state funding levels have a potentially significant impact on a program in terms of policy direction and priority [Neumann, 1997].

2.6.1.5 Review Summary for Tradeoff Analysis

In this section, a number of methods for tradeoff analysis were discussed. These methods generally deal with setting parameters for three major aspects encountered in tradeoffs involving multiple, non-commensurable goals: weighting, scaling, and amalgamation. Properly selecting and implementing these methods are critical to the quality of the final solution. For instance, some of the amalgamation methods, such as the outranking methods and the DEA procedure, are less popular than others and can only be applicable to problems involving a small number of alternatives. Highway asset programming and management involve multiple, non-commensurable goals and also deal with a large number of candidate projects associated with different asset types. Therefore the relative weights of multiple goals must first be determined, benefits under individual goals associated with a candidate project must be scaled into dimensionless values, and the respective values synthesized to come up with a systemwide nondimensional value. Tradeoffs of projects can then be conducted on the basis of the nondimensional value. For these reasons, multiattribute utility functions based on the utility theory appear to be a suitable approach for tradeoff decision-making in highway asset management.

2.6.2 Project Selection and Programming

2.6.2.1 Current Practices in State Transportation Agencies

Most transportation agencies have established procedures for identifying deficiencies, needs, and candidate projects within the planning function. The information is then used as the input in the programming process. Needs assessment and project identification are carried out through a combination of methods: facility management systems; system usage management systems; sufficiency ratings or deficiency threshold criteria; review of accident, traffic, or ridership statistics; and suggestions by agency staff or elected officials. After the needs are identified, specific projects can be developed for consideration in the project priority setting phase. Ranking, prioritization, and optimization offer an approach that allows for analysis and comparison of different types of projects in the priority setting process [FHWA, 1991].

Ranking is the simplest form of priority setting for the selection of highway projects for a single year period, which is also called single year prioritization. The ranking procedure mainly includes two steps. The first step is to determine project items of a highway asset type that should be considered for preservation or improvement. For each set of candidate projects, the best alternative for each candidate project is identified and the corresponding cost is determined. The next step involves prioritization of candidate projects according to a given set of criteria. The ranking procedure may be implemented by using single criterion, such as distress, condition, initial cost, least present cost and timing, life-cycle cost, benefit-cost ratio, cost-effectiveness, or composite criteria such as a ranking function combining condition, geometry, traffic, maintenance, and safety factors [Zimmerman, 1995]. The ranking procedure produces a ranked list of projects to be carried out, the cost associated with each project, and a cut-off line established based upon the level of funding available. As the timings of alternative projects are not considered in the ranking process, the long-term impacts of delaying or accelerating projects from one year to another cannot easily be evaluated.

Multi-year prioritization is a more sophisticated approach to project selection that is closer to an optimal solution for addressing highway network scheduling and budgeting needs. This method requires the use of performance prediction models, or remaining service life estimates. It also requires the definition of trigger points to identify needs and provisions that allow the acceleration or deferral of treatments during the analysis period. Common approaches used to perform prioritization include marginal cost-effectiveness, incremental benefit-cost, and remaining service life analysis. Multi-year prioritization differs from the ranking procedure in a number of ways. First, different strategies that include alternatives and timings are considered in multi-year prioritization. Another difference lies in the complexity of the analysis. In the ranking procedure, the most common criteria considered are current condition and existing traffic levels. In a multi-year prioritization, an agency is able to simulate future conditions through the use of performance models and consider other factors in the analysis. Furthermore, with multi-year prioritization, the option of timing of maintenance, rehabilitation, or reconstruction can be included in the analysis process. The impact of various funding levels can also be assessed [FHWA, 1991].

Through the use of mathematical programming techniques, such as linear programming, integer programming, and dynamic programming, an optimal solution can be developed in accordance with goals established, such as maximizing total agency benefits or minimizing agency cost to achieve certain condition levels [Zimmerman, 1995]. Unlike prioritization, optimization analysis can yield outputs that are provided in terms of percentage of miles of roads or bridges that should be improved from one condition to another, rather than identifying candidate projects. Optimization addresses several important considerations that are not covered in prioritization analysis. These include the incorporation of tradeoff analysis among candidate projects during strategy selection. Optimization also guarantees that the selection of strategies adheres to budgetary limits. Furthermore, optimization allows multi-year network level planning and programming aimed at moving the overall system towards a defined performance level. Table 3 summarizes programs and project selection tools used by state transportation agencies [Cambridge Systematics, 2000].

Table 3: Program Categories and Project Selection Tools Used by State Transportation Agencies

State	Program Category	Project Selection Criterion
Arizona	<ul style="list-style-type: none"> - Interstate construction and reconstruction - Non-Interstate major construction - Bridge, railroad crossing, hazard elimination - Transportation system management 	Prioritization by <ul style="list-style-type: none"> - Benefit-cost analysis - Sufficiency ratings - Engineer's recommendations
California	<ul style="list-style-type: none"> - Highway Operation and Protection Program - Transportation Improvement Program - Traffic Systems Management Plan 	Technical and policy screen, scoring based on technical merits, policy priority, and air quality control measures
Indiana	<ul style="list-style-type: none"> - Bridge preservation - Pavement preservation - Safety and roadside improvements - System expansion - ITS improvements - Maintenance 	<ul style="list-style-type: none"> - Ranking by utility values - Prioritization by incremental benefit-cost analysis - Optimization by mix-integer programming
Minnesota	<ul style="list-style-type: none"> - Preservation - Management and operations - Replacement - Expansion 	Ranking by <ul style="list-style-type: none"> - Sufficiency/ deficiency ratings - Benefit-cost analysis - Cost-effectiveness analysis
Montana	<ul style="list-style-type: none"> - Maintenance - Rehabilitation - Expansion 	<ul style="list-style-type: none"> - Ranking - Prioritization by incremental benefit-cost analysis - Optimization
New York	<ul style="list-style-type: none"> - State pavement - Statewide congestion/ mobility 	Ranking by <ul style="list-style-type: none"> - Sufficiency/ deficiency ratings - Life-cycle cost - Cost-effectiveness - Benefit-cost analysis
Oregon	<ul style="list-style-type: none"> - Preservation - Modernization - Operations Safety 	- Technical ranking and scoring
Pennsylvania	<ul style="list-style-type: none"> - Bridge rehabilitation and replacement - Interstate/ expressway restorations - Congestion reduction - Safety, mobility, and congestion - New facilities and services 	Ranking by <ul style="list-style-type: none"> - Sufficiency ratings
Texas	<ul style="list-style-type: none"> - Added capacity and new location - Highway rehabilitation and construction - Bridge replacement and rehabilitation - Maintenance 	Ranking by <ul style="list-style-type: none"> - Cost-effectiveness, - Sufficiency/deficiency ratings
Washington	<ul style="list-style-type: none"> - Maintenance - Preservation and improvement - Operations 	Ranking by <ul style="list-style-type: none"> - Benefit-cost analysis
Wisconsin	<ul style="list-style-type: none"> - Maintenance - Rehabilitation, restoration, and reconstruction - Interstate - Bridge 	<ul style="list-style-type: none"> - Ranking by deficiency ratings, benefit-cost analysis - Multi-objective optimization

2.6.2.2 Algorithms for Project Selection and Programming in Highway Asset Management

Similar to project selection and programming process used in pavement and bridge management systems, the optimization process for overall highway asset management can also be treated as a Capital Budgeting Problem (CBP) [Lorie and Savage, 1955] because a subset of mixed projects is selected from a systemwide candidate project list to yield maximum system benefits subject to budget constraints. However, the optimization process is more complicated for highway asset management because multiple asset types are involved and additional budget constraints by asset category may be required. Furthermore, as projects are implemented by contracts in which multiple projects may come from different asset types, a project inter-dependence relationship must be considered. In this case, the project selection and programming process for overall highway asset management evolves to a Multi-Choice Multidimensional Knapsack Problem (MCMDKP), where the budget is achievable from different sources and the analysis is conducted for multiple periods.

The MCMDKP problem is considered as NP-hard in the sense that no non-deterministic polynomial algorithm exists, i.e., the time requirement for the optimal solution grows exponentially with the size of the problem instances. Algorithms for these problems can be classified into two groups, exact algorithms and heuristic algorithms. The exact algorithms are mainly based on branch-and-bound, dynamic programming, and are a hybrid of the two techniques. Heuristic algorithms may solve the problem close to optimal in polynomial time but do not guarantee optimality. Notable algorithms are largely based on dual simplex and Lagrangian relaxation techniques [Martello and Toth, 1990]. Algorithms developed during the past two decades for solving the MCMDKP problem, including the Multichoice Knapsack Problem (MCKP), where multiple budget sources and a single analysis period are involved and the Multidimensional Knapsack Problem (MDKP), where a single budget source and multiple periods for the analysis are considered, are briefly discussed as follows.

2.6.2.2.1 Exact Algorithms

Sinha and Zoltners [1979] presented a branch-and-bound algorithm for the MCKP problem that resided with quick solution of linear programming relaxation and its efficient, subsequent re-optimization as a result of branching. This algorithm performed well on the basis of a large set of test problems. Armstrong *et al.* [1983] conducted a computational study based on the branch-and-bound algorithm developed by Sinha and Zoltners, wherein, data list structures, sorting techniques, and fathoming criteria were investigated. These researchers further improved the algorithm by inserting a heap sort in the algorithm, which resulted in a substantial reduction in computational time. Aggarwal *et al.* [1992] proposed a two-stage algorithm based on Lagrangian relaxation and branch-and-bound. In this algorithm, the first stage was aimed at determining in polynomial time an optimal Lagrangian multiplier, which was then used in the second stage within a branch-and-bound scheme to rank order solutions and finally lead to an optimal solution in a relatively low depth of search. A hybrid algorithm that combined dynamic programming and the branch-and-bound algorithm was developed by Dyer *et al.* [1995] to solve the MCKP problem. In this algorithm, Lagrangian duality was used in a computationally efficient manner to compute tight bounds on every active node in the search tree. Computational experience indicated that the resulting algorithm ran fast and was simple to code. Klamroth and Wiecek [2001] also proposed a dynamic programming approach to find all nondominated solution to the MCMDKP problem. Osorio and Glover [2001] presented a method of logic cuts from dual surrogate constraint analysis before solving the MDKP problem with branch-and-bound, and computational testing showed that the approach solved different problems in a reasonable amount of time.

2.6.2.2.2 Heuristic Algorithms

Frieze and Clarke [1984] described a polynomial time approximation scheme for the MDKP problem based on the use of a dual simplex algorithm for linear programming. Toyoda [1975] suggested a simplified heuristic algorithm based on Lagrangian relaxation for an approximate solution to the MCMDKP problem. Magazine and Oguz [1984] presented a polynomial time-generalized Lagrangian Multiplier approach based on Toyoda's algorithm. Volgenant and Zoon [1990] further extended the algorithm, which also enabled the determination of an upper bound to the optimal solution by allowing more multipliers to be computed simultaneously and sharpened the upper bound by changing some multiplier values. Lee and Guignard [1988] presented an approximation algorithm for the MDKP problem that was controlled by three user-controllable parameters affecting the tradeoff between solution quality and computational time. Zemel [1984] presented a linear time algorithm for the linear MCKP problem and its D-dimensional generalization based on Megiddo's algorithm. In the same period, Dyer [1984] also suggested a linear time algorithm for the MCKP problem with solution quality within a constant factor of optimality. Freville and Plateau [1994] introduced a subgradient heuristic algorithm for the MDKP problem that provided sharp lower and upper bounds on the optimal value and also a tighter equivalent representation by reducing the continuous feasible set and by eliminating constraints and variables. Moser *et al.* [1997] introduced a heuristic algorithm based on the Lagrangian multiplier method for a solution to the MCMDKP problem with polynomial time complexity. Teng and Tzeng [1996] suggested an effective distance heuristic optimization algorithm for the MDKP problem involving a project inter-dependence relationship. The algorithm was able to provide a near optimal solution. Chu and Beasley [1998] presented an algorithm that incorporated problem-specific knowledge into the standard genetic algorithm for the MDKP problem. Computational results showed that the genetic algorithm gave superior solutions to a number of other heuristics with only a modest amount of computational efforts. Akbar *et al.* [2001] developed two heuristic algorithms for solving the MCMDKP problem based on sorting the items of each group in

non-decreasing order according to the value associated with each item. The study's experimental results suggested that the heuristic algorithms find near optimal solutions with much less computational complexity.

2.6.2.3 Review Summary for Project Selection and Programming

Project selection and programming in highway asset management is consistent with the standard MCMDKP problem. However, additional constraints need to be included to capture the project inter-dependence effects. Because the MCMDKP problem is NP-hard and no exact algorithm with polynomial computational time exists, using a heuristic algorithm is a viable choice. In the present study an efficient heuristic algorithm for the MCMDKP problem incorporating project inter-dependence relationships will be developed.

2.7 Chapter Summary

Asset valuation, highway asset management system goals and performance indicators, performance modeling, and multicriteria decision-making as a part of highway asset management were discussed in this chapter. Approaches for valuation of physical highway assets and highway user cost computation in previous studies were briefly discussed as well, and a summary of highway performance indicators currently being used by state transportation agencies was given. Different highway pavement performance modeling techniques and their advantages and limitations, as well as methods for weighting, scaling, and amalgamation for tradeoff analysis were presented. Finally, the current practices of project selection and programming in state transportation agencies and an algorithm for system optimization were reviewed.

CHAPTER 3 STUDY METHODOLOGY

3.1 Introduction

This chapter discusses the methodology adopted for addressing various tasks involved in a highway asset management system. These tasks include asset valuation, performance modeling, marginal benefit analysis, tradeoff analysis, and project selection and programming, and an overview of study methodology is shown in Figure 3. The process begins with defining a set of highway asset management system goals and programs. A set of performance indicators associated with various programs under individual system goals is then classified. Historical data on annual expenditure incurred on various highway assets, and measurements of highway system physical and operational characteristics are acquired based on random sampling. This information is used for the computation of network-level highway user cost and development of user cost models to evaluate the extent to which the system goals associated with asset usage are achieved. Analysis of the highway system characteristics enables modeling of the performance of physical highway assets including pavements and bridges. By combining the expenditure information with the system performance characteristics, the benefits of individual projects to achieve individual system goals and the impacts of these projects on the performance indicators under individual system goals are also quantified. To facilitate project tradeoffs under certainty and risk and uncertainty, systemwide multiattribute utility functions and standardized focus gain-over-loss ratio functions are separately developed for each program. These functions are the basis for converting project impacts into a dimensionless unit, allowing for the comparison of different projects on an equal basis. A mathematical optimization model along with a solution algorithm is then formulated to assist in systemwide project selection and programming at a certain budget level in a given analysis period.

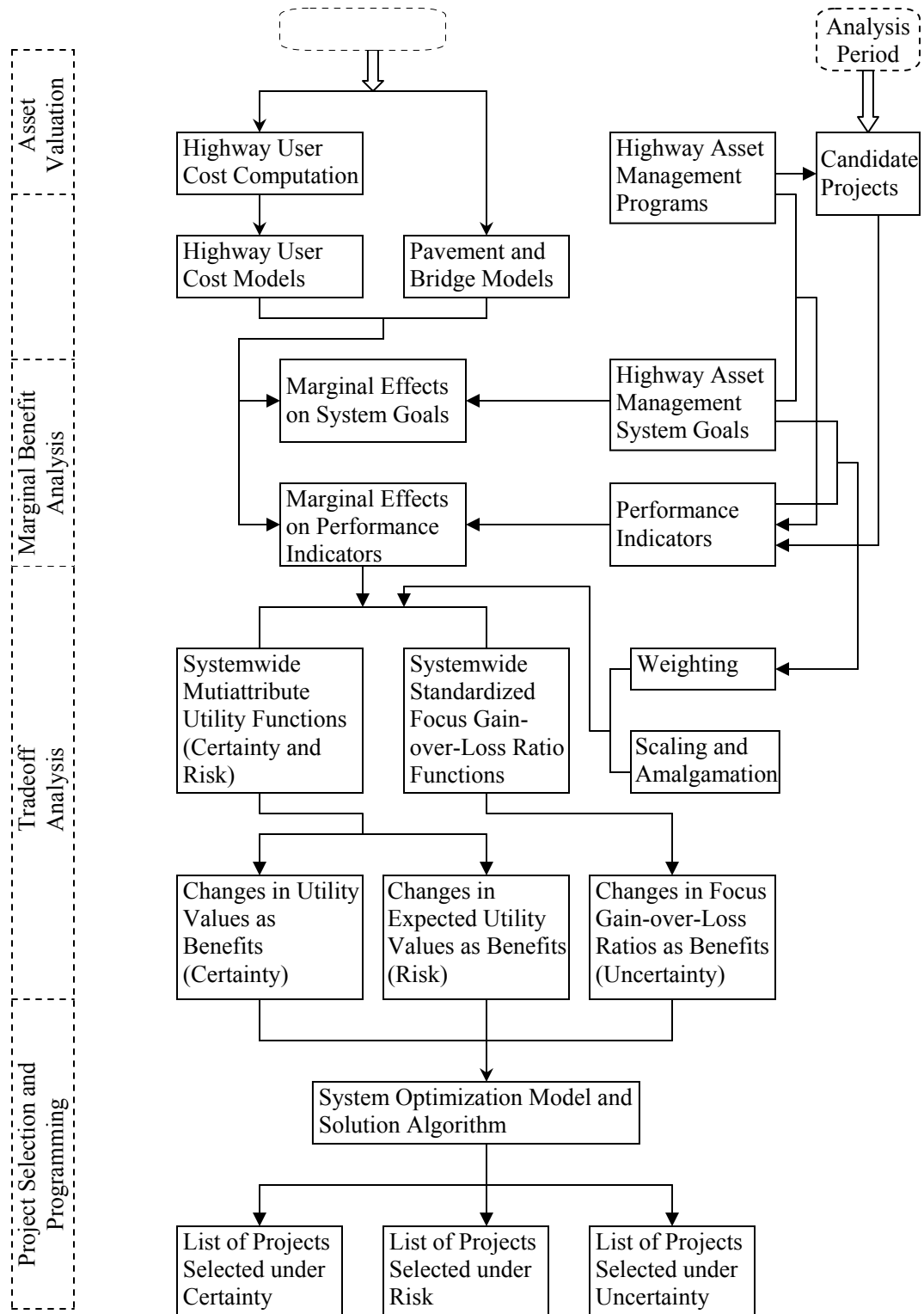


Figure 3: Overview of Study Methodology

3.2 Study Design

The present study is designed in such a manner as to simplify and elucidate the entire analytical approach. A brief discussion of each stage of the analytical framework follows in the subsequent sections.

3.3 Highway Asset Management System Goals and Objectives

In the present study, both agency and highway user goals are considered. On the basis of the literature survey and meetings with officials responsible for statewide highway planning, programming, budgeting, and engineering in Indiana, the following goals were classified for the highway asset management system: system preservation, agency cost, user cost, mobility, safety, and the environment. The objectives and measurement units for individual system goals were established and are listed in Table 4.

Table 4: Highway Asset Management System Goals and Objectives

Asset Management System Goal	Asset Management System Objective	Measurement Unit
System Preservation	Extension of asset service life Preservation of asset condition	Number of years Life-cycle annual average condition rating
Agency Cost	Decrease of agency cost	Life-cycle equivalent uniform annual agency cost in service life
User Cost	Reduction in VOC	Life-cycle equivalent uniform annual VOC per VMT
Mobility	Reduction in travel time	Life-cycle annual average vehicle-hours per VMT
Safety	Reduction in collision rate	Life-cycle annual average no. of collision per million VMT
Environment	Reduction in air pollution rate	Life-cycle annual average emission quantities per VMT

3.4 Project Types under Highway Asset Management Programs

The primary state highway asset management programs in Indiana include the preservation of physical facilities and system expansion. However, there are four different program codes that exist within INDOT, which are the Long Range Plan Code, the Budgetary Code, the Program Management Groups (PMG) Code, and the Engineering Code. The asset management system to be developed in the present study will ultimately be utilized to serve the need of highway programming so the PMG Code was adopted here. Efforts were made in the present study to unify the four coding systems so that there is flexibility in the use of the research products, as shown in Appendix A1. Project types under individual PMG programs (“programs” hereafter) are listed in Table 5, and project definitions are provided in Appendix A2.

Table 5: Project Types under Various Highway Asset Management Programs

General Category	Program Category	Project Type
Bridge Preservation	Bridge Preservation	Rehabilitation Replacement
	Historic Bridges	Preservation
Pavement Preservation	Non-Interstate	Resurfacing Rehabilitation/ reconstruction/replacement
	Interstate	Resurfacing Rehabilitation/ reconstruction/replacement
Safety Improvements	Intersection Improvements	Intersection improvements
	Railroad Crossing Improvements	Railroad crossing projects
	Safety Improvements	Guardrail improvements Sight distance improvements Lighting improvements Traffic signs Pavement markings
	Traffic Signals	Traffic signals
Roadside Improvements	Enhancements	Bicycles/ pedestrians Other transportation enhancements
	Roadside Improvements	Landscaping/ wildflower program Environmental mitigation/ improvement Erosion/ landslide control Access control

Table 5: Project Types under Various Highway Asset Management Programs (Continued)

General Category	Program Category	Project Type
Roadside Improvements (Continued)	New Weigh Station/Rest Area	New weigh station New rest area
	Weigh Station/ Rest Area Modernization	Weigh station modernization Rest area modernization
	Small Structures/ Drainages	Small structure replacement Drainage problem correction
New/ Major Construction	Expansion	New road construction Added travel lanes New interchange construction Interchange modifications
Other State Facilities	Department of Natural Resources Facilities	Park roads Park bridges Cooperative access projects
	Forest Land Highways	Forest land highways
	Other State Institution Facilities	Institution roads Institution bridges Other projects
Intelligent Transportation Systems (ITS)	ITS Installations	ITS traveler information systems ITS management systems ITS monitoring systems ITS operations and maintenance
Miscellaneous	Command and Control Category	Congestion mitigation and air quality (Pre-committed) bonding projects Bridge “watch list” Shelf projects Suspended projects Other command guidance projects
	Local Bridge Inspections	Local bridge inspections
	Local Public Agency Program	State administered Federal aid projects
	Maintenance	Routine maintenance Periodic maintenance
	Multimodal	Inter-modal management projects Inter-modal connectors Airport facilities Passenger rail Railroad corridor preservation Railroad right-of-way preservation Railroad track preservation Transit facilities
	Noise Abatement	Noise abatement projects
	Relinquishments	Transfer of route from state to local level
	Studies	Feasibility/corridor studies
	Utilities	Utility relocation

3.5 Highway Asset Valuation

3.5.1 Introduction

The state-maintained physical highway assets identified for fulfilling GASB34 asset value reporting requirements include roads, bridges, weigh stations, rest areas, railroad crossings, and highway drainage systems. The procedure for assessing physical highway assets is well defined and most state transportation agencies have addressed this issue well. However, little attention has been given to the computation of network-level asset usage cost. The present study, therefore, focuses on filling the gap of computing the network-level highway user cost. This information will assist in evaluating the impacts of highway investment decisions on various highway system usage goals.

3.5.2 Network-Level Highway User Cost Computation and Models

3.5.2.1 Network-Level Highway User Cost Computation

The computation of network-level user cost components in the present study followed a procedure similar to that used in the MicroBENCOST software for estimating user cost, with the exception that the present study was geared towards an entire highway network. Highway user cost components classified include vehicle operation, travel time, vehicle collisions, and vehicle air pollution, and the quantities of different user cost components are associated with the use of the Indiana state highways. Network parameters included the amount of travel, traffic volume, speed, road condition, and geometric characteristics including grade and curvature, and the data used were for the period 1990-2000. The vehicle and highway classes used for the computation are listed in Tables 6 and 7, respectively.

Table 6: Vehicle Classes for Highway User Cost Computation

Vehicle Class	Description	Axle Configuration
1	Unclassified vehicle types	1 steering, 1 single
2	Passenger Cars	1 steering, 1 single
3	Two-axle, 4-tire single units	1 steering, 1 single
4	Buses	1 steering, 1 single
5	Two-axle, 6-tire single units	1 steering, 1 single
6	Three-axle single units	1 steering, 1 tandem
7	Four or more axle single units	1 steering, 1 tridem
8	Four or less axle single trailers	1 steering, 2 or 3 single
9	Five-axle single trailers	1 steering, 2 tandem
10	Six or more axle single trailers	1 steering, 1 tandem, 1 tridem
11	Five or less axle multiple trailers	1 steering, 3 or 4 single
12	Six-axle multiple trailers	1 steering, 3 single, 1 tandem
13	Seven or more axle multiple trailers	1 steering, 2 single, 2 tandem

Table 7: Highway Classes for Highway User Cost Computation

Highway Class	Description
1	Rural interstate
2	Rural principal arterial
3	Rural minor arterial
4	Rural major collector
5	Rural minor collector
6	Urban interstate
7	Urban freeway and expressway
8	Urban principal arterial
9	Urban minor arterial
10	Urban collector

Vehicle operating cost is the mileage-dependent cost of using vehicles, including the expenses for fuel, tires, engine oil, maintenance, and vehicle depreciation, which are attributable to highway mileage traveled. Travel time is measured in terms of vehicle-hours. Delays are considered additional travel time and may be due to congestion and incidents, as well as delays at intersections, railroad crossings, and at workzones. Delay is defined as when the level of travel speed falls under normal traffic conditions because of capacity, geometric, or operational constraints. A county-by-county congestion analysis was performed for the State of Indiana to identify congestion from 1995 to 2015 [Whitford and Opsuth, 1996]. The respective benchmark volume-to-capacity ratios used were

0.9 for urban interstates, 0.8 for urban freeways, arterials and collectors, and 0.7 for rural highway classes. Intersection delay was calculated separately for intersections with stop signs and signalized intersections. Delay at railroad crossings was quantified based on the number of railroad crossings, the number of affected vehicles at each railroad crossing, and the duration of stop time per vehicle at each railroad crossing. Incident delay was estimated in accordance with the FHWA's Traffic Control Systems Handbook, which recommended eight incidents per million VMT when blocking one or more travel lanes [FHWA, 1985]. Details of Indiana workzone characteristics, such as the number of workzones, the length and duration, and the spatial distribution over the highway network were obtained from INDOT construction records, and this information was then processed along with the typical number of vehicles affected and the average travel speed to obtain the total workzone delay. Vehicle collision statistics were extracted from the annual highway safety facts reported in three categories of decreasing severity: fatalities, injury, or property damage by the National Highway Traffic Safety Administration (NHTSA). The major pollutants emitted by vehicles are carbon dioxide (CO₂), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NO_x), total suspended particles (TSP) and sulfur dioxide (SO₂), and emission rates for these pollutants and their respective costs were quantified on the basis of the FHWA's Costs of Air Pollution Abatement Study [FHWA, 1992]. The computation of individual highway user cost components was carried out based on Equations (1)-(8).

$$VOC = \sum_{i=1}^{13} \sum_{j=1}^{10} \left[\left(\sum_{k=1}^5 UVOC_{ijk} \right) \cdot VMT_{ij} \right] \quad (1)$$

$$Travel\ Time = \sum_{i=1}^{13} \left[\left(\sum_{j=1}^{10} \left(\frac{VMT_{ij}}{Speed_{ij}} \right) \right) \right] \quad (2)$$

$$Delay_{intersections} = \sum_{i=1}^{13} \left[\left(\sum_{j=11}^{10} \sum_{l=1}^L \left(N_{jl} \cdot Average\ Delay_{jl} \right) \right) \right] \quad (3)$$

$$\text{Delay}_{\text{railroadcrossings}} = \sum_{i=1}^{13} \left[K_m \cdot \left(\sum_{m=1}^M \text{TSD}_m \right) \right] \quad (4)$$

$$\text{Delay}_{\text{Incidents}} = \sum_{i=1}^{13} \sum_{j=1}^{10} \left[\text{Incident Delay}_{ij} \cdot \text{Incident Rate}_{ij} \cdot \left(\frac{\text{VMT}_{ij}}{1,000,000} \right) \right] \quad (5)$$

$$\text{Delay}_{\text{WorkZones}} = \sum_{i=1}^{13} \sum_{n=1}^N \left[\text{AffectedVehicles}_{in} \cdot \text{WZDuration}_n \cdot \text{WZLength}_n \cdot \left(\frac{1}{\text{Speed}_{in(1)}} - \frac{1}{\text{Speed}_{in(2)}} \right) \right] \quad (6)$$

$$\text{Vehicle Collisions} = \sum_{j=1}^{10} \left[\left(\sum_{p=1}^3 \text{Collision Rate}_{jp} \right) \cdot \left(\sum_{i=1}^{10} \left(\frac{\text{VMT}_{ij}}{1,000,000} \right) \right) \right] \quad (7)$$

$$\text{Air Pollution} = \sum_{i=1}^{13} \sum_{j=1}^{10} \left[\left(\sum_{q=1}^6 \text{Emission Rate}_{iq} \right) \cdot \text{VMT}_{ij} \right] \quad (8)$$

where

VOC = Annual vehicle operating cost, in dollars/year

Travel Time = Annual total travel time, in hours/year

Delay_{intersections} = Annual vehicle delay at intersections and interchanges, in hours/year

Delay_{railroad crossings} = Annual vehicle delay at railroad crossings, in hours/year

Delay_{incidents} = Annual vehicle delay due to incidents, in hours/year

Delay_{workzones} = Annual vehicle delay at work zones, in hours/year

Vehicle Collisions = Annual number of vehicle collisions, in no. of collisions/year

Air Pollution = Annual air pollution quantities, tons/year

VMT_{ij} = Annual vehicle miles of travel for vehicle class *i* on highway class *j*

- $UVOC_{ijk}$ = Unit vehicle operating cost of VOC component k for vehicle class i on highway class j , in \$/VMT
- $Speed_{ij}$ = Annual average travel speed for vehicle class i on highway class j
- N_{jl} = Number of intersections of type l on highway class j
- Average Delay $_{jl}$ = Average delay at intersection of type l on highway class j , in hours/vehicle
- K_m = Number of trains passing railroad crossing m per year
- TSD_m = Total stopped delay time per train at railroad crossing m , in hours/train
- Incident Delay $_{ij}$ = Delay time per incident by vehicle class i on highway class j , in hours/vehicle
- Incident Rate $_{ij}$ = Number of incidents per million VMT by vehicle class i on highway class j
- Affected Vehicles $_{in}$ = Number of affected vehicles of vehicle class i at workzone n
- WZ Duration $_n$ = Duration of work zone n , in days/year
- WZ Length $_n$ = Length of work zone n , in miles
- Speed $_{in(1)}$ = Speed of vehicle class i approaching work zone n , in mph
- Speed $_{in(2)}$ = Speed of vehicle class i in work zone n , in mph
- Collision Rate $_{jp}$ = Number of vehicle collisions of type p per million VMT on highway class j , in no. of collisions/MVMT
- Emission Rate $_{iq}$ = Quantities of pollutant type q emitted by vehicle class i , in tons/VMT
- i = Vehicle class 1 to 13
- j = Highway class 1 to 10
- k = VOC component 1 to 5 for fuel consumption, oil consumption, tire wear, vehicle depreciation, and maintenance and repair

l	= Intersection type 1 to L
m	= Railroad crossing 1 to M
n	= Workzone 1 to N
p	= Collision type 1 to 3 for fatality, injury, and property damage
q	= Pollutant type 1 to 6 for CO ₂ , NMHC, CO, NO _x , TSP, and SO ₂ .

The unit costs of fuel, oil, tire wear, vehicle depreciation, and maintenance and repair were adjusted to reflect the effects of grade, curvature, speed change, and road condition. In order to obtain dollar value of the annual network-level highway user cost, the annual travel time, vehicle collision, and air pollution quantities were first converted into dollar amounts according to the respective unit costs and then added to the annual vehicle operating cost to arrive at the annual total user cost. The unit costs used for the conversion process were updated in each year based on the Consumer Price Index (CPI) for passenger cars and the Producer Price Index (PPI) for trucks accordingly. Details of these computations are discussed in Chapter 4.

3.5.2.2 Network-Level Highway User Cost Models

Network-level highway user cost models were calibrated separately for vehicle operating cost, travel time, vehicle collisions, and air pollution. In order to facilitate model calibration, the individual highway user cost components were first normalized by dividing the estimated annual quantities with the annual amount of travel. In the normalization process, three factors were considered: land use (rural and urban), route type (interstate and non-interstate), and vehicle class (car, single unit truck, and multiple unit truck). For each of the four highway user cost components, a large number of possible combinations among the three factors exist, which would make the entire modeling process quite lengthy. It was necessary to determine whether some aggregation to the

normalized user cost values could be made. As such, an Analysis of Variance (ANOVA) was carried out as a preliminary step. The three-factor factorial model used was of the following form:

$$Y_{ijkm} = \mu + L_i + HC_j + L \cdot HC_{ij} + VC_k + (L \cdot VC)_{ik} + (HC \cdot VC)_{jk} + (L \cdot HC \cdot VC)_{ijk} + e_{m(ijk)} \quad (9)$$

where

Y_{ijkm} = User cost component associated with land use i and route type j for vehicle class k in year m

μ = Average value of user cost component

L_i = Land use, $i = 1, 2$ for rural/urban

HC_j = Highway class, $j = 1, 2$ for interstate/non-interstate

VC_k = Vehicle class, $k = 1, 2, 3$ for car/ single unit/multiple unit truck

$e_{m(ijk)}$ = Error terms within each of the 12 treatments.

Statistical models for the normalized vehicle operating cost, travel time, vehicle collision rate, and air pollution rate were then carried out as a function of network condition, travel speed, and other factors, with levels of aggregation in terms of land use, route type, and vehicle class based on the results of the ANOVA analysis. Results are presented in Chapter 4.

3.6 Modeling of Physical Highway Asset Performance

Pavements and bridges dominate the construction activities of a highway transportation agency, and as shown in Table 8, approximately ninety percent of the total construction budget in Indiana involves pavements and bridges. Consequently, modeling the performance of physical highway assets in the present study focused on pavements and bridges.

Table 8: Share of Expenditure on Pavements and Bridges in Annual Construction Budget in Indiana (in millions, current dollars)

Fiscal Year	Bridge and Pavement Budget				Total Budget	% Total
	Bridge Preservation	Pavement Preservation	New Construction	Subtotal		
1996	68.9	238	161	468	516	91%
1997	68.6	239	163	471	523	90%
1998	79.9	278	190	548	654	84%
1999	73.3	227	257	557	652	85%
2000	62.9	365	166	594	717	83%
2001	99.3	242	389	730	849	86%

Source: INDOT Annual Reports.

3.6.1 Pavement Performance Modeling

The pavement performance analysis focused on two aspects, the effects of traffic loading on rehabilitation and routine maintenance expenditure and relationship between routine maintenance and the rehabilitation interval. The effect of traffic loading on pavement rehabilitation and routine maintenance expenditure was quantified using data collected on state highways in Indiana from a recent study [Li and Sinha, 2000], which established the load and non-load shares of the rehabilitation and routine maintenance expenditure. The findings from that study were adopted for the current research. The relationship between rehabilitation interval and annual maintenance, traffic loading, and weather condition was also determined in another recent study in Indiana [Labi and Sinha, 2001] and these findings were utilized for the tradeoff analysis in the present study.

3.6.2 Bridge Performance Modeling

Bridge performance modeling in the current study focused on two aspects, the impacts of work activities on bridge deck, superstructure, substructure, and wearing surface condition, and the bridge life-cycle agency and user cost. For the bridge condition models, the relationship of changes in the bridge wearing surface and the deck, superstructure, and substructure condition as a function of a work activity, which were represented by a certain level of expenditure, bridge age, and traffic condition at the time of implementing the work action, was established. The cost models sought to express changes in the bridge life-cycle user cost as a function of variables that included expenditure of a work activity, bridge physical condition, age, traffic condition, and load inventory rating. As different types of bridges generally follow different performance trends and have different service lives, model development was conducted separately by bridge type.

3.7 Marginal Benefit Analysis

3.7.1 Marginal Benefit of System Preservation

For physical highway assets, the direct benefit of system preservation was an extension in asset service lives. For instance, tradeoff relationships were found to exist between pavement rehabilitation intervals and the annual maintenance expenditure, traffic loading, and weather severity. Assuming the traffic loading and weather condition remain constant, an increase in maintenance expenditure would result in an extension in the rehabilitation interval. Marginal effects could be determined based on the calibrated pavement performance models. Similarly, in the course of bridge performance modeling, relationships between changes in the bridge wearing surface, deck, superstructure, and substructure structural conditions and the work activities applied to highway bridges were also established. Thus, the marginal effects of various work activities to changes in bridge condition could be quantified.

3.7.2 Marginal Benefit of Agency Cost

A reduction in life-cycle cost for highway pavements and bridges is a direct result of extending the asset service lives. Because, in the long run, less frequent rehabilitation or reconstruction is needed.

3.7.3 Marginal Benefit of Vehicle Operating Cost, Travel Time, Vehicle Collision Rate and Air Emission Rate

In the present study, network-level user cost models were calibrated to relate vehicle operating cost, travel time, vehicle collision rate, and air pollution rate per vehicle mile of travel, respectively, as a function of average traveling speed, road condition, and other factors. The calibrated coefficients were then used to establish the marginal effects of change in vehicle speed and other factors to individual user cost components.

3.8 Tradeoff Analysis

3.8.1 Tradeoff Decision-Making under Certainty

The tradeoff analysis encompasses a number of programs focusing on physical highway assets and asset usage, and it can be conducted for candidate projects under a specific program or across different programs in order to achieve various asset management system goals. As non-commensurable goals are involved, multiattribute utility functions were developed. In addition, projects under different programs are normally implemented for different types of assets or to serve different needs of the system operation. Systemwide multiattribute utility functions were developed separately for individual programs. The calibrated utility functions could then be used to scale benefits associated with a specific project in achieving various asset management system goals into a dimensionless value. Tradeoffs between different types of projects could thus be made on the basis of

these dimensionless values. The following items were used sequentially to establish systemwide multiattribute utility functions for individual programs:

- Relative weights of highway asset management system goals
- Performance indicators for various programs under each system goal
- Weights of performance indicators for individual programs under each goal
- Single attribute utility functions associated with individual performance indicators
- Multiattribute utility functions for individual programs under each goal
- Systemwide multiattribute utility functions for each program.

In order to accomplish the weighing and scaling steps, a series of questionnaire surveys were organized. As a highway asset management system considers the perspectives of not only the agency but also of the highway user, questionnaire surveys about the relative weights of system goals and performance indicators, as well as the utility functions for individual performance indicators, were conducted with both groups. Furthermore, to make the calibrated utility functions both theoretically sound and robust, two different approaches were adopted in the course of developing the utility functions. Details of these surveys are presented in Chapter 7.

3.8.1.1 Performance Indicators for Highway Asset Management Programs

Having established the goals and programs of a highway asset management system, a set of performance indicators for various highway asset management programs was established in consultation with the INDOT officials, as shown in Table 9.

Table 9: Performance Indicators for Various Highway Asset Management Programs

Program Category	Asset Management System Goal					
	Preservation	Agency Cost	User Cost	Mobility	Safety	Environment
Bridge Preservation	Struct condition Surf condition Remain life	Construction Rehabilitation Maintenance	Detour condition Speed	Speed Detour length	Load inventory Deck width Vert clearance (over/under) Hor clearance	Speed
Historical Bridges	Struct condition Surf condition Remain life Bridge age Bridge length	Construction Rehabilitation Maintenance	Detour condition Speed	Speed Detour length	Load Inventory Deck width Vert clearance (over/under) Hor clearance	Speed
Non-Interstate Pavements	Condition	Construction Rehabilitation Maintenance	Condition Speed	Speed	Speed Skid resistance Lane width Shoulder width	Speed
Interstate Pavements	Condition	Construction Rehabilitation Maintenance	Condition Speed	Speed	Speed Skid resistance Lane width Shoulder width	Speed
Intersection Improvements	Condition	Construction Rehabilitation Maintenance	-	Intersect delay	Collision rate	-
Railroad Crossing Improvements	Condition Remain life	Construction Rehabilitation Maintenance	-	-	RR adequacy Collision rate	-
Safety	Remain life	Construction Maintenance	-	-	Sight distance Luminance	-
Traffic Signals	Remain life	Construction Maintenance	-	Intersect delay	Speed Collision rate	-
Enhancements	-	-	-	-	Collision rate	-
Roadside Improvements	-	Construction Maintenance	Speed	Speed	Speed	Speed
Weigh Station/ Rest Area	Remain life	Construction Maintenance	-	-	Collision rate	-
Small Structures/ Drainages	Remain life	Construction Maintenance	-	-	-	-
Expansion	Roads: Condition Remain life	Construction	Condition Speed	Speed	Speed Skid resistance Lane width Shoulder width	Speed
	Bridges: Struct condition Surf condition Remain life	Construction	Detour condition Speed	Speed Detour length	Load inventory Deck width Vert clearance (over/under) Hor clearance	Speed

Table 9: Performance Indicators for Various Highway Asset Management Programs (Continued)

Program Category	Asset Management System Goal					
	Preservation	Agency Cost	User Cost	Mobility	Safety	Environment
DNR Facilities/ Forest Land Highways/ Other State Institutions	Roads: Condition Remain life	Construction Rehabilitation Maintenance	Condition Speed	Speed	Speed Skid resistance Lane width	Speed
	Bridges: Struct condition Surf condition Remain life	Construction Rehabilitation Maintenance	Detour condition Speed	Speed Detour length	Load inventory Deck width Vert clearance (over/under) Hor clearance	Speed
Bridge Inspection	-	-	-	-	Collision rate	-
ITS Projects	Remain life	Procurement Maintenance	Speed	Speed	Collision rate	Speed
CMAQ Projects	-	Construction Maintenance	Speed	Speed	Speed	Speed
Maintenance	Condition Remain life	Maintenance	Condition	-	Skid resistance	-
Multi-modal	Remain life	Construction Maintenance	Speed	Speed	Collision rate	Speed

Note: Struct- Structure, Surf- Surface, Vert- Vertical, and Hor- Horizontal.

3.8.1.2 Relative Weights of System Goals and Multiple Performance Indicators under Each Goal

The Delphi technique [Dalkey and Helmer, 1963] was used to establish relative weights for system goals and performance indicators. As mentioned earlier, two decision groups representing both the agency and the user perspectives participated in the survey. The sequential steps for applying the questionnaire to individual survey groups are listed below:

Step 1 concerned with applying survey questionnaire to the respondents. An example was first provided to allow respondents to comprehend the survey approach.

Step 2 involved analysis of the completed questionnaire and preparation of a concise summary of survey results.

Step 3 focused on presenting the survey summary to each respondent and solicited comments expressing agreement, disagreement, and clarification of the results.

Step 4 dealt with the second survey, using the same questionnaire, and preparation of an updated summary of survey results.

In the summary of survey results, the summary statistics, such as mean and standard deviations associated with the relative weights assigned for system goals and performance indicators, were listed. However, the average weights assigned might not be consistent with the consensus weights because of the differences in the standard deviations among the weights. The raw data were further processed to derive the consensus weights separately for the two groups using the AHP technique [Saaty, 1977].

3.8.1.3 Single Attribute Utility Functions for Individual Performance Indicators

Similar to the procedure used for establishing relative weights for system goals and performance indicators, questionnaire surveys were also used to develop single attribute utility functions for individual performance indicators. In order to acquire input from both the agency and the user perspectives and also maintain the robustness of the derived utility functions, two survey groups and two approaches were utilized. The two groups classified were the agency and the user, with representatives randomly selected. Two approaches were used for the preparation of two different questionnaires as well, the direct questioning approach and the certainty equivalency approach [Keeney and Raiffa, 1993]. The concepts of these approaches are illustrated as follows:

Approach 1: Direct Questioning Approach

- For attribute X , denote its best level as X^H , and worst as X_L ; and assign $U(X_L) = 0$, and $U(X^H) = 1$.

- Consider following situations

(i) Risky prospect of obtaining X_L with probability p and X^H with probability $(1-p)$

(ii) Prospect of obtaining $X = 0.5(X^H - X_L)$ for certain

The value of p is varied until the decision-maker is indifferent between two choices.

- Repeat the same process (twice) by changing X value to $0.25(X^H - X_L)$, and $0.75(X^H - X_L)$, find corresponding p values, respectively. Graphic illustration of the procedure is below:

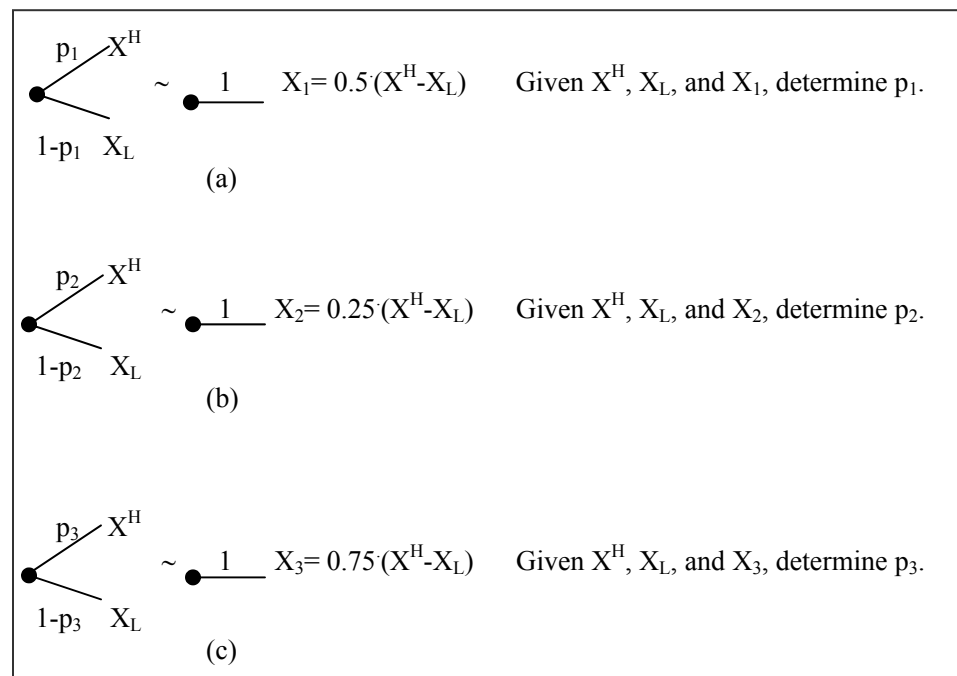


Figure 4: Illustration of Direct Questioning Approach for Establishing Utility Values

Approach 2: Certainty Equivalency Approach

- For attribute X , denote its best level as X^H , and worst level as X_L ; and assign $U(X_L) = 0$, and $U(X^H) = 1$.

- Step 1, consider following situations

(i) Risky prospect of obtaining X_L with probability 0.5 and X^H with probability 0.5

(ii) Prospect of obtaining $X_{0.5}$ for which $U(X_{0.5}) = 0.5$ for certain

The value of $X_{0.5}$ is varied until decision-maker is indifferent between the two choices.

- Step 2, consider following situations

(i) Risky prospect of obtaining X^H with probability 0.5 and $X_{0.5}$ with probability 0.5

(ii) Prospect of obtaining $X_{0.25}$ for which $U(X_{0.25}) = 0.25$ for certain

The value of $X_{0.25}$ is varied until decision-maker is indifferent between the two choices.

- Step 3, consider following situations

(i) Risky prospect of obtaining $X_{0.5}$ with probability 0.5 and X_L with probability 0.5

(ii) Prospect of obtaining $X_{0.75}$ for which $U(X_{0.75}) = 0.75$ for certain

The value of $X_{0.75}$ is varied until decision-maker is indifferent between the two choices.

- Step 4, consistency check between the two situations

(i) Risky prospect of obtaining $X_{0.25}$ and $X_{0.75}$ both with probability 0.5

(ii) Prospect of obtaining $X_{0.5}$ for which $U(X_{0.5}) = 0.5$ for certain

The decision-maker should be indifferent with the two situations. Otherwise, Steps 1-3 need to be repeated. Graphic illustration of the procedure is below:

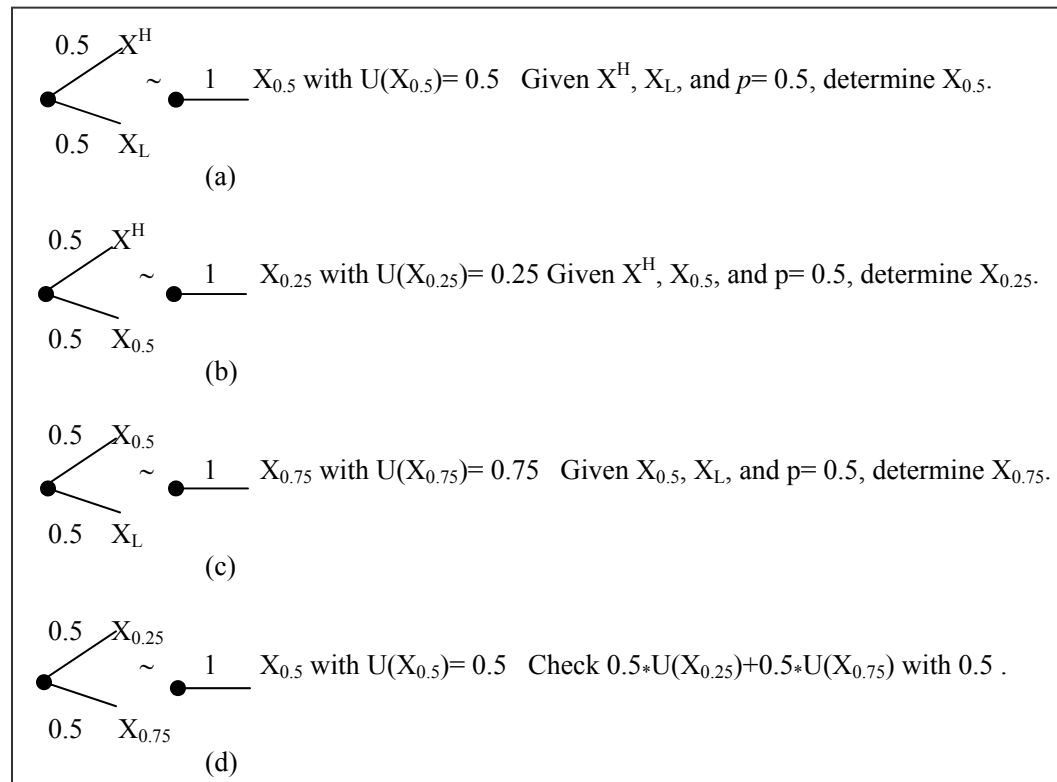


Figure 5: Illustration of Certainty Equivalency Approach for Establishing Utility Values

As two approaches were used by two decision groups to establish utility values, it was needed to investigate whether the results between the decision groups and the approaches used were statistically different. As such, an ANOVA analysis was carried out to determine the level of aggregation for the raw data prior to calibrating the utility functions using OLS techniques. The two-factor factorial ANOVA model adopted was of the following form:

$$U_{ijm} = \mu_U + G_i + A_j + (G \cdot A)_{ij} + e_{m(ij)} \quad (10)$$

where

U_{ijm} = Utility value assigned by decision-maker m in group i using approach j

μ_U = Average utility value assigned by all decision-makers using all approaches

G_i = Decision group, $i = 1, 2$ for the agency and the highway user

A_j = Approach used, $j = 1, 2$ for direct weighting approach and the certainty equivalency approach

$e_{m(ij)}$ = Error terms within each of the 4 group and approach combinations.

3.8.1.4 Systemwide Multiattribute Utility Functions for Individual Programs

Systemwide multiattribute utility functions for individual programs were established by synthesizing the single attribute utility functions in two steps. The first step was to obtain multiattribute utility functions under each system goal from single utility functions, while the second step synthesized the goal-specific multiattribute utility functions into a systemwide multiattribute utility function for each program.

Prior to synthesizing the single attribute utility functions, the underlying assumptions were verified, which included utility independence, additive independence, and preference independence if more than two utility functions were to be combined. Utility independence inferred that each single attribute utility function was not a function of the level of other attributes (i.e., performance indicators). Under this assumption, the underlying multiattribute utility function might be of the additive form, the multilinear form (a special case of multiplicative form), or the multiplicative form. Additive independence applied if, and only if, all single attribute functions were directly additive. Preference independence remained valid if the tradeoffs a decision-maker was willing to make among any two attributes were not dependent on the levels of other attributes.

3.8.2 Incorporation of Risk and Uncertainty into Tradeoff Decision Process

The tradeoff decision process discussed earlier assumed that the expected level of each performance indicator after project implementation would occur under certainty. However, this assumption might not hold true because of the uncertain and dynamic nature of a highway network. Risk and uncertainty associated with performance indicators were incorporated into the tradeoff analysis to further strengthen the robustness of the decision-making process. As the performance indicators relevant to geometric characteristics, such as lane width, and vertical and horizontal clearance, were deterministic in nature, they were excluded for consideration in risk and uncertainty analyses. Performance indicators involving risk and uncertainty in the tradeoff decision process are listed in Table 10.

Table 10: Performance Indicators Involving Risk and Uncertainty in Tradeoff Decision Process

Asset Management System Goal	Performance Indicator
System Preservation	Bridge structural condition Bridge wearing surface condition Pavement surface condition Remaining service life
Agency Cost	Construction cost Rehabilitation cost Maintenance cost
User Cost Mobility Environment	Vehicle speed Detour condition Detour length Intersection delay time
Safety	Vehicle speed Bridge load inventory rating Skid resistance Collision rate

3.8.3 Tradeoff Decision-Making under Risk

For tradeoffs under risk, the multiattribute utility functions developed for tradeoffs under certainty were valid for the conversion of project benefits into dimensionless units. However, in this case, utility values corresponding to the levels of performance indicators after project implementation were replaced by expected utility values to account for the range and distribution of possible outcomes of underlying performance indicators. In order to establish the expected utility values, it was needed to characterize the types of probability distributions and select and calibrate distribution parameters.

3.8.3.1 Categorization of Probability Distributions for Performance Indicators

This step involved identifying whether the possible outcomes of the performance indicators were discrete or continuous. Because discrete values were used to measure the bridge deck, superstructure, substructure, and wearing surface conditions, discrete probability distribution was appropriate. On the other hand, since the remaining performance indicators in risk analysis were measured by continuous values, continuous distributions were used.

3.8.3.2 Selection of Probability Distributions for Performance Indicators

After defining the basic properties of probability distributions for the relevant performance indicators, the next step involved selecting appropriate distributions that best fit the possible outcomes of the respective performance indicators. For discrete performance indicators such as bridge deck, superstructure, substructure, and wearing surface condition, the respective possible outcomes as a result of project implementation might range from a condition rating of 3 (worst) to 9 (best). It was reasonable to assume that there was equal opportunity that the probability would occur at each condition rating, and that this probability was not affected by any knowledge of the previous condition

rating. It was therefore needed to first determine the probabilities of occurrence of outcomes that fall into condition rating 3 only; ratings 3 and 4; ratings 3, 4, and 5; and finally 3, 4, ..., and 9, respectively. Under these circumstances, the binomial distribution was considered to be appropriate.

The binomial distribution function with parameters n , p , and x is given by

$$b(n, p, x) = \binom{n}{x} \cdot p^x \cdot (1-p)^{n-x} \quad (11)$$

with mean and variance: $\mu = np$, and $\sigma^2 = np(1-p)$

where

$n =$ Number of possible outcomes

$p =$ Probability of occurrence of an outcome

$x =$ Number of occurrences over all possible outcomes (i.e., exactly x possible outcomes occurred over n Bernoulli trials).

In practice, Poisson distribution is used as an approximation to the binomial distribution when the parameter n is relatively large ($n \geq 30$). As bridge deck, superstructure, substructure, and wearing surface conditions range from 3 to 9, it is therefore needed to subdivide the six condition intervals into more subintervals to apply Poisson approximation. The justification for Poisson approximation is as follows. For bridge deck, superstructure, substructure, and wearing surface condition with conditions from 3 to 9, it can be imagined that the range of extreme conditions between 3 and 9 is further divided into n subintervals of equal length, i.e., the length of interval between any two consecutive condition levels is further divided into $n/6$ subintervals of equal length. If the subintervals are sufficiently short, it can be assumed that, in each subinterval, there is either 0 or 1 occurrence with the probability of occurrence p . This means that the sequence of subintervals can be thought of as a sequence of Bernoulli trials, with a success corresponding to an occurrence in the subinterval. Suppose that the

average rate of occurrences in a condition interval between 3 and 9 is λ , the probability of occurrence in each subinterval thus becomes $p = \lambda/n$. This yields the following:

$$P(X=0) = b(n, p, 0) = \binom{n}{0} \cdot p^0 \cdot (1-p)^n = \left(1 - \frac{\lambda}{n}\right)^n \approx e^{-\lambda} \quad (12)$$

In general, Poisson approximation of the binomial distribution is obtained as follows:

$$P(X=x) = b(n, p, x) \approx \frac{\lambda^x}{x!} e^{-\lambda} = \frac{(np)^x}{x!} e^{-np} \quad (13)$$

In addition to creating subintervals between two consecutive condition ratings, it is also needed to consider the existing condition rating at the time of project implementation so that the total number of subintervals can be established. The underlying assumption is that the distribution of condition ratings after project implementation will spread from the existing level upward to the best condition rating of 9, as illustrated in Figure 6. In the present study, each two-consecutive condition rating levels is equally divided into 10 subintervals. This brings about a total number of subintervals of 60, 50, 40, 30, 20, 10, 0 corresponding to an existing condition rating of 3, 4, 5, 6, 7, 8, and 9, respectively.

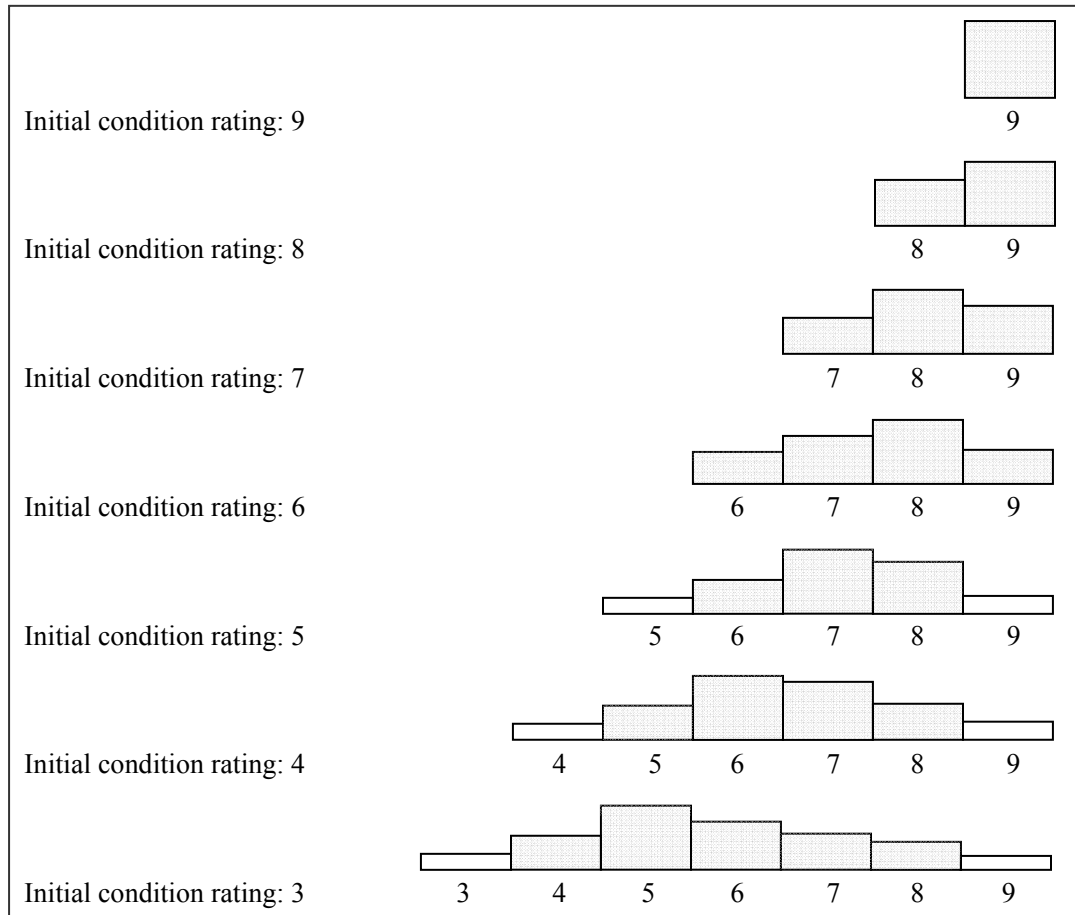


Figure 6: Illustration of Probability Distributions for Bridge Deck, Superstructure, Substructure, and Wearing Surface Conditions after Project Implementation

On the other hand, for continuous performance indicators such as pavement surface condition; remaining service life; construction, rehabilitation, and maintenance costs; average speed; detour condition; detour length; intersection delay time; bridge load inventory rating; pavement skid resistance; and collision rate, the respective outcomes after project implementation were all finitely continuous, i.e., the outcomes spread within a minimum and maximum range continuously. Also, the distributions of possible outcomes could be either symmetric or skewed, and these distributions could be modeled as a beta distribution that accommodates a unimodal shape requirement and allows for virtually any degree of skewness and kurtosis. The general beta distribution has four parameters:

lower range (L), upper range (H), and two shape parameters referred to as α and β . The beta density function is given by

$$f(x|\alpha, \beta, L, H) = \frac{\Gamma(\alpha + \beta) \cdot (x - L)^{\alpha - 1} \cdot (H - x)^{\beta - 1}}{\Gamma(\alpha) \cdot \Gamma(\beta) \cdot (H - L)^{\alpha + \beta - 1}} \quad (L \leq x \leq H) \quad (14)$$

where the Γ -function factors serve to normalize the distribution so that the area under the density function from L to H is exactly 1. The mean and variance for the beta distribution are given by

the following: $\mu = \frac{\alpha}{\alpha + \beta}$ and $\sigma^2 = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}$.

It is seen that the mean of the distribution is a weighted average of L and H such that when $0 < \alpha < \beta$ the mean is closer to L and the distribution is skewed to the right; whereas for $\alpha > \beta > 0$ the mean is closer to H and the distribution is skewed to the left. When $\alpha = \beta$ the distribution is symmetric. Also note that for a given α/β ratio, the mean is constant and the variance varies inversely with the absolute magnitude of $\alpha + \beta$. Thus, by increasing α and β by proportionate amounts, the variance may be decreased while holding the mean constant; and conversely, by decreasing α and β by proportionate amounts, the variance may be increased while leaving the mean unchanged. In practice, the skewness and variance (kurtosis) can be categorized as high, medium, or low based on the magnitude of α and β . Table 11 presents the resulting combinations of skewness and variance (kurtosis) for beta distributions that best approximate the risk situation of possible outcomes of the continuous performance indicators.

Table 11: Approximate Values of Shape Parameters for Beta Distributions under Different Skewness and Variance Combinations

Combination Type	Skewness	Variance (Kurtosis)	α	β
1	Skewed to the left	High	1.50	0.50
2	Symmetric	High	1.35	1.35
3	Skewed to the right	High	0.50	1.50
4	Skewed to the left	Medium	3.00	1.00
5	Symmetric	Medium	2.75	2.75
6	Skewed to the right	Medium	1.00	3.00
7	Skewed to the left	Low	4.50	1.50
8	Symmetric	Low	4.00	4.00
9	Skewed to the right	Low	1.50	4.50

3.8.3.3 Expected Utility for Performance Indicators Involving Risk in Tradeoff Decision Process

In the tradeoff decision process involving risk situations, the binomial distribution and beta distribution were selected for discrete and continuous performance indicators, respectively, to model the possible outcomes after project implementation. The expected utility values corresponding to the possible outcomes of respective performance indicators were computed separately.

For discrete performance indicators, the initial condition rating was a key factor that needed to be explicitly considered. As stated in the previous section, Poisson approximation was applied for the binomial distribution where the number of subintervals (N_k) corresponding to initial condition ratings of 3, 4, 5, 6, 7, and 8 were 60, 50, 40, 30, 20, and 10, respectively. The expected utility values for the possible outcomes of individual performance indicators were calculated as below:

$$E[u(X)] = \sum_{x=0}^{N_k} [u(x) \cdot P(X = x)] = \sum_{x=0}^{N_k} \left\{ u(x) \cdot \left[\frac{(N_k p)^x}{x!} e^{-N_k p} \right] \right\} \quad (15)$$

For continuous performance indicators, it was difficult to assign a single, fixed lower and upper range for the possible outcomes of individual performance indicators after project implementation. This was because the possible range deviated significantly under different

circumstances. For each performance indicator, the beta distribution parameters were first calibrated for a fixed lower and higher range. Truncated beta distributions that allowed varying the minimum and maximum ranges (denoted by “min” and “max”) of possible outcomes of an underlying performance indicator were then used to establish the expected utility values. The formula used was as follows:

$$\begin{aligned}
 E[u(X)] &= \int_{\min}^{\max} u(x) \cdot f(x \mid \min < x < \max) dx \\
 &= \frac{\int_{\min}^{\max} [u(x) \cdot \text{Beta}(\alpha, \beta, x \mid L, H)] dx}{\int_{\min}^{\max} \text{Beta}(\alpha, \beta, x \mid L, H) dx} \\
 &= \frac{\int_{\min}^{\max} \left\{ u(x) \cdot \left[\frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \cdot \Gamma(\beta) \cdot (H - L)^{\alpha + \beta - 1}} \cdot (x - L)^{\alpha - 1} \cdot (H - x)^{\beta - 1} \right] \right\} dx}{\int_{\min}^{\max} \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \cdot \Gamma(\beta) \cdot (H - L)^{\alpha + \beta - 1}} \cdot (x - L)^{\alpha - 1} \cdot (H - x)^{\beta - 1} dx} \quad (16)
 \end{aligned}$$

3.8.4 Tradeoff Decision-Making Involving Uncertainty

3.8.4.1 Introduction

Common to the concept of expected utility is that it employs a weighted average to arrive at an evaluation of outcomes. The underlying assumption made is that the probability or utility associated with a particular outcome is independent of the degree of uncertainty associated with that outcome. However, for a situation where the probability attached to the implementation of a project depends both on the outcome and measure of uncertainty, the need for an alternative approach becomes apparent. In the present study, Shackle’s model, which constituted one of the most original approaches to decision-making under uncertainty, was adopted [Shackle, 1949].

3.8.4.2 Shackle's Model

Shackle's model is different from the expected utility approach which uses weighted averages of outcomes and their probabilities, and it is based on three main elements. The first is the replacement of probability as a measure of uncertainty by degree of surprise. The second is the priority index as a mechanism to evaluate different outcomes and the corresponding degrees of surprise. The third is the standardized focus gain-over-loss ratio as the basis of comparing different projects. The main steps for applying Shackle's model are discussed below.

1) Degree of Surprise Function

Degree of surprise indicates the decision-maker's degree of uncertainty as to the hypothetical outcomes resulting from project implementation with gains (positive returns) and losses (negative returns) from the expectation. Suppose that there are a range of outcomes x_i from an action ($i = 1, 2, \dots, n$), and assign a value as the degree of surprise y , which reflects the decision-maker's degree of belief for a given outcome, ranging from 0 (no surprise) to 10 (extremely surprised), the degree of surprise function $y = y(x)$ can be as shown in Figure 7.

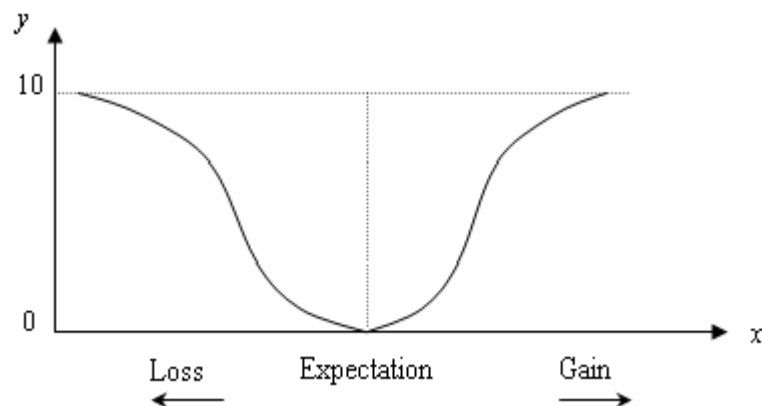


Figure 7: Diagram of Degree of Surprise Function

2) Priority Function and Focus Values

Priority function indicates the weighting index ϕ (0 for lowest priority and 10 for highest priority) that the decision-maker assigns to any given outcome/degree of surprise pair (x, y) . The priority function denoted by $\phi = \phi(x, y)$ possesses properties of $\frac{\partial \phi}{\partial x} > 0$; $\frac{\partial \phi}{\partial y} < 0$ (namely, higher priorities will be given as gaining of outcomes from expectation increases, or as degree of surprise decreases). There also exists an indifference curve $\phi[x, y(x)]$ that traces out different combinations of outcome/degree of surprise pair (x, y) where weight ϕ is kept constant. It is obvious that the priority function is defined by points at which the degree of surprise function $y = y(x)$ intersects the priority indifference curves $\phi[x, y(x)] \equiv 0, 1, 2, \dots, 10$. The priority indifference curves and priority function can then be illustrated as in Figure 8.

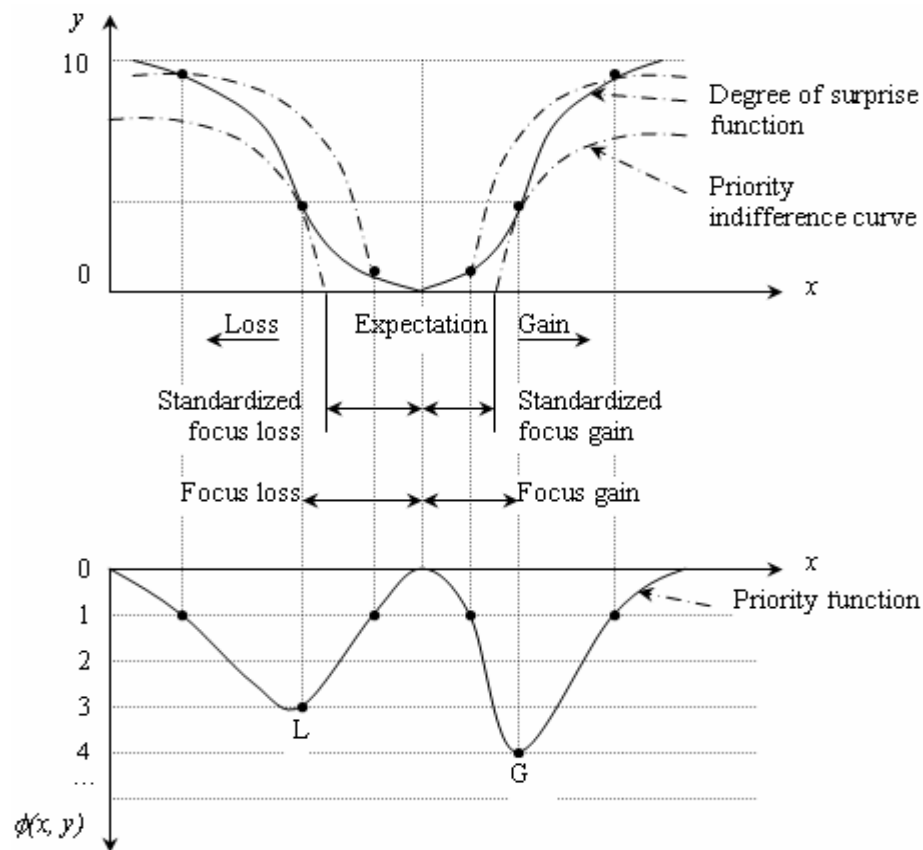


Figure 8: Diagram of Priority Function

Focusing on maximizing the priority function, the decision-maker will arrive at two maximum values termed as focus gain (G) and focus loss (L) from expectation.

3) Standardized Focus Gain-over-Loss Ratio and Function

The focus gain and focus loss values are associated with a certain degree of surprise, i.e., $y(x) \neq 0$. It is therefore desirable to explore the respective gain and loss values on the same priority indifference curves that are attached with zero degree of surprise, namely, to find x for which $\phi(x, y)$ is maximized with $y = 0$. The gain and loss values with zero degree of surprise are called standardized gain and loss values. The ranking of any one project against those of another is achieved by introducing the ratios of standardized focus gain-over-loss pairs. The larger the ratio is, the higher likelihood the selecting the corresponding project. As shown in Figure 9, different standardized focus gain-over-loss ratios are associated with different ranges of deviations in the possible outcomes. As such, the standardized gain-over-loss ratio function can be determined.

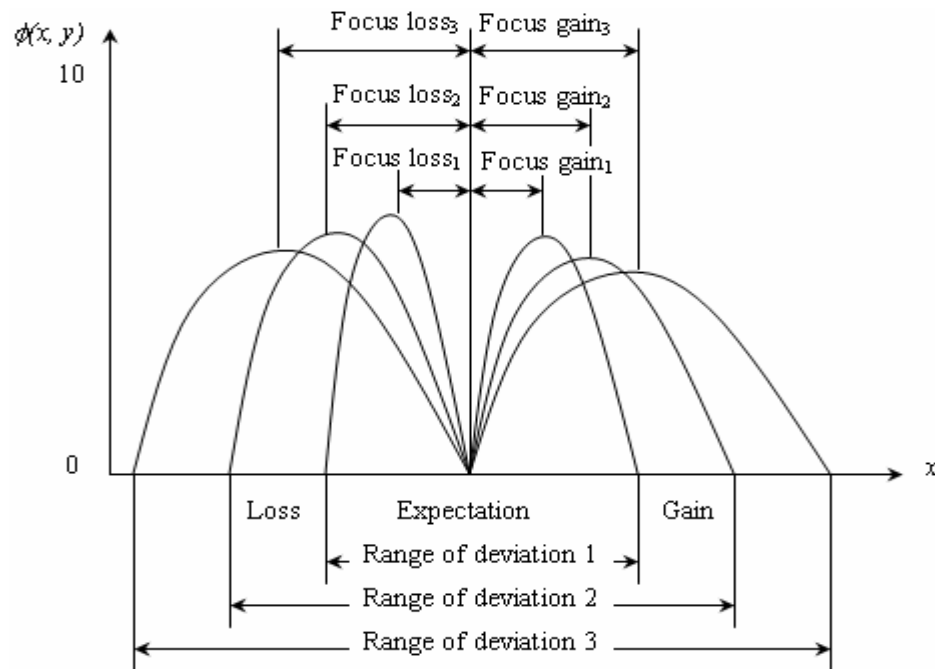


Figure 9: Standardized Gain and Loss Values for Different Ranges of Deviations from Expectation

3.9 Project Selection and Programming

As tradeoff analysis between candidate projects was carried out under certainty, risk, and uncertainty, project selection and programming were separately conducted for the three cases. More specifically, project selection was made on the basis of systemwide benefits resulting from project implementation in terms of changes in utility values, expected utility values, and standardized focus-gain-over-loss ratios, respectively. Systemwide programming involved selecting a subset from all candidate projects in an optimal manner under budget constraints for a given analysis period. A system optimization model was formulated on the basis of the MCMDKP problem. A solution algorithm was also developed accordingly.

3.10 Chapter Summary

This chapter provided a summary of the methodological framework used in the present study. A graphic overview of the study methodology was first provided, which was followed in sequence by the technical details that dealt with key components of a highway asset management system, including network-level highway user cost, asset management goals and programs, performance modeling, marginal benefit analysis, and multicriteria decision-making including tradeoff analysis, and project selection and programming.

CHAPTER 4 NETWORK-LEVEL HIGHWAY USER COST COMPUTATION AND MODELS

4.1 General Information

The physical condition of a highway network and the extent to which the network is being used affect network level highway user cost. All things being equal, as the number of physical facilities on a network such as bridges, intersections, railroad crossings, and workzones increases, the overall average speed of the highway network will decrease. This may lead to an increased vehicle operating cost, travel time, and vehicle air pollution, and thus a high total highway user cost for each unit distance of travel. Also, a high vehicle operating cost will result from a highway network with deteriorated overall road condition. Furthermore, the percentage of trucks in the traffic stream is a key factor affecting total user cost. General information about physical highway assets and their condition, as well as usage of the state highway network in Indiana from 1990 through 2000 is presented in Appendices B and C. Models were calibrated separately for vehicle operating cost, travel time, vehicle collision, and vehicle air pollution.

4.2 Data Collection and Processing of for Highway User Cost Computation

Data items collected for the computation of annual user cost associated with state highways in Indiana are listed in Table 12. These data were mainly acquired from INDOT Highway Performance and Monitoring System (HPMS) reports, FHWA Highway Statistics, Purdue Joint Transportation Research Program (JTRP) reports, Indiana Bureau of Motor Vehicles, and U.S. Bureau of Labor Statistics. In order to utilize the user cost information for development of the network-level user cost

model, data were collected for a relatively long period, from 1990 through 2000. In the course of data collection, it was found that some data items were either not directly available from the original data source or not available for all years, and the missing data were generated through extrapolation or interpolation based on available data.

Table 12: Data Items Used for Highway User Cost Computation

Data Category	Data Item	Data Source
Physical Asset Characteristics	Road mileage Pavement surface condition Bridge surface and structural condition Number of lanes Number of grade separations Number of interchanges Number of intersections Number of stops Number of railroad crossings Number of workzones Distribution of horizontal alignment Distribution of vertical alignment Distribution of length of curves Distribution of length of grades Distribution of signalization Distribution of green time	INDOT HPMS Reports
Vehicle Characteristics	Vehicle registration Gas, diesel, other engine type Engine fuel efficiency Vehicle engine emission rate	Indiana Bureau of Motor Vehicles FHWA Highway Statistics
Traffic and Travel Safety	Annual Average Daily Traffic (AADT) Daily vehicle miles of travel Average traveling speed Directional factors Peak capacity Volume-to-capacity ratio Congested vehicle miles of travel Vehicle collisions	INDOT HPMS Reports Purdue JTRP Reports NHTSA Reports
Price Index	Consumer price index Producer price index	U.S. Bureau of Labor Statistics

4.3 Annual Quantities of Individual Highway User Cost Components

Table 13 presents cost items classified under individual user cost components as well as factors considered affecting each of these items. The computation was carried out on the basis of vehicle miles traveled by various types of vehicles on different highway functional classifications. Vehicle traveling speed is one of the key factors that affect fuel and oil consumption rates and thus the vehicle emission rate, average travel time, and vehicle collisions. Further adjustment was made to these items by factors including speed change cycles and the curvature pattern of the highway network according to the procedure in MicroBENCOST software program [TTI, 1993].

Table 13: Condition and Usage of Indiana State Highway Network

User Cost Component	Item	Influencing Factor
Vehicle Operation	Fuel Oil Tire wear Depreciation Maintenance	Engine type Vehicle type Speed by highway class Speed change cycles Curvature Vehicle idling
Travel Time	Average travel time Delays	Speed by highway class Congestion Stops Intersections/interchanges Railroad crossings Incidents and workzones Discomfort adjustments
Vehicle Collision	Fatality Injury Property damage	Highway class
Air Pollution	CO ₂ , NMHC, CO, NO _x , TSP, SO ₂	Engine type Vehicle type Speed by highway class

4.3.1 Quantification of Vehicle Operating Cost Components

Vehicle operating cost items, including fuel consumption, engine oil consumption, tire wear, annual depreciation, and annual maintenance and repair, were first quantified on the basis of vehicles traveling at uniform speed at grade. Extra fuel consumption, maintenance, and repair were then calculated according to horizontal curvature, vehicle speed change cycles, and idling. Similarly, extra oil consumption was determined based on horizontal curvature and idling. Extra tire wear was calculated for curvature and speed change cycles. Excess depreciation was obtained for speed change cycles and idling.

Information regarding vehicle speed by highway functional classification and distribution of horizontal curvature of the state highway network was retrieved from the annual INDOT HPMS reports. For the computation of the total number of speed change cycles, the number of speed change cycles per vehicle mile of travel as a function of volume-to-capacity ratio developed in NCHRP report 7-12, *Microcomputer Evaluation of Highway User Benefits*, was adopted. The unit running cost of speed change cycles based on a study by Zaniewski *et al.* [1982] was updated and used for the present study. Vehicle delays due to congestion, incidents, stops signs, intersections, railroad crossings, and workzones are the cause of vehicle hours of idling, and fuel consumption rates for each vehicle type during idling were taken from the Zaniewski *et al.* study. Extra oil consumption, tire wear, maintenance and depreciation were considered by road surface condition based on the Zaniewski *et al.* study as well. The annual total of fuel and oil consumption, tire wear, depreciation, and maintenance from 1990-2000 are given in Table 14.

Table 14: Annual Quantities of Vehicle Operating Cost Items Associated with Indiana State Highway Network (in millions)

Year	Fuel (gallon)	Oil (quarter)	Tire Wear (no.)	Depreciation (% new cost)	Maintenance (dollar)
1990	3,245	93	3.5	14	40.0
1991	3,336	95	3.5	14	39.6
1992	3,759	100	3.5	15	38.7
1993	4,062	108	3.9	16	49.9
1994	3,912	117	4.0	16	53.0
1995	4,034	124	4.4	17	56.2
1996	4,126	125	4.5	17	55.4
1997	5,490	131	3.8	18	72.2
1998	4,596	126	4.0	17	58.5
1999	4,703	127	4.0	17	75.5
2000	4,885	131	4.0	18	80.5

The individual vehicle operating cost items were converted into dollar amounts using unit rates for different vehicle classes. The original unit rates were extracted from the Zaniewski *et al.* study [1982] and updated on the basis of annual CPI for passenger cars and annual PPI for trucks, respectively. The updated unit rates and price indices are listed in Appendices D and E, respectively.

The annual vehicle operating cost associated with state highways in Indiana is listed in Table 15. The annual total vehicle operating cost, as shown in the table, increased from 8.9 billion dollars in 1990 to 12.3 billion dollars in 2000, with a net increase of 3.4 billion dollars or an annual average increase of 3.4 percent. As shown in Appendices B and C, annual traffic volume and travel on state highways increased 3.3 percent and 2.1 percent, respectively, and at the same time road surface condition deteriorated by 5.4 percent in each year. The combined effect of increased use and deteriorating network led to an increase in vehicle operating cost.

Table 15: Annual Vehicle Operating Cost Associated with Indiana State Highway Network
(1990\$, in billions)

Year	Category					Land Area		Total
	Fuel	Oil	Tire	Depreciation	Maintenance	Rural	Urban	
1990	3.7	0.2	2.8	2.2	0.04	5.4	3.6	8.9
1991	3.9	0.2	2.8	2.3	0.04	5.6	3.6	9.2
1992	4.3	0.3	2.9	2.4	0.04	6.1	3.8	9.9
1993	4.7	0.3	3.3	2.6	0.05	6.6	4.3	10.9
1994	4.6	0.3	3.3	2.7	0.05	6.7	4.2	10.9
1995	4.7	0.3	3.6	2.8	0.05	7.0	4.5	11.5
1996	4.9	0.3	3.6	2.9	0.05	7.1	4.7	11.8
1997	6.5	0.3	3.5	3.0	0.06	8.1	5.2	13.4
1998	5.3	0.3	3.3	2.8	0.05	6.7	5.0	11.8
1999	5.5	0.3	3.3	2.8	0.06	6.9	5.1	12.0
2000	5.7	0.3	3.4	2.9	0.06	7.0	5.4	12.3

4.3.2 Travel Time Spent on Indiana State Highway Network

Annual total travel time was quantified separately for travel time under uniform speed at grade and excess travel time caused by delays. For each vehicle type and each highway class, daily travel time was determined by dividing the average daily distance of travel by the average traveling speed. The annual travel time of the entire highway network was then obtained on the basis of daily travel time. In a study conducted by Whitford and Opsuth [1996], link-by-link congested VMT of the state highway network was classified. The extra travel time was then quantified based on the congested VMT quantities.

The annual total travel time spent on the state highway network is presented in Table 16. Travel time on the state highway network has increased on an average of 2.3 percent annually since 1990. It can be seen in the table that, even though the annual delay increased by approximately 3.3 percent, the delay portion of travel time out of the total network travel time was still low, which was on the order of 3 percent.

Table 16: Annual Travel Time Associated with Indiana State Highway Network
(in million vehicle-hours)

Year	Category		Land Area		Total
	Travel Time	Delay	Rural	Urban	
1990	553.2	16.5	338.5	231.1	569.7
1991	555.4	18.6	341.3	232.7	574.0
1992	582.0	18.5	357.9	242.7	600.5
1993	621.1	19.3	375.3	265.1	640.5
1994	647.1	21.4	396.6	271.9	668.5
1995	667.0	20.9	404.5	283.3	687.9
1996	677.8	21.7	413.9	285.6	699.5
1997	722.1	22.1	436.4	307.8	744.2
1998	674.4	21.5	388.6	307.3	695.9
1999	674.5	21.8	390.7	305.7	696.3
2000	686.8	22.5	391.8	317.4	709.2

4.3.3 Vehicle Collisions on Indiana State Highway Network

Vehicle collision rates per million VMT in Indiana were obtained from the NHTSA's Annual State Traffic Data Reports. The total numbers of fatal, injury, and property damage collisions were then established by multiplying the respective collision rates by the total VMT. The annual total number of vehicle collisions is listed in Table 17. As shown in the table, the total number of vehicle collisions on the state highway network increased slightly from 1990 to 1994, and then began to decrease until 2000. One obvious change was related to fatal collisions, in that while injury and property damage collision totals remained steady, the fatality number decreased consistently by about 2.4 percent each year.

Table 17: Annual Number of Vehicle Collisions on Indiana State Highway Network

Year	Collision Category			Land Area		Total
	Fatality	Injury	Property Damage	Rural	Urban	
1990	604	28,155	80,962	66,181	43,541	109,721
1991	586	26,117	75,529	61,898	40,334	102,233
1992	512	28,579	95,356	75,364	49,083	124,447
1993	516	30,485	102,231	79,626	53,606	133,232
1994	568	31,648	107,278	83,911	55,583	139,493
1995	552	30,335	101,159	78,615	53,431	132,046
1996	562	30,378	102,019	79,449	53,510	132,959
1997	532	30,598	103,461	80,062	54,530	134,592
1998	523	28,985	98,663	72,155	56,016	128,171
1999	476	28,337	97,086	70,947	54,952	125,899
2000	464	28,136	97,011	69,563	56,049	125,611

4.3.4 Air Pollution Quantities due to Vehicle Emissions

The relative impact of vehicle air pollution in rural and urban areas was estimated by FHWA in a study that established emission rates of various pollutants including CO₂, NMHC, CO, TSP, NO_x, and SO₂ by different vehicle type [FHWA, 1982]. The corresponding emission rates were adopted and multiplied by the annual total VMT to establish the annual vehicle air pollution quantities. As shown in Table 18, CO₂ was the dominant vehicle-emitted pollutant. For each pollutant type, the respective quantity increased by 2 percent in each year, which generally matched with the annual VMT growth rate.

Table 18: Annual Vehicle Air Pollution Associated with Indiana State Highway Network
(in million tons)

Year	Pollutant Category						Land Area		Total
	CO ₂	NMHC	CO	NO _x	TSP	SO ₂	Rural	Urban	
1990	30.04	0.11	0.47	0.48	0.04	0.03	19.24	11.89	31.13
1991	30.20	0.11	0.47	0.48	0.04	0.03	19.42	11.87	31.30
1992	31.55	0.11	0.49	0.50	0.04	0.03	20.30	12.39	32.70
1993	34.08	0.12	0.53	0.54	0.05	0.04	21.65	13.67	35.32
1994	34.66	0.12	0.54	0.55	0.05	0.04	22.17	13.76	35.93
1995	36.10	0.13	0.56	0.57	0.05	0.04	22.84	14.57	37.41
1996	36.72	0.13	0.57	0.58	0.05	0.04	23.31	14.75	38.06
1997	38.94	0.14	0.61	0.62	0.06	0.04	24.62	15.74	40.36
1998	36.00	0.13	0.56	0.57	0.05	0.04	21.55	15.77	37.32
1999	35.94	0.13	0.56	0.57	0.05	0.04	21.53	15.73	37.26
2000	36.47	0.13	0.57	0.58	0.05	0.04	21.48	16.33	37.81

4.4 Conversion of Quantities of User Cost Components into Dollar Values

After establishing the quantities of respective user cost components, it was desirable to further establish the relative shares of the individual user cost components within the context of total network-level highway user cost. The individual user cost components were therefore converted into constant dollar terms to enable comparison.

4.4.1 Determination of Unit Rates

Since annual vehicle operating cost was already established in monetary values, conversion centered on travel time, vehicle collisions, and air pollution. The unit value of travel time was established after updating the estimates developed by Chui and McFarland [1986] using a speed-choice model. For the unit cost of injuries by category, the Rice and MacKenzie [1989] accident cost estimations were updated. Similarly, the urban and rural air pollution cost by vehicle type based on the 1982 FHWA study was adopted, and updated. The updating processes were separately carried out using CPI for passenger cars and PPI for trucks, which were then converted to 1990 constant dollars.

4.4.2 Conversion of Quantities of User Cost Components into Dollar Values

Table 19 shows the constant dollar values of the annual value of travel time, the cost of vehicle collisions and the cost of vehicle air pollution. During 1990-2000, the total highway user cost on the Indiana state highways increased from 25.4 billion dollars to 35.3 billion dollars, resulting in an average increase of 4 percent each year. This value could be well justified by the combined effects of increases in traffic volume, truck traffic percent, age, and network deterioration.

Table 19: Annual User Cost Components Associated with Indiana State Highway Network
(in billions, 1990 constant dollar)

Year	VOC			Travel Time			Vehicle Collisions			Air Pollution			User Cost		
	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total
1990	5.4	3.6	8.9	3.6	2.3	5.9	2.4	1.6	4.0	2.2	4.3	6.6	13.6	11.8	25.4
1991	5.6	3.6	9.2	3.7	2.4	6.1	2.3	1.5	3.9	2.3	4.4	6.7	13.9	11.9	25.9
1992	6.1	3.8	9.9	3.9	2.5	6.4	2.4	1.6	4.0	2.5	4.7	7.2	14.9	12.6	27.5
1993	6.6	4.3	10.9	4.1	2.7	6.8	2.6	1.7	4.3	2.7	5.3	8.0	15.9	14.1	30.0
1994	6.7	4.2	10.9	4.3	2.8	7.1	2.8	1.8	4.6	2.9	5.5	8.3	16.7	14.4	31.1
1995	7.0	4.5	11.5	4.4	2.9	7.4	2.7	1.9	4.6	3.0	6.0	9.0	17.1	15.2	32.4
1996	7.1	4.7	11.8	4.5	3.0	7.5	2.8	1.9	4.7	3.1	6.2	9.3	17.6	15.7	33.3
1997	8.1	5.2	13.4	4.8	3.2	8.0	2.8	1.9	4.8	3.4	6.8	10.2	19.1	17.1	36.2
1998	6.7	5.0	11.8	4.2	3.2	7.3	2.6	2.0	4.7	3.1	6.9	10.0	16.6	17.2	33.8
1999	6.9	5.1	12.0	4.2	3.2	7.4	2.6	2.0	4.6	3.1	7.1	10.2	16.8	17.4	34.3
2000	7.0	5.4	12.3	4.3	3.3	7.6	2.6	2.1	4.6	3.2	7.5	10.7	17.0	18.3	35.3

4.4.3 Discussion of Results

The relative shares of vehicle operating cost, value of travel time, vehicle collision cost, and air pollution cost are illustrated in Figure 10. Of the total highway user cost, vehicle operating cost held the largest share, while vehicle collisions were the lowest. The cost of air pollution and travel time fell in between the two. The relative shares were quite stable over the 11-year period, which were 36 percent for vehicle operation, 23 percent for travel time, 14 percent for vehicle collisions, and 28 percent for vehicle-related air pollution, respectively.

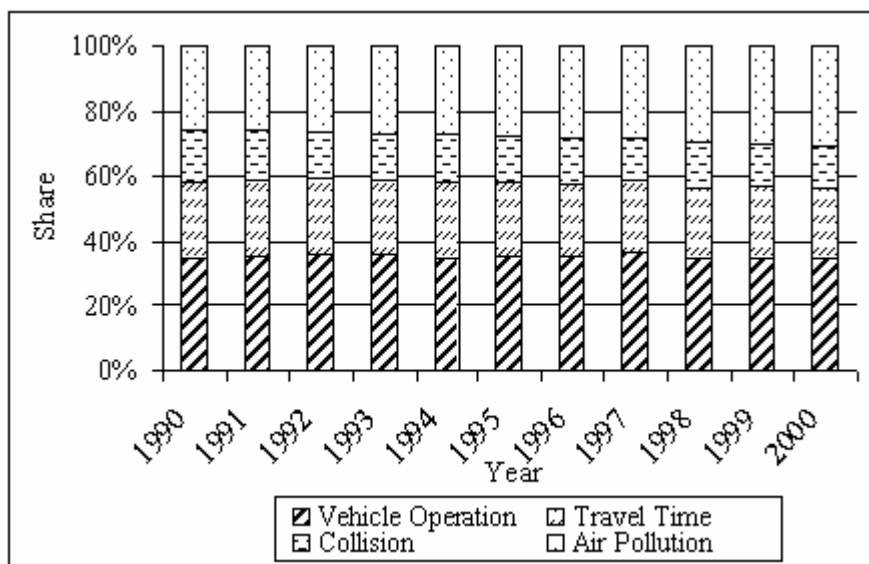


Figure 10: Relative Shares of Different Highway User Cost Components

4.5 Network-Level Highway User Cost Models

For the reasons stated earlier, an ANOVA analysis was carried out using normalized individual highway user cost components, i.e., amount or quantity of individual user cost components per unit mile of travel, to determine the level of aggregation prior to model calibration. As shown in Table 20, VOC and highway user cost were found to be statistically different by vehicle class and land area; travel time was statistically different by highway classification and land area; no difference was found in vehicle collision rate; and vehicle air pollution rate was found to be statistically different by vehicle type. The F-statistic values of the ANOVA analysis are listed in Appendix F.

Table 20: Results of ANOVA Analysis for the Preparation of Network-Level Highway User Cost Modeling (Level of significance: 0.005)

Component Source	VOC	Travel Time	Collision Rate	Air Pollution	User Cost
L	Yes	Yes	No	No	Yes
HC	No	Yes	No	No	Marginal
L·HC	No	Yes	No	Marginal	No
VC	Yes	Marginal	No	Yes	Yes
L·VC	No	No	No	No	Yes
HC·VC	Yes	Yes	No	Yes	Yes
L·HC·VC	No	No	No	No	No

Note: L- Land use, HC- Highway class, and VC- Vehicle class.

The descriptive statistics for VOC, travel time, vehicle collision rate, and air pollution rate per VMT are summarized in Appendix G. The independent variables considered for model calibration were grouped into two sets. The first set was mainly related to the level of physical highway assets, which include network mileage, surface condition, and density of stop controlled intersections, signalized intersections, interchanges, railroad crossings, and workzone characteristics. The second set was associated with network usage, including average speed, traffic volume, truck traffic percent, etc. The following OLS models were selected as being most appropriate to fit in the existing data:

$$\text{VOC / VMT} = \alpha_0 + \alpha_1 \text{CONDITION} + \alpha_2 \text{SPEED} \quad (17)$$

$$\text{TT / VMT} = \alpha_0 + \alpha_2 \text{SPEED} \quad (18)$$

$$\text{COL / MVMT} = \alpha_0 + \alpha_2 \text{SPEED} \quad (19)$$

$$\text{POL / VMT} = \alpha_0 + \alpha_2 \text{SPEED} \quad (20)$$

$$\text{UC / VMT} = \alpha_0 + \alpha_1 \text{CONDITION} + \alpha_2 \text{SPEED} \quad (21)$$

where

VOC/VMT = Vehicle operating cost for per vehicle mile of travel, in 1990\$/VMT

TT/VMT	= Average travel time for per vehicle mile of travel, in veh-hour/VMT
COL/VMT	= Vehicle collision rate for per million vehicle miles of travel, in number/millionVMT
POL/VMT	= Vehicle air pollution rate for per vehicle mile of travel, in kg/VMT
UC/VMT	= Highway user cost for per vehicle mile of travel, in 1990\$/VMT
CONDITION	= Pavement surface condition measured in IRI, in inches/mile
SPEED	= Average vehicle traveling speed, in miles per hour.

α_0 , α_1 , and α_2 are calibrated coefficients for different bridge types as listed in Table 21.

Table 21: Coefficients of Significant Independent Variables for Calibrated Network-Level Highway User Cost Models (Observations: 11)

User Cost Component	Land Use	VC/HC	$y = \alpha_0 + \alpha_1 \text{CONDITION} + \alpha_2 \text{SPEED}$			Adj. R ²	
			α_0	(t-statistic)	α_1 (t-statistic)		α_2 (t-statistic)
Vehicle Operating Cost (1990\$/VMT)	Rural	Car	0.5252	(6.26)	0.0002 (1.27)	-0.0056 (-4.23)	0.94
		SUT	0.2361	(7.92)	0.0001 (1.93)	-0.0008 (-1.81)	0.88
		MUT	1.0553	(5.77)	0.0015 (5.55)	-0.0085 (-2.96)	0.98
	Urban	Car	0.6680	(6.34)	-	-0.0073 (-3.86)	0.58
		SUT	0.2166	(80.64)	0.000013 (5.06)	-0.0003 (-6.64)	0.97
		MUT	0.8525	(20.01)	0.0002 (5.52)	-0.0012 (-1.77)	0.94
Travel Time (Hour/VMT)	Rural	IS	0.0487	(11.41)	-	-0.0005 (-7.49)	0.85
		NIS	0.0382	(11.66)	-	-0.0004 (-5.88)	0.77
	Urban	IS	0.0433	(4.72)	-	-0.0005 (-2.90)	0.43
		NIS	0.0253	(36.77)	-	-0.0001 (-7.29)	0.84
Collision Rate (No./million VMT)	All		-4.9542	(-3.32)	-	0.1595 (5.74)	0.76
Air Pollution (Kg/VMT)	All	Car	0.7307	(1,062.63)	-	0.0001 (10.03)	0.91
		SUT	1.5880	(1,984.84)	-	0.0001 (7.00)	0.83
		MUT	1.5908	(6,197.64)	-	0.0001 (18.32)	0.97
User Cost (1990\$/VMT)	Rural	Car	0.7526	(7.47)	0.0009 (5.97)	-0.0041 (-2.56)	0.98
		SUT	0.6506	(7.61)	0.0012 (8.86)	-0.0008 (-0.58)	0.98
		MUT	1.5719	(4.87)	0.0025 (5.08)	-0.0080 (-1.58)	0.96
	Urban	Car	1.1711	(6.25)	0.0014 (7.95)	-0.0078 (-2.56)	0.97
		SUT	1.2637	(6.69)	0.0017 (9.45)	-0.0062 (-2.02)	0.97
		MUT	1.9960	(8.19)	0.0011 (5.02)	-0.0075 (-1.90)	0.93

Model calibration was also conducted to establish the relationship between network level vehicle delay and volume-to-capacity ratios separately for rural and urban interstate highways, as well as non-interstate highways. The models using OLS techniques were in the following specification

$$\text{Vehicle Delay/VMT} = \alpha_0 + \alpha_1(\text{V-to-C Ratio}) \quad (22)$$

where

Vehicle Delay/VMT = Vehicle delay for per vehicle mile of travel, in vehicle-hour/VMT

V-to-C Ratio = Volume to capacity ratio.

α_0 and α_1 are calibrated coefficients for different bridge types as listed in Table 22.

Table 22: Coefficients of Significant Independent Variables for Calibrated Network-Level Vehicle Delay Models (Observations: 11)

Land Area	Highway Class	Vehicle Delay: Hour/VMT = $\alpha_0 + a_1(\text{V-to-C Ratio})$		Adj. R ²
		α_0 (<i>t</i> -statistic)	α_1 (<i>t</i> -statistic)	
Rural	Interstate	0.0001 (8.30)	0.0001 (6.14)	0.79
	Non-Interstate	0.0001 (18.94)	0.0001 (8.69)	0.88
Urban	Interstate	0.00009 (8.44)	0.0001 (8.50)	0.88
	Non-Interstate	0.0017 (91.54)	0.0002 (6.31)	0.80

Model coefficients obtained for vehicle operating cost, travel time, vehicle collisions, and air pollution as well as total user cost per mile of travel were as expected. For a given level of travel speed, deterioration in the system condition resulted in a higher level of cost for vehicle operation, causing an increased overall highway user cost. Also, with no change in the system condition, higher travel speed was associated with a reduction in travel time, a higher likelihood of vehicle collisions, and increased vehicle air pollution. Regardless of the land area and highway classification, higher volume-to-capacity ratios would lead to higher network-level vehicle delays.

4.6 Chapter Summary

This chapter focused on the computation of the network-level highway user cost. The basis of this computation was the annual vehicle miles of travel associated with state highways in Indiana during 1990-2000 by different vehicle classes on various highway functional classifications. The highway user cost components classified included vehicle operation, travel time, vehicle collisions, and vehicle air pollution, and factors that affected individual user cost components were identified. In order to establish the relative shares of individual highway user cost components, the respective user cost components were further converted into constant dollars using existing unit rates, updated by CPI and PPI accordingly. The dominant user cost component found was vehicle operation cost. Network-level highway user cost models were calibrated separately for the individual highway user cost components; as well as the total highway user cost. Models for network delay were also developed.

CHAPTER 5 PERFORMANCE MODELING FOR PHYSICAL HIGHWAY ASSETS

5.1 Introduction

As pavements and bridges are the dominant asset types in a highway network, the performance modeling was mainly focused on these assets, based on the methods discussed in Chapter 3.

5.2 Data Collection and Preparation

5.2.1 Data Collection

The most common physical assets in a highway network are pavements and bridges. Consequently, data collection in the current study was geared towards these assets and utilized the following database.

The INDIPAVE2000 [JTRP, 2000] database consists of data from 1990 through 2000 on various pavement attributes for the state highways in Indiana, and items in the database include road segment identification, condition, traffic, age, design and construction features, subgrade material characteristics, region and climatic features, and maintenance and rehabilitation history, as listed in Table 23. This database was designed as a relational type to facilitate data management tasks such as querying, sorting, and reporting, either for each of the 9,902 one-mile pavement segments or for contract sections that were typically set between major intersections with lengths stretching up to 15 miles.

Table 23: Data Items Stored in INDIPAVE2000 Database

Data Category	Data Item
Roadway Segment Identification	Starting and ending mileposts Functional class Segment ID number
Road Surface Condition	Roughness Rutting index Pavement quality index Present serviceability index Cracking index Faulting index
Traffic	AADT Percentage of single and multiple unit trucks
Age	Pavement age
Design and Construction Features	Pavement surface type Pavement layer thickness Asphalt content and air voids Concrete elasticity modulus Doweling
Subgrade Material Characteristics	Percent fines California Bearing Capacity Ratio (CBR)
Region and Climatic Features	Air temperature Precipitation Freeze-thaw cycles Freeze index
Maintenance History	Treatment type, level, and expenditure
Rehabilitation History	Rehabilitation type, thickness, and expenditure

Data items associated with state highway bridges were mainly acquired from the Indiana bridge inventory database. Key data items in the database include bridge identification, region, age, traffic, design and construction features, bridge deck, superstructure, substructure, and wearing surface conditions for the period 1996-2000, as listed in Table 24.

Table 24: Data Items in the Indiana Bridge Inventory Database

Data Category	Data Items
Bridge Identification	Highway functional class Route number Bridge number Bridge designation
Region	District code County code
Age	Year of original construction Last reconstruction year
Traffic	AADT Directional traffic distribution
Design and Construction Features	Number of lanes Total and clear deck width Total length Vertical clearance Superstructure material and type Detour length Load inventory rating
Condition	Wearing surface condition rating Deck condition rating Superstructure condition rating Substructure condition rating

5.2.2 Data Preparation

In some cases, the data required for performance modeling were not directly available. So it was necessary to prepare these data from the raw data. Also, some of the secondary data stored in the database, such as the Equivalent Single Axle Load (ESAL) number, were processed on the basis of a formula developed decades ago. Since an updated computational formula has become available, this data therefore needed to be recalibrated and updated. The data that involved significant processing included ESAL computation and expenditures for various bridge-related work activities.

5.2.2.1 ESAL Computation

The AASHTO Design Guide [AASHTO, 1993] provided ESAL factors for flexible, rigid, and composite pavements with traffic loading applied on pavements with different structural numbers or thicknesses. In order to utilize the information for actual design practice, the axle-loading configuration, including the number of steering, single, and tandem or tridem axles need to be determined from the traffic stream. As this information is not available at the time of design, INDOT developed in 1980's an approximate procedure to estimate the ESAL factors for single and multiple unit trucks for flexible and rigid pavements for pavement design. In 2000 INDOT updated the ESAL factors using data from 35 Weigh-in-Motion (WIM) stations in Indiana. In the updating procedure, a structural number of 5 and a slab thickness of 10 inches were used separately for flexible and rigid pavements. A terminal PSI of 2.5 was assumed for both pavement types. In addition, these factors were developed separately for single and multiple unit trucks. Table 25 presents the updated ESAL factors established from the study [Gulen *et al.*, 2000].

Table 25: Updated ESAL Factors for Highway Pavement Design in Indiana

Pavement Type	Vehicle Class	ESAL Factor
Flexible	5, 6, 7	0.6
	8, 9, 10, 11, 12, 13	1.3
Rigid	5, 6, 7	0.9
	8, 9, 10, 11, 12, 13	2.0

Following the concept of the AASHTO formula for ESAL computation, the total annual ESAL values applied on a pavement segment were computed using ESAL factors from Table 25 and by incorporating the adjustments of directional distribution and lane occupancy of the traffic as shown below:

$$\text{Annual ESALs} = 365 \cdot \text{AADT} \cdot D_d \cdot L_f [(\% \text{SUT} \cdot \text{ESAL}_{\text{SUT}}) + (\% \text{MUT} \cdot \text{ESAL}_{\text{MUT}})] \quad (23)$$

where

Annual ESALs = Annual ESAL values applied on a pavement segment

AADT = Annual average daily traffic

D_d = Adjustment factor for traffic directional distribution

L_f = Adjustment factor for lane occupancy

%SUT = Percent of single unit trucks, vehicle classes 5, 6, 7

%MUT = Percent of multiple unit trucks, vehicle classes 8, 9, 10, 11, 12, 13

$ESAL_{SUT}$ = ESAL factor for single unit trucks

$ESAL_{MUT}$ = ESAL factor for multiple unit trucks.

To facilitate establishing the directional distribution, the lane occupancy factors, and the truck percentage for various highway classes, statistical models were developed using traffic characteristics data collected from WIM stations in Indiana. The descriptive statistics of the dependent variables are provided in Appendix H, and the calibrated models are of the following specification:

$$DD = \alpha_0 + \alpha_1(t - 1990) \quad (24)$$

$$LOF = \alpha_0 + \alpha_1(t - 1990) \quad (25)$$

$$\% SUT = \alpha_0 + \alpha_1(t - 1990) \quad (26)$$

$$\% MUT = \alpha_0 + \alpha_1(t - 1990) \quad (27)$$

where

DD = Directional distribution factor, in %

LOF = Lane occupancy adjustment factor

% SUT = Percent of single unit trucks in traffic stream, in %

% MUT = Percent of multiple unit trucks in traffic stream, in %

t = Year of analysis.

α_0 , and α_1 are calibrated coefficients for different highway classifications.

The calibrated coefficients as well as test results of goodness of fit of the proposed models are presented in Table 26. It is shown that, except for rural interstate highways, fairly good fit was achieved for directional distribution and lane occupancy factors. For the percentage of both single and multiple unit trucks, apart from urban non-interstate highways, good fit was obtained. Even though the goodness of fit, i.e., adjusted R^2 , was low for some models, the calibrated coefficients were significant at least at 5 percent level of significance as indicated by t-statistic values.

Table 26: Calibrated Model Coefficients for Directional Distribution, Lane Occupancy Adjustment Factor, and Truck Percentage for ESAL Computation

Designation	Highway Class	$y = \alpha_0 + \alpha_1(t-1990)$				Adjusted R^2
		α_0	t -statistic	α_1	t -statistic	
Directional Distribution (DD) (%)	Rural interstate	53	(752.99)	0.02	(1.91)	0.21
	Rural non-interstate	48	(54.99)	0.67	(4.54)	0.66
	Urban interstate	47	(112.60)	0.88	(12.41)	0.94
	Urban non-interstate	39	(68.27)	2.92	(30.17)	0.99
Lane Occupancy Adjustment Factor (L_f)	Rural interstate	0.76	(137.77)	-0.0021	(-2.21)	0.28
	Rural non-interstate	0.82	(319.45)	-0.0038	(-8.72)	0.88
	Urban interstate	0.70	(117.49)	0.0032	(3.21)	0.48
	Urban non-interstate	0.42	(68.00)	0.0349	(33.71)	0.99
Single Unit Truck (%)	Rural interstate	15	(67.04)	0.90	(23.00)	0.98
	Rural non-interstate	21	(30.91)	0.53	(4.57)	0.67
	Urban interstate	15	(35.49)	0.81	(11.18)	0.93
	Urban non-interstate	17	(21.70)	-0.38	(-2.92)	0.43
Multiple Unit Truck (%)	Rural interstate	15	(24.60)	0.66	(6.43)	0.80
	Rural non-interstate	7	(19.73)	0.52	(8.06)	0.86
	Urban interstate	10	(17.86)	-0.16	(-1.69)	0.66
	Urban non-interstate	2	(20.72)	-0.05	(-2.71)	0.39

5.2.2.2 Expenditures of Various Bridge Related Work Activities

From the Indiana bridge inventory database information was obtained on bridge location, traffic, age, design characteristics, and condition for 4,907 bridges from 1996 through 2000. As shown in Table 27, these bridges are distributed across various highway classifications and are further classified by superstructure type. One challenge encountered for bridge model development was that no bridge expenditure information was provided. The Indiana Bridge Management System (IBMS) software was thus utilized to acquire the missing data relevant to bridge expenditure.

Table 27: Distribution of State Maintained Highway Bridges

Road Type		Functional Classification	Superstructure Type					
			1	2	3	4	5	6
National Highway System (NHS) (2,382)	Interstate (IS) (1,249)	Rural interstate Urban interstate	63	322	53	712	12	87
	Non-IS (1,133)	Rural principal arterial Urban freeway Urban principal arterial	127	228	74	556	45	103
Non-NHS (2,525)	State (2,464)	Rural principal arterial	685	559	269	402	271	278
		Rural minor arterial						
Rural major collector								
Rural minor collector								
Urban principal arterial								
Urban minor arterial								
Urban collector								
Local (61)	Rural local Urban local	13	9	20	7	10	2	
Total		4,907	888	1,118	416	1,677	338	470

Superstructure Type: 1- Concrete slab, 2- Concrete girder, 3- Steel girder, 4- Steel truss, 5- Concrete arch deck, and 6- Concrete channel beam.

The IBMS software is comprised of four modules: decision tree (DTREE), life-cycle cost analysis (COST), multicriteria ranking (RANK), and optimization (OPT). In the present study, the DTREE and COST modules were utilized to establish bridge expenditure information. Based on the assessment of the condition of various elements and the safety status of a bridge, the DTREE module

recommends different improvement activities. The COST module then performs a life-cycle cost analysis for each given activity according to an activity profile that depicts maintenance and other improvements needed on a bridge throughout its service life. The computation is done for user cost in constant dollars in the base year of analysis. In order to establish reliable information for changes in bridge condition, and user cost as a result of implementing a recommended work activity, the cost analysis was conducted using the IBMS software repetitively for a 10-year analysis period (2001-2010).

5.3 Pavement Performance Modeling

Pavement performance modeling concentrated on pavement rehabilitation expenditure, routine maintenance expenditure, and tradeoffs between the maintenance level and the rehabilitation interval. Models were calibrated separately for flexible, rigid, and composite pavements. The descriptive statistics of modeling data are summarized in Appendix I.

5.3.1 Pavement Rehabilitation Expenditure Models

Pavement rehabilitation expenditure models developed by Li and Sinha [2000] were used in the present study. For a pavement segment that received rehabilitation, its service life was considered to be the time interval between the last rehabilitation work and the start of a rehabilitation activity that fell in the analysis period of the present study. The general functions of OLS models for flexible, rigid and composite pavements are as below:

$$\begin{aligned} \text{REHAB}_{\text{FLEXIBLE}} = & \alpha_0 + \alpha_1 \left[\frac{\text{Cumulative ESALs}}{\text{THICKNESS}} \right] + \alpha_3 (\text{P200} \cdot \text{MOIST} \cdot \text{FZI}) \\ & + \alpha_5 \text{DRAINCO} + \alpha_9 [(\text{AGE} - 10) \cdot \text{DM}_{\text{AGE}}] \end{aligned} \quad (28)$$

$$\begin{aligned} \text{REHAB}_{\text{RIGID}} = & \alpha_0 + \alpha_1 (\text{Cumulative ESALs}) + \alpha_2 \text{SLABTH} \\ & + \alpha_6 (\text{DAYS} > 32^{\circ} \text{C}) + \alpha_8 \text{AGE} \end{aligned} \quad (29)$$

$$\begin{aligned} \text{REHAB}_{\text{COMPOSITE}} = & \alpha_0 + \alpha_1 \left[\frac{\text{Cumulative ESALs}}{\text{THICKNESS}} \right] + \alpha_4 (\text{MOIST} \cdot \text{FZI}) \\ & + \alpha_7 \text{MINTEM} + \alpha_9 [(\text{AGE} - 10) \cdot \text{DM}_{\text{AGE}}] \end{aligned} \quad (30)$$

where

REHAB = Expected rehabilitation expenditures after the service of a life-cycle, in 1997\$/lane-mile

Cumulative ESALs= Cumulative ESALs applied to the pavement during a life-cycle

THICKNESS = Total pavement thickness, in inches

SLABTH = Slab thickness of rigid pavements, in inches

P200 = Subgrade material percent passing #200 sieve, in percent

MOIST = Subgrade moisture content, in percent

FZI = Average freeze index during one life-cycle, in degree-days

DRAINCO = Drainage coefficient of the subgrade

DAYS >32⁰C = Average annual no. of days > 32⁰C during one life-cycle

MINTEM = Average annual minimum temperature during one life-cycle, ⁰F

AGE = Pavement age at time of rehabilitation, in years

DM_{AGE} = Dummy variable, =1 if age > 10 years, 0 otherwise.

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8$ and α_9 are calibrated coefficients of significant independent variables as listed in Table 28 [Li and Sinha, 2000].

Table 28: Coefficients of Significant Independent Variables for Calibrated Pavement Rehabilitation Expenditure Models

Significant Independent Variable	Calibrated Coefficient	Flexible (<i>t</i> -statistic)	Rigid-JCP (<i>t</i> -statistic)	Composite (<i>t</i> -statistic)
Constant	α_0	172,431 (5.45)	-628,986 (-3.09)	540,918 (7.41)
Annual ESALs THICKNESS	α_1	0.3113 (50.66)	0.0380 (12.53)	0.2409 (29.39)
SLABTH	α_2	-	-40,021 (-3.66)	-
P200*MOIST*FZI	α_3	301 (5.43)	-	-
MOIST*FZI	α_4	-	-	71 (39.55)
DRAINCO	α_5	-145,378 (-4.67)	-	-
DAYS >32 ⁰ C	α_6	-	13,274 (3.76)	-
MINTEM	α_7	-	-	-10,393 (-6.82)
AGE	α_8	-	34,760 (3.97)	-
(AGE-10)*DM _{AGE}	α_9	701 (3.38)	-	10,593 (8.83)
Goodness of Fit (R^2)		0.96	0.96	0.90
Observations		202	49	621

5.3.2 Pavement Annual Routine Maintenance Expenditure Models

Tobit models developed by Li and Sinha [2000] were used to estimate the expenditure function for pavement segments with routine maintenance work. Four different models were estimated, one for each pavement type. Formulation of the models recognized the lagged relationship between routine maintenance and pavement condition change; the pavement damage at the end of year t was a function of load and non-load factors in year t ; and maintenance decision (and hence, expenditure) in year $t+1$ was influenced by pavement condition change in the previous year t . The calibrated routine maintenance expenditure and pavement condition change functions for flexible, Joint Concrete Pavements (JCP), Continuously Reinforced Concrete (CRC), and composite pavements are as below:

$$\left\{ \begin{array}{l} \text{ARME}_{(\text{FLEXIBLE})_{t+1}} = \alpha_0 + \alpha_1 \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) + \alpha_2 \text{DM}_{\text{IS}} + \alpha_3 \text{DM}_{\text{ST}} \\ \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) = \beta_1 \left(\frac{\text{AnnualESALs}_t}{\text{THICKNESS}} \right) + \beta_2 (\text{FZTHAW}) + \beta_3 (\text{DAYS}\sigma\text{CSF}_t) \end{array} \right. \quad (31)$$

$$\left\{ \begin{array}{l} \text{ARME}_{(\text{JCP})_{t+1}} = \alpha_0 + \alpha_1 \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) + \alpha_2 \text{DM}_{\text{IS}} \\ \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) = \beta_0 + \beta_1 (\text{AnnualESALs}_t) + \beta_3 (\text{DAYS}\sigma\text{CSF}_t) + \beta_6 \text{DM}_{\text{NORTH}} + \beta_7 \text{DM}_{\text{CENTRAL}} \end{array} \right. \quad (32)$$

$$\text{ARME}_{(\text{CRC})_{t+1}} = \beta_1 \left(\frac{\text{Annual ESALs}_t}{\text{THICKNESS}} \right) + \beta_8 (\text{AGE}_t - 8) \cdot \text{DM}_{\text{AGE}} \quad (33)$$

$$\left\{ \begin{array}{l} \text{ARME}_{(\text{COMPOSITE})_{t+1}} = \alpha_0 + \alpha_1 \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) + \alpha_2 \text{DM}_{\text{IS}} \\ \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t} \right) = \beta_1 \left(\frac{\text{AnnualESALs}_t}{\text{THICKNESS}} \right) + \beta_4 \text{MAXTEM}_t + \beta_5 \text{MINTEM}_t + \beta_8 [(\text{AGE}_t - 8) \cdot \text{DM}_{\text{AGE}}] \end{array} \right. \quad (34)$$

where

ARME_{t+1} = Base-10 logarithm of Annual Routine Maintenance Expenditure for year $t+1$ (ARME for composite pavements), in 1998\$/lane-mile/year

IRI = Pavement International Roughness Index, in inches/mile

$(1 + \Delta \text{IRI}_t / \text{IRI}_t)$ = Base-10 logarithm of ratio of IRI values between year $t+1$ and t

Annual ESALs_{*t*} = Base-10 logarithm of annual ESALs applied to the pavement in year t , in ESALs/lane-mile

THICKNESS = Total thickness of the pavement, in inches

FZTHAW_{*t*} = Number of annual freeze-thaw cycles in year t , in no. of days

$\text{DAYS0}^{\circ}\text{CSF}_t$ = Number of days of first min. of 0°C between last spring and current fall

MAXTEM_t = Average annual maximum temperature in year t , in $^{\circ}\text{F}$

MINTEM_t = Average annual minimum temperature in year t , in $^{\circ}\text{F}$

AGE_t = Pavement age in year t , in years

DM_{IS} = Dummy variable: 1 for Interstate roads, 0 otherwise

DM_{ST} = Dummy variable: 1 for state roads, 0 otherwise

DM_{NORTH} = Dummy variable: 1 for northern Indiana, 0 otherwise

$\text{DM}_{\text{CENTRAL}}$ = Dummy variable: 1 for central Indiana, 0 otherwise

DM_{AGE} = Dummy variable: 1 if pavement age is greater than 8 years, 0 otherwise.

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7,$ and β_8 are calibrated coefficients of significant independent variables as listed in Table 29 [Li and Sinha, 2000].

Table 29: Coefficients of Significant Independent Variables for Calibrated Pavement Routine Maintenance Expenditure Models

Significant Independent Variable	Calibrated Coefficient	Flexible (t -statistic)	Rigid-JCP (t -statistic)	Rigid-CRC (t -statistic)	Composite (t -statistic)
Constant	α_0	0.3770 (3.48)	0.7924 (3.37)	-	-114.48 (-8.47)
% IRI Change	α_1	46.02 (7.60)	37.73 (2.80)	-	8,061.98 (13.97)
DM_{IS}	α_2	0.8864 (11.86)	0.2627 (1.81)	-	373.64 (20.06)
DM_{ST}	α_3	0.2537 (3.80)	-	-	-
Constant	β_0	-	0.0756 (1.99)	-	-
Annual ESALs THICKNESS	β_1	0.0052 (5.79)	0.0081 (3.62)	0.4449 (17.64)	0.0062 (7.74)
FZTHAW	β_2	0.0003 (7.25)	-	-	-
$\text{DAYS0}^{\circ}\text{CSF}$	β_3	-0.0002 (-6.82)	-0.0006 (-3.13)	-	-
MAXTEM	β_4	-	-	-	0.00035 (24.83)
MINTEM	β_5	-	-	-	-0.0007(-12.41)
DM_{NORTH}	β_6	-	-0.0087 (-1.73)	-	-
$\text{DM}_{\text{CENTRAL}}$	β_7	-	-0.0116 (-2.14)	-	-
$(\text{AGE}-8)*\text{DM}_{\text{AGE}}$	β_8	-	-	0.2567 (1.74)	0.0012 (3.53)
Goodness of Fit (ρ^2)		0.18	0.06	0.39	0.12
Observations		828	141	29	1,961

5.3.3 Tradeoffs between Routine Maintenance and Rehabilitation Interval

Tradeoff relationships between the rehabilitation interval and maintenance-load-weather were extensively studied using field data from the Indiana state highways by Labi and Sinha [2001]. Models were calibrated using OLS techniques separately by highway functional classification for different pavement types as listed in the following:

$$\text{REHAB INTERVAL} = a + b \cdot c \left[\frac{\text{ARME}}{(\text{Annual ESALs} \cdot \text{WSI})} \right] \quad (35)$$

where

REHAB INTERVAL = Interval of rehabilitation of given pavement section, in years

ARME = Annual routine maintenance expenditure, in 1995\$/lane-mile/year

Annual ESALs = Annual ESALs applied to the pavement, in million ESALs/lane-mile

WSI = A weighted index of precipitation (in millimeter), freeze index (in degree-day), and freeze-thaw cycles (in number of days) with weights being 0.3, 0.35, and 0.35, respectively.

a , b , and c are calibrated coefficients for different pavement types by highway functional classification as listed in Table 30.

Table 30: Calibrated Coefficients for Pavement Rehabilitation Interval Models

Highway Class	Interstate		Non-Interstate		
	Rigid (t -statistic)	Composite (t -statistic)	Flexible (t -statistic)	Rigid (t -statistic)	Composite (t -statistic)
a	34.0793 (3.36)	37.5909 (2.22)	11.9249 (3.73)	39.0608 (1.69)	61.8719 (1.33)
b	-19.8293 (-2.21)	-23.3918 (-4.22)	-8.2775 (-1.44)	-27.0552 (-1.42)	-50.7040 (-2.05)
c	0.2410 (1.46)	0.5394 (1.77)	0.7678 (2.45)	0.9281 (8.61)	0.9824 (4.87)
R^2	0.27	0.38	0.14	0.35	0.23
Observations	16	23	25	24	43

5.3.4 Discussions

Pavement expenditure models were considered separately for rehabilitation and routine maintenance. In addition, the tradeoff relationship between rehabilitation interval and routine maintenance was also included. The models developed in earlier studies were found applicable to the present study. For rehabilitation expenditure and rehabilitation-routine maintenance relationship, OLS models were used, while the routine maintenance expenditure models used Tobit analysis. Tobit model was used because annual routine maintenance levels were restricted by budget constraints, and econometric theory stated that in such cases the OLS model was not appropriate and the Tobit model yielded more consistent estimates [Goldberger, 1964].

5.4 Bridge Performance Modeling

Model calibration focused on the impact of a bridge work activity, represented by a given level of expenditure, on changes in bridge condition, life-cycle agency cost, and user cost. Specifically, models were developed separately for concrete and steel bridges. Model forms are discussed in the following sections and the descriptive statistics of modeling data are summarized in Appendix J.

5.4.1 Impact of Work Activity on Bridge Deck, Superstructure, Substructure, and Wearing Surface Condition

Models were calibrated separately for changes in the deck, superstructure, substructure, and wearing surface conditions for concrete and steel bridges using OLS techniques as a function of traffic, age, and bridge expenditure. The general form of the calibrated models for concrete and steel bridges is as below:

$$\begin{aligned} \text{CONDITION CHANGE} = & \alpha_0 + \alpha_1 \text{AADT} + \alpha_2 \text{AGE} + \alpha_3 \text{EXPENDITURE} + \alpha_4 \text{DM}_{\text{IS}} \\ & + \alpha_5 \text{DM}_{\text{SLAB}} + \alpha_6 \text{DM}_{\text{GIRDER}} + \alpha_7 \text{DM}_{\text{ARCH}} + \alpha_8 \text{DM}_{\text{BOXBEAM}} \end{aligned} \quad (36)$$

where

CONDITION CHANGE = Change in deck, superstructure, substructure, and wearing surface condition of concrete or steel bridge as a result of a work activity, in %

EXPENDITURE = Expenditure associated with a specific work activity, in 1990\$/ft²

AADT = Bridge traffic volume at time of work action, in vehicles

AGE = Bridge age at time of work action, in years

DM_{IS} = Dummy variable, 1 for interstate, 0 otherwise

DM_{SLAB} = Dummy variable, 1 for slab superstructure, 0 otherwise

DM_{GIRDER} = Dummy variable, 1 for girder superstructure, 0 otherwise

DM_{ARCH} = Dummy variable, 1 for arch superstructure, 0 otherwise

DM_{BOXBEAM} = Dummy variable, 1 for box beam superstructure, 0 otherwise.

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7,$ and α_8 are calibrated coefficients for concrete and steel bridges as listed in Tables 31 and 32.

Table 31: Coefficients of Significant Independent Variables for Concrete Bridge Condition Models

Significant Independent Variable	Calibrated Coefficient	Deck (<i>t</i> -statistic)	Superstructure (<i>t</i> -statistic)	Substructure (<i>t</i> -statistic)	Surface (<i>t</i> -statistic)
Constant	α_0	0.0084 (2.20)	-0.0271 (-2.76)	-0.6958 (-11.04)	-
AADT	α_1	0.000003(16.52)	-0.000001(-1.84)	-0.00001 (-2.31)	0.00001 (4.88)
AGE	α_2	-	0.0042 (20.56)	-0.0202 (-103.29)	0.0090 (18.04)
EXPEND (\$/ft ²)	α_3	0.0006 (12.72)	0.0006 (2.55)	0.0512 (18.22)	0.0067 (28.52)
DM _{IS}	α_4	0.0370 (11.68)	0.0496 (8.06)	-	-0.0686 (-3.78)
DM _{SLAB}	α_5	0.0093 (2.00)	-0.1155 (-10.42)	0.3431 (223.43)	-0.1980 (-7.30)
DM _{GIRDER}	α_6	-0.0204 (-6.47)	-0.0347 (-4.95)	-	0.1460 (8.32)
DM _{ARCH}	α_7	-0.0273 (-5.81)	-0.0260 (-2.70)	-0.0177 (-16.50)	0.0738 (2.81)
Goodness of Fit (R ²)		0.20	0.53	0.90	0.81
Observations		3,796	648	15	3,796

Table 32: Coefficients of Significant Independent Variables for Steel Bridge Condition Models

Significant Independent Variable	Calibrated Coefficient	Deck (<i>t</i> -statistic)	Superstructure (<i>t</i> -statistic)	Surface (<i>t</i> -statistic)
Constant	α_0	0.1099 (34.06)	0.0569 (3.37)	-
AADT	α_1	0.0000004 (6.24)	-	-
AGE	α_2	0.0007 (9.01)	0.0016 (4.90)	0.0143 (31.19)
EXPENDITURE (\$/ft ²)	α_3	0.0004 (13.02)	0.0025 (3.29)	0.0038 (13.83)
DM _{IS}	α_4	-0.0035 (-1.72)	-	0.0613 (3.67)
DM _{BOXBEAM}	α_8	-0.0121 (-3.62)	0.0328 (3.29)	-0.0453 (-1.50)
Goodness of Fit (R ²)		0.11	0.20	0.79
Observations		2,946	183	2,946

It can be seen from the above tables that a fairly good fit was obtained for bridge substructure and wearing surface condition models. Even though the goodness of fit, i.e., adjusted R², was low for bridge deck and superstructure models, the calibrated coefficients were significant at least at 5 percent level of significance as indicated by *t*-statistic values. The signs of calibrated coefficients were intuitive. All things being equal, a higher expenditure level would result in an increased rate of change in the condition of individual bridge components. This was true for both concrete and steel bridges. Also, the marginal effects of changes in bridge condition were higher as traffic volume and age increased. However, the magnitude of the change was different for different types of bridges when classified by bridge superstructure type.

5.4.2 Impact of Work Activity on Bridge Life-Cycle Agency and User Costs

Models were calibrated for concrete and steel bridges, respectively, using OLS techniques to relate changes in bridge user cost as a function of traffic, age, bridge expenditure, load inventory rating, and detour length. The general form of the calibrated user cost models for concrete and steel bridges is as follows:

$$\begin{aligned} \text{USER COST CHANGE} = & \alpha_0 + \alpha_1 \text{AADT} + \alpha_2 \text{AGE} + \alpha_3 \text{EXPENDITURE} + \alpha_4 \text{LOAD_INVENTORY} \\ & + \alpha_5 \text{DETOUR_LENGTH} + \alpha_6 \text{DM}_{\text{IS}} + \alpha_7 \text{DM}_{\text{SLAB}} + \alpha_8 \text{DM}_{\text{GIRDER}} + \alpha_9 \text{DM}_{\text{ARCH}} \quad (37) \\ & + \alpha_{10} \text{DM}_{\text{BOXBEAM}} + \alpha_{11} \text{DM}_{\text{DECK}} + \alpha_{12} \text{DM}_{\text{SUPERSTRUCTURE}} \end{aligned}$$

where

USER COST CHANGE= Change in equivalent uniform annual user cost for concrete or steel bridges as a result of a work activity, in %

AADT = Bridge traffic volume at time of work action, in vehicles

AGE = Bridge age at time of work action, in years

EXPENDITURE= Equivalent annual agency cost, in 1990\$/ft²

LOAD_INVENTORY = Bridge load inventory rating at time of work action, in tons

DETOUR_LENGTH = Bridge detour length at time of work action, in miles

DM_{IS} = Dummy variable, 1 for interstate, 0 otherwise

DM_{SLAB} = Dummy variable, 1 for slab superstructure, 0 otherwise

DM_{GIRDER} = Dummy variable, 1 for girder superstructure, 0 otherwise

DM_{ARCH} = Dummy variable, 1 for arch superstructure, 0 otherwise

DM_{BOXBEAM} = Dummy variable, 1 for box beam superstructure, 0 otherwise

DM_{DECK} = Dummy variable, 1 if work action conducted only on deck, 0 otherwise

DM_{SUPERSTRUCRUE} = Dummy variable, 1 if work action conducted only on superstructure, 0 otherwise.

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8, \alpha_9, \alpha_{10}, \alpha_{11}$, and α_{12} are calibrated coefficients for concrete and steel bridges as listed in Table 33.

Table 33: Coefficients of Significant Independent Variables for Concrete Bridge Agency and User Cost Models

Significant Independent Variable	Calibrated Coefficient	Concrete Bridge (<i>t</i> -statistic)	Steel Bridge (<i>t</i> -statistic)
Constant	α_0	-0.2221 (-13.31)	-0.4502 (-30.15)
AADT	α_1	-0.000001 (-1.77)	0.00000023 (1.44)
AGE	α_2	0.0005 (2.72)	0.0015 (7.77)
EXPENDITURE (\$/ft ²)	α_3	0.0002 (2.62)	0.0009 (13.35)
LOAD_INVENTORY	α_4	-0.0075 (-28.20)	-0.0042 (-14.75)
DETOUR_LENGTH	α_5	0.0027 (5.13)	-
DM _{IS}	α_6	-0.0203 (-3.38)	-0.0752 (-13.76)
DM _{SLAB}	α_7	0.0415 (4.79)	-
DM _{GIRDER}	α_8	-0.0687 (-11.56)	-
DM _{ARCH}	α_9	0.0780 (9.38)	-
DM _{BOXBEAM}	α_{10}	-	-0.0750 (-9.31)
DM _{DECK}	α_{11}	-0.1455 (-13.32)	-0.1113 (-11.54)
DM _{SUPERSTRUCTURE}	α_{12}	-0.1151 (-10.86)	-0.0480 (-3.56)
Goodness of Fit (R ²)		0.45	0.28
Observations		4,922	3,414

While the adjusted R² values were small in some cases, all calibrated coefficients were significant at least at 5 percent level of significance as indicated by *t*-statistic values. For both concrete and steel bridges, a higher expenditure level led to a decrease in life-cycle user cost. The marginal effects of changes in bridge user cost were higher as the bridge age increased, and were lower as load inventory rating increased. However, the marginal effects of traffic on the changes in bridge user cost were different by bridge type.

5.5 Chapter Summary

This chapter focused on modeling the performance of physical highway assets, which mainly consisted on pavements and bridges. For pavements, models were calibrated separately for rehabilitation expenditure, routine maintenance expenditure, and tradeoffs between the routine maintenance level and the rehabilitation interval, provided with a certain level of traffic condition and weather severity. For bridges, models were developed for the bridge wearing surface and structural

conditions as well as life-cycle user cost, respectively. The calibrated models could be used to establish the marginal effects of significant explanatory variables that affect the response variables representing the performance of physical highway assets.

CHAPTER 6 MARGINAL BENEFIT ANALYSIS

6.1 Introduction

Marginal benefit analysis was conducted using the calibrated performance models for physical highway assets and network usage. The key marginal effects were pavement rehabilitation and routine maintenance expenditure needed to recover damages caused by load and non-load factors, the pavement routine maintenance expenditure level on the rehabilitation interval, the bridge expenditure level on a change in bridge surface and structural conditions as well as bridge life-cycle agency and user costs, and the change in road condition and vehicle traveling speed on individual user cost components. These effects were determined by taking the first-order derivative of relevant functions with respect to appropriate variables on interest, as discussed in the following sections.

6.2 Marginal Effects Based on Physical Asset Performance Models

6.2.1 Marginal Effect of Traffic Loading on Pavement Rehabilitation Expenditure

Models relating rehabilitation expenditure as a function of a series of the load and non-load factors given in Equations (28)-(30) in Chapter 5 were utilized to establish the marginal effect of cumulative traffic loading on rehabilitation expenditure needs. Information regarding average pavement thickness, cumulative traffic loading, and rehabilitation expenditure associated with these models is provided in Table 34. As an example, a detailed computation using the rehabilitation expenditure model for flexible pavements is provided below. Similar computations were done for rigid and composite pavements.

According to Equation (22), we have

$$\text{REHAB}_{\text{FLEXIBLE}} = 172,431 + 0.3113 \cdot \left[\frac{\text{Cumulative ESALs}}{\text{THICKNESS}} \right] + 301 \cdot (\text{P200} \cdot \text{MOIST} \cdot \text{FZI}) - 145,378 \cdot \text{DRAINCO} + 701 \cdot [(\text{AGE} - 10) \cdot \text{DM}_{\text{AGE}}] \quad (38)$$

$$\text{Hence, } \frac{\partial(\text{REHAB}_{\text{FLEXIBLE}})}{\partial(\text{ESAL})} = \frac{0.3113}{\text{THICKNESS}} \quad (39)$$

Substituting $\text{THICKNESS} = 13.76$ into Equation (39), we get $\frac{\partial(\text{REHAB}_{\text{FLEXIBLE}})}{\partial(\text{ESAL})} = 0.0226$ (in

1997 constant dollar). As overall pavement damage is caused by load and non-load related factors, the total marginal rehabilitation expenditure would thus be attributable to both load and non-load related marginal rehabilitation expenditure. The load shares of rehabilitation expenditure for different pavement types developed by Li and Sinha [2000] were utilized to establish the total marginal rehabilitation expenditure, and the total marginal rehabilitation needs were adjusted to 1990 constant dollars by CPI, and are presented in Table 35.

Table 34: Average Pavement Rehabilitation Expenditure, Pavement Thickness, and Cumulative Traffic Loading in Indiana (1995-1997)

Item	Unit	Flexible	Rigid	Composite
Rehabilitation	1997 \$/lane-mile	186,891	461,637	247,224
Thickness	inch	13.76	22.04	14.12
Cumulative ESALs	ESAL	2,197,969	9,469,897	4,121,405

Table 35: Marginal Effect of Traffic Loading on Total Rehabilitation Expenditure

Pavement Type	Load Related Marginal Rehab. Expenditure (1997, \$/lane-mile/ESAL)	Load Share	Total Marginal Rehab. Expenditure (1990, \$/lane-mile/ESAL)
Flexible	0.0226	28%	0.0671
Rigid	0.0380	78%	0.0405
Composite	0.0200	38%	0.0437

6.2.2 Marginal Effect of Change in Pavement Condition on Routine Maintenance Needs

Models for annual pavement routine maintenance expenditure needs, as a function of a series of load and non-load factors were calibrated using the Tobit approach as listed in Equations (31)-(34) in Chapter 5. To obtain the marginal effect of change in pavement condition on routine maintenance needs, only the first equation of the two-stage equation was required. Information about the average pavement surface condition and the change in the condition as well as the annual average routine maintenance expenditure needed is listed in Table 36. As an example, a detailed calculation using models for flexible pavements on interstate highways is provided below. Similar computations were done for PCC, CRC, and composite pavements.

$$\log_{10}(\text{ARME}_{t+1}) = 0.3770 + 46.0201 \cdot \log_{10}\left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t}\right) + 0.8864 \cdot \text{DM}_{\text{IS}} + 0.2537 \cdot \text{DM}_{\text{ST}} \quad (40)$$

For interstate highways, we therefore have

$$\log_{10}(\text{ARME}_{t+1}) = 1.2634 + 46.0201 \cdot \log_{10}\left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t}\right) \quad (41)$$

$$\text{Hence, } \frac{d(\text{ARME}_{t+1})}{d(\Delta \text{IRI}_t)} = 46.0201 \cdot \left[\frac{\overline{\text{ARME}_{t+1}}}{(\text{IRI}_t + \Delta \text{IRI}_t)} \right] \quad (42)$$

Substituting $\overline{\text{ARME}_{t+1}} = 77.58$, $\text{IRI}_t = 140.94$, and $\Delta \text{IRI}_t = 4.48$ (3.18% change) for interstate flexible pavements into Equation (42), we get $\frac{d(\text{ARME}_{t+1})}{d(\Delta \text{IRI}_t)} = 24.55$ (in 1998 constant dollar). The marginal effects of pavement condition change on annual routine maintenance needs for different pavement types by highway class were adjusted to 1990 constant dollars using CPI, and are listed in Table 37.

Table 36: Average Pavement Routine Maintenance Expenditure, Traffic Loading, and Pavement Condition Change in Indiana (1995-1998)

Item	Unit	Flexible	PCC	CRC	Composite
ARME	(1998\$/lane-mile)	77.58	116.36	188.93	99.29
Annual ESALs	ESAL	193,207	396,660	298,125	278,692
Average IRI	inch/mile	140.94	152.23	-	112.44
IRI Change (IS)	%	3.18%	6.36%	2.70%	-4.46%
IRI Change (NIS)	%	7.18%	8.08%	-	6.30%

Table 37: Marginal Effect of Pavement Condition Change on Annual Routine Maintenance Expenditure Needs

Pavement Type	Highway Class	Marginal ARME (1998, \$/lane-mile/inch/mile)	Marginal ARME (1990, \$/lane-mile/inch/mile)
Flexible	Interstate	24.55	19.64
	Non-Interstate	23.63	18.90
Rigid	Interstate	27.12	21.69
	Non-Interstate	26.68	21.34
Composite	Interstate	32.59	26.07
	Non-Interstate	29.30	23.44

6.2.3 Marginal Effect of Traffic Loading on Routine Maintenance Expenditure

The marginal effect of traffic loading on annual routine maintenance needs was established based on the marginal effect of traffic loading on pavement surface condition change, and the marginal effect of pavement surface condition change on the annual routine maintenance needs established previously. Based on the maintenance expenditure and performance models developed for flexible pavements (Equation 31), we have

$$\frac{\partial(\text{ARME}_{t+1})}{\partial(\text{ESAL}_t)} = \alpha_1 \cdot \beta_1 \cdot \frac{\partial \text{ARME}_{t+1}}{\partial \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t}\right)} \cdot \frac{\partial \left(1 + \frac{\Delta \text{IRI}_t}{\text{IRI}_t}\right)}{\partial \text{ESAL}_t} = \alpha_1 \cdot \beta_1 \cdot \left(\frac{\overline{\text{ARME}_{t+1}}}{\text{AnnualESAL}_s} \right) \quad (43)$$

Substituting $\alpha_1 = 46.0201$, $\beta_1 = 0.005158$, $\text{ARME}_{t+1} = 62.05$, and $\text{AnnualESAL}_s = 193,207$ for flexible pavements into Equation (43), we obtained $\frac{\partial(\text{ARME}_{t+1})}{\partial(\text{ESAL}_t)} = 0.0000953$ (in 1998 constant dollar).

The marginal annual routine maintenance needed to recover the portion of pavement damage caused by traffic loading for different pavement types by highway class is listed in Table 38. As overall pavement damage was caused by load and non-load related factors, the total marginal annual routine maintenance expenditure would therefore be the load-related marginal maintenance expenditure being normalized according to the load share of total routine maintenance expenditure. The load shares of annual routine maintenance expenditure for different pavement types established by Li and Sinha [2000] were utilized for the normalization process. The total marginal annual maintenance needs were adjusted to 1990 constant dollars by CPI and are presented in Table 38.

Table 38: Marginal Effect of Traffic Loading on Annual Total Routine Maintenance Expenditure

Pavement Type	Load Related Marginal ARME (1998, \$/lane-mile/ESAL)	Load Share	Total Marginal ARME (1990, \$/lane-mile/ESAL)
Flexible	0.0000953	26%	0.000293
Rigid-PCC	0.0000897	36%	0.000199
Rigid-CRC	0.0002820	63%	0.000358
Composite	0.0000780	28%	0.000223

6.2.4 Marginal Effect of Pavement Routine Maintenance Level on Rehabilitation Interval

According to the calibrated models shown in Equation (35) in Chapter 5, the pavement rehabilitation interval would increase as the result of a higher level of routine maintenance expenditure, provided that the traffic loading and weather condition are kept constant. However, the magnitude of the marginal effect of routine maintenance expenditure on the extension of the rehabilitation interval varies drastically for different traffic loading and weather combinations as well as the existing routine maintenance levels. This argument is illustrated as below:

Given $\text{REHAB INTERVAL} = a + b \cdot c^{\left[\frac{\text{ARME}}{(\text{Annual ESALs} \cdot \text{WSI})}\right]}$, we have

$$\frac{\partial(\text{REHAB INTERVAL})}{\partial(\text{ARME})} = b \cdot \ln c \cdot \frac{1}{(\text{Annual ESALs} \cdot \text{WSI})} \cdot c^{\left[\frac{\text{ARME}}{(\text{Annual ESALs} \cdot \text{WSI})}\right]} \quad (44)$$

The average traffic loading and average weather severity index in 1995 as shown in Table 39 and routine maintenance expenditure levels ranging from 5 to 50 dollars per lane-mile per year were utilized to illustrate the marginal effect of routine maintenance on the rehabilitation interval for different types of pavements. The results are presented in Table 40. As an example, if the current average routine maintenance expenditure for flexible pavements is \$5/lane-mile/year, every dollar increase in expenditure can be expected to add 0.143 year to the rehabilitation interval of these pavements under average traffic loading and weather conditions.

Table 39: Annual Average Traffic Loading, Weather Severity Index, and Average Rehabilitation Interval in Indiana

Pavement Type	Highway Class	Annual ESALs (in million)	WSI	Average RI (year)
Flexible	All	0.39	0.62	10.18
Rigid	Interstate	0.71	0.72	26.76
	Non-interstate	0.26	0.68	24.71
Composite	Interstate	0.81	0.75	22.04
	Non-interstate	0.28	0.76	14.00

Table 40: Marginal Effect of Maintenance Level on Pavement Rehabilitation Interval under Average Traffic Loading and Average Weather Condition in Indiana (in number of years)

Pavement Type		Flexible	Rigid		Composite	
Highway Class		All	Interstate	Non-interstate	Interstate	Non-interstate
Existing Routine Maintenance Level (\$/lane-mile/year)	5	0.143	0.595	1.478	1.527	0.571
	10	0.003	0.030	0.978	0.317	0.140
	15	0.000	0.001	0.647	0.066	0.035
	20	0.000	0.000	0.429	0.014	0.008
	25	0.000	0.000	0.284	0.003	0.002
	30	0.000	0.000	0.188	0.001	0.001
	35	0.000	0.000	0.124	0.000	0.000
	40	0.000	0.000	0.082	0.000	0.000
	45	0.000	0.000	0.054	0.000	0.000
	50	0.000	0.000	0.036	0.000	0.000

6.2.5 Marginal Effect of Work Activity on Change in Bridge Wearing Surface, Deck, Superstructure, and Substructure Conditions

The marginal effect of a work activity, represented by a certain level of expenditure, on the change in bridge conditions was determined by taking the first order derivative of condition change against the expenditure variable. The marginal effects were established separately for concrete and steel bridges with the results shown in Table 41. For example, deck condition of concrete bridge will be improved by 0.06 percent for every one dollar per square foot of expenditure on deck-related work activities.

Table 41: Marginal Effect of Expenditure on Bridge Condition Change
(Condition Change/\$/ft², 1990\$)

Bridge Type	Deck	Superstructure	Substructure	Wearing Surface
Concrete	0.0006	0.0006	0.0512	0.0067
Steel	0.0004	0.0025	-	0.0038

6.2.6 Marginal Effect of Work Activity on Bridge Life-Cycle User Cost

The marginal effect of bridge-related work on the change in bridge life-cycle user cost was determined by taking the first order derivative of change in user cost against the expenditure variable. The marginal effects were established for concrete and steel bridges, respectively, as shown in Table 42. For instance, the annualized life-cycle user cost for concrete bridges will be reduced by 0.02 for every one dollar per square foot of bridge-related expenditure.

Table 42: Marginal Effect of Expenditure on Bridge Life-Cycle User Cost
(Equivalent Uniform Annual Cost Change/\$/ft², 1990\$)

Bridge Type	User Cost
Concrete	0.0002
Steel	0.0009

6.3 Marginal Effects Based on Network-Level Highway User Cost Models

According to the calibrated models for individual user cost components, the significant variables affecting user cost components were road condition and vehicle traveling speed. The marginal effects of road condition and vehicle speed on respective user cost components were therefore determined by taking the first-order derivative of the respective equations. The marginal effects established are listed in Table 43. For instance, all other things being equal, vehicle operating cost per mile for passenger cars traveling in rural areas will increase by 2 cents for 100 inches per mile increase in IRI of pavement surface condition. Similarly, keeping other factors constant, vehicle operating cost associated with passenger cars using rural highways will reduce by 5.6 cents for every 10 miles per hour increase in vehicle traveling speed.

Table 43: Marginal Effects of Pavement Surface Condition and Average Vehicle Speed on Individual User Cost Components

Marginal Effect on User Cost Component	Land Use	Vehicle Class/ Highway Class	Change in Pavement Condition (per inch/mile increase)	Change in Speed (per mph increase)
Vehicle Operating Cost (1990\$/VMT)	Rural	Passenger Car	0.0002	-0.0056
		Single Unit Truck	0.0001	-0.0008
		Multiple Unit Truck	0.0015	-0.0085
	Urban	Passenger Car	-	-0.0073
		Single Unit Truck	0.000013	-0.0003
		Multiple Unit Truck	0.0002	-0.0012
Travel Time (hour/VMT)	Rural	Interstate	-	-0.0005
		Non-Interstate	-	-0.0004
	Urban	Interstate	-	-0.0005
		Non-Interstate	-	-0.0001
Collision Rate (No./MVMT)	All Area	All Vehicle Type	-	0.1595
Air Pollution (kg/VMT)	All	Passenger Car	-	0.0001
		Single Unit Truck	-	0.0001
		Multiple Unit Truck	-	0.0001
User Cost (1990\$/VMT)	Rural	Passenger Car	0.0009	-0.0041
		Single Unit Truck	0.0012	-0.0008
		Multiple Unit Truck	0.0025	-0.0080
	Urban	Passenger Car	0.0014	-0.0078
		Single Unit Truck	0.0017	-0.0062
		Multiple Unit Truck	0.0011	-0.0075

6.4 Project Benefits under Individual Asset Management System Goals

6.4.1 Benefits on Pavement Rehabilitation Interval and Life-Cycle Agency Cost

The direct benefit of an increased level of routine maintenance is a lengthening of the rehabilitation interval. However, a higher rehabilitation interval will lead to a higher level of cumulative traffic loading within the service interval under a steady traffic condition. As a result of added cumulative traffic loading, a higher level of total rehabilitation expenditure is then required to repair pavement damages caused by load and non-load factors. In order to determine the relative benefits to the life-cycle agency cost, comprised of routine maintenance and rehabilitation expenditure, the difference in life-cycle agency cost for two different levels of routine maintenance and rehabilitation expenditures under two rehabilitation intervals was established using the concept of Equivalent Uniform Annual Cost (EUAC). The method is illustrated as follows:

Denote

$ARME_1$ = Annual routine maintenance level 1, in dollars/lane-mile/year

$ARME_2$ = Annual routine maintenance level 2 (higher), in dollars/lane-mile/year

RI_1 = Rehabilitation interval at routine maintenance level 1, in years

RI_2 = Rehabilitation interval at routine maintenance level 2, in years

$REHAB_1$ = Rehabilitation expenditure needed for rehabilitation interval 1,
in dollars/lane-mile

$REHAB_2$ = Rehabilitation expenditure needed for rehabilitation interval 2,
in dollars/lane-mile

i = Discount rate, in %.

The benefits of service life and agency cost are therefore established as

$$1. \text{ Rehabilitation Interval: } \Delta RI = RI_2 - RI_1 \quad (45)$$

$$2. \text{ Routine Maintenance: } \Delta EUAC_{ARME} = ARME_2 - ARME_1 \quad (46)$$

$$3. \text{ Rehabilitation: } PW_n = REHAB \cdot \frac{1}{(1+i)^n} \quad (47)$$

$$EUAC_n = PW_n \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = \left[\frac{REHAB_n \cdot i}{(1+i)^n - 1} \right] \quad (48)$$

$$\Delta EUAC_{REHAB} = \left[\frac{REHAB_{RI_2} \cdot i}{(1+i)^{RI_2} - 1} \right] - \left[\frac{REHAB_{RI_1} \cdot i}{(1+i)^{RI_1} - 1} \right] \quad (49)$$

6.4.2 Benefits of Vehicle Operating Cost, Travel Time, Collision Rate and Air Pollution Rate per Vehicle Mile of Travel during Road Service Life

As life-cycle cost analysis was conducted for maintenance and rehabilitation expenditures in determining the system benefits, it was desirable to evaluate the vehicle operating cost, travel time, collision rate, and vehicle air pollution rate per VMT for the same service life. The vehicle operating cost per VMT was computed in dollars annually during the road service life. As such, it could be discounted to present worth and then to an EUAC value over the road service life. However, the travel time, vehicle collision rate, and air pollution rate per VMT in each year were calculated in terms of hours, number of collisions, and kilograms per VMT, respectively. As these values were not converted into dollars, they could not be discounted over the road service life. Therefore, to make the comparison of benefits compatible with the concept of life-cycle cost analysis, the respective average values for travel time, collision rate, and air pollution rate per VMT during the road service life were computed. This procedure is illustrated as follows:

Denote

$CONDITION_0$ = Base year road condition, in inches/mile

$SPEED_0$ = Base year average traveling speed, in mph

$\alpha_0, \alpha_1, \alpha_2$ = Coefficients of calibrated models of individual user cost components

K_1 = Annual rate of change in pavement surface condition, in %

K_2 = Annual average speed change rate, in %

n = Road service life

RI_1 = Rehabilitation interval at routine maintenance level 1, in years

RI_2 = Rehabilitation interval at routine maintenance level 2 (higher), in years

i = Discount rate, in %.

Computations can then be made as shown below:

1. Life-Cycle Vehicle Operating Cost per VMT (VOC/VMT)

$$\begin{aligned}
 PW_{VOC/VMT} &= \sum_{t=0}^n [VOC_t] \\
 &= [\alpha_0 + \alpha_1 \cdot CONDITION_0 + \alpha_2 \cdot SPEED_0] + K \\
 K &+ [\alpha_0 + \alpha_1 \cdot CONDITION_0 \cdot (1 + K_1)^n + \alpha_2 \cdot SPEED_0 \cdot (1 + K_2)^n] \\
 &= \alpha_0(n+1) + \alpha_1 \cdot CONDITION_0 \cdot \left[\frac{(1 + K_1)^{n+1} - 1}{K_1} \right] + \alpha_2 \cdot SPEED_0 \cdot \left[\frac{(1 + K_2)^{n+1} - 1}{K_2} \right] \quad (50)
 \end{aligned}$$

$$\begin{aligned}
 EUAC_{VOC/VMT} &= PW_{VOC} \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \\
 &= \left\{ \alpha_0(n+1) + \alpha_1 \cdot CONDITION_0 \cdot \left[\frac{(1 + K_1)^{n+1} - 1}{K_1} \right] + \alpha_2 \cdot SPEED_0 \cdot \left[\frac{(1 + K_2)^{n+1} - 1}{K_2} \right] \right\} \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (51)
 \end{aligned}$$

Substituting rehabilitation intervals RI_2 and RI_1 into Equation (51) and taking the difference, the benefits of life-cycle vehicle operating cost per VMT is determined below:

$$\Delta EUAC_{VOC/VMT} = EUAC_{VOC/VMT}(RI_2) - EUAC_{VOC/VMT}(RI_1) \quad (52)$$

2. Life-Cycle Average Travel Time (TT/VMT):

$$\begin{aligned} \text{Average TT/VMT} &= \frac{(TT_0/VMT + TT_1/VMT + K + TT_n/VMT)}{n+1} \\ &= \frac{\{\alpha_0 + \alpha_2 \cdot \text{SPEED}_0\} + K + \{\alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot (1 + K_2)^n\}}{n+1} \\ &= \alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot \left[\frac{(1 + K_2)^{n+1} - 1}{K_2 \cdot (n+1)} \right] \end{aligned} \quad (53)$$

Similar to the VOC computations, the benefits of life-cycle average travel time is established in the following:

$$\Delta \text{Average TT / VMT} = \text{Average TT / VMT}(RI_2) - \text{Average TT / VMT}(RI_1) \quad (54)$$

3. Life-Cycle Vehicle Collision Rate per Million VMT (COL/MVMT)

$$\begin{aligned} \text{Average COL/MVMT} &= \frac{(COL_0/MVMT + COL_1/MVMT + K + COL_n/MVMT)}{n+1} \\ &= \frac{\{\alpha_0 + \alpha_2 \cdot \text{SPEED}_0\} + K + \{\alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot (1 + K_2)^n\}}{n+1} \\ &= \alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot \left[\frac{(1 + K_2)^{n+1} - 1}{K_2 \cdot (n+1)} \right] \end{aligned} \quad (55)$$

Similar to the VOC and travel time computations, the benefits of life-cycle average vehicle collision rate is calculated as follows:

$$\Delta \text{Average COL / MVMT} = \text{Average COL / MVMT}(RI_2) - \text{Average COL / MVMT}(RI_1)$$

4. Life-Cycle Air pollution Rate per VMT (POL/VMT)

$$\begin{aligned}
 \text{Average POL/VMT} &= \frac{(\text{POL}_0/\text{VMT} + \text{POL}_1/\text{VMT} + K + \text{POL}_n/\text{VMT})}{\text{RI}_2 + 1} \\
 &= \frac{\{[\alpha_0 + \alpha_2 \cdot \text{SPEED}_0] + K + [\alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot (1 + K_2)^n]\}}{n + 1} \\
 &= \alpha_0 + \alpha_2 \cdot \text{SPEED}_0 \cdot \left[\frac{(1 + K_2)^{n+1} - 1}{K_2 \cdot (n + 1)} \right] \quad (57)
 \end{aligned}$$

Similar to the vehicle operating cost, travel time, and vehicle collision rate computations, the benefits of life-cycle average air pollution rate is calculated as follows:

$$\Delta \text{Average POL/VMT} = \text{Average POL/VMT}(\text{RI}_2) - \text{Average POL/VMT}(\text{RI}_1) \quad (58)$$

These relationships were used to estimate impacts on individual highway asset management system goals due to the implementation of various projects, as explained in Chapter 3.

6.5 Chapter Summary

This chapter focused on establishing the marginal effects of factors that influenced the performance of physical highway assets as well as asset usage at the network level. The marginal effects were established on the basis of calibrated performance models. The marginal benefit was then determined on the basis of the marginal effects established. Specifically, marginal benefit analysis was conducted for pavement and bridge-related projects and network level user cost components that include vehicle operation, travel time, vehicle collision rate, and air pollution rate per mile of travel.

CHAPTER 7 TRADEOFF ANALYSIS

7.1 Introduction

In a highway asset management system, there are multiple, non-commensurable system goals. In order to facilitate tradeoffs between different candidate projects under equal parameters, project benefits that achieve individual system goals measured by various performance indicators require conversion into a non-dimensional unit. In the present study, the conversion procedure was achieved by developing systemwide multiattribute utility functions for individual highway asset management programs of which the various candidate projects are a part.

Risk analysis was also incorporated into the tradeoff decision process. This study first identified performance indicators involving risk occurrence, and for each performance indicator identified, a probability distribution of its possible outcomes as a result of project implementation was selected and the distribution parameters were then calibrated using existing Indiana state highways data. In the course of tradeoff analysis for candidate projects under a risk situation, systemwide multiattribute utility functions developed for tradeoffs under certainty were used to establish non-dimensional units as project benefits. However, instead of using utility values, the expected utility values were computed.

In addition to considering a risk situation, the present study further extended the tradeoff analysis by incorporating uncertainty into the decision procedure. For tradeoff analysis under uncertainty, the constraint of establishing a probability distribution for the possible outcomes of a performance indicator was removed, which directly invalidated the application of the utility theory for tradeoff decision-making. An alternative approach, based on Shackle's model [Shackle, 1949], as mentioned in Section 3.8.4, was then applied to derive a commensurable value from non-

commensurable benefits under various system goals associated with a specific candidate project. It should be noted that, similar to tradeoff analysis under risk, the performance indicators included under uncertainty were those also dealing with system usage, where uncertainty is normally encountered. This chapter discusses a systematic procedure to develop systemwide multiattribute utility functions for tradeoff analysis under certainty and risk and focus gain-over-loss ratio functions for dealing with uncertainty.

7.2 Preparation of Data Collection

In the course of establishing tradeoff relationships, a series of questionnaire surveys were administered. These questionnaires were organized to acquire data to establish the relative weights of asset management system goals, relative weights of multiple performance indicators under individual system goals, single attribute utility functions for individual performance indicators, and degree of surprise functions and priority functions for performance indicators involving uncertainty in the tradeoff decision process.

Two factors were considered in the survey process: survey approach for the preparation of questionnaires and decision group represented by survey participants. For the purpose of establishing the relative weights of asset management system goals and performance indicators and also for assigning weighting indices to reflect the decision-maker's degree of surprise and priority, a direct weighting approach was used to prepare survey questionnaires. A weighting scaling from 1 to 10 was used to reflect increased order of importance. In addition, instead of using the direct weighting approach, the certainty equivalency approach, as an alternative, was added to prepare the survey questionnaires to assess the robustness of survey results. The lower and upper ranges of various performance indicators considered for establishing the utility functions, and the deviations of outcomes of performance indicators involving uncertainty are listed in Appendix K. During the course of the questionnaire surveys, both the highway agency and the user groups were considered.

Specifically, survey attendants representing the agency group consisted of the INDOT leadership, while participants representing the user group were randomly selected in the greater Lafayette area.

7.3 Relative Weights of Highway Asset Management System Goals

7.3.1 Data Collection

Twenty nine INDOT personnel, including executive staff, district directors and division chiefs participated in the survey as a group in one session, while twenty eight Purdue employees, including faculty members, staff, and students, participated in the survey in another session. The Delphi technique discussed in Section 3.8.1.2 was followed for the two decision groups. A weighting scale from 1 (least important) to 10 (most important) was adopted to establish the relative weights of asset management goals.

7.3.2 Establishment of Relative Weights of Highway Asset Management System Goals

The descriptive statistics of the relative weights assigned in the final round are listed in Appendix L1. It was found that, for participants within each group, the relative weights established in the final round were quite consistent. Also, the standard deviations in the final round tended to be narrower, indicating a higher level of consensus. However, there were differences in the average and standard deviation values of the weights assigned by participants in the two decision groups. It was therefore necessary to arrive at a set of consensus weights that simultaneously considered the mean and standard deviation values of the assigned weights for each decision group. In this regard, the AHP technique discussed in Section 2.6.1.1 was applied by conducting pairwise comparisons of the weights assigned by individual survey participants within each decision group. As the survey participants were given equal weights, the weights established through AHP technique provided the consensus weights.

As seen in Table 44, the order of final consensus weights assigned by the two decision groups was different. For the agency group, safety received the highest weight, followed by system preservation, mobility, agency cost, user cost, and the environment. For the user group, while safety also received the highest weight, the relative weights of other system goals were in the following order: mobility, environment, system preservation, user cost, and agency cost.

Table 44: Relative Weights of Highway Asset Management System Goals Assigned by the Agency and User Groups

Asset Management System Goal	Agency Group	User Group
System Preservation	0.2259	0.1857
Agency Cost	0.1922	0.1625
Highway User Cost	0.1776	0.1795
Mobility	0.2112	0.1956
Safety	0.2319	0.2294
Environment	0.1715	0.1911

7.4 Relative Weights of Multiple Performance Indicators under Individual Goals

7.4.1 Data Collection

For some asset management programs, multiple performance indicators were identified to represent the extent to which a system goal was achieved through the implementation of a candidate project. For instance, for projects under the bridge preservation program, such performance indicators as bridge structural condition, wearing surface condition, and remaining service life, were selected to represent the goal of system preservation. It was therefore necessary to establish the relative weights of these performance indicators.

A new survey questionnaire was prepared following the similar procedure used for establishing the relative weights of system goals. Nine additional participants in each decision group were randomly selected to fill out the new questionnaire to solicit relative weights of multiple performance indicators within each system goal. The survey was also administered using the Delphi

technique discussed in Section 3.8.1.2 based on a weighting scale from 1 (least important) to 10 (most important).

7.4.2 Establishment of Relative Weights of Multiple Performance Indicators

The descriptive statistics of the relative weights assigned are listed in Appendix L2. The AHP technique was again utilized to establish the consensus weights of the concerning performance indicators, and the results are shown in Table 45.

Table 45: Relative Weights of Multiple Performance Indicators Assigned by the Agency and User Groups

Asset Management System Goal	Asset Management Program	Performance Indicator	Agency Group	User Group
System Preservation	Bridge Preservation	Bridge structural condition	0.3971	0.4162
		Bridge wearing surface condition	0.2679	0.3401
		Bridge remaining service life	0.3349	0.2437
	Historical Bridge Preservation	Bridge structural condition	0.2372	0.2483
		Bridge wearing surface condition	0.1652	0.1788
		Bridge remaining service life	0.2012	0.1954
		Historical bridge age	0.2252	0.2384
		Historical bridge length	0.1712	0.1391
	Pavement Preservation	Surface condition	0.5000	0.5000
Remaining service life		0.5000	0.5000	
Agency Cost	Bridge Preservation	Bridge construction cost	0.3535	0.3769
		Bridge rehabilitation cost	0.3581	0.3015
		Bridge maintenance cost	0.2884	0.3216
	Pavement Preservation	Pavement construction cost	0.3519	0.3547
		Pavement rehabilitation cost	0.3565	0.3153
		Pavement maintenance cost	0.2917	0.3300
ITS Improvements	Procurement cost	0.7083	0.6700	
	Maintenance cost	0.2917	0.3300	
User Cost	Bridge Preservation	Detour condition	0.4609	0.4748
		Vehicle speed	0.5391	0.5252
	Pavement Preservation	Pavement surface condition	0.5000	0.4662
		Vehicle speed	0.5000	0.5338

Table 45: Relative Weights of Multiple Performance Indicators Assigned by the Agency and User Groups (Continued)

Asset Management System Goal	Asset Management Program	Performance Indicator	Agency Group	User Group
Mobility	Bridge Preservation	Detour length	0.4965	0.5133
		Vehicle speed	0.5035	0.4867
Safety	Bridge Preservation	Bridge inventory rating	0.1935	0.2327
		Bridge clear deck width	0.2143	0.2170
		Bridge vertical clearance (over)	0.1905	0.1950
		Bridge vertical clearance (under)	0.2054	0.1698
		Bridge horizontal clearance	0.1964	0.1855
	Pavement Preservation	Vehicle speed	0.2720	0.2698
		Skid resistance	0.2605	0.2619
		Lane width	0.2567	0.2619
		Shoulder width	0.2107	0.2063
	Railroad Crossings	Railroad crossing adequacy	0.5267	0.4863
		Occurrence of collisions	0.4733	0.5137
	Safety	Sight distance	0.3709	0.3397
		Luminance	0.2958	0.3014
		Occurrence of collisions	0.3333	0.3589
Traffic Signals	Vehicle speed	0.4589	0.4604	
	Occurrence of collisions	0.5411	0.5396	
DNR/ Forest/ Other	Vehicle speed	0.3447	0.3400	
	Skid resistance	0.3301	0.3300	
	Lane width	0.3252	0.3300	

7.5 Single Attribute Utility Functions for Individual Performance Indicators

7.5.1 Data Collection and Processing

In order to develop utility functions corresponding to individual performance indicators, another survey was conducted with eighteen participants randomly selected from INDOT and Purdue campus representing the agency and user groups, respectively. The survey was conducted in an interactive manner. In response to the two questionnaires prepared using the approaches described in Section 3.8.1.3, an example was illustrated before filling out each questionnaire to allow the participants to become familiar with the survey approach. Further interactions were made as necessary during the course of the survey. However, the survey participants were required to fill in the

questionnaires independently without having inter-personal discussions. By doing so, it was expected that as much reliable information as possible could be extracted.

7.5.2 Development of Single Attribute Utility Functions

7.5.2.1 Preparation of Model Calibration

As discussed in Section 3.8.1.3, two different approaches were used to develop utility functions, the direct questioning approach and the certainty equivalency approach. One of the main reasons for two different approaches for the two decision groups in the survey process was to verify whether the utility values assigned would be affected by the approaches used and whether the interaction between the decision groups and the approaches was significant. These effects were clarified by ANOVA tests based on a two-factor factorial model as stated in Section 3.8.1.3. The ANOVA analysis was first conducted using all the data points from the four data sets. It was found that neither the effects of decision groups, or the approaches, nor their interaction was significant at a level of significance of 5 percent. This indicated that consistent utility values were assigned by survey participants irrespective of the survey approaches. In order to further confirm this conclusion, a second ANOVA test was carried out based on the four sets of data without having the extreme utility values of 0 and 1. The same conclusion was also reached, given a level of significance of 5 percent, with only one exception of the performance indicator of intersection delay time. The results of the two ANOVA tests are listed in Table 46 with p -values given in Appendix M.

Table 46: Results of ANOVA Analysis for Utility Values Assigned by the Agency and User Groups Based on Two Approaches (Level of significance at 0.05 with 108 observations)

Highway Asset Management System Goal	Performance Indicator	Factor					
		ANOVA I			ANOVA II		
		Group	Approach	Interaction	Group	Approach	Interaction
System Preservation	Bridge structural condition	No	No	No	No	No	No
	Bridge wearing surface condition	No	No	No	No	No	No
	Historical bridge age	No	No	No	No	No	No
	Historical bridge length	No	No	No	No	No	No
	Pavement condition	No	No	No	No	No	No
	Remaining service life	No	No	No	No	No	No
User Cost	Vehicle speed	No	No	No	No	No	No
Mobility	Vehicle speed	No	No	No	No	No	No
	Detour length	No	No	No	No	No	No
	Intersection delay time	No	No	No	No	Yes	No
Safety	Bridge inventory rating	No	No	No	No	No	No
	Bridge deck width	No	No	No	No	No	No
	Bridge vertical clearance- over	No	No	No	No	No	No
	Bridge vertical clearance- under	No	No	No	No	No	No
	Bridge horizontal clearance	No	No	No	No	No	No
	Average speed	No	No	No	No	No	No
	Skid resistance	No	No	No	No	No	No
	Lane width	No	No	No	No	No	No
	Shoulder width	No	No	No	No	No	No
	Railroad crossing	No	No	No	No	No	No
	Sight distance	No	No	No	No	No	No
	Luminance	No	No	No	No	No	No
Environment	Vehicle speed for CO ₂ , TSP, SO ₂	No	No	No	No	No	No
	Vehicle speed for NMHC	No	No	No	No	No	No
	Vehicle speed for CO	No	No	No	No	No	No
	Vehicle speed for NO _x	No	No	No	No	No	No

Figure 11 shows a plot that displays the difference in utility values assigned based on two approaches. It can be seen that the direct questioning approach always yielded higher utility values as opposed to those based on the certainty equivalency approach for the same amount of intersection delay time. This may be due to the fact that the direct questioning approach is less complicated and straightforward, while the certainty equivalency approach involves a more detailed and probing procedure requiring in-depth judgments. Consequently, all four data sets for performance indicators

were combined to develop a single set of utility functions for all indicators except that two separate utility functions were considered for the intersection delay time.

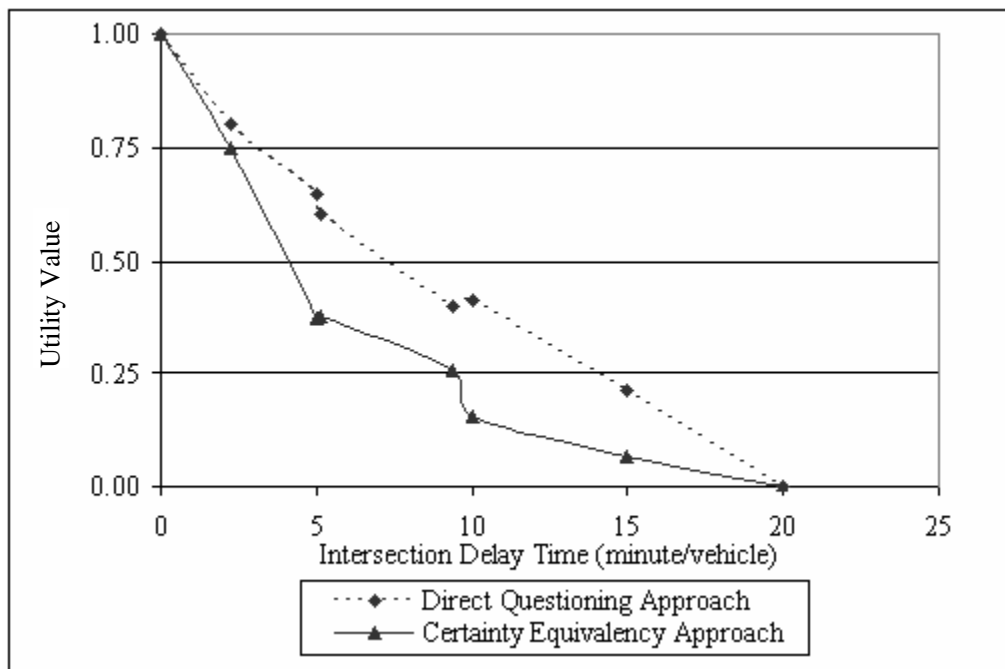


Figure 11: Comparison of Utility Values Assigned by Two Approaches

7.5.2.2 Calibration of Utility Functions and Discussions

The OLS technique was adopted for the calibration of single attribute utility functions. Descriptive statistics of the utility function modeling data are listed in Appendix N. It was found from data scatter plots that the basic shapes of the utility functions generally followed either a strict concave or pseudo-concave pattern, strictly increasing or decreasing, as shown in Figure 12.

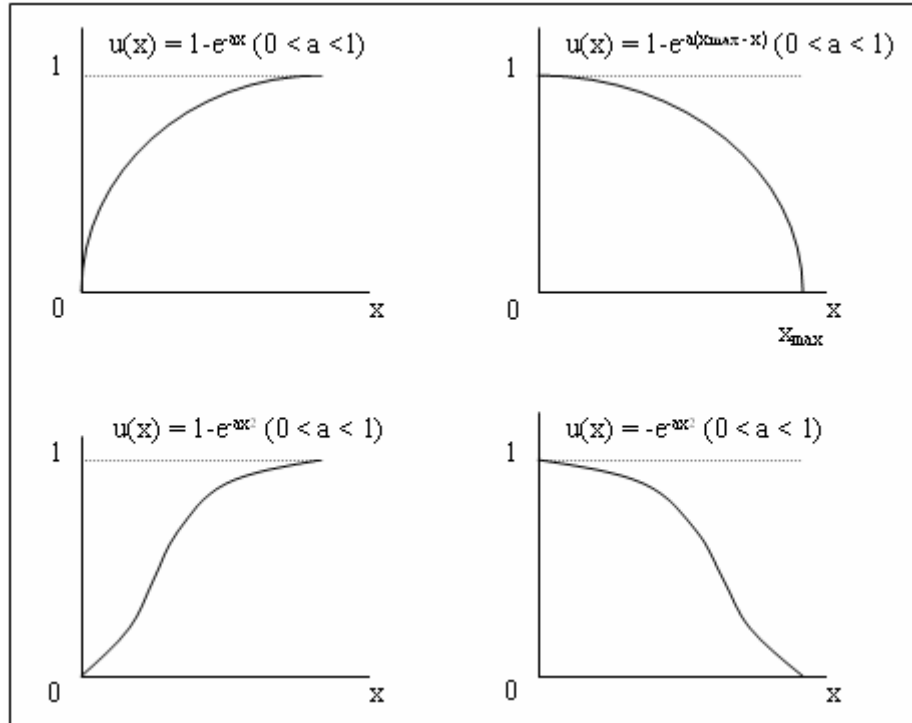


Figure 12: Functional Forms Selected for the Calibration of Single Attribute Utility Functions

The calibrated single attribute utility functions are listed in Table 47. As shown in the table, the calibrated models generally fit well with the modeling data with the exceptions of bridge deck width and pavement lane width, where the actual-over-desired width ratios exceeded one. Based on the calibrated models, it was found that the utility values tended to decrease as the actual deck width and lane width were in excess of the desirable width. This result was consistent with engineering sense in that when lane width became overly wide it would confuse the highway user and thus would receive a low utility value. However, given the fairly low adjusted R^2 values achieved, it further revealed that even though the highway user realized the disadvantage of having an extremely wide lane width, the extent of its disadvantage was as reflected by varying utility values assigned from person to person.

Table 47: Calibrated Utility Functions for Individual Highway Asset Management Performance Indicators (Observations: 108)

System Goal	Performance Indicator (x)	Utility Function u(x)	Coefficient a (or b)	(t-Statistic)	Factor k	Adj. R ²
System Preservation	Bridge structural condition	$k[1 - e^{ax^2}]$	-0.0249	(-26.91)	1.1535	0.98
	Bridge wearing surface	$k[1 - e^{ax^2}]$	-0.025	(-22.17)	1.1521	0.98
	Historical bridge age	$k[1 - e^{a(x-80)}]$	-0.0144	(-72.74)	1.2160	0.99
	Historical bridge length	$k[1 - e^{a(x-40)}]$	-0.0112	(-75.98)	1.1999	0.99
	Pavement surface condition	ke^{ax^2}	-0.000044	(-54.25)	1.0729	0.99
	Remaining service life	$k[1 - e^{ax^2}]$	-0.0195	(-70.92)	1.1659	0.99
User Cost	Average speed	$k[1 - e^{a(x-15)}]$ (x ≤ 55)	-0.0486	(-83.90)	1.1670	0.99
		$k[1 - e^{a(75-x)}]$ (x > 55)	-0.0778	(-72.13)	1.1668	0.99
Mobility	Average speed	$k[1 - e^{ax^2}]$	-0.0005	(-100.78)	1.0425	0.99
	Detour length	ke^{ax}	-0.2145	(-92.02)	1.0000	0.99
	Intersection delay time	ke^{ax}	-0.0982	(-45.81)	1.0000	0.99
		ke^{bx}	-0.1772	(-27.71)	1.0000	0.99
Safety	Bridge load inventory rating	$k[1 - e^{ax^2}]$	-0.0404	(-14.42)	1.0000	0.95
	Bridge deck width	$k[1 - e^{a(x-0.8)}]$ (x ≤ 1.0)	-8.5113	(-93.07)	1.2229	0.99
		$k[1 - e^{a(1.1-x)}]$ (x > 1.0)	-59.2952	(-2.04)	1.0000	0.51
	Bridge vertical clearance (o)	$k[1 - e^{a(x-0.8)}]$	-8.2612	(-56.64)	1.2370	0.99
	Bridge vertical clearance (u)	$k[1 - e^{a(x-0.8)}]$	-8.2672	(-57.41)	1.2367	0.99
	Bridge horizontal clearance	$k[1 - e^{a(x-0.8)}]$	-8.2278	(-61.91)	1.2390	0.99
	Average speed	ke^{ax^2}	-0.0004	(-75.73)	1.0000	0.99
	Skid resistance	$k[1 - e^{a(x-10)}]$	-0.0437	(-53.05)	1.2108	0.99
	Lane width	$k[1 - e^{a(x-0.8)}]$ (x ≤ 1.0)	-8.2827	(-71.83)	1.2358	0.99
		$k[1 - e^{a(1.1-x)}]$ (x > 1.0)	-59.6314	(-2.24)	1.0000	0.57
	Shoulder width	$k[1 - e^{ax^2}]$	-2.4343	(-166.83)	1.0961	0.99
	Railroad crossing	$k[1 - e^{ax}]$	-0.6963	(-37.17)	1.1413	0.99
	Sight distance	$k[1 - e^{a(x-0.6)}]$	-4.5181	(-89.49)	1.1963	0.99
Luminance	$k[1 - e^{a(x-0.6)}]$	-4.6399	(-94.62)	1.1853	0.99	
Environment	Speed for CO ₂ , TSP, SO ₂	$k[1 - e^{a(x-15)}]$ (x ≤ 55)	-0.0478	(-76.72)	1.1734	0.99
		$k[1 - e^{a(75-x)}]$ (x > 55)	-0.0816	(-33.23)	1.1495	0.99
	Speed for NMHC	$k[1 - e^{ax}]$	-0.0338	(-84.00)	1.0717	0.99
	Speed for CO	$k[1 - e^{ax}]$ (x ≤ 35)	-0.0618	(-119.83)	1.1299	0.99
		$k[1 - e^{a(65-x)}]$ (x > 35)	-0.0609	(-83.63)	1.0690	0.99
	Speed for NOx	$k[1 - e^{ax}]$ (x ≤ 15)	-0.0949	(-826.00)	1.3173	0.99
		$k[1 - e^{a(65-x)}]$ (x > 15)	-0.0366	(-46.96)	1.1021	0.99

Note: The functional forms of utility functions are illustrated in Figure 12, where a or b values are calibrated coefficients and k values are adjustment factors to ensure a utility value of 1.0 when performance indicators x are at the most desirable levels.

7.6 Probability Distribution Parameters for Performance Indicators Involving Risk in Tradeoff Decision Process

The underlying assumption of incorporating risk analysis into the tradeoff decision process was that a probability distribution could be assigned to the possible outcomes of a performance indicator as a result of implementing a certain project. Probability distribution parameters were calibrated for discrete and continuous performance indicators based on binomial and beta distributions, respectively. The field data available from INDOT were used to develop these distribution parameters.

7.6.1 Data Preparation

For discrete performance indicators such as bridge deck, superstructure, substructure, and wearing surface conditions, the respective histograms were first prepared. This information was then utilized directly to calibrate the parameters for the binomial distribution on the basis of Poisson approximation. For continuous performance indicators, the descriptive statistics, including mean, minimum, maximum, and standard deviation, were first explored. Histograms corresponding to individual performance indicators were comprised of five data points, i.e., two ranges below and two ranges above the mean, were created according to the descriptive statistical information. Modeling calibration was then conducted accordingly. The descriptive statistics of data values of individual performance indicators are listed in Appendix O.

7.6.2 Calibration of Probability Distribution Parameters

The Slover tool in Excel spreadsheet was used to establish the parameters for binomial and beta distribution parameters. The tool utilizes Newton's search algorithm to find the optimal solution

by minimizing the sum of the squared deviations between the observed probability mass or density function values and those calculated on the basis of the calibrated binomial or beta parameters. The convergence level was set at 0.0001 with 1000 iterations each time. The calibrated parameters are listed in Tables 48-54.

Table 48: Calibrated Parameters of Binomial Distribution for Bridge Structural and Wearing Surface Condition Ratings

Bridge Type	Component Initial Condition	Observations	Binomial Distribution Parameter (p)					
			3 (n= 60)	4 (n= 50)	5 (n= 40)	6 (n= 30)	7 (n= 20)	8 (n= 10)
Concrete	Deck	4,230	0.009	0.200	0.046	0.031	0.015	0.018
	Superstructure	1,097	0.167	0.200	0.056	0.063	0.025	0.012
	Substructure	464	0.167	0.028	0.022	0.017	0.017	0.069
	Wearing Surface	4,230	0.089	0.100	0.173	0.040	0.018	0.069
Steel	Deck	3,218	0.167	0.180	0.125	0.133	0.150	0.154
	Superstructure	422	0.167	0.200	0.054	0.057	0.018	0.050
	Substructure	252	0.167	0.200	0.017	0.043	0.069	0.030
	Wearing Surface	3,218	0.114	0.112	0.077	0.042	0.049	0.069

Table 49: Calibrated Parameters of Beta Distribution for Bridge Remaining Service Life, Detour Length, and Load Inventory Ratings

Bridge Type (Observations)	Item	Beta Distribution Parameters	
		α	β
Concrete (4,922)	AADT	1.38	1.10
	Age	2.75	2.67
	Remaining service life	1.10	1.80
	Load inventory rating	3.29	4.50
	Detour length	2.74	4.50
	Average expenditure	4.50	4.31
	Agency cost	2.17	4.50
	User cost	2.12	4.50
Steel (3,414)	AADT	2.83	4.50
	Age	2.60	2.39
	Remaining service life	1.10	1.67
	Load inventory rating	2.99	4.50
	Detour length	3.03	4.50
	Average expenditure	2.97	2.75
	Agency cost	2.39	4.50
	User cost	2.17	4.50

Table 50: Calibrated Parameters of Beta Distribution for Pavement Surface Condition

Pavement Type	Highway Class	Observations	Beta Distribution Parameters	
			α	β
Flexible	Interstate	172	3.09	4.50
	Non-Interstate	1,884	2.83	2.80
Rigid	Interstate	172	4.36	4.50
	Non-Interstate	303	2.35	2.19
Composite	Interstate	818	3.47	4.50
	Non-Interstate	2,720	3.92	4.50

Table 51: Calibrated Parameters of Beta Distribution for Pavement Maintenance, Rehabilitation, and Construction Expenditures

Pavement Type	Expenditure Category	Observations	Beta Distribution Parameters	
			α	β
Flexible	Maintenance	1,343	2.27	4.50
	Rehabilitation	202	2.56	4.50
	Construction	218	2.49	4.50
Rigid	Maintenance	226	3.10	4.50
	Rehabilitation	49	2.41	4.50
	Construction	74	2.25	4.50
Composite	Maintenance	2,470	2.78	4.50
	Rehabilitation	621	2.41	4.50
	Construction	988	2.17	4.50

Table 52: Calibrated Parameters of Beta Distribution for Average Traveling Speed

Land Area (Observations)	Highway Class	Beta Distribution Parameters	
		α	β
Rural (11)	Rural interstate	1.22	1.17
	Rural principle arterial	1.16	1.15
	Rural minor arterial	4.50	2.70
	Rural major collector	4.50	2.98
Urban (11)	Urban interstate	1.16	1.36
	Urban freeway and expressway	1.17	1.15
	Urban principal arterial	1.15	1.12
	Urban minor arterial	1.43	1.18
	Urban collector	1.30	1.20

Table 53: Calibrated Parameters of Beta Distribution for Intersection Delay Time

Land Area (Observations)	Highway Class	Vehicle Class	Beta Distribution Parameters	
			α	β
Rural (11)	Interstate	Passenger car	1.22	1.14
		Single unit truck	3.11	2.99
		Multiple unit truck	1.24	1.15
	Non- Interstate	Passenger car	1.15	1.13
		Single unit truck	1.22	1.14
		Multiple unit truck	1.11	1.13
Urban (11)	Interstate	Passenger car	4.20	4.50
		Single unit truck	3.91	4.50
		Multiple unit truck	1.10	1.38
	Non- Interstate	Passenger car	1.32	1.37
		Single unit truck	1.16	1.30
		Multiple unit truck	1.14	1.18

Table 54: Calibrated Parameters of Beta Distribution for Vehicle Collision Rate

Collision Type	Observations	Beta Distribution Parameters	
		α	β
Fatality	11	2.40	2.37
Injury	11	1.18	1.15
Property Damage	11	2.56	2.48
All	11	1.26	1.13

7.6.3 Discussions

The calibrated parameters for binomial distribution were quite reasonable, as indicated by the relatively low p -parameter values. In fact, most of the parameters were on the order of less than 0.1. This generally validated the assumption of using Poisson approximation for binomial distribution in that a relatively large number of variable levels and low parameter values were required. The binomial parameters indicated that the distributions for bridge deck, superstructure, substructure, and wearing surface conditions skewed to the left, which provided evidence that the condition ratings were generally distributed above the average levels.

For pavement surface condition, agency cost, detour length and bridge load inventory rating, the distributions skewed to the right, revealing that a higher portion of pavement segments in the network had a condition rating better than network average and that maintenance, rehabilitation, or construction expenditure was below network average. Additionally, a higher number of bridges were found to have a detour length shorter than network average and that the load inventory rating was below the network average. For the remaining service life, average speed, and collision rate, the calibrated beta parameters indicated that the beta distributions skewed to the left, meaning that a higher number of state-maintained highway bridges had remaining service lives that were above network average, and that the vehicle speed and collision rate for a higher number of years were slightly higher than the respective network average.

7.7 Standardized Focus Gain-over-Loss Functions for Performance Indicators Involving Uncertainty in Tradeoff Decision Process

7.7.1 Data Collection

In order to establish the decision maker's degree of surprise and priority weighting indices corresponding to different levels of deviations from the expected values for the underlying performance indicators, another survey was prepared with two questionnaires. Thirteen people, randomly selected from the Purdue campus, participated in the survey process.

Because of the long and involved nature of the two questionnaires, a relatively long time (about two hours) was involved for each participant. Therefore, participants were compensated for their time to complete the questionnaires. The theory behind the degree of surprise function was that people were subject to assigning higher weights to reflect their degree of surprise when encountering larger deviations in the possible outcomes, as compared to their expectations. On the other hand, when the degree of surprise and outcome pair were considered simultaneously, the priority index to be assigned would be different. Correspondingly, a priority function could thus be established. In the

course of preparing the two survey questionnaires, ten different ranges of deviations were considered for each of the performance indicators. For a specific range of deviations, survey participants were asked to assign a weight index using a scale from 0 (no surprise or least priority) to 10 (highest degree of surprise or highest priority) to ten different outcome values of a specific performance indicator. The ranges of deviations selected for individual performance indicators are listed in Appendix P.

7.7.2 Development of Degree of Surprise and Priority Functions

The OLS techniques were used to calibrate the degree of surprise and priority functions. Based on the nature of these functions as discussed in Section 3.8.4.2, quadratic functional form was selected to relate the degree of surprise with the possible outcomes of the underlying performance indicator and also to establish relationship of priority indices with the outcomes and degree of surprise pairs. The calibrated surprise and priority functions are presented in Appendices Q and R, respectively.

7.7.3 Establishment of Standard Gain-over-Loss Ratios

The priority function followed a saddle shape with one maximum priority at the gain from the expectation side and one maximum priority at the loss from the expectation side. The two outcomes of the underlying performance indicator with the maximum priority values were focus gain and focus loss values. As the focus gain and loss values were in fact associated with a certain degree of uncertainty, it was therefore necessary to filter out the uncertainty attached. The standardized focus gain and loss values with zero degree of surprise were obtained from the priority indifference curves at both the gain and the loss sides where the priority weights were equivalent to the respective maximum priorities. The standardizing process is illustrated in Figure 13 using the focus gain case.

impractical to progress with the standardization process directly due to the fact that it is impossible to calibrate two parameters α_2 and β_2 for $\phi_2(\Delta x, y)$ based on one point on the curve. However, information can be utilized from the indifference curve adjacent to $\phi_2(\Delta x, y)$ to accomplish this process. As shown in Figure 13, when the priority indifference curve $\phi_1(\Delta x, y)$ comes close to $\phi_2(\Delta x, y)$, the standardized gain value Δx_1 for $\phi_1(\Delta x, y)$ tends to merge with the standardized focus gain $\Delta x_{\text{std-}\phi_{\text{max}}}$. Hence, the problem reduces to establish a mathematical expression for the standardized gain value Δx_1 .

For points A and B on priority indifference curve $\phi_1(\Delta x, y)$, we have

$$\alpha_1 \cdot \Delta x_A^{0.5} - \beta_1 y_A^2 = k \quad (59)$$

$$\alpha_1 \cdot \Delta x_B^{0.5} - \beta_1 y_B^2 = k \quad (60)$$

Substituting $y_A = \Delta x_A^2$ and $y_B = \Delta x_B^2$ into Equations (59) and (60), and solving them simultaneously, we obtain

$$\alpha_1 = \frac{k(\Delta x_2^4 - \Delta x_1^4)}{(\Delta x_2^4 \cdot x_1^{0.5} - x_2^{0.5} \cdot \Delta x_1^4)} \quad (61)$$

For point $(\Delta x_1, 0)$ on $\phi_1(\Delta x, y)$, we get $\phi_1(\Delta x, y) = \alpha_1 \cdot \Delta x_1^{0.5} - \beta_1 \cdot 0^2$ or $\phi_1(\Delta x, y) = \alpha_1 \cdot \Delta x_1^{0.5}$, thus,

$$\Delta x_1 = \left[\frac{\phi_1(\Delta x_1, 0)}{\alpha_1} \right]^2 \quad (62)$$

$$\text{Hence, } \Delta x_{\text{std-max}} \approx \left[\frac{\phi_{\text{max}}}{\alpha_1} \right]^2 = \left[\phi_{\text{max}} \cdot \frac{(\Delta x_2^4 \cdot x_1^{0.5} - x_2^{0.5} \cdot \Delta x_1^4)}{k(\Delta x_2^4 - \Delta x_1^4)} \right]^2 \quad (63)$$

Following this procedure, the maximum priority, ϕ_{max} , and the corresponding standardized focus gain and loss values, $\Delta x_{\text{std-}\phi_{\text{max}}}$, were established as listed in Table 55.

Table 55: Standardized Focus Gain and Loss Values for Individual Performance Indicators under Different Ranges of Deviations Based on Calibrated Priority Functions

Asset Management System Goal	Performance Indicator	Range of Deviations									
		Standardized Focus Gain					Standardized Focus Loss				
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
System Preservation	Pavement surface condition	3.03	6.05	9.09	12.13	15.09	18.17	16.68	19.15	21.55	23.86
		2.65	5.31	9.09	12.13	15.08	18.17	18.38	21.35	27.09	30.14
System Preservation	Remaining service life	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
		3.90	2.36	2.07	1.91	1.84	1.89	2.01	1.97	2.24	2.47
		3.82	2.35	2.07	1.91	1.83	1.89	2.01	2.01	2.41	2.69
Agency Cost	Construction	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
		21.2	39.7	63.3	90.1	87.3	126.4	142.2	160.9	178.7	198.6
	20.4	39.6	63.2	90.1	87.1	126.4	145.6	168.6	191.5	206.8	
Agency Cost	Rehabilitation	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
		2.05	4.11	6.15	8.23	10.25	11.76	13.71	16.44	18.48	19.48
		2.03	4.07	6.15	8.24	10.26	12.33	14.38	17.62	19.91	21.97
Agency Cost	Routine maintenance	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
		0.21	0.42	0.63	0.81	1.01	1.22	1.46	1.63	1.83	2.03
		0.21	0.42	0.63	0.83	1.04	1.25	1.51	1.72	1.94	2.16
User Cost Mobility Environment	Average speed	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
		3.45	6.91	10.34	12.27	15.33	18.28	21.24	24.43	27.58	30.46
	3.11	6.21	9.31	12.26	15.54	18.63	21.74	27.67	30.95	34.55	
User Cost Mobility Environment	Detour length	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
		0.25	0.48	0.72	1.01	1.26	1.51	1.68	1.92	2.00	2.12
		0.25	0.50	0.75	1.07	1.33	1.61	1.87	2.14	2.40	2.67
User Cost Mobility Environment	Intersection delay time	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
		0.66	1.18	1.59	2.10	2.60	3.10	3.59	3.85	3.84	3.90
		0.54	1.08	1.52	2.02	2.53	3.04	3.54	3.83	3.83	3.83
Safety	Average speed	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
		3.45	6.91	10.34	13.79	15.33	18.28	21.23	24.43	27.57	30.47
	3.11	6.21	10.31	13.79	15.54	18.62	21.74	27.67	30.95	34.55	
	Bridge load inventory rating	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1.12		2.22	3.35	4.46	5.58	6.70	7.80	8.03	9.04	11.14	
		1.04	2.07	3.31	4.45	5.56	6.68	7.80	8.90	10.03	11.11
Safety	Pavement skid resistance	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
		1.12	2.23	3.35	4.46	5.00	6.00	6.99	8.00	9.00	10.01
		1.04	2.08	3.34	4.46	5.20	6.24	7.27	8.32	9.96	11.16
Safety	Vehicle collision rate	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
		0.22	0.43	0.65	0.86	1.08	1.29	1.51	1.56	1.94	1.95
		0.21	0.41	0.62	0.86	1.07	1.29	1.51	1.66	1.86	2.15

7.7.4 Development of Standardized Gain-over-Loss Ratio Functions

After obtaining standardized focus gain and focus loss values in accordance with the different ranges of deviations of the outcomes from the expectation, it was necessary to further investigate the relationship between the gain-over-loss ratios with the ranges of deviations for individual performance indicators. To this end, standardized gain-over-loss ratios were first computed and standardized gain-over-loss ratio functions were then calibrated using the OLS techniques. Descriptive statistics of the ratios for individual performance indicators are listed in Appendix S, and the standardized gain-over-loss ratio functions calibrated are shown in Table 56. It was found from the calibrated functions that the standardized gain-over-loss ratio would decrease as the range of deviations became larger, which indicated that people were inclined to pose a higher weight to losses from their expectations as the deviation ranges became larger compared to gains. The models can be used to establish standardized gain-over-loss ratios for a performance indicator provided that the range of deviations of possible outcomes is given.

Table 56: Calibrated Standardized Gain-over-Loss Ratio Functions for Individual Performance Indicators (Observations: 10)

Goal	Performance Indicator	SGLR = $\alpha_0 + \alpha_1 \cdot \text{Range of Deviation}$				Adjusted R ²
		α_0	(<i>t</i> -statistic)	α_1	(<i>t</i> -statistic)	
System Preservation	Pavement condition	1.1785	(46.55)	-0.7683	(-9.42)	0.91
	Remaining service life	1.0380	(72.61)	-0.0759	(-4.12)	0.64
Agency Cost	Construction	1.0382	(106.66)	-0.1847	(-5.89)	0.79
	Rehabilitation	1.0398	(106.12)	-0.2647	(-8.38)	0.89
	Routine maintenance	1.0132	(216.41)	-0.1538	(-0.19)	0.92
User Cost	Vehicle speed	1.1535	(58.04)	-0.2331	(-9.10)	0.90
Mobility	Detour length	1.0251	(64.62)	-0.2070	(-7.68)	0.87
Environment	Intersection delay time	1.1414	(38.17)	-0.1572	(-3.45)	0.55
Safety	Vehicle speed	1.1248	(56.36)	-0.1330	(-8.05)	0.88
	Bridge load inventory	1.0924	(69.61)	-0.1791	(-7.08)	0.85
	Skid resistance	1.0834	(76.77)	-0.1887	(-8.30)	0.88
	Collision rate	1.0750	(88.34)	-0.1526	(-7.78)	0.87

7.8 Systemwide Multiattribute Utility Functions for Tradeoffs under Certainty and Risk

7.8.1 Multiattribute Utility Functions under Individual System Goals

Some individual system goals have a number of performance indicators. The utility and preference values for these performance indicators are independent of each other. Therefore, an additive form was selected to combine utility functions of performance indicators within a system goal to establish the goal-specific function, as defined below:

$$U(X_i) = \sum_{k=1}^{K_i} w_{ik} \cdot u(x_{ik}) \quad (64)$$

where

$U(X_i)$ = Goal-specific multiattribute utility function for a specific asset management program, $i = 1, 2, 3, 4, 5,$ and 6 for system preservation, agency cost, user cost, mobility, safety, and environment

w_{ik} = Relative weight of performance indicator k under goal i

$u(x_{ik})$ = Single attribute utility function for performance indicator k under goal i

K_i = Number of performance indicators under goal i .

7.8.2 Systemwide Multiattribute Utility Functions

The additive form used for combining performance indicators under individual system goals could not be used for combining all goals into systemwide utility functions. The reason is that strong correlations exist between some of the system goals. For instance, a better preserved system condition would result in reduced highway user cost and also a reduction in vehicle air pollution. Consequently,

a multiplicative form was adopted to establish systemwide multiattribute utility functions for individual asset management programs. The utility functions were of the following specification:

$$[c \cdot U(X_1, X_2, X_3, X_4, X_5, X_6) + 1] = \prod_{i=1}^6 [c \cdot W_i \cdot U(X_i) + 1] \quad (65)$$

$$\text{or } U(X_1, X_2, X_3, X_4, X_5, X_6) = \left(\frac{1}{c}\right) \cdot \left\{ \prod_{i=1}^6 [c \cdot W_i \cdot U(X_i) + 1] - 1 \right\} \quad (66)$$

where

$U(X_1, X_2, X_3, X_4, X_5, X_6)$ = System-level multiattribute utility function for a specific asset management program

W_i = Relative weight of asset management system goal i as listed in Table 54

$U(X_i)$ = Goal-specific multiattribute utility function for an asset management program

c = Scaling constant.

At this stage, the scaling constant c needed to be determined. To do this, the special case where $U(X_i) = 1$ for all six system goals was considered. As a result, Equation (65) was simplified to $[c + 1] = \prod_{i=1}^6 [c \cdot W_i + 1]$. The scaling constant for various weighting combinations between the agency and user decision groups is given in Table 57. Having established systemwide multiattribute utility functions, project benefits could then be quantified as the difference between the utility values before and after implementation of a project.

Table 57: Scaling Constants for Various Weight Combinations between the Agency and User Groups

Relative Weights of the Agency and User Groups	Scaling Constant c
10:0	-0.3825
9:1	-0.3733
8:2	-0.3640
7:3	-0.3545
6:4	-0.3449
5:5	-0.3352
4:6	-0.3252
3:7	-0.3152
2:8	-0.3049
1:9	-0.2945
0:10	-0.2839

7.8.3 Incorporating Risk into Tradeoff Decision Process

In the process of conducting tradeoff decisions involving the risk situation for some of the performance indicators, the systemwide multiattribute utility functions developed were still valid. However, the utility values associated with the performance indicators after project implementation would be replaced by the expected utility values.

7.9 Systemwide Standardized Gain-over-Loss Functions for Tradeoffs under Uncertainty

For tradeoff analysis under uncertainty, the functional structure developed for tradeoff decisions under certainty and risk was maintained. However, the corresponding single attribute utility functions were replaced by standardized focus gain-over-loss ratio functions to arrive at systemwide standardized gain-over-loss ratio functions for individual asset management system programs. Project tradeoffs were then accomplished on the basis of project benefits in terms of differences in systemwide standardized gain-over-loss ratio values before and after project implementation.

7.10 Chapter Summary

This chapter described the results of the proposed methodology for tradeoff analysis in highway asset management. The analysis considered decision-making under certainty, risk, and uncertainty and focused on developing systemwide multiutility functions and calibrating probability distribution parameters for tradeoffs under certainty and risk, as well as establishing systemwide standardized focus gain-over-loss ratio functions to assist in tradeoffs under certainty. To accomplish these tasks, a series of questionnaire surveys were conducted that focused on establishing the relative weights of asset management system goals as well as for weights of multiple performance indicators, single attribute utility functions, and also degree of surprise and priority functions. The collected data were then used to calibrate those functions, which were in turn used to develop the systemwide multiattribute utility functions as well as systemwide standardized focus gain-over-loss functions for individual asset management programs. The systemwide functions developed would assist in the tradeoff decision process and would be the basis for systemwide project selection and programming.

CHAPTER 8 SYSTEM OPTIMIZATION MODEL FOR PROJECT SELECTION AND PROGRAMMING

8.1 Introduction

To assist in highway project selection and programming at the network level incorporating the research results, a system optimization model was formulated. A solution algorithm was also developed for implementation of the optimization model as well.

8.2 Budget Scenarios in Project Selection and Programming

In the system optimization model, budget is the major constraint. As a practical matter, the budget dollars available for individual asset management programs are not always transferable across programs. For instance, the budget for the pavement preservation program can not be used for the bridge rehabilitation program. In addition to this, within each program category, budget constraints can be imposed in two ways, either annually or as a cumulative budget for all years in a given analysis period. For the annual budget scenario, it may be possible that a small amount is left from a preceding fiscal year that is not sufficient to select any single project, and the residual can then be carried over to the next year. It should be noted that for both cases project timings are fixed. Therefore, the multiyear budget scenario is in fact a special case of the annual budget with carryover scenario (“carryover budget scenario” hereafter).

8.3 System Optimization Formulation

The system optimization model associated with carryover budget scenario was formulated as the MCMDKP problem as mentioned in Section 3.9. The details of model formulation are provided below.

8.3.1 Decision Variables

The decision required for project selection is a binary choice process: 1 for selecting the project, and 0, otherwise. As projects are programmed, the decision process can involve single or multiple projects in one contract. Correspondingly, the decision variables are denoted as below:

$$Y_i = \begin{cases} 1, & \text{if contract } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (67)$$

8.3.2 Objective Function

The objective is to maximize the gain in system utility or the standardized focus gain-over-loss ratio values by selecting a subset from the candidate contract list. The factors affecting the selection of a specific contract include the number of projects under the contract, the program category of the projects, and the year for implementing the designated projects. The system objective function was formulated as follows:

$$\text{maximize } \sum_{i=1}^N \left\{ \left[\left(\sum_{j=1}^{N_i} (a_{ijkt} \cdot s_{ij}) \right) / N_i \right] \cdot Y_i \right\} \quad (68)$$

where

a_{ijkt} = Gain in system utility associated with project j under contract i that belongs to program category k and to be implemented in fiscal year t

s_{ij} = Scaling multiplier for project j under contract i , $s_{ij} = \left(\frac{\text{Traffic}_{ij} \cdot \text{Length}_{ij}}{\text{Cost}_{ij}} \right)$

Traffic_{ij} = Traffic volume that project j under contract i can serve during its service life

Length_{ij} = Length of project j under contract i

Cost_{ij} = Cost of project j under contract i

N_i = Number of projects under contract i

i = Contract i , $i = 1, 2, \dots, N$

j = Project j under contract i , $j = 1, 2, \dots, N_i$

k = Program category k , $k = 1, 2, 3, 4, 5, 6, 7$, and 8 for bridge preservation, pavement preservation, safety improvements, roadside improvements, new/major construction, state facilities, ITS installations, and miscellaneous

t = Fiscal year t , $t = 1, 2, \dots, M$.

8.3.3 Constraints

The constraints considered were those imposed by budget by category in each year of the analysis period. In addition, the decision variables only take zero-one integer values. The budget constraints were constructed as follows:

$$\sum_{i=1}^N \left[\left(\sum_{j=1}^{N_i} c_{ijkt} \right) \cdot Y_i \right] \leq B_{kt} \quad (69)$$

$Y_i = 0/1$ integers.

where

c_{ijkt} = Cost of project j under contract i that used budget from budget category k in year t

B_{kt} = Budget for program category k in fiscal year t

k = Program category k , $k = 1, 2, 3, 4, 5, 6, 7, 8$

t = Fiscal year t , $t = 1, 2, \dots, M$.

8.4 Proposed Algorithm for Project Selection and Programming

8.4.1 Preparation

The system optimization model can be redefined as follows:

$$\text{maximize } z(Y) = \sum_{i=1}^N (b_i \cdot Y_i) \quad (70)$$

subject to

$$\sum_{i=1}^N (c_{ikt} \cdot Y_i) \leq B_{kt} \quad (71)$$

$Y_i = 0/1$ integers.

where

b_i = Benefits associated with contract i , for $i = 1, 2, \dots, N$

c_{ikt} = Cost of contract i that uses money from budget category k in year t

B_{kt} = Budget for program category k in fiscal year t

k = Program category k , $k = 1, 2, 3, 4, 5, 6, 7, 8$

t = Fiscal year t , $t = 1, 2, \dots, M$.

Given non-negative, real Lagrangian multipliers λ_{kt} (for $k = 1, 2, \dots, 8$; and $t = 1, 2, \dots, M$), the Lagrangian Relaxation of (70), $z_{LR}(\lambda_{kt})$, can be written as

$$\begin{aligned}
z_{LR}(\lambda_{kt}) &= \text{maximize} \left\{ \sum_{i=1}^N (\mathbf{b}_i \cdot \mathbf{Y}_i) + \sum_{k=1}^8 \sum_{t=1}^M \left[\lambda_{kt} \cdot \left(\mathbf{B}_{kt} - \sum_{i=1}^N (\mathbf{c}_{ikt} \cdot \mathbf{Y}_i) \right) \right] \right\} \\
&= \text{maximize} \left\{ \left[\sum_{i=1}^N (\mathbf{b}_i \cdot \mathbf{Y}_i) - \sum_{k=1}^8 \sum_{t=1}^M \left(\lambda_{kt} \cdot \left(\sum_{i=1}^N (\mathbf{c}_{ikt} \cdot \mathbf{Y}_i) \right) \right) \right] + \sum_{k=1}^8 \sum_{t=1}^M (\lambda_{kt} \cdot \mathbf{B}_{kt}) \right\} \\
&= \text{maximize} \left\{ \left[\sum_{i=1}^N \left(\left(\mathbf{b}_i - \sum_{k=1}^8 \sum_{t=1}^M \left(\lambda_{kt} \cdot \sum_{i=1}^N \mathbf{c}_{ikt} \right) \right) \cdot \mathbf{Y}_i \right) \right] + \sum_{k=1}^8 \sum_{t=1}^M (\lambda_{kt} \cdot \mathbf{B}_{kt}) \right\} \quad (72)
\end{aligned}$$

subject to

$Y_i = 0/1$ integers.

As the second term in Equation (72), $\sum_{k=1}^8 \sum_{t=1}^M (\lambda_{kt} \cdot \mathbf{B}_{kt})$, is a constant, optimization process

can just be concentrated on the first term, namely, maximizing $\left[\sum_{i=1}^N \left(\left(\mathbf{b}_i - \sum_{k=1}^8 \sum_{t=1}^M \left(\lambda_{kt} \cdot \sum_{i=1}^N \mathbf{c}_{ikt} \right) \right) \cdot \mathbf{Y}_i \right) \right]$ (73)

The feasible solution to Equation (73) is $\mathbf{Y}^* = (Y_1^*, Y_2^*, \dots, Y_N^*)$, where

$$Y_i^* = \begin{cases} 1, & \text{if } \left(\mathbf{b}_i - \sum_{k=1}^8 \sum_{t=1}^M \left(\lambda_{kt} \cdot \sum_{i=1}^N \mathbf{c}_{ikt} \right) \right) > 0 \\ 0, & \text{otherwise} \end{cases} \quad (74)$$

Then, \mathbf{Y}^* maximizes $z(\mathbf{Y}) = \sum_{i=1}^N (\mathbf{b}_i \cdot \mathbf{Y}_i)$, subject to $\sum_{i=1}^N (\mathbf{c}_{ikt} \cdot \mathbf{Y}_i) \leq \sum_{i=1}^N (\mathbf{c}_{ikt} \cdot \mathbf{Y}_i^*)$, and $Y_i =$

0/1 (for $i = 1, 2, \dots, N$; $k = 1, 2, 3, 4, 5, 6, 7$, and 8 ; and $t = 1, 2, \dots, M$).

In order to maximize $z(Y) = \sum_{i=1}^N (b_i \cdot Y_i)$, only subject to $Y_i = 0/1$ (i.e., to obtain an optimal solution to the original MCMDKP problem), the following condition needs to be satisfied

$$\sum_{k=1}^8 \sum_{t=1}^M \left[\lambda_{kt} \cdot \left(B_{kt} - \sum_{i=1}^N (c_{ikt} \cdot Y_i) \right) \right] = 0 \quad (75)$$

In this regard, the optimal solution to the underlying problem boils down to determining Lagrangian multipliers λ_{kt} (for $k = 1, 2, \dots, 8$; and $t = 1, 2, \dots, M$) such that conditions (74) and (75) are both satisfied.

8.4.2 Description of the Proposed Algorithm

The proposed algorithm, based on Lagrangian relaxation techniques, is comprised of two parts. The first part deals with system optimization with budget constraints in each year, while the second part focuses on budget carryover between consecutive years by repetitively using the algorithm produced in the first part. The algorithm is described below.

Part I: Main Steps of the Proposed Algorithm prior to Carryover Budget by Year

The heuristic process has the following steps:

Step 0: Sort Benefits by Contract

- Sort benefit b_i in descending order using quick sort.

Step 1: Initialize and Normalize Contract Cost and Budget by Category

- Denote $\lambda_{kt} = 0$, for $k = 1, 2, 3, 4, 5, 6, 7$, and 8 ; $t = 1, 2, \dots, M$;
 $Y_i = 1$ for $i = 1, 2, \dots, N$.

- Normalize contract cost and budget by category in each fiscal year:
Set $c_{ikt}' = c_{ikt}/B_{kt}$, $B_{kt} = 1$ (for $i = 1, 2, \dots, N$; $k = 1, 2, 3, 4, 5, 6, 7, 8$; $t = 1, 2, \dots, M$).
- Compute $C_{kt} = \sum_{i=1}^N c_{ikt}$ for all k and t . If $C_{kt} \leq 1$ for all k and t , then stop.

Step 2: Determine the Least Total Cost Constraint

- Determine $C_{kt}' = \min \{C_{kt}\}$ for all k and t .

Step 3: Compute Increase in Lagrangian Multiplier Values λ_{kt}

$$- \text{ Let } \theta_i = \begin{cases} \frac{\left[b_i - \sum_{k=1}^8 \sum_{t=1}^M (\lambda_{kt} * c_{ikt}') \right]}{\sum_{k=1}^8 \sum_{t=1}^M \left[c_{ikt}' * \left(\frac{C_{kt}}{C_{kt}'} \right) \right]}, & c_{ikt} > 0 \\ \infty, & \text{otherwise} \end{cases}$$

- Set $\theta_i' = \min \{ \theta_i \mid Y_i = 1 \}$ for all i .

Step 4: Establish Values of Lagrangian Multipliers λ_{kt}

$$- \text{ Set } \lambda_{kt} = \lambda_{kt}' + \left[\theta_i' * \left(\frac{C_{kt}}{C_{kt}'} \right) \right] \text{ for all } i \text{ to ensure } \lambda_{(i)kt} > \lambda_{(i')kt} \text{ for } i \neq i'.$$

- Let $Y_i = 0$; and $C_{kt} = C_{kt} - c_{ikt}'$.

If $C_{kt} \leq 1$ for all k and t , then go to Step 5, otherwise, go to Step 2.

Step 5: Improve the Solution

- For all $Y_i = 0$ (Y_i 's have already been sorted in descending order based on their respective benefit b_i' in Step 0), check whether Y_i can be changed from 0 to 1 without violating the budget constraint $C_{kt} \leq 1$. If it is feasible, choose the first Y_i from the $Y_i' = 0$ list.

- Repeat this step, until no such $Y_i = 0$ can be added without violating the budget constraint, and stop.

Part II: Algorithm for Budget Carryover by Program Category for Each Fiscal Year

Denote:

S_{kpt} = Set of selected contracts in period p of category k and using budget from period t , for $t = 1, 2, \dots, M$

$B(S_{kpt})$ = Budget used for S_{kpt}

B_{kt} = Budget for program category k in fiscal year t

k = Program category k , $k = 1, 2, 3, 4, 5, 6, 7, 8$

t = Fiscal year t , $t = 1, 2, \dots, M$.

Step 1: For $p = r, r + 1, \dots, M - 1, M$ (where $r = 1, 2, \dots, M-1$)

- Run the heuristic algorithm in Part I for M period starting with period p
- For period p , place the selected contracts in S_{kpt} and remove S_{kqt} for $q = p+1, p+2, \dots, M$
- For period $p+1$, increase budget $B_{k,p+1}$ by $[B_{kp} - B(S_{kpp})]$; and decrease budget for period s (for $s = p+1, p+2, \dots, M$), B_{ks} , by $B(S_{kps})$

Therefore, budget available for each general category in period s (for $s = p+1, p+2, \dots, M$) then becomes:

$B_{k,p+1} + [B_{kp} - B(S_{kpp})] - B(S_{k,p,p+1})$ for period $p+1$,

$B_{k,p+2} - B(S_{k,p,p+2})$ for period $p+2$,

....., and

$B_{k,M} - B(S_{kpM})$ for period M .

Step 2: Increase r to $r+1$. If $r = M$, then stop. Otherwise, repeat Step 1.

For the analysis under the multiyear budget scenario, the optimization formulation, including decision variables, objective function, and constraints, remains to be the same, except for resetting the total number of analysis periods into one, namely, $M = 1$. As such, the solution algorithm for the multiyear budget scenario is exactly the same as Part I of the algorithm for optimization under the carryover budget scenario with budget constraints for a single analysis period.

8.4.3 Computational Complexity of the Proposed Algorithm

During the execution of Steps 0 to 5 in Part I of the proposed algorithm, the operations needed in each step are listed below:

Step 0 requires $N \cdot (\log_2 N)$ operations using quick sort $\rightarrow O(N(\log_2 N))$;

Step 1 needs $(8 \cdot M + N + 2 \cdot 8 \cdot M \cdot N)$ divisions and additions $\rightarrow O(NM)$;

Step 2 has at most $8 \cdot M$ comparisons $\rightarrow O(M)$;

Step 3 needs $(8 \cdot M \cdot N + N)$ operations $\rightarrow O(NM)$;

Step 4 has $8 \cdot M$ additions and comparisons $\rightarrow O(M)$;

Step 5 needs at most N operations $\rightarrow O(N)$.

For Steps 1 to 5 in Part I, at most N variables can be set to zero, the computation complexity for Part I is thus $O(N^2M)$. The extended step for budget carryover in Part II requires at most M iterations $\rightarrow O(M)$. In total, it leads to a computational complexity of $O(N^2M^2)$. It shall be noted that the value of M decreases by 1 when doing the carryover from one period to the next, until it diminishes to 1 for the last period. In practice, the number of analysis period M is far smaller than the number of candidate projects N for selection. The algorithm thus maintains a complexity of $O(N^2)$.

8.5 Chapter Summary

In this chapter the details of the system optimization formulation and also the solution algorithm for project selection and programming were provided. The system optimization model was formulated as the MCMDKP problem and the solution algorithm was prepared on the basis of Lagrangian relaxation techniques. The computational complexity was also discussed.

CHAPTER 9 CASE STUDY

9.1 General

A highway asset management system software program was developed incorporating multicriteria programming and system optimization under certainty, risk, and uncertainty. In order to validate the procedure, a case study was conducted for project selection and programming using the historical data on state highway programs in Indiana.

9.1.1 Highway Asset Management System Software Package

The Highway Asset Management System (HAMS) software is comprised of four functional components: data input, benefit and utility computation, system optimization, and output and report generation. These components work in a sequential order, and after data input each component uses the output of the preceding component as its input. As seen in Figure 14, the oval shape represents input data fields, the 3-D rectangular shape represents forms (except for “UserInputForm” that maintains both form and module capabilities), the rectangular shape represents modules, and the rounded rectangular shape represents output options.

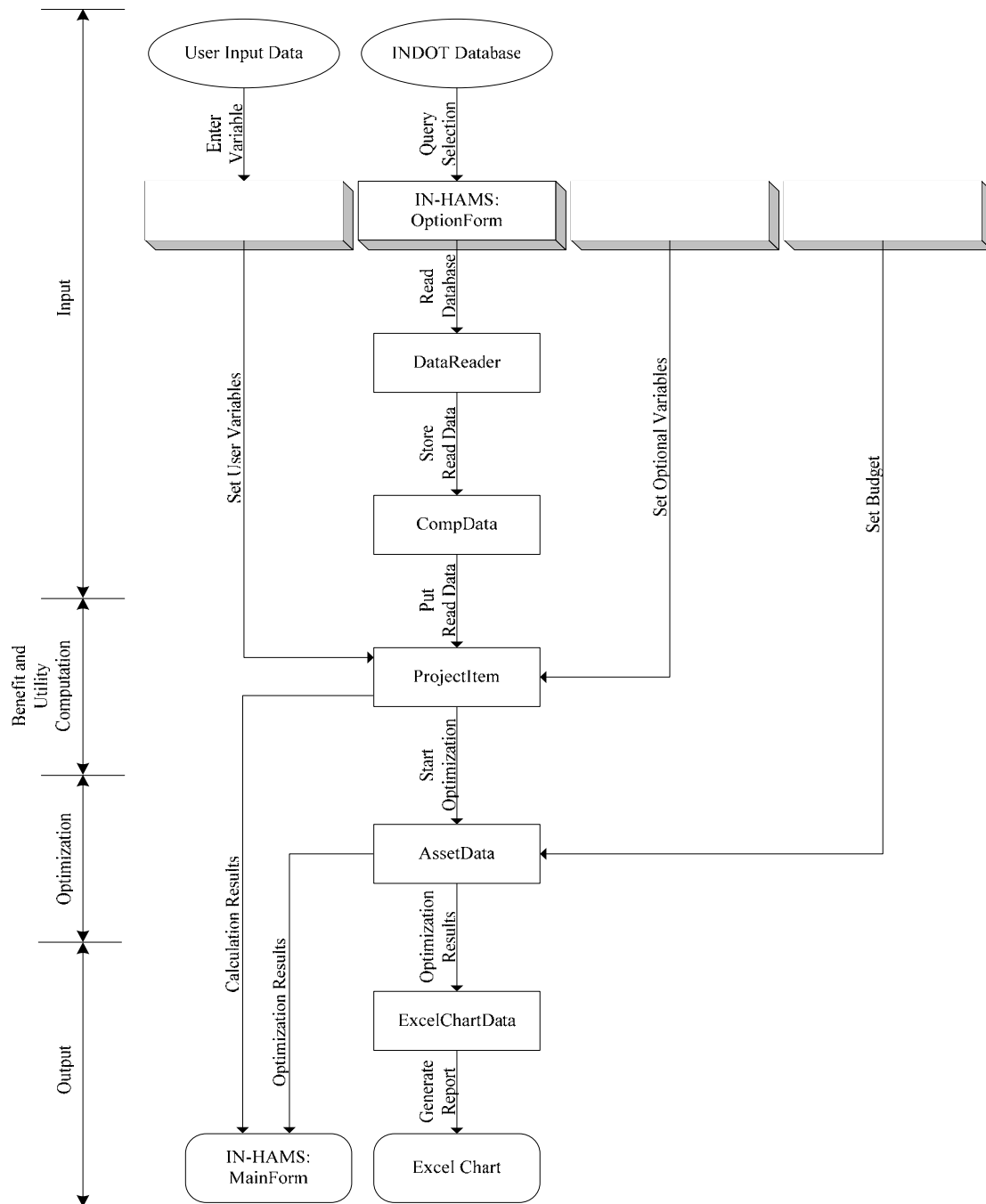


Figure 14: Functional Components of HAMS Software

The data input component reads data from the database according to the project number that is uniquely assigned to each candidate project. Data items contained in the software include: project

let fiscal year, project construction estimate, project length, average daily traffic, number of lanes, project priority, district number, contract number, work category, work type, highway functional classification, transportation system, bridge type, and county code. The data input component consists of “UserInputData” input field, “INDOT Database” input field, “IN-HAMS: OptionForm” form set, “IN-HAMS: AdditionalOptionForm” form set, “IN-HAMS: InputBudgetForm” form set, “UserInputForm” form set and module, “DataReader” module, and “CompData” module.

A total of forty eight highway asset management programs are classified in the software and the computations of project benefits are made separately for each program. The benefits are quantified in two ways. The first type of benefits is the estimated benefits as measured by non-commensurable units under individual asset management system goals. The second type is those benefits after conversion of the estimated benefits under individual system goals into dimensionless units in terms of changes in utility values or in standardized focus gain-over-loss ratios corresponding to tradeoffs under certainty, risk, or uncertainty. The benefit and utility computation component consists of the “ProjectItem” module containing equations for benefit and utility computations.

The project selection and programming tasks are undertaken in the system optimization component of the software. To facilitate examining input data and computed benefit and utility values prior to the optimization process, a printing function was added. As systemwide non-dimensional benefits are quantified independent of project size, they are rescaled according to project size, the cumulative traffic volume that the projects can accommodate during their respective service lives, and the project construction cost.

The output and report generation component of the software deals with generating reports of the optimization results both in tabular and graphic forms. The output information includes the number and budget of the recommended and selected projects or contracts, the fiscal year budget, and the systemwide gain in utility values or standardized focus gain-over-loss ratio values, as well as the benefits under individual asset management system goals. The output and report generation

component consists of “ExcelChartData” module, “IN-HAMS: MainForm” output option, and “Excel Chart” output option.

9.1.2 Case Study Period

According to state highway programming practice in Indiana, the desirable time horizons for short-term and long-term programming are three to five years and seven to ten years, respectively. To facilitate data integrity in the case study, a short-term programming horizon from 1998 to 2001 was chosen. The reason for using historical data on project selection and programming was that the past decision outcomes could be used to verify the reasonableness of the output of the software. Tables 58 and 59 summarize information on the number of candidate projects and annual budgets by category during 1998-2001.

Table 58: Number of Projects Proposed for State Highway Programming in Indiana (1998-2001)

Project Category	1998	1999	2000	2001	Total
Bridge Preservation	128	156	152	138	574
Pavement Preservation	120	94	146	111	471
Safety Improvements	188	187	308	216	899
Roadside Improvements	15	17	28	12	72
Major/New Construction	75	128	235	75	513
Other State Facilities	1	0	0	0	1
ITS Installations	0	12	2	4	18
Miscellaneous	110	100	153	107	470
Total Candidate Projects	637	694	1,024	663	3,018
Total Candidate Contracts	429	412	611	418	1,870

Table 59: Annual Budget for State Highway Programming in Indiana (1998-2001)
(Current dollars, in thousands)

Budget Category	1998	1999	2000	2001	Total
Bridge Preservation	79,900	73,294	62,856	99,312	315,362
Pavement Preservation	277,900	226,925	365,464	242,175	1,112,464
Safety Improvements	43,747	24,667	59,635	53,452	181,501
Roadside Improvements	9,622	7,836	6,404	16,058	39,920
Major/New Construction	190,200	257,106	166,410	389,322	1,003,038
Other State Facilities	2,631	1,677	1,379	5,229	10,916
ITS Installations	4,600	17,889	1,952	2,091	26,532
Miscellaneous	45,391	42,413	52,672	41,089	181,565
Total	653,991	651,807	716,772	848,728	2,871,298

9.2 Case Study Results

9.2.1 Number of Contracts Selected

In the case study, project selection was conducted by contract separately for tradeoff decisions involving certainty, risk, and uncertainty. Figures 15 and 16 present the number of candidate contracts proposed by INDOT and selected by the HAMS software in each year and for all years in total. Of the 429, 412, 611, and 418 contracts proposed respectively in each year for the period 1998-2001, an almost identical number of contracts was selected under the three decision cases.

A higher total number of contracts was selected under the multiyear budget scenario for the entire analysis period, which was not unexpected. All other things being equal, the multiyear budget scenario had fewer constraints in the optimization process, which might yield a better solution. However, as no constraints were imposed for each year under the multiyear budget scenario, the number of projects selected in each year tended to be less balanced as opposed to that of the carryover budget scenario. For instance, for case under uncertainty the number of contracts selected on the basis of multiyear budget scenario was higher than that on the basis of carryover budget scenario for 1999 and 2000 and was lower for 1998 and 2001.

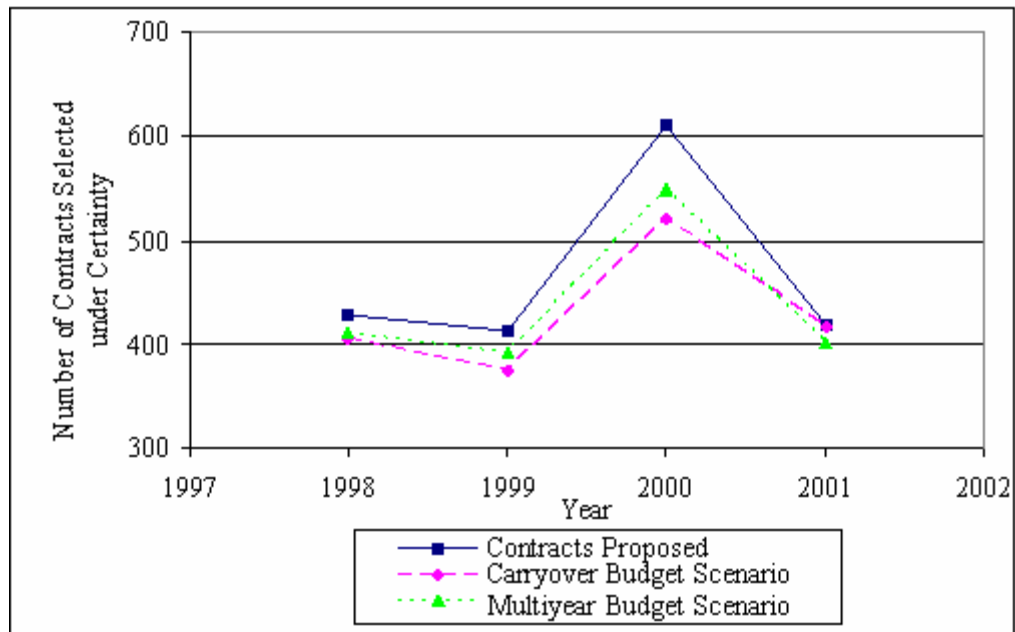


Figure 15(a): Selection under Certainty: Comparison of Contracts Selected by Carryover Budget and Multiyear Budget Scenarios

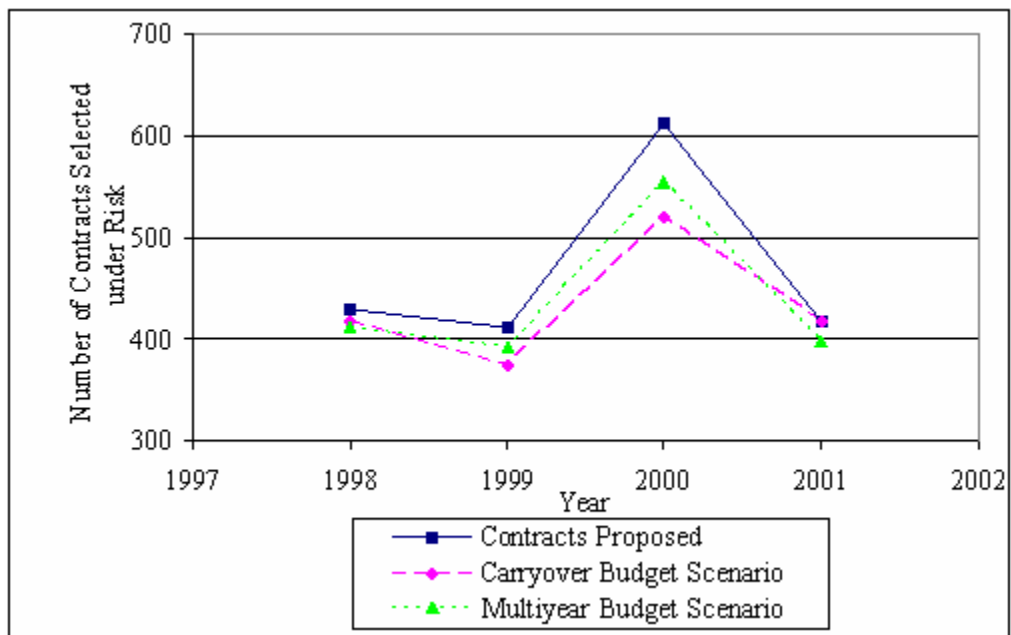


Figure 15(b): Selection under Risk: Comparison of Contracts Selected by Carryover Budget and Multiyear Budget Scenarios

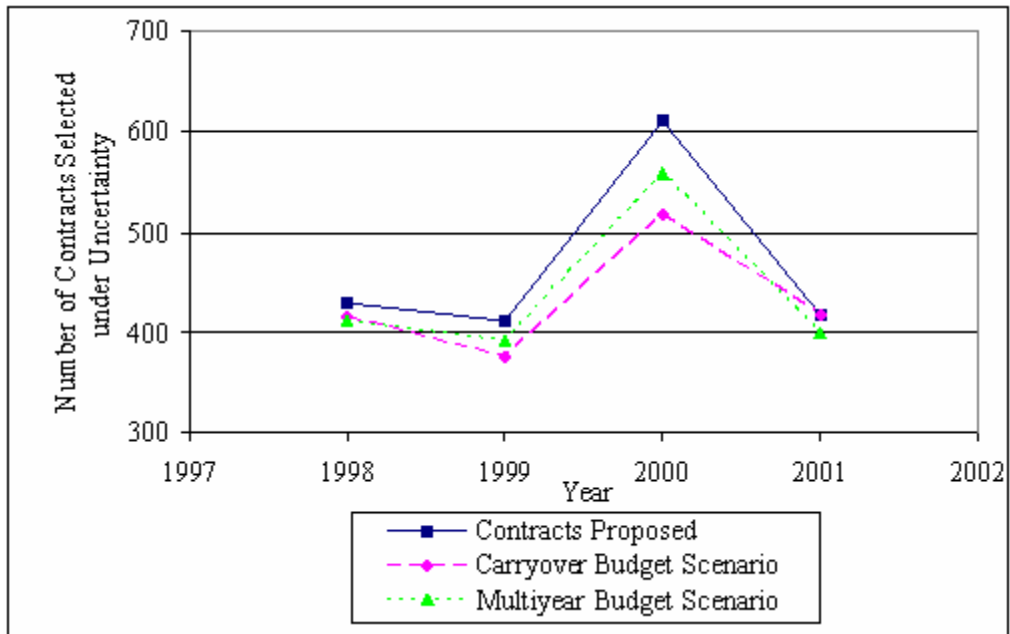


Figure 15(c): Selection under Uncertainty: Comparison of Contracts Selected by Carryover Budget and Multiyear Budget Scenarios

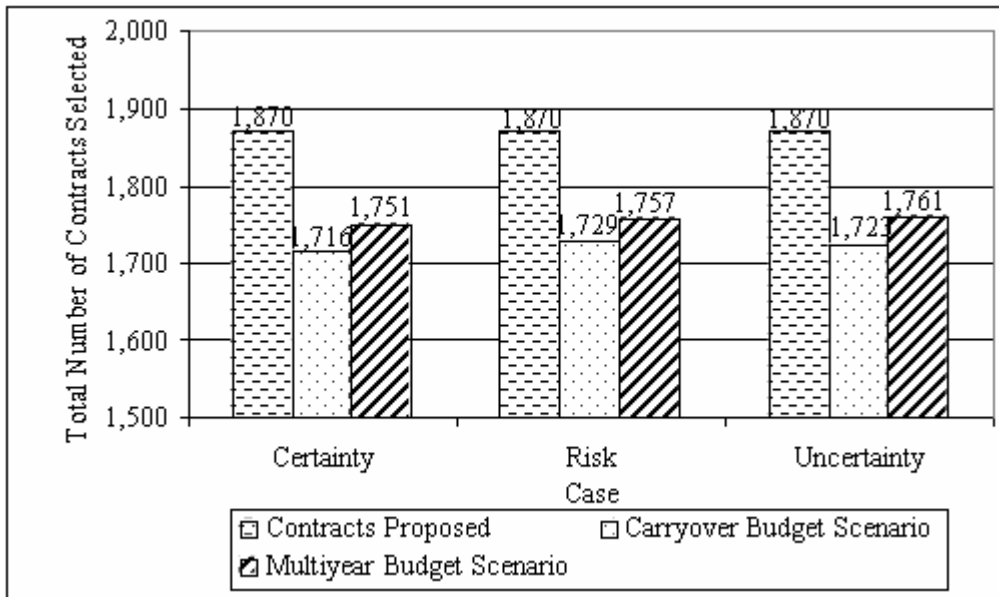


Figure 16: Number of Contracts Proposed by INDOT and Selected under Certainty, Risk, and Uncertainty by Carryover Budget and Multiyear Budget Scenarios

9.2.2 Systemwide Benefits of Selected Contracts

The systemwide benefits of the selected contracts in terms of the gain in system utility or standardized focus gain-over-loss ratio values are shown in Table 60. These values are rescaled utility gains per year from selected contracts in that year as represented by the objective function in Equation (68). It was found that the difference between the quantified benefits for selected contracts under risk and uncertainty was not as much as that between these benefits under certainty and risk or uncertainty. Both the risk and uncertainty cases provided much higher benefits than the certainty case. This might be explained by the fact that the benefits for individual contracts in terms of either expected utility values or standardized gain-over-loss ratio values were slightly higher than those of utility values, leading to a higher total benefits corresponding to all selected contracts.

Comparing the results of the two budget scenarios, the total benefits of all selected contracts based on the multiyear budget scenario were slightly higher than those of the carryover budget scenario, which could also be attributable to having fewer constraints in the optimization process of the multiyear budget scenario.

Table 60: Benefits of Selected Contracts by Carryover Budget and Multiyear Budget Scenarios under Certainty, Risk, and Uncertainty (in Rescaled utility values/year)

Fiscal Year	Case	Carryover Budget Scenario	Multiyear Budget Scenario
1998	Certainty	160	161
	Risk	297	297
	Uncertainty	301	301
1999	Certainty	212	212
	Risk	324	324
	Uncertainty	331	331
2000	Certainty	297	297
	Risk	501	504
	Uncertainty	529	532
2001	Certainty	301	301
	Risk	416	416
	Uncertainty	430	430
Total	Certainty	977	979
	Risk	1,539	1,542
	Uncertainty	1,591	1,594

9.3 Sensitivity Analysis

9.3.1 Sensitivity of Input Budget

After conducting the case study based on the available budget in each fiscal year, a sensitivity analysis was carried out on the basis of two important factors that would affect the outcome of project selection and programming. The first factor was the budget level in each fiscal year and the second factor was the relative weights of the agency and the user decision groups.

The sensitivity analysis for budget level was done by changing the fiscal year budget in increments up to ± 20 percent. The impact of changes in the budget on the number of contracts selected for cases under certainty, risk, or uncertainty was evaluated. Figure 17 presents the results of the budget sensitivity analysis with two budget scenarios. The results were quite intuitive as the total number of contracts selected increased as a result of a higher budget level. This was true for both the carryover budget scenario and the multiyear budget scenario, however, both increased in a diminishing rate as the budget was increased. For the same reason stated earlier, the multiyear budget scenario yielded better results.

In the case of the number of contracts selected for tradeoff decisions under certainty, risk, and uncertainty, there was an obvious gap when the budget level was decreased from the original level, which was due to the fact that for relatively large-scale contracts in the candidate list, removal of the entire contracts from the selection list was necessary when the budget level was reduced. The same was true for the situation of higher budget levels so that only when the added budget reached a certain level could new contracts be added.

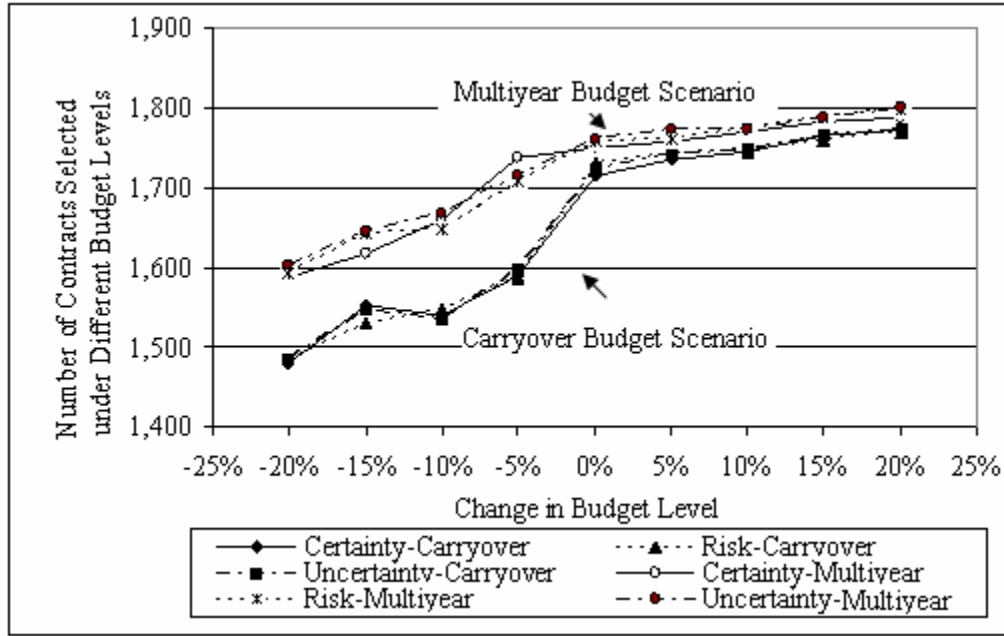


Figure 17: Results of Budget Sensitivity in Programming

9.3.2 Weight Sensitivity

In the case study, equal weights were given to the agency and user groups. A series of tests were conducted with various combinations of the relative weights of the two decision groups to assess the impact of these weights on the program output. The weight sensitivity analysis was also carried out under certainty, risk, and uncertainty, and the results are illustrated in Figure 18. As indicated in the figure, changes in the relative weights between the agency and user groups did not significantly affect the number of contracts selected. However, the specific contracts selected can differ significantly due to a change in relative weights.

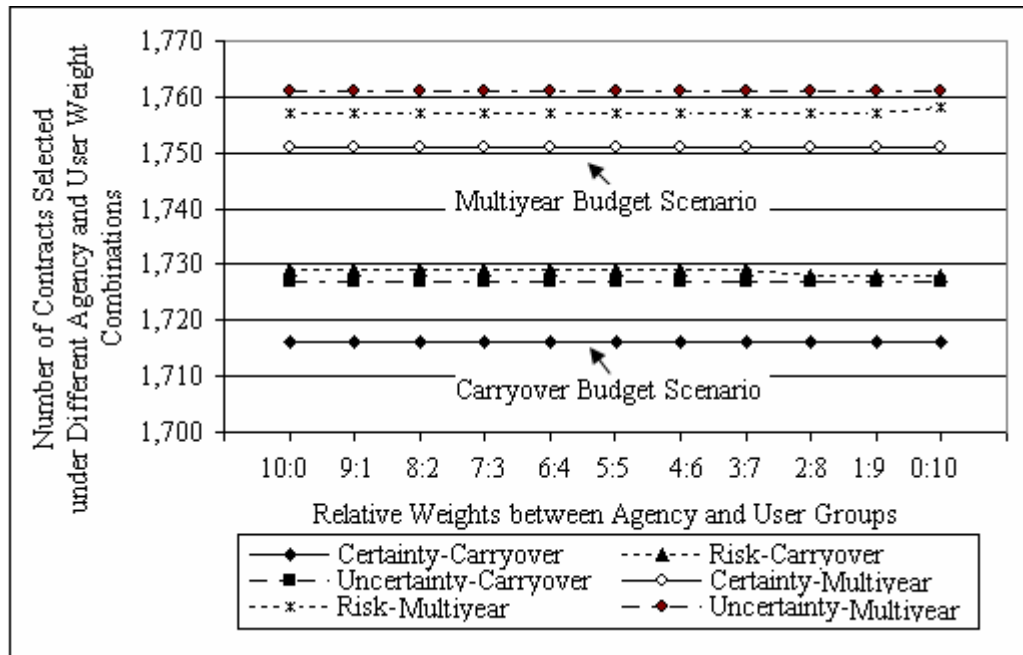


Figure 18: Results of Weight Sensitivity in Programming

9.4 Comparison of Case Study Results with Current Practice

One of the key reasons for the case study using the HAMS software was to compare the output from the software with state highway programming practice in Indiana. Comparisons of the results of the HAMS software based on the two budget scenarios with state highway programs in Indiana were thus made. The performance measure used was the consistency of the total number of contracts selected by both the software and by those actually programmed. As seen in Table 61, there is very good consistency between the HAMS output and the actual highway programs in Indiana. For tradeoffs under certainty, risk, and uncertainty, the consistency matching rates were at a minimum of 85 percent and 90 percent respectively for the carryover budget and the multiyear budget scenarios during the period 1998-2001.

Table 61: Number of Contracts Proposed and Both Authorized and Selected by the HAMS Software

Fiscal Year	Contracts Proposed	Contracts Programmed	Same Contracts Selected by HAMS Package				
			Case	Carryover Budget	% Match	Multiyear Budget	% Match
1998	429	152	Certainty	139	91%	142	93%
			Risk	143	94%	142	93%
			Uncertainty	142	93%	142	93%
1999	412	323	Certainty	292	90%	305	94%
			Risk	293	91%	306	95%
			Uncertainty	292	90%	302	93%
2000	611	583	Certainty	496	85%	524	90%
			Risk	496	85%	530	91%
			Uncertainty	497	85%	535	92%
2001	418	414	Certainty	413	100%	397	96%
			Risk	413	100%	395	95%
			Uncertainty	413	100%	397	96%
Total	1,870	1,472	Certainty	1,340	91%	1,368	93%
			Risk	1,345	91%	1,373	93%
			Uncertainty	1,344	91%	1,376	93%

9.5 Discussions

The case study results revealed that project selection was sensitive to the budget level for a given analysis period. However, the relative weights of the agency and user decision groups appeared to be not as significant, which suggested that the agency and the user maintained consistent perceptions on asset management system goals. All things being equal, the multiyear budget scenario selected a higher number of contracts and thus yielded slightly better system benefits than those from the carryover budget scenario. However, the distribution of the total number of contracts selected and the system benefits in each fiscal year associated with the multiyear budget scenario were less balanced.

9.6 Chapter Summary

This chapter first provided a brief description of the HAMS software that can be used for state highway project selection and programming. In order to validate the tradeoff analysis findings, as well as the system optimization model along with the solution algorithm, a case study was carried out using the information of past candidate projects for state highway programming in Indiana. A sensitivity analysis was further conducted on the basis of two factors, the budget level and the relative weights of the agency and user decision groups. Cross comparisons of the HAMS software outputs with actual state highway programs practice in Indiana were also made. For the case study, the sensitivity analysis, and result comparisons, tradeoff decisions were made separately under certainty, risk, and uncertainty using two budget scenarios, carryover and multiyear. The findings demonstrated that the HAMS software provided reliable results and it could indeed be used by for state highway programming and management.

CHAPTER 10 CONCLUSIONS

10.1 Summary and Findings

In the present study, a methodology was proposed for highway asset management that embraced the top-level agency functions of asset valuation, performance modeling, marginal benefit analysis, and multicriteria decision-making. Models were developed to predict the performance of physical highway assets, including pavements and bridges, and usage of the highway network. For pavements, the models were calibrated based on rehabilitation expenditure, routine maintenance expenditure, and the tradeoff relationship between the level of routine maintenance and the rehabilitation interval at various levels of traffic loading and weather conditions. For bridges, the models were developed based on the bridge wearing surface condition, structural condition, and bridge life cycle user cost. Regarding network-level usage performance, user cost models were calibrated separately for individual user cost components that included vehicle operating cost, travel time, vehicle collisions, and vehicle air pollution per vehicle mile of travel, as well as total highway user cost per vehicle mile of travel. For the pavement expenditure models, the variables found significant were the pavement surface condition, traffic loading, thickness, freeze-thaw cycles, ambient temperature, and pavement age. The variables found significant to bridge performance mainly included traffic volume, bridge age, and superstructure type. For the network-level highway user cost models, the significant variables were the road surface condition and the vehicle traveling speed.

The marginal effects of significant variables affecting asset condition, service life, and agency cost, as well as the network-level highway user cost, were established on the basis of the calibrated models. The marginal benefits were then determined accordingly. Marginal benefit analysis was

specifically carried out for pavement and bridge-related projects and the individual user cost components based on the concept of life-cycle cost analysis.

The multicriteria decision-making process for highway asset management included a tradeoff analysis and project selection and programming. A tradeoff analysis was done for cases under certainty, risk and uncertainty as follows. First, a set of asset management system goals and performance indicators were classified. The relative weights of system goals and multiple performance indicators under individual system goals were then established. For cases of certainty and risk, a utility theory was employed to establish systemwide multiattribute utility functions on the basis of single attribute utility functions developed for various performance indicators. The systemwide utility functions were utilized to establish a non-dimensional value for the benefits associated with a candidate project. As the utility theory is not directly applicable to situations involving uncertainty, an alternative approach based on Shackle's model was employed. In particular, the degree of surprise functions and priority functions were established to develop systemwide standardized focus gain-over-loss ratio functions, which formed the basis of prioritizing candidate projects under uncertainty. A series of questionnaire surveys were conducted to establish relative weights, single attribute utility functions, degree of surprise functions, and priority functions. For the questionnaire surveys, two decision groups and two separate survey approaches were used to assess the robustness of the results. The two decision groups included the agency group and the user group, and the two survey approaches used were the direct questioning approach and the certainty equivalency approach. It was found that the utility functions and standardized focus gain-over-loss ratio functions were not statistically different by decision group or by approach, and it should be noted that the non-dimensional benefits in terms of changes in utility values or standardized gain-over-loss ratio values were independent of project size. These values were rescaled according to the expected traffic during the project life and the construction cost, as well as the number of projects involved in a specific contract prior to the system optimization process. By making such adjustments, it ensured tradeoffs between projects to be conducted equitably. Project selection and programming were conducted

separately using the results of tradeoffs under certainty, risk, and uncertainty. A system optimization model was formulated on the basis of the MCMDKP problem, and a heuristic algorithm based on Lagrangian relaxation techniques was prepared for system optimization using two budget scenarios, annual budget with carryover and multiyear budget.

A Highway Asset Management System software was developed on the basis of the findings of the tradeoff analysis and the system optimization model, as well as the solution algorithm developed. In order to validate the research findings, a case study was carried out for project selection and programming using information on past candidate projects in state highway programs in Indiana. In addition, a sensitivity analysis was also conducted on two factors, the budget level and the relative weights of the agency and the user decision groups. The case study results generated from the HAMS software were then compared with actual state highway programs in Indiana. The comparison revealed that, for tradeoff decisions involving certainty, risk, or uncertainty under both budget scenarios, the consistency matching rate for candidate contracts selected both by the software and by actual highway programs was 85 percent at minimum.

10.2 Implementation Issues

The products of this research are as follows:

- Models to predict the performance of physical highway assets
- Models to estimate network-level highway user cost
- Methodology that can be used by top-level management in INDOT to do tradeoff analysis incorporating risk and uncertainty
- A software package to facilitate implementation of the research findings of present study.

When properly implemented by INDOT top-level management, it is expected that the results of the present study will provide a reliable and objective basis upon which highway investment

decisions can be made. Implementation of the study findings will result in obtaining maximum return from each dollar of investment, and overall savings to the state of Indiana in the long run, without needlessly sacrificing asset performance. It is therefore expected that the implementation of the results will result in changes in state-level highway programming.

Tools to facilitate implementation of the results of this research include training of top-level personnel and organization of workshops to demonstrate the project selection and programming methodology and the investigation of tradeoffs and marginal effects. Possible impediments to successful implementation of the product of the study include inconsistency of inter-agency terminology, peculiar nature of budgeting procedures, and the fact that some management systems have not been fully implemented. However, with close cooperation between concerned parties, improved public relations, and learning from the experiences of agencies that have experimented with implementing different asset management policies, the impact of such barriers to implementation of the study findings can be reduced.

10.3 Directions for Future Research

Asset management is an improved way of overall highway system management that responds to an environment of increasing system demands, aging physical highway assets, and limited resources. One of the major contributions of the present research is that it has incorporated asset usage performance into the overall decision-making framework. Furthermore, tradeoff analysis methods have been introduced to enable tradeoff scenarios being made not only within a specific asset category, but also across various physical highway assets, thereby making the decision-making process rational, objective, and holistic. The issue of uncertainty, which is commonly encountered in highway investment decision process, is also successfully addressed in the research. The asset management system software developed has proven to be a reliable analytical tool to conduct statewide highway asset management decisions. Since the condition and performance of the highway

system change over time, however, it is desirable to refine the research findings so that decision-making in the future can always be attuned to the current situation of the system. In addition, a large part of the research findings for tradeoff analysis was established on the basis of questionnaire surveys, and to some extent, subjective information was acquired based on relatively small sample sizes. A refinement process may be needed, therefore, as a larger number of survey participants becomes available. Finally, it may be worthwhile to explore a new approach that can bridge inconsistencies between the utility theory used for certainty and risk and Shackle's model used for uncertainty.

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Appendix A
Project Coding Systems Used within Indiana Department of Transportation and Definition of Project
Types Classified for Highway Asst Management

Appendix A1

Summary of Project Coding Systems Used within Indiana Department of Transportation

Designation	Long Range Plan Code (LRP)		Budgetary Code (BC)		Program Management Groups Code (PMG)		Engineering Code (EC)		
	LRP Category	LRP Improvement Type	Budgetary Category	Category of Work	PMG Category	PMG Project Type	EC at Planning Level	EC at Pre-Engineering Level	
Bridge Preservation Program	-	-	BC-A000: Bridge preservation program	BC-A100: Bridge rehabilitation	PMG-A000: Bridges	PMG-A100: Bridge rehabilitation	EC-C000: Bridge rehabilitation or repair	EC-C100: Bridge deck reconstruction EC-C200: Bridge widening EC-C300: Replace superstructure EC-C400: Raise bridge/lower pave EC-C500: Bridge painting EC-C600: Superstructure repair and rehab EC-C700: Bridge maintenance and repair EC-C800: Bridge channel correction	
		-		BC-A200: Bridge replacement BC-A300: Emergency bridge BC-A400: Bridge removal		PMG-A200: Bridge replacement		EC-E000: Bridge replacement	EC-E100: Bridge replacement, steel EC-E200: Bridge replace, concrete EC-E300: Bridge replace, other construction
		-		-		PMG-G000: Historic bridges		PMG-G100: Historic bridge preservation	-
Pavement Preservation	LRP-J000: Rehabilitation	-	BC-E000: Pavement preservation	BC-E100: Resurfacing	PMG-P000: Non-Interstate (part 1) PMG-J000: Interstate (part 1)	PMG-P100: NIS resurfacing PMG-J100: IS resurfacing	EC-J000: Pavement repair or rehabilitation	EC-J100: Patch and rehab pavement EC-J200: Resurfacing (non 3R/4R stands) EC-J300: Pavement rehab (3R/4R stands) EC-J400: Wedge and level only EC-J600: Shoulder rehab and repair	
		LRP-J100: Pavement rehabilitation		BC-E500: IS rehabilitation BC-E400: Emergency road projects	PMG-P000: Non-Interstate (part 2) PMG-J000: Interstate (part 2)	PMG-P210: NIS rehabilitation PMG-J210: IS rehabilitation			
	LRP-I000: Reconstruction	LRP-I100: Pavement reconstruction		BC-E200: Road reconstruct (NIS) BC-E300: Road replacement (NIS) BC-E600: Road reconstruction (IS) BC-E700: Road replacement (IS)	PMG-P000: Non-Interstate (part 3) PMG-J000: Interstate (part 3)	PMG-P220: NIS reconstruction PMG-P230: NIS replacement PMG-J220: IS reconstruction PMG-J230: IS replacement	EC-L000: Pavement replacement	EC-L100: Pavement replace, concrete EC-L200: Pavement replace, asphalt	
Safety Improvement Program	LRP-K000: Transport system management	LRP-K100: Intersection improvements	BC-G000: Safety improvement program	BC-G100: Intersection improvements	PMG-I000: Intersections	PMG-I100: Intersection improvements	EC-P000: Intersection improvement	EC-P100: Intersection improvements	
		-		BC-G200: Railroad crossings	PMG-R000: Railroad crossings	PMG-R100: Railroad crossings	EC-X000: Other project type	EC-X200: Railroad work	
	LRP-E100: Median construction	BC-G300: Guardrail improvements		PMG-U000: Safety	PMG-U100: Guardrails	EC-T000: Guardrail work	EC-T100: Install new guardrail EC-T200: Guardrail, maintenance or repair EC-T300: Guardrail attenuators, new or mod EC-T400: Barrier wall EC-T500: Median construction		
	-	BC-G400: Sight distance improvements			PMG-U200: Sight distance	EC-J000: Pavement repair or rehabilitation	EC-J500: Sight distance improvement		
	-	BC-G800: Lighting			PMG-U500: Lighting	EC-V000: Signs, lighting, signals, markings, and ITS (part 1)	EC-V100: Lighting		
	-	BC-G700: Signs		PMG-U400: Signs	PMG-U300: Pavement markings	EC-V200: Signing	EC-V400: Pavement markings		
	-	BC-G500: Pavement markings		PMG-X000: Traffic signals	PMG-X100: Traffic signals	EC-V300: Traffic signals EC-V500: Traffic hardware modernization EC-V600: Traffic, other	EC-V300: Traffic signals EC-V500: Traffic hardware modernization EC-V600: Traffic, other		
	-	BC-G600: Traffic signals		PMG-T000: Roadside improvements	PMG-T100: Landscaping/ wildflower program	EC-N000: Roadside work	EC-N510: Enhancements EC-N520: Environmental mitigation EC-N530: other roadside maintenance EC-N540: Landscaping EC-N100: Roadside maintenance EC-N200: Slide correction		
-	BC-F400: Erosion/landslide control	PMG-T300: Erosion/ landslide control							
Roadside Improvement Program	LRP-L000: Transportation system management	LRP-L100: Transportation operational improvements	BC-F000: Roadside improvement program	BC-F100: Transportation enhancements	PMG-D000: Enhancements	PMG-D100: Bicycles/ pedestrians PMG-D200: Other transport enhance	EC-W000: Small structures and drains construction	EC-N310: Weigh station const/recon	
		LRP-L200: One-way pairs		BC-F200: Environmental mitigation	PMG-Z000: Weigh stations/rest areas modernization or new	PMG-Z100: Weigh station modern PMG-Z200: New weigh station PMG-Z300: Rest area modern PMG-Z400: New rest area		EC-W100: Small structure, replacement	
		LRP-L300: Turn lanes		BC-F300: Landscaping	PMG-V000: Small structures/drainages	PMG-V100: Small structure replacement		EC-W200: Drainage ditch correction EC-W300: Sewer, curb, gutter construction	
		LRP-L400: By pass		BC-F400: Erosion/landslide control		PMG-V200: Drain problem correction			
		LRP-L500: Access control		BC-F500: Access control	PMG-T400: Access control				
		-		BC-F600: Weigh station modern BC-C600: New weigh station					
		-		BC-F700: Rest area modern BC-C700: New rest area					
		-		BC-F800: Small structure replacement					
-	BC-F900: Drain problem correction								

Appendix A1
Summary of Project Coding Systems Used within Indiana Department of Transportation (Continued)

Designation	Long Range Plan Code (LRP)		Budgetary Code (BC)		Program Management Groups Code (PMG)		Engineering Code (EC)	
	LRP Category	LRP Improvement Type	Budgetary Category	Category of Work	PMG Category	PMG Project Type	EC at Planning Level	EC at Pre-Engineering Level
Major/New Construction Program	LRP-H000: New road construction	LRP-H100: New road construction	BC-C000: Major/new construction program	BC-C100: New road construction BC-C200: Completion of IS	PMG-E000: Expansion	PMG-E100: New road construction	EC-G000: Road construction	EC-G100: New road, grading only EC-G200: New road, paving only EC-G300: New road construction
	LRP-A000: Added travel lanes LRP-B000: Freeway update (part 1)	LRP-H100: Added travel lanes LRP-B100: Freeway construct LRP-B200: Added travel lane on freeways		BC-C300: Added travel lanes		PMG-E200: Added travel lanes		EC-G400: Added travel lanes EC-G500: Dual lane existing route EC-G600: Auxiliary lanes
	LRP-F000: New bridge construction	LRP-F100: New bridge construction		-		-	EC-A000: New bridge construction	EC-A100: New bridge, steel construction EC-A200: New bridge, concrete construct EC-A300: New bridge, other construction EC-A400: New bridge, special
	LRP-G000: New interchange construction	LRP-G100: New interchange construction		BC-C400: New interchange construction		PMG-E300: New interchange construct	EC-R000: Interchange work	EC-R100: New interchange construction
	LRP-C000: Interchange modifications	LRP-C100: Interchange modifications		BC-C500: Interchange modifications		PMG-E400: Interchange modifications		EC-R200: Interchange modifications
	LRP-D000: Interstate interchanges	LRP-D100: IS interchange modifications LRP-D200: IS interchange construction		-		-		-
	LRP-B000: Freeway update (part 2)	LRP-B300: New freeway interchange construction LRP-B400: New freeway GS construction		-		-	-	-
Other State Facilities Program	-	-	BC-D000: Park facilities program	BC-D100: Park roads	PMG-C000: DNR Facilities (part 1) PMG-F000: Forest land highways PMG-Q000: Other state inst (part 1)	PMG-C100: Park roads PMG-F100: Forest land highways PMG-Q100: Institution roads	-	EC-J700: Pavement, other
	-	-		BC-D200: Park bridges	PMG-C000: DNR Facilities (part 2) PMG-Q000: Other state inst (part 2)	PMG-C200: Park bridges PMG-Q200: Institution bridges		EC-E400: Bridge replacement, special
	-	-		BC-D300: Cooperative access projects	PMG-C000: DNR Facilities (part 3) PMG-Q000: Other state inst (part 3)	PMG-C300: Cooperative access projects PMG-Q300: Other projects		-
Intelligent Transportation Systems Program	-	-	BC-B000: ITS program	BC-B100: ITS traveler info systems	PMG-H000: Intelligent transportation systems (ITS)	PMG-H100: ITS traveler info systems	EC-V000: Signs, lighting, signals, markings, and ITS (part 2)	EC-V710: ITS traveler info systems
	-	-		BC-B200: ITS management systems		PMG-H200: ITS management systems		EC-V720: ITS management systems
	-	-		BC-B300: ITS monitoring systems		PMG-H300: ITS monitoring systems		EC-V730: ITS monitoring systems
	-	-		BC-B400: ITS operations and maintenance		PMG-H400: ITS operations and maintenance		EC-V750: ITS operations and maintenance
Miscellaneous	LRP-M000: Undetermined	LRP-M100: Undetermined	BC-H000: Unprogrammed/projected	-	PMG-K000: Local bridge inspections	PMG-K100: Local bridge inspections	EC-X000: Other project type	EC-X300: Bridge inspections
				BC-H400: CMAQ projects BC-H300: Toll road	PMG-B000: Command and control category	PMG-B100: CMAQ projects PMG-B200: Bonding projects PMG-B300: Bridge "watch list" PMG-B400: Shelf projects PMG-B500: Suspended projects PMG-B600: other command projects		
				-	PMG-L000: LPA (local) program	PMG-L100: State administered Federal aid projects		
				BC-H100: Traffic maintenance BC-H200: Maintenance	PMG-M000: Maintenance	PMG-M100: Routine maintenance PMG-M200: Periodic maintenance		
				-	PMG-N000: Multi-modal	PMG-N100: Inter-modal mgmt projects PMG-N200: Inter-modal connectors PMG-N300: Airport facilities		
				-		PMG-N400: Passenger rail PMG-N500: Railroad corridor preservation PMG-N600: Railroad right-of-way preservation PMG-N700: Railroad track preservation PMG-N800: Transit facilities		
				-		PMG-O000: Noise abatement		PMG-O100: Noise abatement projects
				-		PMG-S000: Relinquishments		PMG-S100: Transfer of route from State to local jurisdiction
				BC-H500: Feasibility/corridor studies	PMG-W000: Studies	PMG-W100: Feasibility/corridor studies		EC-X413: Relinquishments
				-	PMG-Y000: Utilities	PMG-Y100: Utility relocation		-
				-	-	-		EC-X000: Other project type EC-X111: Bridge removal EC-X112: Demolition, remove bld foundation EC-X113: Remove bridge abutments EC-X411: Protective buying EC-X414: Utility relocation

Appendix A2
Definition of Project Types Classified for Highway Asst Management

1. Access Control: Expenditures preserved to places where efficient movement of through traffic is desired by acquiring the adjacent property's access rights and regulating the number of access points to the highways. This strategy will not only increase the free and efficient movement of through traffic, but also reduce highway accidents by minimizing the number of conflict points or entrances located along the highways.
2. Added Travel Lane: Construction of additional travel or through lanes to existing roadways for increased capacity to obtain a more efficient and safer facility. The existing pavement is usually reconstructed at the same time.
3. Bicycles/Pedestrians: Non-motorized projects aimed at providing bicycling or walking facilities to assist concerns of traffic congestion, exhaust-pipe pollution, unsightly roadsides, and unceasing traffic noise.
4. (Pre-committed) Bonding Projects: Projects implemented with partial funding through a bond issuance and the remaining cost with INDOT pre-committed matching funds.
5. Bridge Rehabilitation: Bridge rehabilitation involves major work required to restore the structural integrity of a bridge as well as work necessary to correct its major safety defects.
6. Bridge Replacement: It refers to total replacement of a structurally deficient or functionally obsolete bridge with a new facility constructed in the same general traffic corridor, resulting in increased capacity and safety.
7. Bridge "Watch List": Specific bridge projects that for some reason (such as safety concerns) must be implemented.
8. Congestion Mitigation & Air Quality Improvement Program (CMAQ): This program directs funds toward transportation improvements on traffic flow, demand management, transit, and non-motorized transportation in clean air non-attainment areas for ozone and carbon monoxide. These projects will contribute to meeting the attainment of the National Ambient Air Quality Standards (NAAQS).
9. Cooperative Access Projects: INDOT involved public transportation projects aimed at providing additional opportunities for access to employment, medical, social service and educational facilities for residents reliant on public transportation and outside the fixed route transit service areas.
10. Environmental Mitigation/Improvements: Alternative projects like transit and transportation enhancement projects implemented to avoid, minimize, or mitigate environmental impacts.
11. Erosion/landslide control: Projects implemented during construction, and operation, and maintenance stages to protect unstable soil along the side of highway embankment by control strategies like side slope vegetation, upper slope stabilization, and other feasible methods.
12. Feasibility / Corridor Studies: Studies that involve feasibility and corridor design of highway projects.
13. Forestland Highways: Highway projects implemented at forestlands.

Appendix A2

Definition of Project Types Classified for Highway Asst Management (Continued)

14. **Guardrail Improvements:** These improvements consist of maintenance, repairs, and rehabilitation of guardrails. Eligible projects include but not limit to installation of new guardrails, cleaning, painting, and repair of existing guardrails, guardrail attenuator installation or modernization.
15. **Historic Bridge Preservation:** Program mainly using Federal funds either to preserve the existing historic bridges when the future traffic conditions are met or to build alternative alignments or new bridges on the existing structure alignments when the future traffic conditions could not be satisfied.
16. **Institution Roads/ Bridges/ Other Projects:** INDOT sponsored roads, bridges and other projects at State institutions, such as roads and bridges at Purdue and Indiana University campuses.
17. **Interchange Modifications:** Construction of improvements to an interchange, ranging from ramp terminal improvements, eliminating two-way ramps, or adding lanes to ramps to replace existing movements with loop ramps or directional ramps.
18. **Inter-Modal Management Systems/ Connectors/ Airport / Passenger Rail/ Transit Facilities:** The multi-modal transportation management systems, connectors and facilities provide travelers with alternatives to serve regional communities and to connect local state to other states and other part of the world.
19. **Intersection Improvements:** Improvements result in a reduction in overall peak hour congestion that provide the most efficient use of existing and future transportation facilities where congestion is occurring or is expected to occur.
20. **ITS Incident Management Systems:** The ITS freeway incident management systems (Hoosier Helpers, Lane Merge system) can assist motorists and clear incidents from the roadway.
21. **ITS Operations and Maintenance:** These refer to toll road operation centers and maintenance related to ITS infrastructures.
22. **ITS Traffic Surveillance and Monitoring Systems:** The ITS traffic surveillance and monitoring systems (trafficwise) use computerized sensors and video cameras to quickly detect highway congestion and to determine reasons for it.
23. **ITS Traveler Information Systems:** The ITS traveler information systems, through Highway Advisory Radio (HAR), Variable Message Signs (VMS), Pagers, are capable of providing real-time traffic information to the traveling public.
24. **Landscaping/ Wildflower Program:** Program mainly deals with safety of drivers, walkers and horseback riders while preserving roadway area's character and scenic beauty.
25. **Lighting Improvements:** These improvements involve provision of continuous freeway lighting, partial lighting of interchanges on unlighted freeways, and lighting of other streets and highways. These improvement projects are identified on the basis of average daily traffic, ratio of night to day crashes, local government participation in the cost, and other factors.

Appendix A2
Definition of Project Types Classified for Highway Asst Management (Continued)

26. Local Bridge Inspections: Activities involved in the inspection of bridges at county, city or township levels.
27. New Interchange Construction: Construction of a new interchange as an improvement to an existing roadway, generally to decrease congestion and to improve safety.
28. New Rest Areas: Provision of new rest areas to facilitate the change of driver's hours-of-service with adequate rest, and ultimately improve driving safety.
29. New Road Construction: Construction of a new or relocated roadway, mostly or completely on a new alignment.
30. New Weigh Stations: Provision of new weigh stations to regulate truck weight limits, and ultimately improve roadway safety.
31. Noise Abatement: Federal-aid highway projects that aimed at reducing impacts of traffic noise upon their implementation.
32. Non-Interstate/ Interstate Reconstruction: Projects that resurface, restore, rehabilitate, and reconstruct the existing pavement (4R) and that typically involves a major change to an existing Interstate or Non-Interstate highway within the same general right-of-way corridor. Reconstruction may also involve making substantial modifications to an older highway's horizontal and vertical alignment in order to eliminate safety and accident problems.
33. Non-Interstate/ Interstate Rehabilitation: Projects that resurface, restore, and rehabilitate the existing Interstate or Non-Interstate highway pavements (3R) and that focus primarily on the preservation and extension of the service life of existing facilities and on safety enhancements. The rehabilitation projects mainly include wider travel lanes, wider shoulders, sight distance improvements, etc.
34. Non-Interstate/ Interstate Replacement: Activities involve the construction of a new Interstate or Non-Interstate highway facility mostly on the existing highway alignment.
35. Non-Interstate/ Interstate Resurfacing: A type of transportation improvements to Non-Interstate highway pavements that preserve the existing facilities not up to rehabilitation (3R) or reconstruction (4R) standards.
36. Other Command Guidance Projects: Priority projects (other than bridge "watch list", bonding, etc.) That under certain command guidance must stay on schedule.
37. Park Roads/ Bridges: Highway and bridge projects implemented in parks under the jurisdiction of Department of Natural Resources.
38. Passenger Rail: The portion of main-line railroad transportation operations that encompass passenger train service for local short-distance travel between a central city and adjacent suburbs. Intercity passenger rail service in Indiana is presently provided by Amtrak. The INDOT sponsored Midwest Regional Rail study is an ongoing effort to develop an expanded and improved passenger rail operation in the Midwest to shorten travel times, increase frequency of service, accessibility and reliability.

Appendix A2

Definition of Project Types Classified for Highway Asst Management (Continued)

39. Pavement Markings: Pavement markings are delineators to assist driver's travel along the carriageways or to separate movements at intersections, merge and diverge areas, weaving sections, and turning lanes.
40. Periodic Maintenance: A higher level of work undertaken at longer intervals of asset service life, as compared to routine maintenance, that has greater degree of impact on asset condition preservation.
41. Railroad Corridor/ Right-of-Way/ Track Preservation: Program to provide funds for railroad corridor and Right-of-Way preservation as well as maintenance and rehabilitation of rail tracks in Indiana to ultimately improve public safety.
42. Railroad Crossing Projects: Projects that aim at improving safety at railroad crossings. Eligible projects are crossing surface rehabilitation, flashing light signals, crossing closure assistance, separations, and/or other lighting or signing improvements.
43. Rest Area Modernization: Projects mainly focus on the modernization of existing rest areas to ensure that drivers have adequate rest to drive safely.
44. Routine Maintenance: Typically, routine maintenance activities consist of those actions necessary to keep an existing highway facility, such as pavements and bridges, in good condition. Major routine maintenance activities include repainting lane and edge lines, removing accumulated debris from drainage inlets, repairing surface drainage features, mowing, and removing snow, etc.
45. Shelf Projects: Projects that are ready to go but reserved for future implementation due to budget shortage.
46. Sight Distance Improvements: These highway improvements mainly focus on upgrading vertical and horizontal curve radius, enhancing super-elevation, and widening roadway to facilitate safer and more efficient operations of passing vehicle operations in the area.
47. Small Structure Replacement/ Drainage Problem Correction: Projects that are related to replacement of small highway structures, such as culverts, or correction of existing drainage problems.
48. State Administered Federal Aid Projects: Projects under Local Public Agencies (LPA), including State, municipalities, and other political subdivisions like public corporation boards, and commissions established under law. Typical projects under LPA program are State administered Federal aid projects to cities, counties, and towns.
49. Suspended Projects: Projects that are suspended or delayed due to external restrictions to their implementation, such as delay in acquisition of right-of-way.
50. Traffic Signals: Traffic control devices that, by means of changing colored lights, regulate the movement of traffic. Most traffic signals are designed to respond to traffic and pedestrian demand rather than follow a fixed allocation of time for each traffic movement.

Appendix A2

Definition of Project Types Classified for Highway Asst Management (Continued)

51. **Traffic Signs:** Traffic control installations to provide regulatory, warning, and guiding traffic. Regulatory signs mainly assign right-of-way, post speed limits, restrict parking, and allow pedestrian movements. Warning signs are used for curves, no passing zones, T- or Y-intersections, merging lanes, one-lane bridges, and steep grades. Guiding signs are usually used as route markers as well as providing destination and distance information to travelers.
52. **Transfer of Route from State to Local Jurisdiction:** Relinquishments of route from State to local jurisdiction.
53. **Transportation Enhancements:** Transportation-related activities that are designed to strengthen the cultural, aesthetic, and environmental aspects of the Nation's inter-modal transportation system. The transportation enhancement activities include:
 - Pedestrian and bicycle facilities
 - Pedestrian and bicycle safety and education activities
 - Acquisition of scenic or historic easements and sites
 - Scenic or historic highway programs including tourist and welcome centers
 - Landscaping and scenic beautification
 - Historic preservation
 - Rehabilitation and operation of historic transportation buildings, structures or facilities
 - Conversion of abandoned railway corridors to trails
 - Control and removal of outdoor advertising
 - Archaeological planning and research
 - Environmental mitigation of runoff pollution and provision of wildlife underpasses
 - Establishment of transportation museums
54. **Utility Relocation:** Program funds the relocation of utilities within the right-of-way of newly implemented highway projects.
55. **Weigh Station Modernization:** Projects mainly focus on the modernization of existing weigh stations to ensure that drivers do not carry loads over specified limits, and ultimately to improve roadway safety.

Appendix B
Summary of Physical Highway Assets and Asset Usage of Indiana State Highway Network

Appendix B1
Summary of Physical Highway Assets of Indiana State Highway Network

Year	Mileage	Lane	Bridge	Stop Controlled Intersection	Signalized Intersection	Grade Separation	Interchange	Railroad Cross	Workzone
1990	10,634	2.5	5,053	6,717	10,850	948	11,761	505	148
1991	10,615	2.5	5,056	6,740	10,939	935	11,339	507	151
1992	11,251	2.5	5,059	7,001	11,036	1,004	12,497	519	154
1993	11,284	2.5	5,062	7,502	11,810	969	9,778	544	124
1994	11,266	2.5	5,065	7,484	11,786	953	9,758	543	182
1995	11,238	2.5	5,068	7,446	11,719	974	9,707	535	174
1996	11,233	2.5	5,070	7,443	11,716	1,070	9,703	535	201
1997	11,242	2.5	5,077	7,452	11,723	1,079	9,707	536	128
1998	10,703	2.5	5,073	7,544	11,712	1,068	8,597	537	170
1999	10,711	2.5	5,076	7,480	11,533	1,086	8,127	527	173
2000	10,585	2.6	5,085	7,549	11,529	1,104	7,786	530	175

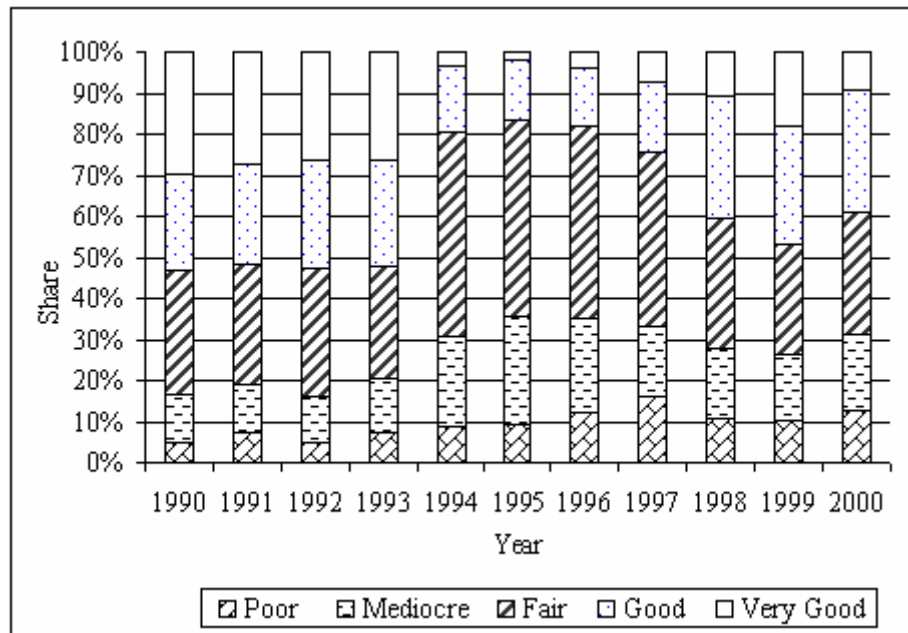
Appendix B2
Summary of Asset Usage of Indiana State Highway Network

Year	Condition (inch/mile)	Bridge SD (%)	Bridge FO (%)	Speed (mph)	AADT (vehicle)	Truck (%)	SUT (%)	MUT (%)	VMT (billion)
1990	86	10%	21%	54.3	7,451	26%	23%	3%	31
1991	92	10%	19%	54.2	7,576	26%	23%	3%	31
1992	99	9%	19%	54.1	7,837	26%	22%	4%	32
1993	97	8%	17%	54.0	8,471	27%	23%	4%	35
1994	115	6%	11%	53.9	8,664	24%	21%	4%	36
1995	117	6%	10%	53.5	9,054	26%	22%	4%	37
1996	119	6%	12%	53.3	9,267	25%	20%	5%	38
1997	125	5%	11%	53.2	9,436	27%	22%	5%	40
1998	132	5%	11%	52.8	9,966	26%	21%	5%	37
1999	138	3%	12%	52.5	10,073	27%	21%	6%	37
2000	144	3%	12%	52.3	10,248	27%	21%	6%	38

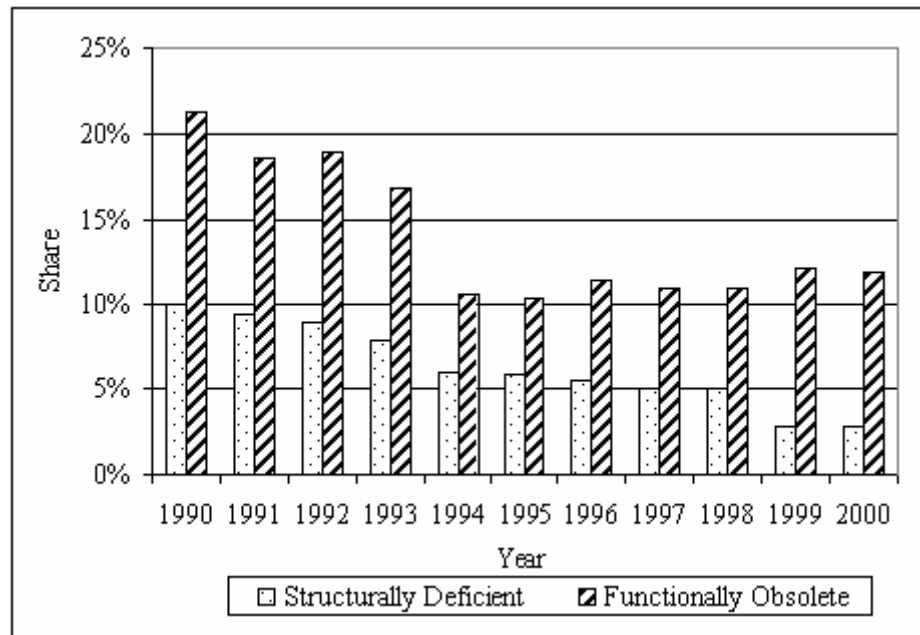
Note: 1. SD- Structurally deficient
2. FO- Functionally obsolete
3. SUT- Single unit truck
4. MUT- Multiple unit truck
5. VMT- Vehicle mile of travel.

Appendix C
Condition of Indiana State Highway Pavements and Bridges

Appendix C1
Condition of Indiana State Highway Pavements



Appendix C2
Condition of Indiana State Highway Bridges



Appendix D
Unit Rates of Fuels, Time Value, Vehicle Collisions, and Vehicle Air Pollutants for Highway User
Cost Computation

Appendix D1
Unit Rates of Fuels for Various Vehicle Classes

Year	Vehicle Class											
	2	3	4	5	6	7	8	9	10	11	12	13
1990	1.07	1.09	1.09	1.09	1.09	1.09	1.15	1.15	1.15	1.15	1.15	1.15
1991	1.12	1.13	1.13	1.13	1.13	1.13	1.20	1.20	1.20	1.20	1.20	1.20
1992	1.15	1.16	1.16	1.16	1.16	1.16	1.23	1.23	1.23	1.23	1.23	1.23
1993	1.18	1.20	1.20	1.20	1.20	1.20	1.26	1.26	1.26	1.26	1.26	1.26
1994	1.21	1.23	1.23	1.23	1.23	1.23	1.30	1.30	1.30	1.30	1.30	1.30
1995	1.24	1.26	1.26	1.26	1.26	1.26	1.33	1.33	1.33	1.33	1.33	1.33
1996	1.28	1.30	1.30	1.30	1.30	1.30	1.37	1.37	1.37	1.37	1.37	1.37
1997	1.31	1.33	1.33	1.33	1.33	1.33	1.40	1.40	1.40	1.40	1.40	1.40
1998	1.32	1.34	1.34	1.34	1.34	1.34	1.42	1.42	1.42	1.42	1.42	1.42
1999	1.37	1.39	1.39	1.39	1.39	1.39	1.47	1.47	1.47	1.47	1.47	1.47
2000	1.40	1.42	1.42	1.42	1.42	1.42	1.50	1.50	1.50	1.50	1.50	1.50

Source: Zaniewski, 1982; updated for the period 1990-2000.

Appendix D2
Unit Rates of Time Value for Various Vehicle Classes

Year	Vehicle Class											
	2	3	4	5	6	7	8	9	10	11	12	13
1990	8.8	11.3	11.3	11.3	11.3	11.3	18.6	18.6	18.6	18.6	18.6	18.6
1991	9.2	11.7	11.7	11.7	11.7	11.7	19.4	19.4	19.4	19.4	19.4	19.4
1992	9.4	12.1	12.1	12.1	12.1	12.1	20.0	20.0	20.0	20.0	20.0	20.0
1993	9.7	12.4	12.4	12.4	12.4	12.4	20.5	20.5	20.5	20.5	20.5	20.5
1994	9.9	12.7	12.7	12.7	12.7	12.7	21.0	21.0	21.0	21.0	21.0	21.0
1995	10.2	13.1	13.1	13.1	13.1	13.1	21.6	21.6	21.6	21.6	21.6	21.6
1996	10.5	13.5	13.5	13.5	13.5	13.5	22.3	22.3	22.3	22.3	22.3	22.3
1997	10.8	13.8	13.8	13.8	13.8	13.8	22.8	22.8	22.8	22.8	22.8	22.8
1998	10.9	13.9	13.9	13.9	13.9	13.9	23.0	23.0	23.0	23.0	23.0	23.0
1999	11.2	14.4	14.4	14.4	14.4	14.4	23.8	23.8	23.8	23.8	23.8	23.8
2000	11.5	14.7	14.7	14.7	14.7	14.7	24.3	24.3	24.3	24.3	24.3	24.3

Source: Chui and McFarland, 1986; updated for the period 1990-2000.

Appendix D3
Unit Rates of Vehicle Collision by Category

Collision Category	Fatal	Injury	Property Damage
1990	2,632,016	80,580	1,564
1991	2,738,146	83,829	1,627
1992	2,817,572	86,260	1,675
1993	2,896,998	88,692	1,722
1994	2,970,262	90,935	1,765
1995	3,054,481	93,513	1,815
1996	3,143,493	96,239	1,868
1997	3,213,333	98,377	1,910
1998	3,244,487	99,331	1,928
1999	3,358,263	102,814	1,996
2000	3,436,342	105,204	2,042

Source: Rice, MacKenzie, and Associates, 1989; updated for the period 1990-2000.

Appendix D4
Unit Rates of Various Vehicle Air Pollutants

Pollutant (\$/kg)	Rural Area						Urban Area					
	CO ₂	NMHC	CO	NO _x	TSP	SO ₂	CO ₂	NMHC	CO	NO _x	TSP	SO ₂
1990	0.10	7.20	0.00	0.06	0.00	0.0003	0.10	3.60	12.00	4.50	0.11	0.19
1991	0.10	7.49	0.00	0.06	0.00	0.0003	0.10	3.75	12.48	4.68	0.11	0.19
1992	0.10	7.71	0.00	0.06	0.00	0.0003	0.10	3.85	12.85	4.82	0.11	0.20
1993	0.10	7.92	0.00	0.06	0.00	0.0003	0.10	3.96	13.21	4.95	0.12	0.20
1994	0.11	8.13	0.00	0.06	0.00	0.0003	0.11	4.06	13.54	5.08	0.12	0.21
1995	0.11	8.36	0.00	0.06	0.00	0.0003	0.11	4.18	13.93	5.22	0.12	0.21
1996	0.11	8.60	0.00	0.07	0.00	0.0004	0.11	4.30	14.33	5.37	0.13	0.22
1997	0.12	8.79	0.00	0.07	0.00	0.0004	0.12	4.40	14.65	5.49	0.13	0.23
1998	0.12	8.88	0.00	0.07	0.00	0.0004	0.12	4.44	14.79	5.55	0.13	0.23
1999	0.12	9.19	0.00	0.07	0.00	0.0004	0.12	4.59	15.31	5.74	0.13	0.24
2000	0.12	9.40	0.00	0.07	0.00	0.0004	0.12	4.70	15.67	5.88	0.14	0.24

Source: Haugaard, 1981; FHWA, 1982; and Pace, 1990; updated for the period 1990-2000.

Appendix E
Consumer and Producer Price Indices for State of Indiana

Year	Consumer Price Index					Producer Price Index
	Maintenance	Construction				
		Excavation	Resurfacing	Structures	Composite	
1978	57.4	63.5	73.3	70.7	70.7	69.9
1979	63.9	66.8	89.0	88.6	85.5	78.7
1980	72.5	75.5	102.2	100.0	97.2	89.8
1981	80.0	72.6	101.4	94.9	94.2	98.0
1982	84.9	65.6	95.3	90.0	88.5	100.0
1983	89.3	71.8	94.4	86.7	87.6	101.3
1984	92.6	78.4	102.7	88.2	92.6	103.7
1985	95.4	92.4	109.6	98.1	102.0	103.2
1986	96.5	94.0	107.0	98.0	101.1	100.2
1987	100.0	100.0	100.0	100.0	100.0	102.8
1988	103.8	112.2	99.8	111.0	106.6	106.9
1989	108.6	99.0	99.4	118.4	107.7	112.2
1990	113.9	98.1	102.3	117.8	108.5	116.3
1991	118.3	95.5	106.5	112.5	107.5	116.5
1992	121.6	90.8	106.9	108.4	105.1	117.2
1993	125.1	103.2	113.5	105.3	108.3	118.9
1994	128.7	113.2	122.3	109.0	115.1	120.4
1995	132.6	112.8	127.9	119.5	121.9	124.7
1996	136.7	120.6	118.7	121.6	120.2	127.7
1997	140.0	117.6	133.0	132.7	130.6	127.6
1998	142.4	124.3	120.8	133.4	126.9	124.4
1999	145.4	120.9	140.3	138.3	136.5	125.5
2000	150.4	124.1	152.2	146.9	145.6	132.7
2001	154.4	125.9	158.1	138.8	144.8	134.2

Note:

1. Highway user cost and maintenance constant dollars are calculated using Consumer Price Index and Producer Price Index from U.S. Department of labor Bureau of Labor Statistics.
2. Construction constant dollars are calculated using Federal-Aid Highway Construction Index from Federal Highway Administration (see Highway Statistics 2001, Section IV, Table PT-1).

Appendix F
The ANOVA Test Results for the Preparation of Network-Level Highway User Cost Modeling

Component	Source	F-statistic	$\alpha = 0.005$	Significant
Vehicle Operating Cost	L	10.7	8.18	Yes
	HC	0.8	8.18	No
	L·HC	0.7	8.18	No
	VC	6,716.4	5.54	Yes
	L·VC	4.8	5.54	No
	HC·VC	62.5	5.54	Yes
	L·HC·VC	1.0	5.54	No
Travel Time	L	107.5	8.18	Yes
	HC	1,169.6	8.18	Yes
	L·HC	70.8	8.18	Yes
	VC	7.4	5.54	Yes
	L·VC	4.9	5.54	No
	HC·VC	9.8	5.54	Yes
	L·HC·VC	4.7	5.54	No
Collisions	L	0.00	8.18	No
	HC	0.00	8.18	No
	L·HC	0.00	8.18	No
	VC	0.00	5.54	No
	L·VC	0.01	5.54	No
	HC·VC	0.01	5.54	No
	L·HC·VC	0.01	5.54	No
Air Pollution	L	0.0	8.18	No
	HC	0.0	8.18	No
	L·HC	21.8	8.18	Yes
	VC	2.E+15	5.54	Yes
	L·VC	5.5	5.54	No
	HC·VC	120.0	5.54	Yes
	L·HC·VC	0.0	5.54	No
User Cost	L	1,570.7	8.18	Yes
	HC	13.2	8.18	Yes
	L·HC	0.3	8.18	No
	VC	3,958.5	5.54	Yes
	L·VC	21.2	5.54	Yes
	HC·VC	27.6	5.54	Yes
	L·HC·VC	0.5	5.54	No

Note: L- Land use, HC- Highway class, and VC- Vehicle class.

Appendix G
Descriptive Statistics of Variables for Network-Level Highway User Cost Modeling

Component	Land Use	Vehicle Class/ Highway Class	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Vehicle Operating Cost (1990\$/VMT)	Rural	Passenger Car	0.25	0.22	0.27	0.01	5%
		Single Unit Truck	0.20	0.19	0.20	0.00	2%
		Multiple Unit Truck	0.78	0.71	0.84	0.04	6%
	Urban	Passenger Car	0.26	0.25	0.28	0.01	5%
		Single Unit Truck	0.20	0.20	0.20	0.00	1%
		Multiple Unit Truck	0.81	0.80	0.82	0.01	1%
Travel Time (hour/VMT)	Rural	Interstate	0.0170	0.0164	0.0177	0.0005	3%
		Non-Interstate	0.0189	0.0184	0.0197	0.0004	2%
	Urban	Interstate	0.0172	0.0168	0.0177	0.0003	2%
		Non-Interstate	0.0203	0.0198	0.0207	0.0003	1%
Delay (hour/VMT)	Rural	Interstate	0.0002	0.0001	0.0002	0.0000	16%
		Non-Interstate	0.0002	0.0001	0.0002	0.0000	15%
	Urban	Interstate	0.0002	0.0001	0.0003	0.0001	26%
		Non-Interstate	0.0019	0.0018	0.0020	0.0001	3%
Collision Rate (No./MVMT)	All		3.60	3.33	3.95	0.25	7%
Air Pollution Rate (kg/VMT)	All	Passenger Car	0.7376	0.7372	0.7378	0.0002	1%
		Single Unit Truck	1.5936	1.5933	1.5938	0.0002	1%
		Multiple Unit Truck	1.5955	1.5953	1.5958	0.0001	1%
User Cost (1990\$/VMT)	Rural	Passenger Car	0.64	0.60	0.68	0.02	4%
		Single Unit Truck	0.74	0.71	0.77	0.02	3%
		Multiple Unit Truck	1.43	1.34	1.52	0.06	4%
	Urban	Passenger Car	0.91	0.85	0.97	0.04	4%
		Single Unit Truck	1.12	1.06	1.20	0.04	4%
		Multiple Unit Truck	1.72	1.67	1.77	0.04	2%

Appendix H
Descriptive Statistics of Variables for Directional Distribution, Lane Occupancy Adjustment Factor,
and Truck Percentage Modeling

Designation	Highway Class	Mean	Minimum	Maximum	Std. Dev.	Coeff. of Var.
Directional Distribution (DD) (%)	Rural interstate	53	53	53	0	0%
	Rural non-interstate	52	48	55	3	5%
	Urban interstate	51	47	56	3	6%
	Urban non-interstate	54	39	68	10	18%
Lane Occupancy Adjustment Factor (L_f)	Rural interstate	0.75	0.73	0.77	0.01	2%
	Rural non-interstate	0.80	0.78	0.82	0.01	2%
	Urban interstate	0.72	0.70	0.74	0.01	2%
	Urban non-interstate	0.59	0.42	0.77	0.12	20%
Single Unit Truck (%)	Rural interstate	20	16	25	3	15%
	Rural non-interstate	24	21	26	2	9%
	Urban interstate	19	15	23	3	14%
	Urban non-interstate	15	12	18	2	12%
Multiple Unit Truck (%)	Rural interstate	18	16	22	2	13%
	Rural non-interstate	10	8	13	2	18%
	Urban interstate	9	8	11	1	12%
	Urban non-interstate	2	2	3	0	12%

Appendix I
Descriptive Statistics of Variables for Highway Pavement Performance Modeling

Appendix II
Descriptive Statistics of Pavement Rehabilitation Expenditure in Indiana (1990\$)

Pavement Type	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Flexible	155,287	29,147	1,119,863	242,260	156%
Rigid	383,704	57,952	2,052,896	509,879	133%
Composite	207,634	53,399	1,602,124	440,193	212%

Appendix I2
Descriptive Statistics of Highway Pavement Maintenance Expenditure in Indiana (1990\$)

Category	Level	Treatment Type	Unit	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Preventive	Minor	Crack sealing	\$/ln-mi	381	17	2,100	541	142%
		Crumb rubber seal	\$/ln-mi	613	341	894	165	27%
		Joint/bump repair	\$/no.	63	18	264	35	56%
		Underdrain maint.	\$/no.	5	3	8	1	27%
	Moderate	Seal coating	\$/ln-mi	4,120	186	21,999	6,544	159%
	Major	Micro-surfacing	\$/ln-mi	23,552	15,819	32,412	6,810	29%
Thin overlay		\$/ln-mi	52,938	26,364	101,602	19,689	37%	
Corrective	All	Shallow patching	\$/ton	260	145	364	68	26%
		Deep patching	\$/ton	195	107	342	77	40%
		Premix leveling	\$/ton	61	45	76	9	15%

Appendix I3

Descriptive Statistics of Annual ESAL on Various Highway Pavement Types in Indiana (in Millions)

Pavement Type	Highway Class	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Flexible	All	0.39	0.00	0.15	0.12	80%
Rigid	Interstate	0.71	0.20	2.43	0.53	75%
	Non-interstate	0.26	0.07	0.97	0.19	73%
Composite	Interstate	0.81	0.36	1.96	0.48	59%
	Non-interstate	0.28	0.03	0.94	0.20	69%

Appendix I4
Weather Severity Index for Individual Counties in Indiana

County	Region	WSI	County	Region	WSI	County	Region	WSI
Adams	NE	0.72	Hendricks	WC	0.74	Pike	SW	0.59
Allen	NE	0.78	Henry	EC	0.74	Porter	NW	0.80
Bartholomew	SE	0.63	Howard	NW	0.78	Posey	SW	0.55
Benton	NW	0.77	Huntington	NE	0.82	Pulaski	NW	0.76
Blackford	NE	0.75	Jackson	SE	0.64	Putnum	WC	0.76
Boone	NW	0.73	Jasper	NW	0.72	Randolph	EC	0.77
Brown	SE	0.70	Jay	NE	0.75	Ripley	SE	0.62
Carroll	NW	0.72	Jefferson	SE	0.59	Rush	EC	0.71
Cass	NW	0.77	Jennings	SE	0.63	St. Joseph	NW	0.85
Clarke	SE	0.59	Johnson	EC	0.70	Scott	SE	0.60
Clay	WC	0.70	Knox	SW	0.58	Shelby	EC	0.71
Clinton	NW	0.70	Kosciusko	NE	0.81	Spence	SW	0.54
Crawford	SW	0.61	Lagrange	NE	0.83	Starke	NW	0.79
Daviess	SW	0.58	Lake	NW	0.86	Steuben	NE	0.85
Dearborn	SE	0.60	LaPorte	NW	0.81	Sullivan	SW	0.63
Decatur	SE	0.66	Lawrence	SW	0.64	Switzerland	SE	0.58
Dekalb	NE	0.84	Madison	EC	0.83	Tippecanoe	WC	0.70
Delaware	EC	0.78	Marion	EC	0.75	Tipton	EC	0.82
Dubois	SW	0.59	Marshall	NW	0.82	Union	EC	0.70
Elkhart	NE	0.83	Martin	SW	0.65	Vanderburg	SW	0.55
Fayette	EC	0.68	Miami	NW	0.82	Vermilion	WC	0.68
Floyd	SE	0.58	Monroe	SW	0.59	Vigo	WC	0.62
Fountain	WC	0.69	Montgomery	WC	0.78	Wabash	NE	0.83
Franklin	EC	0.71	Morgan	WC	0.71	Warren	WC	0.71
Fulton	NW	0.79	Newton	NW	0.79	Warrick	SW	0.54
Gibson	SW	0.59	Noble	NE	0.85	Washington	SE	0.61
Grant	NE	0.77	Ohio	SE	0.50	Wayne	EC	0.73
Greene	SW	0.61	Orange	SW	0.63	Wells	NE	0.79
Hamilton	EC	0.72	Owen	WC	0.69	White	NW	0.72
Hancock	EC	0.76	Parke	WC	0.71	Whitney	NE	0.81
Harrison	SE	0.55	Perry	SW	0.54			

Note: WSI- Weather severity index.

Appendix I5
Descriptive Statistics of Rehabilitation Intervals for Various Highway Pavement Types in Indiana
(in Years)

Pavement Type	Highway Class	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Flexible	All	16.00	6.00	10.18	3.03	30%
Rigid	Interstate	26.76	12.00	38.40	7.94	30%
	Non-interstate	24.71	13.00	34.00	5.13	21%
Composite	Interstate	22.04	14.00	31.00	5.36	24%
	Non-interstate	14.00	6.00	24.00	4.03	28%

Appendix J
Descriptive Statistics of Variables for Highway Bridge Performance Modeling

Appendix J1
Descriptive Statistics of Variable for Concrete Bridge Performance Modeling

Item	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Deck	Condition rating	7	4	9	1	14%
	% Condition change	7%	0%	25%	8%	118%
	AADT	6,939	0	69,425	7,627	110%
	Age (year)	32	11	75	13	42%
	Average expenditure (1990, \$/ft ²)	71	1	468	27	38%
Superstructure	Condition rating	6	3	9	1	16%
	% Condition change	14%	0%	33%	8%	57%
	AADT	8,588	100	44,235	7,542	88%
	Age (year)	44	11	75	11	26%
	Average expenditure (1990, \$/ft ²)	143	5	273	34	23%
Substructure	Condition rating	4	4	4	0	0%
	% Condition change	15%	0%	25%	13%	85%
	AADT	1,126	674	2,050	362	32%
	Age (year)	42	30	49	7	16%
	Average expenditure (1990, \$/ft ²)	26	26	28	0	2%
Wearing Surface	Condition rating	4	2	7	1	20%
	% Condition change	93%	0%	167%	30%	32%
	AADT	6,939	0	69,425	7,627	110%
	Age (year)	32	11	75	13	42%
	Average expenditure (1990, \$/ft ²)	71	1	468	27	38%

Appendix J2
Descriptive Statistics of Variable for Steel Bridge Performance Modeling

Item	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Deck	Condition rating	6	3	9	1	17%
	% Condition change	16%	0%	33%	5%	31%
	AADT	14,778	0	111,620	16,935	115%
	Age (year)	40	13	70	12	31%
	Average expenditure (1990, \$/ft ²)	57	0	387	30	53%
Superstructure	Condition rating	6	3	9	1	15%
	% Condition change	15%	0%	33%	8%	52%
	AADT	13,813	0	69,780	18,661	135%
	Age (year)	40	14	70	14	36%
	Average expenditure (1990, \$/ft ²)	97	0	305	64	66%
Substructure	Condition rating	4	4	4	0	0%
	% Condition change	25%	25%	25%	0%	0%
	AADT	5,744	3,991	17,618	4,798	84%
	Age (year)	50	47	53	2	5%
	Average expenditure (1990, \$/ft ²)	27	25	29	2	6%
Wearing Surface	Condition rating	4	3	7	1	21%
	% Condition change	89%	0%	167%	31%	35%
	AADT	14,778	0	111,620	16,935	115%
	Age (year)	40	13	70	12	31%
	Average expenditure (1990, \$/ft ²)	57	0	387	30	53%

Appendix J3
Descriptive Statistics of Variable for Bridge Agency and User Cost Modeling

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete	AADT	7,054	0	69,425	7,700	109%
	Age (year)	34	11	75	14	39%
	Number of lanes	2	0.0	6	1	26%
	Bridge length before work (ft)	124	22.0	1,234	108	87%
	Bridge length after work (ft)	126	22.0	1,234	108	85%
	Approach length (ft)	3	0.0	1,250	34	1074%
	Total deck width (ft)	37	2.9	98	9	25%
	Clear deck width (ft)	35	5.8	95	9	26%
	Vertical clearance (ft)	1	0.0	11	2	347%
	Substructure height (ft)	86	0.0	224	111	129%
	Detour length (mile)	3	0	20	4	126%
	Load inventory rating (ton)	33	0	96	11	32%
	Rehabilitation expenditure (1990\$, in 1,000)	301	7.0	1,061	153	51%
	Unit rehabilitation expenditure (1990\$/ft ²)	82	0.9	468	39	47%
	Construction expenditure (1990\$, in 1,000)	379	1.6	1,023	203	53%
	Unit construction expenditure (1990\$/ft ²)	225	0.3	734	91	40%
	EUAUC before work (1990\$, in 1,000)	10,102	0.0	245,987	17,686	175%
	EUAUC after work (1990\$, in 1,000)	3,548	0.0	92,169	6,154	173%
EUAUC change (%)	-57%	47%	-100%	71%	-124%	
Steel	AADT	14,509	0	117,220	16,996	117%
	Age (year)	39	10	86	13	32%
	Number of lanes	2	0.0	8	1	40%
	Bridge length before work (ft)	284	28.0	4,932	268	94%
	Bridge length after work (ft)	285	30.0	4,932	267	94%
	Approach length (ft)	6	0.0	923	40	652%
	Total deck width (ft)	39	1.9	114	13	34%
	Clear deck width (ft)	36	4.2	109	13	35%
	Vertical clearance (ft)	3	0.0	11	4	124%
	Substructure height (ft)	169	0.0	3,021	154	91%
	Detour length (mile)	3	0	20	6	213%
	Load inventory rating (ton)	37	0	84	10	26%
	Rehabilitation expenditure (1990\$, in 1,000)	447	0.7	1,059	198	44%
	Unit rehabilitation expenditure (1990\$/ft ²)	60	0.1	387	36	59%
	Construction expenditure (1990\$, in 1,000)	516	68.1	1,058	278	54%
	Unit construction expenditure (1990\$/ft ²)	126	1.7	372	100	79%
	EUAUC before work (1990\$, in 1,000)	16,167	0.0	304,191	27,145	168%
	EUAUC after work (1990\$, in 1,000)	5,317	0.0	117,991	9,924	187%
EUAUC change (%)	-63%	63%	-100%	17%	-27%	

Appendix K
Lower and Upper Ranges for the Development of Utility Functions Corresponding to Individual
Performance Indicators

Goal	Performance Indicator	Unit	Lower	Upper
System Preservation	Bridge structural condition	rating scale	3	9
	Bridge wearing surface condition	rating scale	3	9
	Historical bridge age	year	80	200
	Historical bridge length	ft	40	200
	Pavement surface condition	inch/mile	40	240
	Remaining service life	year	2	10
User Cost	Average speed (part 1)	mph	15	55
	Average speed (part 2)		55	75
Mobility	Average speed	mph	0	80
	Detour length	mile	0	10
	Intersection delay time	min/vehicle	0	20
Safety	Bridge load inventory rating	ton	0	40
	Bridge clear deck width (part 1)	ratio	0.8	1.0
	Bridge clear deck width (part 2)	ratio	1.0	1.1
	Bridge vertical clearance- over	ratio	0.8	1.0
	Bridge vertical clearance- under	ratio	0.8	1.0
	Bridge horizontal clearance	ratio	0.8	1.0
	Average speed	mph	0	80
	Skid resistance	number	10	50
	Lane width (part 1)	ratio	0.8	1.0
	Lane width (part 2)	ratio	1.0	1.1
	Shoulder width	ratio	0	1.0
	Railroad crossing	number	0	3
	Sight distance	ratio	0.6	1.0
Luminance	ratio	0.6	1.0	
Environment	Average speed for CO ₂ , TSP, SO ₂ (part 1)	mph	15	55
	Average speed for CO ₂ , TSP, SO ₂ (part 2)		55	75
	Average speed for NMHC		0	60
	Average speed for CO (part 1)		0	35
	Average speed for CO (part 2)		35	65
	Average speed for NO _x (part 1)		0	15
	Average speed for NO _x (part 2)		15	65

Appendix L
Descriptive Statistics of Relative Weights Assigned to Asset Management System Goals and
Performance Indicators

Appendix L1
Descriptive Statistics of Relative Weights Assigned to Asset Management System Goals

System Goal	Agency Group		User Group	
	Mean	Std. Dev.	Mean	Std. Dev.
System Preservation	9	1	7	2
Agency Cost	8	1	7	2
User Cost	7	1	7	2
Mobility	8	1	8	2
Safety	9	1	9	1
Environment	7	1	8	2
Survey Participants	29		28	

Appendix L2
Descriptive Statistics of Relative Weights Assigned to Performance Indicators under Various Asset Management System Goals

Asset Management System Goal	Asset Management Program	Weight Assigned Performance Indicator	Agency Group		User Group	
			Mean	Std. Dev.	Mean	Std. Dev.
System Preservation	Bridge Preservation	Bridge structural condition	9	1	9	1
		Bridge wearing surface condition	6	1	7	1
		Bridge remaining service life	8	2	5	3
	Historical Bridge Preservation	Bridge structural condition	9	1	8	2
		Bridge wearing surface condition	6	1	6	2
		Bridge remaining service life	7	2	7	3
		Historical bridge age	8	1	8	2
	Pavement Preservation	Historical bridge length	6	2	5	2
		Surface condition	9	1	8	1
	Agency Cost	Bridge Preservation	Remaining service life	9	1	8
Bridge construction cost			8	1	8	2
Bridge rehabilitation cost			9	1	7	2
Pavement Preservation		Bridge maintenance cost	7	1	7	2
		Pavement construction cost	8	1	8	2
		Pavement rehabilitation cost	9	1	7	2
ITS Improvements		Pavement maintenance cost	7	1	7	2
		Procurement cost	9	1	8	2
		Maintenance cost	4	1	4	1
User Cost	Bridge Preservation	Detour condition	7	2	7	2
		Average travel speed	8	2	8	2
	Pavement Preservation	Pavement surface condition	8	1	8	2
		Average travel speed	8	1	9	1
Mobility	Bridge Preservation	Detour length	8	1	9	1
		Average travel speed	8	1	8	2
Safety	Bridge Preservation	Bridge inventory rating	7	2	8	1
		Bridge clear deck width	8	1	8	2
		Bridge vertical clearance (over)	7	2	7	2
		Bridge vertical clearance (under)	8	1	6	3
		Bridge horizontal clearance	7	1	7	2
	Pavement Preservation	Average speed	8	2	8	2
		Skid resistance	8	1	7	2
		Lane width	7	1	7	2
		Shoulder width	6	1	6	2
	Railroad Crossings	Railroad crossing adequacy	9	1	8	2
		Occurrence of collisions	8	1	8	2
	Safety	Sight distance	9	1	8	2
		Luminance	7	1	7	2
		Occurrence of collisions	8	1	8	2
	Traffic Signals	Average speed	7	1	7	2
Occurrence of collisions		9	1	8	2	
DNR/Forest/Other	Average speed	8	2	8	2	
	Skid resistance	8	1	7	2	
	Lane width	7	1	7	2	
Survey Participants			9		9	

Appendix M
The ANOVA Test Results for the Preparation of Calibrating Single Attribute Utility Functions

Asset Management System Goal	Performance Indicator	Factor (<i>p</i> -Value)					
		ANOVA I			ANOVA II		
		Group	Approach	Interaction	Group	Approach	Interaction
System Preservation	Bridge structural condition	0.8624	0.7594	0.9791	0.6660	0.4471	0.9480
	Bridge wearing surface condition	0.9316	0.7346	0.8652	0.8179	0.3669	0.6494
	Historical bridge age	0.8378	0.9090	0.7704	0.6887	0.8229	0.5683
	Historical bridge length	0.8591	0.6907	0.8988	0.7246	0.4311	0.8006
	Pavement condition	0.3615	0.4376	0.8247	0.1452	0.2138	0.7206
	Remaining service life	0.7836	0.8157	0.7870	0.5686	0.6282	0.5747
User Cost	Vehicle speed	0.5654	0.9854	0.8257	0.4003	0.9786	0.7470
Mobility	Vehicle speed	0.7627	0.3183	0.7401	0.6512	0.1390	0.6194
	Detour length	0.6255	0.2686	0.6688	0.4311	0.0783	0.4898
	Intersection delay time	0.4548	0.1400	0.8900	0.2258	0.0197	0.8211
Safety	Bridge inventory rating	0.8804	0.3235	0.7244	0.8043	0.1090	0.5620
	Bridge deck width	0.5921	0.9184	0.5887	0.4527	0.8857	0.4486
	Bridge vertical clearance- over	0.9626	0.8864	0.5285	0.9280	0.7828	0.2279
	Bridge vertical clearance- under	0.9623	0.8955	0.5141	0.9267	0.7980	0.2082
	Bridge horizontal clearance	0.9699	0.9037	0.6544	0.9416	0.8143	0.3869
	Vehicle speed	0.7162	0.9275	0.8074	0.3182	0.8012	0.5014
	Skid resistance	0.7766	0.4847	0.5439	0.5786	0.1755	0.2379
	Lane width	0.3310	0.6888	0.6366	0.1626	0.5632	0.4954
	Shoulder width	0.5313	0.7937	0.7918	0.4615	0.3932	0.7559
	Railroad crossing	0.9581	0.9682	0.9581	0.9581	0.9682	0.9581
	Sight distance	0.5096	0.5663	0.9201	0.2824	0.3491	0.8694
	Luminance	0.7471	0.5326	0.9102	0.6167	0.3346	0.8608
Environment	Vehicle speed for CO ₂ , TSP, SO ₂	0.6954	0.6984	0.9458	0.5796	0.5835	0.9233
	Vehicle speed for NMHC	0.8547	0.6335	0.7942	0.7572	0.4222	0.6598
	Vehicle speed for CO	0.7826	0.5827	0.7563	0.7004	0.4441	0.6653
	Vehicle speed for NO _x	0.8688	0.5952	0.8923	0.8101	0.4404	0.8439

Appendix N
Descriptive Statistics of Variables for the Calibration of Utility Functions Associated with Individual
Performance Indicators

Asset Management System Goal	Performance Indicator	Mean	Min	Max	Std. Dev.	Coeff. of Var.
System Preservation	Bridge structural condition	0.5472	0.0000	1.0000	0.3285	60%
	Bridge wearing surface	0.5359	0.0000	1.0000	0.3390	63%
	Historical bridge age	0.4860	0.0000	1.0000	0.3028	62%
	Historical bridge length	0.4977	0.0000	1.0000	0.3041	61%
	Pavement surface condition	0.5655	0.0000	1.0000	0.3196	57%
	Remaining service life	0.4759	0.0000	1.0000	0.3051	64%
User Cost	Average speed	0.5002	0.0000	1.0000	0.3071	61%
		0.5038	0.0000	1.0000	0.2897	58%
Mobility	Average speed	0.5422	0.0000	1.0000	0.2985	55 %
	Detour length	0.4884	0.0000	1.0000	0.2815	58%
	Intersection delay time	0.5068	0.0000	1.0000	0.2869	57%
		0.3622	0.0000	1.0000	0.3133	87%
Safety	Bridge load inventory rating	0.5634	0.0000	1.0000	0.3165	56%
	Bridge deck width	0.4619	0.0000	1.0000	0.3083	67 %
		0.9484	0.9236	1.0000	0.0355	4%
	Bridge vertical clearance (o)	0.4837	0.0000	1.0000	0.3032	63%
	Bridge vertical clearance (u)	0.4839	0.0000	1.0000	0.3022	62%
	Bridge horizontal clearance	0.4825	0.0000	1.0000	0.3023	63%
	Average speed	0.4997	0.0000	1.0000	0.2974	60%
	Skid resistance	0.5074	0.0000	1.0000	0.3072	61%
	Lane width	0.4952	0.0000	1.0000	0.3032	61%
		0.9513	0.9167	1.0000	0.0352	4%
	Shoulder width	0.4975	0.0000	1.0000	0.3016	61%
	Railroad crossing	0.5581	0.0000	1.0000	0.4296	77%
	Sight distance	0.4528	0.0000	1.0000	0.3202	71%
Luminance	0.4448	0.0000	1.0000	0.3286	74%	
Environment	Speed for CO ₂ , TSP, SO ₂	0.4947	0.0000	1.0000	0.3070	62%
		0.5051	0.0000	1.0000	0.3038	60%
	Speed for NMHC	0.5534	0.0000	1.0000	0.2766	50%
	Speed for CO	0.5733	0.0000	1.0000	0.2783	49%
		0.5336	0.0000	1.0000	0.2934	55%
	Speed for NOx	0.5300	0.0000	1.0000	0.3557	67%
		0.5110	0.0000	1.0000	0.2868	56%

Appendix O
Descriptive Statistics of Performance Indicators Involving Risk in Tradeoff Decision Process

Appendix O1
Descriptive Statistics of Condition of Interstate Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Deck rating	7	5	9	1	13%
	Superstructure rating	7	5	9	1	12%
	Substructure rating	6	5	8	1	11%
	Structure rating	6	0	9	1	15%
	Wearing surface rating	7	4	9	1	13%
Concrete Girder	Deck rating	7	4	9	1	10%
	Superstructure rating	7	5	9	1	9%
	Substructure rating	7	5	9	0	6%
	Structure rating	7	4	9	1	12%
	Wearing surface rating	7	4	9	1	14%
Steel Beam	Deck rating	7	5	8	1	11%
	Superstructure rating	7	5	8	0	6%
	Substructure rating	7	5	7	1	8%
	Structure rating	7	2	8	1	14%
	Wearing surface rating	7	5	9	1	11%
Steel Girder	Deck rating	7	4	9	1	15%
	Superstructure rating	7	3	9	1	8%
	Substructure rating	7	4	9	1	8%
	Structure rating	7	3	9	1	13%
	Wearing surface rating	7	4	9	1	17%
Concrete Arch Deck	Deck rating	7	4	8	1	18%
	Superstructure rating	6	4	8	1	19%
	Substructure rating	6	5	7	1	12%
	Structure rating	6	5	7	1	14%
	Wearing surface rating	7	4	8	1	19%
Concrete Channel Beam	Deck rating	8	5	9	1	10%
	Superstructure rating	8	5	9	1	10%
	Substructure rating	8	5	9	1	9%
	Structure rating	8	5	9	1	12%
	Wearing surface rating	8	5	9	1	10%

Appendix O2
Descriptive Statistics of Condition of NHS Non-Interstate Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Deck rating	6	3	9	1	18%
	Superstructure rating	6	3	9	1	18%
	Substructure rating	6	2	9	1	19%
	Structure rating	6	2	9	1	22%
	Wearing surface rating	7	4	9	1	15%
Concrete Girder	Deck rating	7	4	9	1	11%
	Superstructure rating	7	4	9	1	9%
	Substructure rating	7	5	9	1	9%
	Structure rating	7	4	9	1	12%
	Wearing surface rating	7	4	9	1	14%
Steel Beam	Deck rating	7	4	9	1	14%
	Superstructure rating	7	2	9	1	13%
	Substructure rating	6	3	9	1	18%
	Structure rating	7	2	9	1	17%
	Wearing surface rating	7	4	9	1	14%
Steel Girder	Deck rating	7	4	9	1	14%
	Superstructure rating	7	1	9	1	9%
	Substructure rating	7	3	9	1	10%
	Structure rating	7	2	9	1	14%
	Wearing surface rating	7	3	9	1	16%
Concrete Arch Deck	Deck rating	7	5	9	1	10%
	Superstructure rating	7	6	8	1	8%
	Substructure rating	7	5	9	1	11%
	Structure rating	7	5	9	1	13%
	Wearing surface rating	7	5	9	1	13%
Concrete Channel Beam	Deck rating	7	5	9	1	11%
	Superstructure rating	8	5	9	1	10%
	Substructure rating	7	0	9	1	12%
	Structure rating	7	5	9	1	11%
	Wearing surface rating	7	5	9	1	15%

Appendix O3
Descriptive Statistics of Condition of Non-NHS State Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Deck rating	6	3	9	1	15%
	Superstructure rating	6	3	9	1	16%
	Substructure rating	6	3	9	1	13%
	Structure rating	6	2	9	1	21%
	Wearing surface rating	7	3	9	1	13%
Concrete Girder	Deck rating	7	4	9	1	13%
	Superstructure rating	7	3	9	1	12%
	Substructure rating	7	4	9	1	10%
	Structure rating	7	2	9	1	14%
	Wearing surface rating	7	4	9	1	14%
Steel Beam	Deck rating	7	3	9	1	16%
	Superstructure rating	6	3	9	1	16%
	Substructure rating	6	3	9	1	15%
	Structure rating	6	2	9	1	21%
	Wearing surface rating	7	3	9	1	14%
Steel Girder	Deck rating	7	3	9	1	15%
	Superstructure rating	7	3	9	1	10%
	Substructure rating	7	3	9	1	11%
	Structure rating	7	2	9	1	14%
	Wearing surface rating	7	3	9	1	16%
Concrete Arch Deck	Deck rating	7	4	9	1	12%
	Superstructure rating	7	4	9	1	13%
	Substructure rating	7	3	9	1	18%
	Structure rating	6	0	9	2	34%
	Wearing surface rating	7	4	9	1	13%
Concrete Channel Beam	Deck rating	7	4	9	1	11%
	Superstructure rating	7	4	9	1	10%
	Substructure rating	7	4	9	1	10%
	Structure rating	7	2	9	1	15%
	Wearing surface rating	7	3	9	1	15%

Appendix O4
Descriptive Statistics of Condition of Non-NHS Local Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Deck rating	6	4	9	1	18%
	Superstructure rating	7	5	9	1	16%
	Substructure rating	6	4	7	1	13%
	Structure rating	6	4	8	1	20%
	Wearing surface rating	7	4	9	1	18%
Concrete Girder	Deck rating	7	5	9	1	11%
	Superstructure rating	7	6	9	1	12%
	Substructure rating	7	6	9	1	14%
	Structure rating	7	6	9	1	14%
	Wearing surface rating	7	5	9	1	14%
Steel Beam	Deck rating	5	1	7	1	30%
	Superstructure rating	5	3	7	1	24%
	Substructure rating	5	2	7	1	24%
	Structure rating	4	0	9	2	55%
	Wearing surface rating	6	3	9	1	24%
Steel Girder	Deck rating	7	4	8	1	14%
	Superstructure rating	7	5	8	1	14%
	Substructure rating	6	5	8	1	17%
	Structure rating	6	5	8	1	17%
	Wearing surface rating	7	4	8	1	14%
Concrete Arch Deck	Deck rating	7	4	9	2	23%
	Superstructure rating	7	4	9	1	20%
	Substructure rating	7	5	9	1	16%
	Structure rating	6	2	8	2	36%
	Wearing surface rating	7	4	9	2	23%
Concrete Channel Beam	Deck rating	8	8	9	0	4%
	Superstructure rating	8	8	9	1	6%
	Substructure rating	8	7	8	1	7%
	Structure rating	8	8	8	0	0%
	Wearing surface rating	8	7	9	1	10%
Prestressed Concrete Box Beam	Deck rating	7	5	9	1	16%
	Superstructure rating	8	5	9	1	18%
	Substructure rating	8	6	9	1	14%
	Structure rating	7	2	9	3	38%
	Wearing surface rating	7	5	9	1	20%

Appendix O5
Descriptive Statistics of Usage of Interstate Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Age (year)	39	26	52	5	14%
	AADT	18,465	763	78,250	13,698	74%
	Detour length (mile)	2	1	18	3	167%
	Load invent rating (ton)	41	32	59	6	14%
Concrete Girder	Age (year)	33	5	47	8	23%
	AADT	16,057	0	114,440	13,474	84%
	Detour length (mile)	1	1	10	1	98%
	Load invent rating (ton)	34	16	62	7	20%
Steel Beam	Age (year)	30	5	51	13	44%
	AADT	27,930	0	117,220	29,284	105%
	Detour length (mile)	3	1	18	4	121%
	Load invent rating (ton)	37	0	54	6	17%
Steel Girder	Age (year)	33	7	51	8	25%
	AADT	27,404	0	127,450	24,653	90%
	Detour length (mile)	1	0	56	3	230%
	Load invent rating (ton)	39	23	79	8	20%
Concrete Arch Deck	Age (year)	36	34	37	1	3%
	AADT	21,993	7,595	53,740	14,670	67%
	Detour length (mile)	2	1	18	5	196%
	Load invent rating (ton)	42	26	63	10	23%
Concrete Channel Beam	Age (year)	17	8	40	11	63%
	AADT	13,429	0	127,450	20,428	152%
	Detour length (mile)	2	1	10	2	133%
	Load invent rating (ton)	39	22	89	8	21%

Appendix O6
Descriptive Statistics of Usage of NHS Non-Interstate Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Age (year)	56	5	86	15	27%
	AADT	12,003	191	43,347	8,316	69%
	Detour length (mile)	4	0	15	3	74%
	Load invent rating (ton)	36	0	64	8	21%
Concrete Girder	Age (year)	35	5	74	11	31%
	AADT	6,564	0	44,036	6,508	99%
	Detour length (mile)	3	0	11	2	73%
	Load invent rating (ton)	35	19	58	7	19%
Steel Beam	Age (year)	35	5	85	18	52%
	AADT	13,772	763	69,127	13,231	96%
	Detour length (mile)	7	1	40	11	168%
	Load invent rating (ton)	37	28	59	6	16%
Steel Girder	Age (year)	31	5	72	10	32%
	AADT	8,146	0	74,912	11,640	143%
	Detour length (mile)	4	0	52	4	115%
	Load invent rating (ton)	38	0	80	7	18%
Concrete Arch Deck	Age (year)	34	7	78	24	69%
	AADT	11,576	219	30,621	8,625	75%
	Detour length (mile)	3	1	10	3	76%
	Load invent rating (ton)	42	23	68	12	28%
Concrete Channel Beam	Age (year)	27	5	93	19	69%
	AADT	8,576	1	27,500	7,234	84%
	Detour length (mile)	3	1	40	5	142%
	Load invent rating (ton)	39	21	73	9	24%

Appendix O7
Descriptive Statistics of Usage of Non-NHS State Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Age (year)	55	1	94	18	33%
	AADT	4,585	0	29,062	3,927	86%
	Detour length (mile)	5	0	23	3	64%
	Load invent rating (ton)	35	0	85	9	26%
Concrete Girder	Age (year)	23	3	76	16	69%
	AADT	4,401	152	41,882	4,703	107%
	Detour length (mile)	4	1	23	2	58%
	Load invent rating (ton)	33	0	68	6	18%
Steel Beam	Age (year)	44	4	100	25	57%
	AADT	7,298	0	992,572	56,465	774%
	Detour length (mile)	4	0	40	5	135%
	Load invent rating (ton)	31	0	70	17	55%
Steel Girder	Age (year)	33	4	90	17	51%
	AADT	6,257	0	40,846	6,702	107%
	Detour length (mile)	5	0	98	7	146%
	Load invent rating (ton)	37	0	77	8	22%
Concrete Arch Deck	Age (year)	44	4	90	24	54%
	AADT	3,260	0	54,570	4,813	148%
	Detour length (mile)	4	0	15	3	57%
	Load invent rating (ton)	34	0	96	19	56%
Concrete Channel Beam	Age (year)	25	4	100	16	64%
	AADT	3,871	0	24,086	3,886	100%
	Detour length (mile)	5	1	26	4	69%
	Load invent rating (ton)	36	0	75	8	22%
Timber Stringer	Age (year)	12	7	15	4	30%
	AADT	3,433	2,060	4,613	1,156	34%
	Detour length (mile)	6	4	9	2	39%
	Load invent rating (ton)	35	32	36	2	5%

Appendix O8
Descriptive Statistics of Usage of Non-NHS Local Highway Bridges in Indiana

Bridge Type	Designation	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Concrete Slab	Age (year)	55	9	86	21	38%
	AADT	483	1	1,165	498	103%
	Detour length (mile)	5	1	9	2	43%
	Load invent rating (ton)	33	20	50	6	18%
Concrete Girder	Age (year)	28	9	50	14	49%
	AADT	671	10	3,126	981	146%
	Detour length (mile)	4	1	6	2	40%
	Load invent rating (ton)	30	25	36	5	15%
Steel Beam	Age (year)	65	8	116	35	54%
	AADT	80	0	186	48	60%
	Detour length (mile)	5	0	12	3	60%
	Load invent rating (ton)	18	0	36	14	75%
Steel Girder	Age (year)	47	9	80	25	54%
	AADT	579	100	1,500	581	100%
	Detour length (mile)	4	0	8	3	62%
	Load invent rating (ton)	40	23	84	19	49%
Concrete Arch Deck	Age (year)	28	5	80	22	81%
	AADT	337	100	2,354	682	202%
	Detour length (mile)	15	2	99	29	197%
	Load invent rating (ton)	28	0	41	11	41%
Concrete Channel Beam	Age (year)	14	8	20	6	46%
	AADT	2,172	1,500	2,843	718	33%
	Detour length (mile)	5	4	5	1	12%
	Load invent rating (ton)	41	36	45	5	12%
Prestressed Concrete Box Beam	Age (year)	44	4	162	58	133%
	AADT	125	100	200	44	35%
	Detour length (mile)	6	3	6	1	21%
	Load invent rating (ton)	29	3	36	12	43%

Appendix O9

Descriptive Statistics of Condition, Service Life, Maintenance, Rehabilitation, and Traffic Loading of Flexible, Rigid, and Composite Pavements in Indiana

Pavement Type	Highway Class	Item	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Flexible	All	IRI (inch/mile)	146	41	347	68	46%
		RI (year)	16	6	10	3	30%
		AAME (1990\$/ln-mi)	1,092	18	474	341	72%
		Rehab. expenditure (1990\$/ln-mi)	155,287	29,147	1,119,863	242,260	156%
		Annual ESALs (in million)	0.39	0.00	0.15	0.12	80%
Rigid	IS	IRI (inch/mile)	128	48	305	42	33%
		RI (year)	27	12	38	8	30%
		AAME (1990\$/ln-mi)	304	51	1,171	304	100%
		Rehab. expenditure (1990\$/ln-mi)	383,704	57,952	2,052,896	509,879	133%
		Annual ESALs (in million)	0.71	0.20	2.43	0.53	75%
	Non-IS	IRI (inch/mile)	178	44	354	61	34%
		RI (year)	25	13	34	5	21%
		AAME (1990\$/ln-mi)	758	41	3,384	676	89%
		Rehab. expenditure (1990\$/ln-mi)	383,704	57,952	2,052,896	509,879	133%
		Annual ESALs (in million)	0.26	0.07	0.97	0.19	73%
Composite	IS	IRI (inch/mile)	93	35	312	32	34%
		RI (year)	22	14	31	5	24%
		AAME (1990\$/ln-mi)	364	80	1,052	278	76%
		Rehab. expenditure (1990\$/ln-mi)	207,634	53,399	1,602,124	440,193	212%
		Annual ESALs (in million)	0.81	0.36	1.96	0.48	59%
	Non-IS	IRI (inch/mile)	124	40	355	53	42%
		RI (year)	14	6	24	4	28%
		AAME (1990\$/ln-mi)	681	68	4,489	761	112%
		Rehab. expenditure (1990\$/ln-mi)	207,634	53,399	1,602,124	440,193	212%
		Annual ESALs (in million)	0.28	0.03	0.94	0.20	69%

Appendix O10

Descriptive Statistics of Unit Cost of Various Pavement Maintenance Treatments in Indiana (1990\$)

Treatment Type	Unit	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Crack Sealing	\$/lane-mile	381	17	2,100	541	142%
Crumb Rubber Sealing	\$/lane-mile	613	341	894	165	27%
Joint/Bump Repair	\$/Number	63	18	264	35	56%
Underdrain Maintenance	\$/Number	5	3	8	1	27%
Seal Coating	\$/lane-mile	4,120	186	21,999	6,544	159%
Micro-Surfacing	\$/lane-mile	23,552	15,819	32,412	6,810	29%
Thin HMA Overlay	\$/lane-mile	52,938	26,364	101,602	19,689	37%
Shallow Patching	\$/ton	260	145	364	68	26%
Deep Patching	\$/ton	195	107	342	77	40%
Premix Leveling	\$/ton	61	45	76	9	15%

Appendix O11
Descriptive Statistics of Average Traveling Speed on
Indiana State Highway Network (in mph)

Land Use	Highway Class	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Rural	Rural interstate	59.5	57.0	61.7	1.6	3%
	Rural principle arterial	54.3	49.6	58.6	3.2	6%
	Rural minor arterial	56.8	55.0	57.0	0.6	1%
	Rural major collector	49.7	48.0	50.0	0.6	1%
Urban	Urban interstate	59.0	57.3	60.0	1.0	2%
	Urban freeway and expressway	59.5	57.8	61.6	1.3	2%
	Urban principal arterial	54.0	52.7	55.2	0.9	2%
	Urban minor arterial	54.3	53.2	56.4	1.0	2%
	Urban collector	56.4	54.3	58.3	1.4	2%

Appendix O12
Descriptive Statistics of Average Delay per Vehicle Mile of Travel on Indiana State Highway
Network (in Minute)

Land Use	HC	VC	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Rural	IS	Car	0.010	0.007	0.013	0.002	17%
		SUT	0.011	0.009	0.016	0.002	18%
		MUT	0.015	0.012	0.018	0.002	13%
	Non-IS	Car	0.011	0.008	0.013	0.002	16%
		SUT	0.012	0.009	0.016	0.002	17%
		MUT	0.016	0.013	0.019	0.002	12%
Urban	IS	Car	0.011	0.007	0.019	0.003	29%
		SUT	0.013	0.008	0.024	0.004	33%
		MUT	0.016	0.012	0.020	0.002	14%
	Non-IS	Car	0.103	0.095	0.110	0.005	5%
		SUT	0.153	0.145	0.156	0.003	2%
		MUT	0.092	0.079	0.100	0.007	7%

Appendix O13
Descriptive Statistics of Average Collision Rate per Million VMT on
Indiana State Highway Network (in No./million VMT)

Collision Type	Mean	Min	Max	Std. Dev.	Coeff. of Var.
Fatality	0.0152	0.0123	0.0195	0.0023	15%
Injury	0.82	0.75	0.91	0.06	7%
Property Damage	2.70	2.43	3.01	0.18	7%
All	3.54	3.29	3.91	0.22	6%

Appendix P
Deviations of Outcomes of Performance Indicators Involving Uncertainty in Tradeoff Decision
Process

Asset Management System Goal	Performance Indicator	Range of Deviation (%)		Increment (%)
		Minimum	Maximum	
System Preservation	Pavement surface condition	5	50	5
	Remaining service life	12.5	125	12.5
Agency Cost	Construction cost	5	50	5
	Rehabilitation cost	5	50	5
	Maintenance cost	5	50	5
User Cost	Vehicle speed	12.5	125	12.5
Mobility	Detour length	12.5	125	12.5
Environment	Intersection delay time	12.5	125	12.5
Safety	Vehicle speed	12.5	125	12.5
	Bridge load inventory rating	10	100	10
	Skid resistance	10	100	10
	Collision rate	10	100	10

Appendix Q
Calibrated Degree of Surprise Functions for Performance Indicators Involving Uncertainty in Tradeoff
Decision Process

Appendix Q1
 Calibrated Degree of Surprise Functions for Bridge Structural Condition

Range of Deviation	Data Set	$y(x) = c \cdot (x-7)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
57%	All	0.6554	(6.45)	0.85

Appendix Q2
Calibrated Degree of Surprise Functions for Pavement Surface Condition

Range of Deviation	Data Set	$y(x) = c.(x-120)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
5%	All	0.2488	(9.62)	0.89
	Loss	0.2780	(7.56)	0.90
10%	All	0.0622	(9.62)	0.89
	Loss	0.0695	(7.56)	0.90
15%	All	0.0276	(9.62)	0.89
20%	All	0.0155	(9.62)	0.89
25%	All	0.0100	(9.62)	0.89
30%	All	0.0069	(9.62)	0.89
35%	Gain	0.0045	(7.02)	0.89
	Loss	0.0057	(7.56)	0.90
40%	Gain	0.0034	(7.02)	0.89
	Loss	0.0043	(7.56)	0.90
45%	Gain	0.0027	(7.02)	0.89
	All	0.0031	(9.62)	0.89
50%	Gain	0.0022	(7.02)	0.89
	All	0.0025	(9.62)	0.89

Appendix Q3
Calibrated Degree of Surprise Functions for Remaining Service Life

Range of Deviation	Data Set	$y(x) = c \cdot (x-5)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
13%	Gain	22.1287	(7.02)	0.89
	All	0.3666	(1.89)	0.18
25%	All	0.4038	(2.12)	0.24
38%	All	0.4552	(2.62)	0.35
50%	All	0.5018	(3.41)	0.49
63%	All	0.5204	(4.56)	0.64
75%	All	0.5002	(6.11)	0.77
88%	All	0.4500	(7.77)	0.84
100%	Gain	0.3458	(7.02)	0.89
	Loss	0.4296	(6.34)	0.87
113%	Gain	0.2732	(7.02)	0.89
	All	0.3268	(8.9)	0.88
125%	Gain	0.2213	(7.02)	0.89
	All	0.2737	(8.38)	0.86

Appendix Q4
Calibrated Degree of Surprise Functions for Construction Expenditure

Range of Deviation	Data Set	$y(x) = c.(x-1000)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
5%	All	0.0038	(10.08)	0.90
10%	Gain	0.0010	(7.45)	0.90
	All	0.0010	(10.08)	0.90
15%	Gain	0.0004	(7.45)	0.90
	All	0.0004	(10.08)	0.90
20%	All	0.0002	(10.08)	0.90
25%	All	0.0002	(10.08)	0.90
30%	All	0.0001	(10.08)	0.90
35%	All	0.0001	(10.08)	0.90
	Loss	0.0001	(6.95)	0.89
40%	Gain	0.0001	(7.45)	0.90
	Loss	0.0001	(6.95)	0.89
45%	Gain	0.00005	(7.45)	0.90
	Loss	0.00005	(6.95)	0.89
50%	Gain	0.00004	(7.45)	0.90
	Loss	0.00004	(6.95)	0.89

Appendix Q5
Calibrated Degree of Surprise Functions for Rehabilitation Expenditure

Range of Deviation	Data Set	$y(x) = c.(x-100)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
5%	All	0.3725	(9.74)	0.90
10%	All	0.0931	(9.74)	0.90
15%	All	0.0414	(9.74)	0.90
20%	All	0.0233	(9.74)	0.90
25%	All	0.0149	(9.74)	0.90
30%	Gain	0.0107	(7.01)	0.90
	All	0.0103	(9.74)	0.89
35%	Gain	0.0079	(7.01)	0.90
	All	0.0076	(9.74)	0.89
40%	All	0.0058	(9.74)	0.90
	Loss	0.0056	(6.83)	0.88
45%	All	0.0046	(9.74)	0.90
	Loss	0.0044	(6.83)	0.88
50%	Gain	0.0039	(7.01)	0.89
	Loss	0.0036	(6.83)	0.88

Appendix Q6
Calibrated Degree of Surprise Functions for Routine Maintenance Expenditure

Range of Deviation	Data Set	$y(x) = c.(x-10)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
5%	All	35.5678	(10.22)	0.90
10%	All	8.8919	(10.22)	0.90
15%	All	3.9520	(10.22)	0.90
20%	Gain	2.2882	(7.88)	0.91
	All	2.2230	(10.22)	0.90
25%	Gain	1.4644	(7.88)	0.91
	All	1.4227	(10.22)	0.90
30%	Gain	1.0170	(7.88)	0.91
	All	0.9880	(10.22)	0.90
35%	All	0.7259	(10.22)	0.90
	Loss	0.7046	(6.71)	0.88
40%	Gain	0.5720	(7.88)	0.91
	Loss	0.5395	(6.71)	0.88
45%	Gain	0.4520	(7.88)	0.91
	Loss	0.4262	(6.71)	0.88
50%	Gain	0.3661	(7.88)	0.91
	Loss	0.3453	(6.71)	0.88

Appendix Q7
 Calibrated Degree of Surprise Functions for Vehicle Traveling Speed
 (Where Higher Speed is Preferred)

Range of Deviation	Data Set	$y(x) = c.(x-55)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
13%	All	0.2059	(8.57)	0.87
	Loss	0.2301	(5.88)	0.85
25%	All	0.0515	(8.57)	0.87
	Loss	0.0575	(5.88)	0.85
38%	All	0.0229	(8.57)	0.87
	Loss	0.0256	(5.88)	0.85
50%	Gain	0.0114	(7.79)	0.91
	Loss	0.0144	(5.88)	0.85
63%	Gain	0.0073	(7.79)	0.91
	Loss	0.0092	(5.88)	0.85
75%	Gain	0.0050	(7.79)	0.91
	Loss	0.0064	(5.88)	0.85
88%	Gain	0.0037	(7.79)	0.91
	Loss	0.0047	(5.88)	0.85
100%	Gain	0.0028	(7.79)	0.91
	All	0.0032	(8.57)	0.87
113%	Gain	0.0022	(7.79)	0.91
	All	0.0027	(8.57)	0.87
125%	Gain	0.0018	(7.79)	0.91
	All	0.0023	(8.57)	0.87

Appendix Q8
 Calibrated Degree of Surprise Functions for Vehicle Traveling Speed
 (Where Lower Speed is Preferred)

Range of Deviation	Data Set	$y(x) = c.(x-55)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
13%	All	0.2059	(8.57)	0.87
	Loss	0.2301	(5.88)	0.85
25%	All	0.0515	(8.57)	0.87
	Loss	0.0575	(5.88)	0.85
38%	All	0.0229	(8.57)	0.87
50%	All	0.0129	(8.57)	0.87
63%	Gain	0.0073	(7.79)	0.91
	Loss	0.0092	(5.88)	0.85
75%	Gain	0.0050	(7.79)	0.91
	Loss	0.0064	(5.88)	0.85
88%	Gain	0.0037	(7.79)	0.91
	Loss	0.0047	(5.88)	0.85
100%	Gain	0.0028	(7.79)	0.91
	All	0.0032	(8.57)	0.87
113%	Gain	0.0022	(7.79)	0.91
	All	0.0027	(8.57)	0.87
125%	Gain	0.0018	(7.79)	0.91
	All	0.0023	(8.57)	0.87

Appendix Q9
Calibrated Degree of Surprise Functions for Vehicle Detour Length

Range of Deviation	Data Set	$y(x) = c.(x-5)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
13%	All	25.6915	(10.27)	0.90
25%	Gain	6.6544	(7.10)	0.89
	All	6.4229	(10.27)	0.90
38%	Gain	2.9575	(7.10)	0.89
	All	2.8546	(10.27)	0.90
50%	All	1.6057	(10.27)	0.90
	Loss	1.5478	(7.60)	0.90
63%	All	1.0277	(10.27)	0.90
	Loss	0.9906	(7.60)	0.90
75%	All	0.7137	(10.27)	0.90
	Loss	0.6879	(7.60)	0.90
88%	Gain	0.5432	(7.1)	0.89
	Loss	0.5054	(7.60)	0.90
100%	Gain	0.4159	(7.1)	0.89
	Loss	0.3870	(7.60)	0.90
113%	Gain	0.3840	(9.21)	0.93
	Loss	0.3057	(7.60)	0.90
125%	Gain	0.3454	(10.20)	0.95
	Loss	0.2477	(7.60)	0.90

Appendix Q10
Calibrated Degree of Surprise Functions for Intersection Delay Time

Range of Deviation	Data Set	$y(x) = c.(x-10)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
13%	All	6.4562	(10.22)	0.90
	Loss	6.3221	(7.93)	0.91
25%	All	1.6141	(10.22)	0.90
	Loss	1.5805	(7.93)	0.91
38%	All	0.7174	(10.22)	0.90
50%	All	0.4035	(10.22)	0.90
63%	All	0.2582	(10.22)	0.90
75%	All	0.1793	(10.22)	0.90
88%	All	0.1318	(10.22)	0.90
100%	All	0.1009	(10.22)	0.90
	Loss	0.0988	(7.93)	0.91
113%	Gain	0.0951	(8.5)	0.92
	Loss	0.0781	(7.93)	0.91
125%	Gain	0.0855	(9.27)	0.93
	All	0.0718	(10.4)	0.91

Appendix Q11
Calibrated Degree of Surprise Functions for Bridge Load Inventory Rating

Range of Deviation	Data Set	$y(x) = c.(x-25)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
10%	All	1.5855	(9.99)	0.90
	Loss	1.7147	(6.71)	0.88
20%	All	0.3964	(9.99)	0.90
	Loss	0.4287	(6.71)	0.88
30%	All	0.1762	(9.99)	0.90
40%	All	0.0991	(9.99)	0.90
50%	All	0.0634	(9.99)	0.90
60%	All	0.0440	(9.99)	0.90
70%	All	0.0324	(9.99)	0.90
80%	Gain	0.0228	(8.59)	0.92
	All	0.0248	(9.99)	0.90
90%	Gain	0.0180	(8.59)	0.90
	All	0.0196	(9.99)	0.92
100%	All	0.0159	(9.99)	0.90

Appendix Q12
Calibrated Degree of Surprise Functions for Pavement Skid Resistance

Range of Deviation	Data Set	$y(x) = c.(x-25)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
10%	All	1.7545	(9.18)	0.88
	Loss	1.8645	(6.22)	0.86
20%	All	0.4386	(9.18)	0.88
	Loss	0.4661	(6.22)	0.86
30%	All	0.1949	(9.18)	0.88
40%	All	0.1097	(9.18)	0.88
50%	Gain	0.0658	(7.25)	0.90
	Loss	0.0746	(6.22)	0.86
60%	Gain	0.0457	(7.25)	0.90
	Loss	0.0518	(6.22)	0.86
70%	Gain	0.0336	(7.25)	0.90
	Loss	0.0381	(6.22)	0.86
80%	Gain	0.0257	(7.25)	0.90
	Loss	0.0291	(6.22)	0.86
90%	Gain	0.0203	(7.25)	0.90
	All	0.0217	(9.18)	0.88
100%	Gain	0.0164	(7.25)	0.90
	All	0.0175	(9.18)	0.88

Appendix Q13
Calibrated Degree of Surprise Functions for Vehicle Collision Rate

Range of Deviation	Data Set	$y(x) = c \cdot (x-5)^2$		Adjusted R ²
		Coefficient c	(t-statistic)	
10%	All	34.2739	(11.86)	0.93
	Loss	37.6404	(8.72)	0.93
20%	All	8.5685	(11.86)	0.93
	Loss	9.4101	(8.72)	0.93
30%	All	3.8082	(11.86)	0.93
	Loss	4.1823	(8.72)	0.93
40%	All	2.1421	(11.86)	0.93
50%	All	1.3710	(11.86)	0.93
60%	All	0.9521	(11.86)	0.93
70%	All	0.6995	(11.86)	0.93
80%	Gain	0.4829	(9.66)	0.94
	Loss	0.5881	(8.72)	0.93
90%	All	0.4231	(11.86)	0.93
	Loss	0.4647	(8.72)	0.93
100%	Gain	0.3091	(9.66)	0.94
	All	0.3427	(11.86)	0.93

Appendix R
Calibrated Priority Functions for Performance Indicators Involving Uncertainty in
Tradeoff Decision Process

Appendix R1
Calibrated Priority Functions for Bridge Structural Condition Rating

Range of Deviation	Data Set	$\phi(x) = a.(x-7)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(<i>t</i> -statistic)	Coefficient b	(<i>t</i> -statistic)	
57%	All	1.2216	(3.37)	-0.0198	(-1.42)	0.79

Appendix R2
Calibrated Priority Functions for Pavement Surface Condition

Range of Deviation	Data Set	$\phi(x) = a.(x-120)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
5%	All	0.6445	(3.07)	-0.0106	(-0.93)	0.71
	Loss	1.0977	(6.56)	-0.0229	(-3.03)	0.95
10%	All	0.4557	(3.07)	-0.0106	(-0.93)	0.71
	Loss	0.7762	(6.56)	-0.0229	(-3.03)	0.95
15%	All	0.3721	(3.07)	-0.0106	(-0.93)	0.71
20%	All	0.3223	(3.07)	-0.0106	(-0.93)	0.71
25%	All	0.2882	(3.07)	-0.0106	(-0.93)	0.71
30%	All	0.2631	(3.07)	-0.0106	(-0.93)	0.71
35%	Gain	0.3068	(4.48)	-0.0392	(-2.98)	0.83
	Loss	0.4149	(6.56)	-0.0229	(-3.03)	0.95
40%	Gain	0.2870	(4.48)	-0.0392	(-2.98)	0.83
	Loss	0.3881	(6.56)	-0.0229	(-3.03)	0.95
45%	Gain	0.2706	(4.48)	-0.0392	(-2.98)	0.83
	All	0.2148	(3.07)	-0.0106	(-0.93)	0.71
50%	Gain	0.2567	(4.48)	-0.0392	(-2.98)	0.83
	All	0.2038	(3.07)	-0.0106	(-0.93)	0.71

Appendix R3
Calibrated Priority Functions for Remaining Service Life

Range of Deviation	Data Set	$\phi(x) = a.(x-5)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
13%	Gain	3.4792	(4.35)	-0.0469	(-2.99)	0.81
	All	1.0613	(1.05)	-0.0013	(-0.06)	0.35
25%	All	2.0547	(2.37)	-0.0307	(-1.35)	0.55
38%	All	2.1274	(3.22)	-0.0394	(-2.02)	0.66
50%	All	1.8819	(3.50)	-0.0376	(-2.14)	0.69
63%	All	1.6246	(3.49)	-0.0335	(-2.04)	0.69
75%	All	1.4145	(3.40)	-0.0296	(-1.87)	0.68
88%	All	1.2498	(3.30)	-0.0262	(-1.71)	0.67
100%	Gain	1.2301	(4.35)	-0.0469	(-2.99)	0.81
	Loss	2.0245	(5.27)	-0.0469	(-3.39)	0.90
113%	Gain	1.1597	(4.35)	-0.0469	(-2.99)	0.81
	All	1.0169	(3.11)	-0.0211	(-1.44)	0.65
125%	Gain	1.1002	(4.35)	-0.0469	(-2.99)	0.81
	All	0.9327	(3.04)	-0.0192	(-1.33)	0.64

Appendix R4
Calibrated Priority Functions for Construction Expenditure

Range of Deviation	Data Set	$\phi(x) = a.(x-1000)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
5%	All	0.5209	(6.94)	-0.0460	(-4.33)	0.88
10%	Gain	0.2725	(4.84)	-0.0338	(-3.26)	0.85
	All	0.3683	(6.94)	-0.0460	(-4.33)	0.88
15%	Gain	0.2225	(4.84)	-0.0338	(-3.26)	0.85
	All	0.3007	(6.94)	-0.0460	(-4.33)	0.88
20%	All	0.2604	(6.94)	-0.0460	(-4.33)	0.88
25%	All	0.2329	(6.94)	-0.0460	(-4.33)	0.88
30%	All	0.2127	(6.94)	-0.0460	(-4.33)	0.88
35%	All	0.1969	(6.94)	-0.0460	(-4.33)	0.88
	Loss	0.2346	(6.81)	-0.0544	(-3.84)	0.94
40%	Gain	0.1362	(4.84)	-0.0338	(-3.26)	0.85
	Loss	0.2195	(6.81)	-0.0544	(-3.84)	0.94
45%	Gain	0.1285	(4.84)	-0.0338	(-3.26)	0.85
	Loss	0.2069	(6.81)	-0.0544	(-3.84)	0.94
50%	Gain	0.1219	(4.84)	-0.0338	(-3.26)	0.85
	Loss	0.1963	(6.81)	-0.0544	(-3.84)	0.94

Appendix R5
Calibrated Priority Functions for Rehabilitation Expenditure

Range of Deviation	Data Set	$\phi(x) = a.(x-100)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
5%	All	1.3535	(6.58)	-0.0386	(-3.95)	0.88
10%	All	0.9571	(6.58)	-0.0386	(-3.95)	0.88
15%	All	0.7815	(6.58)	-0.0386	(-3.95)	0.88
20%	All	0.6768	(6.58)	-0.0386	(-3.95)	0.88
25%	All	0.6053	(6.58)	-0.0386	(-3.95)	0.88
30%	Gain	0.4536	(5.31)	-0.0347	(-3.7)	0.87
	All	0.5526	(6.58)	-0.0386	(-3.95)	0.88
35%	Gain	0.4199	(5.31)	-0.0347	(-3.7)	0.87
	All	0.5116	(6.58)	-0.0386	(-3.95)	0.88
40%	All	0.4785	(6.58)	-0.0386	(-3.95)	0.88
	Loss	0.5102	(6.92)	-0.0348	(-3.27)	0.96
45%	All	0.4512	(6.58)	-0.0386	(-3.95)	0.88
	Loss	0.4810	(6.92)	-0.0348	(-3.27)	0.96
50%	Gain	0.3513	(5.31)	-0.0347	(-3.7)	0.87
	Loss	0.4563	(6.92)	-0.0348	(-3.27)	0.96

Appendix R6
Calibrated Priority Functions for Routine Maintenance Expenditure

Range of Deviation	Data Set	$\phi(x) = a.(x-10)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
5%	All	4.1599	(5.94)	-0.0386	(-3.35)	0.86
10%	All	2.9415	(5.94)	-0.0386	(-3.35)	0.86
15%	All	2.4017	(5.94)	-0.0386	(-3.35)	0.86
20%	Gain	1.4465	(6.37)	-0.0282	(-4.00)	0.91
	All	2.0800	(5.94)	-0.0386	(-3.35)	0.86
25%	Gain	1.2938	(6.37)	-0.0282	(-4.00)	0.91
	All	1.8604	(5.94)	-0.0386	(-3.35)	0.86
30%	Gain	1.1810	(6.37)	-0.0282	(-4.00)	0.91
	All	1.6983	(5.94)	-0.0386	(-3.35)	0.86
35%	All	1.5723	(5.94)	-0.0386	(-3.35)	0.86
	Loss	1.9730	(8.93)	-0.0463	(-4.50)	0.97
40%	Gain	1.0228	(6.37)	-0.0282	(-4.00)	0.91
	Loss	1.8455	(8.93)	-0.0463	(-4.50)	0.97
45%	Gain	0.9643	(6.37)	-0.0282	(-4.00)	0.91
	Loss	1.7400	(8.93)	-0.0463	(-4.50)	0.97
50%	Gain	0.9148	(6.37)	-0.0282	(-4.00)	0.91
	Loss	1.6507	(8.93)	-0.0463	(-4.50)	0.97

Appendix R7
 Calibrated Priority Functions for Vehicle Traveling Speed
 (Where Higher Speed is Preferred)

Range of Deviation	Data Set	$\phi(x) = a.(x-55)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
13%	All	0.7363	(6.14)	-0.0112	(-1.89)	0.92
	Loss	0.9519	(7.40)	-0.0167	(-3.15)	0.98
25%	All	0.5207	(6.14)	-0.0112	(-1.89)	0.92
	Loss	0.6731	(7.40)	-0.0167	(-3.15)	0.98
38%	All	0.4251	(6.14)	-0.0112	(-1.89)	0.92
	Loss	0.5496	(7.40)	-0.0167	(-3.15)	0.98
50%	Gain	0.4332	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.4759	(7.40)	-0.0167	(-3.15)	0.98
63%	Gain	0.3875	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.4257	(7.40)	-0.0167	(-3.15)	0.98
75%	Gain	0.3537	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.3886	(7.40)	-0.0167	(-3.15)	0.98
88%	Gain	0.3275	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.3598	(7.40)	-0.0167	(-3.15)	0.98
100%	Gain	0.3063	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2603	(6.14)	-0.0112	(-1.89)	0.92
113%	Gain	0.2888	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2379	(5.89)	-0.0097	(-1.63)	0.92
125%	Gain	0.2740	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2194	(5.67)	-0.0084	(-1.41)	0.91

Appendix R8
 Calibrated Priority Functions for Vehicle Traveling Speed
 (Where Lower Speed is Preferred)

Range of Deviation	Data Set	$\phi(x) = a.(x-55)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
13%	All	0.7363	(6.14)	-0.0112	(-1.89)	0.92
	Loss	0.9519	(7.40)	-0.0167	(-3.15)	0.98
25%	All	0.5207	(6.14)	-0.0112	(-1.89)	0.92
	Loss	0.6731	(7.40)	-0.0167	(-3.15)	0.98
38%	All	0.4251	(6.14)	-0.0112	(-1.89)	0.92
50%	All	0.3682	(6.14)	-0.0112	(-1.89)	0.92
63%	Gain	0.3875	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.4257	(7.40)	-0.0167	(-3.15)	0.98
75%	Gain	0.3537	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.3886	(7.40)	-0.0167	(-3.15)	0.98
88%	Gain	0.3275	(7.08)	-0.0266	(-3.32)	0.95
	Loss	0.3598	(7.40)	-0.0167	(-3.15)	0.98
100%	Gain	0.3063	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2603	(6.14)	-0.0112	(-1.89)	0.92
113%	Gain	0.2888	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2379	(5.89)	-0.0097	(-1.63)	0.92
125%	Gain	0.2740	(7.08)	-0.0266	(-3.32)	0.95
	All	0.2194	(5.67)	-0.0084	(-1.41)	0.91

Appendix R9
Calibrated Priority Functions for Vehicle Detour Length

Range of Deviation	Data Set	$\phi(x) = a.(x-5)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
13%	All	3.6590	(5.45)	-0.0342	(-3.53)	0.80
25%	Gain	1.8368	(3.89)	-0.0266	(-2.94)	0.74
	All	2.5873	(5.45)	-0.0342	(-3.53)	0.80
38%	Gain	1.4997	(3.89)	-0.0266	(-2.94)	0.74
	All	2.1125	(5.45)	-0.0342	(-3.53)	0.80
50%	All	1.8295	(5.45)	-0.0342	(-3.53)	0.80
	Loss	2.0887	(5.99)	-0.0340	(-3.13)	0.93
63%	All	1.6363	(5.45)	-0.0342	(-3.53)	0.80
	Loss	1.8682	(5.99)	-0.0340	(-3.13)	0.93
75%	All	1.4938	(5.45)	-0.0342	(-3.53)	0.80
	Loss	1.7054	(5.99)	-0.0340	(-3.13)	0.93
88%	Gain	0.9818	(3.89)	-0.0266	(-2.94)	0.74
	Loss	1.5789	(5.99)	-0.0340	(-3.13)	0.93
100%	Gain	0.9184	(3.89)	-0.0266	(-2.94)	0.74
	Loss	1.4769	(5.99)	-0.0340	(-3.13)	0.93
113%	Gain	0.8237	(3.61)	-0.0241	(-2.65)	0.71
	Loss	1.3925	(5.99)	-0.0340	(-3.13)	0.93
125%	Gain	0.7472	(3.39)	-0.0221	(-2.43)	0.68
	Loss	1.3210	(5.99)	-0.0340	(-3.13)	0.93

Appendix R10
Calibrated Priority Functions for Intersection Delay Time

Range of Deviation	Data Set	$\phi(x) = a.(x-10)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
13%	All	2.4699	(5.01)	-0.0316	(-3.16)	0.78
	Loss	2.8929	(6.57)	-0.0312	(-3.37)	0.94
25%	All	1.7465	(5.01)	-0.0316	(-3.16)	0.78
	Loss	2.0456	(6.57)	-0.0312	(-3.37)	0.94
38%	All	1.4260	(5.01)	-0.0316	(-3.16)	0.78
50%	All	1.2350	(5.01)	-0.0316	(-3.16)	0.78
63%	All	1.1046	(5.01)	-0.0316	(-3.16)	0.78
75%	All	1.0083	(5.01)	-0.0316	(-3.16)	0.78
88%	All	0.9335	(5.01)	-0.0316	(-3.16)	0.78
100%	All	0.8732	(5.01)	-0.0316	(-3.16)	0.78
	Loss	1.0228	(6.57)	-0.0312	(-3.37)	0.94
113%	Gain	0.5432	(3.99)	-0.0227	(-2.88)	0.77
	Loss	0.9643	(6.57)	-0.0312	(-3.37)	0.94
125%	Gain	0.4910	(3.71)	-0.0206	(-2.61)	0.74
	All	0.7572	(5.1)	-0.0290	(-3.1)	0.79

Appendix R11
Calibrated Priority Functions for Bridge Load Inventory Rating

Range of Deviation	Data Set	$\phi(x) = a.(x-25)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
10%	All	1.3210	(3.12)	-0.0176	(-1.43)	0.65
	Loss	2.3143	(5.69)	-0.0341	(-3.28)	0.92
20%	All	0.9341	(3.12)	-0.0176	(-1.43)	0.65
	Loss	1.6365	(5.69)	-0.0341	(-3.28)	0.92
30%	All	0.7627	(3.12)	-0.0176	(-1.43)	0.65
40%	All	0.6605	(3.12)	-0.0176	(-1.43)	0.65
50%	All	0.5908	(3.12)	-0.0176	(-1.43)	0.65
60%	All	0.5393	(3.12)	-0.0176	(-1.43)	0.65
70%	All	0.4993	(3.12)	-0.0176	(-1.43)	0.65
80%	Gain	0.4108	(3.37)	-0.0264	(-2.2)	0.69
	All	0.4670	(3.12)	-0.0176	(-1.43)	0.65
90%	Gain	0.3873	(3.37)	-0.0264	(-2.2)	0.69
	All	0.4403	(3.12)	-0.0176	(-1.43)	0.65
100%	All	0.4177	(3.12)	-0.0176	(-1.43)	0.65

Appendix R12
Calibrated Priority Functions for Pavement Skid Resistance

Range of Deviation	Data Set	$\phi(x) = a.(x-25)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
10%	All	1.0693	(2.99)	-0.0116	(-1.35)	0.69
	Loss	1.9070	(6.63)	-0.0235	(-3.77)	0.95
20%	All	0.7561	(2.99)	-0.0116	(-1.35)	0.69
	Loss	1.3485	(6.63)	-0.0235	(-3.77)	0.95
30%	All	0.6174	(2.99)	-0.0116	(-1.35)	0.69
40%	All	0.5347	(2.99)	-0.0116	(-1.35)	0.69
50%	Gain	0.4133	(4.79)	-0.0168	(-3.13)	0.85
	Loss	0.8528	(6.63)	-0.0235	(-3.77)	0.95
60%	Gain	0.3773	(4.79)	-0.0168	(-3.13)	0.85
	Loss	0.7785	(6.63)	-0.0235	(-3.77)	0.95
70%	Gain	0.3493	(4.79)	-0.0168	(-3.13)	0.85
	Loss	0.7208	(6.63)	-0.0235	(-3.77)	0.95
80%	Gain	0.3268	(4.79)	-0.0168	(-3.13)	0.85
	Loss	0.6742	(6.63)	-0.0235	(-3.77)	0.95
90%	Gain	0.3081	(4.79)	-0.0168	(-3.13)	0.85
	All	0.3564	(2.99)	-0.0116	(-1.35)	0.69
100%	Gain	0.2923	(4.79)	-0.0168	(-3.13)	0.85
	All	0.3382	(2.99)	-0.0116	(-1.35)	0.69

Appendix R13
Calibrated Priority Functions for Vehicle Collision Rate

Range of Deviation	Data Set	$\phi(x) = a.(x-5)^{0.5} + b.y^2$				Adjusted R ²
		Coefficient a	(t-statistic)	Coefficient b	(t-statistic)	
10%	All	4.0647	(3.34)	-0.0366	(-1.76)	0.60
	Loss	6.4974	(5.5)	-0.0559	(-3.24)	0.89
20%	All	2.8742	(3.34)	-0.0366	(-1.76)	0.60
	Loss	4.5944	(5.5)	-0.0559	(-3.24)	0.89
30%	All	2.3468	(3.34)	-0.0366	(-1.76)	0.60
	Loss	3.7513	(5.5)	-0.0559	(-3.24)	0.89
40%	All	2.0324	(3.34)	-0.0366	(-1.76)	0.60
50%	All	1.8178	(3.34)	-0.0366	(-1.76)	0.60
60%	All	1.6594	(3.34)	-0.0366	(-1.76)	0.60
70%	All	1.5363	(3.34)	-0.0366	(-1.76)	0.60
80%	Gain	1.3469	(3.25)	-0.0598	(-2.37)	0.63
	Loss	2.2972	(5.5)	-0.0559	(-3.24)	0.89
90%	All	1.3549	(3.34)	-0.0366	(-1.76)	0.60
	Loss	2.1658	(5.5)	-0.0559	(-3.24)	0.89
100%	Gain	1.2047	(3.25)	-0.0598	(-2.37)	0.63
	All	1.2854	(3.34)	-0.0366	(-1.76)	0.60

Appendix S
Descriptive Statistics of Data for the Calibration of Standardized Focus Gain-Over-Loss Ratio
Functions

Asset Management System Goal	Performance Indicator	Mean	Min	Max	Std. Dev.	Coeff. of Var.
System Preservation	Pavement condition	0.9672	0.7917	1.1400	0.1214	13%
	Remaining service life	0.9858	0.9175	1.0235	0.0348	4%
Agency Cost	Construction cost	0.9874	0.9333	1.0400	0.0310	3%
	Rehabilitation cost	0.9670	0.8864	1.0091	0.0423	4%
	Maintenance cost	0.9709	0.9396	1.0013	0.0242	2%
User Cost Mobility Environment	Vehicle speed	0.9933	0.8818	1.1125	0.0924	9%
	Detour length	0.9170	0.7941	1.0079	0.0634	7%
	Intersection delay time	1.0499	1.0042	1.2170	0.0651	6%
Safety	Vehicle speed	0.9824	0.8820	1.1124	0.0831	8%
	Bridge load inventory	0.9939	0.9015	1.0764	0.0584	6%
	Skid resistance	0.9796	0.8970	1.0738	0.0604	6%
	Collision rate	0.9910	0.9078	1.0420	0.0492	5%