OPTIMAL INVESTMENT DECISION-MAKING FOR HIGHWAY TRANSPORTATION ASSET MANAGEMENT UNDER RISK AND UNCERTAINTY

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16. Abstract
Efficient highway investment decision-making becomes increasingly important in transportation. In order to facilitate such a decision process, one of the key issues is to estimate benefits of highway projects and utilize those values for project selection to yield optimal investment decisions. The existing methodologies for highway project evaluation are limited to probabilistic risk assessments of input factors such as construction, rehabilitation, and maintenance costs; travel demand; and discount rates that are inherited with risks. This research introduces a new approach for highway project evaluation extended from Shackle's model to explicitly address cases where those input factors are under uncertainty with no definable probability distributions. Then, a generalized methodology for highway project evaluation with input factors under certainty, risk, and uncertainty is established. If an input factor is under certainty, its single value is directly used. If an input factor is under risk, the mathematical expectation of the factor based on the probabilistic risk assessment can be determined. If an input factor is under uncertainty, a single-valued outcome of the factor can be estimated according to a preset decision rule in the extension of Shackle's model. The values of input factors separately determined under certainty, risk, and uncertainty can be used to compute the overall benefits of a highway project in the physical asset's one service life-cycle and in perpetuity horizon, respectively. The developed methodology offers flexibility for the decision-maker to consider any combination of input factors under certainty, risk or uncertainty and it could be applied to estimate the amount of benefits associated with sub-project benefit items (if a specific benefit item is further separable) under certainty, risk or uncertainty in accordance with available information.

For project selection, a stochastic optimization model is developed as the multi-choice multidimensional Knapsack problem with Ω-stage budget recourses. The model facilitates the selection of a subset of candidate highway projects across a multiyear analysis period under budget uncertainty aimed to achieve maximized overall project benefits. Contract-, corridor-, and deferment-based tradeoff methods are employed to assess the impacts of spatial and temporal restrictions on project selection results. An efficient solution algorithm with the computational complexity of $O(N^2)$ is developed for the proposed stochastic model. A case study using data on state highway programming in Indiana for period 1996-2006 is conducted to apply the methodology for project evaluation with input factors under certainty, risk, and uncertainty and the stochastic model for project selection under budget uncertainty. Cross comparisons of project benefits estimated with and without uncertainty considerations are made. The overall benefits of projects selected using different tradeoff analysis methods in the stochastic model are compared. Furthermore, the respective project selection results are matched with the actual programming decisions and relatively high consistency rate is obtained. The new methodology for project evaluation and model for project selection can be adopted by state transportation agencies to improve the efficiency of highway investment decisions.

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Final Report

Optimal Investment Decision-Making for Highway Transportation Asset Management under Risk and Uncertainty

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EXECUTIVE SUMMARY

Efficient, economical, and safe movement of people and goods by various transportation modes is critical to a society in meeting its goals toward economic progress, social welfare, and emergency preparedness. Each year, a major share of public sector investments is made to preserve, operate, and build transportation infrastructure. Population growth and economic development have led to a steady increase in travel demand, which has in turn led to accelerated deterioration of physical highway asset conditions and increased concerns over congestion, safety, and the environment. Consequently, there has been an increased pressure to upgrade physical asset conditions and to improve system operations within a constrained budget. Responding to these challenges, transportation agencies are increasingly adopting asset management concepts that identify needs of the entire highway system and strategically determine optimal investments in a holistic and proactive manner.

Study Objectives. One of the key steps in the highway investment decision-making process is to realistically estimate the benefits of highway projects in the physical asset useful service life-cycle. The existing life-cycle costing approaches for highway project evaluation maintain limited capacity of risk-based analysis by incorporating probabilistic risk assessments of input factors such as construction, rehabilitation, and maintenance costs; travel demand; and discount rates that are inherited with risks. However, they do not explicitly address cases where those input factors are under uncertainty with no definable probability distributions. Moreover, existing models for project selection are typically suited for a specific type of physical highway assets (such as pavements and bridges) or a single aspect of system operations (such as safety and congestion) and they do not consider uncertainty associated with the available budget. Therefore, they will at best produce locally optimal investment decisions. The proposed research aims to develop a new methodology for project evaluation that rigorously handles input factors under certainty, risk and uncertainty; and a stochastic model for integrated project selection using different tradeoff methods under budget uncertainty.

A Generalized Methodology for Highway Project Evaluation. Project life-cycle cost analyses estimate costs incurred over the physical highway asset useful service life. As such, it provides a basis for comparing various investment alternatives. Typical physical asset life-cycle activity profiles, represented by the timing, frequency, and magnitude of treatments occurred over the physical asset useful service life, propose the best combination of treatments taken to minimize the overall life-cycle costs. In the current study, typical highway life-cycle activity profiles are established for two types of pavements and nine types of bridges, respectively. For non-pavement and non-bridge projects, the benefits are indirectly estimated using the pavement and bridge asset related life-cycle activity profiles.

Agency and user costs are separately considered in project life-cycle cost analyses. Agency costs include costs of construction, rehabilitation, and maintenance. User costs cover cost items of vehicle operation, travel time, vehicle crashes, and vehicle air emissions under normal operation and work zone conditions, respectively. The agency costs and individual user cost items in physical asset service life-cycle are separately computed according to the typical physical asset life-cycle activity profiles. The differences of life-cycle agency and user costs between the actual and the typical physical asset life-cycle activity profiles are regarded as agency and user benefits, correspondingly. The overall project benefits in the physical asset's one service life-cycle are the aggregation of agency and user benefits. Further, the overall project benefits in physical asset's one service life are expanded to perpetuity time horizon to establish the overall project benefits in perpetuity.

Project life-cycle agency and user costs, and project benefits will change according to changes in factors regarding construction, rehabilitation, and maintenance costs; traffic demand; and discount rates over time. These factors are identified as primary input factors for risk-based project benefit estimation. The mathematical expectation of project benefits is determined for each project by assigning probability distributions to the above input factors.

The above factors selected for risk-based analyses may not be exactly characterized by reliable probability distributions. Consequently, a meaningful mathematical expectation for an input factor may not be established and this invalidates risk-based analysis, thereby necessitating the uncertainty-based analysis. Shackle's model overcomes the limitation of inability to compute the mathematical expectation. The model first determines an expected outcome as the mean or mode of a number of possible outcomes. It then uses the degree of surprise as a measure of uncertainty associated with a number of possible outcomes of the factor in place of a probability distribution. Then, it establishes a priority weighting index by jointly evaluating each pair of a possible outcome and its degree of surprise. Finally, it identifies two outcomes maintaining maximum priority weighting indices separately on the gain side from the expected outcome and the loss side from the expected outcome. The two outcomes are terms as the focus gain outcome and the focus loss outcome. This model helps establish a triple set comprised of the expected outcome, focus gain outcome, and focus loss outcome. As an extension of Shackle's model for uncertainty-based analysis, a decision rule is introduced to calculate a unique value for the input factor under uncertainty using information on the expected outcome, focus gain outcome, and focus loss outcome. The unique value is then used for computing project benefits under uncertainty.

The degree of uncertainty associated with an input factor for estimating the benefits of a highway project can be classified as certainty, risk or uncertainty. A generalized methodology for highway project evaluation with input factors under certainty, risk, and uncertainty is then introduced. If an input factor is under certainty, its single value is directly used. If an input factor is under risk, the mathematical expectation of the factor based on the probabilistic risk assessment can be determined. If an input factor is under uncertainty, a single-valued outcome of the factor can be estimated according to a preset decision rule in the extension of Shackle's model. The values of input factors separately determined under certainty, risk, and uncertainty can be used to compute the overall benefits of a highway project in the physical asset's one service life-cycle and in perpetuity horizon, respectively. The developed methodology offers flexibility for the decision-maker to consider any combination of input factors under certainty, risk or uncertainty and it could be applied to estimate the amount of benefits associated with sub-project benefit items (if a specific benefit item is further separable) under certainty, risk or uncertainty in accordance with available information. For instance, vehicle operating costs consist of fuel and oil use, tire wear, vehicle maintenance, and vehicle depreciation. The benefits associated with reduction in vehicle operating costs can be computed by separately estimating each of the sub-benefit items under vehicle operating costs according to the relevant input factors under certainty, risk or uncertainty. The respective amounts of benefits concerning the sub-benefit items can then be combined to arrive at the total benefits as the reduction in vehicle operation costs.

A Stochastic Model for Highway Project Selection. In the current practices, state transportation agencies have typically established different highway asset management programs like pavement and bridge preservation, safety and roadside improvements, system expansion, Intelligent Transportation Systems installations, and maintenance programs to manage different types of physical highway assets and system operations. Budgets allocated for different programs are generally not transferable. However, multiyear budgets for each management program may be handled in two ways: either being treated as year-by-year constrained budgets or as a cumulative budget for all years combined. In the contracting process, projects related to multiple types of highway assets and/or multiple aspects of system operations are grouped into contract packages. One contract may contain multiple projects, requesting funds across different management programs, and it may be funded over multiple years. Selection of the contract necessitates selecting all constituent projects. Otherwise, all underlying projects must be declined. The project interdependency relationships need to be explicitly handled in the project selection process. In addition, highway investment decisions are usually made based on an estimated budget years ahead of the project implementation period. As time passes by updated budget information would become available, project selection decisions thus must be updated accordingly to maintain realistic results.

The project selection that aims to select a subset from all economically feasible candidate projects for maximized overall project benefits must address issues of budget constraints by management program category, project interdependency relationships for individual contracts, and budget uncertainty. A stochastic optimization model, along with an efficient solution algorithm, is developed for network-level highway project selection. The model is formulated as the stochastic multi-choice multidimensional Knapsack problem with Ω-stage budget recourses to explicitly address budget constraint, project interdependency, and budget uncertainty issues. The model can be applied to any combination of multiple management programs and multiple analysis years, and the budget profile may be updated any number of times according to updated budget information. In addition, the model facilitates the implementation of contract-, corridor-, and deferment-based project tradeoff analysis methods in the project selection process. The objectivity, flexibility, robustness, and holistic nature of the developed stochastic model would ensure achieving truly global optimal investment decisions.

A Case Study. Data on projects proposed for Indiana state highway programming for period 1996-2006 are used in a case study to validate the developed methodology and model. The eleven-year data contain 7,380 projects that belong to 5,068 contracts. Based on the confidence levels in the extent of input factor variability, project benefit items concerning the reduction of life-cycle agency costs of construction, rehabilitation, and maintenance; vehicle operating costs; and vehicle emission costs are selected for risk-based analyses, while benefit items associated with the decrease in travel time and vehicle crashes are chosen for uncertainty-based analyses. The present worth of project benefits estimated in perpetuity horizon, the present worth of project costs directly provided, and available budgets are utilized as the basis of project selection. Two budget constraint scenarios (the yearly constrained budgets and the cumulative budget), four budget recourse stages (initially estimated budget and three-time updated budgets in the multi-year analysis period), and three tradeoff methods (contract-, corridor-, and deferment-based tradeoffs) are used for project selection in the case study.

The case study results reveal that corridor-based and deferment-based project tradeoff analysis methods do not necessarily generate higher overall benefits from the selected contracts as compared to the overall benefits of contracts selected using the contract-based tradeoff method. For each budget recourse stage and tradeoff method combination, a higher number of contracts is selected under the cumulative budget scenario and slightly higher overall benefits of selected contracts under the cumulative budget scenario are also achieved. This is attributable to fewer constraints in the optimization process, yielding a better solution. Except for the last several years without accurate budget information, high matching percentages are consistently obtained between contracts selected using the stochastic model according to different budget constraint, budget uncertainty, and tradeoff analysis method combinations and contracts actually authorized for implementation.

The developed methodology for highway project evaluation offers flexibility while being robust, without limiting any combination of the input factors for estimating project benefits under certainty, risk or uncertainty. The proposed stochastic model for highway project selection that explicitly addresses budget constraint, project interdependency, and budget uncertainty issues and facilitates implementing different project tradeoff analysis methods offers new possibilities for transportation agencies to improve the efficiency of investment decisions.

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LIST OF ABBREVIATIONS

AAA	American Automobile Association
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Agency Costs
AVC	Average Variable Cost
CAL-B/C	California Life Cycle Benefit/Cost Analysis Model
CALTRANS	California Department of Transportation
CAS	Crack and Seating
CCD	Complementary of Cumulative Distribution
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRCP	Continuously Reinforced Concrete Pavement
DOT	Department of Transportation
EUAAC	Equivalent Uniform Annual Agency Costs
EUAUC	Equivalent Uniform Annual User Costs
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HDM	Highway Development and Management
HERS	Highway Economic Requirements System
HMA	Hot Mix Asphalt
HOV	High-Occupancy Vehicle
IDAS	ITS Deployment Analysis System
INDOT	Indiana Department of Transportation
ITS	Intelligent Transportation Systems
JCP	Jointed Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
LCAC	Life-Cycle Agency Costs
LCCA	Life-Cycle Cost Analysis

LCUC	Life-Cycle User Costs
MC	Marginal Cost
MCKP	Multi-Choice Knapsack Problem
MCMDKP	Multi-Choice Multidimensional Knapsack Problem
MDKP	Multidimensional Knapsack Problem
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NMHC	Non-Methane Hydrocarbons
NO_X	Nitrogen Oxides
NSC	National Safety Council
NYDOT	New York State Department of Transportation
PC	Project Costs
PCC	Portland Cement Concrete
PM	Particulate Matter
PDO	Property Damage Only
PSI	Present Serviceability Index
PW	Present Worth
SO_2	Sulfur Oxides
STEAM	Surface Transportation Efficiency Analysis Model
SUV	Sport Utility Vehicle
TRB	Transportation Research Board
TSP	Total Suspended Particles
TTC	Travel Time Costs
TTI	Texas Transportation Institute
UC	User Costs
USDOT	U.S. Department of Transportation
UTTC	Unit Travel Time Costs
UVCC	Unit Vehicle Crash Costs
UVEC	Unit Vehicle Emission Costs
UVOC	Unit Vehicle Operating Costs

VCC	Vehicle Crash Costs
VEC	Vehicle Emission Costs
VMT	Vehicle Miles of Travel
VOC	Vehicle Operating Costs / Volatile Organic Compounds
WZ	Work Zone
WZUC	Work Zone User Costs

CHAPTER 1:
INTRODUCTION

Highway preservation, operation, and improvement programs account for a substantial portion of the budget in almost every state, county, and locality. With such large sums at stake, it is important to deliver the best possible return on investment. Deciding which highway projects to fund usually turns out to be a complicated process. Projects are often intertwined: completion of one project may necessary to make another project or phase viable. Schedules and cost estimates are sometimes hard to pin down: even minor shifts in the cost or timing of one project can have a ripple effect on the rest of the program. Most agencies appoint some types of expert panel to guide the decision-making process, but even the most experienced panels are not always successful in consistently selecting the combination of projects that results in the highest overall benefits. Decisions that seem wise on day one may suddenly seem ill-advised a few months later when funding levels change, the engineering staff reports that large project cannot be completed on time or political imperatives override staff-level decisions.

This study discusses a specialized analysis strategy to help guide highway investment decision-making. While this strategy does not eliminate the need for human judgment, it could help experts make better decisions by using mathematical techniques to account for frequently encountered risks and uncertainties. After explaining the technical details of this technique, we test it using real data from the late 1990s Indiana state highway programming to identify the potential scale of opportunities for improvement.

In preparing this report we have attempted to provide both technical and non-technical information; some readers may wish to skip over the mathematics and focus on the broader concepts of the analysis strategy.

1.1 Problem Statement

Over the past two decades, state transportation agencies have developed management systems as analytical tools to support investment decision-making in Statewide Transportation Improvement Programs (STIP) and long-range plans. The most common management systems dealing with physical highway assets are those for pavements, bridges, and maintenance. In addition, there are management systems handling highway system operations, namely, congestion and safety. The existing methodologies for project evaluation in these management systems maintain limited capacity of risk-based analysis of project benefits affected by factors such as travel demand and costs of construction, rehabilitation, and maintenance using probabilistic risk assessments. However, they do not handle cases when such factors are under uncertainty without definable probability distributions. Moreover, existing models for project selection do not explicitly address budget uncertainty. Furthermore, the management systems typically work independent of each other or are partially integrated. Hence, they do not treat all interrelated physical highway assets and system operations simultaneously, which will at best generate locally optimal investment decisions for each type of physical highway assets or single aspect of system operations. This motivates developing a new procedure that explicitly addresses uncertainty and system integration issues in highway project evaluation and project selection to produce globally optimal investment decisions.

1.2 Research Objectives

1.2.1 Background

Figure 1.1 shows the key functions of management systems dealing with individual categories of physical highway assets such as pavements and bridges or system operations regarding congestion and safety. In general, each management system assists the decision-maker in performing the following tasks for its given physical asset or system operations category: i) establishing system goals and performance measures, ii) monitoring highway system performance regarding physical asset conditions or operational service levels, iii) predicting future performance trends, iv) recommending candidate projects to sustain physical asset and system operations performance, v) evaluating project benefits and costs in physical asset service life-cycle, vi) conducting project selection, and vii) providing feedbacks after project implementation to refine the analyses in subsequent decision cycles.

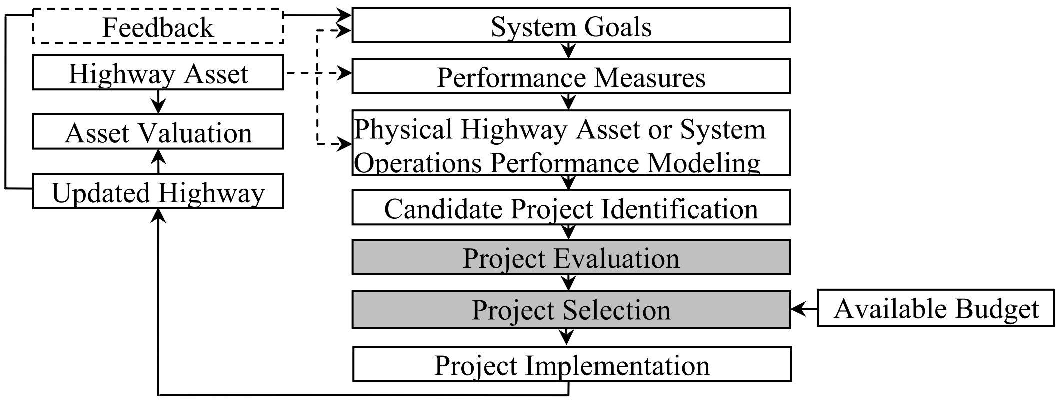


FIGURE 1.1. Key functions of management systems dealing with physical highway assets or system operations.

1.2.2 Study Objectives

A general objective of this study is to advance transportation asset management for optimal system performance. Optimal performance includes preserving physical highway assets and agency resources, enhancing accessibility and mobility, improving safety and security, minimizing impacts on the environment, and sustaining economic development. The specific objectives are as follows:

- Developing a methodology for highway project evaluation under certainty, risk, and uncertainty in physical asset useful service life-cycle that ensures consistency of analysis results for projects associated with physical highway assets and system operations; and

- Developing a model for highway project selection to examine the effects of spatial and temporal tradeoff analysis methods on project selection results:

  1) Selecting projects according to contract-based selection criterion;
  2) Selecting projects based on corridor-based selection criterion; and
  3) Deferring the implementation of some large-scale projects.

1.2.3 Delineation of Tasks

Task 1: Information Search

The information search will focus on two principal areas: i) highway project evaluation under certainty, risk, and uncertainty; and ii) highway project tradeoff analyses. Three sources will be searched for relevant materials, including archived publications, internal reports, and Websites.

Task 2: Highway Project Evaluation under Certainty and Risk

This task will thoroughly examine the following: i) typical agency cost profiles for major physical highway assets and estimates of user cost trends currently in use by state transportation agencies; ii) potential risk sources of various types of highway projects; and iii) historical data associated with a highway system, engineering models, and expert opinion that can be utilized in Bayesian reasoning to obtain firmer probability distributions for probabilistic risk assessments of project benefits.

Task 3: Highway Project Evaluation under Uncertainty

The application of Shackle's model ultimately establishes three values: expected outcome, focus gain, and focus loss. This task will extend Shackle's model by introducing a decision rule that helps establish a weighed-value based on the three values. This new approach will ensure consistency of results with those derived from risk-based analyses in Task 2.

Task 4: Stochastic Model for Highway Project Selection
A stochastic model, along with an efficient solution algorithm, will be developed to facilitate project selection using different tradeoff analysis methods under budget uncertainty.

Task 5: Collection of Data for a Case Study
The Joint Transportation Research Program, jointly sponsored by the Indiana Department of Transportation (DOT) and Purdue University, maintains a data clearinghouse containing detailed information on system inventory, historical costs, physical asset conditions, and operations associated with the Indiana state highways dating back to 1980. The data will be used for the case study with permission.

Task 6: Case Study for Methodology and Model Application
The case study will evaluate the methodology for project evaluation under certainty, risk, and uncertainty developed in Tasks 2 and 3; and the stochastic model for project selection using different tradeoff analysis methods developed in Task 4. For agencies that use individualized management systems, the study findings will enhance agency's capacity to perform project evaluation and project selection, and eventually help integrated investment decisions.

Task 7: Report Preparation and Submission
Interim reports documenting information search, methodology for project evaluation, and optimization model for project selection, as well as case study results will be submitted. A final report on findings of Tasks 1-6, an implementation plan, and future research directions will be submitted.

1.3 Report Organization

The report is comprised of six chapters. Chapter 1 discusses the increasing need for a new procedure that addresses uncertainty and system integration in highway project evaluation and project selection, as well as research objectives and tasks. Chapter 2 provides background information on methods for highway project evaluation and project selection. Chapter 3 elaborates on the proposed methodology for highway project evaluation under certainty, risk, and uncertainty. Chapter 4 focuses on the proposed stochastic model for project selection. Chapter 5 discusses a case study for validating the proposed methodology and model. Finally, Chapter 6 presents a summary of the study findings, an implementation plan of study findings, and areas for future research.

CHAPTER 2:
LITERATURE REVIEW

As the first step of the research, literature review was conducted on existing methodologies for highway project benefit-cost analyses and project selection as summarized in the following sections.

2.1 Methods for Highway Project Evaluation

2.1.1 Project-Level versus Network-Level Analyses

Highway project benefit-cost analysis frequently provides a quantitative basis for comparing and prioritizing alternative projects. When choosing a method for benefit-cost analysis, tradeoffs must be considered between the accuracy and it simplicity of a method. In general, the methods fall into one of the following two categories: i) project-level benefit-cost analysis that uses standard assumptions to compute direct project benefits in immediate project area and indirect benefits of project affected areas; and ii) network-level benefit-cost analysis that estimates project benefits based upon the output of a regional planning model so as to capture significant project benefits.

The ease or difficulty in implementation is crucial in adopting project-level versus network-level analysis. As compared to project-level analysis, network-level analysis generally requires more time, data, and assumptions, necessitates the use of travel demand forecasting models such as the traditional four-step model, and is more costly than route-specific analysis. Project, physical asset, and land area type characteristics well suited for project-level and network-level analyses are listed in Table 2.1.

TABLE 2.1. Decision Criteria for Project-Level versus Network-Level Analyses

Benefit-Cost Analysis	Decision Criterion	
	Project Type	Physical Asset or Area Type
Project Level	- Resurfacing, restoration, and rehabilitation - Safety improvements, including roadway geometry, lane, access, and roadside improvements - Minor capacity improvement, such as addition of passing, auxiliary, and truck climbing lanes	- Physical assets with no alternative routes, such as bridges and tunnels - Low-volume systems well under capacity - Rural areas with relatively sparse roadway networks
Network Level	- ITS projects, such as ramp metering, traffic surveillance, and region-wide traveler information systems - Addition of high-occupancy-vehicle (HOV) lanes - New or improved park-and-ride lots - Interchange additions or improvements - New construction and significant capacity expansion - Traffic signal systems - Traffic control	- High-volume systems at or over capacity - Urban areas with relatively dense roadway networks with alternative path choices

2.1.2 The Concept of Life-Cycle Cost Analysis

The costing procedure that includes all agency and user costs in project service life-cycle is called life-cycle costing. Agency costs mainly consist of capital costs associated with project construction and the discounted future costs of maintenance and rehabilitation (including resurfacing, restoration, and reconstruction). Whereas user costs are those concerned with vehicle operation, travel time, vehicle crashes, and vehicle air emissions. The life-cycle cost analysis allows the decision-maker to determine how much cost savings will occur with higher initial capital costs, if these higher costs result in lower overall life-cycle agency and user costs. State transportation agencies have begun to use life-cycle cost analysis for asset management in recent years (FHWA, 1999). The following sections summarize the general procedure for life-cycle cost analysis.

2.1.2.1 Project Direct Costs

The project direct costs generally include direct agency costs and additional user costs associated with construction. Direct agency cost elements largely cover capital costs of project land acquisition, design and engineering support, and construction. User costs associated with construction include increased costs of vehicle operation, delays, crashes, and air emissions within work zones.

2.1.2.2 Life-Cycle Agency and User Costs

In life-cycle cost analysis, the overall agency costs generally include direct agency costs regarding project construction and subsequent costs of maintenance and rehabilitation incurred during project service life-cycle. On the user costs side, the primary cost categories include vehicle operating costs, travel time, crashes, and air emissions. Life-cycle user costs are estimated based on the four user cost elements for all years in project service life-cycle.

2.1.2.3 Project Life-Cycle Benefits

The overall benefits of a highway project in its service life-cycle may be extracted from both the agency and user perspectives. With investments on project construction, it may reduce project life-cycle agency costs and also result in savings of life-cycle user costs in terms of vehicle operation, travel time, crashes, and air emissions. In order to estimate the change in life-cycle agency costs, the activity profiles containing information on frequency, timing, and magnitude of construction, rehabilitation, and maintenance work for principal highway assets such as pavements and bridges need to be established. For instance, different activity profiles are needed for flexible, right, and composite pavements; and for concrete and steel bridges, respectively. The potential reduction in life-cycle agency and user costs after project implementation (i.e., with certain investments) is considered as the overall project life-cycle benefits. Table 2.2 lists the generic steps involved with project benefit-cost analysis (AASHTO, 2003).

TABLE 2.2. Analytical Steps of Highway Project Benefit-Cost Analyses

Analytical Step	Information Needed
1. Define base case and project alternatives	- The network elements affected - Engineering characteristics - Project build-out schedule - Project agency cost schedule - Project user cost schedule
2. Determine level of details required	- Types of benefits and costs - Link versus corridor perspective - Vehicle classes to be studied - Hourly, daily, and seasonal details - Time periods within a day to be explicitly modeled
3. Develop basic agency cost factors	- Physical asset performance models - Activity frequency, timing, and magnitude
4. Develop basic user cost factors	- Vehicle operating unit costs - Vehicle occupancy rates - Values of travel time - Vehicle crash rates and unit costs - Vehicle air emission rates and units costs
5. Select economic factors	- Discount and inflation rates - Analysis period - Physical asset service life-cycle assumptions - Physical asset salvage values at the end of service life-cycle
6. Obtain traffic data for base case and project alternatives for explicitly-modeled periods	- Travel demand and traffic assignment models - Hourly, daily, and seasonal traffic volumes, speeds, and occupancy before and after improvement - Traffic growth rate factors - Volume-delay function factors - Peak-spreading assumptions
7. Measure agency costs for base case and project alternatives	- Project direct agency costs of construction - Discounted life-cycle costs of maintenance and rehabilitation
8. Measure user costs for base case and project alternatives for affected links or networks	- Operating, delay, crash, and emission costs during construction - Life-cycle vehicle operating costs - Life-cycle travel time costs (including delay costs) - Life-cycle accident costs - Life-cycle air emission costs
9. Calculate overall agency and user benefits as the summation of respective differences in agency and user costs between a project alternative and the base case	- Data from Steps 7 and 8 - Life-cycle agency benefit formulae - Life-cycle user benefit formulae

2.1.3 Calculation of Agency Benefits Using the Life-Cycle Cost Analysis

Life-cycle cost analysis for physical 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 and rehabilitation associated with the assets. The agency benefits are regarded as reductions in life-cycle agency costs resulted from a certain amount of investments. As highway asset management involves various physical assets that have different service lives, life-cycle costing needs to be carried out to allow comparing the merits of investments on an equal basis. The following section briefly describes life-cycle agency cost analyses conducted on highway pavements and bridges in the last ten years.

2.1.3.1 Pavement Life-Cycle Agency Cost Analysis

The Federal Highway Administration (FHWA) has made a concerted effort for the use of life-cycle cost analysis in highway pavement design (FHWA, 1998). In a research on life-cycle cost analysis of rigid pavements, Wilde et al. (1999) came up with the life-cycle cost component framework for rigid pavements. Three cost components were indicated as agency costs, user costs, and external costs. In the agency cost component, it included initial construction cost and subsequent costs of maintenance, rehabilitation, and overlays. Rehabilitation and maintenance costs were calculated as per the prediction of distress that would occur by the end of each year and initial costs as per the design.

Hicks and Epps (1999) presented the establishment of alternative design strategies with a logical comparison between conventional mixtures and the mixture containing asphalt rubber pavement materials. Estimate of agency costs included the construction costs, all administrative costs including supervision and preliminary engineering costs, and routine and preventive maintenance and rehabilitation costs that would be invested within the analysis period. Salvage value was taken into account to compare the investments by the end of the analysis period and is a function of expected life of rehabilitation alternate, a portion of expected life consumed, and costs of rehabilitation strategies.

Hall et al. (2003) presented guidelines for life-cycle cost analysis of pavement rehabilitation strategies. These researchers discussed key issues that need serious considerations while adopting rehabilitation strategies. The key issues included selection of appropriate analysis period difference in vehicle operating costs in relation to predicted serviceability trends and differences in user delay costs in relation to lane drop time and length.

Falls and Tighe (2003) presented improving life-cycle cost analysis through the development of cost models using the Alberta roadway maintenance and rehabilitation analysis application. These researchers particularly examined maintenance cost models to compute maintenance costs that form a part of life-cycle cost analysis and could be utilized to analyze the rehabilitation alternatives using location-based data relevant to surface condition data and maintenance work. Such type of application would help improve system for monitoring and tracking costs.

Labi and Sinha (2003) developed life-cycle preventive maintenance cost-effectiveness models for different pavement families that were categorized according to pavement type, traffic, and service class. The functional forms of the preventive maintenance cost-effectiveness models suggested that the cost-effectiveness of preventive maintenance was a function of preventive maintenance effort, expressed in dollar values per lane-mile of road. The models could help conduct tradeoff analysis of different investment strategies over pavement service life-cycle.

Peshkin et al. (2005) studied systematic preventive maintenance and the optimum timing strategies to achieve minimum life-cycle costs. The methodology was based on analyzing pavement performance over a period of time to identify the optimal timing of treatment. The optimal timing was said to be the point of greatest benefit-to-cost ratio. Benefits were measured as the quantitative influence on pavement performance measured in relation to one or more condition indicators as rutting, cracking, and friction. Costs included agency costs for the treatments, work-zone user delay costs, costs of rehabilitation at the point where the preventive maintenance was considered failed, and costs of routine maintenance.

Harrigan (2002) investigated the performance of pavement subsurface drainage and conducted the life-cycle cost analysis to illustrate the various subsurface drainage features. Effects of subsurface drainage on flexible and rigid pavements were studied. The methodology adopted for the study was on impact of subsurface drainage, direct comparisons of the performance of drained and non-drained experimental sections, and distress predictions for mechanistic-empirical models based on all available performance data.

2.1.3.2 Bridge Life-Cycle Agency Cost Analysis

Purvis et al. (1994) conducted life-cycle cost analysis of protection and rehabilitation of concrete bridges relative to reinforcement corrosion. The rehabilitation work was applied only when the concrete deterioration was associated with chloride induced corrosion of reinforcing steel. Agency costs included deck and structural treatment costs, while user costs included prior treatment costs for their effect on traffic flow and during treatment costs. Computer method of life-cycle cost analysis was proposed to determine the activity timing aimed to minimize life-cycle overall discounted agency and user costs.

Meiarashi et al. (2002) compared two highway suspension bridges made both of conventional steel and advanced all-composite of carbon fiber using life-cycle cost analysis. The initial construction and maintenance costs were taken into account for the life-cycle cost analysis.

Hawk (2003) carried out bridge life-cycle cost analysis that categorized the overall costs into three different categorizes: agency costs, user costs, and vulnerability costs that included both agency and user costs. In the life-cycle agency cost analysis, cost items included routine maintenance costs, bridge element rehabilitation costs, bridge element replacement costs, and bridge replacement costs. User costs included detour costs and crash costs. Vulnerability costs consisted of condition-related reduction in load capacity, life or both, seismic vulnerability, bridge scour, and overloads. As part of the study, a Bridge Life-Cycle Cost Analysis software tool was developed to evaluate two fronts associated with bridges. First, it could be used to assess the tradeoffs between the initial cost and long term maintenance. Second, it could provide information on whether rebuild of a bridge to the future capacity was feasible or expansion in the future would be better. The strength of the program was its flexibility of varying costs and timing in the analysis.

Chandler (2004) developed life-cycle cost models to evaluate the sustainability of bridge decks. Both agency costs and social costs were considered in the analysis. Agency costs included construction costs and salvage value at the end of useful service life-cycle. The social costs were comprised of emission damage costs from agency activities, congestion, delays, crashes, and vehicle operating costs across all stages of bridge service life-cycle. To model the life-cycle cost, two types of bridge decks were compared. Decks with conventional concrete joints were compared with engineered cement composite link-slabs. It was found that fluctuations on annual average daily traffic had major effect while detours had little effect on bridge life-cycle costs.

2.1.4 Calculation of User Benefits

2.1.4.1 Average Variable Cost, Marginal Cost, and Price (Lee, 2000)

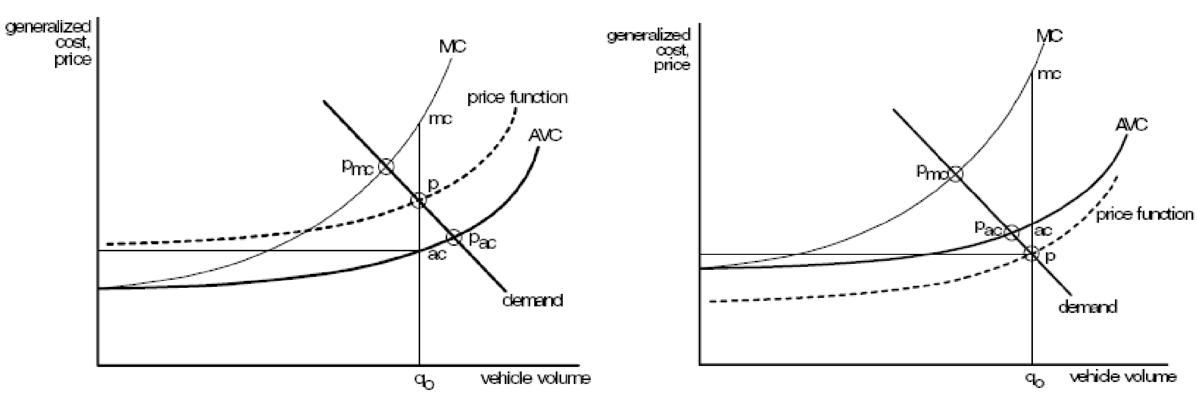
The total transportation costs can be broken down into fixed costs and total variable costs. As Table 2.3, total variable costs are classified as agency costs, user costs, externalities, and user charges. Variable social costs include agency costs, user costs, and externalities, excluding user charges. These costs are variable because they increase with vehicle miles traveled. The average variable cost, defined as the combined average unit cost per vehicle-mile of variable social costs, might rise, decline or remain constant with vehicle volume. Most of the components of variable social costs vary slightly with volume due to congestion, but the one that varies by far the most is travel time. The marginal cost is the additional cost associated with the supply of an additional unit of travel. Price is the cost to the road user and it includes user costs and user charges that vary with usage. The average variable cost (AVC), marginal cost (MC), and price as a function of the vehicle volume provide the information necessary for calculating user benefits.

Table 2.3. Transportation Variable Cost Categories and Items

Variable Cost Category	Variable Cost Item	Total Variable Costs	Variable Social Costs	Price
Agency Costs	- Construction costs	√	√	
	- Rehabilitation costs	√	√	
	- Maintenance costs	√	√	
	- Operation costs	√	√	
User Costs	- Vehicle operating costs	√	√	√
	- Travel time	√	√	√
	- Vehicle crashes	√	√	√
Externalities	- Vehicle air emissions	√	√	
	- Vehicle noise pollution	√	√	
User Charges	- Fuel tax	√		√
	- Tolls	√		√

Assuming a base case and one project alternative case, the physical characteristics of each case are given by the marginal cost and average variable cost curves (excluding fixed costs and fixed charges such as the annual vehicle registration fee), while the price curve constitutes the policies affecting how the highway system is operated. The marginal cost, average variable cost, and price are assumed to be converted into dollar values, referred to as generalized cost or generalized price, meaning that it combines money and in-kind components on the same scale.

As shown in Figure 2.1, marginal cost, average variable cost, and price to the user at any given vehicle volume are all different. Marginal cost and average variable cost are mathematically related, and will diverge if any component of cost varies with volume or volume-to-capacity ratio. That is, marginal cost is unequal to average variable cost if average variable cost goes up or down with volume. Because travel time for unit distance of travel rises with congestion, for most volume levels marginal cost lies above average variable cost.



(a) Price function above average variable cost function (b) Price function below average variable cost function

FIGURE 2.1. Illustration of marginal cost, average variable cost, and price curves.

Because users are faced with the average rather than the marginal cost, it is frequently assumed that price and average variable cost are the same, but this usually is not true because of user charges, agency costs, and externalities. The marginal cost and average variable cost functions are mathematically related, such that either one could be derived from the other, but only average variable cost can be observed empirically. Total variable cost can be measured either as the area under the marginal cost curve (up to q_0) or as the average variable cost (ac) times the volume (q_0), the later being a rectangle.

The price function in Figure 2.1(a) is shown as lying above average variable cost. This might be the case if variable user charges exceed variable agency costs and externalities. If the reverse is true, then the price curve lies below average variable cost curve, as shown in Figure 2.1(b).

For congested conditions, it is unlikely that price will be above marginal cost without a congestion-related toll, but price could be above average variable cost. Whether price is above or below average variable cost depends upon the magnitude and valuation of agency costs and externalities relative to user charges.

Vehicle volume could be determined by any of the three functions: by marginal cost at p_{mc} for efficient pricing and first-best evaluation; by average variable cost at p_{ac}, which ignores actual user charges, agency costs, and externalities; or by the price function at *p*, which is the most general case. The inefficiency from not pricing at marginal cost is given by the triangular bounded by p_{mc}, mc, and *p*.

2.1.4.2 Project Net User Benefits

A highway improvement project will change user costs by some amount, resulting in user benefits. Reductions in vehicle operating costs, travel time, and vehicle crashes are both reductions in price and real benefits. Savings in agency costs and externalities are real benefits but not included in the price, whereas savings in user fees are not real benefits. The impacts of each improvement can be estimated from its induced traffic volume based on the price and demand curves and variable cost savings. These net user benefits are estimated for the current period, and subsequent periods, over the lifetime of the improved highway facility.

Highway improvements such as reconstruction, rehabilitation, and capacity expansion that reduce congestion by expanding capacity or that reduce vehicle operating costs or vehicle crashes, have the effect of lowering the price to the user and stimulating greater volumes, depending upon the elasticity of demand. If the short-run price elasticity is non-zero, changes in the generalized price will cause changes in volume, within the same period, by movement along the demand curve. To some extent, capacity expansions are self-limiting, in that induced traffic reintroduces congestion, which offsets some of the initial time savings from expansion. This supply-demand equilibrium may not result in as high a volume as would be the case without congestion, but congestion will remain below the original congestion level before the capacity expansion. It is not possible for the same level of congestion to return after the expansion as before, because the short-run demand curve shifts downward to the right, and demand in the short run stays on the same demand curve. In subsequent demand periods, shifts in the demand curve might lead to higher congestion than in the current period, but such demand growth would be at least partly exogenous.

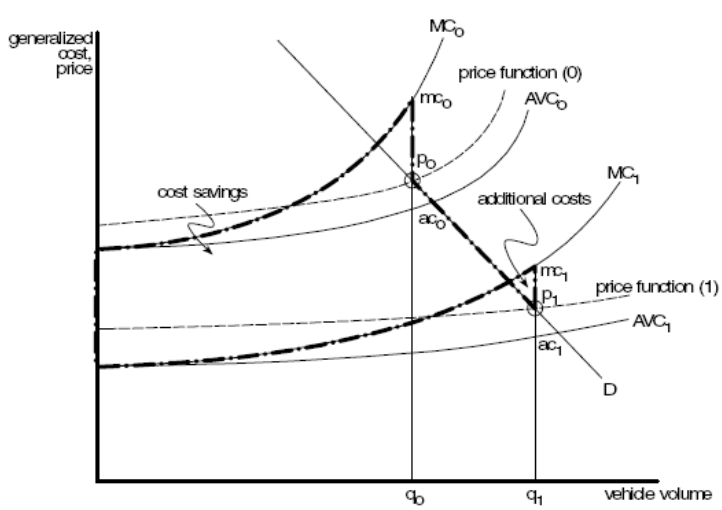


FIGURE 2.2. Illustration of the user benefits of a highway project.

Benefits of a highway project are generally a combination of cost savings and additional travel. Figure 2.2 illustrates the user benefits of the project. It assumes price lies above average variable cost. The project user benefits can be estimated in two ways: i) using the combination of marginal cost and demand curve; and ii) using the combination of average variable cost and demand curve.

2.1.4.3 Project User Benefits Estimated Using Marginal Cost and Demand Curves

As Figure 2.2, total variable costs for the base case without project implementation are represented by the area under the marginal cost curve up to the existing volume q_0. For the alternative case with project implementation, the corresponding area is lower but extends out to volume q_1. The cost difference is an area of cost savings between the two curves up to q_0, and an area of additional costs under marginal cost curve MC_1 from q_0 to q_1. The latter is offset by the (not necessarily equal) incremental benefits from the additional travel, represented by the area under the demand curve from q_0 to q_1. The resulting project user benefits are the area outlined by the dot-dash line. It can be described as the area between the two marginal cost curves and under the demand curve.

Where marginal cost crosses above the demand curve, the area marked “additional costs” is negative. These negative benefits are a consequence of under-pricing the project alternative, relative to marginal cost pricing. The project user benefits could be increased by this amount if the new project is efficiently priced. Correspondingly, the project user benefits would be smaller if the inefficiency from under-pricing the base case is not included.

2.1.4.4 Project User Benefits Estimated Using Average Variable Cost and Demand Curves

Areas under the marginal cost curve can also be represented by rectangles constructed from the average variable cost curve using the following relation:

$$\int_0^q MC = q \times AVC_q \qquad (2\text{-}1)$$

Without loss of generality, assuming that the price curve is positioned above the average variable cost curve. As shown in Figure 2.3, the area under MC_0 up to q_0 is equal to the rectangle whose length is q_0 and whose height is ac_0. Similarly, the area under MC_1 up to q_1 is equal to the rectangle q_1 by ac_1. The difference between these two rectangles is the shaded area labeled “delay and cost savings,” minus the additional costs from q_0 to q_1, plus the area under the demand curve from q_0 to q_1. This shaded area is exactly equal to the outlined area derived from the marginal curves.

In practice, a distinction is made between trips that are already being made in the base case old trips q_0, and new trips from q_0 up to q_1 generated by the reduction in price from p_0 to p_1. A reason for making this distinction is the nature of the benefits to the two groups: Existing old users have demonstrated their willingness to pay for their travel, and so the benefits to them are the cost savings over their previous generalized cost. In contrast, new trip makers on this facility have not shown any willingness to pay. Their benefits must be estimated from the demand curve as incremental consumer surplus and producer surplus over what they actually pay when using the improved facility.

Consumer surplus is the amount users would be willing to pay above what they actually pay, measured as an area under the demand curve between the “with” and “without” induced vehicle volumes and above the price. The incremental consumer surplus applies to induced “new” trips and the relevant volumes are q_0 (without improvement) and q_1 (with improvement). The incremental consumer surplus is a triangular area whose hypotenuse is the demand curve between p_0 and p_1, and whose legs are (p_0 - p_1) and (q_1 - q_0).

Producer surplus is an area under the demand curve that is below what users pay but above short-run variable cost. Normally, user fees are regarded as transfers and therefore ignored in estimating benefits, but here it is simply a part of the means for valuing induced travel. Like consumer surplus, it indicates a willingness to pay for new trips. A congestion toll generates producer surplus, but only the portion on new trips is counted as a benefit; the portion applying to old trips is already counted in the cost and time savings on old trips. The net of toll revenues above incremental agency costs and externalities is producer surplus.

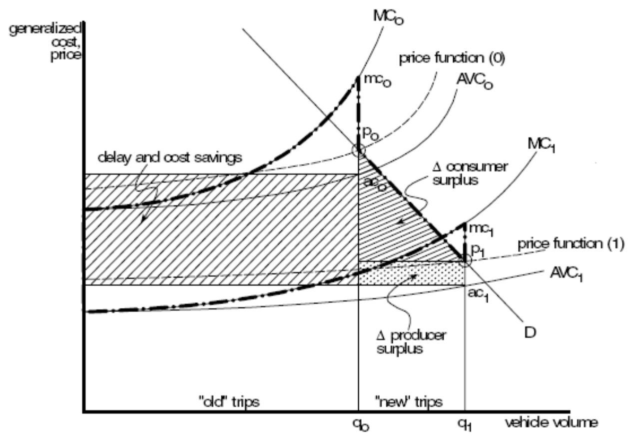


FIGURE 2.3. Estimation of project user benefits using average variable cost with price curve above average variable cost curve.

Figure 2.4 shows a situation in which price curve is below average variable curve for both the base case and project alternative case. The outline of project user benefits based on marginal cost is essentially the same, but the area defined by average variable cost curves has a somewhat different shape. Savings on old trips start above the current price, because the elimination of externalities in the base case is a benefit. Correspondingly, the benefits stop farther up, because some of vehicle operating cost and travel time savings are offset by agency costs or externalities in the project alternative case. Cost savings would come down to p_1 were it not for the new externalities. The incremental consumer surplus is the same in both figures, but a share of it is offset by the negative producer surplus where the toll revenues are below incremental agency costs and externalities.

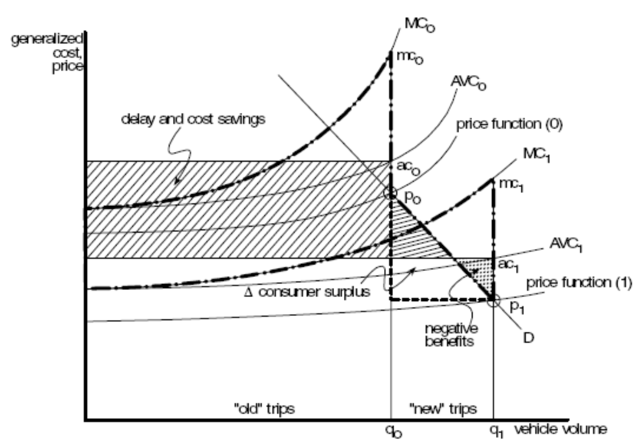


FIGURE 2.4. Estimation of project user benefits using average variable cost with price curve below average variable cost curve.

In summary, the primary components of project user benefits are savings of vehicle operating costs, travel time, and crash costs on old trips, incremental consumer surplus on new trips, and producer surplus on new trips.

2.1.4.5 Calculation of User Benefits on a Directly Affected Road Segment with Shift in Demand

Provided with a demand curve, the consumer surplus is the difference between what road users in the aggregate would have been willing to pay, and what they are actually asked to pay. The change in consumer surplus between a project alternative and the base case is considered as the user benefits associated with the project alternative. For a generalized case where the demand curve shifts upward as a result of a project improvement, the user benefits can be calculated as illustrated in Figure 2.5. The user benefits could be the daily, weekly, monthly or annual benefits of either element of vehicle operating costs, travel time, and vehicle crashes. The reduction in vehicle emissions can be considered as external user benefits.

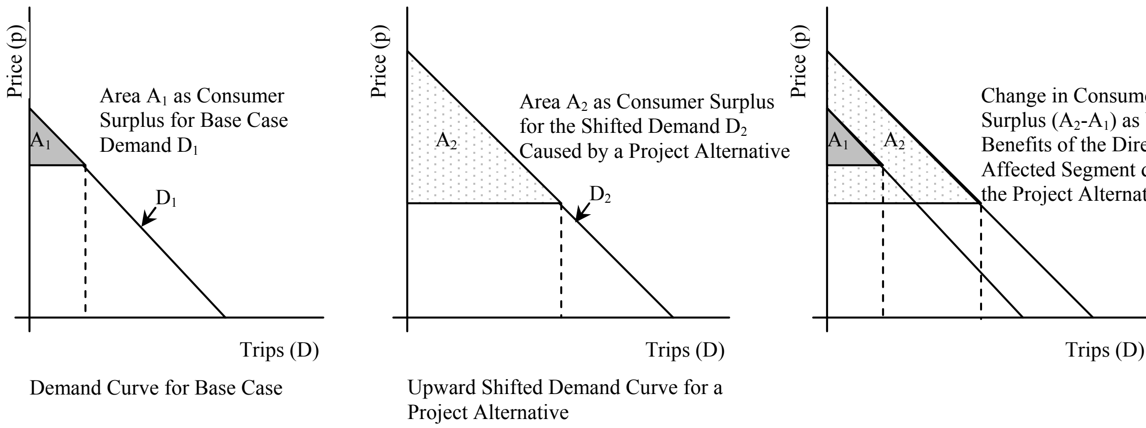


FIGURE 2.5. Illustration of calculating user benefits on a directly affected road segment with shift in demand.

2.1.4.6 Calculation of User Benefits on an Indirectly Affected Road Segment with Shift in Demand

If improvements cause traffic to shift to the improved segment, other indirectly affected segments may see a backward shift in demand on the indirectly-affected segments. That is, the travel demand on the indirectly-affected segments is less at every user cost. As illustrated in Figure 2.6, the change in consumer surplus is just analogues of the change of consumer surplus that is measured on the directly affected segment. The approach can be applied to every affected link to accounts for all changes in consumer surplus.

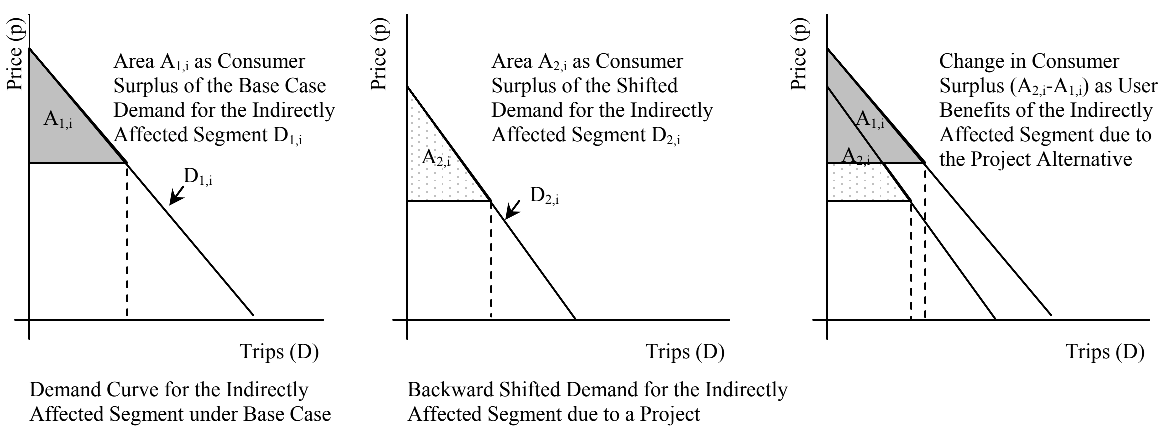


FIGURE 2.6. Illustration of calculating user benefits on an indirectly affected road segment with shift in demand.

2.1.4.7 Overall User Benefits of a Project

The overall user benefits of a highway project is the aggregation of changes in all consumer surpluses associated with project directly and indirectly affected road segments. Once obtaining an estimation of the overall user benefits in the first year of the physical asset useful service life, the overall user benefits for the future years can be extrapolated. This will help determined the life-cycle user benefits for the project.

2.1.5 Unit Values of User Cost Elements

2.1.5.1 Vehicle Operating Unit Costs

Vehicle operating costs refer to costs of fuel, oil, tire wear, maintenance and repair, and mileage-dependent vehicle depreciation and are measured in terms of dollars per vehicle-mile of travel.

Transportation projects can affect vehicle operating costs directly by improving operating conditions such as fewer changes in speed, reduced grades, smoother pavements, and wider curves or indirectly by influencing traveler behavior including more frequent usage and more direct routing. The highway vehicle operating costs are affected by vehicle type, vehicle speed, speed changes, gradient, curvature, and road surface condition, as briefly described in Table 2.4. In addition, Table 2.5 provides a range of estimates used in several benefit-cost models.

TABLE 2.4. Factors Affecting Vehicle Operating Costs

Factor	Brief Description
1. Vehicle type	Generally, cars have lower operating costs than trucks, due to lower fuel and oil consumption, and lower price of vehicle and parts, maintenance and repairs. Since vehicle technology, fuel efficiency and price/costs change over time, vehicle operating costs for various classes of vehicles will also change and must be periodically updated.
2. Vehicle speed	Empirical research indicates that vehicle speed is the dominant factor in determining vehicle operating costs. They decreases as vehicle speed increases, reaching an optimum efficiency point at mid-range speeds of approximately 55 mph, after which point costs will increase as vehicle speed increases further. Obviously, vehicle operating costs will get higher under congested traffic conditions and when vehicles are idling at stop-controlled/signalized intersections, ramp meters, and railroad crossings.
3. Speed changes	Empirical research indicates that vehicle operating costs increase with speed change cycles and the added cost of speed cycling is higher at higher speeds.
4. Gradient	Driving a vehicle up a steep, positive grade requires more fuel than driving it along a level road at the same speed, and the additional load on the engine imposes added costs of maintenance. Roadway sections with negative gradient would have an opposite effect. However, as the steepness of the down grade increases, it may be necessary to apply the brakes and this also imposes an added operating cost burden.
5. Curvature	Curves impose costs through the centrifugal force that tends to keep the vehicle following a tangent rather than a radial path. The force is countered by super-elevation of the roadway and the side friction between the tire tread and the roadway surface. As a result, there is a greater usage of energy and more fuel is required to negotiate curved sections. In addition, the side friction increases tire wear and raises this component of operating costs.
6. Road surface condition	The motion of a vehicle on a rough surface meets with greater rolling resistance, which requires more fuel consumption compared to traveling at a similar speed on a smooth surface. The roughness of road surface contributes to reduction of speed, additional tire wear and influences the vehicle maintenance and repair expenses incurred in the operation of a vehicle.

TABLE 2.5. Summary of Vehicle Operating Cost Estimation Methods

Model	Attribute				
	VOC Items	Factors Considered	VOC Range $/veh-mile (Year)	Vehicle Types Included	Source
2003 AASHTO Red Book	Fuel, oil, tire, maintenance	speed, speed cycling, grade, curvature, pavement condition	Auto: - 0.039-0.117 gal fuel/veh-mile Truck: - 0.158-0.503 gal fuel/veh-mile (1992) Car, SUV, and van: - $0.095 - 0.124/ veh-mile (2000)	Car, SUV, van, truck	AAA (1999) Cohn et al. (1992)
CAL-B/C	Fuel, non-fuel	Speed (for fuel only)	Auto: - 0.033-0.182 gal fuel/veh-mile - $0.165/veh-mile for non-fuel cost (2000) Truck: - 0.008-0.511 gal fuel/veh-mile - $0.285/veh-mile for non-fuel cost (2000)	Auto, truck	USDOT (1992)
HERS-ST	Fuel, oil, tire, maintenance and repair, depreciation	Speed, speed cycling, grade, curvature, and pavement condition	$0.18 (1995)	2 car types, 5 truck types	Zaniewski et al. (1982)
STEAM	Fuel, tire, maintenance and repair	Speed (for fuel only)	$0.05 - 0.09 (1994)	Car, truck	USDOT (1992)
StratBENCOST	Fuel, oil, tire, maintenance and repair, depreciation	Speed, speed cycling, grade, curvature, and pavement condition	$0.17 - 0.32 (1996)	Car, truck, bus	Zaniewski et al. (1982)

2.1.5.2 Value of Travel Time

Highway improvement projects often lead to higher speeds and lower travel times for drivers, passengers, and freight. Since travel time reductions can make-up a major portion of user benefits, it is important to use an appropriate value of time when converting these benefits into dollar amounts. The time cost of travel generally includes two components: the resource cost reflecting the value to the traveler of an alternative use of time such as work; and the disutility cost as the level of discomfort, boredom or other negative aspect associated with time lost due to travel. Table 2.6 lists factors affecting the value of travel time.

TABLE 2.6. Factors Affecting the Value of Travel Time

Travel Time Cost Component	Factor	
1. Resource Cost	a. Wage rate	It is generally thought that higher income groups value travel time at a higher price than lower income groups. The USDOT recommends that different wage rates be used as the basis for calculating time values for truck drivers, air travelers, and travelers on surface passenger modes.
	b. Trip purpose	There is consensus that on-the-clock work travel should be valued at the wage rate including fringe benefits, while other trip purposes should be valued at some fraction of the wage rate.
	c. Amount of timing saving	There has been substantial disagreement in the literature on the value of small units of time. Some studies suggest that small increments of time have lower unit values than do larger increments of time. Other valued time savings at the same rate, regardless of the amount of time savings.
2. Disutility cost	a. Congestion	Travel under congested conditions puts extra stress on the driver. As a result, reductions in travel time during peak periods, which are most likely to be congested, are likely to be valued more highly than reductions in travel time during off-peak periods.
	b. Passenger versus driver time	It is logical that the stresses of driving may make travel time savings more important to drivers than to passengers and to suggest a higher value of time for drivers.
	c. Level of service, walking, and waiting time	There is disagreement about whether distinctions should be made between transportation modes due to differences in comfort and other service attributes. It is generally accepted that time spent walking and waiting for a vehicle exposure to adverse weather has a higher value to the rider than time spent riding in the vehicle.

The methods derived for measuring value of travel time typically fall into five types of analyses: mode choice, route choice, speed choice, dwelling choice, and wage rate-based analyses. These methods are briefly summarized in Table 2.7.

TABLE 2.7. Methods for Estimating the Value of Travel Time

Method	Brief Description
1. Mode choice	Mode choice analysis attempts to compare a fast, but expensive mode with inexpensive, but slow one. The difference in cost is presumably equal to the value of the difference in time. Most of these analyses compare automobiles with some sort of transit.
2. Route choice	In route choice analysis, a slow and inexpensive route option is compared with a faster and more expensive route option for a single travel mode. The difference in cost is presumably equal to the value of the difference in time.
3. Speed choice	Speed choice analysis is one attempt to supplement the results of route choice analysis. The analyses are based on the economic assumption that rational, utility maximizing individuals adopt driving speeds that minimize their total trip costs. While travel time is one component of the trip cost, there are other trip costs, such as vehicle operating costs and accident costs. Assuming that all costs are perceived by drivers and that the least cost speed is selected, the perceived time costs can then be determined.
4. Dwelling choice	In this form of analysis, the value of time is calculated by comparing housing value against the time it takes to reach the work. The analysis results can be used to corroborate other estimating methods.
5. Wage rate	For "off-the-clock" travel, the hourly wage rate is treated as a standard against which the value of time is measured. The concept underlying this approach is that travelers' hourly wages give the opportunity cost of their time. The percentage of wage rate appears to be a convenient metric to measure value of time associated with "off-the-clock" travel.
	For the value of "on-the-clock" travel time, there is a general consensus that a driver's wage rate is the right measure of the value of his or her time when highway travel is part of the person's work. Thus, the average labor cost for truck drivers is an appropriate value of time for truck traffic.

The values of travel time established in various existing models are summarized in Table 2.8.

TABLE 2.8. Summary of Values of Travel Time in Existing Models

Model	Auto	Bus	Truck	Source
2003 AASHTO Red Book STEAM CAL-B/C	- 50% of the wage rate for driving alone commute - 60% of the wage rate for carpool driver commute - 40% of the wage rate for carpool passenger commute - 50% of the wage rate for personal local trip - 70% of the wage rate for personal intercity trip - 100% of total compensation for business	- 50% of the wage rate for in-vehicle commute - 50% of the wage rate for in-vehicle personal - 100% of the wage rate for non-business waiting, walking or transfer time - 100% of total compensation for business	- 100% of total compensation for in-vehicle business - 100% of total compensation for business waiting time	USDOT (1992)
HERS-ST	Work-related travel: $9.59/veh-hour (1988 dollar)	-	Work-related travel: - $10.87/veh-hour for 4-tire truck - $20.42/veh-hour for 6-tire truck - $23.34/veh-hour for 3-4 axle truck - $25.94/veh-hour for 4-axle comb. truck - $26.09/veh-hour for 5-axle comb. truck	USDOT (1992)
	Non-work travel: 60% of the wage rate	-	Non-work travel: 60% of the wage rate	Jack Faucett Assoc. (1991)
StratBENCOST	- Low: $10.97/veh-hour - Med: $11.78/veh-hour - High: $23.36/veh-hour (1996 dollar)	- Low: $77.25/veh-hour - Med: $82.94/veh-hour - High: $164.46/veh-hour (1996 dollar)	- Low: $30.07/veh-hour - Med: $32.28/veh-hour - High:$64.01/veh-hour (1996 dollar)	TTI (1990) Jack Faucett Assoc. (1991)

Note: The unit dollar values can be updated to current year dollars using relevant consumer price indices and producer price indices for non-trucks and trucks, respectively.

2.1.5.3 Vehicle Crash Unit Costs

Vehicle crashes can vary in severity and the number of individuals involved. By severity, vehicle crashes can be divided into fatal, injury, and property damage only (PDO) categories. Fatalities result in lost years of life, while injuries result in lost years of productive life. Injuries may also cause pain and suffering. In addition, all vehicle crashes result in property damages of varying severity. Table 2.9 presents methods valuating vehicle crash losses.

TABLE 2.9. Methods for Valuating Vehicle Crash Losses

Method	Brief Description
1. Direct cost	This method measures only the easily-measurable out-of-pocket costs of accidents, which include crash clean-up, injury treatment, property repair and replacement, accounting for workplace disruption, and insurance claims processing and related costs. The personal costs, emotional and physical, are ignored in the direct costs method.
2. Human capital	This method calculates values as a function of salary. As a result, lower values are computed for women and children than for men. This method ignores pain, suffering, and lost quality of life. Human capital costs are useful to determine the dollars lost to injury and death, and form the basis for legal compensation awards.
3. Years of loss plus direct cost	This method estimates two sets of costs: the years of life lost to fatalities and the years of productive life lost to nonfatal injuries, and the dollar value of the medical costs. Since the medical costs for a serious injury are much higher than for a sudden death, the combined value could be misleading.
4. Willingness-to-pay	This method involves evaluating the reduction of accident risk by estimating the amount people pay for small decreases in safety and health risks, often obtained through the analysis of safety equipment purchases made by individuals. The method places a value on people’s behavior of exchanging money, time, comfort, and convenience for safety. Frequently these values are added to the results of the direct cost approach to obtain an overall crash value.

The unit costs of vehicle crashes established in various existing models are summarized in Table 2.10.

TABLE 2.10. Summary of Vehicle Crash Unit Costs in Existing Models

Model	Fatality	Injury	PDO	Source
2003 AASHTO Red Book (2000 dollar)	Cost per fatal crash: $3,366,388	Cost per injury crash: Critical: $2,402,997 Severe: $731,580 Serious: $314,204 Moderate: $157,958 Minor: $15,017	Cost per PDO crash: $3,900	NHTSA (2000)
	Delay component: $9,148	Delay component: Critical: $9,148 Severe: $999 Serious: $940 Moderate: $846 Minor: $777		
CAL-B/C (2000 dollar)	$3,104,738	$81,572	$6,850	NSC (1995)
HERS-ST (1988 dollar)	$2,000,000	Urban: $10,000- 18,000 Rural: $17,000- 20,000	Urban: $5,000- 6,000 Rural: $4,000- 5,000	Jack Faucett (1991)
STEAM (1997 dollar)	$2,726,350	$59,718	$3,323	FHWA (1994)
StratBENCOST (1996 dollar)	Low: $809,054 Med: $3,521,359 High: $8,097,408	Low: $14,946 Med: $83,848 High: $216,698	Low: $1,442 Med: $5,806 High: $11,720	FHWA (1994)

2.1.5.4 Vehicle Air Emission Unit Costs

Transportation investments affect the environment because of the construction process, impacts of the physical asset itself, and resulting changes in travel behavior. Vehicle emissions generally fall into two categories: vehicle emit pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_X), volatile organic compounds (VOC), particulate matter (PM), and oxides of sulfur (SO_2); and greenhouse gas emissions, mainly caused by carbon dioxide (CO_2). Air pollutants can cause damage to human health, building materials, and agriculture and vegetation, as well as limit visibility. Increasing concentrations of greenhouse gases in the atmosphere may be causing changes in the Earth's climate that could potentially impose substantial costs on society in terms of flooding, crop loss, and increased incidence of disease. Factors that affect vehicle air emission quantities are summarized in Table 2.11.

TABLE 2.11. Factors Affecting Vehicle Air Emission Quantities

Factor	Description
1. Vehicle age	The engine fuel efficiency decreases with the increase of vehicle age. This accordingly will increase air emission rates.
2. Vehicle speed	Speeds are of particular importance in determining vehicle emission rates. In general, VOC emission rates tend to drop as speed increases, whereas NO_X and CO emission rates increase at higher speeds (above 55 miles per hour).
3. Vehicle mix	Mix of vehicle types in the traffic stream and mix changes affect emission rates.
4. Traffic condition	Emission rates are also higher during stop-and-go, congested traffic conditions than during free flow conditions at the same average speed.
5. Ambient air temperature and cold-start trips	Starting a cold vehicle results in additional emissions because a vehicle's emissions control equipment has not reached its optimal operating temperature.

The air emission unit costs are typically estimated based either on damage costs or control costs. Damage cost valuation involves estimating the actual value of the harm caused by air emissions, whereas control cost valuation simply examines the cost of the measures necessary to reduce air pollutant emissions. Damage cost valuation is preferable because studies that use control costs to value air pollution rely on the assumption that the controls placed on pollution are efficient. The steps involved with a damage cost valuation are listed in Table 2.12.

TABLE 2.12. Damage Cost Method for Estimating the Unit Cost of Vehicle Air Emissions

Step	Description
1. Impact of pollutant emissions on air quality	Ambient air pollution concentrations are the result of air pollutant dispersion, reaction, and residence, complicated by meteorology and topography. These processes result in non-linear relationships between pollutant emissions and air concentrations that can be determined through computer modeling.
2. Increase of health problems caused by air quality deterioration	The dose-response functions can be used to estimate the increased risk of developing a certain adverse health effect, such as headaches, chronic respiratory problems or mortality, in response to increased air pollutant concentrations.
3. Dollar costs per health effect	Health impacts in monetary terms can be quantified using revealed preferences method that estimates costs based on people's behavior; and expressed preferences that asks people about the cost of an impact.
4. Estimation of unit costs	The unit costs per ton of pollutants emitted can be estimated based on information in Steps 1-3.

The unit costs of vehicle air emissions established in existing models are summarized in Table 2.13.

TABLE 2.13. Summary of Vehicle Air Emission Costs per Ton in Existing Models

Model	CO	NO_X	PM	SO_2	VOC	Source
CAL-B/C HERS-ST STEAM StratBENCOST (1996 dollar)	Rural - Mod: $10 - High: $50 Urban - Mod: $20 - High: $100	Rural - Mod: $1,525 - High: $3,625 Urban - Mod: $2,288 - High: $5,438	Rural - Mod: $1211 - High: $2411 Urban - Mod: $2422 - High: $4822	Rural - Mod: $1,601 - High: $8,401 Urban - Mod: $2,402 - High: $12,602	Rural - Mod: $1,054 - High: $2,754 Urban - Mod: $1,581 - High: $4,131	McCubbin and Delucchi (1996)

2.1.6 Classical Benefit-Cost Analysis Methods

2.1.6.1 Net Present Worth Method

The net present worth method uses the chosen discount rate to convert the project benefits and costs to equivalent present values and then compares these values. The present value of the benefits and costs is equal to the summation of the values of these effects multiplied by the present worth factor appropriate to the period over which the benefits and costs occur. The net present worth then equals the difference between the present-value benefits and costs.

2.1.6.2 Equivalent Uniform Annual Cost Method

The equivalent uniform annual cost method converts non-uniform series of project benefits and costs into uniform annualized amounts of benefits and costs, respectively. The annualized benefits and costs are then used to compare project alternatives on equal basis.

2.1.6.3 Benefit-to-Cost Ratio Method

The benefit-to-cost method compares the discounted benefits and costs for each project and then evaluates each alternative to another.

2.1.6.4 Cost-Effectiveness Method

The effectiveness of a project alternative is usually represented as a scaled quantity relating to a specific goal. For instance, number of car pools formed and reduction in vehicle air emission quantities. Cost-effectiveness ratios can thus be calculated to show the degree of goal attainment per dollar of net expenditure. This method is particularly useful when it is difficult to reach a consensus in unit values of user cost elements, such as values of travel time, vehicle crashes, and air emissions.

2.1.7 Risk Considerations in Highway Project Benefit-Cost Analysis

Highway project benefit-cost analysis is fraught with risk and uncertainty because of the nature of the information that is available, developed, and used. Forecasting future conditions of pavements and bridges, travel patterns, costs, and effect levels is based on many assumptions, extrapolation of past behavior, and less-than-perfect understanding of causal relationships. 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. Some notable probabilistic project benefit-cost analyses conducted are briefly discussed in the following:

Walls and Smith (1998) recommended life-cycle analysis on pavements and provided the detail computation process of user costs which they distributed evenly among the useful life period and introduced a probabilistic approach to deal with risk and uncertainty associated with the project. In the user cost analysis the study did not take account of the vehicle emissions but it put forth the idea of computing work zone user costs which were the delays, crashes, and increased vehicle operating costs during the maintenance and rehabilitation process. It combined variability of inputs to generate the probability distribution of the results. It essentially quantified the uncertainties using probability distribution resulted either from subjective or objective analysis. The normal distribution was used to define the variability of agency costs but for the cases which did not have measurable data triangular distribution was used.

Tighe (2001) conducted a probabilistic life-cycle cost analysis by incorporating mean, variance, and probability distribution for the typical construction variables, such as thickness and costs. The researcher concluded that the cost distribution followed a lognormal distribution rather than a normal distribution. Ignoring the lognormal nature of these variables would introduce significant biases in the overall life-cycle cost estimation.

Setunge et al. (2002) developed a methodology for life-cycle cost analysis of alternative rehabilitation treatments for bridge structures. The input parameters for the analysis were identified as initial construction costs; maintenance, monitoring, and repair costs; user costs; and failure costs. The methodology utilized Monte Carlo simulation to combine a number of probability distributions to establish the distribution of bridge whole life-cost costs.

2.1.8 Comparison of Available Benefit-Cost Analysis Software Tools

Table 2.14 lists software packages most often used by analysts to estimate the benefits of highway projects. The features of individual models in terms of level of analysis, special features, and software limitations are summarized.

TABLE 2.14. Comparison of Some Notable Benefit-Cost Analysis Models

Name	Source	Project Type	Level of Analysis	Special Feature	Limitation
2003 AASHTO Red Book	AASHTO	Highway operational improvements and safety projects	Project level	Travel time, VOC, and crash benefits of additional lanes, new highways, traffic control, signal systems, ITS improvements, pricing and regulatory policies; geometry, lane, access, and roadside safety improvements	Limited accounting for network effects; no accounting for modal interaction
Cal- B/C	CALTRANS	Highway, transit	Network level	Travel time, VOC, crash, and emission benefits of highway improvements, ITS, and transit improvements	No accounting for interaction between modes
HDM4	World Bank	Highway improvements	Network level	Includes 16 motorized and 8 non-motorized vehicle types; includes roadway deterioration model for asphalt, concrete, gravel, and dirt roads; estimates emissions and energy consumption	No accounting for interaction between modes
IDAS	Cambridge Systematics	ITS improvements	Project level	Estimates benefits and costs for signals, ramp metering, incident management, electronic payment, traveler information, weigh-in-motion, and traffic surveillance	Evaluates ITS options only
MicroBENCOST	TTI	Highway improvements and safety projects	Project level	Includes intersection and interchange delay, bridges, RR crossings, HOVs, and safety improvements; analyze emissions, construction delays; estimates discomfort costs based on road condition	Limited accounting for network effects; no accounting for interaction between modes
Roadside	AASHTO	Roadside improvements	Project level	Integrated with design tool	Only accounts for safety-related benefits
STEAM	FHWA	Highway, transit, TDM, tolls, multimodal	Network level	Accepts input from four-step models; separate analysis of peak and off-peak periods by trip purpose and mode; emissions; fuel consumption; revenue transfers	Some costs must be estimated outside model; requires trip tables and network from external travel demand model
StratBENCOST	HLB	Highway improvements	Network level	Risk analysis, environmental effects, separate modules for network-wide or single-roadway analysis; includes construction delays	No accounting for interaction between modes

2.2 Methods for Highway Project Selection

2.2.1 Classical Project Selection Techniques

Highway asset management entails a comprehensive view across a range of physical highway assets and their usage. The decision-making 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. 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 achievable at different funding levels can be defined. Ranking, prioritization, and optimization offer an approach that allows for selection 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. The impact of various funding levels can also be assessed (FHWA, 1991).

Optimization formulations using linear programming, integer programming, and dynamic programming techniques have been developed for project selection in the last decade in accordance with the objective of maximizing total agency benefits or minimizing agency costs to achieve certain condition levels. 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 2.15 summarizes typical project selection techniques used by selected state transportation agencies (Cambridge Systematics, 2000).

TABLE 2.15. Typical Highway Project Selection Techniques Used by Selected State Transportation Agencies

State	Asset Management Program Category	Typical Project Selection Technique
Arizona	- Interstate construction and reconstruction - Non-Interstate major construction - Bridge, railroad crossing, hazard elimination - Transportation system management	- Prioritization by benefit-cost analysis and sufficiency ratings - Expert opinion
California	- Highway Operation and Protection Program - Transportation Improvement Program - Traffic Systems Management Plan	Prioritization by scoring based on project technical merits
Indiana	- Bridge preservation - Pavement preservation - Safety and roadside improvements - System expansion - ITS improvements - Maintenance	- Prioritization by incremental benefit-cost analysis - Optimization by utility values
Minnesota	- Preservation - Management and operations - Replacement - Expansion	Ranking by sufficiency/ deficiency ratings, benefit-cost analysis, and cost-effectiveness analysis
Montana	- Maintenance - Rehabilitation - Expansion	Prioritization by incremental benefit-cost analysis
New York	- State pavement - Statewide congestion/ mobility	Ranking by sufficiency/ deficiency ratings, life-cycle cost, benefit-cost analysis, and cost-effectiveness
Oregon	- Preservation - Modernization - Operations Safety	Ranking by scoring based on project technical merits
Pennsylvania	- Bridge rehabilitation and replacement - Interstate/ expressway restorations - Congestion reduction - Safety, mobility, and congestion - New assets and services	Ranking by sufficiency ratings
Texas	- Added capacity and new location - Highway rehabilitation and construction - Bridge replacement and rehabilitation - Maintenance	Ranking by sufficiency/ deficiency ratings, and cost-effectiveness analysis
Washington	- Maintenance - Preservation and improvement - Operations	Ranking by benefit-cost analysis
Wisconsin	- Maintenance - Rehabilitation, restoration, and reconstruction - Interstate - Bridge	- Ranking by deficiency ratings, benefit-cost analysis - Multi-objective optimization by benefit-cost analysis

2.2.2 Optimization Models Developed for Project Selection

Due to budget restrictions, only a subset of candidate projects can be selected for implementation. Techniques used could be categorized as deterministic models and probabilistic models. These mainly included integer programming (Isa Al-Subhi et al., 1989; Weissmann et al., 1990; Zimmerman, 1995; Neumann, 1997), mixed integer nonlinear programming (Ouyang and Madanat, 2004), goal programming (Gepffrey and Shufon, 1992), dynamic programming (Feighan et al., 1988), multi-objective optimization (Teng and Tzeng, 1996; Vitale et al., 1996; Li and Sinha, 2004), agency-based analysis (Bernhardt and McNeil, 2004), Adaptive control approach (Durango and Madanat, 2002), stochastic optimization under uncertain future demand and model prediction (Friesz and Fernandez, 1979; Ben-Akiva et al., 1991), risk-based Markovian and Bayesian analyses (Harper et al., 1990; Harper and Majidzadeh, 1991; Madanat and Ben-Akiva, 1994; Cesare et al., 1994), fuzzy logic (Rewinski, 1991; Harper and Majidzadeh, 1993), and simulation (de la Garza et al., 1998).

2.2.3 Solution Algorithms for the Optimization Models for Project Selection

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 (Lorie and Savage, 1955). The capital budgeting problem is a special case of the Knapsack problem, where the objective is to select a subset of mixed projects from a large number of candidate projects proposed for the entire highway system in order to yield maximized overall benefits subject to budget constraints.

The optimization process for highway asset management is however more complicated 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, project interdependence relationships must be considered. In this case, project selection and programming for overall highway asset management evolves to a multi-choice multidimensional Knapsack problem. Multi-choice corresponds to multiple budgets for different asset management program categories, while multi-dimension refers to a multi-year analysis period. The objective is to select a subset from all economically feasible candidate projects to achieve maximized overall benefits under various constraints.

The multi-choice multidimensional Knapsack problem is considered as NP-hard. NP stands for non-deterministic polynomial. A NP-problem refers to the case if there exists a solution algorithm, a candidate solution to the problem can be verified in polynomial time. We will know whether the candidate solution is correct or wrong. A NP-hard problem is a problem such that any problem in NP category can be reduced to it in polynomial time, before being considered for verifying a candidate solution. Loosely speaking, the NP-hard problem is harder than the NP problem. For the Knapsack problem as being a NP-hard problem, the time requirement for generating the optimal solution grows exponentially with the size of the problem instances. Hence, an exact solution may not be readily available if the problem size becomes too large.

Algorithms for these problems can be classified into two group, exact algorithms and heuristic algorithms for approximate solutions. 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 multi-choice multidimensional Knapsack problem, including the multi-choice Knapsack problem, where multiple budget sources and a single analysis period are involved and the multidimensional Knapsack problem, where a single budget source and multiple periods for the analysis are considered, are briefly discussed as follows.

2.2.3.1 Exact Solution Algorithms

Sinha and Zoltners (1979) presented a branch-and-bound algorithm for the multi-choice Knapsack 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 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 led 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 multi-choice Knapsack 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 non-dominated solution to the multi-choice multidimensional Knapsack problem. Osorio and Glover (2001) presented a method of logic cuts from dual surrogate constraint analysis before solving the multidimensional Knapsack problem with branch-and-bound, and computational testing showed that the approach solved different problems in a reasonable amount of time.

2.2.3.2 Heuristic Solution Algorithms

Heuristic Solution Algorithms for the Multi-Choice Knapsack Problem. Zemel (1984) presented a linear time algorithm for the linear multi-choice Knapsack 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 multi-choice Knapsack problem with solution quality within a constant factor of optimality.

Heuristic Solution Algorithms for the Multidimensional Knapsack Problem. Frieze and Clarke (1984) described a polynomial time approximation scheme for the multidimensional Knapsack problem based on the used of a dual simplex algorithm for linear programming. Lee and Guignard (1988) presented an approximation algorithm for the multidimensional Knapsack problem that was controlled by three user-controllable parameters affecting the tradeoff between solution quality and computational time. Freville and Plateau (1994) introduced a subgradient heuristic algorithm for the multidimensional Knapsack 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. Teng and Tzeng (1996) suggested an effective distance heuristic optimization algorithm for the multidimensional Knapsack 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 multidimensional Knapsack problem. Computational results showed that the genetic algorithm generated superior solutions to a number of other heuristics with only a modest amount of computational efforts.

Heuristic Solution Algorithms for the Multi-Choice Multidimensional Knapsack Problem. Toyoda (1975) suggested a simplified heuristic algorithm based on Lagrangian relaxation for an approximate solution to the multi-choice multidimensional Knapsack 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. Moser et al. (1997) introduced a heuristic algorithm based on the Lagrangian multiplier method for a solution to the multi-choice multidimensional Knapsack problem with polynomial time complexity. Akbar et al. (2001) developed two heuristic algorithms for solving the multi-choice multidimensional Knapsack 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. More recently, Li and Sinha (2004) and Patidar et al. (2007) developed heuristic algorithms for overall highway asset management and bridge management using Lagrangian relaxation techniques.

2.3 Review Summary

2.3.1 Critiques on the Existing Methods for Project Evaluation and Expected Improvements

The existing methods for highway project evaluation generally estimate project agency and user benefits using the deterministic life-cycle costing approaches. A few studies found in the literature incorporated risk-based analyses of construction, rehabilitation, and maintenance variables for pavements and bridges, as well as highway user costs using Monte Carlo simulation to combine a number of probability distributions, such as lognormal and triangular distributions. These methods/studies treated all of the above mentioned variables simultaneously under risk. As a practical matter, in the analysis process some of the variables might be under certainty, while others might be under risk, and the combination of certain and risk cases might vary project by project according to their unique characteristics. Moreover, none of those methods/studies explicitly addressed cases where the agency cost and user cost variables are under uncertainty with no definable probability distributions.

The inability of existing methods to evaluate highway projects involved with uncertain factors motivates developing a new methodology that rigorously handles factors such as construction, rehabilitation, and maintenance costs; travel demand; discount rates under any combination of certainty, risk, and uncertainty in the project evaluation process. A factor under certainty refers to the case that it only maintains a single value. A factor under risk refers to the case where there exists a number of possible values associated with the factor and such values can be characterized by a defined probability distribution. A factor under uncertainty stands for the case where there are a number of possible values associated with the factor and a probability distribution for the possible values is not definable. The proposed methodology for project evaluation is expected to be applied as follows: If a factor is under certainty, its single value can be used for the computation. If a factor is under risk, the mathematical expectation of the possible values of the factor can be used for the computation. If a factor is under uncertainty, a single value will be estimated according to the possible values related to the factor using the uncertainty analysis theory and this value can then be utilized for the computation. For any highway project involved with any combination of certain, risk, and uncertain factors, the proposed methodology will help establish a unique amount of overall project benefits.

2.3.2 Critiques on the Models for Project Selection and Expected Improvements

State transportation agencies have been using ranking, prioritization, and optimization models for project selection. Optimization models are popular because of the inherent mathematical rigor. Both deterministic and stochastic optimization models were developed. Those stochastic models separately handled uncertainty inherited with travel demand and uncertainty induced by data and predictability of performance models on the selection of highway projects associated with pavements, bridges, and maintenance, respectively. In overall highway asset management, projects are bundled into contract packages for implementation. A single contract may contain multiple projects, requesting funds across different programs over a multi-year period. Hence, the optimization model for project selection must consider project interdependencies. In addition, highway investment decisions are usually made based on an estimated budget years ahead of the project implementation period. As time passes by updated budget information would become available, project selection decisions thus must be updated using the updated budget information. This study proposes to develop a new stochastic optimization model, along with an efficient solution algorithm, explicitly addressing project interdependency relationships and budget uncertainty that may significantly affect the project selection results.

CHAPTER 3:
PROPOSED METHODOLOGY FOR HIGHWAY PROJECT EVALUATION UNDER CERTAINTY, RISK, AND UNCERTAINTY

Increase of costs associated with construction, rehabilitation, and maintenance of highway pavement and bridge assets, coupled with shortfalls in highway budget, has led highway agencies to seek requisite decision-making tools that utilize economic and operations research techniques to arrive at long-term and cost-effective investments. One of such tools is life-cycle cost analysis (LCCA) that helps in the evaluation of overall long-term economic efficiency between competing investment alternatives for physical highway assets such as pavements and bridges (FHWA, 1998). However, the existing LCCA methods mainly deal with highway agency costs and do not always address the impacts of highways user costs in the analysis. Furthermore, the agency cost-based analysis does not necessarily examine the explicit effect of preventive maintenance in reducing the overall life-cycle costs in detail. The lack of user cost and maintenance cost considerations limits achieving the intended purpose of more comprehensive LCCA methods that incorporate risk- and uncertainty-based analysis functions. This chapter presents a generalized methodology for highway project benefit-cost analyses under certainty, risk, and uncertainty that overcomes these limitations.

3.1 Framework of the Proposed Methodology

The proposed methodology considers all agency and user costs in the service life-cycle of primary physical highway assets, such as pavements and bridges. Agency costs mainly consist of capital costs involved with project construction and the discounted future costs of maintenance and rehabilitation work. Whereas user costs are those concerned with vehicle operation, travel time, vehicle crashes, and vehicle air emissions under normal operations and work zone conditions (Figure 3.1). This section provides an overview of the methodology and detailed descriptions follow in the subsequent sections.

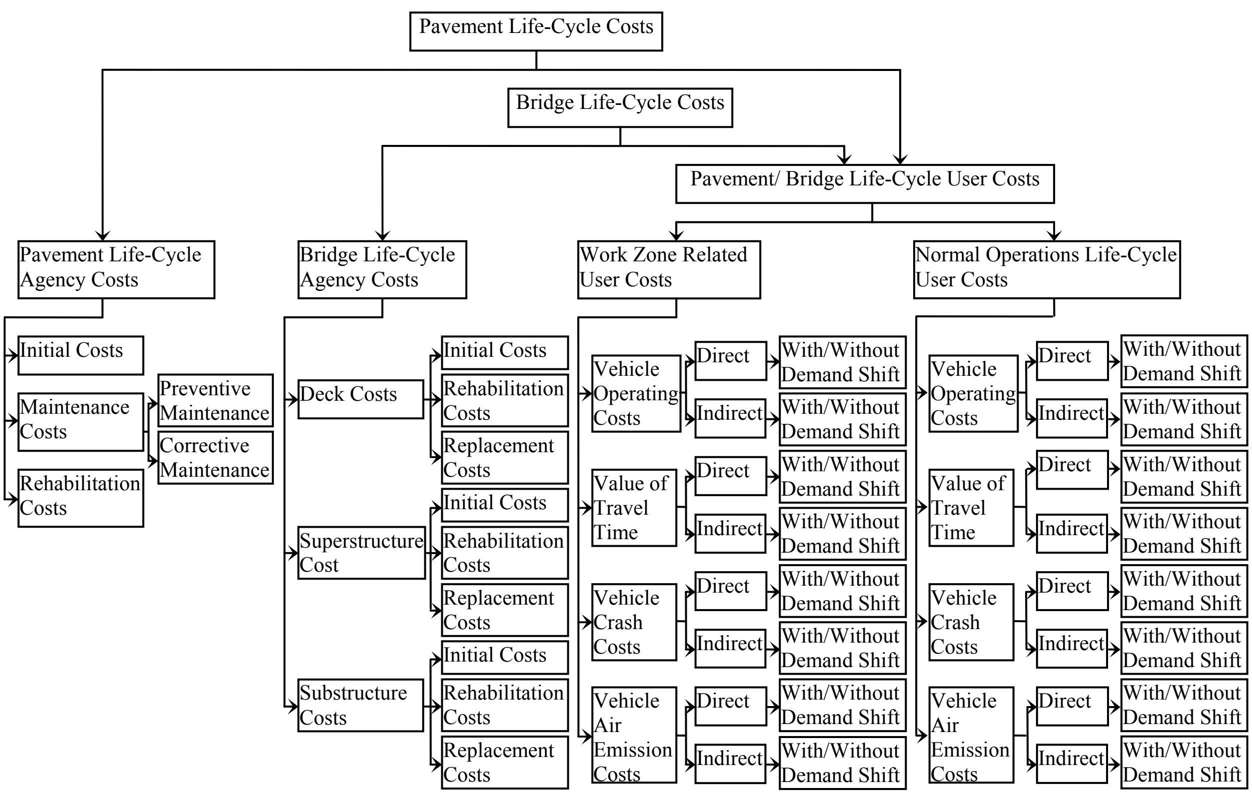


FIGURE 3.1. Highway pavement and bridge agency and user cost categories.

3.1.1 Project Direct Costs
The project direct costs generally include direct agency costs and additional user costs resulting from construction work zones. Direct agency cost elements largely cover capital costs of project land acquisition, design and engineering support, and construction. User costs related to construction activities include increased costs of vehicle operation and delays immediately upstream of and within work zones.

3.1.2 Physical asset Life-Cycle Agency and User Costs
In life-cycle cost analysis, the overall agency costs generally include direct agency costs regarding project construction and subsequent costs of maintenance and rehabilitation such as resurfacing and restoration incurred during physical asset service life-cycle. On the user costs side, the principal cost categories include vehicle operating costs, travel time, vehicle crashes, and vehicle air emissions and life-cycle user costs are estimated based on these user components for all years in the physical asset service life-cycle.

3.1.3 Overall Project Life-Cycle Benefits
3.1.3.1 Mechanistic versus Surrogate Effectiveness Measures of Benefits
Some studies have developed relationships that link the condition deterioration of physical highway assets such as pavements and bridges with traffic loading and non-load factors, and the expenditures needed for physical asset condition improvements. With such mechanistic methods, the benefits of highway projects could be measured directly in monetary terms. Other studies have surrogated project benefits by the area under the performance curve, with the rationale that physical highway assets with gentle sloping performance curves indicate better condition and higher service lives compared to those with steep sloping curves and consequently smaller area under the curves. The proposed methodology utilizes monetary terms to measure project benefits.

3.1.3.2 Overall Project Benefits in One Service Life-Cycle of Physical Highway Assets
The overall benefits of a highway project in physical asset service life-cycle may be extracted from both the agency and user perspectives. With the investment in physical highway assets as funded by projects, it may decrease physical asset life-cycle agency costs and instigate reductions or savings of life-cycle user costs. Such potential reduction in life-cycle agency and user costs is considered as the overall project benefits.

In order to estimate the change of life-cycle agency costs, the activity profiles represented by the frequency, timing, and magnitude of construction, maintenance, and rehabilitation work for major physical highway assets such as pavements and bridges need to be established. For instance, different activity profiles need to be established for flexible, rigid, and composite pavements; and for concrete and steel bridges, respectively.

3.1.3.3 Overall Project Life-Cycle Benefits in Perpetuity
For pavement or bridge assets, the life-cycle benefits in perpetuity can be quantified assuming that the predetermined life-cycle activity profiles be repeated infinite times.

3.2 Methodology for Deterministic Pavement Life-Cycle Agency Cost Analysis
This section briefly discusses the deterministic highway pavement life-cycle agency cost analysis. The discussion starts with an introduction to pavement types, design service life-cycle, repair treatment types, and repair strategies. Explanations are then given to the typical pavement life-cycle activity profiles. The next portion of the section concentrates on pavement life-cycle agency cost analysis for one service life and finally extends to perpetuity time horizon.

3.2.1 *Categorization of Pavement Types*

3.2.1.1 Flexible Pavements

Flexible pavements have a surface layer that consists entirely of an asphalt/aggregate mix laid over a granular treated or untreated base layer, and sometimes an untreated natural gravel subbase layer. For purposes of the present study, an asphalt pavement is one where all surface, base, and subbase layers contain an asphalt binder in varying proportions and aggregate gradations and quality (AASHTO, 1993; INDOT, 2002).

3.2.1.2 Rigid Pavements

Rigid pavements are commonly classified as jointed plain concrete pavements, jointed reinforced concrete pavements, and continuously reinforced concrete pavements. All three rigid pavement types are typically constructed on a layer of untreated or treated granular subbase layer. In some cases, an additional but lower-quality natural gravel or crushed rock layer is used to separate the granular layer from the subgrade.

3.2.1.3 Composite Pavements

Composite pavements are mainly constructed from existing flexible or rigid pavements that are resurfaced with asphalt or concrete overlays after many years of service. There have been recent attempts to construct new composite long life (approximately 40 years) pavements, designed with a layer of crushed rock followed by an asphalt layer topped by a Portland cement concrete (PCC) layer. The detailed classification of various pavement types is illustrated in Figure 3.2.

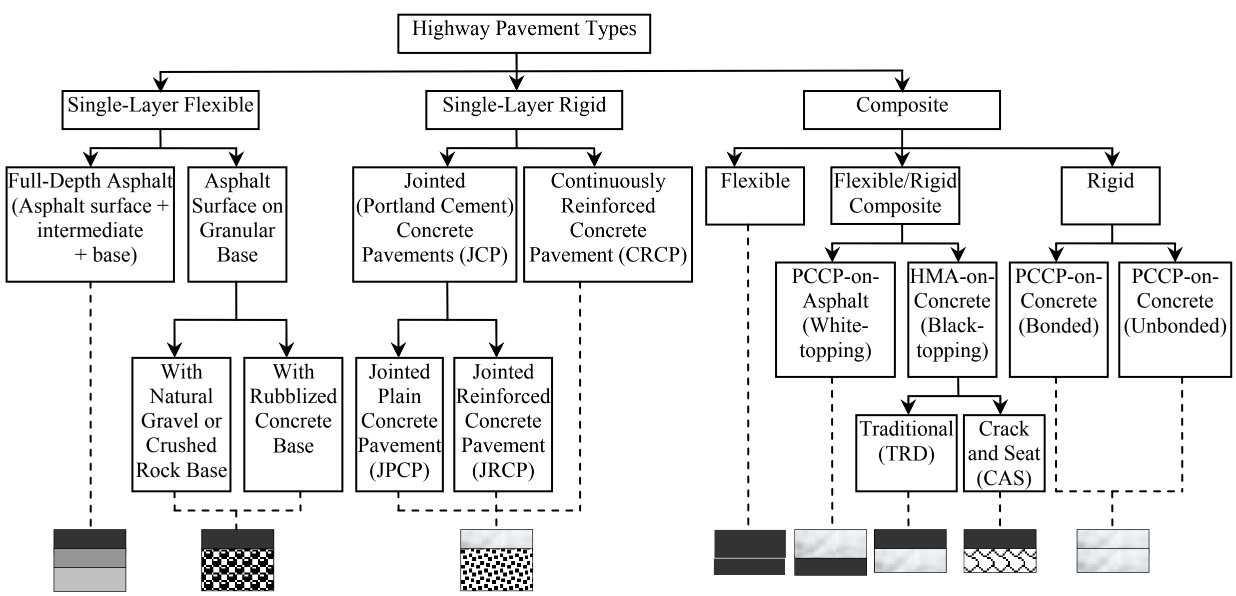


FIGURE 3.2. Categorization of typical pavement types.

3.2.2 *Pavement Design Service Life-Cycle*

The design life is the estimated service life of the pavement. It is therefore desirable to use the design lives for various construction, rehabilitation or maintenance treatment options as the basis of life-cycle cost analysis. Table 3.1 lists the design lives of some standard treatments recommended by the FHWA and state transportation agencies (FHWA, 1987; INDOT, 2002; NYDOT, 1992, 1993, 1999). For a specific maintenance or rehabilitation treatment indicated on this table, it is worth noting that the design life is not the time to first application, but rather gives an indication of the subsequent time a higher level of treatment is needed. The estimated design life may vary based on engineering judgment of the existing pavement conditions, past performance or the drainage system conditions.

TABLE 3.1. Recommended Pavement Design Life-Cycle

Pavement Type	Treatment	Design Life (Year)
Flexible	New full depth Hot Mix Asphalt (HMA) pavements	20
	Thin milling and resurfacing	8
	Micro-surfacing overlay	6
	Chip sealing	4
	Crack sealing	3
Rigid	New Portland Cement Concrete (PCC) pavements	30
	PCC pavement joint sealing	8
	Concrete pavement rehabilitation (CPR) techniques	7
Composite	Concrete pavements over existing pavements	25
	HMA overlay over rubblized PCC pavements	20
	HMA overlay over cracked and seated PCC pavements	15
	HMA overlay over CRC pavements	15
	HMA overlay over jointed concrete, sawed and sealed joints	15
	HMA overlay over jointed concrete	12
	HMA overlay over asphalt pavements	15
	Micro-surfacing overlay	6

3.2.3 Pavement Treatment Types

Pavement treatment types are generally classified as maintenance and rehabilitation categories. In the maintenance category, it can be further divided into preventive and corrective maintenance treatments, depending on the purpose of the maintenance activity as listed in Table 3.2 (FHWA, 1991; Geoffroy, 1996; Labi and Sinha, 2002).

TABLE 3.2. Typical Maintenance and Rehabilitation Treatments

Pavement Type	Preventive Maintenance	Corrective Maintenance	Rehabilitation
Flexible	- Thin Resurfacing Thin asphalt/concrete overlay Micro-surfacing - Seal Coating - Localized Crack sealing, bump grinding	- Shallow patching - Deep patching	- Cold milling and resurfacing - Hot or cold recycling
Rigid	- Thin Resurfacing Thin asphalt/concrete overlay - Localized Crack sealing Fault grinding Under-sealing Retrofitting	- Shallow patching - Deep patching	- Resurfacing - Rubblization followed by resurfacing - Crack seating followed by resurfacing - (Un)bonded concrete overlay - Concrete pavement restoration
Composite	- Thin resurfacing: Thin asphalt overlay/inlay Micro-surfacing Ultra-thin concrete overlay - Seal Coating - Localized Crack sealing, bump grinding, sawing, and sealing	- Shallow Patching - Deep Patching	- Resurfacing - Milling followed by resurfacing - Milling followed by rubblization and resurfacing - Milling followed by crack-and-seating and resurfacing

3.2.4 Pavement Life-Cycle Maintenance and Rehabilitation Strategies

3.2.4.1 Pavement Service Life-Cycle and Rehabilitation Life-Cycle

In this study, a *pavement service life-cycle* is defined as the time interval between two consecutive construction activities. Similarly, a *pavement rehabilitation life-cycle* is defined as the time interval of adjacent construction to rehabilitation, rehabilitation to rehabilitation or rehabilitation to reconstruction or new construction work.

3.2.4.2 Maintenance and Rehabilitation Strategies

A strategy is defined as a combination of treatments or work activities and their respective timings. Within the pavement service life-cycle, a *rehabilitation strategy* involved with a combination of rehabilitation activities such as HMA resurfacing and thick overlays, concrete overlays, and concrete restoration applied at various times can be established. Within pavement rehabilitation life-cycle, a *maintenance strategy* consisting of a combination of maintenance activities applied at various times can be developed (Peshkin et al., 2005). Figure 3.3 provides a schematic illustration of maintenance and rehabilitation strategies in a pavement service life-cycle.

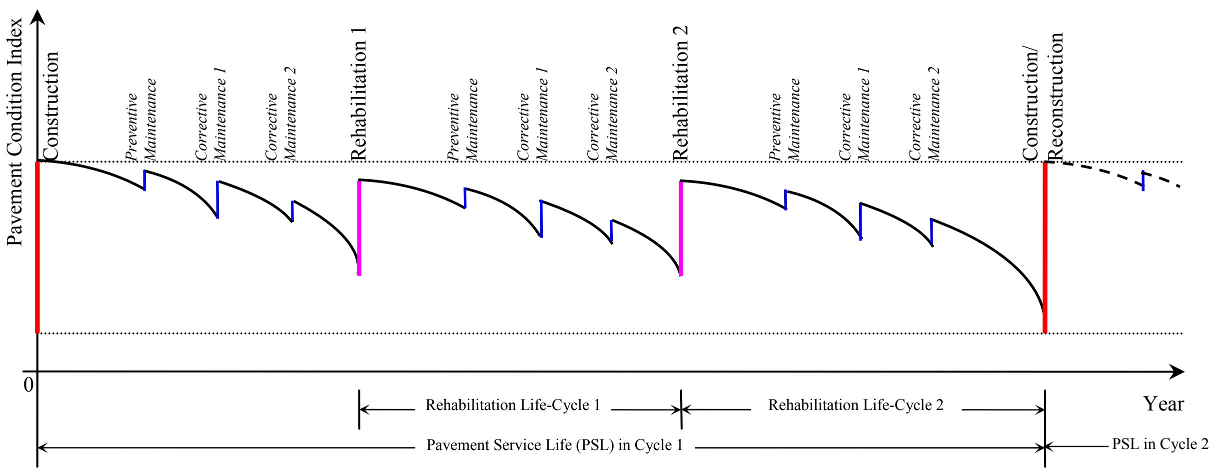


FIGURE 3.3. Maintenance and rehabilitation strategies in pavement service life-cycle.

Pavement maintenance strategies are typically comprised of preventive treatments, such as crack sealing, chip sealing, and thin overlays. Such preventive treatments are applied before the onset of significant structural deterioration (O'Brien, 1989). In the past, corrective maintenance treatments have generally been excluded from strategy formulations because it has been argued that unlike preventive maintenance, they are typically carried out not in anticipation of distress, but to address distress that have already occurred. This study will consider corrective maintenance treatments for correcting pavement distresses in a pavement maintenance strategy that can be reliably predicted. Table 3.3 presents the application criteria of preventive and corrective maintenance treatments (Labi and Sinha, 2002).

TABLE 3.3. Application Criteria of Preventive and Corrective Maintenance Treatments

Pavement Type	Treatment	Average Age at 1st Application (Year)	Average Frequency of Application (Yearly Interval)	Average Perceived Treatment Life (Year)
Flexible	Crumb rubber sealing	2	N/I	N/I
	Crack sealing	3	4	3
	Chip sealing	7	5	6
	Sand sealing	12	4	5
	Micro-surfacing	15	N/I	3
	Thin Hot Mixed Asphalt (HMA) overlay	17	11	11
Rigid	Under-drain maintenance	1	2	2
	Crack sealing	6	4	6
	Joint sealing	8	6	10
Composite	Under-drain maintenance	1	1	2
	Crumb rubber sealing	2	N/I	N/I
	Crack sealing	2	3	4
	Chip sealing	10	5	5
	Sand sealing	12	4	5
	Micro-surfacing	15	N/I	3
	Thin HMA overlay	20	11	9

Note: N/I- Not indicated.

3.2.5 Typical Pavement Life-Cycle Activity Profiles

Maintenance and rehabilitation activities that make up pavement repair strategies in the pavement service life-cycle may be determined based on two ways: i) preset time intervals according to pavement age or combined efforts of cumulative traffic loading and non-load factors; and ii) condition triggers for treatments using disaggregated measures including cracking, rutting, and faulting indices or aggregated measures such as Present Serviceability Index (PSI).

In current practices, many state transportation agencies use preset time intervals rather than condition triggers to develop pavement repair strategies. In condition trigger based strategies, a specific activity is carried out any time a selected measure of pavement condition or performance reaches a certain threshold value. This approach is theoretically sound, but difficult to implement in practice. Problems associated with the use of condition trigger values for strategy formulation include the following: i) lacking established trigger values to carry out treatments; ii) lacking reliable current pavement condition data; iii) lacking consistent historical data on individual distresses or aggregate performance indices for modeling; and iv) matching distress types and treatments for situations where more than one distress are addressed by the same treatment or where one distress is addressed by more than one treatment.

For the option of using preset time intervals, pavement age is commonly adopted to determine pavement repair strategies. This implicitly assumes that pavement condition follows a pattern than can be predicted on the basis of pavement age. The justifications are two-fold. First, age is considered a surrogate for combined efforts of cumulative load and non-load factors. Second, reliable data on traffic loading and all other non-load effects are relatively difficult to collect. While this may generally be true, the success of developing realistic pavement repair strategies depends on the integrity of age/load/condition relationship, and may be weakened by subsequent changes in the highway environment such as better materials, heavier than expected loading, and more severe weather conditions. In the current study, the combination of age and cumulative traffic loading effects is used to developed typical pavement repair strategies.

The existing literature suggests 20-year and 30-year design lives for new full-depth HMA flexible and PCC rigid pavements, respectively. The current practices also propose a 15-year design life for HMA overlays over in-service flexible pavements, a 12 to 15-year design life for HMA over in-service rigid pavements, and a 25-year design life for concrete over in-service flexible or rigid pavements. Given a new or in-service pavement, the expected design life may not be reached without adequately implementing preventive or corrective maintenance treatments. On the other hand, the design life can be extended if appropriate preventive maintenance and rehabilitation treatments are applied. The portion of service life of a new pavement after applying the first rehabilitation treatment can be regarded as the service life of a composite pavement.

In the current study, a 40-year service life is proposed for the life-cycle cost analysis of new flexible and rigid pavements. Within the 40-year period, one rehabilitation, one or more major preventive maintenance, and regular or irregular routine or corrective maintenance treatments are expected to be implemented. The timing of applying rehabilitation and preventive maintenance treatments is relative to pavement age. It will, however, be slightly adjusted according to cumulative traffic loading. If a higher level of cumulative traffic loading is expected, those treatments will be implemented a few years earlier. Otherwise, the treatments can be deferred to some extent. Table 3.4 summarizes the criteria used to separately establish the typical pavement life-cycle activity profiles for flexible, rigid, and composite pavements.

TABLE 3.4. Criteria Considered for Establishing Typical Pavement Life-Cycle Activity Profiles

Criterion	Pavement Type		
	Flexible	Rigid	Composite
Extended Service Life	A fixed 40-year service life-cycle for flexible pavements extended from 20 years of design lives	A fixed 40-year service life-cycle for rigid pavements extended from 30 years of design lives	With passage of time, new flexible or rigid pavements will eventually become composite pavements depending on types of materials used for rehabilitation , i.e., HMA over HMA, HMA over PCC or PCC over PCC
Repair Frequency	- Once for rehabilitation - Once or twice for preventive maintenance	- Once for rehabilitation - Four times for preventive maintenance	
Repair Timing	- First treatment and treatment intervals first determined by pavement age - The treatment timing then adjusted by traffic loading	- First treatment and treatment intervals first determined by pavement age - The treatment timing then adjusted by traffic loading	

The recommended life-cycle activity profiles for new flexible and rigid pavements are presented in Figures 3.4-3.7. To provide sufficient flexibility for the life-cycle cost analysis, two different activity profiles are prepared for each pavement type. The life-cycle activity profiles for composite pavements are embedded into individual life-cycle activity profiles for new flexible and rigid pavements.

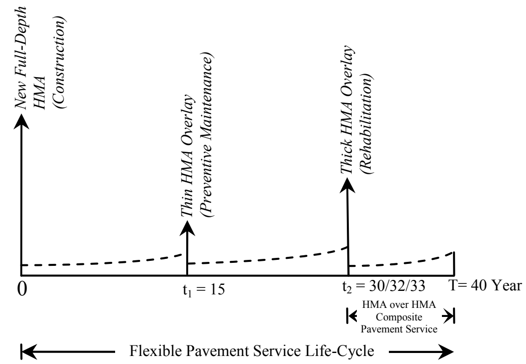


FIGURE 3.4. Typical life-cycle activity profile for flexible pavements- strategy I.

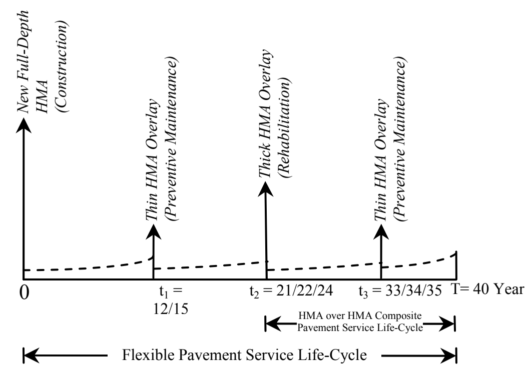


FIGURE 3.5. Typical life-cycle activity profile for flexible pavements- strategy II.

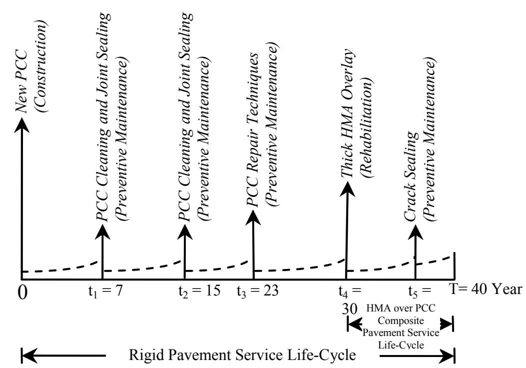


FIGURE 3.6. Typical life-cycle activity profile for rigid pavements- strategy I.

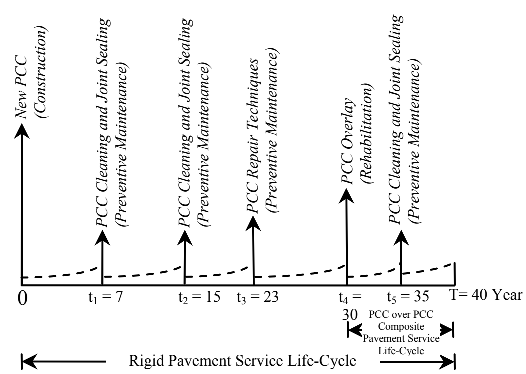


FIGURE 3.7. Typical life-cycle activity profile for rigid pavements- strategy II.

3.2.6 Pavement Life-Cycle Agency Cost Analysis

3.2.6.1 Pavement Life-Cycle Activity Cost Categories

Cost analysis is a cardinal element of any highway LCCA study. All costs incurred over the highway pavement service life-cycle including those of construction, rehabilitation, and maintenance must be considered in the analysis. Some adjustments to the respective costs occurring over time need to be made to account for inflation so that all such costs are expressed in constant dollars. The constant dollars can then be discounted to establish the present worth of life-cycle costs in reference to a base year (FHWA, 1998, 2000; Labi and Sinha, 2002).

Pavement maintenance costs are incurred to preserve the capital investments made in the highway pavements and to ensure that the pavement provides a satisfactory level of service to highway users. Maintenance treatments are implemented for either preventive or corrective purposes on a routine or periodic basis. Maintenance costs may be expressed in average unit accomplishment costs per treatment or in average costs of all maintenance treatments per lane-mile received by pavement type and age group.

Pavement construction/rehabilitation costs are the capital costs incurred in all phases of the design and construction such as feasibility studies, surveying, geometric and pavement design services, right-of-way (ROW) acquisition, and construction of pavements, as well as costs of subsequent rehabilitation activities. Like maintenance costs, construction and rehabilitation costs may be reported by unit accomplishment costs per treatment activity or by pavement section considering all types of treatments the pavement receives for the period between initial construction and the next reconstruction.

3.2.6.2 Quantification of Pavement Life-Cycle Agency Costs

The pavement life-cycle agency costs for one service life-cycle can be quantified on the basis of the proposed pavement life-cycle activity profiles. It is assumed that the routine maintenance costs will increase slightly in response to pavement condition deterioration. A geometric gradient rate of annual growth is introduced for future years to facilitate the calculation of pavement life-cycle agency costs. Different gradients are proposed for different periods between major repair treatments. Assuming that such service life-cycle will repeat infinite times, the life-cycle agency costs in perpetuity can be determined.

Denote:

PW_{LCAC} = Present worth of pavement life-cycle agency costs
$PW_{LCAC\infty}$ = Present worth of pavement life-cycle agency costs in perpetuity
EUAAC = Equivalent uniform annual pavement agency costs
$EUAAC_{\infty}$ = Equivalent uniform annual pavement agency costs in perpetuity
C_{CON} = Pavement construction cost
C_{REH} = Pavement rehabilitation cost
C_{PM1} = Pavement 1st preventive maintenance cost
C_{PM2} = Pavement 2nd preventive maintenance cost
C_{PM3} = Pavement 3rd preventive maintenance cost
C_{PM4} = Pavement 4th preventive maintenance cost
C_{MAIN1} = Annual pavement maintenance cost incurred between construction and 1st major repair
C_{MAIN2} = Annual pavement maintenance cost incurred between the 1st and 2nd major repairs
C_{MAIN3} = Annual pavement maintenance cost incurred between the 2nd and 3rd major repairs
C_{MAIN4} = Annual pavement maintenance cost incurred between the 3rd and 4th major repairs
C_{MAIN5} = Annual pavement maintenance cost incurred between the 4th and 5th major repairs
C_{MAIN6} = Annual pavement maintenance cost incurred between the 5th and 6th major repairs
g_{M1} = Growth rate of annual pavement maintenance cost between construction and 1st major repair
g_{M2} = Growth rate of annual pavement maintenance cost between the 1st and 2nd major repairs
g_{M3} = Growth rate of annual pavement maintenance cost between the 2nd and 3rd major repairs
g_{M4} = Growth rate of annual pavement maintenance cost between the 3rd and 4th major repairs

g_{M5}	= Growth rate of annual pavement maintenance cost between the 4th and 5th major repairs
g_{M6}	= Growth rate of annual pavement maintenance cost between the 5th and 6th major repairs
i	= Discount rate
t	= Time of year a major treatment is implemented
T	= Number of years of service life.

The procedures for computing pavement life-cycle agency costs use the respective activity profiles established for flexible and rigid pavements presented in the previous subsection. For each life-cycle activity profile, the computation is first made for one service life and then extended to perpetuity horizon under the assumption that the same life-cycle activity profile would be repeated an infinite number of times. The results are expressed in present worth and equivalent uniform annual amounts. The details are presented in Tables 3.5 and 3.6.

TABLE 3.5. Computation of Flexible Pavement Life-Cycle Agency Costs

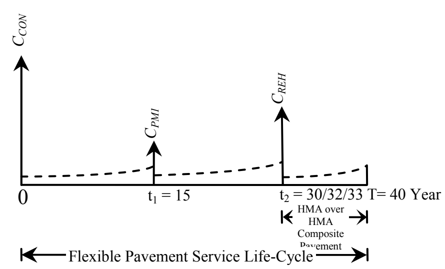
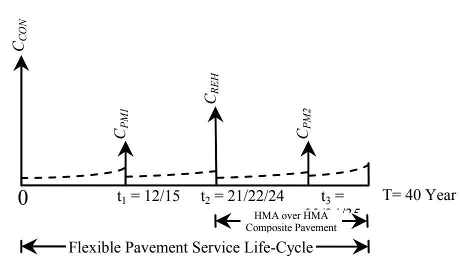
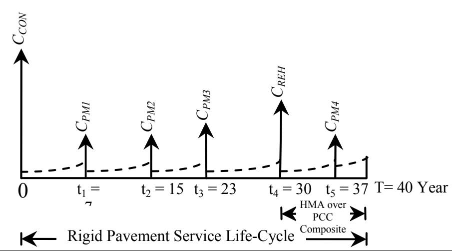
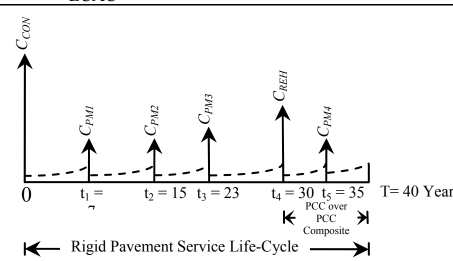
Strategy	Computation	
Strategy I	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{PM1}/(1+i)^{t_1} + C_{REH}/(1+i)^{t_2} + (C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1}) + ((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1} + ((C_{MAIN3}(1-(1+g_{M3})^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Strategy II	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{PM1}/(1+i)^{t_1} + C_{REH}/(1+i)^{t_2} + C_{PM2}/(1+i)^{t_3} + (C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1}) + ((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1} + ((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2} + ((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$

TABLE 3.6. Computation of Rigid Pavement Life-Cycle Agency Costs

Strategy	Computation	
Strategy I	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{REH}/(1+i)^{t_4}$ $+C_{PM1}/(1+i)^{t_1}+C_{PM2}/(1+i)^{t_2}+C_{PM3}/(1+i)^{t_3}+C_{PM5}/(1+i)^{t_5}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(t_4-t_3)}(1+i)^{-(t_4-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$ $+((C_{MAIN5}(1-(1+g_{M5})^{(t_5-t_4)}(1+i)^{-(t_5-t_4)}))/(i-g_{M5}))/(1+i)^{t_4}$ $+((C_{MAIN6}(1-(1+g_{M6})^{(T-t_5)}(1+i)^{-(T-t_5)}))/(i-g_{M6}))/(1+i)^{t_5}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Strategy II	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{REH}/(1+i)^{t_4}$ $+C_{PM1}/(1+i)^{t_1}+C_{PM2}/(1+i)^{t_2}+C_{PM3}/(1+i)^{t_3}+C_{PM5}/(1+i)^{t_5}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(t_4-t_3)}(1+i)^{-(t_4-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$ $+((C_{MAIN5}(1-(1+g_{M5})^{(t_5-t_4)}(1+i)^{-(t_5-t_4)}))/(i-g_{M5}))/(1+i)^{t_4}$ $+((C_{MAIN6}(1-(1+g_{M6})^{(T-t_5)}(1+i)^{-(T-t_5)}))/(i-g_{M6}))/(1+i)^{t_5}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$

3.3 Methodology for Deterministic Bridge Life-Cycle Agency Cost Analysis

This section briefly describes deterministic highway bridge life-cycle agency cost analysis. The discussion covers bridge types, design service life-cycle, repair treatment strategies, life-cycle activity profiles, and life-cycle agency cost analysis for one service life-cycle and in perpetuity.

3.3.1 Categorization of Bridge Types

A bridge is comprised of substructure, superstructure, and deck components. Five types of superstructure (reinforced concrete slab or box-beam, concrete I-beam, steel beam, and steel girder) and two types of substructure (solid stem and pile type) are commonly encountered in practice. Reinforced concrete and composite materials are commonly used for bridge decks. The detailed classification of various highway bridge types is illustrated in Figure 3.8.

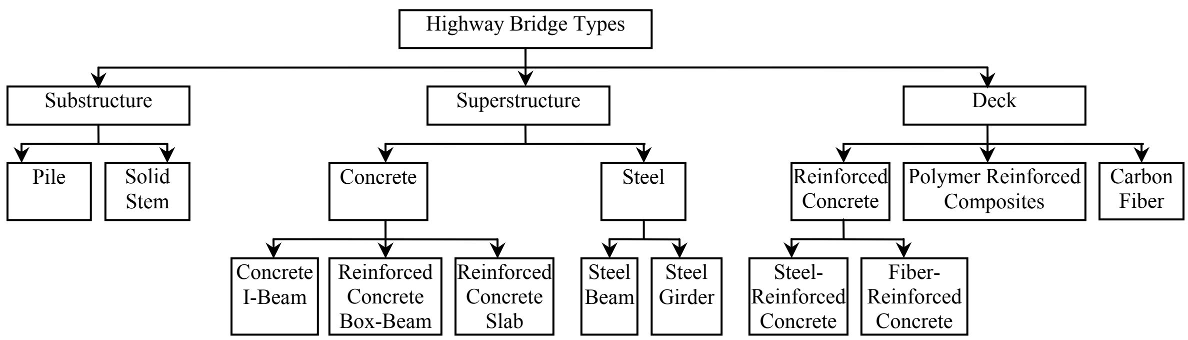


FIGURE 3.8. Categorization of typical highway bridge types.

3.3.2 Bridge Design Service Life-Cycle

Similar to using design service lives for pavement life-cycle agency cost analysis, the design service lives are also proposed for use in bridge life-cycle agency cost analysis. In this study, a *bridge service life-cycle* is defined as the time interval between two consecutive bridge replacements or new bridge construction work and a *bridge rehabilitation life-cycle* is defined as the time interval of adjacent construction to rehabilitation, rehabilitation to rehabilitation or rehabilitation to replacement or new construction work (Gion et al., 1993; Hawk, 2003). Table 3.7 lists the recommended bridge design lives classified by superstructure type.

TABLE 3.7. Recommended Bridge Design Service Life-Cycle

Superstructure Material	Superstructure Type	Design Life (Year)
Concrete	Channel Beam	35
	T-Beam	70
	Slab	60
	Girder	70
Prestressed Concrete	Box-Beam	65
	Segmental Box Girder	50
Steel	Box-Beam	70
	Girder	70
	Truss	80

3.3.3 Typical Bridge Treatment Types

Maintenance, rehabilitation, and replacement treatments can be applied to a specific substructure, superstructure or deck component or be jointly applied to deck and superstructure components (Gion et al., 1993; Hawk, 2003). Table 3.8 presents typical bridge treatment types.

TABLE 3.8. Typical Bridge Maintenance, Rehabilitation, and Replacement Treatments

Bridge Component	Maintenance	Rehabilitation	Replacement
Deck	-Deck maintenance	-Deck rehabilitation -Deck rehabilitation and bridge widening	-Deck replacement -Deck replacement and bridge widening
Superstructure	-Superstructure maintenance	-Superstructure strengthening -Superstructure strengthening and bridge widening	-Superstructure replacement and bridge widening
Deck and Superstructure	-Deck and superstructure maintenance	-Deck and superstructure rehabilitation -Deck and superstructure rehabilitation and bridge widening	-Deck replacement and superstructure rehabilitation -Deck replacement, superstructure rehabilitation, and bridge widening
Substructure	-Substructure maintenance	-Substructure rehabilitation	-Substructure replacement as part of bridge replacement

3.3.4 Bridge Life-Cycle Repair Strategies and Activity Profiles

Of various types of treatments to bridge components, deck rehabilitation is the most commonly used alternative. The review of existing literature indicates that typically the first deck rehabilitation is implemented 20 years after the initial construction. Depending on bridge superstructure types, deck replacement or superstructure replacement is scheduled 15 years after the first deck rehabilitation. Within the same bridge service life-cycle, the second deck rehabilitation is carried out 20 or 25 years after deck or superstructure replacement. The recommended life-cycle activity profiles for various types of concrete and steel bridges are shown in Figures 3.9-3.17.

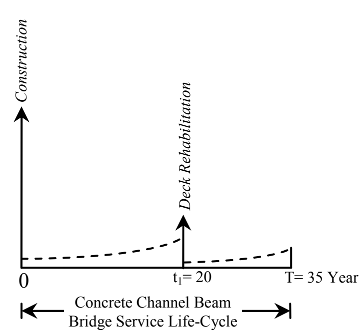


FIGURE 3.9. Typical life-cycle activity profile of concrete channel beam bridges.

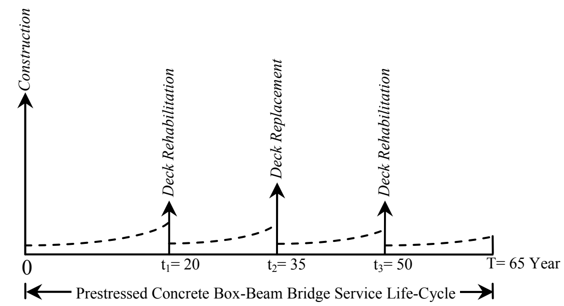


Figure 3.10. Typical Life-Cycle Activity Profile of Prestressed Concrete Box-Beam Bridges.

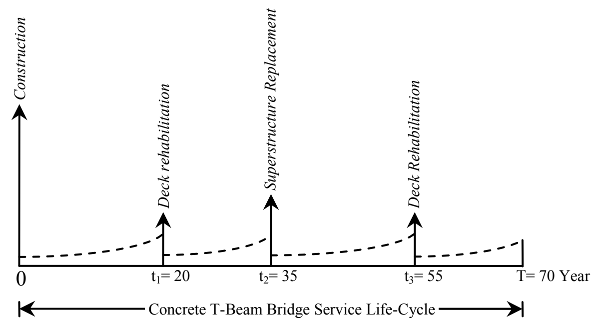


Figure 3.11. Typical Life-Cycle Activity Profile of Concrete T-Beam Bridges.

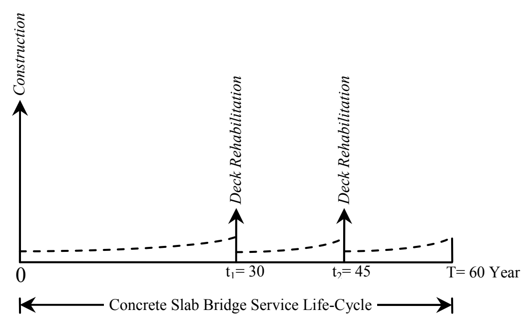


Figure 3.12. Typical Life-Cycle Activity Profile of Concrete Slab Bridges.

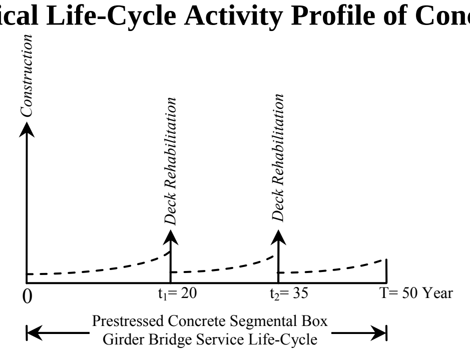


Figure 3.13. Typical Life-Cycle Activity Profile of Prestressed Concrete Segmental Box Girder Bridges.

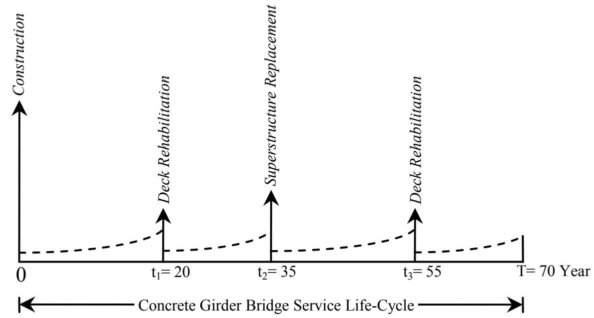


FIGURE 3.14. Typical life-cycle activity profile of concrete girder bridges.

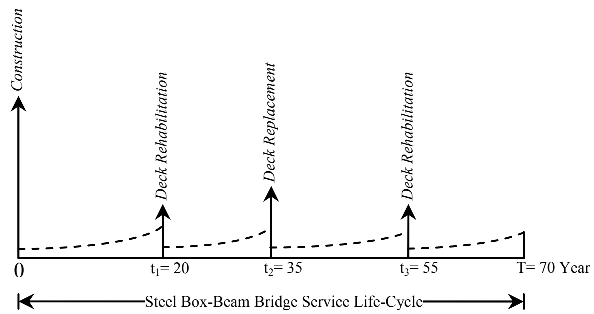


FIGURE 3.15. Typical life-cycle activity profile of steel box-beam bridges.

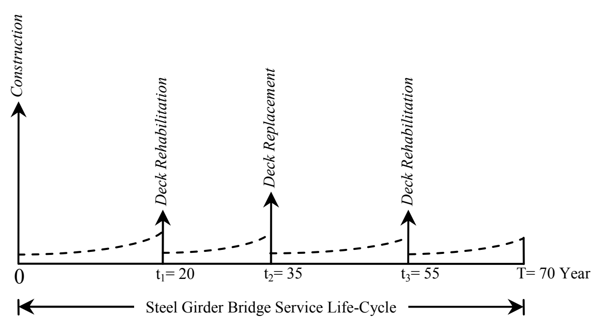


FIGURE 3.16. Typical life-cycle activity profile of steel girder bridges.

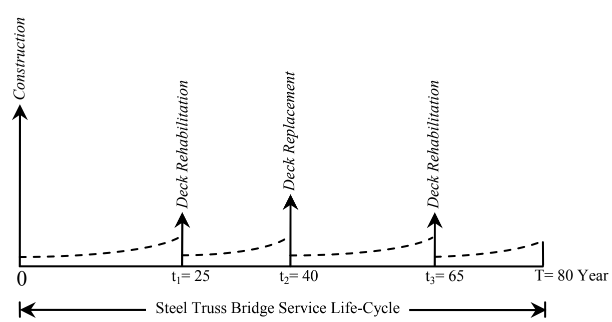


FIGURE 3.17. Typical life-cycle activity profile of steel truss bridges.

3.3.5 Bridge Life-Cycle Agency Cost Analysis

3.3.5.1 Bridge Agency Cost Categories

Bridge agency costs are primarily concerned with design and construction, routine maintenance, deck and superstructure rehabilitation and replacement, and bridge replacement. Design costs include all the costs related to the engineering design, field tests and related equipment, and human resource costs. Construction costs include the costs of materials, equipment, and labor. Design and construction costs also include all the administrative costs associated with the bridge project. Routine maintenance costs are a function of type of material, weather condition, location, and traffic levels. Routine maintenance costs are normally estimated for individual bridge components. Rehabilitation costs of bridge components include major repair activities and require engineering analysis. The costs associated with the replacement of any bridge component by the end of its service life are taken as the component replacement costs. The analysis follows the same procedure adopted for component rehabilitation costs.

3.3.5.2 Estimation of Bridge Element Costs

Cost estimation of the activities related to bridge is an important part of the bridge life-cycle cost analysis. Accurate cost estimations provide firmer support to make analysis between various alternatives. Cobb-Douglas production functions can be utilized to estimate bridge component replacement costs as a function of bridge length, deck width, and vertical clearance.

3.3.5.3 Typical Bridge Life-Cycle Cost Analysis

The bridge life-cycle agency costs for one service life-cycle can be quantified on the basis of the proposed bridge life-cycle activity profiles. It is assumed that the routine maintenance costs will increase slightly in response to bridge condition deterioration. A geometric gradient rate of annual growth is introduced for future years to facilitate the calculation of bridge life-cycle agency costs. Different gradients are proposed for different periods between major repair treatments. Given that such service life-cycle will repeat infinite times, the bridge life-cycle agency costs in perpetuity can be calculated.

Denote:

PW_{LCAC} = Present worth of bridge life-cycle agency costs
$PW_{LCAC\infty}$ = Present worth of bridge life-cycle agency costs in perpetuity
EUAAC = Equivalent uniform annual bridge agency costs
$EUAAC_{\infty}$ = Equivalent uniform annual bridge agency costs in perpetuity
C_{CON} = Bridge construction cost
$C_{DECK\ REH1}$ = First bridge deck rehabilitation cost
$C_{DECK\ REH2}$ = Second bridge deck rehabilitation cost
$C_{DECK\ REP}$ = Bridge deck replacement cost
$C_{SUP\ REP}$ = Bridge superstructure replacement cost
C_{MAIN1} = Annual bridge maintenance cost incurred between construction and 1st major repair
C_{MAIN2} = Annual bridge maintenance cost incurred between the 1st and 2nd major repairs
C_{MAIN3} = Annual bridge maintenance cost incurred between the 2nd and 3rd major repairs
C_{MAIN4} = Annual bridge maintenance cost incurred between the 3rd and 4th major repairs
g_{M1} = Growth rate of annual bridge maintenance cost between construction and 1st major repair
g_{M2} = Growth rate of annual bridge maintenance cost between the 1st and 2nd major repairs
g_{M3} = Growth rate of annual bridge maintenance cost between the 2nd and 3rd major repairs
g_{M4} = Growth rate of annual bridge maintenance cost between the 3rd and 4th major repairs
i = Discount rate
t = Time of year a major treatment is implemented
T = Number of years of service life.

The procedures for computing bridge life-cycle agency costs use the respective activity profiles established for various concrete and steel bridges presented in the previous subsection. For each life-cycle activity profile, the computation is first made for one service life and then extended to perpetuity horizon under the assumption that the same life-cycle activity profile would be repeated infinite times. The results are expressed in present worth and equivalent uniform annual amounts, as Tables 3.9 and 3.10.

TABLE 3.9. Computation of Concrete Bridge Life-Cycle Agency Costs

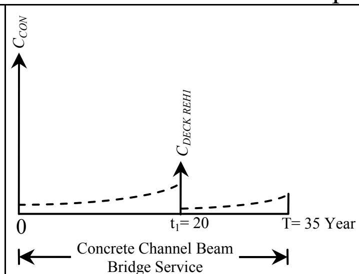
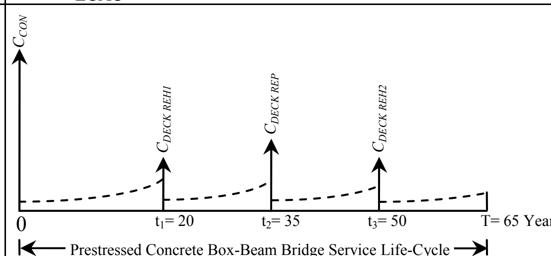
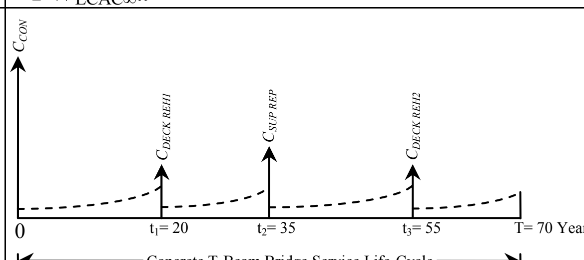
Bridge Type	Computation	
Concrete Channel Beam	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + (C_{MAIN1}(1-((1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1}) + ((C_{MAIN2}(1-(1+g_{M2})^{(T-t_1)}(1+i)^{-(T-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Prestressed Concrete Box-Beam	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REHAB1}/(1+i)^{t_1} + C_{DECK\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Concrete T-Beam	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REHAB1}/(1+i)^{t_1} + C_{SUP\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$

TABLE 3.9. Computation of Concrete Bridge Life-Cycle Agency Costs (Continued)

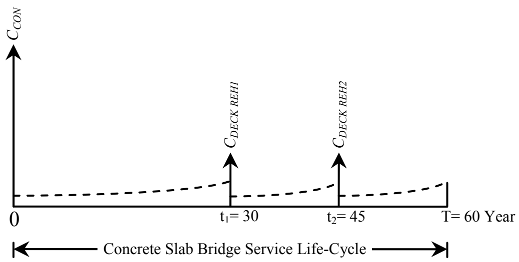
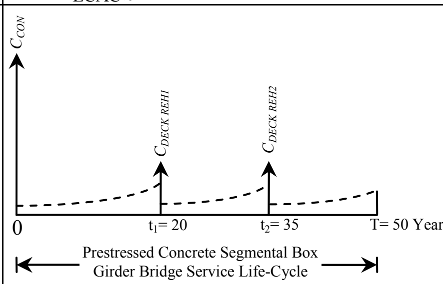
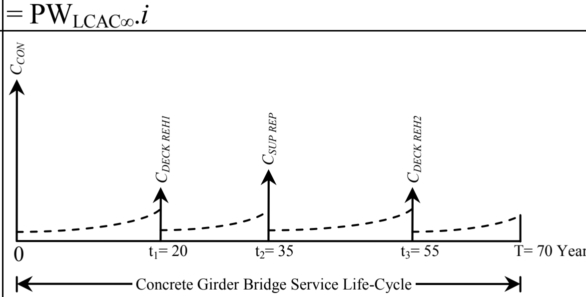
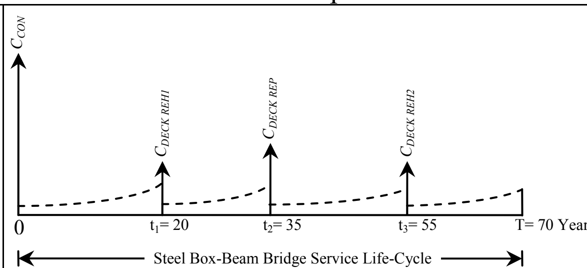
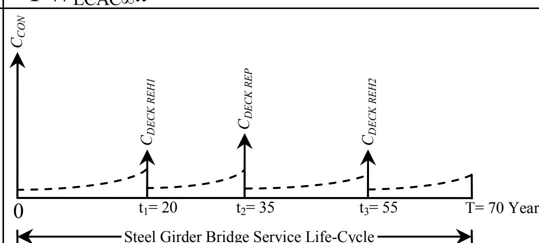
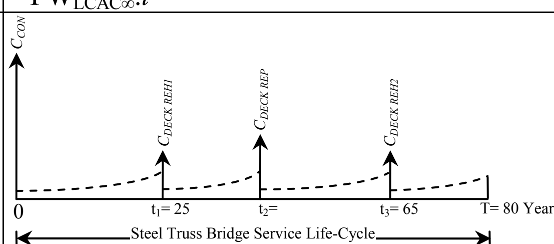
Bridge Type	Computation	
Concrete Slab	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{DECK\ REH2}/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Prestressed Concrete Segmental Box Girder	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{DECK\ REH2}/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Concrete Girder	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{SUP\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$

TABLE 3.10. Computation of Steel Bridge Life-Cycle Agency Costs

Bridge Type	Computation	
Steel Box-Beam	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{SUP\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Steel Girder	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{DECK\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3} = C_{CON}$ $+C_{DECK\ REH1}/(1+i)^{t_1} + C_{SUP\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$
Steel Truss	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + C_{DECK\ REP}/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_{M1})^{t_1}(1+i)^{-t_1}))/(i-g_{M1})$ $+((C_{MAIN2}(1-(1+g_{M2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{M2}))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_{M3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{M3}))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g_{M4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{M4}))/(1+i)^{t_3}$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^{T}))$
	EUAAC	$= PW_{LCAC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$

3.4 Methodology for Deterministic Highway Life-Cycle User Cost Analysis

3.4.1 Highway User Cost Components and Categories

User costs are costs incurred by highway users over the physical asset service life-cycle, depending on the highway improvements and associated repair strategies over the service life-cycle. User costs consist of a substantial part of the total transportation costs for highway investments and can often be the major determining factor in life-cycle cost analysis. As illustrated in Figure 3.18, there are two dimensions of highway user costs: i) user cost *components* (vehicle operating costs (VOC), travel time costs, crash costs, and air emission costs) (AASHTO, 2003; FHWA, 2000; Zaniewski et al., 1982); and ii) user cost *categories* (work zone user costs and normal operations user costs) (FHWA, 1998).

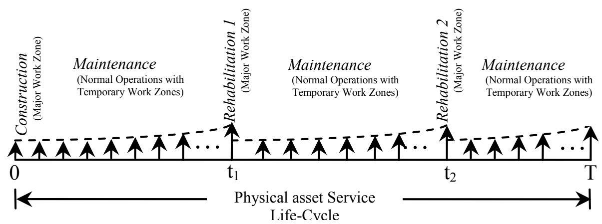


FIGURE 3.18. User cost trends in highway physical asset service life-cycle.

3.4.1.1 Highway User Cost Components

Vehicle operating costs are mileage-dependent costs of running automobiles, trucks, and other motor vehicles on highways, including the expenses of fuel, tires, engine oil, maintenance and the portion of vehicle depreciation attributable to highway mileage traveled. Factors affecting vehicle operating costs include vehicle type, vehicle speed, speed changes, gradient, curvature, and pavement surface conditions.

Travel time costs refer to the value of time spent in travel and include costs to businesses of time by their employees, vehicles and goods, and costs to consumers of personal unpaid time spent on travel, including time spent parking and walking to and from a vehicle.

Vehicle crash costs are costs related to motor vehicle crashes classified by severity as fatality, injury, and property damage only (PDO) categories.

Vehicle air emission costs are external costs associated with major pollutants emitted by vehicles, including carbon dioxide (CO_2), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NO_X), total suspended particles (TSP) and sulfur dioxide (SO_2).

3.4.1.2 Highway User Cost Categories

Work zone user costs are the increased vehicle operating costs, delay, and crash costs to highway users resulting from construction, maintenance, and rehabilitation activities. User costs in this category are a function of the work zone configuration, duration, timing, and scope; and also depend on the volume and operating characteristics of the traffic traversing the work zones.

Normal operations user costs reflect highway user costs associated with using a physical asset during periods free of construction, maintenance or rehabilitation activities that restrict the physical asset capacity. Of individual user cost components in this category, vehicle operating costs vary considerably according to vehicle type, speed, speed changes, design features, and physical asset conditions. During normal operations, little difference exists between delay and crash costs resulting from physical asset design alternatives.

3.4.2 Calculation of Work Zone User Costs

The Highway Capacity Manual (HCM) defines a work zone as an area of a highway where highway preservation activities impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the area (TRB, 2000). Highway construction, rehabilitation and maintenance activities can significantly reduce the highway capacity and vehicle operating speed, which may result in queue development and consequently travel delays and increased vehicle operating costs. User costs for work zone operations are influenced by a variety of factors such as physical asset type, work type, traffic volume and vehicle composition, and work zone characteristics. Recent research showed little impact of work zones on crash rates, which are omitted from work zone user cost computation. Table 3.11 lists individual components of excessive vehicle operating costs and delays caused by work zones.

TABLE 3.11. Components of Excessive Vehicle Operating Costs and Delays Caused by Work Zones

Flow Characteristic	Existence of		VOC Components	Delay Components	
	Work Zone	Queue	Work Zone Upstream	Work Zone Upstream	Within Work Zone
Uncongested	Yes	No	- Speed change	- Speed change	- WZ reduced speed
Congested	Yes	Yes	- Speed change - Stopping - Queue idling	- Speed change - Stopping - Queue reduced speed	- WZ reduced speed
	No	Yes	- Stopping - Queue idling	- Stopping - Queue reduced speed	None

Table 3.12 provides a systematic methodology for quantifying and costing the additional vehicle operating costs and delay costs resulting from work zones.

TABLE 3.12. Computation of Excessive Work Zone User Costs

Procedure		Method
Step 0	Determine inputs	- Determine project future-year traffic demand (AADT, directional hourly demand, vehicle composition) - Determine normal operations characteristics (highway capacity, speed) - Determine work zone characteristics (construction duration, work zone operation hours and length)
Step 1	Determine future-year traffic demand	- Vehicle class *i* future year $AADT_i$ = (Base year AADT) x(% vehicle class *i*)x((1+class *i* annual growth)$^{\text{(Future year-base year)}}$)
Step 2	Calculate work zone directional hourly traffic demand	- Vehicle class *i* directional hourly volume DHV_i = (Future year $AADT_i$)x(Directional distribution *i*) x(Hourly traffic distribution factor *i*)
Step 3	Determine roadway capacity	- Determine physical asset normal operations capacity using HCM - Determine work zone capacity using HCM
Step 4	Identify user cost components	- Identify various VOC and delay components for each hour as listed in Table 3.11
Step 5	Quantify traffic affected for each VOC and delay component	- Hourly queue rate = DHV- normal/work zone capacity - Hourly vehicles queued = cumulative hourly queue rates - Vehicles traverse work zone = DHV with work zone - Vehicles traverse queue = normal/WZ capacity with queue - Vehicles stopped for the queue = DHV with queue - Vehicles slowed down = DHV with work zone, no queue
Step 6	Compute queue reduced speed delay	- Hourly volumes through queue and upstream of queue - Hourly speeds through queue and upstream of queue - Hourly densities through queue and upstream of queue - WZ delay = WZ length/WZ speed- WZ length/upstream speed - Queue delay = Queue length/queue speed- queue length/upstream speed - Average hourly vehicles in queue = Arithmetic average of vehicles queued at the beginning and end of each hour - Average hourly queue length = Average hourly vehicles in queue/(density in queue - density upstream of queue) - Average queue delay per vehicle = Average hourly queue length/queue speed
Step 7	Select added VOC rates	- Select added VOC rates due to speed change, stopping, and queue idling by vehicle class
Step 8	Select added delay time and hourly time values	- Select added delay time due to speed change, stopping, queue reduced speed, and work zone reduced speed by vehicle class - Select hourly time values by vehicle class - Compute added delay costs
Step 9	Assign traffic to vehicle classes	- Distribute respective number of vehicles affected by speed change, stopping, queue, and traversing work zone to each vehicle class
Step 10	Compute work zone user costs	- Compute total added VOC costs for the construction duration - Compute total added delay costs for the construction duration

3.4.3 Calculation of Normal Operations Life-Cycle User Costs

3.4.3.1 <u>Calculation of Normal Operations Annual User Costs for Individual User Cost Components</u>

For highway segments with traffic operations affected by a specific project, the annual costs of vehicle operation, travel time including delays, vehicle crashes, and vehicle air emissions for the initial-year are separately calculated on the basis of the corresponding vehicle miles of travel (VMT) and respective per VMT unit rates of individual user cost components. The quantified individual user cost components are then converted into dollar values and aggregated to arrive at the annual total user costs (AASHTO, 2003; FHWA, 2000; Zaniewski et al., 1982). Table 3.13 presents detailed steps for computing the annual user costs under normal operations conditions.

Denote:

UC	= Annual total highway user costs
VOC	= Annual vehicle operating costs, in dollars per year
TTC	= Annual travel time costs, in dollars per year
$Delay_{intersections}$	= Annual vehicle intersection delay costs, in dollars per year
$Delay_{RR\ crossings}$	= Annual vehicle railroad crossing delay costs, in dollars per year
$Delay_{incidents}$	= Annual vehicle incident delay costs, in dollars per year
VCC	= Annual vehicle crash costs, in dollars per year
VEC	= Annual vehicle emission costs, in dollars per year
VMT_i	= Annual vehicle miles of travel for vehicle class *i*
$UVOC_{ik}$	= Unit cost of VOC component *k* for vehicle class *i*, in dollars per VMT
$UTTC_i$	= Unit travel time value for vehicle class *i*, in dollars per hour
$UVCC_p$	= Unit cost of vehicle crashes for crash severity *p*, in dollars per crash
$UVEC_{iq}$	= Unit rate of vehicle emitted pollutant type *q* for vehicle class *i*, in dollars per VMT
$Speed_i$	= Average travel speed for vehicle class *i*
N_l	= Number of intersections of type *l*
Average $Delay_l$	= Average delay at intersection of type *l*, 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 $Delay_i$	= Delay time per incident by vehicle class *i*, in hours/vehicle
Incident $Rate_i$	= Number of incidents per million VMT by vehicle class *i*
Crash $Rate_p$	= Vehicle rashes of type *p* per million VMT, in crashes/million VMT
Emission $Rate_{iq}$	= Quantities of pollutant type *q* emitted by vehicle class *i*, in tons/VMT
i	= Vehicle class 1 to 13
j	= Number of project indirectly affected highway segments
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
p	= Crash severity type 1 to 3
q	= Pollutant type 1 to 6 for CO_2, NMHC, CO, NO_X, TSP, and SO_2.

Note: Subscripts "direct" and "indirect" refer to project directly and indirectly affected highway segments.

TABLE 3.13. Computation of Normal Operations User Costs in the Initial Year

Procedure		Method
Step 0	Determine inputs	- Identify project affected highway segments (directly affected segments, indirectly affected segments) - Determine initial-year traffic demand of affected segments (AADT, directional hourly demand, vehicle composition) - Determine normal operations characteristics (highway capacity, speed)
Step 1	Determine initial-year VMT for project directly and indirectly affected segments	- Vehicle class *i* initial year $VMT_{i,direct}$ for project directly affected highway segment= 365x(initial year AADT)x(% vehicle class *i*)x(length of the directly affected segment) - Vehicle class *i* initial year $VMT_{i,indirect(j)}$ for project indirectly affected highway segment *j*= 365x(initial year AADT)x(% vehicle class *i*)x(length of indirectly affected segment *j*)
Step 2	Compute vehicle operating costs	- Determine initial-year VOC for project affected segments $VOC_{direct} = \sum_{i=1}^{13}[(\sum_{k=1}^{5} UVOC_{ik}).VMT_{i,direct}]$, $VOC_{indirect(j)} = \sum_{i=1}^{13}[(\sum_{k=1}^{5} UVOC_{ik}).(\sum_{j=1}^{N} VMT_{i,indirect(j)})]$
Step 3	Calculate travel time cost	- Determine initial-year travel time costs for project affected segments $TTC_{direct} = \sum_{i=1}^{13}[(VMT_{i,direct}/Speed_i).UTTC_i]$, $TTC_{indirect} = \sum_{i=1}^{13}[(\sum_{j=1}^{N} VMT_{i,indirect(j)}/Speed_{i(j)}).UTTC_i]$
Step 4	Quantify delay costs	- Determine initial-year delay costs for project affected segments $Delay_{intersections,direct/indirect} = \sum_{i=1}^{13}[(\sum_{l}^{L}(N_l.Average\ Delay_l)).UTTC_i]$ $Delay_{RR\ crossings,direct/indirect} = \sum_{i=1}^{13}[(K_m.\sum_{m=1}^{M}(TSD_m)).UTTC_i]$ $Delay_{incidents,direct} = \sum_{i=1}^{13}[(Incident\ Delay_i.Incident\ Rate_i.(VMT_{i,direct}/1{,}000{,}000)).UTTC_i]$ $Delay_{incidents,indirect} = \sum_{i=1}^{13}[(Incident\ Delay_i.Incident\ Rate_i.((\sum_{j=1}^{N}VMT_{i,indirect(j)})/1{,}000{,}000)).UTTC_i]$
Step 5	Establish vehicle crash costs	- Determine initial-year vehicle crash costs for project affected segments $VCC_{direct} = \sum_{p=1}^{3}[CrashRate_p.(\sum_{i=1}^{13}(VMT_{i,direct}/1{,}000{,}000)).UVCC_p]$ $VCC_{indirect} = \sum_{p=1}^{3}[Crash\ Rate_p.(\sum_{i=1}^{13}((\sum_{j=1}^{N}VMT_{i,indirect(j)})/1{,}000{,}000)).UVCC_p]$
Step 6	Calculate vehicle air emission costs	- Determine initial-year emission costs for project affected segments $VEC_{direct} = \sum_{q=1}^{6}[\sum_{i=1}^{13}(Emission\ Rate_q.VMT_{i,direct}.UVEC_{iq})]$ $VEC_{indirect} = \sum_{q=1}^{6}[\sum_{i=1}^{13}(Emission\ Rate_q.(\sum_{j=1}^{N}VMT_{i,indirect(j)}).UVEC_{iq})]$
Step 7	Determine initial-year total user costs	- Determine initial-year total user costs for project affected segments $UC_{direct} = VOC_{direct} + TTC_{direct} + Delay_{intersections,direct} + Delay_{RR\ crossings,direct} + Delay_{incidents,direct} + VCC_{direct} + VEC_{direct}$ $UC_{indirect} = VOC_{indirect} + TTC_{indirect} + Delay_{intersections,indirect} + Delay_{RR\ crossings,indirect} + Delay_{incidents,indirect} + VCC_{indirect} + VEC_{indirect}$

3.4.3.2 Calculation of Life-Cycle User Costs under Normal Operations Conditions

It is assumed that the constant-dollar annual total user costs will increase slightly in response to traffic demand increase. A geometric gradient rate of annual growth is used for future years to facilitate the calculation of life-cycle user costs. Different gradients are proposed for different periods between major repair treatments. The detailed computation is presented in Tables 3.14-3.16.

Denote:

PW_{LCUC} = Present worth of highway physical asset life-cycle user costs
$PW_{LCUC\infty}$ = Present worth of highway physical asset life-cycle user costs in perpetuity
EUAUC = Equivalent uniform annual highway physical asset user costs
$EUAUC_{\infty}$ = Equivalent uniform annual highway physical asset user costs in perpetuity
C_{AUC2} = Annual physical asset user cost incurred between the 1^{st} and 2^{nd} major repairs
C_{AUC3} = Annual physical asset user cost incurred between the 2^{nd} and 3^{rd} major repairs
C_{AUC4} = Annual physical asset user cost incurred between the 3^{rd} and 4^{th} major repairs
C_{AUC5} = Annual physical asset user cost incurred between the 4^{th} and 5^{th} major repairs
C_{AUC6} = Annual physical asset user cost incurred between the 5^{th} and 6^{th} major repairs
g_{AUC1} = Growth rate of annual physical asset user cost between initial construction and 1^{st} major repair
g_{AUC2} = Growth rate of annual physical asset user cost between the 1^{st} and 2^{nd} major repairs
g_{AUC3} = Growth rate of annual physical asset user cost between the 2^{nd} and 3^{rd} major repairs
g_{AUC4} = Growth rate of annual physical asset user cost between the 3^{rd} and 4^{th} major repairs
g_{AUC5} = Growth rate of annual physical asset user cost between the 4^{th} and 5^{th} major repairs
g_{AUC6} = Growth rate of annual physical asset user cost between the 5^{th} and 6^{th} major repairs
i = Discount rate
t = Time of year a major physical asset treatment is implemented
T = Number of years of service life for a highway physical asset.

TABLE 3.14. Computation of Pavement-Related Life-Cycle User Costs

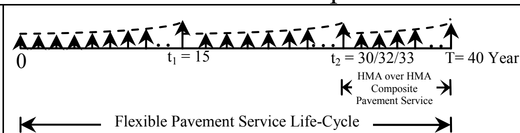
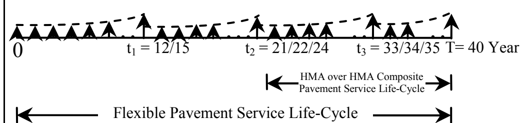
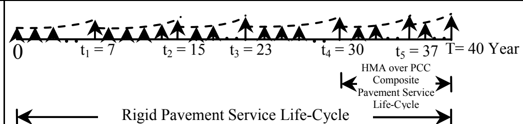
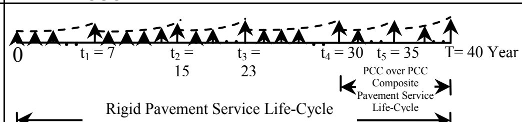
Pavement Type	Computation	
Flexible Strategy I	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC1})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC1}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC1})^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_{AUC1}))/(1+i)^{t_2}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Flexible Strategy II	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Rigid Strategy I	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(t_4-t_3)}(1+i)^{-(t_4-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$ $+((C_{AUC5}(1-(1+g_{AUC5})^{(t_5-t_4)}(1+i)^{-(t_5-t_4)}))/(i-g_{AUC5}))/(1+i)^{t_4}$ $+((C_{AUC6}(1-(1+g_{AUC6})^{(T-t_5)}(1+i)^{-(T-t_5)}))/(i-g_{AUC6}))/(1+i)^{t_5}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Rigid Strategy II	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(t_4-t_3)}(1+i)^{-(t_4-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$ $+((C_{AUC5}(1-(1+g_{AUC5})^{(t_5-t_4)}(1+i)^{-(t_5-t_4)}))/(i-g_{AUC5}))/(1+i)^{t_4}$ $+((C_{AUC6}(1-(1+g_{AUC6})^{(T-t_5)}(1+i)^{-(T-t_5)}))/(i-g_{AUC6}))/(1+i)^{t_5}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$

TABLE 3.15. Computation of Concrete Bridge-Related Life-Cycle User Costs

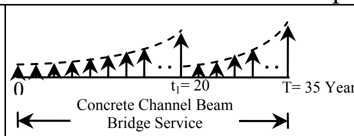
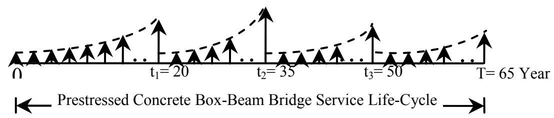
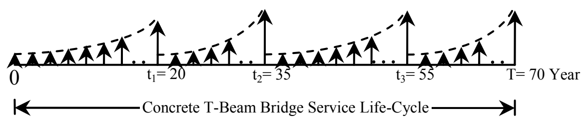
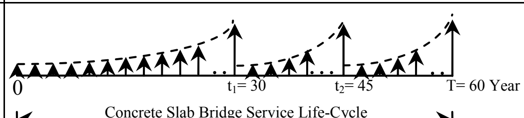
Bridge Type	Computation	
Concrete Channel Beam	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}\ (1-((1+g_{AUC1})^{t_1}\ (1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}\ (1-((1+g_{AUC2})^{(T-t_1)}\ (1+i)^{-(T-t_1)}))/(i-g_{AUC2}))\ /(1+i)^{t_1}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Prestressed Concrete Box-Beam	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+g_{AUC1})^{t_1}\ (1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}\ (1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}\ (1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}\ (1-(1+g_{AUC4})^{(T-t_3)}\ (1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Concrete T-Beam	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+g_{AUC1})^{t_1}\ (1+i)^{-t_1}))/(i-g_{AUC1}))$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}\ (1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}\ (1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}\ (1-(1+g_{AUC4})^{(T-t_3)}\ (1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Concrete Slab	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}\ (1-(1+g_{AUC1})^{t_1}\ (1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}\ (1-(1+g_{AUC2})^{(t_2-t_1)}\ (1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}\ (1-(1+g_{AUC3})^{(T-t_2)}\ (1+i)^{-(T-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$

TABLE 3.15. Computation of Concrete Bridge-Related Life-Cycle User Costs (Continued)

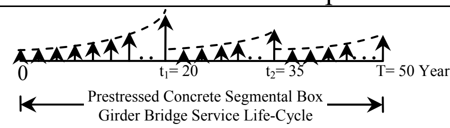
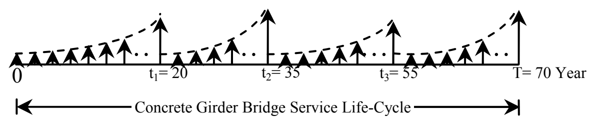
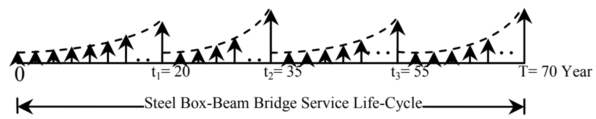
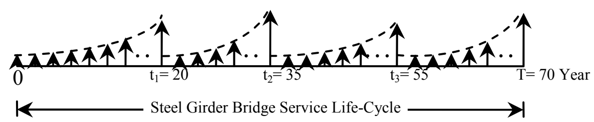
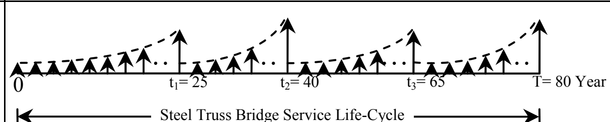
Bridge Type	Computation	
Prestressed Concrete Segmental Box Girder	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1} (1-(1+g_{AUC1})^{t_1} (1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2} (1-(1+g_{AUC2})^{(t_2-t_1)} (1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3} (1-(1+g_{AUC3})^{(T-t_2)} (1+i)^{-(T-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$
	EUAUC	$= PW_{LCUC} .((i(1+i)^T)/((1+i)^T-1))$
	$EUAUC_\infty$	$= PW_{LCUC\infty}.i$
Concrete Girder	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+g_{AUC1})^{t_1} (1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)} (1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)} (1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4} (1-(1+g_{AUC4})^{(T-t_3)} (1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$
	EUAUC	$= PW_{LCUC} .((i(1+i)^T)/((1+i)^T-1))$
	$EUAUC_\infty$	$= PW_{LCUC\infty}.i$

TABLE 3.16. Computation of Steel Bridge-Related Life-Cycle User Costs

Bridge Type	Computation	
Steel Box-Beam	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Steel Girder	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$
Steel Truss	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+g_{AUC1})^{t_1}(1+i)^{-t_1}))/(i-g_{AUC1})$ $+((C_{AUC2}(1-(1+g_{AUC2})^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_{AUC2}))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+g_{AUC3})^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_{AUC3}))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+g_{AUC4})^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_{AUC4}))/(1+i)^{t_3}$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$

3.5 Computation of Project Life-Cycle Benefits in Perpetuity

3.5.1 Project Life-Cycle Agency Benefits Caused by Service Life-Cycle Shift

The typical activity profiles for various types of pavements and bridges proposed in the previous sections represent the physical asset service lives under the ideal situation. That is, the recommended service lives are achievable providing that the physical asset repair strategies are effectively implemented. Early termination of a service life may occur if inappropriate treatments are applied and/or the activity timing fails the optimal treatment time window. As such, the typical service life-cycle can be used as the base case scenario and the cases with early terminations can be used as alternative scenarios. In order to maintain the typical service life-cycle, additional project costs are needed. The resulting difference in physical asset life-cycle agency costs between the base case and an alternative scenario can be regarded as the overall project life-cycle agency benefits due to service life-cycle shift.

3.5.2 Project Life-Cycle User Benefits Caused by Physical asset Service Life-Cycle Shift without Demand Shift

As in the calculation of project agency benefits in one service life-cycle, the reduction in life-cycle user costs is considered as life-cycle user benefits due to service life-cycle shift.

3.5.3 Project Life-Cycle User Benefits Caused by Demand Shift without Physical asset Service Life-Cycle Shift

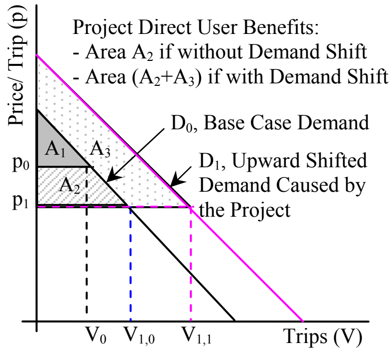
Other than the life-cycle user benefits due to physical asset service life-cycle shift, life-cycle user benefits may be achieved because of traffic demand shift after highway project implementation. The upward shift of demand curve associated with the project directly affected highway segment may trigger downward shift or reduction in traffic demand on alternative routes (AASHTO, 2003). The calculation of change in annual total highway user costs due to demand shift as user benefits is explained in the following:

3.5.3.1 Calculation of Annual User Benefits on a Directly Affected Road Segment with Demand Shift

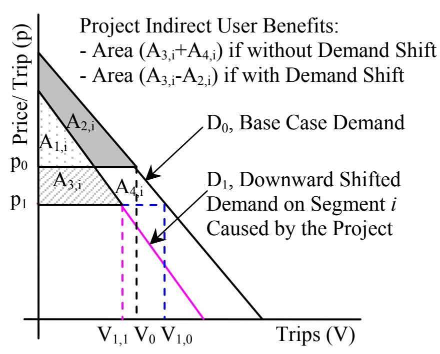
The annual user benefits as a result of a highway project is captured by the concept of consumer surplus. Given a demand curve, the consumer surplus is the difference between what highway users in the aggregate would have been willing to pay, and what they are actually asked to pay. The change in consumer surplus before and after project implementation is considered as the user benefits associated with the project. For a generalized case where the demand curve shifts upward as a result of a project improvement, the user benefits can be calculated as illustrated in Figure 3.19(a). The annual user benefits associated with the project directly affected highway segment could be related to vehicle operating costs, travel time, vehicle crashes, and emissions, respectively.

3.5.3.2 Calculation of Annual User Benefits on an Indirectly Affected Road Segment with Demand Shift

If the implementation of a highway project causes traffic to shift to the improved segment, other indirectly affected segments may see a backward shift in demand. That is, the travel demand on the indirectly-affected segments is less at every user cost. As illustrated in Figure 3.19(b), the change in consumer surplus is just analogues to the change of consumer surplus that is measured on the directly affected segment. The approach can be applied to each indirectly affected highway segment to account for all changes in consumer surplus. The annual user benefits for the project indirectly affected highway segment(s) could be relevant to vehicle operating costs, travel time, vehicle crashes, and emissions, respectively.



a) Directly Affected Highway Segment



b) Indirectly Affected Highway Segment *i*

FIGURE 3.19. Illustration of calculating annual user benefits of project directly and indirectly affected highway segments caused by demand shift.

3.5.3.3 Overall Life-Cycle User Benefits due to Demand Shift

The annual total life-cycle user benefits of a highway project due to demand shift is the summation of changes in all consumer surpluses for all user cost components associated with directly and all indirectly affected highway segments. Once obtaining an estimation of annual total user benefits for the base year with demand shift, the annual total user benefits involving demand shifts for the future years in a typical service life-cycle can be extrapolated using a linear or geometric gradient rate of increase or decrease. Having established all annual total user benefits for the typical service life-cycle, the project overall life-cycle user benefits due to demand shift can be determined by discounting future-year benefits to the base year values.

3.5.4 Project Life-Cycle User Benefits with Both Demand Shift and Physical Asset Service Life-Cycle Shift

The computation consists of two steps. First, the annual total user benefits for the base year with demand shift can be established using the concept of consumer surplus. Then, the annual total user benefits for future years in a reduced service life-cycle (because of service life-cycle shift) can be extrapolated in a similar manner as discussed in the above subsection. Finally, the project overall life-cycle user benefits with demand shift and service life-cycle shift can be determined by discounting future-year benefits to the base year values.

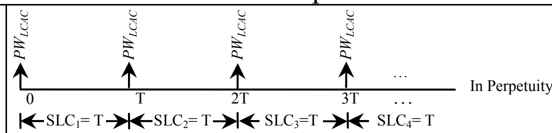
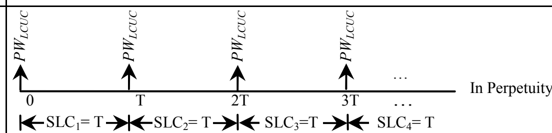
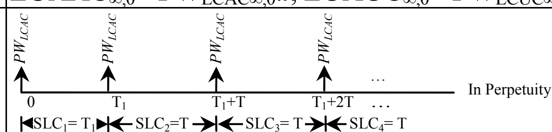
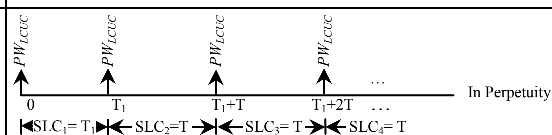
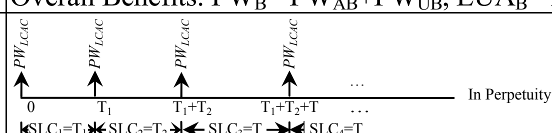
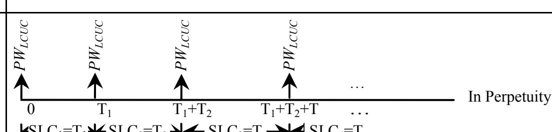
3.5.5 Overall Project Life-Cycle Benefits in Perpetuity

As compared to the base case that maintains the typical physical asset service life-cycle for infinite times, an alternative scenario may have an early service life termination for the first life-cycle and then follow the typical service life-cycle from the second cycle to perpetuity. It is also possible that the alternative scenario will have early service life terminations for the first and second life cycles, and then follow the typical service life-cycle from the third cycle onward to perpetuity, and so forth. The difference in life-cycle agency and user costs in perpetuity between the base case and an alternative scenario is considered as the overall project life-cycle benefits in perpetuity. Table 3.17 illustrates the detailed computation of overall highway project life-cycle benefits in perpetuity for two alternative scenarios.

Denote:

$PW_{LCAC\infty}$ = Present worth of physical asset life-cycle agency costs in perpetuity
$PW_{LCUC\infty}$ = Present worth of physical asset life-cycle user costs in perpetuity
$EUAAC_{\infty}$ = Equivalent uniform annual agency costs in perpetuity
$EUAUC_{\infty}$ = Equivalent uniform annual user costs in perpetuity
PW_{AB} = Present worth of project agency benefits in perpetuity
PW_{UB} = Present worth of project user benefits in perpetuity
PW_{B} = Present worth of overall project benefits in perpetuity
EUA_{AB} = Equivalent uniform annual project agency benefits in perpetuity
EUA_{UB} = Equivalent uniform annual project user benefits in perpetuity
EAU_{B} = Equivalent uniform annual overall project benefits in perpetuity
i = Discount rate
T = Number of years of service life for a highway physical asset.

TABLE 3.17. Computation of Project Life-Cycle Overall Benefits in Perpetuity

<table>
<tr><th>Case</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="4">Base Case: No Early Termination</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,0}= PW_{LCAC}/(1-(1/(1+i)^{T}))$
$PW_{LCUC\infty,0}= PW_{LCUC}/(1-(1/(1+i)^{T}))$</td></tr>
<tr><td>Annual Worth</td><td>$EUAAC_{\infty,0}= PW_{LCAC\infty,0}.i$, $EUAUC_{\infty,0}= PW_{LCUC\infty,0}.i$</td></tr>
<tr><td rowspan="5">Case 1: Early Termination in Cycle 1</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,1}= PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$
$PW_{LCUC\infty,1}= PW_{LCUC1}+(PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$</td></tr>
<tr><td>Annual Worth</td><td>$EUAAC_{\infty,1}= PW_{LCAC\infty,1}.i$, $EUAUC_{\infty,1}= PW_{LCUC\infty,1}.i$</td></tr>
<tr><td>Base Case Benefits</td><td>Agency Benefits: $PW_{AB}= PW_{LCAC\infty,1}-PW_{LCAC\infty,0}$
$EUA_{AB}= EUAAC_{LCAC\infty,1}-EUAAC_{LCAC\infty,0}$
User Benefits: $PW_{UB}= PW_{LCUC\infty,1}-PW_{LCUC\infty,0}$
$EUA_{UB}= EUAUC_{LCAC\infty,1}-EUAUC_{LCUC\infty,0}$
Overall Benefits: $PW_{B}= PW_{AB}+PW_{UB}$, $EUA_{B}= EUA_{AB}+EUA_{UB}$</td></tr>
<tr><td rowspan="5">Case 2: Early Termination in Cycles 1 and 2</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,2}=PW_{LCAC1}+PW_{LCAC2}/(1+i)^{T_1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{(T_1+T_2)}$
$PW_{LCUC\infty,2}=PW_{LCUC1}+PW_{LCUC2}/(1+i)^{T_1}+(PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{(T_1+T_2)}$</td></tr>
<tr><td>Annual Worth</td><td>$EUAAC_{\infty,2}= PW_{LCAC\infty,2}.i$, $EUAUC_{\infty,2}= PW_{LCUC\infty,2}.i$</td></tr>
<tr><td>Base Case Benefits</td><td>Agency Benefits: $PW_{AB}= PW_{LCAC\infty,2}-PW_{LCAC\infty,0}$
$EUA_{AB}= EUAAC_{LCAC\infty,2}-EUAAC_{LCAC\infty,0}$
User Benefits: $PW_{UB}= PW_{LCUC\infty,2}-PW_{LCUC\infty,0}$
$EUA_{UB}= EUAUC_{LCAC\infty,2}-EUAUC_{LCUC\infty,0}$
Overall Benefits: $PW_{B}= PW_{AB}+PW_{UB}$, $EUA_{B}= EUA_{AB}+EUA_{UB}$</td></tr>
</table>

3.6 Methodology for Deterministic Project Benefit-Cost Analysis in Perpetuity

3.6.1 Distribution of Project Costs in Perpetuity

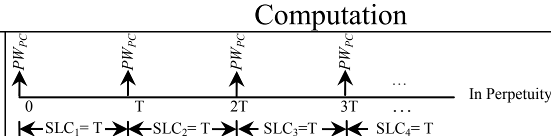
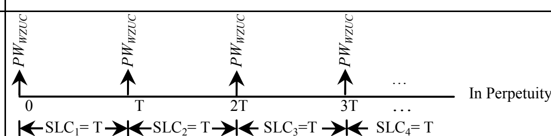
The total costs associated with a highway project consist of project direct costs and additional work zone user costs during project construction. Since the typical physical asset service life-cycle is treated as the base case, the total project costs are distributed according to the typical physical asset service life-cycle for perpetuity horizon, as illustrate in Table 3.18.

Denote:

PW_{PC}	= Present worth of project direct construction, maintenance or rehabilitation costs
PW_{WZUC}	= Present worth of excessive work zone user costs caused by the project
$PW_{C,\infty}$	= Present worth of the total of project direct costs and work zone user costs in perpetuity
$EUA_{C,\infty}$	= Total of annualized project direct costs and work zone user costs in perpetuity
i	= Discount rate
T	= Number of years of service life for a highway physical asset.

The detailed computation is presented in Table 3.18.

TABLE 3.18. Distribution of Project Costs in Perpetuity Horizon

<table>
<tr><th>Case</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="4">Base Case: No Early Termination</td><td>Project Direct Cost Profile</td><td>
</td></tr>
<tr><td>Project Work Zone User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{C,\infty,0} = (PW_{PC}+PW_{WZUC})/(1-(1/(1+i)^{T}))$</td></tr>
<tr><td>Annual Worth</td><td>$EUA_{C,\infty,0} = PW_{C,\infty,0}.i$</td></tr>
</table>

3.6.2 Project Benefit-Cost Analysis in Perpetuity Horizon

The computational procedure is illustrated in Table 3.19.

TABLE 3.19. Project Benefit-Cost Analysis in Perpetuity Horizon

Case		Present Worth: Agency Costs	Present Worth: User Costs	Annual Worth: Agency Costs	Annual Worth: User Costs
Base Case: No Early Termination	Life-Cycle Cost	$PW_{LCAC\infty,0}$	$PW_{LCUC\infty,0}$	$EUAAC_{\infty,0}$	$EUAUC_{\infty,0}$
Case 1: Early Termination in Cycle 1	Life-Cycle Cost	$PW_{LCAC\infty,1}$	$PW_{LCUC\infty,1}$	$EUAAC_{\infty,1}$	$EUAUC_{\infty,1}$
	Base Case Benefits	$PW_{AB,\infty}$= $PW_{LCAC\infty,1}$-$PW_{LCAC\infty,0}$ $PW_{UB,\infty}$= $PW_{LCUC\infty,1}$-$PW_{LCUC\infty,0}$		$EUA_{AB,\infty}$= $EUAAC_{LCAC\infty,1}$-$EUAAC_{LCAC\infty,0}$ $EUA_{UB,\infty}$= $EUAUC_{LCAC\infty,1}$-$EUAUC_{LCUC\infty,0}$	
	Base Case Project Costs	$PW_{C,\infty,0}$		$EUA_{C,\infty,0}$	
	Benefit/Cost Analysis	NPW= ($PW_{AB,\infty}$+$PW_{UB,\infty}$)-$PW_{C,\infty,0}$ B/C Ratio = ($PW_{AB,\infty}$+$PW_{UB,\infty}$)/$PW_{C,\infty,0}$		NPW= ($EUA_{AB,\infty}$+ $EUA_{UB,\infty}$)-$EUA_{C,\infty,0}$ B/C Ratio = ($EUA_{AB,\infty}$+$EUA_{UB,\infty}$)/$EUA_{C,\infty,0}$	
Case 2: Early Termination in Cycles 1 and 2	Life-Cycle Cost	$PW_{LCAC\infty,2}$	$PW_{LCUC\infty,2}$	$EUAAC_{\infty,2}$	$EUAUC_{\infty,2}$
	Base Case Benefits	$PW_{AB,\infty}$= $PW_{LCAC\infty,2}$-$PW_{LCAC\infty,0}$ $PW_{UB,\infty}$= $PW_{LCUC\infty,2}$-$PW_{LCUC\infty,0}$		$EUA_{AB,\infty}$= $EUAAC_{LCAC\infty,2}$-$EUAAC_{LCAC\infty,0}$ $EUA_{UB,\infty}$= $EUAUC_{LCAC\infty,2}$-$EUAUC_{LCUC\infty,0}$	
	Base Case Project Costs	$PW_{C,\infty,0}$		$EUA_{C,\infty,0}$	
	Benefit/Cost Analysis	NPW= ($PW_{AB,\infty}$+$PW_{UB,\infty}$)-$PW_{C,\infty,0}$ B/C Ratio = ($PW_{AB,\infty}$+$PW_{UB,\infty}$)/$PW_{C,\infty,0}$		NPW= ($EUA_{AB,\infty}$+ $EUA_{UB,\infty}$)-$EUA_{C,\infty,0}$ B/C Ratio = ($EUA_{AB,\infty}$+$EUA_{UB,\infty}$)/$EUA_{C,\infty,0}$	

3.7 Risk Considerations for Highway Project Benefit-Cost Analysis

The total benefits of a highway project in physical asset service life-cycle are established by assessing the overall impacts of investing the project on life-cycle agency costs of construction, rehabilitation, and maintenance; vehicle operating costs; travel time; crashes; and air emissions (Sinha and Fwa, 1988). The input factors for computing each of these benefit items after project implementation may be changed to a single new value and this will result in a single benefit outcome for the concerning benefit item. Often, the input factors may be changed to multiple possible new values after project implementation and a number of possible benefit outcomes will be obtained correspondingly. When a probability distribution can be assigned to the set of possible values of an input factor, the probabilistic risk assessment can be performed to ultimately establish its mathematical expectation (or expected value) after project implementation. The expected value of the input factor can then be used to compute the expected outcome of benefits for the benefit item. The following discusses the primary input factors inherited with risks and concepts of probabilistic risk assessments of the input factors.

3.7.1 Primary Input Factors under Risk

Construction and repair costs may not remain as predicted. The changes in market remains volatile and the political decisions or the changes may cause unexpected changes on the unit costs of materials and labor. This causes a two-fold effect: the increase in cost for the same activity versus the predicted one and the cost incurred by the functional deficiencies because of deferred activity.

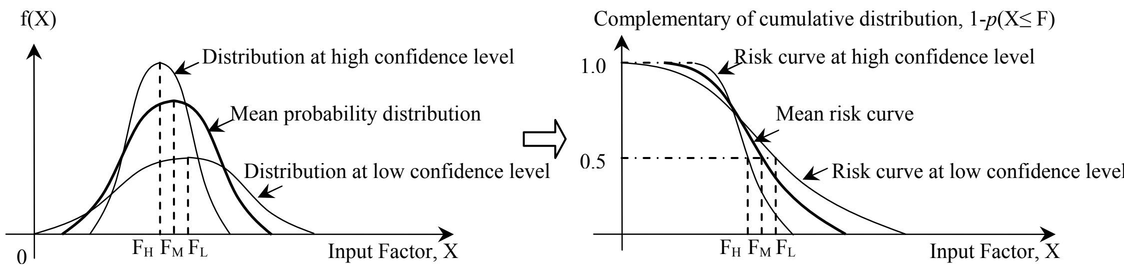
Traffic demand may not follow the projected path. The increased use of physical highway assets especially by heavy vehicles will trigger the change in the useful service lives of pavement and bridge assets. As a result, the project life-cycle benefits and costs will change accordingly.

Discount rate may fluctuate over time during the physical asset service life-cycle.

3.7.2 Probabilistic Risk Assessment

3.7.2.1 Bayesian Updating for Probability Distributions

The probability risk analysis may produce a family of probability distributions for the individual input factors needed for computing project life-cycle benefits at different confidence levels. The average of these distributions represents a mean probability distribution. As seen in Figure 3.20, the corresponding risk curves associated with a specific input factor as the complementary of cumulative distributions (CCD) can be derived. The expected value of the input factor (corresponding to CCD value of 0.5) based on the mean risk curve or a risk curve at higher confidence level may be used for estimating the project life-cycle benefits (Paté-Cornell, 2002; Winkler, 2003). Bayesian updating can help improve the confidence level of a distribution, thus improved confidence level of the risk curve.



Note: X_M, X_L, X_H- the expected value of an input factor according to a distribution at mean, low or high confidence level.

FIGURE 3.20. Characterization of risks in highway project benefit-cost analysis.

Without loss of generality, Bayesian updating for a continuous input factor variable X for computing project life-cycle benefits is

$$f(X=F|\varepsilon)=\frac{f(X=F).f(\varepsilon|X=F)}{f(\varepsilon)}$$

where ε = Newly available information for assessing X
f(X=F) = Prior distributions for X; f(X=F|ε) = Posterior distributions for X
f(ε|X=F) = Likelihood function of having X equal to F, and
f(ε) = Prior predictive distribution of new information, $f(\varepsilon)=\int_{-\infty}^{\infty} f(\varepsilon|X)f(X)dX$.

As an example, assuming that travel speed as the input factor for computing project benefits in terms of travel time reduction follows a normal distribution. The normal parameters for the prior distribution of speed based on engineering judgment are m_1=60 mph and σ_1=10 mph. If additional information from 100 simulation runs implies a mean and standard deviation of m=45 mph and σ=5 mph, the normal parameters for the posterior distribution become $m_2=\frac{(1/\sigma_1^2)m_1+(n/\sigma^2)m}{(1/\sigma_1^2)+(n/\sigma^2)}=\frac{(1/10^2)\times 60+(100/5^2)\times 45}{(1/10^2)+(100/5^2)}=45.04$ mph and $\sigma_2=\sqrt{\frac{\sigma_1^2\sigma^2}{n\sigma_1^2+\sigma^2}}=\sqrt{\frac{10^2\times 5^2}{100\times 10^2+5^2}}=0.5$ mph.

As such, the expected speed for computing benefits of travel time reduction is updated from 60 mph to 45.04 mph, while the standard deviation is narrowed down from 10 mph to 0.5 mph. This provides a firmer distribution for travel speed as an input factor for the computation.

3.7.2.2 Selection of Input Probability Distributions

Strictly speaking, construction and repair costs, traffic demand, and discount rate are discrete variables. Their minimum and maximum values of possible outcomes are bounded by non-negative values. In addition, the distributions of the possible outcomes could be either symmetric or skewed. Such characteristics can be modeled by the beta distribution that is continuous over a finite range 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 $f(x|\alpha, \beta, L, H) = \frac{\Gamma(\alpha+\beta)\cdot(x-L)^{\alpha-1}\cdot(H-x)^{\beta-1}}{\Gamma(\alpha)\cdot\Gamma(\beta)\cdot(H-L)^{\alpha+\beta-1}} \quad (L \le x \le H)$, where the Γ -function factors serve to normalize the distribution so that the area under the density function from L to H is exactly one. The mean and variance for the beta distribution are given as $\mu = \frac{\alpha}{\alpha+\beta}$ and $\sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$.

It is seen that the distribution mean 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 decrease 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 3.20 presents the combinations of skewness and variance (kurtosis) for beta distributions that best approximate the risk factor.

TABLE 3.20. Approximate Values of Shape Parameters for Beta Distributions

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

3.7.2.3 Determination of Distribution Controlling Parameters

For state-maintained highway networks, historical data on highway construction and repair costs, traffic volumes, and discount rates are generally available. Such data can be processed to obtain the values of input factors for risk-based life-cycle benefit-cost analysis.

3.7.2.4 Performing Simulation

Simulation is essentially a rigorous extension of sensitivity analysis that uses randomly sampled values from the input probability distributions to calculate separate discrete results. Two types of sampling techniques are commonly used. The first type is Monte Carlo sampling that uses random numbers to select values from probability distributions. The second type is Latin Hypercube sampling where the probability scale of the cumulative distribution curve is divided into an equal number of probability ranges. The number of ranges used is equal to the number of iterations performed in the simulation. Because of stratified sampling used in the Latin Hypercube simulation, it is possible to achieve convergence in fewer iterations as compared to those of the Monte Carlo simulation (FHWA, 1998; Reigle, 2000).

3.8 Methodology for Uncertainty-Based Project Benefit-Cost Analysis

3.8.1 Highway Project Benefit-Cost Analysis under Uncertainty

As a practical matter, the probability distribution for the possible values or even the full range of possible values of a certain input factor for computing individual project benefit items may not be known. Hence, the expected value of the input factor cannot be determined and the expected outcome of benefits cannot be estimated correspondingly. This section introduces an approach extended from Shackle's model to explicitly address cases where those input factors are under uncertainty with no definable probability distributions. Finally, a generalized methodology for project benefit-costs analyses under certainty, risk, and uncertainty is established.

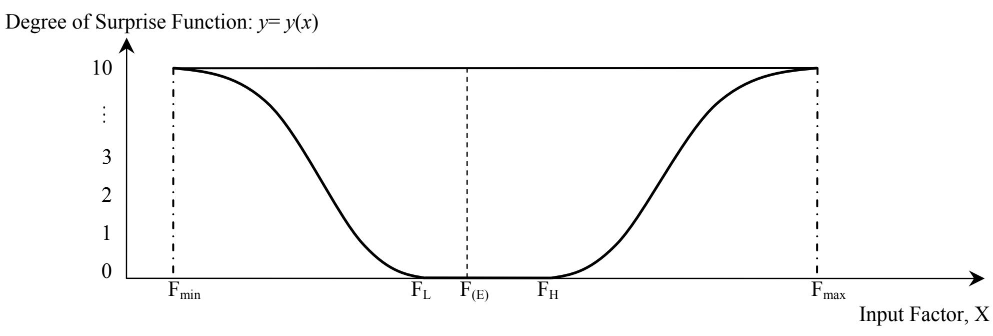
3.8.2 Basic Concepts of Shackle's Model

Shackle's model overcomes the limitation of inability to compute the mathematical expectation for each input factor for computing project benefits according to the following procedure. First, it uses degree of surprise as a measure of uncertainty associated with the input factor for computing project benefits in place of probability distribution. Then, it introduces a priority weight by jointly evaluating each known outcome of an input factor for computing project benefits and its degree of surprise pair. Finally, it identifies and standardizes the focus gain and focus loss values relative to an expected outcome from maximum priority weights (Ford and Ghose, 1998; Shackle, 1949; Young, 2001).

3.8.2.1 Degree of Surprise Function

The degree of surprise reflects the decision-maker's reaction to degree of uncertainty regarding possible outcomes of an input factor for computing a specific item of project benefits resulted from any investment option, with gains and losses from the expected outcome being considered separately (Figure 3.21). A degree of surprise function for an input factor for computing a specific item of project benefits can be established in the following:

- Assume a range of *s* possible outcomes of an input factor X for computing a specific item of project benefits from an investment option ($X = F_1, F_2, \ldots, F_S$ ranging from F_{min} to F_{max})
- Denote $F_{(E)}$ as the expected outcome for the input factor for computing a specific item of project benefits
- Let the deviation of an outcome of the input factor X relative to the expected outcome $F_{(E)}$ to be x, $x = X - F_{(E)}$
- Assign a value as degree of surprise y, ranging from 0 for no surprise to 10 for highest surprise, to reflect the decision maker's degree of belief for a given outcome X as captured by the deviation x
- Establish a degree of surprise function y = f(x).



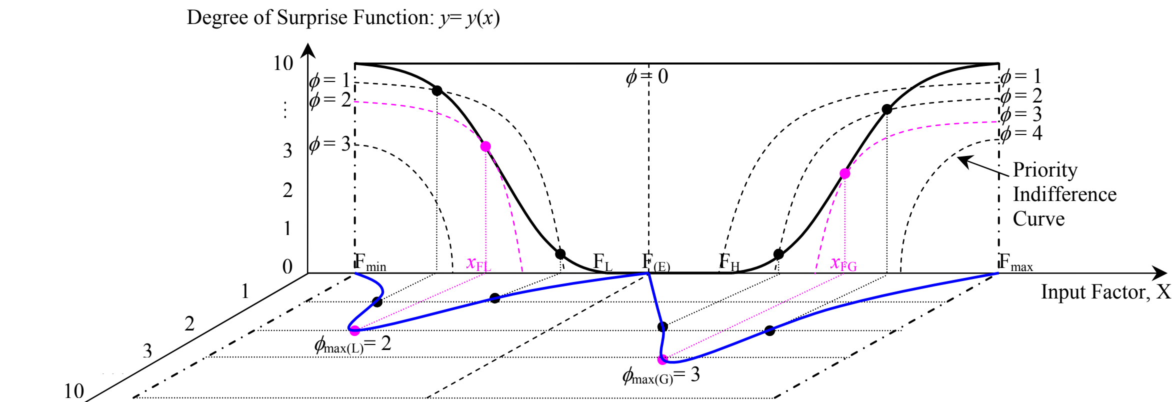
Note: F_{min}, F_{max}- minimum and maximum values of an input factor for computing a specific item of project benefits; F_L, F_U- lower and upper extreme values of an input factor with no degree of surprise; $F_{(E)}$- expected outcome of an input factor; x- deviation of a possible outcome X from $F_{(E)}$, $x = X - F_{(E)}$

FIGURE 3.21. Diagram of a degree of surprise function.

3.8.2.2 <u>Priority Function and Focus Gain and Loss Values from the Expected Outcome</u>

The priority function indicates the weight assigns to the deviation of any outcome of an input factor for computing a specific item of project benefits from the expected outcome and degree of surprise pair (x, y) or in Shackle's terminology, the power of any pair to attract the attention of the decision-maker (Figure 3.22). A priority function for a number of possible outcomes related to an input factor for computing a specific item of project benefits can be developed as follows:

- Determine a priority weight index ϕ by jointly considering the deviation of each outcome of the input factor and degree of surprise pair (x, y), using an index of 0 for lowest priority weight and indices of 2, 3, 4, 5,… for higher priorities
- Denote the decision-maker's priority function by $\phi = \phi(x, y)$ and the function possesses following properties: $\frac{\partial \phi}{\partial x} \rangle 0$; $\frac{\partial \phi}{\partial y} \langle 0$. A priority function can be defined in the following function forms $\phi = \alpha \cdot x^{0.5} - \beta \cdot y^2$, $\phi = \alpha \cdot x - \beta \cdot y^2$ or $\phi = \alpha \cdot x^{0.5} - \beta \cdot y$, where α and β are coefficients with respect to the deviation of the input factor from the expected outcome and degree of surprise
- Priority function ϕ is a saddle shaped curve that maintains a maximum priority weight on the gain side from expected outcome and a maximum priority weight on the loss side from expected outcome. The deviations of the two outcomes corresponding to the two maximum priority weights are called focus gain (x_{FG}) and focus loss (x_{FL}) values.

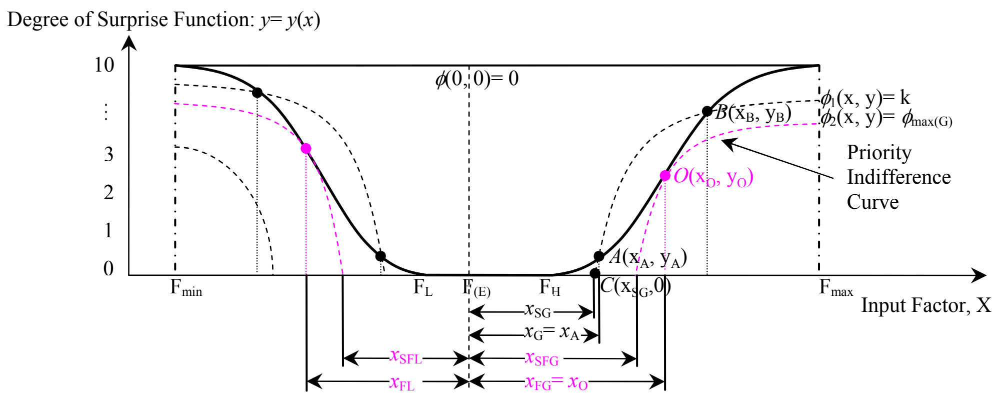


Note: F_{min}, F_{max}- minimum and maximum values of an input factor for computing a specific item of project benefits; F_L, F_U- lower and upper extreme values of the input factor with no degree of surprise; $F_{(E)}$- expected outcome of the input factor; x- deviation of a possible outcome X from $F_{(E)}$, $x = X - F_{(E)}$; x_{FG}, x_{FL}- focus gain and focus loss

FIGURE 3.22. Diagram of a priority function.

3.8.2.3 Standardized Focus Gain and Loss Values

The focus gain and loss values are involved with uncertainty because of associated non-zero degrees of surprise. It is therefore necessary to filter out such uncertainty to establish the standardized focus gain and loss values with zero degree of surprise. The standardization process can be accomplished by using the priority indifference curves at both the gain side and the loss side from the expected outcome that retain the maximum priority weights consistent with those of the focus gain and focus loss values, respectively.



Note: F_{min}, F_{max}- minimum and maximum values of an input factor for computing a specific item of project benefits; F_L, F_U- lower and upper extreme values of th input factor with no degree of surprise; $F_{(E)}$- expected outcome of the input factor; x- deviation of a possible outcome X from $F_{(E)}$, $x = X - F_{(E)}$; x_{FG}, x_{SFG} - focus gain and standardized focus gain; x_{FL}, x_{SFL} - focus loss and standardized focus loss

FIGURE 3.23. Illustration of the standardized focus gain and loss values.

Denote

x	= Deviation of a possible outcome of an input factor X from the expected outcome $F_{(E)}$
y(x)	= Degree of surprise function, set $y(x) = c \cdot x^2$
$\phi_1(x, y)$	= Priority indifference curve, set $\phi_1(x, y) = \alpha_1 \cdot x^{0.5} - \beta_1 \cdot y^2 = k$ $(k \geq 0)$
$\phi_2(x, y)$	= Maximum priority indifference curve on the gain side, $\phi_2(x, y) = \alpha_2 \cdot x^{0.5} - \beta_2 \cdot y^2 = \phi_{max(G)}$
x_{SG}	= Standardized gain value on indifference curve $\phi_1(x, y)$ with no surprise
x_{FG}	= Focus gain value on maximum priority indifference curve $\phi_2(x, y)$
x_{SFG}	= Standardized focus gain value on maximum priority indifference curve $\phi_2(x, y)$ with no surprise

A, *B*, *C* are points on $\phi_1(x, y)$, and *O* is a point on $\phi_2(x, y)$.

The purpose is to find the standardized focus gain x_{SFG} from the underlying focus gain x_{FG} on the maximum priority indifference curve $\phi_2(x, y)$. As $\phi_2(x, y)$ only intersects with the degree of surprise function y(x) at point *O*, it would be impractical to further progress the standardization process. This is because it is impossible to simultaneously calibrate two parameters α_2 and β_2 for $\phi_2(x, y)$ based solely on one point on the curve. To overcome this restriction, the indifference curve $\phi_1(x, y)$ closest to $\phi_2(x, y)$ that intersects with the degree of surprise function y(x) twice at points *A* and *B* can be utilized. As shown in Figure 3.23, when the priority indifference curve $\phi_1(x, y)$ approaching $\phi_2(x, y)$ (i.e., $\phi_1(x, y) = k \rightarrow \phi_{max(G)}$), the standardized gain value x_{SG} for $\phi_1(x, y)$ will overlap with the standardized focus gain x_{SFG}. Hence, the process reduces to establishing a mathematical expression for the standardized gain value x_{SG}.

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

$$\alpha_1 \cdot x_A^{0.5} - \beta_1 \cdot y_A^2 = k \quad (3\text{-}1)$$

$$\alpha_1 \cdot x_B^{0.5} - \beta_1 \cdot y_B^2 = k \quad (3\text{-}2)$$

Substituting $y_A = c \cdot x_A^2$ and $y_B = c \cdot x_B^2$ into Equations (3-1) and (3-2), we obtain

$$\alpha_1 = \frac{k\left(x_B^4 - x_A^4\right)}{\left(x_B^4 . x_A^{0.5} - x_B^{0.5} . x_A^4\right)} \quad (3\text{-}3)$$

For point $C(x_{SG}, 0)$ on $\phi_1(x, y)$, we get $\phi_1(x, y) = \alpha_1 \cdot x_{SG}^{0.5} - \beta_1 \cdot 0^2 = \alpha_1 \cdot x_{SG}^{0.5}$ (3-4)

Thus,

$$x_{SG} = [\frac{\varphi_1(x_{SG}, 0)}{\alpha_1}]^2 \quad (3\text{-}5)$$

and

$$x_{SFG} \approx [\frac{\varphi_{max(G)}}{\alpha_1}]^2 = [\frac{\varphi_{max(G)} . (x_B^4 . x_A^{0.5} - x_B^{0.5} . x_A^4)}{k\left(x_B^4 - x_A^4\right)}]^2 \quad (3\text{-}6)$$

Following this procedure, the standardized focus gain and loss values for an input factor for computing a specific project benefit item, x_{SFG} and x_{SFL}, corresponding to the maximum priority indices, $\phi_{max(G)}$ and $\phi_{max(L)}$, on the gain side and loss side from the expected outcome can be determined (Li and Sinha, 2004).

3.8.3 Extension of Shackle's Model for Project Benefit-Costs Analysis under Uncertainty

3.8.3.1 <u>Dollar Value Benefits of Individual Project Benefit Items under Uncertainty</u>

Shackle's model first assigns degrees of surprise to possible outcomes of an input factor for computing a specific item of project benefits that deviate from the expected outcome. It then designates a priority weight for the deviation of each outcome from the expected outcome and its degree of surprise pair. The deviations of two outcomes separately maintaining the highest priority weights on the gain side and loss side from the expected outcome are identified and denoted as focus gain and focus loss values. Finally, the focus gain and loss values are standardized to remove associated uncertainty.

The process of identifying focus gain and loss values and further standardizing those values facilitates complete filtration of uncertainty associated with an input factor for computing a specific item of project benefits. In the original Shackle's model, the ratio of standardized focus gain over focus loss is utilized to assess the project merits. The theory behind this is that a project is more preferred if it preserves a higher focus gain-over-loss ratio. For highway project evaluation that compares various projects using dollar value benefits, it is desirable to simultaneously consider the expected outcome with the focus gain and focus loss values regarding the input factor. With this in mind, an extension of Shackle's model is introduced in the following:

Denote

$F_{(E)}$	= Expected outcome of an input factor for computing a specific item of project benefits
x_{SFG}	= Standardized focus gain from the expected outcome
x_{SFL}	= Standardized focus loss from the expected outcome
F_{SFG}	= Outcome of an input factor with standardized focus gain, $F_{SFG} = F_{(E)} + x_{SFG}$
F_{SFL}	= Outcome of an input factor with standardized focus loss, $F_{SFL} = F_{(E)} - x_{SFL}$
F	= A single value determined according to a decision rule for an input factor under uncertainty

Given a triple $< F_{SFL}, F_{(E)}, F_{SFG} >$ concerning an input factor for computing a specific item of project benefits, a decision rule can be set in order to determine a single value that will be eventually used for project benefit computation. Assuming that the decision-maker only tolerates loss of the value from the expected outcome for an input factor for computing a specific item of project benefits by ΔX, the decision is set below:

$$F = \begin{cases} F_{(E)}, & \text{if } \left| F_{SFL} - F_{(E)} \right| \leqslant \Delta X \\ \dfrac{F_{SFL}}{[1-\Delta X/F_{(E)}]}, & \text{otherwise} \end{cases} \tag{3-7}$$

In some cases, lower values for an input factor under uncertainty are preferred. For instance, all other things being equal, an increase in the discount rate could result in loss of benefits for a given project. The decision rule thus becomes

$$F = \begin{cases} F_{(E)}, & \text{if } \left| F_{SFL} - F_{(E)} \right| \leqslant \Delta X \\ \dfrac{F_{SFL}}{[1+\Delta X/F_{(E)}]}, & \text{otherwise} \end{cases} \tag{3-8}$$

If the deviation of focus loss F_{SFL} from the expected outcome $F_{(E)}$ does not exceed ΔX, the expected outcome will be assigned. This will yield identical decision outcome between uncertainty-based analysis and risk-based analysis, which maintains methodological consistency. Different tolerance level ΔX may be used for different input factors under uncertainty.

3.9 A Generalized Methodology for Highway Project Evaluation under Certainty, Risk, and Uncertainty

The total benefits of a highway project consist of multiple benefit items and each of which may be quantified under certainty, risk or uncertainty. Figure 3.24 shows a generalized framework for computing the overall benefits of a highway project.

If a specific item of project benefits is quantified under certainty, the deterministic life-cycle costing approach can be used to compute the single value of benefits for the project benefit item in physical asset service life-cycle. If a specific item of project benefits is quantified under risk, the life-cycle costing analysis and Bayesian updating can be performed to compute updated probability distribution of possible benefit outcomes and then calculate the mathematical expectation of dollar value benefits for the project benefit item in physical asset service life-cycle. If a specific item of project benefits is quantified under uncertainty, single dollar value benefits for the project benefit item can be computed using a pre-specified decision rule as the extension of Shackle's model. This value can either be equivalent to the expected outcome or the outcome of benefits corresponding to the standardized focus loss with penalty.

Having computed the dollar value benefits for each project benefit item, the itemized benefits can be combined to arrive at the total project benefits in physical asset service life-cycle. In order to facilitate cross comparisons of different types of highway projects associated with different physical asset types, the total project benefits are typically expressed in equivalent uniform annual amounts to cancel out the effect of differences in physical asset service lives.

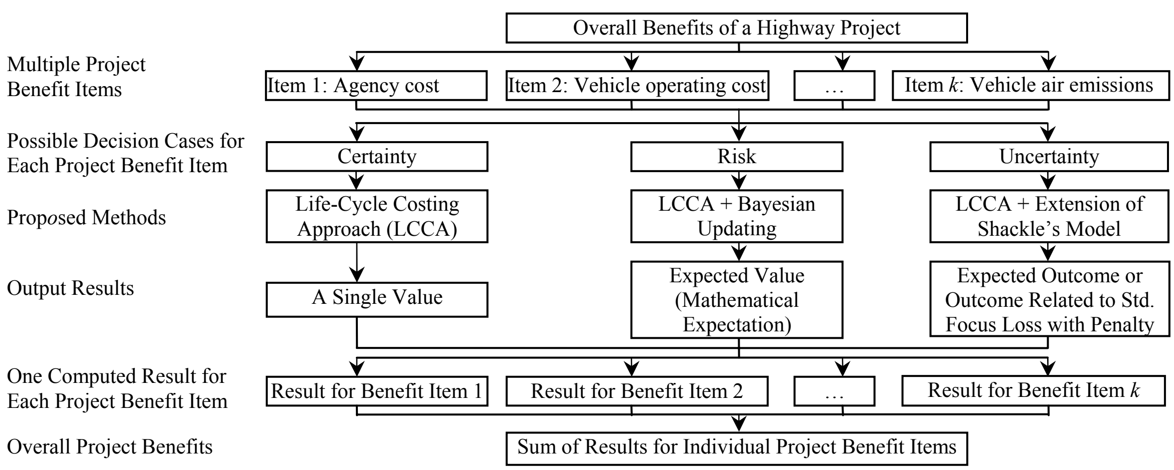


FIGURE 3.24. A generalized framework for project evaluation under certainty, risk and uncertainty.

CHAPTER 4:
PROPOSED STOCHASTIC MODEL FOR PROJECT SELECTION

In the transportation investment decision-making process, project evaluation focuses on quantifying the dollar value project benefits and costs in physical asset service life-cycle. The project benefits can be calculated using the above framework for project evaluation under certainty, risk, and uncertainty. The project costs are normally estimated using existing cost models.

Subsequently, project selection is conducted on the basis of estimated project life-cycle benefits and costs. Due to limited budget available, only some of the highway projects proposed for funding are actually selected for implementation. From the network-level investment decision perspective, project selection aims to select a subset of mixed types of highway projects from a large number of candidate projects proposed to yield the maximized overall benefits subject to budget and other constraints. In the project selection process, different tradeoff methods are normally considered to evaluate the impacts of such decision policies on the overall benefits to be generated from the investment. The optimization problem for project selection is known in the literature as the capital budgeting problem (Lorie and Savage, 1955; Weingartner, 1963). More generally, this problem falls in the category of the multi-choice multidimensional Knapsack problem (MCMDKP) (Sinha and Zoltners, 1979), where budget is achievable from different budget sources and the analysis is conducted for a multiyear period.

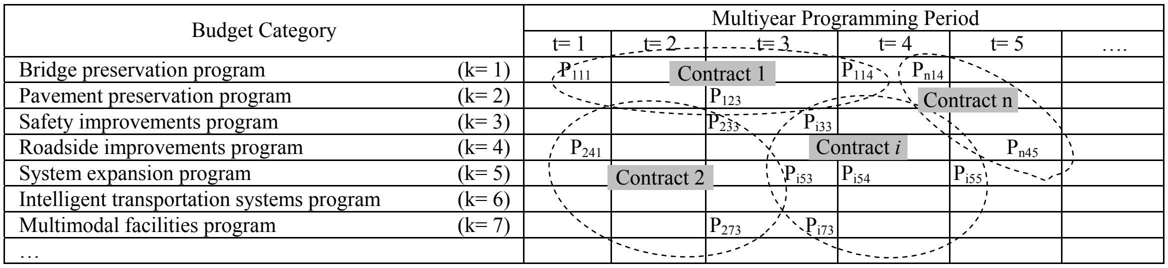
4.1 Characteristics of Project Selection

4.1.1 Issue of Budget Constraints

Project selection focusing on an entire highway system is influenced by several key issues. One of such issues is the available budget for the multiyear project selection and programming period. In the current practice, state transportation agencies generally maintain a number of asset management programs to handle different system management issues, such as pavement and bridge preservation, safety improvements, roadside improvements, system expansion, ITS, multimodal facilities, and maintenance. A certain level of budget is designated to each program per year and the budget for a particular program is not to be transferred across different programs for use. Candidate projects are proposed to compete for funding within eligible programs. Hence, project selection is constrained by the annual budget for each program across a multiyear period.

4.1.2 Issue of Project Interdependency Relationships

As a practical matter, multiple projects that use funds from different programs may be bundled into contract packages for implementation. For example, a new highway construction contract may contain pavement, bridge, and ITS projects that use funds from pavement and bridge preservation as well as ITS programs over a number of years. In the decision-making process, selection of any one of such contract necessitates the selection of all constituent projects and vice versa. This reveals that in the project selection process the project interdependency relationships must be taken into consideration (Figure 4.1). Adding project interdependency constraints for integrated decision-making are necessary to ensure globally optimal decisions. This is fundamentally different from the existing models in the individualized pavement, bridge, maintenance, safety, and congestion management systems that only select projects related to same type of physical highway assets or a single aspect of system operations.



Note: P_{ikt} refers to a project under contract package *i* using budget from budget category *k* in year *t*

FIGURE 4.1. Illustration of project interdependency relationships in the project selection process.

4.1.3 Issue of Budget Uncertainty

Apart from issues concerning constraints of available budget by program category and project interdependency relationships, the program-specific budget in each year is inherent with uncertainty. Investment decisions are usually made based on an estimated budget years ahead of the project programming period. As time passes by updated budget information would become available, project selection decisions must be updated accordingly to maintain realistic results.

4.2 Proposed Stochastic Optimization Formulations for Project Selection

This section presents a stochastic optimization formulation and its improved versions for finding the optimal subset of highway projects from a large number of candidate projects where there is budget uncertainty. Consider a state transportation agency that carries out highway project selection covering an entire highway system over a future analysis period of t_Ω years. The agency makes first round of investment decisions many years ahead of the programming period using an estimated budget for all years. With time elapsing, updated budget information on the first few years of the multiyear programming period becomes available that motivates the agency to refine the investment decisions. In each refined decision-making process, the annual budget for each program for the first few years that can be accurately determined is treated as a deterministic value, while the budget for the remaining years without accurate information is still processed as stochastic budget.

Assuming that the multiyear budget is refined **Ω** times and each time an increasing number of years with accurate budget information from the first analysis year onward is obtained. Hence, **Ω**-decision stages are involved. Without loss of generality, we assume a discrete probability distribution of budget possibilities for each year where no accurate budget estimate is available. As illustrated in Figure 4.2, for the first stage decisions the multi-program, multiyear budget matrix is comprised of the expected budget for all years that can be best estimated at the time of decision-making. For the second stage decisions, accurate information on budget for years 0 to t_1 is known and is treated as deterministic, and there are ($p_2 = s_2.s_3.\ldots.s_{(L-1)}.s_L.s_{(L+1)}.\ldots.s_\Omega$) possible budget combinations for the remaining years from t_1+1 to t_Ω. For the generic stage *L* decisions, the budget up to year $t_{(L-1)}$ is deterministic and there are ($p_L = s_L.s_{L+1}.\ldots.s_\Omega$) possible combinations for years $t_{(L-1)}$+1 to t_Ω. The final stage has a deterministic budget up to year $t_{(\Omega-1)}$ and $p_\Omega = s_\Omega$ budget possibilities from year $t_{(\Omega-1)}$+1 to t_Ω.

Year	1 to t_1	t_1+1 to t_2	…	$t_{(L-2)}$+1 to $t_{(L-1)}$	$t_{(L-1)}$+1 to t_L	t_L+1 to $t_{(L+1)}$	…	$t_{(\Omega-1)}$+1 to t_Ω
Budget	1 possibility	s_2 possibilities	…	$s_{(L-1)}$ possibilities	s_L possibilities	$s_{(L+1)}$ possibilities	…	s_Ω possibilities
Stage 1:	Deterministic (initially estimated budget)							
Stage 2:	Deterministic	Stochastic						
…	…							
Stage L-1:	Deterministic			Stochastic				
Stage L:	Deterministic				Stochastic			
Stage L+1:	Deterministic					Stochastic		
…	…							
Stage Ω:	Deterministic							Stochastic

FIGURE 4.2. Budget attributes in an Ω-stage recourse decision process.

4.2.1 Basic Model Formulation

As explained in the above, budget actually available for a multiyear programming period in the future could deviate from the budget that can be best estimated at the time when the investment decisions are made. Stochastic formulation can reduce the gap in that it replaces one-stage static decisions based on the expected budget for all years by multi-stage recourse decisions using probabilistic budget estimates. This provides opportunities for the decision-maker to refine the investment decisions when the budget level becomes manifested over time. In the model formulation, discrete probability distributions for the budget possibilities in different years are considered. The stochastic model with **Ω**-stage budget recourses is formulated as a deterministic equivalent program that combines first stage decisions using the initial budget estimate with expected values of recourse functions for the remaining (**Ω** -1) stages (Birge and Louveaux, 2002).

Denote:

x_i = Decision variable of contract i, $i = 1, 2, \ldots, N$

a_i = Benefits of contract i, $i = 1, 2, \ldots, N$

c_{ikt} = Cost of contract i using budget from program category k in year t

ξ_L = Randomness associated with budget in stage L and decision space

$X_L(p)$ = Decision vector using budget $B_{kt}^L(p)$ in stage L, $X_L(p) = (x_1, x_2, \ldots, x_N)^T$

A = Vector of benefits of N contracts, $A = (a_1, a_2, \ldots, a_N)^T$

C_{kt} = Vector of costs of N contracts using budget from program category k in year t, $C_{kt} = (c_{1kt}, c_{2kt}, \ldots, c_{Nkt})^T$

$Q(X_L(p), \xi_L)$ = Recourse function in stage L

$E_{\xi_2}(Q(X_L(p), \xi_L))$ = Mathematical expectation of the recourse function in stage L

$B_{kt}^L(p)$ = The p^{th} possibility of budget for program category k in year t in stage L

$p(B_{kt}^L(p))$ = Probability of having budget scenario $B_{kt}^L(p)$ occur in stage L

$E(B_{kt}^L)$ = Expected budget in stage L, where $E(B_{kt}^L) = \sum_{p=1}^{p_L} \left[P\left(B_{kt}^L(p)\right) \cdot B_{kt}^L(p) \right]$

p = $1, 2, \ldots, p_L$, where $p_L = s_L . s_{L+1} \ldots . s_\Omega$

L = $1, 2, \ldots, \Omega$

i = $1, 2, \ldots, N$

k = $1, 2, \ldots, K$

t = $1, 2, \ldots, M$

A stochastic model with **Ω**-stage budget recourses, under budget constraints by program category and by year as well as integrality constraints restricting the decision variables, as a MCMDKP formulation is shown below:

Maximize $A^T.X_1 + \sum_{\omega=2}^{\Omega} E_{\xi_\omega}\left[Q_\omega\left(X_\omega(p),\xi_\omega\right)\right]$ (3-9)

Stage 1

Subject to $C_{kt}^T.X_1 \leq E(B^1_{kt})$ (3-10)

X_1 is a decision vector with 0/1 integer elements.

Stage 2

$E_{\xi_2}(Q_2(X_2(p), \xi_2)) = \max \{ A^T.X_2(p) \mid B^2_{kt}(p) = E(B^2_{kt}) \}$ (3-11)

Subject to $C_{kt}^T.X_2(p) \leq B^2_{kt}(p)$ (3-12)

$X_1 + X_2(p) \leq 1$ (3-13)

X_1 and $X_2(p)$ are decision vectors with 0/1 integer elements.

...

Stage L

$E_{\xi_L}(Q_L(X_L(p), \xi_L)) = \max \{ A^T.X_L(p) \mid B^L_{kt}(p) = E(B^L_{kt}) \}$ (3-14)

Subject to $C_{kt}^T.X_L(p) \leq B_{kt}^L(p)$ (3-15)

$X_1 + X_2(p) + \ldots + X_L(p) \leq 1$ (3-16)

$X_1, X_2(p), \ldots, X_L(p)$ are decision vectors with 0/1 integer elements.

...

Stage Ω

$E_{\xi_\Omega}(Q_\Omega(X_\Omega(p), \xi_\Omega)) = \max \{ A^T.X_\Omega(p) \mid B^\Omega_{kt}(p) = E(B^\Omega_{kt}) \}$ (3-17)

Subject to $C_{kt}^T.X_\Omega(p) \leq B_{kt}^\Omega(p)$ (3-18)

$X_1 + X_2(p) + \ldots + X_L(p) + \ldots + X_\Omega(p) \leq 1$ (3-19)

$X_1, X_2(p), \ldots, X_L(p), \ldots, X_\Omega(p)$ are decision vectors with 0/1 integer elements.

In the objective function as Equation (3-9), the first term is for the overall project benefits in the first stage decisions using the initial budget estimate and the second term is for the expected value of overall project benefits for the remaining (Ω -1)-stage recourse decisions. Equations (3-10), (3-12), (3-15), and (3-18) are employed to hold budget constraints by program category and by year for the investment decisions at each stage. Equations (3-11), (3-14), and (3-17) compute the expected values of optimal project benefits that use one possible budget closest to the budget updated following the preceding decision stage. Equations (3-13), (3-16), and (3-19) ensure that one highway project that is contained in a specific construction contract is selected at most once in the process of multi-stage recourse decisions.

4.2.2 Improved Model Using Two Budget Constraint Options

Although the budget designated for each program is not transferable across different programs, the year-by-year constrained budget for each program may be handled as a cumulative budget for all years combined. With this alternative treatment of budget constraints, system optimization can thus be conducted using two budget constraint options: the year-by-year constrained budget and cumulative budget. For either option, budget constraints by program category are retained. For the option of cumulative budget constraints, the notations $B_{kt}^L(p)$, $p(B_{kt}^L(p))$, and $E(B_{kt}^L)$ are replaced by $\sum_{t=1}^{M} B^L_{kt}(p)$, $p(\sum_{t=1}^{M} B^L_{kt}(p))$, and $E(\sum_{t=1}^{M} B^L_{kt})$, where $E(\sum_{t=1}^{M} B^L_{kt}) = \sum_{p=1}^{P_L}[p(\sum_{t=1}^{M} B^L_{kt}(p)).\sum_{t=1}^{M} B^L_{kt}(p)]$ ($L = 1, 2, \ldots, \Omega$), accordingly.

4.2.3 Further Enhanced Model Considering Three Tradeoff Methods

The proposed stochastic model that uses two budget constraint options can be further enhanced by incorporating three tradeoff scenarios in project selection. The first tradeoff scenario is to allow comparison of project selection results using contract-based constraints as the basic model.

The second tradeoff method is utilizing corridor-based constraints. For the corridor-based tradeoff scenario, the 0/1 integer decision variable x_i for contract i (i = 1, 2,…, N) in the basic model is replaced by 0/1 integer decision variable y_c for corridor c (c = 1, 2,…, C). For instance, if both contract i and contract (i+5) belong to one corridor (C-2), the respective decision variables x_i and $x_{(i+5)}$ are replaced by one decision variable $y_{(C-2)}$. This reduces number of elements in the decision vector in stage L decisions from $X_L(p)= (x_1, x_2,\ldots, x_N)^T$ to $Y_L(p)= (y_1, y_2,\ldots, y_C)^T$ (L = 1, 2,…, Ω).

The third tradeoff scenario is to assess the impacts of deferring the implementation of some large-scale projects. Essentially, the improved model using two budget constraint options for project selection remain unchanged. Only the inputs of project benefits, costs, and the years in which budgets are needed corresponding to the underlying projects are adjusted.

4.3 Solution Algorithm for the Proposed Models

As mentioned in the review of solution algorithms, the Knapsack problem is NP-hard and the computation time for exact algorithms increases exponentially with the size of a problem instance. With this in mind, we turn to search for an efficient heuristic algorithm. Specifically, this new algorithm stems from the heuristic algorithm developed by Volgenant and Zoon (1990) using the Lagrangian relaxation technique. It establishes the upper bound to the optimal solution by simultaneously computing multiple Lagrangian multipliers, where the number of Lagrangian multipliers computed each time equals to the number of years considered in the programming period (i.e, the number of simultaneously computed multipliers is the total dimensions of the MCMDKP problem). This significantly improves the computational efficiency as compared with the algorithm developed by Volgenant and Zoon that uses two Lagrangian multipliers.

4.3.1 Determination of Budget for Stage L Computation

In an **Ω**-stage recourse decision-making process as Figure 4.2, budget for each program category in stage L has the following characteristics: i) period from years 1 to $t_{(L-2)}$, it will be kept the same as that in stage L-1; ii) period from $t_{(L-2)}+1$ to $t_{(L-1)}$, it will inherit the budget used for computation in stage L-1 selected from $s_{(L-1)}$ possibilities; and iii) period from $t_{(L-1)}+1$ to last year t_Ω, it has $p_L=s_L.s_{L+1}\ldots s_\Omega$ possible combinations. The choice of a specific budget combination is determined by the rule of least squared deviations between a budget possibility $B_{kt}^L(p)$ and the expected budget $E(B_{kt}^L)$ in stage L decisions. The squared deviations $\Delta B^L(p)$ can be separately computed according to the two budget constraint options, namely, $\Delta B^L(p)=\sum_{k=1}^{K}\sum_{t=1}^{M}\left[\left(B_{kt}^L(p)-E\left(B_{kt}^L\right)\right)^2\right]$ for the year-by-year constrained budget option, and

$$\Delta B^L(p)=\sum_{k=1}^{K}\left[\left(\sum_{t=1}^{M}B_{kt}^L(p)-\sum_{t=1}^{M}E\left(B_{kt}^L\right)\right)^2\right]$$ for the cumulative budget option.

4.3.2 Feasibility of Preceding Stage Solution

The first stage decisions in the proposed stochastic model are reached on the basis of the initial budget estimate. For the case of having a lower budget in the second stage, the feasibility of first stage solution may have already been violated. This failure is corrected in the algorithm by checking at the beginning of each stage for budget violations caused by projects selected in the preceding stage. If there exists budget violations, projects under the selected contracts are removed in an optimal manner until no violation of the current stage budget is found.

4.3.3 General Concept of the Lagrangian Relaxation Technique

The stage *L* optimization can be reformulated in the following:

Objective maximize $z(Y_L) = A^T.Y_L$ (3-20)

Subject to $C_{kt}^T.Y_L \le B_{kt}^L$ (3-21)

Y_L is stage *L* decision vector with 0/1 integer elements.

Given non-negative, real Lagrangian multipliers λ_{kt}, the Lagrangian Relaxation of (3-20), $z_{LR}(\lambda_{kt})$, can be written as

Objective $z_{LR}(\lambda_{kt})$ = maximize $\left\{A^T \cdot Y_L + \sum_{k=1}^{K}\sum_{t=1}^{M}\left[\lambda_{kt} \cdot \left(B_{kt}^L - C_{kt}^T \cdot Y_L\right)\right]\right\}$

$$= \text{maximize } \left\{\left(A^T - \sum_{k=1}^{K}\sum_{t=1}^{M}\left(\lambda_{kt} \cdot C_{kt}^T\right)\right).Y_L + \sum_{k=1}^{K}\sum_{t=1}^{M}\left(\lambda_{kt} \cdot B_{kt}^L\right)\right\} \quad (3\text{-}22)$$

Subject to Y_L with 0/1 integer elements.

Because $\sum_{k=1}^{K}\sum_{t=1}^{M}\left(\lambda_{kt} \cdot B_{kt}^L\right)$ in (3-22) is a constant, optimization can just be concentrated on the first term,

namely, maximizing $\left(A^T - \sum_{k=1}^{K}\sum_{t=1}^{M}\left(\lambda_{kt} \cdot C_{kt}^T\right)\right).Y_L$. (3-23)

The solution to (3-23) is Y_L^*, where $Y_L^* = \begin{cases} 1, \text{ if } \left(A^T - \sum_{k=1}^{K}\sum_{t=1}^{M}\left(\lambda_{kt} \cdot C_{kt}^L\right)\right) > 0 \\ 0, \text{ otherwise} \end{cases}$ (3-24)

Then, Y_L^* maximizes $z(Y_L) = A^T.Y_L$, subject to Y_L with 0/1 integer elements.

In order to obtain optimal solution by maximizing $z(Y_L) = A^T.Y_L$, only subject to Y_L with 0/1 integer elements, the following condition needs to be satisfied $\sum_{k=1}^{K}\sum_{t=1}^{M}\left[\lambda_{kt} \cdot \left(B_{kt}^L - C_{kt}^T \cdot Y_L\right)\right] = 0$ (3-25)

In this regard, stage *L* optimization operations need to focus on determining Lagrangian multipliers λ_{kt} such that i) Y_L^* obtained in (3-24) is feasible to the original optimization model, i.e., $C_{kt}^T.Y_L \le B_{kt}^L$ is valid, and ii) condition (3-25) is satisfied to maintain optimality to the original optimization model as Equations (3-20) and (3-21).

4.3.4 Main Steps of the Solution Algorithm for the Basic Model

Denote

X^*_L = Optimal decision vector in stage L

$s(X'_{(L-1)})$ = Set of contracts selected in stage L-1

$s(X'_L)$ = Set of contracts selected in stage L

S(X'L) = Set of contracts selected in stage L-1 so that each of these contracts has at least one project from year 1 to t(L-1), where budget in stage L remains the same as that in stage L-1 for period from year 1 to t(L-1). This means that contract i Є s(X'(L-1)) and cikt > 0 for any k and at least one t (t =1, 2 … t(L-1)). As such, S(X'L)⊆s(X'(L-1))

$S(X''_L)$ = Set of contracts not selected in stage L-1 or selected contracts that do not have a project component between year 1 and year $t_{(L-1)}$ (complement of $S(X'_L)$)

Step 0:

- Outer loop (perform steps 1-12), repeat for stage L = 1 to $L = \Omega$

  Input $B_{kt}^L(p)$ (p =1, 2, …, p_L), $p(B_{kt}^L(p))$, and $X^*_{(L-1)}$

  Compute $E(B_{kt}^L)$, $\Delta B^L(p)$ (p =1, 2, …, p_L)

- Inner loop (perform Steps 1-11), use budget $B_{kt}^L(p)$ such that $\Delta B^L(p) = \min\{B_{kt}^L(1), B_{kt}^L(2), \dots, B_{kt}^L(p_L)\}$ for contract selection in stage L

  Check feasibility of contracts selected in previous stage ($S(X'_L)$) using budget $B_{kt}^{L-1}(p)$, against budget at the current stage ($B_{kt}^L(p)$).

  Initialization for Stage 1

  Set $X^*_0 = \{0, 0, \dots, 0\}$ (No contract selected in stage 0). Hence, $s(X'_0) = S(X'_1) = \Phi$.

Part I: Find an Initial Feasible Solution without Budget Carryover

Step 1: For contract i Є $S(X'_L)$, sort the contracts by benefits (A_i) in descending order.

Step 2: Normalize the cost of contract i Є $S(X'_L)$, c_{ikt}, by dividing the budget $B_{kt}^L(p)$ for stage L decisions, and compute sum of normalized costs of all contract i Є $S(X'_L)$. If no budget violation is found for all (k, t), go to Step 6. Otherwise, go to Step 3.

Step 3: Select the least sum of normalized costs of all contract i Є $S(X'_L)$ for all (k, t).

Step 4: Compute the benefit-to-cost ratio for all contract i Є $S(X'_L)$ and identify contract i in $S(X'_L)$ that has the minimum benefit-to-cost ratio.

Step 5: Remove contracts i with minimum benefit-to-cost ratio and update Lagrangian multiplier. If no budget violation is found for all (k, t), go to Step 6. Otherwise, go to Step 3.

Step 6: Update the list of contracts in $S(X'_L)$ and in $S(X''_L)$, as well as the remaining budget $B_{kt}^L(p)$.

Step 7: Repeat Steps 1-6 for contracts in $S(X''_L)$ using above remaining budget $B_{kt}^L(p)$.

Step 8: Update list of contracts in $S(X'_L)$ and in $S(X''_L)$.

Step 9: Improve the initial feasible solution if possible.

Part II: Improve the Initial Feasible Solution by One-Period Budget Carryover

Step 10: Let S_{kut} = Subset of $s(X'_L)$, using budget from category k in year t, such that each contract in S_{kut} has at least one project component from year 1 to year u

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

Perform Steps 1-9 using budget carryover starting from year u (for $u = r$, r+1,…, M, where r = 1, 2, …, M-1):

For year u, place a contract in $s(X'_L)$ to S_{kut} only if the contract has at least one project component from year 1 to year u (i.e., at least one $c_{ikt} > 0$ for $t= 1, 2, \ldots, u$). In the meantime, remove other contracts from $s(X'_L)$

For year t ($t = 1, 2, \ldots, M$), decrease budget B_{kt} by $B(S_{kut})$

One-period budget carryover for remaining budget in year u to year u+1: Increase budget $B_{k(u+1)}$ by (B_{ku} - $B(S_{kuu})$) and this leaves $B_{ku} = 0$ after budget carryover.

Step 11: Increase r to r+1.

If $r = M$, Set $X^*_L = X_L(p)$ and then go to Step 12. Otherwise, repeat Step 10.

Part III: Repeat for Next Stage L+1

Step 12: Set Stage L to next Stage L+1

If $L = \Omega$, stop. X^*_L is final. Otherwise, go to Step 0 and repeat Steps 1-11 for next stage L+1.

4.3.5 Computational Complexity of the Proposed Algorithm

Number of iterations involved with **Ω**-stage recourses is no more than number of M years in the programming period. Budget categories K and analysis years M are much smaller than number of contracts N. Practically, 3 budget possibilities for each year may be considered to represent low, medium, and high budget levels. This gives possible budget combinations for stages 1, 2, 3,…, and **Ω** to be p_1=1, $p_2=3^{M-1}$, $p_3=3^{M-2}$, …, $p_{(\Omega-1)}=3^2$, and p_Ω=3 with stage 2 having the highest possible combinations. Computational complexity of the algorithm for Steps 1-9 in Part I is $O(MN^2)$. The extended steps in Part II for budget carryover require M iterations and **Ω**-stage recourses in Part III entail at most M iterations. This leads to an overall complexity of $O(M^3N^2)$. Since M is far smaller than N, the algorithm thus maintains a complexity of $O(N^2)$.

CHAPTER 5:
CASE STUDY

The purpose of this case study is to validate the methodology developed for highway project benefit-cost analyses under certainty, risk, and uncertainty and the stochastic model for project selection using different tradeoff methods under budget uncertainty. Benefits associated with each project were computed using the life-cycle activity profiles established for two types of pavements and nine types of bridges, respectively. For non-pavement and non-bridge projects, the benefits were indirectly estimated using the pavement and bridge related activity profiles. Subsequently, the computed benefits and costs directly provided for individual projects were utilized for project selection by applying the stochastic model introduced in this research. The outcomes of project selection based on different budget constraint, budget stage, and tradeoff method combinations were then compared with actual project programming decisions for methodology and model validation.

5.1 Data Collection and Processing

The data on projects proposed for Indiana state highway programming were used for the case study. The data were extracted from a data clearinghouse with details of system inventory, historical costs, asset conditions, and operations concerning the Indiana state highways dating back to 1980.

5.1.1 Case Study Period

According to the Indiana state highway programming practices, the desirable time horizons for short-term and long-term programming are 3-5 years and 7-10 years, respectively. For the methodology and model validation purpose, it is desirable to choose a relatively long programming period for analysis. One constraint encountered was the available information on budget in each year. The annual budgets were only available from 1996 onward. As such, eleven-year data from 1996-2006 were used for this case study. Table 5.1 summarizes project and contract information by program category during 1996-2006.

TABLE 5.1. Summary of Total Number of Project and Contracts

Program Category	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
Bridge Preservation	185	159	136	178	228	171	140	161	163	106	88	1,715
Pavement Preservation	170	132	162	123	201	138	157	202	72	25	41	1,423
Safety Improvements	240	297	232	269	384	243	195	228	398	179	157	2,822
Roadside Improvements	47	37	35	50	63	50	53	86	100	54	38	613
Major / New Construction	17	16	37	38	106	21	28	34	104	38	38	477
Other State Facilities	0	0	0	0	0	0	0	0	1	0	0	1
ITS	0	0	0	12	2	4	6	1	9	4	1	39
Miscellaneous	27	28	35	24	40	36	35	30	15	6	14	290
Total No. of Projects	686	669	637	694	1,024	663	614	742	862	412	377	7,380
Total No. of Contracts	464	412	429	411	610	418	422	469	649	408	376	5,068

5.1.2 Data Processing

The eleven-year data for period 1996-2006 contain 7,380 projects grouped into 5,068 contracts. The data were further classified according to the applicable types of life-cycle activity profiles to facilitate the life-cycle cost applications for project benefit computation. To reference the computed project benefits and costs from single point in time, all amounts were converted into 1990 constant dollar values.

5.1.2.1 Agency Costs

The physical asset life-cycle agency costs consist of construction, rehabilitation, and maintenance costs. For the life-cycle agency cost computation, unit costs derived from historic data were utilized. For pavement-related work, the unit costs were expressed in 1990 constant dollars per lane-mile. While for bridge-related work, the unit costs for substructure, superstructure, deck and surface components were expressed in 1990 constant dollars per square foot, respectively. The original database had missing fields on project length. It was indirectly estimated by using the project costs and the unit costs applicable for the particular type of work.

5.1.2.2 Highway User Costs

Highway user cost items considered in the case study include vehicle operating costs, travel time, crashes, and air emissions. The vehicle operating costs and air emissions are mainly influenced by vehicle speed and roadway surface conditions. Whereas travel time and crashes, they are mainly affected by vehicle speed. The annual amounts of individual user cost items were computed on vehicle miles of travel multiplied by the unit costs for individual user cost items for per mile of travel. The unit user costs were first obtained from the historical data and were updated using regression models calibrated to relate unit user costs with speed and roadway surface condition.

5.2 Computation of Project Benefits in Physical asset Service Life-Cycle

The difference in life-cycle agency and user costs between the actual activity profile and the standard base case life-cycle activity profile was estimated and regarded as benefits triggered by a project. Such difference was first computed for the first service life-cycle and expanded to perpetuity. For the actual life-cycle activity profile in perpetuity, only the first service life-cycle was considered for early termination and the standard base case life-cycle profile was assumed to resume back from the second cycle onward. The rationale behind this is that transportation investments are made to match the standard base case activity profile proposed from design to ensure lowest life-cycle costs. Project benefits in perpetuity are expressed in present worth amounts. A user-friendly interactive tool in Microsoft Excel was built to automate the project benefit computation.

5.2.1 Project Benefit Items

5.2.1.1 Agency Costs

The standard base case profiles are the ideal case of the investments occurred across the service life-cycle of pavements or bridges, allowing the particular infrastructure to sustain the desired useful service life. The profiles for the actual case analyses differ from the base case, in which the timing of the activity was determined from the comparison of project cost directly provided with historical average costs of such type of project. Changes in the timing of the major activity would trigger change in the life-cycle profile and the difference of agency costs between the two profiles was considered as agency benefits generated by the project.

The project cost data possess high variations. Such variations may be attributable to several factors, such as project location, price change of construction materials, amount of associated work for the specific site, land acquisition, etc. Taking these factors into account some penalty on the life-cycle reduction was given as long as the project costs go beyond the historical average cost value added up to three standard deviations. In each case, the penalty was confined within half of the time interval between any two major investments. An annual increasing gradient of 3 percent was assumed for routine maintenance costs.

5.2.1.2 Highway User Costs

The user cost profiles for computing annual vehicle operation, travel time, crash, and air emission costs remained identical in terms of timing in base case and actual life-cycle activity profiles used for agency cost estimations. For each of the user cost components, the annual costs for the first year between two major activities were calculated and an annual increasing gradient of 2 percent was assumed for the subsequent years. The 2 percent increase was maintained until the next major investment and the annual user costs for the first year were resumed back to the initial value after each major investment. The difference in the life-cycle user costs based on the base case and actual life-cycle user cost profiles thus was considered as the user benefits.

5.2.2 Risk and Uncertainty Factors Affecting Project Benefits

Variations of factors like unit costs of construction, rehabilitation, and maintenance work; traffic growth; and discount rate would alter physical asset life-cycle agency and user costs, and thus yield change in project benefits. As a result, this would influence highway investment decision-making. In this case study, risk-based analyses were performed for agency costs, vehicle operating costs, and vehicle air emissions, while uncertainty-based analyses were conducted for travel time and vehicle crashes because these user cost items were more difficult to obtain objective probabilities and measurable quantities for the concerning input factors inherited with uncertainty.

5.2.3 Computation of Project Benefit Items under Risk

Unit costs of construction, rehabilitation, and maintenance work, traffic growth rate, and discount rate are factors considered for risk-based analysis. For each factor, the minimum and maximum values of their possible outcomes are bounded by non-negative values. In addition, the distribution of the possible outcomes could be either symmetric or skewed. These characteristics can be readily modeled by the Beta distribution. The general Beta distribution has four parameters: lower bound, upper bound, and two parameters that control the distribution shape.

Risk analysis was performed by using the @RISK software, Version 4.5 with simulation tools embedded in Microsoft Excel. The @RISK software for risk analysis encompasses four steps: developing a model, identifying uncertainty, analyzing the model with simulation, and making a decision. The software uses Monte Carlo and Latin Hypercube sampling techniques to perform risk analysis. This case study used the Latin Hypercube sampling technique for 10 simulation runs, each with 1,000 iterations. For individual unit costs of construction, rehabilitation, and maintenance work; traffic growth rate; and discount rate, the average of the expected values computed in multiple simulation runs was adopted as the input for project benefit estimations under risk.

5.2.4 Computation of Project Benefit Items under Uncertainty

For each input factor for computing a specific item of project benefits that involves uncertainty, it is assumed that a number of possible outcomes are known and objective probabilities and measurable outcomes are unknown. Hence, a mathematical expectation for the input factor cannot be established. We may only estimate an expected outcome for the input factor based on the best available knowledge pertaining to the factor. To simplify the uncertainty-based analysis, the average of outputs from multiple simulation runs can be used as the expected outcome $F_{(E)}$, and, if more is better, the average of outcomes lower than the expected outcome may be used as focus loss F_{SFL}. The two values are then compared with the tolerance level ΔX to determine the single-valued outcome for the factor under uncertainty. Appendices 1 and 2 present computation details for one pavement project and one bridge project.

5.2.5 Results of the Computed Project Benefits

The overall project benefits are comprised of overall agency benefits and user benefits aggregated from changes in vehicle operating and emission costs obtained through risk-based analysis and changes in travel time and vehicle crashes estimated through uncertainty-based analysis. The average benefit-to-cost ratio for pavement-related projects is 5.5 and for bridge-related project is 3.8, respectively. Among the pavement-related projects considered for life-cycle cost analyses, 87 percent of the projects have benefit-to-cost ratio greater than one while rest of the 13 percent have the ratio smaller than one. Among the bridge projects, 70 percent have benefit-to-cost ratio more than one while rest of the 30 percent has the ratio less than one.

5.2.6 Discussions of the Computed Project Benefits

Total projects benefits were calculated under risk and uncertainty by applying the life-cycle activity profiles. The projects for which life-cycle activity profiles were not directly applicable, benefits were computed proportional to the average benefit-to-cost ratios corresponding to pavement- and bridge-related project categories. The present worth amounts of computed benefits in perpetuity and costs directly provided for each project were utilized as the input in the project selection process.

5.3 Application of Stochastic Optimization Model for Project Selection

A highway asset management system software tool developed by the PI in the past was augmented to incorporate the solution algorithm for the stochastic model for project selection introduced in this research. The software consists of three functional components: data input, system optimization, and output and report generation. The data input component reads data from programming project database according to project description number that is uniquely assigned to each candidate project. Information on each project read in the software includes: project let fiscal year, project costs, project length, average daily traffic, number of lanes, project priority, DOT district number, contract number, work category, work type, highway functional classification, transportation system, bridge type, county code, and present worth of project benefits at perpetuity computed by a user friendly interactive tool developed in the Microsoft Excel. The system optimization component contains the solution algorithm for solving the stochastic model. Reports of optimization results could be automatically generated both in tabular and graphic forms in the Microsoft Excel.

The case study utilized the computed project benefits under risk and uncertainty and project costs of 5,068 contracts proposed for the period 1996-2006 as inputs. Due to budget limitations, only a subset of the proposed contracts could be selected in individual years. The objective of the optimization model is to yield maximized benefits of all selected contracts under budget constraints.

5.3.1 Tradeoff Methods for Project Selection

In this case study, the stochastic model that considers stochasticity of available budget and other constraints adopted three tradeoff methods:

- Conducting project selection on contract-by-contract basis;
- Conducting project selection on corridor basis; and
- Conducting project selection by deferring the implementation of some large-scale projects.

Contract-based tradeoff analysis was a straightforward approach, where projects were grouped into contracts. If a contract was selected, all underlying projects must be selected. Otherwise, all projects under the same contract were eliminated. For the corridor-based tradeoff analysis, the projects implemented along Interstates I-64, I-65, I-69, I-70, I-74, I-80, I-90, and I-94 were grouped together as one contract by Interstate number and project implementation year. For the deferment-based tradeoff method, two-year deferment in the project implementation was considered for projects that cost over ten million dollars.

5.3.2 Budget Recourses in the Project Selection Period

The annual budgets were updated three times from the initially estimated budget during 1996-2006. This gave 4-stage budget recourses in the application of the stochastic model. Initially estimated budget and final budget are listed in Tables 5.2 and 5.3. Pavement and bridge preservation, new construction, and miscellaneous (mainly maintenance) programs were allocated major proportion of annual budget across the analysis years.

TABLE 5.2. Indiana Annual Highway Programming Budgets (Current dollars, in Millions)

a. Initially Estimated Budget in Stage 1

Program	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bridge Preservation	74	109	80	95	63	81	90	65	69	63	86
Pavement Preservation	235	260	278	281	365	431	358	292	218	284	386
Safety Improvements	29	41	43	41	60	37	48	47	36	45	62
Roadside Improvements	6	9	10	9	6	8	10	10	8	10	14
Major / New Construction	166	96	197	273	166	176	155	254	366	247	213
Other State Facilities	2	2	3	2	1	2	3	3	2	3	4
ITS	4	6	6	6	2	1	26	18	8	18	24
Miscellaneous	53	55	56	62	53	66	67	70	74	74	95
Total	569	579	672	769	717	803	757	760	781	744	883

b. Updated Budget in Stage 4

Program	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bridge Preservation	74	109	80	82	63	88	85	56	75	63	86
Pavement Preservation	235	260	278	286	268	466	336	254	239	284	386
Safety Improvements	29	41	44	32	56	40	45	41	40	45	62
Roadside Improvements	6	9	10	7	12	9	10	9	9	10	14
Major / New Construction	166	96	190	265	266	190	145	221	402	247	213
Other State Facilities	2	2	3	2	3	2	3	2	2	3	4
ITS	4	6	5	16	12	2	24	16	9	18	24
Miscellaneous	53	55	45	42	62	63	61	72	74	74	95
Total	569	579	654	732	743	860	708	671	851	744	883

TABLE 5.3. Budget Variations from the Original Estimates at Different Stages

a. Change in Budget at Stage 2 from the Originally Estimated Budget in Stage 1

Program	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bridge Preservation	0%	0%	0%	-14%	0%	8%	0%	9%	0%	0%	0%
Pavement Preservation	0%	0%	0%	2%	-27%	8%	0%	10%	0%	0%	0%
Safety Improvements	0%	0%	1%	-21%	-5%	8%	0%	-33%	0%	0%	0%
Roadside Improvements	0%	0%	1%	-21%	94%	8%	0%	-33%	0%	0%	0%
Major / New Construction	0%	0%	-3%	-3%	60%	8%	0%	27%	0%	0%	0%
Other State Facilities	0%	0%	1%	-21%	146%	8%	0%	-33%	0%	0%	0%
ITS	0%	0%	-27%	175%	499%	8%	0%	-50%	0%	0%	0%
Miscellaneous	0%	0%	-19%	-32%	17%	-4%	0%	0%	0%	0%	0%
Total	0%	0%	-3%	-5%	4%	7%	0%	10%	0%	0%	0%

b. Change in Budget at Stage 3 from Budget at Stage 2

Program	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bridge Preservation	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Pavement Preservation	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Safety Improvements	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Roadside Improvements	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Major / New Construction	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Other State Facilities	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
ITS	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%
Miscellaneous	0%	0%	0%	0%	0%	0%	-9%	0%	0%	0%	0%
Total	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%	0%

c. Change in Budget at Stage 4 from Budget at Stage 3

Program	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bridge Preservation	0%	0%	0%	0%	0%	0%	0%	-20%	10%	0%	0%
Pavement Preservation	0%	0%	0%	0%	0%	0%	0%	-21%	10%	0%	0%
Safety Improvements	0%	0%	0%	0%	0%	0%	0%	30%	10%	0%	0%
Roadside Improvements	0%	0%	0%	0%	0%	0%	0%	30%	10%	0%	0%
Major / New Construction	0%	0%	0%	0%	0%	0%	0%	-31%	10%	0%	0%
Other State Facilities	0%	0%	0%	0%	0%	0%	0%	30%	10%	0%	0%
ITS	0%	0%	0%	0%	0%	0%	0%	74%	10%	0%	0%
Miscellaneous	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%
Total	0%	0%	0%	0%	0%	0%	0%	-20%	9%	0%	0%

There was no change in the budget considered for years 1996-1997, 2002, and 2004-2006 (still estimated). In budget stage 2, the budgets varied from -32 percent to +499 percent, with changes in 1999, 2000, and 2003 to be most significant. In addition, the largest fluctuations were associated with ITS and miscellaneous programs. In budget stage 3, there were no changes in the total budget of all program categories except for a 6 percent reduction in year 2002. In stage 4, budget varied from -20 percent to +74 percent in 2003 and increased by 9-10 percent in 2004.

5.3.3 Budget Constraint Scenarios

Budget for each program is not transferable across different programs. For instance, budget for pavement program is not supposed to be used for bridge program. However, multi-year budget for each program can be constrained year-by-year or treated as a cumulative budget for all years combined. Accordingly, system optimization can be conducted separately under the two scenarios. For yearly constrained budget scenario, a small amount may be left from a preceding year that is not sufficient to select any additional contract and this surplus budget amount can then be carried over to the following year to fully utilize available funds. For cumulative budget scenario, it is just a single-period analysis with no carryover.

5.3.4 Project Selection Results

5.3.4.1 Number of Contracts Selected

In the case study, project selection was conducted under two budget constraint scenarios, four budget stages, and three tradeoff methods. Table 5.4 presents the number of candidate contracts proposed and actually authorized by Indiana DOT, and selected by the software in each year according to various budget constraint, budget stage, and tradeoff method combinations.

TABLE 5.4. Contract Selection Results under Yearly Constrained and Cumulative Budget Scenarios at All Stages

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Yearly Constrained Budget				Cumulative Budget			
			STG 1	STG 2	STG 3	STG 4	STG 1	STG 2	STG 3	STG 4
1996	464	443	422	407	421	421	439	439	439	437
1997	412	358	385	375	383	383	395	397	397	395
1998	429	275	414	404	415	415	411	412	412	412
1999	411	323	406	393	392	392	382	383	381	383
2000	610	578	516	526	526	526	535	536	537	533
2001	418	412	415	415	414	415	403	405	403	404
2002	422	421	404	402	401	404	392	393	392	393
2003	469	461	432	432	433	432	429	431	429	430
2004	649	648	284	284	283	283	592	591	590	592
2005	408	406	64	64	65	65	393	393	393	394
2006	376	375	55	54	54	55	367	367	367	366
Total	5,068	4,700	3,797	3,756	3,787	3,791	4,738	4,747	4,740	4,739

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Yearly Constrained Budget				Cumulative Budget			
			STG 1	STG 2	STG 3	STG 4	STG 1	STG 2	STG 3	STG 4
1996	464	443	447	447	447	447	418	422	420	423
1997	412	358	392	391	391	391	401	402	402	402
1998	429	275	421	421	421	421	400	401	401	401
1999	411	323	401	399	399	398	371	386	386	371
2000	610	578	499	521	521	521	495	500	500	503
2001	418	412	412	412	412	412	399	400	400	400
2002	422	421	400	403	403	401	390	390	391	391
2003	469	461	439	443	442	441	452	453	453	455
2004	649	648	305	307	307	307	558	559	559	559
2005	408	406	97	100	100	98	393	393	393	393
2006	376	375	59	61	62	60	349	363	362	363
Total	5,068	4,700	3,871	3,904	3,904	3,896	4,625	4,668	4,666	4,660

TABLE 5.4. Contract Selection Results under Yearly Constrained and Cumulative Budget Scenarios at All Stages (Continued)

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Yearly Constrained Budget				Cumulative Budget			
			STG 1	STG 2	STG 3	STG 4	STG 1	STG 2	STG 3	STG 4
1996	464	443	422	422	422	422	438	439	439	437
1997	412	358	385	383	383	383	396	397	398	398
1998	429	275	413	414	414	414	412	412	412	412
1999	411	323	404	391	391	391	383	384	382	381
2000	610	578	561	570	570	570	534	537	538	535
2001	418	412	414	413	413	414	404	404	402	402
2002	422	421	398	395	395	399	392	393	392	393
2003	469	461	426	426	426	426	429	431	430	431
2004	649	648	279	280	277	278	592	591	591	593
2005	408	406	63	63	61	62	393	393	393	394
2006	376	375	49	48	49	48	366	366	366	366
Total	5,068	4,700	3,814	3,805	3,801	3,807	4,739	4,747	4,743	4,742

For each budget stage and tradeoff method combination, higher numbers of contracts were selected under the cumulative budget scenario for the entire analysis period. This is obvious, as all other things remain unchanged; the cumulative budget scenario has fewer constraints in the optimization process, which might yield a better solution. However, as no constraints were imposed for each year under the cumulative budget scenario, the numbers of projects selected in each year tended to be less balanced as opposed to those of the yearly-constrained budget scenario.

The contracts selected by both the yearly constrained budget and cumulative budget scenarios at each budget stage were moreover matching with Indiana DOT authorized contracts except for the years from 2004 to 2006. The difference is due to the unavailability of more accurate budget information. The same trend was observed for the rest of the tradeoff methods. On an average 81 percent of the contracts are matched with Indiana DOT authorized contracts under yearly constrained budget scenario and there is approximately same number of contracts selected under cumulative budget scenario as of authorized by Indiana DOT. Fewer restrictions in the cumulative budget scenario attribute the difference in the contracts selected. Very similar trend was observed across other tradeoff methods.

5.3.4.2 System-Wide Benefits of Selected Contracts

The system-wide benefits of the selected contracts in terms of the present worth of benefits in perpetuity are illustrated in Figure 5.1. The benefits under cumulative budget scenario were always found to be more than the yearly constrained budget scenario in each tradeoff method, due to fewer restrictions in the optimization process. Benefits were more for stage four budget (representing the stochastic budget) than stage one budget (representing deterministic budget). This could mainly be attributable to the true representations of the temporal variations in the monetary values of the stage four budget. The deferment-based tradeoff method yielded slightly higher benefits than those using contract-base and corridor-based tradeoff methods.

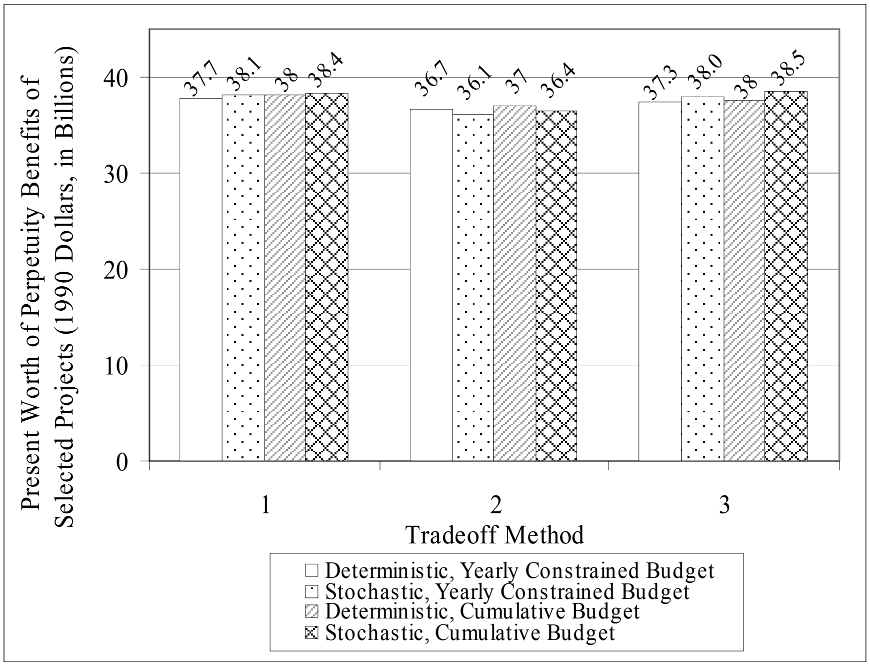


FIGURE 5.1. Comparison of total benefits of selected contracts under yearly constrained and cumulative budget scenarios with and without budget recourses (1996-2006).

5.3.4.3 Comparison of Results

One of the key reasons of the case study is to compare the software outputs with the actual State Highway programming practice. As mentioned, two budget scenarios namely yearly constrained and cumulative budget scenarios, each with four budget recourses and three tradeoff methods were considered. The performance measure used was the consistency of the total number of contracts selected by both the software and actually authorized by Indiana DOT. As seen in Table 5.5, relative high consistency was maintained between the software outputs and the actual programming practices in Indiana. During the years 1996 to 2003, contracts selected by the contract-based tradeoff method under all scenarios are 88 percent matched averagely with Indiana DOT authorized projects. The percentage matching for the rest of the analysis period varies from 36 percent to 12 percent from 2004 to 2006, respectively. The lower percentages were due to inconsistency in the budget information. In total, similar trend was observed among the three-tradeoff methods, with approximately 70 percent of average matching with Indiana DOT authorized contracts. Comparatively, deferment-based tradeoff method results were better matched than others did across all budget years.

TABLE 5.5. Contracts both Authorized by the Indiana DOT and Selected under Yearly Constrained and Cumulative Budget Scenarios at All Stages

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	No. of Contracts	% Match
1996	464	443	383	86%
1997	412	358	334	93%
1998	429	275	260	95%
1999	411	323	284	88%
2000	610	578	466	81%
2001	418	412	395	96%
2002	422	421	373	89%
2003	469	461	391	85%
2004	649	648	231	36%
2005	408	406	53	13%
2006	376	375	45	12%
Total	5,068	4,700	3,215	68%

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	No. of Contracts	% Match
1996	464	443	392	88%
1997	412	358	351	98%
1998	429	275	267	97%
1999	411	323	283	88%
2000	610	578	454	79%
2001	418	412	392	95%
2002	422	421	375	89%
2003	469	461	422	92%
2004	649	648	263	41%
2005	408	406	96	24%
2006	376	375	43	11%
Total	5,068	4,700	3,338	71%

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	No. of Contracts	% Match
1996	464	443	399	90%
1997	412	358	342	96%
1998	429	275	265	96%
1999	411	323	286	89%
2000	610	578	479	83%
2001	418	412	393	95%
2002	422	421	373	89%
2003	469	461	391	85%
2004	649	648	231	36%
2005	408	406	53	13%
2006	376	375	45	12%
Total	5,068	4,700	3,257	69%

As seen in Table 5.6, on an average 65 percent of the projects selected by using three tradeoff methods under all budget scenarios at all budget recourse stages were matched with Indian DOT authorized contracts.

TABLE 5.6. Contracts both Authorized by Indiana DOT and Selected Using Contract-, Corridor-, and Deferment-Based Tradeoff Methods under Yearly Constrained and Cumulative Budget Scenarios at All Stages

Year	Candidate Contracts	INDOT Authorized	No. of Contracts	% Match
1996	464	443	352	79%
1997	412	358	334	93%
1998	429	275	258	94%
1999	411	323	272	84%
2000	610	578	428	74%
2001	418	412	381	92%
2002	422	421	360	86%
2003	469	461	390	85%
2004	649	648	208	32%
2005	408	406	51	13%
2006	376	375	40	11%
Total	5,068	4,700	3,074	65%

More details of the case study are shown in Appendices 3-9.

CHAPTER 6:
CONCLUSIONS

6.1 Summary and Findings

In the present study, a generalized framework with emphases on project benefit-cost analysis and project selection was developed to facilitate optimal highway investment decision-making. In aspect of project benefit-cost analysis, a methodology for quantifying highway project benefits in physical asset useful service lives was developed using the life-cycle costing approach. Issues of risk and uncertainty commonly inherited with costs of construction, rehabilitation, and maintenance work; traffic demand; and discount rate in highway project evaluation were explicitly addressed in the methodology. A stochastic optimization model was developed for project selection. Practical issues of project interdependence relationships, budget constraint scenarios, and budget uncertainty involved with project selection were considered in the model. A case study was conducted to validate the developed methodology and model in this research.

Project life-cycle cost analysis estimates costs incurred over the physical asset useful service life as such it provides a basis for comparing alternative investment options. Typical physical asset life-cycle activity profiles were established for major highway facilities such as pavements and bridges, represented by the timing, frequency, and magnitude of construction, maintenance, and rehabilitation treatments occurred over the physical asset useful service life. For non-pavement and non-bridge projects, the benefits were indirectly estimated using the pavement and bridge related activity profiles. The agency costs of construction, maintenance, and rehabilitation; and individual user cost items concerning vehicle operation, travel time, vehicle crashes, and vehicle air emissions were separately computed according to the typical physical asset life-cycle activity profiles. Geometric gradients were used for annual maintenance costs and individual user cost items on an annual basis between two major investments. The differences of life-cycle agency and user costs between the actual and the typical physical asset life-cycle activity profiles were regarded as agency and user benefits, correspondingly. The overall project benefits in one physical asset service life-cycle were the aggregation of agency and user benefits and they were expanded to perpetuity time horizon to estimate the overall project benefits in perpetuity.

Construction, rehabilitation, and maintenance costs; traffic demand; and discount rates are often inherited with variability and these factors were considered as primary input factors for risk- and uncertainty-based project benefit analyses in this research. When firm probability distributions are definable for the possible outcomes of those input factors, the expected project benefits could be determined using their mathematical expectations. The probability distributions of the respective factors were defined as the Beta distribution which has the both end bounded by non-negative values. In addition, the above factors might not be exactly characterized by reliable probabilistic distributions. Consequently, a meaningful mathematical expectation for each factor could not be established and this prohibited risk-based analysis, thereby necessitating the uncertainty-based analysis. An extension of Shackle's model was developed to establish a single-valued outcome for a specific factor under uncertainty and the value was then used as input for uncertainty-based project benefit estimation.

The degree of uncertainty associated with an input factor for estimating the benefits of a highway project might be classified as certainty, risk or uncertainty. The respective values of input factors computed under certainty, risk or uncertainty were adopted to estimate overall benefits of highway projects in one physical asset service life-cycle and in perpetuity horizon. The developed methodology offers flexibility for the decision-maker to consider any combination of input factors for the cases of certainty, risk or uncertainty and allows to compute the benefits of sub-items (if further separable) under certainty, risk or uncertainty in accordance with the available information. For instance, the vehicle operating cost item consists of expenses of fuel, tires, engine oil, and maintenance and depreciation. The values of these sub-items could be separately estimated according to the relevant input factors under certainty, risk or uncertainty and then be combined to arrive at the total value of vehicle operation costs.

The project selection process aims to choose a subset of the candidate projects under budget and other constraints such that the overall benefits of selected projects are maximized. A system optimization model was formulated on the basis of the multi-choice multidimensional Knapsack problem, and a heuristic algorithm based on Lagrangian relaxation techniques was prepared for the model. As a practical matter, project interdependent relationships was preserved. The inability to predict the budget before-hand was addressed involving budget recourses. In addition, yearly constrained and cumulative budget constraints were taken into account. The contract-, corridor-, and deferment-based tradeoff methods were introduced to the model to facilitate project tradeoff analyses at the network-level. The stochastic model developed could be applied to any combination of multiple program categories and analysis years. The decision-maker might update the budget profile any number of times. The objectivity, flexibility, robustness, and holistic nature of the developed stochastic model would ensure achieving truly global optimal investment decisions.

In order to validate the research findings, a case study was conducted for project benefit estimation and project selection using eleven-year data on past candidate projects for state highway programming in Indiana. The case study results revealed that corridor-based and deferment-based tradeoff analysis methods did not necessarily generate additional benefits from the selected contracts as compared to the overall benefits of contracts selected using the contract-based tradeoff method. It was also found that budget uncertainty did affect the project selection results significantly. For each combination of budget profiles (with/without uncertainty) and tradeoff methods (contract/corridor/deferment-based), higher numbers of contracts were selected and slightly higher overall benefits of selected contracts were achieved under the cumulative budget scenario due to fewer constraints in the optimization process. Except for several years without accurate budget information, high matching percentages were consistently obtained between contracts selected using the proposed stochastic model according to different budget constraint, budget uncertainty, and tradeoff analysis combinations and contracts actually authorized for implementation. The case study results thus bolster idea that state transportation agencies could use the research findings to improve the efficiency of highway investment decision making.

6.2 Implementation Issues

The products of this research are as follows:

- A methodology for project life-cycle benefit-cost analyses under certainty, risk and uncertainty
- A stochastic optimization model, along with an efficient algorithm, to facilitate project selection using different tradeoff analysis methods under budget uncertainty.

The proper implementation of the methodology by agencies can 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 on investments, and overall savings on agency and user costs in the long run, without sacrificing physical asset performance. It is therefore expected that the implementation of the results will result in changes in network-level highway programming.

Tools to facilitate implementation of the results of this research include training to personnel and organization via workshops to demonstrate the project evaluation and selection methodology and model. 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.

6.3 Directions for Future Research

The findings of this research is an improved way of holistic highway system management that responds to an environment of increasing system traffic demand, aging physical highway assets, and limited resources. One of the major contributions of the present research is that it has explicitly addressed uncertainty and integration issues on overall decision-making framework. Furthermore, tradeoff analysis methods were introduced to enable project tradeoffs 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 further research could be directed towards refinement to the methodology for project benefit-cost analyses in aspect of synthesizing individual benefit items that account for their positive or negative correlations. In addition, the stochastic model could be augmented to include the uncertainty nature of additional constraints.

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APPENDICES

APPENDIX 1: An Example of Highway Pavement Project Evaluation under Certainty, Risk, and Uncertainty

I. Deterministic Project Benefit Analysis Using the Life-Cycle Cost Analysis Approach

1. Base Case Deterministic Life-Cycle Agency Cost Analysis
(Using the Typical Pavement Life-Cycle Activity Profile)

1.1 <u>Basic Data</u>

Let Fiscal Year:	2000
Construction Estimate:	$15,000,000
Project Length:	10 miles
Average Daily Traffic Year:	2000
Average Daily Traffic Count:	7,380
Number of Lanes:	2
Work Type Description:	Pavement Rehabilitation (3R/4R standards)

1.2 <u>Pavement Lane-Mile Calculation</u>

Length	= 10 miles
Lane	= 2
Total Lane-Miles	= 20

1.3 <u>Base Case Agency Cost Items</u>

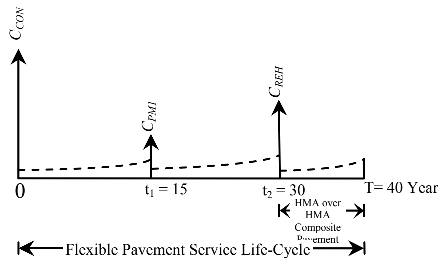
Agency Cost Item	Unit Cost (1990$/lane-mile)	Project-Related Agency Cost
Construction	1,353,536.53	= 1,353,536.53*20 = 27,070,730.60
Rehabilitation	155,287.00	= 155,287.00*20 = 3,105,740.00
Resurfacing	52,938.00	= 52,938.00*20 = 1,058,760.00
Preventive Maintenance	4,120.00	= 4,120.00*20 = 82,400.00
Annual Maintenance	138.00	= 138.00*20 = 2,760.00

1.4 <u>Additional Input Factors</u>

Discount Rate *i*: 4%

Annual Maintenance Cost Gradient g_1, g_2, g_3: 3%

1.5 Base Case Life-Cycle Agency Cost Calculation

Pavement Type	Computation	
Flexible Pavement	Agency Cost Profile	
	PW_{LCAC}	$=C_{CON}+C_{PM1}/(1+i)^{t_1}+C_{REH}/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$ $+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_3))/(1+i)^{t_2}$ $= 27,070,730.60+82,400.00/(1+4\%)^{15}+3,105,740.056/(1+4\%)^{30}$ $+(2,760.00(1-(1+3\%)^{15}(1+4\%)^{-15}))/(4\%-3\%)$ $+((2,760.00(1-(1+3\%)^{(30-15)}(1+4\%)^{-(30-15)}))/(4\%-3\%))/(1+4\%)^{15}$ $+((2,760.00(1-(1+3\%)^{(40-30)}(1+4\%)^{-(40-30)}))/(4\%-3\%))/(1+4\%)^{30}$ $= 28,139,792.32$
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$ $= 28,139,792.32/(1-(1/(1+4\%)^{40})) = 35,543,012.42$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$ $= 28139792.32((4\%(1+4\%)^{40})/((1+4\%)^{40}-1)) = 1,421,720.49$
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i = 35,543,012.42*4\% = 1,421,720.49$

2. Base Case Deterministic Life-Cycle User Cost Analysis
(Using the Typical Pavement Life-Cycle Activity Profile)

2.1 Basic Data

Let Fiscal Year:	2000
Average Daily Traffic year:	2000
Average Daily Traffic Count:	7,380
Project Base Year:	1968
Project Length:	10 miles
Highway Classification:	Rural Principal Arterial
Average Speed:	59.37mph (for Rural Principal Arterial)
Base Year AADT:	7,380/[(1+2%)^{32}] = 3916 (An annual growth rate of 2%)

2.2 Project-Related Base Year User Costs

Vehicle Opt. Cost ($/VMT)	= 0.3523 - 0.0022*Speed	= 0.3523 - 0.0022*59.37	= 0.2217
Travel Time ($/VMT)	= 0.40327-0.004245*Speed	= 0.4033-0.004245**59.37	= 0.1534
Crash Cost ($/VMT)	= -0.1483+0.004877*Speed	= -0.1483+0.004877**59.37	= 0.1413
Emission Cost ($/VMT)	= 0.2059+0.00006256*Speed	= 0.2059+0.00006256*59.37	= 0.2096

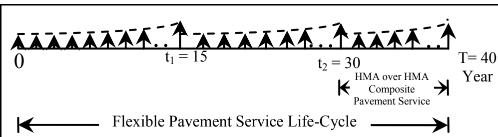
Note: In 1990 constant dollars, based in an earlier Indiana study, Li and Sinha (2003)

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.2217*3916*10miles*365 = $3,168,846.78
Annual Travel Time Cost	= 0.1534*3916*10miles*365 = $2,192,607.56
Annual Vehicle Crash Cost	= 0.1413*3916*10miles*365 = $2,019,657.42
Annual Vehicle Air Emission Cost	= 0.2096*3916*10miles*365 = $2,995,896.64
Total	$10,377,008.40

2.3 Additional Input Parameters

Annual User Cost Gradient r_1, r_2, r_3: 2%

2.4 Base Case Life-Cycle User Cost Calculation

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1} (1-(1+r_1)^{t_1} (1+ i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2} (1-(1+r_2)^{(t_2-t_1)} (1+ i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3} (1-(1+r_3)^{(T-t_2)} (1+ i)^{-(T-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $=(10,377,008.40 (1-(1+2\%)^{15} (1+ 4\%)^{-15}))/(4\%-2\%)$ $+((10,377,008.40 (1-(1+2\%)^{(30-15)} (1+ 4\%)^{-(30-15)}))/(4\%-2\%))/(1+4\%)^{15}$ $+((10,377,008.40 (1-(1+2\%)^{(40-30)} (1+4\%)^{-(40-30)}))/(4\%-2\%))/(1+4\%)^{30}$ = 232,139,250.65
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$ $= 232,139,250.65/(1-(1/(1+4\%)^{40})) = 293,212,123.80$
	EUAUC	$= PW_{LCUC} .((i(1+i)^T)/((1+i)^T-1))$ $=232,139,250.65 ((4\%(1+4\%)^{40})/((1+4\%)^{40}-1)) =11,728,484.95$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i = 317,396,882.50*4\% = 11,728,484.95$

3. Alternative Case Deterministic Life-Cycle Agency Cost Analysis with Early Termination

3.1 Determination the Reduction in Pavement Useful Service Life

No.	Type	Case	α	Reduction
1	If PC < PM	a. (Unit PM Cost -Unit Project Cost)/Unit PM Cost <=0.5 b. 0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost) <=0.5 c. ((Unit PM Cost+ σ_{pm})-Unit Project Cost))/(Unit PM Cost+ σ_{pm}) <=0.5 d. ((Unit PM Cost+2σ_{pm})-Unit Project Cost))/(Unit PM Cost+2σ_{pm}) <=0.5 e. ((Unit PM Cost+3σ_{pm})-Unit Project Cost))/(Unit PM Cost+3 σ_{pm}) <=0.5 f. Otherwise	(Unit PM Cost-Unit Project Cost)/Unit PM Cost 0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost) ((Unit PM Cost+ σ_{pm})-(Unit Project Cost))/(Unit PM Cost+ σ_{pm}) ((Unit PM Cost+2σ_{pm})-Unit Project Cost))/(Unit PM Cost+ 2σ_{pm}) ((Unit PM Cost+3σ_{pm})-Unit Project Cost))/(Unit PM Cost+3σ_{pm}) 0.5	$y=\alpha*(t_1-0)$
2	If PM < PC < (PM+Rehab)	a.((Unit PM Cost+ Rehab Cost) -Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5 b.0.33((Unit PM Cost+ Rehab Cost)) -Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5 c.((Unit PM Cost+ σ_{pm} + Rehab Cost +σ_{reh})-Unit Project Cost)/(Unit PM Cost+ σ_{pm}+ Rehab Cost+ σ_{reh}) <=0.5 d. ((Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})-Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh}) <=0.5	((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost) 0.33((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost)) ((Unit PM Cost+ σ_{pm} + Rehab Cost+σ_{reh})-Unit Project Cost)/(Unit PM Cost+ σ_{pm} + Rehab Cost+ σ_{reh}) ((Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})-Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh})	$y=\alpha*(t_2- t_1)$

		e.((Unit PM Cost+ 3σ_{pm} + Rehab Cost +3σ_{reh})-Unit Project Cost)/(Unit PM Cost+3σ_{pm}+ Rehab Cost+ 3σ_{reh}) <=0.5	((Unit PM Cost+ 3σ_{pm} + Rehab Cost +3σ_{reh})-Unit Project Cost)/(Unit PM Cost+3σ_{pm}+ Rehab Cost+ 3σ_{reh})	
		f. Otherwise	0.5	
3	If PC > (PM+Rehab)	a.(-(Unit PM Cost+ Rehab Cost) +Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5	(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost)	$y=\alpha*(t_2 - t_1)$
		b.0.33(-(Unit PM Cost+ Rehab Cost)) +Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5	0.33(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost))	
		c.(-(Unit PM Cost+ σ_{pm} + Rehab Cost +σ_{reh})+Unit Project Cost)/(Unit PM Cost+ σ_{pm}+ Rehab Cost+ σ_{reh}) <=0.5	(-(Unit PM Cost+ σ_{pm} + Rehab Cost+σ_{reh})+Unit Project Cost)/(Unit PM Cost+ σ_{pm} + Rehab Cost+ σ_{reh})	
		d. (-(Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})+Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh}) <=0.5	(-(Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})+Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh})	
		e.(-(Unit PM Cost+ 3σ_{pm} + Rehab Cost +3σ_{reh})+Unit Project Cost)/(Unit PM Cost+3σ_{pm}+ Rehab Cost+ 3σ_{reh}) <=0.5	(-(Unit PM Cost+ 3σ_{pm} + Rehab Cost +3σ_{reh})+Unit Project Cost)/(Unit PM Cost+3σ_{pm}+ Rehab Cost+ 3σ_{reh})	
		f. Otherwise	0.5	

3.2 Project Timing

Unit Project Cost = (15,000,000/ (1+4%)^{10}/20) = \$506,673.00 (1990\$/lane-mile)
Unit Rehabilitation Cost = \$155,287.00 (1990\$/lane-mile)
Unit Preventive Maintenance Cost = \$4,120.00 (1990\$/lane-mile)

Unit Project Cost > (Unit Preventive Maintenance Cost + Unit Rehabilitation Cost)
Check Type a:
α = ((Unit Project cost) - (Unit PM Cost+ Rehab Cost))/ (Unit PM Cost+ Rehab Cost)
= (506,673-(4120+155287))/ (4120+155287) = 2.18 > 0.5, Not Applicable

Check Type b:
α = 0.33(((Unit Project cost) - (Unit PM Cost+ Rehab Cost))/ (Unit PM Cost+ Rehab Cost))
= 0.33((506,673-(4120+155287))/ (4120+155287)) = 0.72> 0.5, Not Applicable

Check Type c:

α = 0.33(((Unit Project cost) – (Unit PM Cost+ σ_{pm}+ Rehab Cost+ σ_{reh}))/ (Unit PM Cost+ σ_{pm} + Rehab Cost+ σ_{reh}))

= ((506,673-(4120+6544+155287+242260))/ (4120+6544+155287+242260)) = 0.24< 0.5

$y = \alpha*(T-t_2) = 0.24*(40-30) = 2.4 \approx 2$ Years

Base Year = 2000 - 32 = 1968

3.3 Conversion of Construction Estimate into 1990 Constant Dollars

$Dollar_{2000} = Dollar_{1990} (1+i)^{2000-1990}$

$Dollar_{1990} = 15{,}000{,}000/ (1+4\%)^{10}$

$Dollar_{1990}$ = \$10,133,462.53

3.4 Pavement Maintenance Gradient Adjustment

Due to the late implementation of the project compared with the timing in the base case profile, we assumed that the annual routine maintenance cost would increase in a faster pace for the period after project implementation as

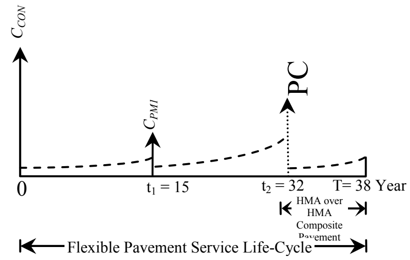
$g'_3 = g_3 + (10\%*((1+ g_2)^{(32-15)}-1))$

$= 3\% + (10\%*((1+ 3\%)^{(32-15)}-1)) = 9.528\%$

3.5 Project-Related Agency Cost Items in 1990$

Agency Cost Item	Unit Cost (1990$/lane-mile)	Project-Related Cost (1990$)
Project Cost	-	10,133,462.53
Construction	1,353,536.53	= 1,353,536.53*20 = 27,070,730.60
Rehabilitation	155,287.00	= 155,287.00*20 = 3,105,740.00
Resurfacing	52,938.00	= 52,938.00*20 = 1,058,760.00
Preventive Maintenance	4,120.00	= 4,120.00*20 = 82,400.00
Annual Maintenance	138.00	= 138.00*20 = 2,760.00

3.6 Alternative Case Deterministic Life-Cycle Agency Cost Calculation

Pavement Type	Computation	
Flexible Pavement	Agency Cost Profile	
	PW_{LCAC}	$=C_{CON}+C_{PM1}/(1+i)^{t_1}+PC/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$ $+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g'_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g'_3))/(1+i)^{t_2}$ $= 27{,}070{,}730.60+82{,}400.00/(1+4\%)^{15}+10{,}133{,}462.53/(1+4\%)^{32}$ $+(2{,}760.00(1-(1+3\%)^{15}(1+4\%)^{-15}))/(4\%-3\%)$ $+((2{,}760.00(1-(1+3\%)^{(32-15)}(1+4\%)^{-(32-15)}))/(4\%-3\%))/(1+4\%)^{15}$ $+((2{,}760.00(1-(1+9.528\%)^{(38-32)}(1+4\%)^{-(38-32)}))/$ $(4\%-9.528\%))/(1+4\%)^{32}$ $= 30{,}070{,}745.45$
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$ $= 30{,}070{,}745.45((4\%(1+4\%)^{40})/((1+4\%)^{40}-1)) = 1{,}552{,}610.30$

4. Alternative Case Deterministic Life-Cycle User Cost Analysis with Early Termination

4.1 Basic Data

Let Fiscal Year:	2000
Average Daily Traffic Year:	2000
Average Daily Traffic Count:	7,380
Project Base Year:	1968
Project Length:	10 miles
Highway Classification:	Rural Principal Arterial
Average Speed:	59.37mph (for Rural Principal Arterial)
Base Year AADT:	$7{,}380/[(1+2\%)^{32}] = 3916$ (An annual growth rate of 2%)

4.2 Project-Related Base Year User Costs

Vehicle Opt. Cost (\$/VMT)	= 0.2217
Travel Time (\$/VMT)	= 0.1534
Crash Cost (\$/VMT)	= 0.1413
Emission Cost (\$/VMT)	= 0.2096

User Cost Item	Annual Cost (1990\$/year)
Annual Vehicle Operating Cost	= 0.2217*3916*10miles*365 = \$3,168,846.78
Annual Travel Time Cost	= 0.1534*3916*10miles*365 = \$2,192,607.56
Annual Vehicle Crash Cost	= 0.1413*3916*10miles*365 = \$2,019,657.42
Annual Vehicle Air Emission Cost	= 0.2096*3916*10miles*365 = \$2,995,896.64
Total	\$10,377,008.40

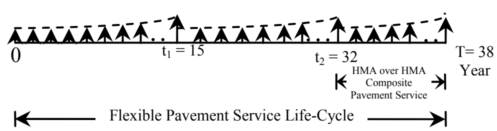
4.3 Additional Input Parameters

Annual User Cost Gradient r_1, r_2: 2%

Due to the late implementation of the project compared with the timing in the base case profile, we assumed that the costs of annual vehicle operating costs, travel time, vehicle crashes, and vehicle emissions would increase in a faster pace for the period after project implementation as

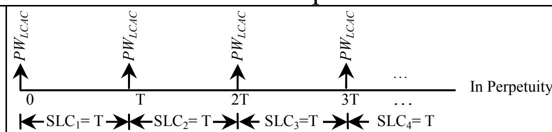
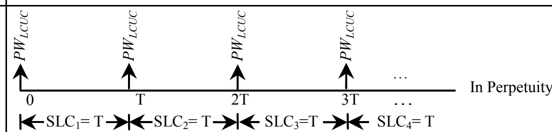
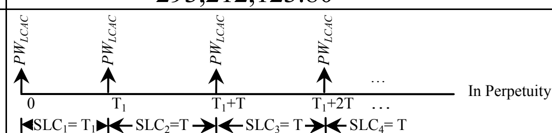
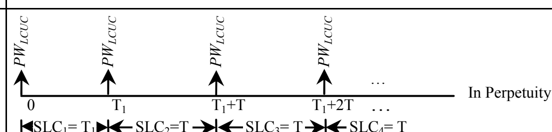
$$r'_3 = r_3 + (10\%*((1+r_2)^{(32-15)}-1))$$
$$= 2\% + (10\%*((1+2\%)^{(32-15)}-1)) = 6\%$$

4.4 Alternative Case Deterministic Life-Cycle User Cost Calculation

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $=(10{,}377{,}008.40(1-(1+2\%)^{15}(1+4\%)^{-15}))/(4\%-2\%)$ $+((10{,}377{,}008.40(1-(1+2\%)^{(32-15)}(1+4\%)^{-(32-15)}))/(4\%-2\%))/(1+4\%)^{15}$ $+((10{,}377{,}008.40(1-(1+6\%)^{(38-32)}(1+4\%)^{-(38-32)}))/(4\%-6\%))/(1+4\%)^{32}$ $= 230{,}015{,}425.70$
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $=230{,}015{,}425.70((4\%(1+4\%)^{38})/((1+4\%)^{38}-1)) = 11{,}876{,}137.86$

5. Computation of Project Life-Cycle Overall Benefits in Perpetuity

Only consider early termination in useful service life in the first life-cycle and the typical service life-cycle as in the base case will follow for the rest of cycles into perpetuity. The justification is that the pavement system manager will always try to upkeep the typical life-cycle activity profile that warrants the lowest life-cycle agency and user costs. If the first life-cycle was not completed as the typical profile, s/he will make every effort to follow the typical life-cycle activity profile in subsequent cycles in order to achieve the lowest total life-cycle costs.

Case		Computation
Base Case: No Early Termination	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,0} = PW_{LCAC}/(1-(1/(1+i)^{T}))$ $= 28{,}139{,}792.32/(1-(1/(1+4\%)^{40}))$ $= 35{,}543{,}012.42$ $PW_{LCUC\infty,0} = PW_{LCUC}/(1-(1/(1+i)^{T}))$ $= 232{,}139{,}250.65/(1-(1/(1+4\%)^{40}))$ $= 293{,}212{,}123.80$
Early Termination in Cycle 1	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,1} = PW_{LCAC1} + (PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 30{,}070{,}745.45 + (28{,}139{,}792.32/(1-(1/(1+4\%)^{40})))/(1+4\%)^{38}$ $= 38{,}078{,}068.31$ $PW_{LCUC\infty,1} = PW_{LCUC1} + (PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 230{,}015{,}425.70 + 232{,}139{,}250.65\ 1(1/(1+4\%)^{40})))/(1+4\%)^{38}$ $= 296{,}071{,}845.3$
	Base Case Benefits	Agency Benefits: $PW_{AB} = PW_{LCAC\infty,1} - PW_{LCAC\infty,0}$ $= 38{,}078{,}068.31 - 35{,}543{,}012.42$ $= 2{,}535{,}055.89$ User Benefits: $PW_{UB} = PW_{LCUC\infty,1} - PW_{LCUC\infty,0}$ $= 296{,}071{,}845.3 - 293{,}212{,}123.80$ $= 2{,}859{,}721.50$ Overall Benefits: $PW_{B} = PW_{AB} + PW_{UB}$ $= 2{,}535{,}055.89 + 2{,}859{,}721.50$ $= 5{,}394{,}777.393$

II. Project Life-Cycle Benefit Analysis Incorporating Risk

Input factors considered for risk-based analysis include bridge agency costs of construction, maintenance, and rehabilitation; traffic growth rates; and discount rates. Monte Carlo simulations were simultaneously performed for those factors using Beta distributions. In this case study, 10 simulation runs and each run with 1,000 iterations were used. For each input factor involving risk consideration, the grand average was established based on the average values of 10 simulation runs and each of which was determined in accordance with the 1,000 iteration outcomes.

In the end, the grand average values for all factors considered for probabilistic risk analysis were used for computing the expected project life-cycle benefits incorporating risk. The analytical procedure used is identical to that for deterministic life-cycle benefit analysis.

It should be noted that the analysis incorporating risk is essentially an analysis under mixed case of certainty and risk. This is because apart from the agency costs, traffic growth rates, and discount rate, the remaining input factors such as useful service life and project size are still treated under certainty.

1. Base Case Life-Cycle Agency Cost Analysis Incorporating Risk

1.1 Unit Costs for Flexible Pavement Activities (1990$/Lane-Mile)

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Construction	1,353,536.53	694,614.00	588,385.00	3,165,840.00	2.49	4.50	51%
Rehabilitation	155,287.00	509,879.00	29,147.00	1,119,863.00	2.56	4.50	328%
Prevent. Maintenance	4,120.00	6,544.00	186.00	21,999.00	2.56	4.50	159%
Annual Maintenance	137.97	499.00	4.00	2,186.00	2.27	4.50	362%

b. Average Values from Simulation Outputs

Cost Item	Unit Cost (1990$/lane-mile)
Construction	1,492,234.51
Rehabilitation	417,362.84
Preventive Maintenance	7,954.30
Annual Maintenance	732.84

1.2 Agency Cost Items for Base Case Life-Cycle Agency Cost Analysis

Agency Cost Item	Project-Related Cost (1990$)
Construction	= 1,492,234.51 *20 = 29,844,690.20
Rehabilitation	= 417,362.84 *20 = 8,347,256.80
Preventive Maintenance	= 7,954.30 *20 = 159,086.00
Maintenance	= 732.84*20 = 14,656.80

1.3 Additional Input Factors

a. Simulation Inputs

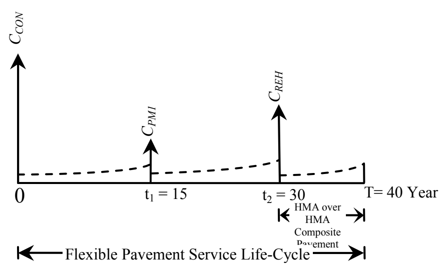
Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate *i*	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Maintenance Gradient g_1	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_2	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_3	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%

b. Average Values from Simulation Outputs

Discount Rate: 4.01%

Annual Maintenance Gradient g_1, g_2, g_3: 2.998%

1.4 Base Case Life-Cycle Agency Cost Calculation Using Average Values from Simulation

Pavement Type	Computation	
Flexible Pavement	Agency Cost Profile	
	PW_{LCAC}	$=C_{CON}+C_{PM1}/(1+i)^{t_1}+C_{REH}/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$ $+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_3))/(1+i)^{t_2}$ $= 29{,}844{,}690.20+159{,}086.00/(1+4.01\%)^{15}+8{,}347{,}256.80/(1+4.01\%)^{30}$ $+(14{,}656.80(1-(1+2.998\%)^{15}(1+4.01\%)^{-15}))/(4.01\%-2.998\%)$ $+((14{,}656.80(1-(1+2.998\%)^{(30-15)}(1+4.01\%)^{-(30-15)}))/(4.01\%-2.998\%))/(1+$ $4.01\%)^{15}+((14{,}656.80(1-(1+2.998\%)^{(40-30)}(1+4.01\%)^{-(40-30)}))/$ $(4.01\%-2.998\%))/(1+4.01\%)^{30}$ = 32,847,688.62
	$PW_{LCAC\infty}$	$= PW_{LCAC}/(1-(1/(1+i)^T))$ $= 32847688.62/(1-(1/(1+4.01\%)^{40}))$ = 41,447,638.91
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$ $= 32{,}847{,}688.62.((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{40}-1))$ = 1,662,050.32
	$EUAAC_{\infty}$	$= PW_{LCAC\infty}.i$ $= 41{,}447{,}638.91*4.01\%$ = 1,662,050.32

2. Base Case Life-Cycle User Cost Analysis

2.1 Basic Data

Let Fiscal Year:	2000
Average Daily Traffic Year:	2000
Average Daily Traffic Count:	7,380
Project Base Year:	1968
Project Length:	10 miles
Average Speed:	59.37mph (for Rural Principal Arterial)
Base Year AADT:	$7{,}380/[(1+2.011\%)^{32}] = 3903$(An annual growth rate of 2.011% as the average of simulation outputs)

2.2 Project-Related Base Year User Cost Calculation

Vehicle Opt. Cost ($/VMT)	= 0.2217
Travel Time ($/VMT)	= 0.1534
Crash Cost ($/VMT)	= 0.1413
Emission Cost ($/VMT)	= 0.2096

Note: In 1990 constant dollars, based in an earlier Indiana study, Li and Sinha (2003)

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.2217*3,903*10miles*365 = $3,158,327.12
Annual Travel Time Cost	= 0.1534*3,903*10miles*365 = $2,185,328.73
Annual Vehicle Crash Cost	= 0.1413*3,903*10miles*365 = $2,012952.74
Annual Vehicle Air Emission Cost	= 0.2096*3,903*10miles*365 = $2,985,951.12
Total	$10,342,559.71

2.3 Additional Input Parameters

a. Simulation Inputs

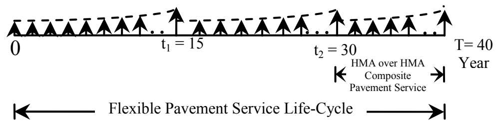
Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%

Annual User Cost Gradient r_1, r_2, r_3: 1.9959%

2.4 Base Case Life-Cycle User Cost Calculation Using Average Values from Simulation

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1} (1-(1+r_1)^{t_1} (1+ i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2} (1-(1+r_2)^{(t_2-t_1)} (1+ i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3} (1-(1+r_3)^{(T-t_2)} (1+ i)^{-(T-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $=(10{,}342{,}559.71 (1-(1+1.9959\%)^{15} (1+ 4.01\%)^{-15}))/(4.01\%-1.9959\%)$ $+((10{,}342{,}559.71 (1-(1+1.9959\%)^{(30-15)} (1+ 4.01\%)^{-(30-15)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{15}$ $+((10{,}342{,}559.71 \quad (1-(1+1.9959\%)^{(40-30)} (1+4.01\%)^{-(40-30)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{30}$ $= 230{,}960{,}466.15$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$ $= 230{,}960{,}466.15/(1-(1/(1+4.01\%)^{40})) = 291{,}428{,}907.31$
	EUAUC	$= PW_{LCUC} .((i(1+i)^T)/((1+i)^T-1))$ $= 230{,}960{,}466.15((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{40}-1)) = 11{,}686{,}299.18$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i = 291{,}428{,}907.31 *4.01\% = 11{,}686{,}299.18$

3. Alternative Case Life Cycle Agency Cost Analysis with Early Termination

3.1 Determination of the Reduction in Pavement Useful Service Life

No.	Type	Case	α	Reduction
1	If PC < PM	a. (Unit PM Cost -Unit Project Cost)/Unit PM Cost <=0.5	(Unit PM Cost-Unit Project Cost)/Unit PM Cost	$y=\alpha^*(t_1-0)$
		b. 0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost) <=0.5	0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost)	
		c. ((Unit PM Cost+ σ_{pm})-Unit Project Cost))/(Unit PM Cost+ σ_{pm}) <=0.5	((Unit PM Cost+ σ_{pm})-(Unit Project Cost))/(Unit PM Cost+ σ_{pm})	
		d. ((Unit PM Cost+2σ_{pm})-Unit Project Cost))/(Unit PM Cost+2σ_{pm}) <=0.5	((Unit PM Cost+2σ_{pm})-Unit Project Cost))/(Unit PM Cost+ 2σ_{pm})	
		e. ((Unit PM Cost+3σ_{pm})-Unit Project Cost))/(Unit PM Cost+3 σ_{pm}) <=0.5	((Unit PM Cost+3σ_{pm})-Unit Project Cost))/(Unit PM Cost+3σ_{pm})	
		f. Otherwise	0.5	
2	If PM < PC < (PM+Rehab)	a.((Unit PM Cost+ Rehab Cost) -Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5	((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost)	$y=\alpha^*(t_2- t_1)$
		b.0.33((Unit PM Cost+ Rehab Cost)) -Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5	0.33((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost))	
		c.((Unit PM Cost+ σ_{pm} + Rehab Cost +σ_{reh})-Unit Project Cost)/(Unit PM Cost+ σ_{pm}+ Rehab Cost+ σ_{reh}) <=0.5	((Unit PM Cost+ σ_{pm} + Rehab Cost+σ_{reh})-Unit Project Cost)/(Unit PM Cost+ σ_{pm} + Rehab Cost+ σ_{reh})	
		d. ((Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})-Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh}) <=0.5	((Unit PM Cost+ 2σ_{pm} + Rehab Cost +2σ_{reh})-Unit Project Cost)/(Unit PM Cost+2σ_{pm}+ Rehab Cost+ 2σ_{reh})	

		e.((Unit PM Cost+ $3\sigma_{pm}$ + Rehab Cost +$3\sigma_{reh}$)-Unit Project Cost)/(Unit PM Cost+$3\sigma_{pm}$+ Rehab Cost+ $3\sigma_{reh}$) <=0.5	((Unit PM Cost+ $3\sigma_{pm}$ + Rehab Cost +$3\sigma_{reh}$)-Unit Project Cost)/(Unit PM Cost+$3\sigma_{pm}$+ Rehab Cost+ $3\sigma_{reh}$)	
		f. Otherwise	0.5	
3	If PC > (PM+Rehab)	a.(-(Unit PM Cost+ Rehab Cost) +Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5	(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost)	$y=\alpha*(t_2- t_1)$
		b.0.33(-(Unit PM Cost+ Rehab Cost)) +Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5	0.33(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost))	
		c.(-(Unit PM Cost+ σ_{pm} + Rehab Cost +σ_{reh})+Unit Project Cost)/(Unit PM Cost+ σ_{pm}+ Rehab Cost+ σ_{reh}) <=0.5	(-(Unit PM Cost+ σ_{pm} + Rehab Cost+σ_{reh})+Unit Project Cost)/(Unit PM Cost+ σ_{pm} + Rehab Cost+ σ_{reh})	
		d. (-(Unit PM Cost+ $2\sigma_{pm}$ + Rehab Cost +$2\sigma_{reh}$)+Unit Project Cost)/(Unit PM Cost+$2\sigma_{pm}$+ Rehab Cost+ $2\sigma_{reh}$) <=0.5	(-(Unit PM Cost+ $2\sigma_{pm}$ + Rehab Cost +$2\sigma_{reh}$)+Unit Project Cost)/(Unit PM Cost+$2\sigma_{pm}$+ Rehab Cost+ $2\sigma_{reh}$)	
		e.(-(Unit PM Cost+ $3\sigma_{pm}$ + Rehab Cost +$3\sigma_{reh}$)+Unit Project Cost)/(Unit PM Cost+$3\sigma_{pm}$+ Rehab Cost+ $3\sigma_{reh}$) <=0.5	(-(Unit PM Cost+ $3\sigma_{pm}$ + Rehab Cost +$3\sigma_{reh}$)+Unit Project Cost)/(Unit PM Cost+$3\sigma_{pm}$+ Rehab Cost+ $3\sigma_{reh}$)	
		f. Otherwise	0.5	

3.2 Project Timing

Unit Project Cost = $(15{,}000{,}000/(1+4.01\%)^{10}/20)$= \$506,186.20 (1990\$/lane-mile)
Unit Rehabilitation Cost = \$ 417,362.84 (1990\$/lane-mile)
Unit Preventive Maintenance Cost = \$7,954.30 (1990\$/lane-mile)

Type 1: Unit Project cost > Unit PM Cost, Not applicable
Type 2: Unit Project cost > Unit PM cost + Unit Rehabilitation Cost, Not applicable
Type3: Unit Project cost > Unit PM Cost + Unit Rehabilitation Cost, Applicable

α = ((Unit Project cost –(Unit PM Cost+ Rehab Cost))/(Unit PM Cost+ Rehab Cost)
= ((506,186.20 – (7,954.30+417,362.84))/ (7,954.30+417,362.84) = 0.19 < 0.5
$y = \alpha*(T-t_2) = 0.19*(40-30) = 1.9 \approx 2$ years
Base Year = 2000-32 = 1968

3.3 Conversion of Construction Estimate into 1990$ Value

$Dollar_{2000} = Dollar_{1990}\,(1+i)^{\,2000-1990}$

$Dollar_{1990} = 15{,}000{,}000/(1+4.01\%)^{10}$

$Dollar_{1990} = \$10{,}123{,}723.969$

3.4 Pavement Maintenance Gradient

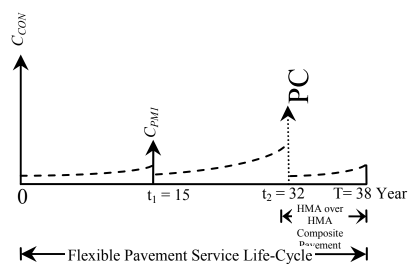
$g'_3 = g_3 + (10\%*((1+ g_2)^{(32-15)}-1))$

$\quad = 2.998\% + (10\,\%*((1+ 2.998\%)^{(32-15)}-1)) = 9.52\%$

3.5 Project-Related Agency Cost Items Using Average Values from Simulation

Agency Cost Item	Unit Cost (1990$/lane-mile)	Project-Related Agency Cost
Project Cost	-	10,123,723.969
Construction	1,492,234.51	= 1,492,234.51 *20 = 29,844,690.20
Rehabilitation	417,362.84	= 417,362.84 *20 = 8,347,256.80
Preventive Maintenance	7,954.30	= 7,954.30 *20 = 159,086.00
Maintenance	732.84	= 732.84*20 = 14,656.80

3.6 Alternative Case Life-Cycle Agency Cost with Early Termination Using Average Values from Simulation

<table>
<tr><th>Pavement Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Flexible Pavement</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$=C_{CON} + C_{PM1}/(1+i)^{t_1} + C_{REH}/(1+i)^{t_2}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+ i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+ i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+ g'_3)^{(T-t_2)}(1+ i)^{-(T-t_2)}))/(i- g'_3))/(1+i)^{t_2}$

$= 29{,}844{,}690.20+159086.00/(1+4.01\%)^{15}+10{,}123{,}723.969/(1+4.01\%)^{32}$
$+(14{,}656.80\,(1-(1+2.998\%)^{15}(1+ 4.01\%)^{-15}))/(4.01\%-2.998\%)$
$+((14{,}656.80(1-(1+2.998\%)^{(32-15)}(1+4.01\%)^{-(30-15)}))/(4.01\%-2.998\%))/$
$(1+4.01\%)^{15} +((14{,}656.80\,(1-(1+9.52\%)^{(38-32)}(1+ 4.01\%)^{-(38-32)}))/$
$(4.01\%-9.52\%))/(1+4.01\%)^{32}$
= 33,157,868.79</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}\,.((i(1+i)^T)/((1+i)^T-1))$
$= 33{,}157{,}868.79.((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{38}-1))$
= 1,714,466.149</td></tr>
</table>

4. Alternative Case Life-Cycle User Cost Analysis with Early Termination Using Average Values from Simulation

4.1 Basic Data

Let Fiscal Year: 2000
Average Daily Traffic year: 2000
Average Daily Traffic Count: 7,380
Project Base Year: 1968
Project Length: 10 miles
Average Speed: 59.37mph (for Rural Principal Arterial)
Base Year AADT: $7{,}380/[(1+2.011\%)^{32}] = 3903$(An annual growth rate of 2.011% as the average of simulation outputs)

4.2 Project-Related Base Year User Cost Calculation

Vehicle Opt. Cost ($/VMT) = 0.2217
Travel Time ($/VMT) = 0.1534
Crash Cost ($/VMT) = 0.1413
Emission Cost ($/VMT) = 0.2096

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.2217*3903*10miles*365 = $3,158,327.12
Annual Travel Time Cost	= 0.1534*3903*10miles*365 = $2,185,328.73
Annual Vehicle Crash Cost	= 0.1413*3903*10miles*365 = $2,012952.74
Annual Vehicle Air Emission Cost	= 0.2096*3903*10miles*365 = $2,985,951.12
Total	$10,342,559.71

4.3 Additional Input Parameters

a. Simulation Inputs

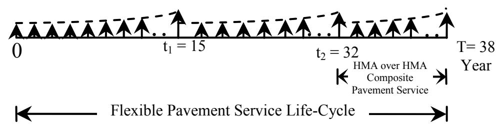
Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

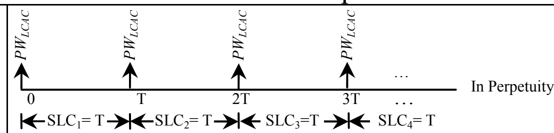
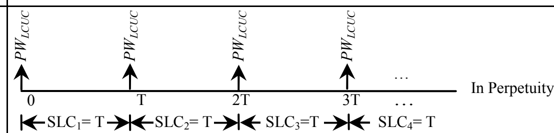
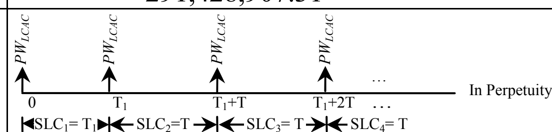
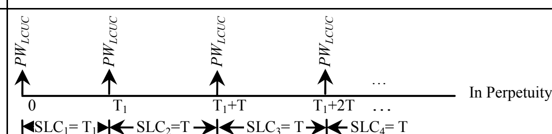
Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2: 1.9959%

$$r'_3 = r_3 + (10\%*((1+ r_2)^{(32-15)}-1))$$
$$= 1.9959\% + (10\%*((1+ 1.9959\%)^{(32-15)}-1)) = 5.9887\%$$

4.4 Alternative Case Life-Cycle User Cost Calculation with Early Termination Using Average Values from Simulation

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	PW_{LCUC}	$=(C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $= (10{,}342{,}559.71\ (1-(1+1.9959\%)^{15}(1+4.01\%)^{-15}))/(4.01\%-1.9959\%)$ $+((10{,}342{,}559.71\ (1-(1+1.9959\%)^{(32-15)}(1+4.01\%)^{-(32-15)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{15}$ $+((10{,}342{,}559.71(1-(1+5.9887\%)^{(38-32)}(1+4.01\%)^{-(38-32)}))/$ $(4.01\%-5.9887\%))/(1+4.01\%)^{30}$ $= 228{,}847{,}472.20$
	EUAUC	$= PW_{LCUC}\ .((i(1+i)^T)/((1+i)^T-1))$ $= 228{,}847{,}472.20\ ((4.01\%(1+4.01\%)^{38})/((1+4.01\%)^{38}-1))$ $= 11{,}832{,}824.57$

5. <u>Computation of Expected Project Life-Cycle Overall Benefits in Perpetuity</u>

<table>
<tr><th>Case</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Base Case: No Early Termination</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,0}= PW_{LCAC}/(1-(1/(1+i)^{T}))$
$= 32,847,688.62 /(1-(1/(1+4.01\%)^{40}))$
$= 41,447,638.91$
$PW_{LCUC\infty,0}= PW_{LCUC}/(1-(1/(1+i)^{T}))$
$= 230,960,466.15/(1-(1/(1+4.01\%)^{40}))$
$= 291,428,907.31$</td></tr>
<tr><td rowspan="4">Early Termination in Cycle 1</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,1}= PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$
$= 33,157,868.79$
$+(32,847,688.62/(1(1/(1+4.01\%)^{40})))/(1+4.01\%)^{38}$
$= 42,504,847.8$

$PW_{LCUC\infty,1}= PW_{LCUC1}+(PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$
$= 228,847,472.20$
$+ 230,960,466.15(/(1(1/(1+4.01\%)^{40})))/(1+4.01\%)^{38}$
$= 294,568,462.6$</td></tr>
<tr><td>Base Case Benefits</td><td>Agency Benefits: $PW_{AB}= PW_{LCAC\infty,1}-PW_{LCAC\infty,0}$
$= 42,504,847.80 - 41,447,638.91$
$= 1,057,208.89$

User Benefits: $PW_{UB}= PW_{LCUC\infty,1}-PW_{LCUC\infty,0}$
$= 294,568,462.6 - 291,428,907.31$
$= 3,139,555.30$

Overall Benefits: $PW_{B}= PW_{AB}+PW_{UB}$
$= 1,057,208.89+3,139,555.30$
$= 4,196,764.19$</td></tr>
</table>

III. Project Life-Cycle Benefit Analysis under Certainty, Risk and Uncertainty

It the process of conducting risk-based analysis of project benefits, it was found that benefits items associated with agency costs, vehicle operating costs, and vehicle emission costs were with relatively smaller magnitude of variations. Whereas travel time and crash costs changed considerably in multiple simulation runs. As such, travel time and crash costs were further selected for uncertainty-based analyses.

For each project, the project benefits resulted from reduction in agency costs, vehicle operating costs, and vehicle emission costs were kept the same as those of risk-based analyses. The benefits concerning reduction in travel time and vehicle crashes were computed using uncertainty-based analyses. The individual benefit items were added together to arrive at the overall project life-cycle benefits under certainty, risk, and uncertainty.

1. Base Case Life-Cycle Agency Cost Analysis Incorporating Risk

1.1 Unit Costs for Flexible Pavement Activities (1990$/Lane-Mile)

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Construction	1,353,536.53	694,614.00	588,385.00	3,165,840.00	2.49	4.50	51%
Rehabilitation	155,287.00	509,879.00	9,147.00	1,119,863.00	2.56	4.50	328%
Prevent. Maintenance	4,120.00	6,544.00	186.00	21,999.00	2.56	4.50	159%
Annual Maintenance	137.97	499.00	4.00	2,186.00	2.27	4.50	362%

b. Average Values from Simulation Outputs

Cost Item	Unit Cost (1990$/lane-mile)
Construction	1,492,234.51
Rehabilitation	417,362.84
Preventive Maintenance	7,954.30
Annual Maintenance	732.84

1.2 Agency Cost Items for Base Case Life-Cycle Agency Cost Analysis

Agency Cost Item	Project-Related Cost (1990$)
Construction	= 1,492,234.51 *20 = 29,844,690.20
Rehabilitation	= 417,362.84 *20 = 8,347,256.80
Preventive Maintenance	= 7,954.30 *20 = 159,086.00
Maintenance	= 732.84*20 = 14,656.80

1.3 Additional Input Factors

a. Simulation Inputs

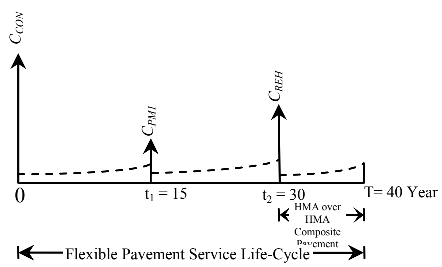
Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate *i*	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Maintenance Gradient g_1	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_2	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_3	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%

b. Average Values from Simulation Outputs

Discount Rate: 4.01%

Annual Maintenance Gradient g_1, g_2, g_3: 2.998%

1.4 Base Case Life-Cycle Agency Cost Calculation Using Average Values from Simulation

<table>
<tr><th>Pavement Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="5">Flexible Pavement</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$=C_{CON}+C_{PM1}/(1+i)^{t_1}+C_{REH}/(1+i)^{t_2}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g_3))/(1+i)^{t_2}$

$= 29{,}844{,}690.20+159{,}086.00/(1+4.01\%)^{15}+8{,}347{,}256.80/(1+4.01\%)^{30}$
$+(14{,}656.80\ (1-(1+2.998\%)^{15}(1+4.01\%)^{-15}))/(4.01\%-2.998\%)$
$+((14{,}656.80(1-(1+2.998\%)^{(30-15)}(1+4.01\%)^{-(30-15)}))/(4.01\%-2.998\%))/(1+4.01\%)^{15}$
$+((14{,}656.80\ (1-(1+2.998\%)^{(40-30)}(1+4.01\%)^{-(40-30)}))/(4.01\%-2.998\%))/(1+4.01\%)^{30}$
$= 32{,}847{,}688.62$</td></tr>
<tr><td>$PW_{LCAC\infty}$</td><td>$= PW_{LCAC}/(1-(1/(1+i)^T))$
$= 32847688.62/(1-(1/(1+4.01\%)^{40})) = 41{,}447{,}638.91$</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}\ .((i(1+i)^T)/((1+i)^T-1))$
$= 32847688.62.((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{40}-1)) = 1{,}662{,}050.32$</td></tr>
<tr><td>$EUAAC_\infty$</td><td>$= PW_{LCAC\infty}.i$
$= 41{,}447{,}638.91*4.01\% = 1{,}662{,}050.32$</td></tr>
</table>

2. Base Case Life-Cycle Vehicle Operating Costs and Emission Costs under Risk

2.1 Basic Data

Let Fiscal Year:	2000
Average Daily Traffic Year:	2000
Average Daily Traffic Count:	7,380
Project Base Year:	1968
Project Length:	10 miles
Average Speed:	59.37mph (for Rural Principal Arterial)
Base Year AADT:	$7{,}380/[(1+2.011\%)^{32}] = 3903$(An annual growth rate of 2.011% as the average of simulation outputs)

2.2 Project-Related Base Year User Cost Calculation

Vehicle Opt. Cost ($/VMT)	= 0.2217
Travel Time ($/VMT)	= 0.1534
Crash Cost ($/VMT)	= 0.1413
Emission Cost ($/VMT)	= 0.2096

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.2217*3903*10miles*365 = $3,158,327.12
Annual Vehicle Air Emission Cost	= 0.2096*3903*10miles*365 = $2,985,951.12
Total	$6,144,278.24

2.3 Additional Input Parameters

a. Simulation Inputs

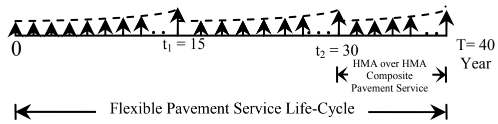
Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%

Annual User Cost Gradient r_1, r_2, r_3: 1.9959%

2.4 <u>Calculation of Base Case Life-Cycle Vehicle Operating Costs and Emission Costs Using Average Values from Simulation</u>

<table>
<tr><th>Pavement Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="5">Flexible Pavement</td><td>User Cost Profile</td><td>
</td></tr>
<tr><td>$PW_{LCVOC/EC}$</td><td>$=(C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$
$+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$
$+((C_{AUC3}(1-(1+r_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-r_3))/(1+i)^{t_2}$

$=(6{,}144{,}278.24(1-(1+1.9959\%)^{15}(1+4.01\%)^{-15}))/(4.01\%-1.9959\%)$
$+((6{,}144{,}278.24(1-(1+1.9959\%)^{(30-15)}(1+4.01\%)^{-(30-15)}))/(4.01\%-1.9959\%))/(1+4.01\%)^{15}$
$+((6{,}144{,}278.24(1-(1+1.9959\%)^{(40-30)}(1+4.01\%)^{-(40-30)}))/(4.01\%-1.9959\%))/(1+4.01\%)^{30}$
= 137,208,332.14</td></tr>
<tr><td>$PW_{LCVOC/EC\infty}$</td><td>$= PW_{LCVOC/EC}/(1-(1/(1+i)^T))$
$= 137{,}208{,}332.14/(1-(1/(1+4.01\%)^{40})) = 173{,}131{,}250.45$</td></tr>
<tr><td>$EUA_{VOC/EC}$</td><td>$= PW_{LCVOC/EC}.((i(1+i)^T)/((1+i)^T-1))$
$= 137{,}208{,}332.14.((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{40}-1)) = 6{,}942{,}563.14$</td></tr>
<tr><td>$EUA_{VOC/EC\infty}$</td><td>$= PW_{LCVOC/EC\infty}.i = 173{,}131{,}250.45*4.01\% = 6{,}942{,}563.14$</td></tr>
</table>

3. Base Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

3.1 Basic Data

Let Fiscal Year: 2000
Average Daily Traffic Year: 2000
Average Daily Traffic Count: 7,380
Project Base Year: 1968
Project Length: 10 miles
Highway Classification: Rural Principal Arterial
Average Speed: 59.37mph (for Rural Principal Arterial)
Base Year AADT: $7,380/[(1+1.63\%)^{32}] = 4,399$(An annual growth rate of 1.63% adjusted from the average of simulation outputs)

3.2 Project-Related Base Year User Cost Calculation

Travel Time Cost ($/VMT): 0.1534
Vehicle Crash Cost ($/VMT): 0.1413

User Cost Item	Annual Cost (1990$/year)
Annual Travel Time Cost	= 0.1534*4,399*10miles*365 = $2,463,044.09
Annual Vehicle Crash Cost	= 0.1413*4,399*10miles*365 = $2,268,762.26
Total	$4,731,806.35

3.3 Additional Input Parameters

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate *i*	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Discount Rate *i*: 4.01%
Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2, r_3: 1.9959%

c. Values Adjusted from Simulation Using Penalty Rules for Uncertainty-Based Analysis

Cost Item	Average, $X_{(E)}$	X_{SFL}	X_{SFG}	Tolerance (ΔX)	X
Discount Rate *i*	4.01%	5.00%	3.00%	20% of μ = 4.00%	4.17%
Annual Traffic Growth Rate r	2.011%	1.00%	3.00%	39% of μ = 2.00%	1.63%
Annual User Cost Gradient r_1	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_2	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_3	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%

Penalty Rule:

If more is better, $$X = \begin{cases} X_{(E)}, & \text{if } \left|X_{SFL} - X_{(E)}\right| \leq \Delta X \\ \dfrac{X_{SFL}}{[1-\Delta X/X_{(E)}]}, & \text{otherwise} \end{cases}$$

If less is better, $$X = \begin{cases} X_{(E)}, & \text{if } \left|X_{SFL} - X_{(E)}\right| \leq \Delta X \\ \dfrac{X_{SFL}}{[1+\Delta X/X_{(E)}]}, & \text{otherwise} \end{cases}$$

- For discount rate *i*, less is better.
  Since $|X_{SFL} - X_{(E)}| = |5\% - 4.01\%| = 0.99\% > \Delta X = 20\%*4\% = 0.8\%$
  $X_i = X_{SFL}/[1+\Delta X/ X_{(E)}] = 5\%/[1+0.8\%/ 4.01\%] = 4.17\%$

- For annual traffic growth rate *r*, more is better.
  Since $|X_{SFL} - X_{(E)}| = |1\% - 2.011\%| = 1.011\% > \Delta X = 39\%*2\% = 0.78\%$
  $X_r = X_{SFL}/[1-\Delta X/ X_{(E)}] = 1\%/[1- (0.78\%/ 2.011\%)] = 1.63\%$

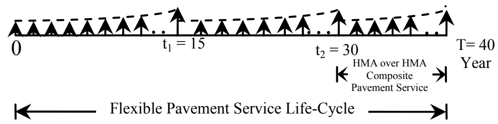
- For annual user cost gradients r_1, r_2, r_3, more is better.
  Since $|X_{SFL} - X_{(E)}| = |1\% - 1.995\%| = 0.995\% > \Delta X = 39\%*2\% = 0.78\%$
  $X_{r1} = X_{r2} = X_{r3}=X_{SFL}/[1-\Delta X/ X_{(E)}] = 1\%/[1- (0.78\%/ 1.995\%)] = 1.64\%$

Note:

1. The ΔX's are set as per the preference of the decision-maker. In addition, r, r_1, r_2, and r_3 could also be thought of less is better in some cases. In so doing, the adjusted values for r would be 3%/[1+ (0.78%/ 2.011%)] = 2.16% and for r_1, r_2, and r_3 would be 3%/[1+ (0.78%/ 1.995%)] = 2.16% instead.

2. The adjusted values for discount rate *i* = 4.17%, for annual traffic growth rate r = 1.63%, and for annual user cost gradients r_1, r_2, and r_3 = 1.64% were used as inputs for uncertainty-based analysis.

3.4 Calculation of Base Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	$PW_{LCTT/VC}$	$=(C_{AUC1} (1-(1+r_1)^{t_1} (1+ i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2} (1-(1+r_2)^{(t_2-t_1)} (1+ i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3} (1-(1+r_3)^{(T-t_2)} (1+ i)^{-(T-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $= (4,731,806.35 (1-(1+1.64\%)^{15} (1+ 4.17\%)^{-15}))/(4.17\%-1.64\%)$ $+((4,731,806.35 (1-(1+1.64\%)^{(30-15)} (1+ 4.17\%)^{-(30-15)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{15}$ $+((4,731,806.35 (1-(1+1.64\%)^{(40-30)} (1+4.17\%)^{-(40-30)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{30}$ = 100,911,545.69
	$PW_{LCTT/VC\infty}$	$= PW_{LCTT/VC}/(1-(1/(1+i)^T))$ $= 100,911,545.69 \quad /(1-(1/(1+4.17\%)^{40}))$ = 125,374,062.16
	$EUA_{TT/VC}$	$= PW_{LCTT/VC} .((i(1+i)^T)/((1+i)^T-1))$ $=100,911,545.69 ((4.17\%(1+4.17\%)^{40})/((1+4.17\%)^{40}-1))$ =5,228,098.39
	$EUA_{TT/VC\infty}$	$= PW_{LCTT/VC\infty}.i$ = 125,374,062.16 *4.17% = 5,228,098.39

4. Base Case Life-Cycle User Cost Calculation

Pavement Type	Computation	
Flexible Pavement	PW_{LCUC}	$= PW_{LCVOC/EC} + PW_{LCTT/VC}$ = 137,208,332.14+ 100,911,545.69 = 238,119,877.70
	$PW_{LCUC\infty}$	$= PW_{LCVOC/EC\infty} + PW_{LCTT/VC\infty}$ =173,131,250.45 + 125,374,062.16 = 298,505,312.50
	EUAUC	$= EUA_{VOC/EC} + EUA_{LCTT/VC}$ = 6,942,563.14 + 5,228,098.39= 12,170,661.53
	$EUAUC_{\infty}$	$= EUA_{LCVOC/EC\infty} + EUA_{LCTT/VC\infty}$ = 6,942,563.14 + 5,228,098.39= 12,170,661.53

5. Alternative Case Life Cycle Agency Cost Analysis with Early Termination

5.1 <u>Determination of the Reduction in Pavement Useful Service Life</u>

No.	Type	Case	α	Reduction
1	If PC < PM	a. (Unit PM Cost -Unit Project Cost)/Unit PM Cost <=0.5	(Unit PM Cost-Unit Project Cost)/Unit PM Cost	y=α*(t_1-0)
		b. 0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost) <=0.5	0.33((Unit PM Cost-Unit Project Cost)/Unit PM Cost)	
		c. ((Unit PM Cost+ σpm)-Unit Project Cost))/(Unit PM Cost+ σpm) <=0.5	((Unit PM Cost+ σpm)-(Unit Project Cost))/(Unit PM Cost+ σpm)	
		d. ((Unit PM Cost+2σpm)-Unit Project Cost))/(Unit PM Cost+2σpm) <=0.5	((Unit PM Cost+2σpm)-Unit Project Cost))/(Unit PM Cost+ 2σpm)	
		e. ((Unit PM Cost+3σpm)-Unit Project Cost))/(Unit PM Cost+3 σpm) <=0.5	((Unit PM Cost+3σpm)-Unit Project Cost))/(Unit PM Cost+3σpm)	
		f. Otherwise	0.5	
2	If PM < PC < (PM+Rehab)	a.((Unit PM Cost+ Rehab Cost) -Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5	((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost)	y=α*(t2- t1)
		b.0.33((Unit PM Cost+ Rehab Cost)) -Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5	0.33((Unit PM Cost+ Rehab Cost)-Unit Project Cost)/(Unit PM Cost+ Rehab Cost))	
		c.((Unit PM Cost+ σpm + Rehab Cost +σreh)-Unit Project Cost)/(Unit PM Cost+ σpm+ Rehab Cost+ σreh) <=0.5	((Unit PM Cost+ σpm + Rehab Cost+σreh)-Unit Project Cost)/(Unit PM Cost+ σpm + Rehab Cost+ σreh)	
		d. ((Unit PM Cost+ 2σpm + Rehab Cost +2σreh)-Unit Project Cost)/(Unit PM Cost+2σpm+ Rehab Cost+ 2σreh) <=0.5	((Unit PM Cost+ 2σpm + Rehab Cost +2σreh)-Unit Project Cost)/(Unit PM Cost+2σpm+ Rehab Cost+ 2σreh)	

		e.((Unit PM Cost+ 3σpm + Rehab Cost +3σreh)-Unit Project Cost)/(Unit PM Cost+3σpm+ Rehab Cost+ 3σreh) <=0.5 f. Otherwise	((Unit PM Cost+ 3σpm + Rehab Cost +3σreh)-Unit Project Cost)/(Unit PM Cost+3σpm+ Rehab Cost+ 3σreh) 0.5	
3	If PC > (PM+Rehab)	a.(-(Unit PM Cost+ Rehab Cost) +Unit Project Cost)/(Unit PM Cost +Rehab Cost) <=0.5 b.0.33(-(Unit PM Cost+ Rehab Cost)) +Unit Project Cost)/(Unit PM Cost+ Rehab Cost) <=0.5 c.(-(Unit PM Cost+ σpm + Rehab Cost +σreh)+Unit Project Cost)/(Unit PM Cost+ σpm+ Rehab Cost+ σreh) <=0.5 d. (-(Unit PM Cost+ 2σpm + Rehab Cost +2σreh)+Unit Project Cost)/(Unit PM Cost+2σpm+ Rehab Cost+ 2σreh) <=0.5 e.(-(Unit PM Cost+ 3σpm + Rehab Cost +3σreh)+Unit Project Cost)/(Unit PM Cost+3σpm+ Rehab Cost+ 3σreh) <=0.5 f. Otherwise	(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost) 0.33(-(Unit PM Cost+ Rehab Cost)+Unit Project Cost)/(Unit PM Cost+ Rehab Cost)) (-(Unit PM Cost+ σpm + Rehab Cost+σreh)+Unit Project Cost)/(Unit PM Cost+ σpm + Rehab Cost+ σreh) (-(Unit PM Cost+ 2σpm + Rehab Cost +2σreh)+Unit Project Cost)/(Unit PM Cost+2σpm+ Rehab Cost+ 2σreh) (-(Unit PM Cost+ 3σpm + Rehab Cost +3σreh)+Unit Project Cost)/(Unit PM Cost+3σpm+ Rehab Cost+ 3σreh) 0.5	$y=\alpha*(t_2- t1)$

5.2 Project Timing

Unit Project Cost = $(15,000,000/(1+4.01\%)^{10}/20)$= \$506,186.20 (1990\$/lane-mile)
Unit Rehabilitation Cost = \$ 417,362.84 (1990\$/lane-mile)
Unit Preventive Maintenance Cost = \$7,954.30 (1990\$/lane-mile)

Type 1: Unit Project cost > Unit PM Cost, Not applicable
Type 2: Unit Project cost > Unit PM cost + Unit Rehabilitation Cost, Not applicable
Type3: Unit Project cost > Unit PM Cost + Unit Rehabilitation Cost, Applicable
α = ((Unit Project cost –(Unit PM Cost+ Rehab Cost))/(Unit PM Cost+ Rehab Cost)
= ((506,186.20 – (7,954.30+417,362.84))/ (7,954.30+417,362.84) = 0.19 < 0.5

$y = \alpha*(T-t_2) = 0.19*(40-30) = 1.9 \approx 2$ years
Base Year = 2000-32 = 1968

5.3 Conversion of Construction Estimate into 1990$ Value

$Dollar_{2000} = Dollar_{1990}\,(1+i)^{2000\text{-}1990}$
$Dollar_{1990} = 15{,}000{,}000/(1+4.01\%)^{10}$
$Dollar_{1990} = \$10{,}123{,}723.969$

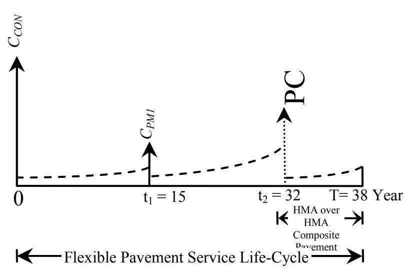
5.4 Pavement Maintenance Gradient Adjustment

$g'_3 = g_3 + (10\%*((1+g_2)^{(32-15)}-1))$
$= 2.998\% + (10\%*((1+2.998\%)^{(32-15)}-1)) = 9.52\%$

5.5 Project-Related Agency Cost Items Using Average Values from Simulation

Agency Cost Item	Unit Cost (1990$/lane-mile)	Project-Related Agency Cost
Project Cost	-	10,123,723.969
Construction	1,492,234.51	= 1,492,234.51 *20 = 29,844,690.20
Rehabilitation	417,362.84	= 417,362.84 *20 = 8,347,256.80
Preventive Maintenance	7,954.30	= 7,954.30 *20 = 159,086.00

5.6 Alternative Case Life-Cycle Agency Cost with Early Termination Using Average Values from Simulation

Pavement Type	Computation	
Flexible Pavement	Agency Cost Profile	
	PW_{LCAC}	$= C_{CON} + C_{PM1}/(1+i)^{t_1} + C_{REH}/(1+i)^{t_2}$ $+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$ $+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g'_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-g'_3))/(1+i)^{t_2}$ $= 29{,}844{,}690.20+159086.00/(1+4.01\%)^{15}+10{,}123{,}723.969/(1+4.01\%)^{32}$ $+(14{,}656.80\,(1-(1+2.998\%)^{15}(1+4.01\%)^{-15}))/(4.01\%-2.998\%)$ $+((14{,}656.80(1-(1+2.998\%)^{(32-15)}(1+4.01\%)^{-(30-15)}))/(4.01\%-2.998\%))/$ $(1+4.01\%)^{15}$ $+((14{,}656.80\,(1-(1+9.52\%)^{(38-32)}(1+4.01\%)^{-(38-32)}))/(4.01\%-9.52\%))/(1+4.01\%)^{32}$ $= 33{,}157{,}868.79$
	EUAAC	$= PW_{LCAC}\,.((i(1+i)^{T})/((1+i)^{T}-1))$ $= 33{,}157{,}868.79((4.01\%(1+4.01\%)^{40})/((1+4.01\%)^{38}-1)) = 1{,}714{,}466.149$

6. Alternative Case Life-Cycle Vehicle Operating Costs and Emission Costs under Risk

6.1 Basic Data

Let Fiscal Year:	2000
Average Daily Traffic Year:	2000
Average Daily Traffic Count:	7,380
Project Base Year:	1968
Project Length:	10 miles
Average Speed:	59.37mph (for Rural Principal Arterial)
Base Year AADT:	$7{,}380/[(1+2.011\%)^{32}] = 3{,}903$(An annual growth rate of 2.011% as the average of simulation outputs)

6.2 Project-Related Base Year User Cost Calculation

Vehicle Opt. Cost ($/VMT) = 0.2217

Emission Cost ($/VMT) = 0.2096

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.2217*3,903*10miles*365 = $3,158,327.12
Annual Vehicle Air Emission Cost	= 0.2096*3,903*10miles*365 = $2,985,951.12
Total	$6,144,278.24

6.3 Additional Input Parameters

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

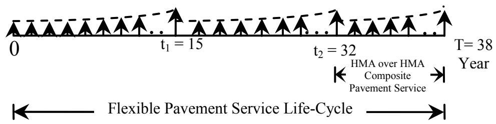
b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%

Annual User Cost Gradient r_1, r_2, r_3: 1.9959%

$$r'_3 = r_3 + (10\%*((1+ r_2)^{(32-15)}-1))$$
$$= 1.9959\%+ (10\%*((1+ 1.9959\%)^{(32-15)}-1)) = 5.9887\%$$

6.4 Calculation of Alternative Case Life-Cycle Vehicle Operating Costs and Emission Costs Using Average Values from Simulation

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	$PW_{LCVOC/EC}$	$= (C_{AUC1}\ (1-(1+r_1)^{t_1}\ (1+ i\ )^{-t_1}))/(i-r_1)$ $+((\ C_{AUC2}\ (1-(1+r_2)^{(t_2-t_1)}\ (1+ i\ )^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((\ C_{AUC3}\ (1-(1+ r'_3)^{(T-t_2)}\ (1+ i\ )^{-(T-t_2)}))/(i- r'_3))/(1+i)^{t_2}$ $= (6{,}144{,}278.24\ (1-(1+1.9959\%)^{15}\ (1+ 4.01\%\ )^{-15}))/(4.01\%-1.9959\%)$ $+((\ 6{,}144{,}278.24\ (1-(1+1.9959\%)^{(32-15)}\ (1+ 4.01\%\ )^{-(32-15)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{15}$ $+((\ 6{,}144{,}278.24\ \ (1-(1+5.9887\%)^{(38-32)}\ (1+4.01\%)^{-(38-32)}))/$ $(4.01\%-5.9887\%))/(1+4.01\%)^{32}$ $= 135{,}953{,}050.7$
	$EUA_{VOC/EC}$	$= PW_{LCVOC/EC}/(1-(1/(1+i)^T))$ $= 135{,}953{,}050.7/(1-(1/(1+4.01\%)^{40})) = 7{,}029{,}610.523$

7. Alternative Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

7.1 Basic Data

Let Fiscal Year: 2000
Average Daily Traffic Year: 2000
Average Daily Traffic Count: 7,380
Project Base Year: 1968
Project Length: 10 miles
Highway Classification: Rural Principal Arterial
Average Speed: 59.37mph (for Rural Principal Arterial)
Base Year AADT: $7{,}380/[(1+1.63\%)^{32}] = 4{,}399$(An annual growth rate of 1.63% adjusted from the average of simulation outputs)

7.2 Project-Related Base Year User Cost Calculation

Travel Time Cost ($/VMT): 0.1534
Vehicle Crash Cost ($/VMT): 0.1413

User Cost Item	Annual Cost (1990$/year)
Annual Travel Time Cost	= 0.1534*4,399*10miles*365 = $2,463,044.09
Annual Vehicle Crash Cost	= 0.1413*4,399*10miles*365 = $2,268,762.26
Total	$4,731,806.35

7.3 Additional Input Parameters

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate *i*	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Discount Rate *i*: 4.01%
Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2: 1.9959%

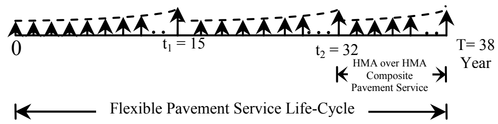
c. Values Adjusted from Simulation Using Penalty Rules for Uncertainty-Based Analysis

Cost Item	Average, $X_{(E)}$	X_{SFL}	X_{SFG}	Tolerance (ΔX)	X
Discount Rate *i*	4.01%	5.00%	3.00%	20% of μ = 4.00%	4.17%
Annual Traffic Growth Rate r	2.011%	1.00%	3.00%	39% of μ = 2.00%	1.63%
Annual User Cost Gradient r_1	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_2	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_3	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%

$r'_3 = r_3 + (10\%*((1+r_2)^{(32-15)}-1))$

$= 1.64\% + (10\%*((1+1.64\%)^{(32-15)}-1)) = 4.825\%$

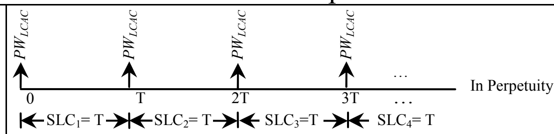
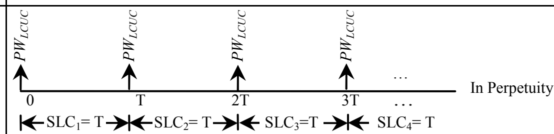
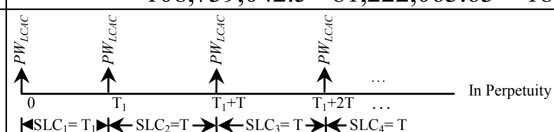
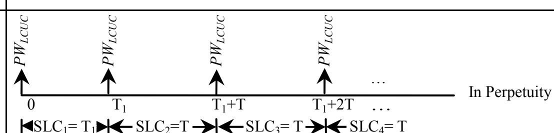
7.4 Calculation of Alternative Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

Pavement Type	Computation	
Flexible Pavement	User Cost Profile	
	$PW_{LCTT/VC}$	$=(C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(T-t_2)}(1+i)^{-(T-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $= (4{,}731{,}806.35(1-(1+1.64\%)^{15}(1+4.17\%)^{-15}))/(4.17\%-1.64\%)$ $+((4{,}731{,}806.35(1-(1+1.64\%)^{(32-15)}(1+4.17\%)^{-(32-15)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{15}$ $+((4{,}731{,}806.35(1-(1+4.825\%)^{(38-32)}(1+4.17\%)^{-(38-32)}))/$ $(4.17\%-4.825\%))/(1+4.17\%)^{32}$ = 99,796,360.96
	$EUA_{TT/VC}$	$= PW_{LCTT/VC}.((i(1+i)^T)/((1+i)^T-1))$ $= 99{,}796{,}360.96.((4.17\%(1+4.17\%)^{38})/((1+4.17\%)^{38}-1)) = 5{,}279{,}281.077$

8. Alternative Case Life-Cycle User Cost Calculation

Pavement Type	Computation	
Flexible Pavement	PW_{LCUC}	$= PW_{LCVOC/EC} + PW_{LCTT/VC}$ = 135,953,050.7+ 99,796,360.96= 235,749,411.70
	$EUAUC$	$= EUA_{VOC/EC} + EUA_{LCTT/VC}$ =7,029,610.523+5,279,281.077= 12,308,891.60

9. Computation of Project Life-Cycle Overall Benefits in Perpetuity

<table>
<tr><th>Case</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Base Case: No Early Termination</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,0}= PW_{LCAC}/(1-(1/(1+i)^T))$
$= 32{,}847{,}688.62 /(1-(1/(1+4.01\%)^{40}))$
$= 41{,}447{,}638.91$
$PW_{LCUC\infty,0}= PW_{LCUC(VOC+VAE)}/(1-(1/(1+i)^T))$
$+ PW_{LCUC(VTT+VCC)}/(1-(1/(1+i)^T))$
$= 137{,}208{,}332.14 /(1(1/(1+4.01\%)^{40}))$
$+ 100{,}911{,}545.69/(1(1/(1+4.17\%)^{40}))$
$= 108{,}739{,}042.5+ 81{,}222{,}063.63 = 189{,}961{,}106.17$</td></tr>
<tr><td rowspan="2">Early Termination in Cycle 1</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td></td><td>Present Worth</td><td>$PW_{LCAC\infty,1}= PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^T)))/(1+i)^{T_1}$
$= 33157868.79$
$+ (32{,}847{,}688.62/(1(1/(1+4.01\%)^{40})))/(1+4.01\%)^{38}$
$= 42{,}504{,}847.8$
$PW_{LCUC\infty,1}= PW_{LCUC1(VTT+VCC)}+(PW_{LCUC(VTT+VCC)}/(1(1/(1+i)^T)))/(1+i)^{T_1}$
$+PW_{LCUC1(VOC+VAE)}+(PW_{LCUC(VOC+VAE)}/(1-(1/(1+i)^T)))/(1+i)^{T_1}$
$= (99{,}796{,}360.96$
$+ 100{,}911{,}545.69(1/(1(1/(1+4.17\%)^{40})))/(1+4.17\%)^{38})$
$+ 135953050.7$
$+ 137{,}208{,}332.14 (/(1-(1/(1+4.01\%)^{40})))/(1+4.01\%)^{38})$
$= 126{,}341{,}588.9 + 174{,}814{,}751.5 = 301{,}156{,}340.40$</td></tr>
<tr><td></td><td>Base Case Benefits</td><td>Agency Benefits: $PW_{AB}= PW_{LCAC\infty,1}-PW_{LCAC\infty,0}$
$= 42{,}504{,}847.80– 41{,}447{,}638.91 = 1{,}057{,}208.89$
User Benefits: $PW_{UB}= PW_{LCUC\infty,1}-PW_{LCUC\infty,0}$
$= 301{,}156{,}340.40 - 189{,}961{,}106.17$
$= 111{,}195{,}234.3$
Overall Benefits: $PW_B = PW_{AB}+PW_{UB}$
$= 1{,}057{,}208.89 + 111{,}195{,}234.3$
$= 112{,}252{,}443.2$</td></tr>
</table>

IV. Analysis Summary

1. Basic Input Data

a. Analysis under Certainty

Data Item	AC	VOC	TT	VC	EC
Project Cost	10,133,462.53				
Construction Cost	27,070,730.60				
Rehabilitation Cost	3,105,740.00				
Preventive Maintenance	82,400.00				
Annual Routine Maintenance	2,760.00				
RM Gradient g_1, g_2, g_3/g_3'	3.00%/9.528%				
Discount Rate *i*	4.00%	4.00%	4.00%	4.00%	4.00%
Base Year AADT	3,916	3,916	3,916	3,916	3,916
Annual Traffic Growth *r*	2.00%	2.00%	2.00%	2.00%	2.00%
Annual UC Gradient r_1, r_2, r_3/ r_3'		2.00%/6.00%	2.00%/6.00%	2.00%/6.00%	2.00%/6.00%
Service Life for Base Case	40	40	40	40	40
Service Life for Alt Case	38	38	38	38	38

b. Analysis under Certainty and Risk

Data Item	AC	VOC	TT	VC	EC
Project Cost	10,123,723.969				
Construction Cost	29,844,690.20				
Rehabilitation Cost	8,347,256.80				
Preventive Maintenance	159,086.00				
Annual Routine Maintenance	14,656.80				
RM Gradient g_1, g_2, g_3/ g_3'	2.998%/9.52%				
Discount Rate *i*	4.01%	4.01%	4.01%	4.01%	4.01%
Base Year AADT	3,903	3,903	3,903	3,903	3,903
Annual Traffic Growth *r*	2.011%	2.011%	2.011%	2.011%	2.011%
Annual UC Gradient r_1, r_2, r_3/ r_3'		1.995%/ 5.9887%	1.995%/ 5.9887%	1.995%/ 5.9887%	1.995%/ 5.9887%
Service Life for Base Case	40	40	40	40	40
Service Life for Alt Case	38	38	38	38	38

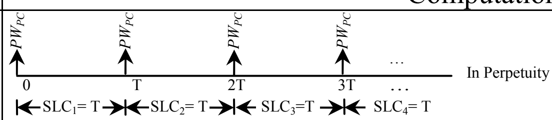
c. Analysis under Certainty, Risk, and Uncertainty

Data Item	AC	VOC	TT	VC	EC
Project Cost	10,123,723.969				
Construction Cost	29,844,690.20				
Rehabilitation Cost	8,347,256.80				
Preventive Maintenance	159,086.00				
Annual Routine Maintenance	14,656.80				
RM Gradient g_1, g_2, g_3/ g_3'	2.998%/9.52%				
Discount Rate *i*	4.01%	4.01%	4.17%	4.17%	4.01%
Base Year AADT	3,903	3,903	4,399	4,399	3,903
Annual Traffic Growth *r*	2.011%	2.011%	1.63%	1.63%	2.011%
Annual UC Gradient r_1, r_2, r_3/ r_3'		1.995%/ 5.9887%	1.64%/ 4.825%	1.64%/ 4.825%	1.995%/ 5.9887%
Service Life for Base Case	40	40	40	40	40
Service Life for Alt Case	38	38	38	38	38

2. Estimated Project Benefits

Item	Certainty	Certainty and Risk	Certainty, Risk and Uncertainty
$PW_{Agency\ Benefits}$	2,535,055.89	1,057,208.89	1,057,208.89
$PW_{User\ Benefits}$	2,859,721.50	3,139,555.30	111,195,234.3
$PW_{Total\ Benefits}$	5,394,777.39	4,196,764.19	112,252,443.2

3. Project Costs in Perpetuity

Case	Computation
Project Cost Profile	
Certainty (i = 4%)	PW_{LCPC} = Project Cost/((1+i)$^{(2000-1990)+Project\ Timing}$) = 15,000,000/((1+4%)$^{(2000-1990)+32}$) = 2,888,623.955 $PW_{LCPC\infty}$ = PW_{LCPC}/(1-(1/(1+i)^{T})) = 2,888,623.955/(1-(1/(1+4%)^{40})) = 3,648,584.039
Certainty and Risk (i = 4.01%)	PW_{LCPC} = Project Cost/((1+i)$^{(2000-1990)+Project\ Timing}$) = 15,000,000/((1+4.01%)$^{(2000-1990)+32}$) = 2,876,982,441 $PW_{LCPC\infty}$ = PW_{LCPC}/(1-(1/(1+i)^{T})) = 2,876,982,441/(1-(1/(1+4.01%)^{40})) = 3,630,213.703
Certainty, Risk, and Uncertainty (i = 4.01%)	PW_{LCPC} = 2,876,982,441 $PW_{LCPC\infty}$ = 3,630,213.703

4. Summary of Project Benefit-Cost Analysis Results

Item	Certainty	Certainty and Risk	Certainty, Risk and Uncertainty
NPW	= 5,394,777.39 - 3,648,584.039 = 1,746,193.351	= 4,196,764.19 - 3,630,213.703 = 566,550.487	= 112,252,443.2 - 3,630,213.703 = 108,622,229.5
B/C	= 5,394,777.39/ 3,648,584.039 = 1.48	= 4,196,764.19/ 3,630,213.703 = 1.16	= 112,252,443.2/ 3,630,213.703 = 30.9

APPENDIX 2: An Example of Highway Bridge Project Evaluation under Certainty, Risk, and Uncertainty

I. Deterministic Project Benefit Analysis Using the Life-Cycle Cost Analysis Approach

1. Base Case Deterministic Life-Cycle Agency Cost Analysis
(Using the Typical Bridge Life-Cycle Activity Profile)

1.1 Basic Data

Let Fiscal Year:	2001
Construction Estimate:	$3,390,000
Project Length:	0.934 miles
Bridge Length:	246.6 ft
Average daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Number of Lanes:	6
Work Type Description:	Superstructure Replacment for a Steel Truss Bridge

1.2 Bridge Area Calculation

Length = 246.6 ft
Number of lanes = 6
Total Area (s ft) = Length*((Number of Lanes*12) + (2*Shoulder Width))
= 246.6*((6 *12) + (2*6))
= 20,714.40 ft2

1.3 Base Case Agency Cost Items

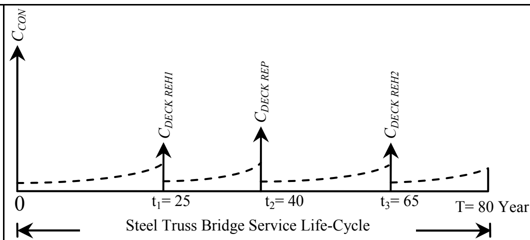
Agency Cost Item	Unit Cost (1990$/ft^2)	Project-Related Agency Cost
Construction	348.25	= 348.25*20,714.4 = 7,213,789.80
Deck Rehabilitation	62.019	= 62.019*20,714.4 = 1,284,686.37
Deck Replacement	124.04	= 124.04*20,714.4 = 2,569,414.18
Maintenance Cost	-	= (2.5%*7,213,789.80)/80 =2,254.31

First Year Annual Maintenance Cost = (2.5%*Construction Cost)/ (Base Case Life in years)

1.4 Additional Input Factors

Discount Rate *i*: 4%
Annual Maintenance Cost Gradient g_1, g_2, g_3, g_4: 3%

1.5 Base Case Life-Cycle Agency Cost Calculation

<table>
<tr><th>Bridge Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="5">Steel Truss Bridge</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$= C_{CON} + C_{DREH1}/(1+i)^{t_1} + C_{DREP}/(1+i)^{t_2} + C_{DREH2}/(1+i)^{t_1}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_3))/(1+i)^{t_2}$
$+((C_{MAIN4}(1-(1+g_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_4))/(1+i)^{t_3}$

$= 7{,}213{,}789.80+1{,}284{,}686.37/(1+4\%)^{25}$
$+ 2{,}569{,}414.18/(1+4\%)^{40}$
$+ 1{,}284{,}686.37/(1+4\%)^{65}$
$+ (2{,}254.31(1-(1+3\%)^{25}(1+4\%)^{-25}))/(4\%-3\%)$
$+ ((2{,}254.31(1-(1+3\%)^{(40-25)}(1+4\%)^{-(40-25)}))/(4\%-3\%))/(1+4\%)^{25}$
$+ ((2{,}254.31(1-(1+3\%)^{(65-40)}(1+4\%)^{-(65-40)}))/(4\%-3\%))/(1+4\%)^{40}$
$+ ((2{,}254.31(1-(1+3\%)^{(80-65)}(1+4\%)^{-(80-65)}))/(4\%-3\%))/(1+4\%)^{65}$
= 8, 403,486.02</td></tr>
<tr><td>$PW_{LCAC\infty}$</td><td>$= PW_{LCAC}/(1-(1/(1+i)^T))$
$= 8{,}403{,}486.02/(1-(1/(1+4\%)^{80}))$
= 8,784,599.97</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}((i(1+i)^T)/((1+i)^T-1))$
$= 8{,}403{,}486.02((4\%(1+4\%)^{80})/((1+4\%)^{80}-1))$
= 351,384.00</td></tr>
<tr><td>$EUAAC_{\infty}$</td><td>$= PW_{LCAC\infty}.i = 8{,}784{,}599.97 * 4\% = 351{,}384.00$</td></tr>
</table>

2. Base Case Deterministic Life-Cycle User Cost Analysis (Using the Typical Bridge Life-Cycle Activity Profile)

2.1. Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1968
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	108,210/ $[(1+2\%)^{24}]$ = 67,276 (An annual growth rate of 2%)

2.2 Project-Related Base Year User Costs

Vehicle Opt. Cost ($/VMT)	= 0.8156 - 0.0077*Speed	= 0.8156 - 0.0077*56.78	= 0.3784
Travel Time ($/VMT)	= 0.4595-0.00531*Speed	= 0.4595-0.00531*56.78	= 0.1582
Crash Cost ($/VMT)	= -0.22+0.005612*Speed	= -0.22+0.005612*56.78	= 0.0986
Emission Cost ($/VMT)	= 0.2037+0.000013*Speed	= 0.2037+0.000013*56.78	= 0.2038

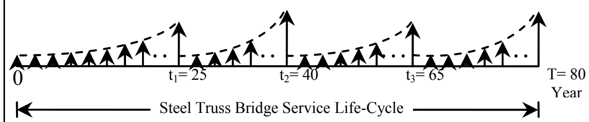
Note: In 1990 constant dollars, based in an earlier Indiana study, Li and Sinha (2003)

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*67,276*0.934miles*365 = $8,678,627.14
Annual Travel Time Cost	= 0.1582*67,276*0.934miles*365 = $3,628,326.67
Annual Vehicle Crash Cost	= 0.0986*67,276*0.934miles*365 = $2,261,397.03
Annual Vehicle Air Emission Cost	= 0.2038*67,276*0.934miles*365 = $4,674,165.46
Total	$19,242,516.30

2.3 Additional Input Parameters

Annual User Cost Gradient r_1, r_2, r_3, r_4: 2%

2.4 Base Case Life-Cycle User Cost Calculation

Bridge Type	Computation	
Steel Truss	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r_4))/(1+i)^{t_3}$ $= (19{,}242{,}516.30(1-(1+2\%)^{25}(1+4\%)^{-25}))/(4\%-3\%)$ $+((19{,}242{,}516.30(1-(1+2\%)^{(40-25)}(1+4\%)^{-(40-25)}))/(4\%-2\%))/(1+4\%)^{25}$ $+((19{,}242{,}516.30(1-(1+2\%)^{(65-40)}(1+4\%)^{-(65-40)}))/(4\%-2\%))/(1+4\%)^{40}$ $+((19{,}242{,}516.30(1-(1+2\%)^{(80-65)}(1+4\%)^{-(80-65)}))/(4\%-2\%))/(1+4\%)^{65}$ = 557,278,148.56
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$ $= 557{,}278{,}148.56/(1-(1/(1+4\%)^{80}))$ = 582,551,764.29
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $= 557{,}278{,}148.56((4\%(1+4\%)^{80})/((1+4\%)^{80}-1))$ =23,302,070.57
	$EUAUC_\infty$	$= PW_{LCUC\infty}.i$ = 582,551,764.29*4%=23,302,070.57

3. Alternative Case Deterministic Life-Cycle Agency Cost Analysis with Early Termination

3.1 Determination the Reduction in Bridge Useful Service Life

No.	Type	Case	α	Reduction
1	If (Unit PC < Unit Deck Rehab Cost)	a. (Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost <=0.5	(Unit Deck Rehab Cost-Unit Project Cost)/Unit Deck Rehab Cost	$y=\alpha*(t_1-0)$
		b. 0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost) <=0.5	0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost)	
		c. ((Unit Deck Rehab Cost $+\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		d. ((Unit Deck Rehab Cost $+2\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+2\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		e. ((Unit Deck Rehab Cost $+3\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+3\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		f. Otherwise	0.5	
2	If (Unit Deck Rehab< Unit PC < (Unit Deck Rehab + Unit Deck Replacement))	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost) <=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost)	$y=\alpha*(t_2- t_1)$
		b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost)) <=0.5	0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost))	
		c. ((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))<=0.5	((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))	

		d. ((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$))<=0.5 e. ((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$))<=0.5 f. Otherwise	((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$)) ((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$)) 0.5	
3	If (Unit Deck Rehab + Unit Deck Replacement)<Unit PC > (Unit Deck Rehab + Unit Deck Replacement + Unit Deck Rehab)	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5 b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5 c. ((Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) ((Unit Deck Rehab Cost +σ_{dehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab})	$y=\alpha*(t_3- t_2)$

		d. ((Unit Deck Rehab Cost $+2\sigma_{drehab}$+Unit Deck Replacement Cost$+2\sigma_{drep}$+Unit Deck Rehab Cost$+2\sigma_{drehab}$)-Unit Project Cost)/(Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost + $2\sigma_{drep}$ +Unit Deck Rehab Cost+ $2\sigma_{drehab}$) <=0.5 e. ((Unit Deck Rehab Cost $+3\sigma_{drehab}$+Unit Deck Replacement Cost$+3\sigma_{drep}$+Unit Deck Rehab Cost$+3\sigma_{drehab}$)-Unit Project Cost)/(Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost + $3\sigma_{drep}$ +Unit Deck Rehab Cost+ $3\sigma_{drehab}$) <=0.5 f. otherwise	((Unit Deck Rehab Cost $+2\sigma_{drehab}$+Unit Deck Replacement Cost$+2\sigma_{drep}$+Unit Deck Rehab Cost$+2\sigma_{drehab}$)-Unit Project Cost)/(Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost + $2\sigma_{drep}$ +Unit Deck Rehab Cost+ $2\sigma_{drehab}$) ((Unit Deck Rehab Cost $+3\sigma_{drehab}$+Unit Deck Replacement Cost$+3\sigma_{drep}$+Unit Deck Rehab Cost$+3\sigma_{drehab}$)-Unit Project Cost)/(Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost + $3\sigma_{drep}$ +Unit Deck Rehab Cost+ $3\sigma_{drehab}$) 0.5	
4	If Unit PC>(Unit Deck Rehab + Unit Deck Unit Replacement + Deck Rehab)	a. (-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5 b. 0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5 c. (-(Unit Deck Rehab Cost $+\sigma_{drehab}$+Unit Deck Replacement Cost$+\sigma_{drep}$+Unit Deck Rehab Cost$+\sigma_{drehab}$)+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck	(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) 0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) (-(Unit Deck Rehab Cost $+\sigma_{drehab}$+Unit Deck Replacement Cost$+\sigma_{drep}$+Unit Deck Rehab Cost$+\sigma_{drehab}$)+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+	$y=\alpha*(T- t_3)$

		Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	σ_{drehab})	
		d. (-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab})	
		e. (-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab})	
		f. otherwise	0.5	

3.2 Project Timing

Unit Project Cost = ((3,390,000)/(1+4%)^{11})/20714.4) = \$106.31 (1990\$/ft^2)
Unit Deck Rehabilitation Cost = \$62.019 (1990\$/ft^2)

Type I: Unit Project Cost > Unit Deck Rehabilitation Cost, Not Applicable
Type II:
Unit Deck Rehabilitation Cost < Unit Project Cost < Unit Deck Rehabilitation Cost+ Unit Deck Replacement Cost, Applicable
Case a: ((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost))/ (Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5
α = ((62.019+124.04)-106.31)/ (62.019+124.04)
α = 0.43 (<=0.5), OK
$y = \alpha*(t_2- t_1)$ = 0.43*(40-25) ≈ 7 Years
Base Year = 2001-33 = 1968

3.3 Conversion of Construction Estimate into 1990 Constant Dollars

$Dollar_{2000} = Dollar_{1990}\,(1+i)^{\,2001-1990}$
$Dollar_{1990}$ = 3,390,000/(1+4%)^{11}
$Dollar_{1990}$ = \$2,202,079.35

3.4 Bridge Maintenance Gradient Adjustment

It was assumed that the annual routine maintenance cost would increase in a faster pace for the period after project implementation as

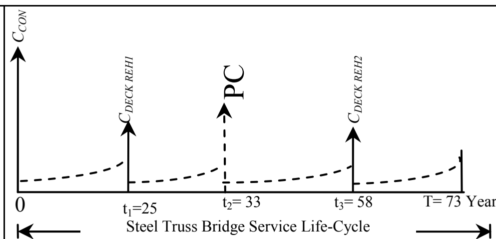
$g'_3 = (g_3 + 5\%*(1+ g_2)^{(33-25)} - 1) = 4.334\%$
$g'_4 = (g_3 + 5\%*(1+ g_3)^{(58-33)} - 1) = 8.469\%$

3.5 Project-Related Agency Cost Items in 1990$

Agency Cost Item	Unit Cost (1990$/ft^2)	Project-Related Cost (1990$)
Project Cost	-	2,202,079.35
Construction	348.25	= 348.25*20714.4 = 7,213,789.80
Deck Rehabilitation	62.019	= 62.019*20714.4 = 1,284,686.37
Deck Replacement	124.04	= 124.04*20714.4 = 2,569,414.18
Maintenance Cost	-	= (2.5%*7,213,789.80)/80 =2254.31

First Year Annual Maintenance Cost = (2.5%*Construction Cost)/(Base Case Life in years)

3.6 Alternative Case Deterministic Life-Cycle Agency Cost Calculation

<table>
<tr><th>Bridge Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Steel Truss Bridge</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + PC/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g'_3))/(1+i)^{t_2}$
$+((C_{MAIN4}(1-(1+g'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g'_4))/(1+i)^{t_3}$

$= 7,213,789.80+1,284,686.37/(1+4\%)^{25}+2,202,079.36/(1+4\%)^{33}$
$+ 1,284,686.37/(1+4\%)^{58}$
$+(2254.31(1-(1+3\%)^{25}(1+4\%)^{-25}))/(4\%-3\%)$
$+((2254.31(1-(1+3\%)^{(33-25)}(1+4\%)^{-(33-25)}))/(4\%-3\%))/(1+4\%)^{25}$
$+((2254.31(1-(1+4.334\%)^{(58-33)}(1+4\%)^{-(58-33)}))/(4\%4.334\%\%))/(1+4\%)^{33}$
$+((2254.31(1-(1+8.469\%)^{(73-58)}(1+4\%)^{-(73-58)}))/(4\%-8.469\%))/(1+4\%)^{58}$
$= 8,506,025.26$</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
$= 8,506,025.26((4\%(1+4\%)^{73})/((1+4\%)^{73}-1))$
$= 360,841.76$</td></tr>
</table>

4. Alternative Case Deterministic Life-Cycle User Cost Analysis with Early Termination

4.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1968
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	108,210/ [(1+2%)^{24}] = 67,276 (An annual growth rate of 2%)

4.2 Project-Related Base Year User Costs

Vehicle Operating Cost ($/VMT) = 0.3784
Travel Time ($/VMT) = 0.1582
Crash ($/ VMT) = 0.0986
Emission ($/VMT) = 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*67,276*0.934miles*365 = $8,678,627.14
Annual Travel Time Cost	= 0.1582*67,276*0.934miles*365 = $3,628,326.67
Annual Vehicle Crash Cost	= 0.0986*67,276*0.934miles*365 = $2,261,397.03
Annual Vehicle Air Emission Cost	= 0.2038*67,276*0.934miles*365 = $4,674,165.46
Total	$19,242,516.30

4.3 Additional Input Parameters

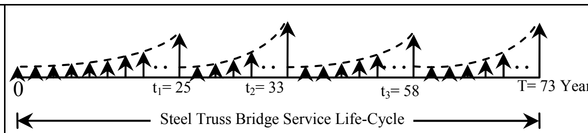
Annual User Cost Gradient r_1, r_2: 2%

It was assumed that the costs of annual vehicle operating costs, travel time, vehicle crashes, and vehicle emissions would increase in a faster pace for the period after project implementation as

$r'_3 = (r_3 + 5\%*(1+ r_2)^{(33-25)} - 1) = 2.858\%$

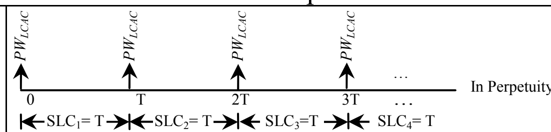
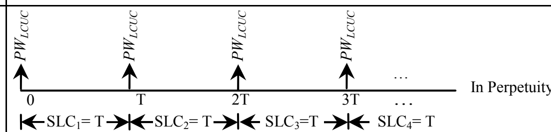
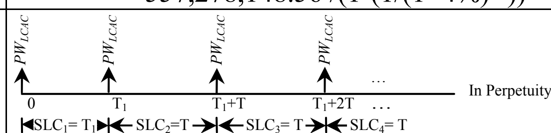
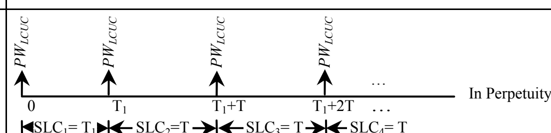
$r'_4 = (r_4 + 5\%*(1+ r_3)^{(33-25)} - 1) = 5.203\%$

4.4 Alternative Case Deterministic Life-Cycle User Cost Calculation

Bridge Type	Computation	
Steel Truss	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r'_4))/(1+i)^{t_3}$ $= (19{,}242{,}516.30\ (1-(1+2\%)^{25}(1+4\%)^{-25}))/(4\%-2\%)$ $+((19{,}242{,}516.30\ (1-(1+2\%)^{(33-25)}(1+4\%)^{-(33-25)}))/(4\%-2\%))/(1+4\%)^{25}$ $+((19{,}242{,}516.30\ (1+2.858\%\%)^{(58-33)}(1+4\%)^{-(58-33)}))/(4\%-2.858\%))/(1+4\%)^{33}$ $+((19{,}242{,}516.30\ (1-(1+5.203\%)^{(73-58)}(1+4\%)^{-(73-58)}))/(4\%-5.203\%))/(1+4\%)^{58}$ = 564,316,892.21
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $= 564{,}316{,}892.21\ ((4\%(1+4\%)^{73})/((1+4\%)^{73}-1))$ = 23,939,395.24

5. Computation of Project Life-Cycle Overall Benefits in Perpetuity

Only consider early termination in useful service life in the first life-cycle and the typical service life-cycle as in the base case will follow for the rest of cycles into perpetuity. The justification is that the bridge system manager will always try to upkeep the typical life-cycle activity profile that warrants the lowest life-cycle agency and user costs. If the first life-cycle was not completed as the typical profile, s/he will make every effort to follow the typical life-cycle activity profile in subsequent cycles in order to achieve the lowest total life-cycle costs.

Case		Computation
Base Case: No Early Termination	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,0}= PW_{LCAC}/(1-(1/(1+i)^{T}))$ $= 8,403,486.02 /(1-(1/(1+4\%)^{80})) = 8,784,599.97$ $PW_{LCUC\infty,0}= PW_{LCUC}/(1-(1/(1+i)^{T}))$ $= 557,278,148.56 /(1-(1/(1+4\%)^{80})) = 582,551,764.29$
Early Termination in Cycle 1	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,1}= PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 8,506,025.26 +(8,403,486.02/(1(1/(1+4\%)^{80})))/(1+4\%)^{73}$ $= 9,007,545.22$ $PW_{LCUC\infty,1}= PW_{LCUC1}+(PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 564,316,892.21+557,278,148.56(/(1(1/(1+4\%)^{80})))/(1+4\%)^{73}$ $= 597,575,246.32$
	Base Case Benefits	Agency Benefits: $PW_{AB}= PW_{LCAC\infty,1}-PW_{LCAC\infty,0}$ $= 9,007,545.22 - 8,784,597.78 = 222,945.24$ User Benefits: $PW_{UB}= PW_{LCUC\infty,1}-PW_{LCUC\infty,0}$ $= 597,575,246.32 - 582,551,764.29$ $= 15,023,482.03$ Overall Benefits: $PW_{B}= PW_{AB}+PW_{UB}$ $= 222,945.24 +15,023,482.03$ $= 15,246,427.27$

II. Project Life-Cycle Benefit Analysis Incorporating Risk

Input factors considered for risk-based analysis include bridge agency costs of construction, maintenance, and rehabilitation; traffic growth rates; and discount rates. Monte Carlo simulations were simultaneously performed for those factors using Beta distributions. In this case study, 10 simulation runs and each run with 1,000 iterations were used. For each input factor involving risk consideration, the grand average was established based on the average values of 10 simulation runs and each of which was determined in accordance with the 1,000 iteration outcomes.

In the end, the grand average values for all factors considered for probabilistic risk analysis were used for computing the expected project life-cycle benefits incorporating risk. The analytical procedure used is identical to that for deterministic life-cycle benefit analysis.

It should be noted that the analysis incorporating risk is essentially an analysis under mixed case of certainty and risk. This is because apart from the agency costs, traffic growth rates, and discount rate, the remaining input factors such as useful service life and project size are still treated under certainty.

1. Base Case Life-Cycle Agency Cost Analysis Incorporating Risk

1.1 Unit Costs for Steel Truss Bridge Activities (1990$/ft^2)

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Deck Expenditure	62.019	42.00	0.10	387.00	2.39	4.50	68%
Superstructure Expenditure	109.617	82.00	0.20	372.00	2.39	4.50	75%
Substructure Expenditure	114.597	92.00	0.10	372	2.39	4.50	80%
Surface Expenditure	62.019	42.00	0.10	387.00	2.39	4.50	68%

Note:

Construction Cost = Deck Expenditure + Superstructure Expenditure + Substructure Expenditure + Surface Expenditure

Deck Rehabilitation = Deck Expenditure

Deck Replacement = Deck Expenditure + Surface Expenditure

b. Average Values from Simulation Outputs

Cost Item	Unit Cost (1990$/ft^2)
Deck Expenditure	130.45
Superstructure Expenditure	129.34
Substructure Expenditure	130.62
Surface Expenditure	135.46

1.2. Agency Cost Items for Base Case Life-Cycle Agency Cost Analysis

Agency Cost Item	Project-Related Cost (1990$)
Construction	= 525.87 *20,714.40 = 10,893,081.53
Deck Rehabilitation	= 130.45 *20,714.40=2,702,193.48
Deck Replacement	= 265.91 *20,714.40 = 5,508,166.10
Maintenance	= (0.025* 10,893,081.53)/80= 3404.08

1.3 Additional Input Factors

a. Simulation Inputs

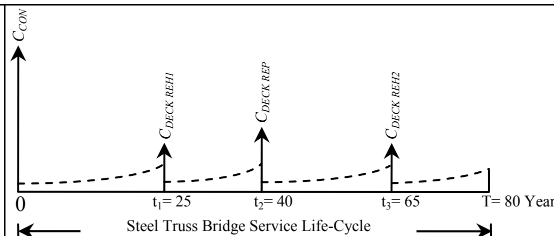
Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate i	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Maintenance Gradient g_1	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_2	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_3	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_4	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%

b. Average Values from Simulation Outputs

Discount Rate: 4.01%

Annual Maintenance Gradient g_1, g_2, g_3, g_4: 2.998%

1.4 Base Case Life-Cycle Agency Cost Calculation Using Average Values from Simulation

<table>
<tr><th>Bridge Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="5">Steel Truss Bridge</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$=C_{CON}+C_{DECK\ REH1}/(1+i)^{t_1}+PC/(1+i)^{t_2}+C_{DECK\ REH2}/(1+i)^{t_3}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_3))/(1+i)^{t_2}$
$+((C_{MAIN4}(1-(1+g_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_4))/(1+i)^{t_3}$

$= 10{,}893{,}081.53+2{,}702{,}193.48/(1+4.01\%)^{25}$
$+ 5{,}508{,}166.10/(1+4.01\%)^{40}$
$+ 2{,}702{,}193.48/(1+4.01\%)^{65}$
$+ (3404.08\ (1-(1+2.998\%)^{25}(1+4.01\%)^{-25}))/(4.01\%-2.998\%)$
$+ ((3404.08\ (1-(1+2.998\%)^{(40-25)}(1+4.01\%)^{-(40-25)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{25}$
$+((3404.08\ (1-(1+2.998\%)^{(65-40)}(1+4.01\%)^{-(65-40)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{40}$
$+((3404.08\ (1-(1+2.998\%)^{(80-65)}(1+4.01\%)^{-(80-65)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{65}$
= 13, 365,800.29</td></tr>
<tr><td>$PW_{LCAC\infty}$</td><td>$= PW_{LCAC}/(1-(1/(1+i)^T))$
$= 13{,}365{,}800.29/(1-(1/(1+4.01\%)^{80}))$
= 13,967,110.90</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$
$= 13{,}365{,}800.29.((4.01\%(1+4.01\%)^{80})/((1+4.01\%)^{80}-1))$
= 560,081.15</td></tr>
<tr><td>$EUAAC_\infty$</td><td>$= PW_{LCAC\infty}.i = 13{,}965{,}727.00*4.01\% = 560{,}081.15$</td></tr>
</table>

2. Base Case Life-Cycle User Cost Analysis

2.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1981
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	$108,210/[(1+2.011\%)^{11}] = 86,926$ (An annual growth rate of 2.011% as the average of simulation outputs)

2.2 Project-Related Base Year User Cost Calculation

Vehicle Operating Cost ($/VMT) = 0.3784
Travel Time ($/VMT) = 0.1582
Crash ($/ VMT) = 0.0986
Emission ($/VMT) = 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*86,926 *0.934miles*365 = $11,213,483.90
Annual Travel Time Cost	= 0.1582*86,926 *0.934miles*365 = $4,688,089.73
Annual Vehicle Crash Cost	= 0.0986*86,926 *0.934miles*365 = $2,921,906.75
Annual Vehicle Air Emission Cost	= 0.2038*86,926 *0.934miles*365 = $6,039,397.51
Total	$24,862,877.89

2.3 Additional Input Parameters

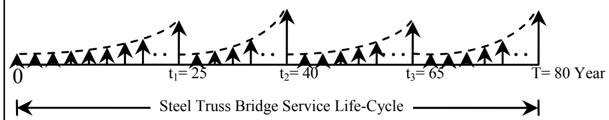
a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2, r_3, r_4: 1.9959%

2.4 Base Case Life-Cycle User Cost Calculation Using Average Values from Simulation

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r_4))/(1+i)^{t_3}$ $= (24{,}862{,}877.89\ (1-(1+1.9959\%)^{25}(1+4.01\%)^{-25}))/(4\%-1.9959\%)$ $+((24{,}862{,}877.89\ (1-(1+1.9959\%)^{(40-25)}(1+4.01\%)^{-(40-25)}))/(4.01\%-1.9959\%))/(1+4.01\%)^{25}$ $+((24{,}862{,}877.89\ (1-(1+1.9959\%)^{(65-40)}(1+4.01\%)^{-(65-40)}))/(4.01\%-1.9959\%))/(1+4.01\%)^{40}$ $+((24{,}862{,}877.89\ (1-(1+1.9959\%)^{(80-65)}(1+4.01\%)^{-(80-65)}))/(4.01\%-1.9959\%))/(1+4.01\%)^{65}$ =718,104,044.70
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$ $= 718{,}104{,}044.70\ /(1-(1/(1+4.01\%)^{80}))$ = 750,410,646.36
	EUAUC	$= PW_{LCUC}\ .((i(1+i)^T)/((1+i)^T-1))$ $= 718{,}104{,}044.70((4.01\%(1+4.01\%)^{80})/((1+4.01\%)^{80}-1))$ = 30,091,466.92
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i = 750{,}410{,}646.36 * 4.01\% = 30{,}091{,}466.92$

3. Alternative Case Life Cycle Agency Cost Analysis with Early Termination

3.1 Determination of the Reduction in Bridge Useful Service Life

No.	Type	Case	α	Reduction
1	If (Unit PC < Unit Deck Rehab Cost)	a. (Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost <=0.5 b. 0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost) <=0.5 c. ((Unit Deck Rehab Cost +σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost <=0.5 d. ((Unit Deck Rehab Cost +2σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost <=0.5 e. ((Unit Deck Rehab Cost +3σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost <=0.5 f. Otherwise	(Unit Deck Rehab Cost-Unit Project Cost)/Unit Deck Rehab Cost 0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost) ((Unit Deck Rehab Cost +σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost ((Unit Deck Rehab Cost +2σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost ((Unit Deck Rehab Cost +3σ_{drehab})-Unit Project Cost)/Unit Deck Rehab Cost 0.5	$y=\alpha*(t_1-0)$
2	If (Unit Deck Rehab< Unit PC < (Unit Deck Rehab + Unit Deck Replacement))	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost) <=0.5 b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost)) <=0.5 c. ((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))<=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost) 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost)) ((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))	$y=\alpha*(t_2- t_1)$

		d. ((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$))<=0.5 e. ((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$))<=0.5 f. Otherwise	((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$)) ((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$)) 0.5	
3	If (Unit Deck Rehab + Unit Deck Replacement)< Unit PC > (Unit Deck Rehab + Unit Deck Replacement + Unit Deck Rehab)	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5 b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5 c. ((Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) ((Unit Deck Rehab Cost +σ_{dehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab})	$y=\alpha*(t_3- t_2)$

		d. ((Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab}) <=0.5	((Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab})	
		e. ((Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab}) <=0.5	((Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab})	
		f. otherwise	0.5	
4	If Unit PC>(Unit Deck Rehab + Unit Deck Unit Replacement + Deck Rehab)	a. (-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5	(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)	$y=\alpha*(T- t_3)$
		b. 0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5	0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost))	
		c. (-(Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck	(-(Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+	

		Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	σ_{drehab})	
		d. (-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab})	
		e. (-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab})	
		f. otherwise	0.5	

3.2 Project Timing

Unit Project Cost = (3,390,000.00 / $(1+4.01\%)^{11}$/20,714.40)= \$106.20 (1990\$/ft^2)
Unit Deck Rehabilitation Cost = \$130.45 (1990\$/ft^2)

Type I: Unit Project Cost <Unit Deck Rehabilitation Cost, Applicable

Case a:
α = (((Unit Deck Rehabilitation Cost)- Unit Project Cost)/ (Unit Deck Rehabilitation Cost)
= ((130.45)- 106.20)/130.45 = 0.185 < 0.5

$y = \alpha*(t_1-0) = 0.185*(25-0) = 4.64 \approx 5$ years

Base Year = 2001 - 20 = 1981

3.3 Conversion of Construction Estimate into 1990$ Value

$Dollar_{2000} = Dollar_{1990}\,(1+i)^{2001-1990}$
$Dollar_{1990} = 3,390,000/(1+4.01\%)^{11} = \$2,199,751.58$

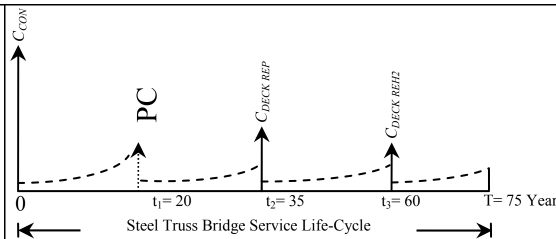
3.4 Bridge Maintenance Gradient Adjustment

$g'_2 = (g_2 + 3.33\%*(1+ g_1)^{(20-0)} - 1) \quad = 5.68\%$
$g'_3 = (g_3 + 3.33\%*(1+ g_2)^{(35-20)} - 1) \quad = 4.855\%$
$g'_4 = (g_4 + 3.33\%*(1+ g_3)^{(60-35)} - 1) \quad = 6.637\%$

3.5 Project-Related Agency Cost Items Using Average Values from Simulation

Agency Cost Item	Unit Cost (1990\$/ft^2)	Project-Related Agency Cost
Project Cost	-	2,199,751.58
Construction	525.87	= 525.87 *20,714.40 = 10,893,081.53
Deck Rehabilitation	130.45	= 130.45 *20,714.40=2,702,193.48
Deck Replacement	265.91	= 265.91 *20,714.40 = 5,508,166.10
Maintenance	-	=(0.025*217,839,747.6)/80=3404.08

3.6 Alternative Case Life-Cycle Agency Cost with Early Termination Using Average Values from Simulation

Bridge Type	Computation	
Steel Truss Bridge	Agency Cost Profile	
	PW_{LCAC}	$=C_{CON}+PC/(1+i)^{t_1}+C_{DREP}/(1+i)^{t_2}+C_{DREH2}/(1+i)^{t_3}$ $+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$ $+((C_{MAIN2}(1-(1+g'_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g'_2))/(1+i)^{t_1}$ $+((C_{MAIN3}(1-(1+g'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g'_3))/(1+i)^{t_2}$ $+((C_{MAIN4}(1-(1+g'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g'_4))/(1+i)^{t_3}$ =10, 893,081.53+2, 199,751.58 $/(1+4.01\%)^{20}$+5,508,166.10$/(1+4.01\%)^{35}$ +2,702,193.48$/(1+4.01\%)^{60}$ $+(3404.08\ \ (1-(1+2.998\%)^{20}(1+4.01\%)^{-20}))/(4.01\%-2.998\%)$ $+((3404.08\ \ (1-(1+5.68\%)^{(35-20)}(1+4.01\%)^{-(35-20)}))/$ $(4.01\%-5.68\%))/(1+4.01\%)^{20}$ $+((3404.08\ \ (1-(1+4.855\%)^{(60-35)}(1+4.01\%)^{-(60-35)}))/$ $(4.01\%-4.855\%))/(1+4.01\%)^{35}$ $+((3404.08\ \ (1-(1+6.637\%)^{(75-60)}(1+4.01\%)^{-(75-60)}))/$ $(4.01\%-6.637\%))/(1+4.01\%)^{60}$ = 13,654,838.15
	EUAAC	$= PW_{LCAC}.((i(1+i)^T)/((1+i)^T-1))$ $= 13,654,838.15 .((4.01\%(1+4.01\%)^{75})/((1+4.01\%)^{75}-1))$ = 577,840.39

4. Alternative Case Life-Cycle User Cost Analysis with Early Termination Using Average Values from Simulation

4.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1981
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	$108{,}210/[(1+2.011\%)^{11}] = 86{,}926$ (An annual growth rate of 2.011% as the average of simulation outputs)

4.2 Project-Related Base Year User Cost Calculation

Vehicle Operating Cost ($/VMT)= 0.3784
Travel Time ($/VMT) = 0.1582
Crash ($/ VMT) = 0.0986
Emission ($/VMT) = 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*86,926 *0.934miles*365 = $11,213,483.90
Annual Travel Time Cost	= 0.1582*86,926 *0.934miles*365 = $4,688,089.73
Annual Vehicle Crash Cost	= 0.0986*86,926 *0.934miles*365 = $2,921,906.75
Annual Vehicle Air Emission Cost	= 0.2038*86,926 *0.934miles*365 = $6,039,397.51
Total	$24,862,877.89

4.3 Additional Input Parameters

a. Simulation Inputs

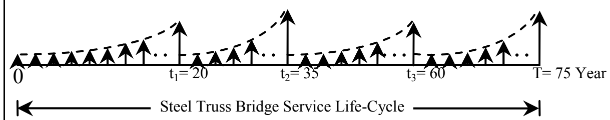
Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

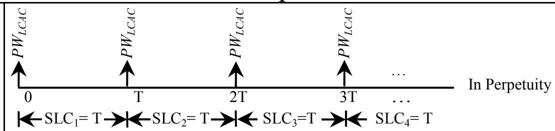
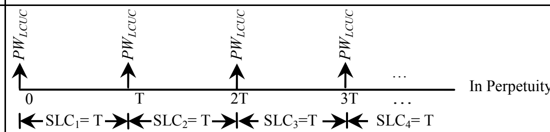
Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1: 1.9959%

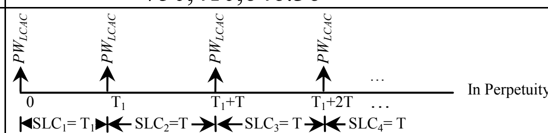
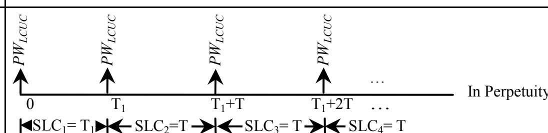
$r'_2 = (r_2 + 3.33\%*(1+ r_1)^{(20-0)} - 1) = 3.608\%$
$r'_3 = (r_3 + 3.33\%*(1+ r_2)^{(35-20)} - 1) = 3.143\%$
$r'_4 = (r_4 + 3.33\%*(1+ r_3)^{(60-35)} - 1) = 4.122\%$

4.4 Alternative Case Life-Cycle User Cost Calculation with Early Termination Using Average Values from Simulation

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1} (1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r'_2)^{(t_2-t_1)} (1+i)^{-(t_2-t_1)}))/(i-r'_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(t_3-t_2)} (1+i)^{-(t_3-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r'_4)^{(T-t_3)} (1+i)^{-(T-t_3)}))/(i-r'_4))/(1+i)^{t_3}$ $= (24{,}862{,}877.89 (1-(1+1.9959\%)^{20} (1+4.01\%)^{-20}))/(4\%-1.9959\%)$ $+((24{,}862{,}877.89 (1-(1+3.608\%)^{(35-20)} (1+4.01\%)^{-(35-20)}))/$ $(4.01\%-3.608\%))/(1+4.01\%)^{20}$ $+((24{,}862{,}877.89 (1-(1+3.143\%)^{(60-35)} (1+4.01\%)^{-(60-35)}))/$ $(4.01\%-3.143\%))/(1+4.01\%)^{35}$ $+((24{,}862{,}877.89(1-(1+4.122\%)^{(75-60)} (1+4.01\%)^{-(75-60)}))/$ $(4.01\%-4.122\%))/(1+4.01\%)^{60}$ $= 729{,}430{,}638.39$
	EUAUC	$= PW_{LCUC} .((i(1+i)^T)/((1+i)^T-1))$ $= 729{,}430{,}638.39((4.01\%(1+4.01\%)^{75})/((1+4.01\%)^{75}-1))$ $= 30{,}867{,}775.95$

5. Computation of Expected Project Life-Cycle Overall Benefits in Perpetuity

<table>
<tr><th>Case</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Base Case: No Early Termination</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,0} = PW_{LCAC}/(1-(1/(1+i)^{T}))$
$= 13{,}365{,}800.29 /(1-(1/(1+4.01\%)^{80}))$
$= 13{,}967{,}110.90$

$PW_{LCUC\infty,0} = PW_{LCUC}/(1-(1/(1+i)^{T}))$
$= 718{,}104{,}044.70 /(1-(1/(1+4.01\%)^{80}))$
$= 750{,}410{,}646.36$</td></tr>
<tr><td rowspan="4">Early Termination in Cycle 1</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>User Cost Profile</td><td>
</td></tr>
<tr><td>Present Worth</td><td>$PW_{LCAC\infty,1} = PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$
$=13{,}654{,}838.15$
$+(13{,}365{,}800.29/(1(1/(1+4.01\%)^{80})))/(1+4.01\%)^{75}$
$= 14{,}386{,}776.24$

$PW_{LCUC\infty,1} = PW_{LCUC1}+(PW_{LCUC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$
$= 729{,}430{,}638.39$
$+(718{,}104{,}044.70/(1(1/(1+4.01\%)^{80})))/(1+4.01\%)^{75}$
$= 768{,}755{,}459.80$</td></tr>
<tr><td>Base Case Benefits</td><td>Agency Benefits: $PW_{AB} = PW_{LCAC\infty,1}-PW_{LCAC\infty,0}$
$= 14{,}386{,}776.24 - 13{,}967{,}110.90$
$= 419{,}665.34$

User Benefits: $PW_{UB} = PW_{LCUC\infty,1}-PW_{LCUC\infty,0}$
$= 768{,}755{,}459.80 - 750{,}410{,}646.36$
$= 18{,}344{,}813.42$

Overall Benefits: $PW_{B} = PW_{AB}+PW_{UB}$
$= 419{,}665.34 +18{,}344{,}813.42$
$= 18{,}764{,}478.76$</td></tr>
</table>

III. Project Life-Cycle Benefit Analysis under Certainty, Risk and Uncertainty

It the process of conducting risk-based analysis of project benefits, it was found that benefits items associated with agency costs, vehicle operating costs, and vehicle emission costs were with relatively smaller magnitude of variations. Whereas travel time and crash costs changed considerably in multiple simulation runs. As such, travel time and crash costs were further selected for uncertainty-based analyses.

For each project, the project benefits resulted from reduction in agency costs, vehicle operating costs, and vehicle emission costs were kept the same as those of risk-based analyses. The benefits concerning reduction in travel time and vehicle crashes were computed using uncertainty-based analyses. The individual benefit items were added together to arrive at the overall project life-cycle benefits under certainty, risk, and uncertainty.

1. Base Case Life-Cycle Agency Cost Analysis Incorporating Risk

1.1 Unit Costs for Steel Bridge Activities (1990$/ft^2)

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Deck Expenditure	62.019	42.00	0.10	387.00	2.39	4.50	68%
Superstructure Expenditure	109.617	82.00	0.20	372.00	2.39	4.50	75%
Substructure Expenditure	114.597	92.00	0.10	372.00	2.39	4.50	80%
Surface Expenditure	62.019	42.00	0.10	387.00	2.39	4.50	68%

b. Average Values from Simulation Outputs

Cost Item	Unit Cost (1990$/ft^2)
Deck Expenditure	130.45
Superstructure Expenditure	129.34
Substructure Expenditure	130.62
Surface Expenditure	135.46

1.2. Agency Cost Items for Base Case Life-Cycle Agency Cost Analysis

Agency Cost Item	Project-Related Cost (1990$)
Construction	= 525.87 *20,714.40 = 10,893,081.53
Deck Rehabilitation	= 130.45 *20,714.40=2,702,193.48
Deck Replacement	= 265.91 *20,714.40 = 5,508,166.10
Maintenance	= (0.025* 217,839,747.6)/80= 3404.08

1.3 Additional Input Factors

a. Simulation Inputs

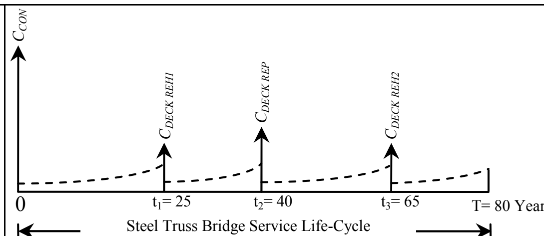
Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate i	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Maintenance Gradient g_1	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_2	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_3	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%
Annual Maintenance Gradient g_4	3.00%	1.00%	1.00%	5.00%	4.50	4.50	33%

b. Average Values from Simulation Outputs

Discount Rate: 4.01%

Annual Maintenance Gradient g_1, g_2, g_3, g_4: 2.998%

1.4 Base Case Life-Cycle Agency Cost Calculation Using Average Values from Simulation

<table>
<tr><th>Bridge Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="5">Steel Truss Bridge</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$= C_{CON} + C_{DECK\ REH1}/(1+i)^{t_1} + PC/(1+i)^{t_2} + C_{DECK\ REH2}/(1+i)^{t_3}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g_3))/(1+i)^{t_2}$
$+((C_{MAIN4}(1-(1+g_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g_4))/(1+i)^{t_3}$

$= 10{,}893{,}081.53 + 2{,}702{,}193.48/(1+4.01\%)^{25}$
$+5{,}508{,}166.10/(1+4.01\%)^{40}$
$+2{,}702{,}193.48/(1+4.01\%)^{65}$
$+(3404.08\ (1-(1+2.998\%)^{25}(1+4.01\%)^{-25}))/(4.01\%-2.998\%)$
$+((3404.08\ (1-(1+2.998\%)^{(40-25)}(1+4.01\%)^{-(40-25)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{25}$
$+((3404.08\ (1-(1+2.998\%)^{(65-40)}(1+4.01\%)^{-(65-40)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{40}$
$+((3404.08\ (1-(1+2.998\%)^{(80-65)}(1+4.01\%)^{-(80-65)}))/$
$(4.01\%-2.998\%))/(1+4.01\%)^{65}$
$=13{,}365{,}800.29$</td></tr>
<tr><td>$PW_{LCAC\infty}$</td><td>$= PW_{LCAC}/(1-(1/(1+i)^T))$
$= 13{,}365{,}800.29\ /(1-(1/(1+4.01\%)^{80}))$
$= 13{,}967{,}110.90$</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC}\ .((i(1+i)^T)/((1+i)^T-1))$
$= 13{,}365{,}800.29((4.01\%(1+4.01\%)^{80})/((1+4.01\%)^{80}-1))$
$= 560{,}081.15$</td></tr>
<tr><td>$EUAAC_\infty$</td><td>$= PW_{LCAC\infty}.i = 13{,}965{,}727.00 * 4.01\% = 560{,}081.15$</td></tr>
</table>

2. Base Case Life-Cycle Vehicle Operating Costs and Emission Costs under Risk

2.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1981
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	$108{,}210/[(1+2.011\%)^{11}] = 86{,}926$ (An annual growth rate of 2.011% as the average of simulation outputs)

2.2 Project-Related Base Year User Cost Calculation

Vehicle Operating Cost ($/VMT): 0.3784
Emission Cost ($/VMT): 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*86,926 *0.934miles*365 = $11,213,483.90
Annual Vehicle Air Emission Cost	= 0.2038*86,926 *0.934miles*365 = $6,039,397.51
Total	$17,252,881.41

2.3 Additional Input Parameters

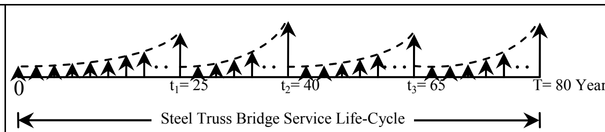
a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2, r_3, r_4: 1.9959%

2.4 Calculation of Base Case Life-Cycle Vehicle Operating Costs and Emission Costs Using Average Values from Simulation

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r_4))/(1+i)^{t_3}$ $= (17{,}252{,}881.41(1-(1+1.9959\%)^{25}(1+4.01\%)^{-25}))/(4\%-1.9959\%)$ $+((17{,}252{,}881.41(1-(1+1.9959\%)^{(40-25)}(1+4.01\%)^{-(40-25)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{25}$ $+((17{,}252{,}881.41\ (1-(1+1.9959\%)^{(65-40)}(1+4.01\%)^{-(65-40)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{40}$ $+((17{,}252{,}881.41(1-(1+1.9959\%)^{(80-65)}(1+4.01\%)^{-(80-65)}))/$ $(4.01\%-1.9959\%))/(1+4.01\%)^{65}$ $= 498{,}307{,}717.12$
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^T))$ $= 498{,}307{,}717.12/(1-(1/(1+4.01\%)^{80})) = 520{,}725{,}957.26$
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $= 498{,}307{,}717.12((4.01\%(1+4.01\%)^{80})/((1+4.01\%)^{80}-1))$ $= 20{,}881{,}110.89$
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i$ $= 520{,}725{,}957.26*4.01\% = 20{,}881{,}110.89$

3. Base Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

3.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1981
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	$108{,}210/[(1+1.63\%)^{11}] = 90{,}579$ (An annual growth rate of 1.63% as the average of simulation outputs)

3.2 Project-Related Base Year User Cost Calculation

Travel Time ($/VMT) = 0.1582

Crash ($/ VMT) = 0.0986

User Cost Item	Annual Cost (1990$/year)
Annual Travel Time Cost	= 0.1582*90,579 *0.934miles*365 = $4,885,103.19
Annual Vehicle Crash Cost	= 0.0986*90,579 *0.934miles*365 = $3,044,697.69
Total	7,929,800.88

3.3 Additional Input Parameters

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate i	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Discount Rate *i*: 4.01%

Annual Traffic Growth Rate r: 2.011%

Annual User Cost Gradient r_1, r_2, r_3, r_4: 1.9959%

c. Values Adjusted from Simulation Using Penalty Rules for Uncertainty-Based Analysis

Cost Item	Average, $X_{(E)}$	X_{SFL}	X_{SFG}	Tolerance (ΔX)	X
Discount Rate i	4.01%	5.00%	3.00%	20% of μ = 4.00%	4.17%
Annual Traffic Growth Rate r	2.011%	1.00%	3.00%	39% of μ = 2.00%	1.63%
Annual User Cost Gradient r_1	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_2	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_3	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_4	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%

Penalty Rule:

If more is better, $X = \begin{cases} X_{(E)}, & \text{if } |X_{SFL} - X_{(E)}| \leq \Delta X \\ \dfrac{X_{SFL}}{[1-\Delta X/X_{(E)}]}, & \text{otherwise} \end{cases}$

If less is better, $X = \begin{cases} X_{(E)}, & \text{if } |X_{SFL} - X_{(E)}| \leq \Delta X \\ \dfrac{X_{SFL}}{[1+\Delta X/X_{(E)}]}, & \text{otherwise} \end{cases}$

- For discount rate *i*, less is better.
  Since $|X_{SFL} - X_{(E)}| = |5\% - 4.01\%| = 0.99\% > \Delta X = 20\%*4\% = 0.8\%$
  $X_i = X_{SFL}/[1+\Delta X/ X_{(E)}] = 5\%/[1+0.8\%/ 4.01\%] = 4.17\%$

- For annual traffic growth rate *r*, more is better.
  Since $|X_{SFL} - X_{(E)}| = |1\% - 2.011\%| = 1.011\% > \Delta X = 39\%*2\% = 0.78\%$
  $X_r = X_{SFL}/[1-\Delta X/ X_{(E)}] = 1\%/[1- (0.78\%/ 2.011\%)] = 1.63\%$

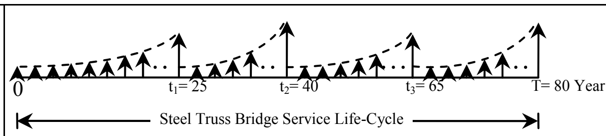
- For annual user cost gradients r_1, r_2, r_3, more is better.
  Since $|X_{SFL} - X_{(E)}| = |1\% - 1.995\%| = 0.995\% > \Delta X = 39\%*2\% = 0.78\%$
  $X_{r1} = X_{r2} = X_{r3}=X_{SFL}/[1-\Delta X/ X_{(E)}] = 1\%/[1- (0.78\%/ 1.995\%)] = 1.64\%$

Note:

1. The ΔX's are set as per the preference of the decision-maker. In addition, r, r_1, r_2, r_3, and r_4 could also be thought of less is better in some cases. In so doing, the adjusted values for r would be 3%/[1+ (0.78%/ 2.011%)] = 2.16% and for r_1, r_2, r_3, and r_4 would be 3%/[1+ (0.78%/ 1.995%)] = 2.16% instead.

2. The adjusted values for discount rate *i* = 4.17%, for annual traffic growth rate r = 1.63%, and for annual user cost gradients r_1, r_2, r_3, and r_4 = 1.64% were used as inputs for uncertainty-based analysis.

3.4 Calculation of Base Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r_4))/(1+i)^{t_3}$ $= (7{,}929{,}800.88(1-(1+1.64\%)^{25}(1+4.17\%)^{-25}))/(4.17\%-1.64\%)$ $+((7{,}929{,}800.88(1-(1+1.64\%)^{(40-25)}(1+4.17\%)^{-(40-25)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{25}$ $+((7{,}929{,}800.88(1-(1+1.64\%)^{(65-40)}(1+4.17\%)^{-(65-40)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{40}$ $+((7{,}929{,}800.88(1-(1+1.64\%)^{(80-65)}(1+4.17\%)^{-(80-65)}))/$ $(4.17\%-1.64\%))/(1+4.17\%)^{65}$ = 213,609,916.30
	$PW_{LCUC\infty}$	$= PW_{LCUC}/(1-(1/(1+i)^{T}))$ $= 213{,}609{,}916.30/(1-(1/(1+4.17\%)^{80}))$ = 222,063,969.29
	EUAUC	$= PW_{LCUC}.((i(1+i)^{T})/((1+i)^{T}-1))$ $= 213{,}609{,}916.30((4.17\%(1+4.17\%)^{80})/((1+4.17\%)^{80}-1))$ = 9,260,067.52
	$EUAUC_{\infty}$	$= PW_{LCUC\infty}.i = 222{,}063{,}969.29 * 4.17\% = 9{,}260{,}067.52$

4. Base Case Life-Cycle User Cost Calculation

Bridge Type	Computation	
Steel Truss Bridge	PW_{LCUC}	$= PW_{LCVOC/EC} + PW_{LCTT/VC}$ = 498,307,717.12 + 213,609,916.30 = 711,917,633.42
	$PW_{LCUC\infty}$	$= PW_{LCVOC/EC\infty} + PW_{LCTT/VC\infty}$ = 520,725,957.26 + 222,063,969.29 = 742,789,926.55
	EUAUC	$= EUA_{VOC/EC} + EUA_{LCTT/VC}$ = 20,881,110.89 + 9,260,067.52 = 30,141,178.41
	$EUAUC_{\infty}$	$= EUA_{LCVOC/EC\infty} + EUA_{LCTT/VC\infty}$ = 20,881,110.89 + 9,260,067.52 = 30,141,178.41

5. Alternative Case Life Cycle Agency Cost Analysis with Early Termination

5.1 <u>Determination of the Reduction in Bridge Useful Service Life</u>

No.	Type	Case	α	Reduction
1	If (Unit PC < Unit Deck Rehab Cost)	a. (Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost <=0.5	(Unit Deck Rehab Cost-Unit Project Cost)/Unit Deck Rehab Cost	$y=\alpha*(t_1-0)$
		b. 0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost) <=0.5	0.33((Unit Deck Rehab Cost -Unit Project Cost)/Unit Deck Rehab Cost)	
		c. ((Unit Deck Rehab Cost $+\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		d. ((Unit Deck Rehab Cost $+2\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+2\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		e. ((Unit Deck Rehab Cost $+3\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost <=0.5	((Unit Deck Rehab Cost $+3\sigma_{drehab}$)-Unit Project Cost)/Unit Deck Rehab Cost	
		f. Otherwise	0.5	
2	If (Unit Deck Rehab< Unit PC < (Unit Deck Rehab + Unit Deck Replacement))	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost) <=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost)	$y=\alpha*(t_2- t_1)$
		b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost)) <=0.5	0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost)-Unit Project Cost)/ (Unit Deck Rehab Cost +Deck Replacement Cost))	
		c. ((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))<=0.5	((Unit Deck Rehab Cost + σ_{drehab}+Unit Deck Replacement Cost+σ_{drep})-Unit Project Cost)/ (Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost+ σ_{drep}))	

		d. ((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$))<=0.5	((Unit Deck Rehab Cost + $2\sigma_{drehab}$+Unit Deck Replacement Cost+$2\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $2\sigma_{drehab}$ +Deck Replacement Cost+ $2\sigma_{drep}$))	
		e. ((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$))<=0.5	((Unit Deck Rehab Cost + $3\sigma_{drehab}$+Unit Deck Replacement Cost+$3\sigma_{drep}$)-Unit Project Cost)/ (Unit Deck Rehab Cost+ $3\sigma_{drehab}$ +Deck Replacement Cost+ $3\sigma_{drep}$))	
		f. Otherwise	0.5	
3	If (Unit Deck Rehab + Unit Deck Replacement)< Unit PC > (Unit Deck Rehab + Unit Deck Replacement + Unit Deck Rehab)	a. (Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5	(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)	$y=\alpha^*(t_3- t_2)$
		b. 0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5	0.33((Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)-Unit Project Cost)/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost))	
		c. ((Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	((Unit Deck Rehab Cost +σ_{dehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab})	

		d. ((Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab}) <=0.5	((Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab})	
		e. ((Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab}) <=0.5	((Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})-Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab})	
		f. otherwise	0.5	
4	If Unit PC>(Unit Deck Rehab + Unit Deck Unit Replacement + Deck Rehab)	a. (-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost) <=0.5	(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)	$y=\alpha*(T- t_3)$
		b. 0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost)) <=0.5	0.33(-(Unit Deck Rehab Cost +Unit Deck Replacement Cost +Unit Deck Rehab Cost)+Unit Project Cost))/(Unit Deck Rehab Cost +Deck Replacement Cost +Unit Deck Rehab Cost))	
		c. (-(Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck	(-(Unit Deck Rehab Cost +σ_{drehab}+Unit Deck Replacement Cost+σ_{drep}+Unit Deck Rehab Cost+σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ σ_{drehab} +Deck Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+	

		Replacement Cost + σ_{drep} +Unit Deck Rehab Cost+ σ_{drehab}) <=0.5	σ_{drehab})	
		d. (-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +2σ_{drehab}+Unit Deck Replacement Cost+2σ_{drep}+Unit Deck Rehab Cost+2σ_{drehab})+(Unit Project Cost))/(Unit Deck Rehab Cost+ 2σ_{drehab} +Deck Replacement Cost + 2σ_{drep} +Unit Deck Rehab Cost+ 2σ_{drehab})	
		e. (-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab}) <=0.5	(-(Unit Deck Rehab Cost +3σ_{drehab}+Unit Deck Replacement Cost+3σ_{drep}+Unit Deck Rehab Cost+3σ_{drehab})+(Unit Project Cost)/(Unit Deck Rehab Cost+ 3σ_{drehab} +Deck Replacement Cost + 3σ_{drep} +Unit Deck Rehab Cost+ 3σ_{drehab})	
		f. otherwise	0.5	

5.2 Project Timing

Unit Project Cost = (3,390,000.00/(1+4.01%)^{11}/20,714.40)= \$106.20 (1990\$/ft^2)
Unit Deck Rehabilitation Cost = \$ 130.45 (1990\$/ft^2)

Type I: Unit Project Cost <Unit Deck Rehabilitation Cost, Applicable
Case a:
α = (((Unit Deck Rehabilitation Cost)- Unit Project Cost)/ (Unit Deck Rehabilitation Cost)
= ((130.45)- 106.20)/130.45= 0.185 < 0.5

$y = \alpha*(t_1\text{-}0) = 0.185*(25\text{-}0) = 4.64 \approx 5$ years

Base Year = 2001 – 20 = 1981

5.3 Conversion of Construction Estimate into 1990\$ Value

$Dollar_{2000} = Dollar_{1990}\,(1+i)^{2001\text{-}1990}$
$Dollar_{1990}$ = 3,390,000/(1+.0401)^{11} = \$2,199,751.58

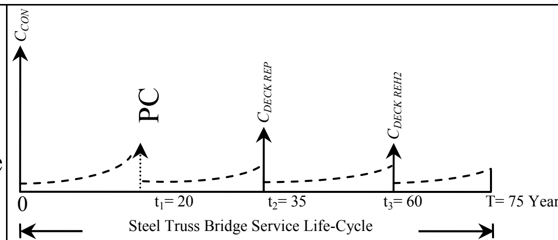
5.4 Bridge Maintenance Gradient Adjustment

$g'_2 = (g_2 + 3.33\%*(1+ g_1)^{(20\text{-}0)}\text{-} 1)$ = 5.68%
$g'_3 = (g_3 + 3.33\%*(1+ g_2)^{(35\text{-}20)}\text{-} 1)$ = 4.855%
$g'_4 = (g_4 + 3.33\%*(1+ g_3)^{(60\text{-}35)}\text{-} 1)$ = 6.637%

5.5 Project-Related Agency Cost Items Using Average Values from Simulation

Agency Cost Item	Unit Cost (1990$/ft^2)	Project-Related Agency Cost
Project Cost	-	2,199,751.58
Construction	525.87	= 525.87 *20,714.40 = 10,893,081.53
Deck Rehabilitation	130.45	= 130.45 *20,714.40= 2,702,193.48
Deck Replacement	265.91	= 265.91 *20,714.40 = 5,508,166.10
Maintenance	-	= (0.025*10,893,081.53)/80= 3404.08

5.6 Alternative Case Life-Cycle Agency Cost with Early Termination Using Average Values from Simulation

<table>
<tr><th>Bridge Type</th><th colspan="2">Computation</th></tr>
<tr><td rowspan="3">Steel Truss Bridge</td><td>Agency Cost Profile</td><td>
</td></tr>
<tr><td>PW_{LCAC}</td><td>$=C_{CON} + PC/(1+i)^{t_1} + C_{DREP}/(1+i)^{t_2} + C_{DREH2}/(1+i)^{t_3}$
$+(C_{MAIN1}(1-(1+g_1)^{t_1}(1+i)^{-t_1}))/(i-g_1)$
$+((C_{MAIN2}(1-(1+g'_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-g'_2))/(1+i)^{t_1}$
$+((C_{MAIN3}(1-(1+g'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-g'_3))/(1+i)^{t_2}$
$+((C_{MAIN4}(1-(1+g'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-g'_4))/(1+i)^{t_3}$

$= 10,893,081.53+2,199,751.58$
$/(1+4.01\%)^{20}+5,508,166.10/(1+4.01\%)^{35}$
$+2,702,193.48/(1+4.01\%)^{60}$
$+ (3404.08(1-(1+2.998\%)^{20}(1+4.01\%)^{-20}))/(4.01\%-2.998\%)$
$+((3404.08(1-(1+5.68\%^{(35-20)}(1+4.01\%)^{-(35-20)}))/$
$(4.01\%-5.68\%))/(1+4.01\%)^{20}$
$+((3404.08(1-(1+4.855\%)^{(60-35)}(1+4.01\%)^{-(60-35)}))/$
$(4.01\%-4.855\%))/(1+4.01\%)^{35}$
$+((3404.08(1-(1+6.637\%)^{(75-60)}(1+4.01\%)^{-(75-60)}))/$
$(4.01\%-6.637\%))/(1+4.01\%)^{60}$
$= 13,654,838.15$</td></tr>
<tr><td>EUAAC</td><td>$= PW_{LCAC} .((i(1+i)^T)/((1+i)^T-1))$
$= 13,654,838.15((4.01\%(1+4.01\%)^{75})/((1+4.01\%)^{75}-1))$
$= 577,840.39$</td></tr>
</table>

6. Alternative Case Life-Cycle Vehicle Operating Costs and Emission Costs under Risk

6.1 Basic Data

Let Fiscal Year: 2001
Average Daily Traffic Year: 1992
Average Daily Traffic Count: 108,210
Project Base Year: 1981
Project Length: 0.934 miles
Highway Classification: Urban Interstate
Average Speed: 56.78 mph
Base Year AADT: $108,210/[(1+2.011\%)^{11}] = 86,926$ (An annual growth rate of 2.011% as the average of simulation outputs)

6.2 Project-Related Base Year User Cost Calculation

Vehicle Operating Cost ($/VMT): 0.3784
Emission Cost ($/VMT): 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Vehicle Operating Cost	= 0.3784*86,926 *0.934miles*365 = $11,213,483.90
Annual Vehicle Air Emission Cost	= 0.2038*86,926 *0.934miles*365 = $6,039,397.51
Total	$17,252,881.41

6.3 Additional Input Parameters

a. Simulation Inputs

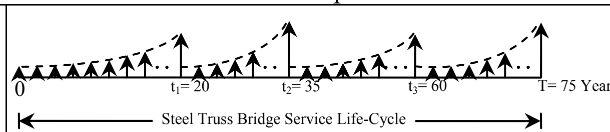
Cost Item	μ	σ	L	H	α_1	α_2	COV
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

b. Average Values from Simulation Outputs

Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2, r_3, r_4: 1.9959%

$r'_2 = (r_2 + 3.33\%*(1+ r_1)^{(20-0)} - 1)$ = 3.608%
$r'_3 = (r_3 + 3.33\%*(1+ r_2)^{(35-20)} - 1)$ = 3.143%
$r'_4 = (r_4 + 3.33\%*(1+ r_3)^{(60-35)} - 1)$ = 4.122%

6.4 Calculation of Alternative Case Life-Cycle Vehicle Operating Costs and Emission Costs Using Average Values from Simulation

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r'_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r'_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r'_4))/(1+i)^{t_3}$ $= (17{,}252{,}881.41(1-(1+1.9959\%)^{20}(1+4.01\%)^{-20}))/(4\%-1.9959\%)$ $+((17{,}252{,}881.41(1-(1+3.608\%)^{(35-20)}(1+4.01\%)^{-(35-20)}))/$ $(4.01\%-3.608\%))/(1+4.01\%)^{20}$ $+((17{,}252{,}881.41(1-(1+3.143\%)^{(60-35)}(1+4.01\%)^{-(60-35)}))/$ $(4.01\%-3.143\%))/(1+4.01\%)^{35}$ $+((17{,}252{,}881.41(1-(1+4.122\%)^{(60-35)}(1+4.01\%)^{-(75-60)}))/$ $(4.01\%-4.122\%))/(1+4.01\%)^{60}$ = 506,167,482.13
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $= 506{,}167{,}482.13((4.01\%(1+4.01\%)^{80})/((1+4.01\%)^{80}-1))$ = 21,419,808.28

7. Alternative Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

7.1 Basic Data

Let Fiscal Year:	2001
Average Daily Traffic Year:	1992
Average Daily Traffic Count:	108,210
Project Base Year:	1981
Project Length:	0.934 miles
Highway Classification:	Urban Interstate
Average Speed:	56.78 mph
Base Year AADT:	$108{,}210/[(1+1.63\%)^{11}] = 90{,}579$ (An annual growth rate of 1.63% as the average of simulation outputs)

7.2 Project-Related Base Year User Cost Calculation

Vehicle Operating Cost ($/VMT) = 0.3784
Travel Time ($/VMT) = 0.1582
Crash ($/ VMT) = 0.0986
Emission ($/VMT) = 0.2038

User Cost Item	Annual Cost (1990$/year)
Annual Travel Time Cost	= 0.1582*90,579 *0.934miles*365 = $4,885,103.19
Annual Vehicle Crash Cost	= 0.0986*90,579 *0.934miles*365 = $3,044,697.69
Total	7,929,800.88

7.3 Additional Input Parameters

a. Simulation Inputs

Cost Item	μ	σ	L	H	α_1	α_2	COV
Discount Rate i	4.00%	1.00%	3.00%	5.00%	4.50	4.50	25%
Annual Traffic Growth Rate r	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_1	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_2	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_3	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%
Annual User Cost Gradient r_4	2.00%	1.00%	1.00%	3.00%	4.50	4.50	50%

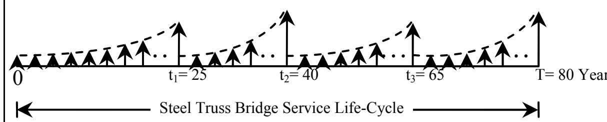
b. Average Values from Simulation Outputs

Discount Rate *i*: 4.01%
Annual Traffic Growth Rate r: 2.011%
Annual User Cost Gradient r_1, r_2, r_3, r_4: 1.9959%
$r'_2=(r_2 + 3.33\%*(1+ r_1)^{(20-0)}- 1)$ = 2.920%
$r'_3=(r_3 + 3.33\%*(1+ r_2)^{(35-20)}- 1)$ = 2.560%
$r'_4=(r_4 + 3.33\%*(1+ r_3)^{(60-35)}- 1)$ = 3.311%

c. Values Adjusted from Simulation Using Penalty Rules for Uncertainty-Based Analysis

Cost Item	Average, $X_{(E)}$	X_{SFL}	X_{SFG}	Tolerance (ΔX)	X
Discount Rate i	4.01%	5.00%	3.00%	20% of μ = 4.00%	4.17%
Annual Traffic Growth Rate r	2.011%	1.00%	3.00%	39% of μ = 2.00%	1.63%
Annual User Cost Gradient r_1	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_2	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_3	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%
Annual User Cost Gradient r_4	1.9959%	1.00%	3.00%	39% of μ = 2.00%	1.64%

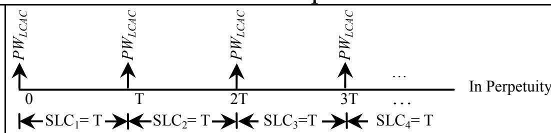
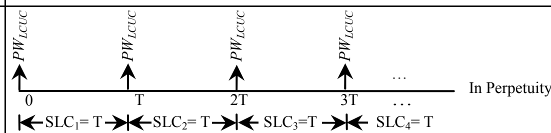
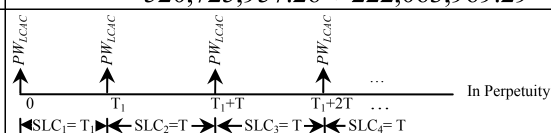
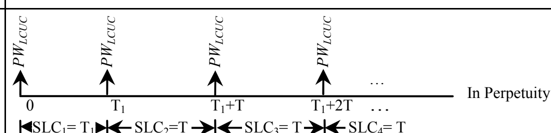
7.4 Calculation of Alternative Case Life-Cycle Travel Time and Vehicle Crash Costs under Uncertainty

Bridge Type	Computation	
Steel Truss Bridge	User Cost Profile	
	PW_{LCUC}	$= (C_{AUC1}(1-(1+r_1)^{t_1}(1+i)^{-t_1}))/(i-r_1)$ $+((C_{AUC2}(1-(1+r'_2)^{(t_2-t_1)}(1+i)^{-(t_2-t_1)}))/(i-r'_2))/(1+i)^{t_1}$ $+((C_{AUC3}(1-(1+r'_3)^{(t_3-t_2)}(1+i)^{-(t_3-t_2)}))/(i-r'_3))/(1+i)^{t_2}$ $+((C_{AUC4}(1-(1+r'_4)^{(T-t_3)}(1+i)^{-(T-t_3)}))/(i-r'_4))/(1+i)^{t_3}$ $= (7,929,800.88\ (1-(1+1.64\%)^{20}(1+4.17\%)^{-20}))/(4.17\%-1.64\%)$ $+((7,929,800.88\ (1-(1+2.920\%\%)^{(35-20)}(1+4.17\%)^{-(35-20)}))/$ $(4.17\%-2.920\%\%))/(1+4.17\%)^{20}$ $+((7,929,800.88\ (1-(1+2.560\%)^{(60-35)}(1+4.17\%)^{-(60-35)}))/$ $(4.17\%-2.560\%))/(1+4.17\%)^{35}$ $+((7,929,800.88\ (1-(1+3.311\%)^{(75-60)}(1+4.17\%)^{-(75-60)}))/$ $(4.17\%-3.311\%))/(1+4.17\%)^{60}$ = 215,479,142.15
	EUAUC	$= PW_{LCUC}.((i(1+i)^T)/((1+i)^T-1))$ $= 215,479,142.15((4.17\%(1+4.17\%)^{80})/((1+4.17\%)^{80}-1))$ = 9,425,640.73

8. Alternative Case Life-Cycle User Cost Calculation

Bridge Type	Computation	
Steel Truss Bridge	PW_{LCUC}	$= PW_{LCVOC/EC} + PW_{LCTT/VC}$ = 506,167,482.13+ 215,479,142.15 = 721,646,624.28
	EUAUC	$= EUA_{VOC/EC} + EUA_{LCTT/VC}$ = 21,419,808.28 +9,425,640.73 = 30,845,449.01

9. Computation of Project Life-Cycle Overall Benefits in Perpetuity

Case	Computation	
Base Case: No Early Termination	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,0}= PW_{LCAC}/(1-(1/(1+i)^{T}))$ $= 13{,}365{,}800.29 /(1-(1/(1+4.01\%)^{80})) = 13{,}967{,}110.90$ $PW_{LCUC\infty,0}= PW_{LCUC(VOC+VAE)}/(1-(1/(1+i)^{T}))$ $+ PW_{LCUC(VTT+VCC)}/(1-(1/(1+i)^{T}))$ $= 498{,}307{,}717.12 /(1(1/(1+4.01\%)^{80}))$ $+213{,}609{,}916.30/(1(1/(1+4.17\%)^{80}))$ $= 520{,}725{,}957.26 + 222{,}063{,}969.29 = 742{,}789{,}926.55$
Early Termination in Cycle 1	Agency Cost Profile	
	User Cost Profile	
	Present Worth	$PW_{LCAC\infty,1}= PW_{LCAC1}+(PW_{LCAC}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 13{,}654{,}838.15 +(13{,}365{,}800.29/(1(1/(1+4.01\%)^{80})))/(1+4.01\%)^{75}$ $= 14{,}386{,}776.24$ $PW_{LCUC\infty,1}= PW_{LCUC1(VOC+VAE)}$ $+(PW_{LCUC(VOC+VAE)}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $+PW_{LCUC1(VTT+VCC)}$ $+(PW_{LCUC(VTT+VCC)}/(1-(1/(1+i)^{T})))/(1+i)^{T_1}$ $= 506{,}167{,}482.13$ $+498{,}307{,}717.12\ (1/(1(1/(1+4.17\%)^{75})))/(1+4.17\%)^{80})$ $+215{,}479{,}142.15$ $+213{,}609{,}916.30\ (/(1(1/(1+4.01\%)^{75})))/(1+4.01\%)^{80})$ $= 533{,}455{,}814.67 + 225{,}849{,}130.93$ $= 759{,}304{,}945.60$
	Base Case Benefits	Agency Benefits: $PW_{AB}= PW_{LCAC\infty,1} - PW_{LCAC\infty,0}$ $= 14{,}386{,}776.24 - 13{,}967{,}110.90$ $= 419{,}665.34$ User Benefits: $PW_{UB}= PW_{LCUC\infty,1} - PW_{LCUC\infty,0}$ $= 759{,}304{,}945.60 - 742{,}789{,}926.55$ $= 16{,}515{,}019.15$ Overall Benefits: $PW_{B}= PW_{AB} + PW_{UB}$ $= 419{,}665.34 + 16{,}515{,}019.15$ $= 16{,}934{,}684.49$

IV. Analysis Summary

1. Basic Input Data

a. Analysis under Certainty

Data Item	AC	VOC	TT	VC	EC
Project Cost	2,202,079.35				
Construction Cost	7,213,789.80				
Deck Rehabilitation Cost	1,284,686.37				
Deck Replacement Cost	2,569,414.18				
Annual Routine Maintenance	2254.31				
BM Gradient g_1, g_2, g_3, g_4/ BM Gradient g_3', g_4'	3.00% / 4.334%, 8.469%				
Discount Rate *i*	4.00%	4.00%	4.00%	4.00%	4.00%
Base Year AADT	67,276	67,276	67,276	67,276	67,276
Annual Traffic Growth *r*	2.00%	2.00%	2.00%	2.00%	2.00%
Annual UC Gradient r_1, r_2, r_3, r_4/ Annual UC Gradient r_3', r_4'		2.00% / 2.858%, 5.203%	2.00% / 2.858%, 5.203%	2.00% / 2.858%, 5.203%	2.00% / 2.858%, 5.203%
Service Life for Base Case	80	80	80	80	80
Service Life for Alt Case	73	73	73	73	73

b. Analysis under Certainty and Risk

Data Item	AC	VOC	TT	VC	EC
Project Cost	2,199,751.58				
Construction Cost	10,893,081.53				
Deck Rehabilitation Cost	2,702,193.48				
Deck Replacement Cost	5,508,166.104				
Annual Routine Maintenance	3404.08				
BM Gradient g_1, g_2, g_3, g_4/ BM Gradient g_2', g_3', g_4'	2.998% / 5.68%, 4.855%, 6.637%				
Discount Rate *i*	4.01%	4.01%	4.01%	4.01%	4.01%
Base Year AADT	86,926	86,926	86,926	86,926	86,926
Annual Traffic Growth *r*	2.011%	2.011%	2.011%	2.011%	2.011%
Annual UC Gradient r_1, r_2, r_3, r_4/ Annual UC Gradient r_2', r_3', r_4'		1.995%/ 3.608% 3.143%, 4.122%	1.995%/ 3.608% 3.143%, 4.122%	1.995%/ 3.608% 3.143%, 4.122%	1.995%/ 3.608% 3.143%, 4.122%
Service Life for Base Case	80	80	80	80	80
Service Life for Alt Case	75	75	75	75	75

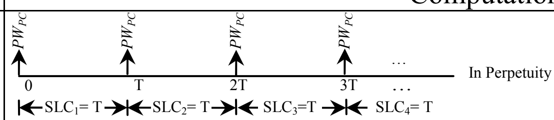
c. Analysis under Certainty, Risk, and Uncertainty

Data Item	AC	VOC	TT	VC	EC
Project Cost	2,199,751.58				
Construction Cost	10,893,081.53				
Deck Rehabilitation Cost	2,702,193.48				
Deck Replacement Cost	5,508,166.104				
Annual Routine Maintenance	3404.08				
BM Gradient g_1, g_2, g_3, g_4/ BM Gradient g_2', g_3', g_4'	2.998% / 5.68%, 4.855%, 6.637%				
Discount Rate *i*	4.01%	4.01%	4.17%	4.17%	4.01%
Base Year AADT	86,926	86,926	90,579	90,579	86,926
Annual Traffic Growth *r*	2.011%	2.011%	1.63%	1.63%	2.011%
Annual UC Gradient r_1, r_2, r_3, r_4/ Annual UC Gradient r_2', r_3', r_4'		1.995%/ 3.608% 3.143%, 4.122%	1.64%/ 2.920%, 2.560%, 3.311%	1.64%/ 2.920%, 2.560%, 3.311%	1.995%/ 3.608% 3.143%, 4.122%
Service Life for Base Case	80	80	80	80	80
Service Life for Alt Case	75	75	75	75	75

2. Estimated Project Benefits

Item	Certainty	Certainty and Risk	Certainty, Risk and Uncertainty
$PW_{Agency\ Benefits}$	222,945.24	419,665.34	419,665.34
$PW_{User\ Benefits}$	15,023,482.03	18,344,813.42	16,515,019.15
$PW_{Total\ Benefits}$	15,246,427.27	18,764,478.76	16,934,684.49

3. Project Costs in Perpetuity

Case	Computation
Project Cost Profile	
Certainty (i = 4%)	PW_{LCPC} = Project Cost/((1+i)$^{(2001-1990)+Project\ Timing}$) = \$3,390,000/((1+4%)$^{(2001-1990)+33}$) = 603,577.1208 $PW_{LCPC\infty}$ = PW_{LCPC}/(1-(1/(1+i)^T)) = 603,577.1208/(1-(1/(1+4%)^{80})) = 630,950.48
Certainty and Risk (i = 4.01%)	PW_{LCPC} = Project Cost/((1+i)$^{(2001-1990)+Project\ Timing}$) = \$3,390,000/((1+4.01%)$^{(2001-1990)+33}$) = 601,029.0418 $PW_{LCPC\infty}$ = PW_{LCPC}/(1-(1/(1+i)^T)) = 601,029.0418/(1-(1/(1+4.01%)^{80})) = 628,068.59
Certainty, Risk, and Uncertainty (i = 4.01%)	PW_{LCPC} = 601,029.0418 $PW_{LCPC\infty}$ = 628,068.59

4. Summary of Project Benefit-Cost Analysis Results

Item	Certainty	Certainty and Risk	Certainty, Risk and Uncertainty
NPW	= 15,246,427.27 - 630,950.48 = 14,615,476.79	= 18,764,478.76 - 628,068.59 = 18,136,410.17	= 16,934,684.49 - 628,068.59 = 16,306,615.90
B/C	= 15,246,427.27/ 630,950.48 = 24.16	= 18,764,478.76/ 628,068.59 = 29.87	= 16,934,684.49/ 628,068.59 = 26.96

APPENDIX 3: Total Benefits of Contracts Selected Using Contract-Based Tradeoff Method under Yearly Constrained and Cumulative Budgets at All Stages (Present Worth in Perpetuity, 1990 Dollars)

a. Contract Selection Using Contract-Based Tradeoff Method

Year	One-Stage Deterministic Budget		Four-Stage Stochastic Budgets	
	Yearly Constrained	Cumulative	Yearly Constrained	Cumulative
1996	3,754,065,431	3,275,697,497	3,753,988,417	3,321,615,668
1997	3,528,990,550	3,060,467,276	3,528,535,593	3,060,445,195
1998	3,117,435,731	2,544,264,809	3,117,826,852	2,573,123,492
1999	3,394,392,403	2,364,811,330	3,369,989,451	2,397,118,845
2000	3,715,077,362	4,037,338,425	4,194,540,988	3,730,408,632
2001	4,631,047,857	3,383,161,281	4,631,047,857	3,880,829,125
2002	4,542,830,357	3,875,016,221	4,542,830,357	3,875,322,206
2003	7,829,867,892	7,174,324,544	7,829,867,892	7,173,977,819
2004	2,506,847,668	3,418,688,707	2,471,047,310	3,419,434,740
2005	166,522,164	1,550,111,604	240,272,391	1,551,291,310
2006	528,854,632	3,384,820,373	528,854,632	3,382,764,666
Total	37,715,932,047	38,068,702,067	38,208,801,740	38,366,331,698

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	One-Stage Deterministic Budget		Four-Stage Stochastic Budgets	
	Yearly Constrained	Cumulative	Yearly Constrained	Cumulative
1996	3,697,973,620	2,906,936,961	3,697,973,620	2,969,909,513
1997	3,413,797,558	3,066,085,740	3,412,652,017	3,083,357,948
1998	2,814,338,978	2,260,711,673	2,814,338,978	2,289,570,356
1999	3,071,028,894	2,327,073,152	3,007,592,691	2,327,073,152
2000	3,142,397,753	2,936,563,204	3,474,743,146	3,102,702,947
2001	4,585,522,958	3,554,145,883	4,585,522,958	3,562,531,520
2002	4,249,115,878	3,720,043,706	4,196,715,171	3,720,236,607
2003	8,306,960,159	7,895,682,150	8,309,426,980	7,904,257,813
2004	2,853,590,186	2,873,411,994	2,854,750,838	2,874,176,713
2005	364,031,284	1,198,693,416	364,173,268	1,198,693,416
2006	246,828,260	3,371,598,733	247,070,102	3,397,929,460
Total	36,745,585,526	36,110,946,612	36,964,959,769	36,430,439,445

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	One-Stage Deterministic Budget		Four-Stage Stochastic Budgets	
	Yearly Constrained	Cumulative	Yearly Constrained	Cumulative
1996	3,754,065,431	3,321,775,472	3,754,041,899	3,334,506,021
1997	3,528,990,550	3,077,739,485	3,528,535,593	3,176,928,506
1998	2,978,342,340	2,573,123,492	2,978,733,461	2,573,123,492
1999	3,211,523,023	2,398,399,146	3,162,044,215	2,363,315,688
2000	4,922,020,641	3,749,178,929	5,329,268,559	3,735,227,058
2001	4,630,801,766	3,465,524,347	4,630,801,766	3,878,366,584
2002	4,254,552,243	3,875,016,221	4,254,630,902	3,875,322,206
2003	7,492,475,469	7,174,324,544	7,492,475,469	7,176,232,535
2004	2,111,237,294	3,418,688,707	2,085,670,549	3,419,868,721
2005	165,994,750	1,550,111,604	165,693,277	1,551,291,310
2006	291,800,767	3,382,764,666	213,075,077	3,382,764,666
Total	37,341,804,276	37,986,646,612	37,594,970,767	38,466,946,788

APPENDIX 4: Contracts Consistently Selected under Yearly Constrained and Cumulative Budgets

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	412	399	413	412
1997	412	358	372	365	373	372
1998	429	275	402	393	404	404
1999	411	323	379	368	366	368
2000	610	578	507	505	506	502
2001	418	412	402	404	402	403
2002	422	421	374	375	374	375
2003	469	461	395	397	395	396
2004	649	648	233	232	231	233
2005	408	406	53	53	53	54
2006	376	375	46	46	46	45
Total	5,068	4,700	3,575	3,537	3,563	3,564

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	405	409	407	410
1997	412	358	384	385	385	385
1998	429	275	398	399	399	399
1999	411	323	369	381	381	365
2000	610	578	485	487	487	490
2001	418	412	397	398	398	398
2002	422	421	376	376	376	376
2003	469	461	429	430	430	432
2004	649	648	263	265	264	265
2005	408	406	96	96	96	96
2006	376	375	43	57	56	57
Total	5,068	4,700	3,645	3,683	3,679	3,673

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	412	413	413	413
1997	412	358	373	373	374	374
1998	429	275	403	404	404	404
1999	411	323	380	369	368	367
2000	610	578	514	511	512	509
2001	418	412	403	403	401	401
2002	422	421	374	375	374	375
2003	469	461	395	397	396	397
2004	649	648	233	232	232	234
2005	408	406	53	53	53	54
2006	376	375	45	45	45	45
Total	5,068	4,700	3,585	3,575	3,572	3,573

APPENDIX 5: Matching of Contracts Consistently Selected under Yearly Constrained and Cumulative Budget Scenarios

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Stage 1		Stage 2		Stage 3		Stage 4	
			B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
1996	464	443	98%	94%	98%	91%	98%	94%	98%	94%
1997	412	358	97%	94%	97%	92%	97%	94%	97%	94%
1998	429	275	97%	98%	97%	95%	97%	98%	97%	98%
1999	411	323	93%	99%	94%	96%	93%	96%	94%	96%
2000	610	578	98%	95%	96%	94%	96%	94%	95%	94%
2001	418	412	97%	100%	97%	100%	97%	100%	97%	100%
2002	422	421	93%	95%	93%	95%	93%	95%	93%	95%
2003	469	461	91%	92%	92%	92%	91%	92%	92%	92%
2004	649	648	82%	39%	82%	39%	82%	39%	82%	39%
2005	408	406	83%	13%	83%	13%	82%	13%	83%	14%
2006	376	375	84%	13%	85%	13%	85%	13%	82%	12%
Total	5,068	4,700	94%	75%	94%	75%	94%	75%	94%	75%

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Stage 1		Stage 2		Stage 3		Stage 4	
			B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
1996	464	443	91%	97%	91%	97%	91%	97%	92%	97%
1997	412	358	98%	96%	98%	96%	98%	96%	98%	96%
1998	429	275	95%	100%	95%	100%	95%	100%	95%	100%
1999	411	323	92%	99%	95%	99%	95%	99%	92%	98%
2000	610	578	97%	98%	93%	97%	93%	97%	94%	97%
2001	418	412	96%	99%	97%	100%	97%	100%	97%	100%
2002	422	421	94%	96%	93%	96%	93%	96%	94%	96%
2003	469	461	98%	95%	97%	95%	97%	95%	98%	95%
2004	649	648	86%	47%	86%	47%	86%	47%	86%	47%
2005	408	406	99%	24%	96%	24%	96%	24%	98%	24%
2006	376	375	73%	12%	93%	16%	90%	15%	95%	16%
Total	5,068	4,700	94%	79%	94%	79%	94%	79%	94%	79%

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Stage 1		Stage 2		Stage 3		Stage 4	
			B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
1996	464	443	98%	94%	98%	94%	98%	94%	98%	95%
1997	412	358	97%	94%	97%	94%	98%	94%	98%	94%
1998	429	275	98%	98%	98%	98%	98%	98%	98%	98%
1999	411	323	94%	99%	94%	96%	94%	96%	94%	96%
2000	610	578	92%	96%	90%	95%	90%	95%	89%	95%
2001	418	412	97%	100%	98%	100%	97%	100%	97%	100%
2002	422	421	94%	95%	95%	95%	95%	95%	94%	95%
2003	469	461	93%	92%	93%	92%	93%	92%	93%	92%
2004	649	648	84%	39%	83%	39%	84%	39%	84%	39%
2005	408	406	84%	13%	84%	13%	87%	13%	87%	14%
2006	376	375	92%	12%	94%	12%	92%	12%	94%	12%
Total	5,068	4,700	94%	76%	94%	75%	94%	75%	94%	75%

APPENDIX 6: Contracts Both Authorized by the Indiana DOT and Selected under Yearly Constrained Budget Scenario

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	405	390	404	404
1997	412	358	346	339	345	345
1998	429	275	266	263	267	267
1999	411	323	319	308	307	307
2000	610	578	488	497	497	497
2001	418	412	409	409	408	409
2002	422	421	403	401	400	403
2003	469	461	428	428	429	428
2004	649	648	284	284	283	283
2005	408	406	64	64	65	65
2006	376	375	55	54	54	55
Total	5,068	4,700	3,467	3,437	3,459	3,463

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	432	432	432	432
1997	412	358	355	355	355	355
1998	429	275	274	274	274	274
1999	411	323	314	312	312	311
2000	610	578	471	492	492	492
2001	418	412	407	407	407	407
2002	422	421	399	402	402	400
2003	469	461	432	436	435	434
2004	649	648	305	307	307	307
2005	408	406	97	100	100	98
2006	376	375	59	61	62	60
Total	5,068	4,700	3,545	3,578	3,578	3,570

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	405	405	405	405
1997	412	358	346	345	345	345
1998	429	275	266	267	267	267
1999	411	323	317	306	306	306
2000	610	578	531	539	539	539
2001	418	412	408	407	407	408
2002	422	421	397	394	394	398
2003	469	461	422	422	422	422
2004	649	648	279	280	277	278
2005	408	406	63	63	61	62
2006	376	375	49	48	49	48
Total	5,068	4,700	3,483	3,476	3,472	3,478

APPENDIX 7: Matching Percent of Contracts Both Authorized by the Indiana DOT and Selected under Yearly Constrained Budget Scenario

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	91%	88%	91%	91%
1997	412	358	97%	95%	96%	96%
1998	429	275	97%	96%	97%	97%
1999	411	323	99%	95%	95%	95%
2000	610	578	84%	86%	86%	86%
2001	418	412	99%	99%	99%	99%
2002	422	421	96%	95%	95%	96%
2003	469	461	93%	93%	93%	93%
2004	649	648	44%	44%	44%	44%
2005	408	406	16%	16%	16%	16%
2006	376	375	15%	14%	14%	15%
Total	5,068	4,700	74%	73%	74%	74%

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	98%	98%	98%	98%
1997	412	358	99%	99%	99%	99%
1998	429	275	100%	100%	100%	100%
1999	411	323	97%	97%	97%	96%
2000	610	578	81%	85%	85%	85%
2001	418	412	99%	99%	99%	99%
2002	422	421	95%	95%	95%	95%
2003	469	461	94%	95%	94%	94%
2004	649	648	47%	47%	47%	47%
2005	408	406	24%	25%	25%	24%
2006	376	375	16%	16%	17%	16%
Total	5,068	4,700	75%	76%	76%	76%

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	91%	91%	91%	91%
1997	412	358	97%	96%	96%	96%
1998	429	275	97%	97%	97%	97%
1999	411	323	98%	95%	95%	95%
2000	610	578	92%	93%	93%	93%
2001	418	412	99%	99%	99%	99%
2002	422	421	94%	94%	94%	95%
2003	469	461	92%	92%	92%	92%
2004	649	648	43%	43%	43%	43%
2005	408	406	16%	16%	15%	15%
2006	376	375	13%	13%	13%	13%
Total	5,068	4,700	74%	74%	74%	74%

APPENDIX 8: Contracts Both Authorized by the Indiana DOT and Selected under Cumulative Budget Scenario

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	423	423	423	421
1997	412	358	350	351	351	349
1998	429	275	268	269	269	269
1999	411	323	298	299	297	298
2000	610	578	506	507	508	504
2001	418	412	397	399	397	398
2002	422	421	391	392	391	392
2003	469	461	422	424	422	423
2004	649	648	591	590	589	591
2005	408	406	391	391	391	392
2006	376	375	366	366	366	365
Total	5,068	4,700	4,403	4,411	4,404	4,402

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	401	405	403	406
1997	412	358	354	355	355	355
1998	429	275	267	268	268	268
1999	411	323	290	302	302	290
2000	610	578	468	473	473	476
2001	418	412	393	394	394	394
2002	422	421	389	389	390	390
2003	469	461	444	445	445	447
2004	649	648	557	558	558	558
2005	408	406	391	391	391	391
2006	376	375	348	362	361	362
Total	5,068	4,700	4,302	4,342	4,340	4,337

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	422	423	423	421
1997	412	358	351	351	351	351
1998	429	275	269	269	269	269
1999	411	323	299	300	298	297
2000	610	578	505	508	509	506
2001	418	412	398	398	396	396
2002	422	421	391	392	391	392
2003	469	461	422	424	423	424
2004	649	648	591	590	590	592
2005	408	406	391	391	391	392
2006	376	375	365	365	365	365
Total	5,068	4,700	4,404	4,411	4,406	4,405

APPENDIX 9: Matching Percent of Contracts Both Authorized by the Indiana DOT and Selected under Cumulative Budget Scenario

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	95%	95%	95%	95%
1997	412	358	98%	98%	98%	97%
1998	429	275	97%	98%	98%	98%
1999	411	323	92%	93%	92%	92%
2000	610	578	88%	88%	88%	87%
2001	418	412	96%	97%	96%	97%
2002	422	421	93%	93%	93%	93%
2003	469	461	92%	92%	92%	92%
2004	649	648	91%	91%	91%	91%
2005	408	406	96%	96%	96%	97%
2006	376	375	98%	98%	98%	97%
Total	5,068	4,700	94%	94%	94%	94%

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	91%	91%	91%	92%
1997	412	358	99%	99%	99%	99%
1998	429	275	97%	97%	97%	97%
1999	411	323	90%	93%	93%	90%
2000	610	578	81%	82%	82%	82%
2001	418	412	95%	96%	96%	96%
2002	422	421	92%	92%	93%	93%
2003	469	461	96%	97%	97%	97%
2004	649	648	86%	86%	86%	86%
2005	408	406	96%	96%	96%	96%
2006	376	375	93%	97%	96%	97%
Total	5,068	4,700	92%	92%	92%	92%

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	95%	95%	95%	95%
1997	412	358	98%	98%	98%	98%
1998	429	275	98%	98%	98%	98%
1999	411	323	93%	93%	92%	92%
2000	610	578	87%	88%	88%	88%
2001	418	412	97%	97%	96%	96%
2002	422	421	93%	93%	93%	93%
2003	469	461	92%	92%	92%	92%
2004	649	648	91%	91%	91%	91%
2005	408	406	96%	96%	96%	97%
2006	376	375	97%	97%	97%	97%
Total	5,068	4,700	94%	94%	94%	94%

APPENDIX 10: Contracts Both Authorized by the Indiana DOT and Selected under Yearly Constrained and Cumulative Budget Scenarios

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	399	386	400	399
1997	412	358	341	336	342	341
1998	429	275	264	262	266	266
1999	411	323	296	287	285	286
2000	610	578	480	477	478	474
2001	418	412	396	398	396	397
2002	422	421	373	374	373	374
2003	469	461	392	394	392	393
2004	649	648	233	232	231	233
2005	408	406	53	53	53	54
2006	376	375	46	46	46	45
Total	5,068	4,700	3,273	3,245	3,262	3,262

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	392	396	394	397
1997	412	358	351	352	352	352
1998	429	275	267	268	268	268
1999	411	323	289	298	298	285
2000	610	578	458	460	460	463
2001	418	412	392	393	393	393
2002	422	421	375	375	375	375
2003	469	461	422	423	423	425
2004	649	648	263	265	264	265
2005	408	406	96	96	96	96
2006	376	375	43	57	56	57
Total	5,068	4,700	3,348	3,383	3,379	3,376

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	399	400	400	400
1997	412	358	342	342	342	342
1998	429	275	265	266	266	266
1999	411	323	297	288	287	286
2000	610	578	487	483	484	481
2001	418	412	397	397	395	395
2002	422	421	373	374	373	374
2003	469	461	392	394	393	394
2004	649	648	233	232	232	234
2005	408	406	53	53	53	54
2006	376	375	45	45	45	45
Total	5,068	4,700	3,283	3,274	3,270	3,271

APPENDIX 11: Matching Percent of Contracts Both Authorized by the Indiana DOT and Selected under Yearly Constrained and Cumulative Budget Scenarios

a. Contract Selection Using Contract-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	90%	87%	90%	90%
1997	412	358	95%	94%	96%	95%
1998	429	275	96%	95%	97%	97%
1999	411	323	92%	89%	88%	89%
2000	610	578	83%	83%	83%	82%
2001	418	412	96%	97%	96%	96%
2002	422	421	89%	89%	89%	89%
2003	469	461	85%	85%	85%	85%
2004	649	648	36%	36%	36%	36%
2005	408	406	13%	13%	13%	13%
2006	376	375	12%	12%	12%	12%
Total	5,068	4,700	70%	69%	69%	69%

b. Contract Selection Using Corridor-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	88%	89%	89%	90%
1997	412	358	98%	98%	98%	98%
1998	429	275	97%	97%	97%	97%
1999	411	323	89%	92%	92%	88%
2000	610	578	79%	80%	80%	80%
2001	418	412	95%	95%	95%	95%
2002	422	421	89%	89%	89%	89%
2003	469	461	92%	92%	92%	92%
2004	649	648	41%	41%	41%	41%
2005	408	406	24%	24%	24%	24%
2006	376	375	11%	15%	15%	15%
Total	5,068	4,700	71%	72%	72%	72%

c. Contract Selection Using Deferment-Based Tradeoff Method

Year	Candidate Contracts	INDOT Authorized	Budget Stage			
			1	2	3	4
1996	464	443	90%	90%	90%	90%
1997	412	358	96%	96%	96%	96%
1998	429	275	96%	97%	97%	97%
1999	411	323	92%	89%	89%	89%
2000	610	578	84%	84%	84%	83%
2001	418	412	96%	96%	96%	96%
2002	422	421	89%	89%	89%	89%
2003	469	461	85%	85%	85%	85%
2004	649	648	36%	36%	36%	36%
2005	408	406	13%	13%	13%	13%
2006	376	375	12%	12%	12%	12%
Total	5,068	4,700	70%	70%	70%	70%