Final Report

AAPTP 06-06

LIFE CYCLE COST ANALYSIS FOR AIRPORT PAVEMENTS

Prepared For:

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January 2011

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ACKNOWLEDGMENTS

This report was prepared for Auburn University under the Airport Asphalt Pavement Technology Program (AAPTP). Funding was provided by the Federal Aviation Administration (FAA) under Cooperative Agreement Number 04-G-038. Dr. David Brill was the Contracting Officer's Technical Representative and serves as a Program Manager in the FAA Airport Technology Branch at the William J. Hughes Technical Center. Mr. Monte Symons served as the Project Director for this project. The AAPTP and the FAA thank the Project Technical Panel that willingly gave of their expertise and time for the development of this report. They were responsible for the oversight and the technical direction. The names of those individuals on the Project Technical Panel follow:

- Mr. Monte Symons, AAPTP.
- Mr. Rodney Joel, Federal Aviation Administration.
- Mr. Michael Moore, Reynolds, Smith, & Hills, Inc.
- Mr. William Schauz, US Air Force Civil Engineering Support Agency
- Mr. Michael Smith, Federal Highway Administration (FHWA).
- Mr. Gary Mitchell, American Concrete Pavement Association.
- Mr. Kent Hansen, National Asphalt Pavement Association.

Others who participated in Panel meetings included:

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- Bill Tudor, Campbell & Paris—Atlanta.
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- Nadarajah Sivaneswaran (Siva), FHWA.

DISCLAIMER

ABSTRACT

The objective of this study was to provide a comprehensive document that describes life cycle cost analysis (LCCA) for airport pavements, along with a companion spreadsheet based tool for conducting LCCA. The methodology developed is applicable to both flexible and rigid airport pavements and addresses all aspects of LCCA. The intent of the methodology is to provide engineers and airport management with a fair, unbiased, and defensible procedure to evaluate alternative pavement types during the design and/or bid process. The results of the project provide airport consultants and management with information to meet Federal Aviation Administration Order 5100.38C, paragraph 910, Life Cycle Costs in Competitive Sealed Bids.

This report addresses the following items:

- Airport pavement construction, maintenance, and rehabilitation activities that are to be used in airport pavement LCCA procedures.
- Typical costs and sources of data for costs of all elements used in LCCA.
- Use of airport pavement management data and systems in LCCA procedures.
- Review of other appropriate LCCA methods and their applicability to airport pavements.

The LCCA methodology developed under this study considers:

- Applicability of different types of cost comparisons, such as present worth and equivalent uniform annual cost.
- Process for fair comparison of remaining service life of rigid and flexible pavement systems.
- Guidance and data sources to determine appropriate discount rates.
- Guidance for analysis period and difference to pavement system design life.
- Guidance for evaluating both direct and indirect user and operator costs.
- Deterministic and probabilistic life cycle cost methods.

CHAPTER 1. INTRODUCTION

Background

The conduct of life cycle cost analysis (LCCA) for airport pavement projects in the US civil arena is governed primarily by Federal Aviation Administration (FAA) Order 5100.38C and Advisory Circular (AC) 150/5320-6D. Section 508 of FAA Order 5100.38C states:

> Life-cycle costs shall be considered in AIP procurement where specified in bidding documents. This is a requirement of Title 49, Code of Federal Regulations, Part 18. Life-cycle costs are defined to encompass the entire period facilities or equipment progress through a budget, including the stages for the airport planning, construction, commission, operating, management, maintenance, repair, improvements, and activities decommissioning the project. Regional personnel should exercise care to treat life-cycle airport costs fairly for sponsors without requiring unreasonable initial capital expenditures.

In Section 910 of Order 5100.38C, FAA Airports Offices are directed to "encourage life-cycle costing" when the following conditions can be met:

1. The invitation for bid (IFB) states that life-cycle costs will be used in determining the low bidder;
2. The factors to be considered are specified and the costs associated with the factors must be quantifiable: (a) "Specified" means that the invitation for bid specifically states the factors that will be included in the life-cycle cost computation. Examples of factors that could be specified include annual fuel consumption for a motor vehicle, electrical consumption, and lamp replacement for lighting equipment, recurring inspection, and maintenance. All factors that have quantifiable costs should be specified in the bidding document. (b) "Quantifiable" means that there is sufficient information available so that costs associated with these factors can be readily calculated. Generally, costs associated with maintenance should only be

included in the life-cycle costs computation if a fair and accurate calculation of such costs can be made. Maintenance costs, if used, should be independently validated.

3. The IFBs must explain how the costs for each of the specified factors will be calculated: (a) The costs associated with a factor can vary substantially depending upon how they are calculated. For this reason, any assumptions that will be used in making the calculations should be included in the bidding document. (b) The period of time over which the life cycle costs will be calculated should also be stated."

Section 910 then states: "The item that meets the bidding specification and has the lowest life cycle cost is the successful bid. Sponsors desiring to use the life-cycle cost concept should be advised to consult with their FAA Airports Office before issuing an IFB to assure that their procurement procedure will meet grant requirements."

Guidance in conducting pavement LCCA is provided in appendix 1 of AC 150/5320-6D. A step-by-step procedure for conducting the LCCA and determining pavement type is given, along with recommendations for using the net present worth (NPW) economic analysis formula, a 4 percent discount rate, and a 20-year analysis period for evaluating airport pavement design or rehabilitation alternatives. NPW (sometimes called net present value, or NPV) is defined as the total present value (PV) of a time series of cash flows. It is a standard method for using the time value of money to appraise long-term projects. Used for capital budgeting and widely throughout economics, it measures the excess or shortfall of cash flows, in present value terms, once financing charges are met. Appendix 1 of AC 150/5320-6D also recommends that salvage values be calculated on the straight-line depreciated value of the alternative at the end of the analysis period (a method commonly referred to as the remaining life method). In concluding the LCCA and type selection process, all alternatives are summarized, ranked, and evaluated by initial cost, life cycle cost, construction time, and probability for success.

The use of LCCA in military airfield projects is somewhat unclear. Chapter 5 of Unified Facilities Criteria (UFC) 3-270-08 discusses a procedure for performing economic analysis of maintenance and rehabilitation (M&R) alternatives, including use of the NPW economic formula, an analysis period of between 10 and 30 years, and a discount rate that is based on

United States Army policies (US Army, 2004). Air Force Instruction (AFI) 32-1023 emphasizes the need to base design decisions for a variety of facilities (buildings, infrastructure, etc.) on life cycle cost considerations (US Air Force, 1994). However, no specific guidance is given for LCCA.

History of LCCA

The concept of LCCA, or benefit-cost analysis (BCA), was introduced in the 1950s as a factor in selecting pavement design alternatives. Since that time, several major initiatives at the national, state, and local levels have advanced the application of LCCA principles to pavement design and pavement type selection. These include the following:

- American Association of State Highway Officials (AASHO) Guide: *Road User Benefit Analyses for Highway Improvements* (1952 and 1960).
- National Cooperative Highway Research Program (NCHRP) Project 1-10: *Systems Approach to Pavement Design* (1974).
- The 1972 American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide recommended the concept of life cycle costing, along with various costs that should be considered in LCCA.
- Intermodal Surface Transportation Efficiency Act (ISTEA) required "the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement" (1991).
- The 1993 AASHTO Pavement Design Guide recommended the concept of life cycle costing along with various costs that should be considered in LCCA.
- The 1993 AASHTO LCCA Survey and Symposium revealed the tremendous variation in how states conduct project-level LCCAs and resulted in a push for national leadership and guidance on improving LCCA application and making the process more consistent (FHWA, 1994).
- Executive Order 12893, Principles for Federal Infrastructure Investments (1994), required that Federal infrastructure spending decisions be based on a systematic analysis of benefits and costs measured and appropriately discounted over the full life cycle of each project (Federal Register, 1994a).

- The Transportation Equity Act for the 21st Century (TEA-21) (Walls et al., 1998) expanded the knowledge of implementing LCCA in transportation as follows: (1) establishing an appropriate analysis period and discount rates, (2) learning how to value and properly consider user costs, (3) determining tradeoffs between reconstruction and rehabilitation, and (4) establishing methodologies for balancing higher initial costs of new technologies and improved or advanced materials against lower maintenance costs.
- Spawned by a 1994 Inspector General's Government Accounting Office (OIG/GAO) Highway Infrastructure Report, the Federal Highway Administration (FHWA) issued an Interim LCCA Policy Statement containing guidance in the form of "good practice" (Federal Register, 1994b) and later a Final LCCA Policy Statement asserting the importance of LCCA in helping make highway investment decisions (Federal Register, 1996).
- As a direct outgrowth of the above, FHWA developed and published its *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998) and initiated Demonstration Project (DP) 115, a technology transfer project involving the development and instruction of a 2-day workshop on LCCA, development of a probabilistic-based LCCA spreadsheet program, and conduct of a case studies forum demonstrating the newly developed program (FHWA, 1998).
- NCHRP Project 1-37A, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures, recommended the procedures contained in the FHWA *Interim Technical Bulletin on LCCA* and developed life cycle costing guidance as part of the Mechanistic-Empirical Pavement Design Guide (MEPDG) (ARA, 2004).
- In 2004 and 2005, FHWA developed RealCost, a formal probabilistic LCCA spreadsheet program, and many state highway agencies (SHAs) have adapted and use this program.

Several definitions have been developed to describe the process of LCCA. Dell'Isola and Kirk (1981) defined LCCA as an economic assessment of an item, area, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars. The 1993 AASHTO Guide expressed LCCA as an economic evaluation of "all costs (and in the complete sense, all benefits) which are involved in the provision of a pavement during its complete life cycle." In TEA-21, LCCA was defined as a process for evaluating the total economic worth of a useable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (Walls and Smith, 1998).

Although several definitions have been developed over the years to describe the process of LCCA, the general consensus is that it is an economic analysis technique that allows comparison of investment alternatives having different cost streams. In the field of pavements, LCCA is a decision tool that aids pavement designers and planners in identifying the most cost-effective pavement strategies.

There are three primary components of pavement LCCA: the LCCA framework, the input parameters, and the execution and outputs. The LCCA framework represents the governing criteria and principles by which the costs of alternative design strategies are compared. It includes the following:

- Analysis period—The time period over which initial and future costs associated with alternative pavement strategies are evaluated.
- Economic analysis technique—The technique used to assess proposed engineering alternatives on the basis of their economic consequences over time. It consists of both the economic formula to be used in equating costs expended at various points in time and the type of dollar values (real or nominal) to be used in the analysis.
- Cost factors—The specific types of costs that will be considered in the LCCA. These costs may consist of direct or agency costs (e.g., construction costs, maintenance and rehabilitation [M&R] costs, salvage value) and indirect or user costs (e.g., travel time delay costs, aircraft/vehicle operating costs).
- Statistical computation approach—A deterministic approach treats all inputs as discrete values, with no tendency for variation. A probabilistic approach treats each input as a range of values to reflect uncertainty and variation.

Input parameters are the mathematical variables that must be quantified for LCCA. These variables fall under the categories of discount rate, pavement structure and/or treatment costs, pavement structure and/or treatment performance, user costs, and salvage value.

Execution and outputs consist of the computation of life cycle costs and the recorded results, available in terms of the raw output data, key summary statistics, or illustrative graphics.

The LCCA process is the sequence of steps taken to complete a LCCA. As presented in the FHWA *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998) and appendix C of the MEPDG (ARA, 2004), it consists of the following eight steps, the first six of which are performed for each alternative strategy:

1. Establish alternative pavement strategies for the analysis period.
2. Determine pavement performance periods and establish M&R activity timing.
3. Estimate agency costs.
4. Estimate user costs.
5. Develop expenditure stream diagrams.
6. Compute NPW.
7. Analyze results.
8. Reevaluate pavement strategies.

A key part of the LCCA process is the determination of the input parameter values, which if not properly estimated, can give biased or erroneous results.

The outputs of an LCCA provide important decision-making information for the pavement designer/analyst. Combined with engineering judgment and other feasibility information, the projected economic implications of alternative design strategies can be used to identify the preferred pavement strategy. Depending on the economic formula chosen and the computational approach used (deterministic versus probabilistic), the output will consist of some form of life cycle costs for the various alternatives, which can be displayed in tabular or graphical format. For probabilistic LCCA, the life cycle cost data from many simulations can be analyzed visually and statistically to aid in the selection process.

Problem Statement

Over the course of the last couple decades, the FHWA and SHAs have made substantial progress in transforming pavement LCCA from an art form to a science. Most agencies have a documented LCCA process and corresponding computer program, and several have followed FHWA's lead in updating their process to reflect the principles and practices contained in the *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998) and updating their program to mimic the features/capabilities of RealCost (FHWA, 2004).

Although much remains to be done in the highways arena to complete the goal of a fully scientific-based LCCA methodology, this community has applied LCCA more consistently, and at a higher level, than the airport pavements community. Current LCCA practices for airport pavement projects consist mainly of in-house tools developed on spreadsheets by a given airport sponsor/design consultant or highway LCCA tools adapted for airfield pavement use.

To help ensure that airport sponsors make the wisest economic decisions regarding the pavements they build and maintain—and thereby make the best use of taxpayer dollars—it is critical that a widely accepted and standardized LCCA procedure be developed, tested, validated, and disseminated. Such a process must clearly identify the key elements and issues to be considered, be applicable to both flexible and rigid airport pavements and non-typical pavements such as composite pavements, and be useable within the realm of the design and contracting scenarios that are typical for airport pavement projects.

Also, to help assure the developed LCCA procedure gets implemented and used on a significant scale, it must be accompanied by detailed guidance and instructional information on all aspects of LCCA, including development of inputs (e.g., estimates of pavement performance and costs, selected discount rate), defining of LCCA parameters for a fair and proper assessment of costs, and assessment or interpretation of results. It also must be incorporated into an easy-to-use, spreadsheet-based computer program.

Project Objectives and Scope

The objective of this study was to provide a comprehensive document that describes LCCA for airport pavements and develop a companion software package for conducting LCCA. The guidance is applicable to both flexible and rigid airport pavements and addresses all aspects of LCCA. Specific items addressed in this study include:

- Construction, maintenance, and rehabilitation activities to be used in airport pavement LCCA procedures.
- Typical costs and sources of data for costs of all elements used in the LCCA.
- Use of airport pavement management data and systems in the LCCA.
- LCCA methodology, as defined by cost factors, economic analysis techniques, discount rate, analysis period, delay costs, risk analysis techniques, and processes for fairly comparing service lives of different pavements/strategies.
- Case studies and examples to demonstrate a variety of scenarios using airport pavement LCCA.

This research project consisted of nine tasks intended to:

- Identify and provide guidance on the most appropriate procedures for (a) developing LCCA inputs and (b) computing and evaluating life cycle costs of alternative designs/strategies for airport pavements.
- Develop a probabilistic LCCA spreadsheet program and accompanying user manual for use by airport sponsors/consultants engaged in pavement design/strategy selection issues.
- Develop training materials and case study/example applications that fully demonstrate the principles and practices of the recommended LCCA methodology.

Overview of Report

This report is presented in five chapters. Chapter 1 is, of course, this introduction. Chapter 2 presents the state of the technology in pavement LCCA in terms of the underlying principles and procedures and the computer programs commonly used in both airport and highway applications.

It also discusses the process of pavement alternate bidding and its application in airport and highway pavement projects. Chapter 3 contains detailed guidance for conducting LCCA for airport pavement projects. It presents the guidance in the form of a 10-step process that begins with defining the project scope and ends with interpreting the LCCA results and determining the need to refine the LCCA. Chapter 4 provides an overview of the development of a spreadsheet-based LCCA program for use by airports/consultants. Chapter 5 provides a summary of the research and a list of recommendations for further research and development of airport LCCA procedures and programs.

Appendix A presents some of the LCCA spreadsheets currently used by airport sponsors/consultants. Appendix B discusses and illustrates some of the more advanced software programs available for conducting highway pavement LCCA. Appendix C provides the help menu or user guidance for application of the developed LCCA software, AirCost.

CHAPTER 2. STATE OF THE TECHNOLOGY IN PAVEMENT LCCA

To assess the state of the technology in pavement LCCA, a comprehensive search/review of literature on the subject was performed, followed by a limited LCCA interview with airport sponsor/consultant representatives. As part of both efforts, a variety of pavement LCCA software programs were obtained and evaluated to (a) further understand the applications of LCCA and (b) formulate a vision for a new LCCA software program for airport pavements.

While the focus of both activities was on applications of LCCA in the airport pavements arena, the limited amount of information and software available in this area necessitated broadening the focus to LCCA for highway pavements and other similar fields. Also, with the impetus in recent years toward innovative contracting techniques, the subject of pavement alternate bidding as related to the LCCA process was investigated.

Table 1 provides a summary of the various LCCA documents and software programs collected and reviewed as part of the literature search/review. Table 2 presents the materials on alternate bidding that were gathered and examined.

In the airport sponsor/consultant interviews, a short survey was emailed to selected individuals known or believed to be in the capacity of performing airport LCCAs. Substantive feedback was obtained from five sponsors/consultants, with each submitting sample spreadsheets (and/or reports) used in conducting LCCA for a given pavement project. Airports represented and the responding entities included:

- Pensacola Regional, Reynolds, Smith, and Hills.
- Tulsa International, Applied Research Associates, Inc.
- George Bush Intercontinental, Post, Buckley, Shuh, and Jernigan.
- John F. Kennedy International (JFK), Port Authority of New York & New Jersey.
- Jefferson County (Broomfield Colorado), CH2M Hill.

Table 1. Summary of LCCA guide/report documents and software programs reviewed.

Source	Guide/Report Title	Software Program
FAA	Federal Aviation Administration Order 5100.38C, Chapter 9, Section 910 (2005)	
	AC 150/5320-6E, Airport Pavement Design and Evaluation, Appendix 1 Economic Analysis (2009)	
	Design Guide Supplement Portland Cement Concrete Airport Pavements (2003)	
FHWA	Life Cycle Cost Analysis in Pavement Design, Interim Technical Bulletin (1998)	RealCost v. 2.1 and v. 2.2 (2004/2005)
	RealCost User Manual (2004)	
	Life Cycle Cost Analysis Primer (2002)	
AASHTO/NCHRP	Mechanistic-Empirical Pavement Design of New and Rehabilitated Pavement Structures, Appendix C-Life Cycle Cost Analysis Guidelines (2004)	LCCA2002 (adaptation of RealCost)
National Institute of Standards and Technology (NIST)	Life-Cycle Costing Manual, Handbook 135 (1996)	
American Concrete Pavement Association (ACPA)	Life-Cycle Cost Analysis: A Guide for Comparing Alternate Pavement Designs (2002)	
Asphalt Pavement Alliance (APA)	Pavement Life-Cycle Cost Studies Using Actual Cost Data: A Synthesis (2005)	Life Cycle Cost Analysis Program v. 3.1 (2005)
	Pavement Type Selection Processes: A Position Paper (2004)	
Asphalt Institute (AI)	State of the Practice: Pavement Type Selection (2004)	LCCOST (not for comparing alternate designs, more for pavement management applications)
National Lime Association (NLA)	Life Cycle Costs for Lime in Hot Mix Asphalt: Volume I-Summary Report (2003)	Life-Cycle Cost Analysis, v. 1.3.0 (2002) (adaptation of RealCost)
	Life Cycle Costs for Lime in Hot Mix Asphalt: Volume II-Appendices (2003)	
	Life Cycle Costs for Lime in Hot Mix Asphalt: Volume III-LCCA Software User's Guide (2003)	
California Department of Trasportation (Caltrans)	Interim Life-Cycle Cost Analysis Procedures Manual (2007)	Caltrans RealCost v. 2.2 (adaptation of RealCost)
Colorado Department of Transportation (DOT)	Life-Cycle Cost Analysis and Discount Rate on Pavements for the Colorado DOT (2006)	
Indiana DOT	Life-Cycle Cost Analysis for INDOT Pavement Design Procedures (2005)	Indiana DOT RealCost v. 1.0 (standalone enhancement of

		RealCost)
Kansas DOT	Determination of the Appropriate Use of Pavement Surface History in the KDOT LCCA Process (ARA, 2007)	Spreadsheet-based LCCA (deterministic)
Kentucky Transportation Cabinet (KTC)	KTC Pavement Type Selection Policy (2006)	
Missouri DOT	Pavement Design and Type Selection Process (2004)	
Minnesota DOT	Pavement Type Determination Task Force Final Report (2003)	Minnesota DOT RealCost v. 1.0 (adaptation of RealCost)

Table 2. Summary of pavement alternate bidding documents reviewed.

Source	Guide/Report Title
FHWA	Federal Aid Policy Guide, Transmittal 25 23 CFR 500B (1999)
	Special Experimental Project No. 14—Innovative Contracting (1990)
Louisiana Department of Transportation and Development (DOTD)	Agency Process for Alternate Design and Alternate Bid of Pavements (Temple et al., 2004)
Missouri DOT	Pavement Design and Type Selection Process (2004)
	Alternate Pavement Update (2008)
KTC	Appendix E of Pavement Type Selection Policy (2006)

LCCA Procedures

Airport Sponsor/Consultant Procedures

The search for literature pertaining specifically to airport LCCA was not very productive. Besides FAA Order 5100 and ACe 150/5320-6D, the most noteworthy documentation consisted of the following:

- FAA Northwest Mountain Region's *Design Guide Supplement: PCC Airport Pavements* (Scott, 2003)—Although primarily focused on portland cement concrete (PCC) thickness, drainage, and joint design issues, this document emphasized the need for LCCA in the pavement design process and recommended that cost components include:

- Initial costs.
- Future maintenance, repair, and rehabilitation costs.
- User expenses from the loss of usage.
- User costs incurred by both the airport and the airport users (e.g., airlines, fixed-base operators [FBOs]) through traffic delays, re-routings, etc.

The document pointed out that, although pavement structural life is anticipated to be 20 years based on the FAA design tables, pavement lives vary with climate, soils, and other specific conditions (e.g., fuel spillage); thus, LCCA should use a pavement life that is based on past experience (possibly extending up to 30 to 40 years).

- FAA-sponsored study, *Operational Life of Airport Pavements* (Garg, Guo, and McQueen, 2004)—In determining whether the FAA thickness design standards for flexible and rigid pavements are consistent with the FAA's standard for a 20-year pavement design life requirement, this study established methods for determining the structural condition index (SCI) of flexible and rigid pavements based on the distress types, extents, and severities used in computing the pavement condition index (PCI). Historical PCI condition survey data were gathered and analyzed to show that flexible and rigid runway, taxiway, and apron pavements all project to have SCI values at or above 80 after 20 years.
- Full-Cost Approach to Airport Pavement Management (McNerney and Harrison, 1995)—As part of an overall discussion of the need for enhanced airport pavement management systems, the case is made in this document for LCCA procedures that take into account both traditional airport owner costs and the costs associated with user delays and environmental impacts. Specific user delay costs suggested include those associated with aircraft operations, such as air delay and additional aircraft vehicle operating costs (VOCs) (e.g., fuel), and those associated with passenger time (with passengers broken down into an appropriate business/social mix and hourly rates assigned to each traveler type). Specific environmental costs suggested include the noise associated with taxiing and waiting and air quality pollution stemming from increased holding patterns around airports with restricted runway availability. The effect of runway roughness accelerations on aircraft fatigue also is discussed.

With regard to the procedures identified in the airport sponsor/consultant interviews, the methodology recommended in appendix 1 of FAA AC 150/5320-6D generally was followed. All used NPW as the economic technique, and about half utilized the recommended analysis period of 20 years. The remainder used analysis periods of 30 or 40 years. Discount rates ranged from 3.5 to 5 percent.

FHWA and Other Highway Agency Procedures

Based on an extensive evaluation of LCCA practices, the FHWA developed and published an *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998). This document presented best practices for establishing the various LCCA inputs and introduced the concept of risk analysis (i.e., probabilistic analysis) and gave detailed guidance in determining user costs associated with work zones.

FHWA DP 115 involved the development and conduct of a 2-day LCCA workshop designed to reinforce the principles and practices contained in the Interim Technical Bulletin. The workshop, which has been held for many SHAs since the late 1990s, also included demonstration of the DP 115 probabilistic spreadsheet program (a precursor to the current RealCost program) and a case studies forum demonstrating LCCA for actual pavement projects using both existing deterministic procedures and probabilistic procedures.

Although the concepts and principles of LCCA are fairly uniform, the application of LCCA in design varies considerably among highway agencies. Differences in agency philosophies, policies, and preferences typically result in different cost factors being included or excluded, different methods being used to determine input values, and different analysis periods being used. The fact that different computer programs are used to compute life cycle costs, and that LCCA results are interpreted in different ways, also adds to the variation.

Despite the current variation in practice, much greater consistency has been achieved in recent years, due in large part to the FHWA's LCCA development and implementation efforts. Since the mid-1990s, the FHWA has worked closely with states and industry alike to better define the

LCCA process and to build greater consensus within the pavement community as to how LCCA should be performed at the project level. The LCCA principles and process outlined in the FHWA *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998) and promoted under the DP 115 project were recognized under NCHRP Project 1-37A as representing the state of the technology at the design level, and thus were adopted for use with the MEPDG methodology (ARA, 2004). While a detailed discussion of the technical guidance contained in the FHWA Interim Technical Bulletin and the MEPDG could be provided here, it is sufficient to recognize these documents as the standard-bearers for LCCA in highway pavement applications and note that the basic components (framework, input parameters, execution and outputs) are largely applicable to airport LCCA.

As part of the FHWA's seminal work on LCCA, a survey of 52 SHAs was conducted in which it nearly two-thirds reported using formal LCCA procedures for determining the type of pavement to use in a new construction or reconstruction project (FHWA, 1998b). Most of the remaining one-third reported using informal procedures or had plans to develop a set of procedures in the near future. Since that survey in 1997, many agencies have evaluated and upgraded their LCCA processes and programs to ensure more fairness in the approach, instill greater confidence in the results, and provide better clarity in interpreting the results. Major LCCA studies have been performed in states like Ohio, Pennsylvania, Missouri, Kansas, Colorado, South Dakota, and Wisconsin, as well as in Canadian provinces like Ontario and Quebec (ARA, 2004).

For most highway agencies, LCCA is a major component of the pavement type selection process. LCCA may be coupled with the subjective consideration of other factors, such as scope of project, adjoining pavement, constructability, designer and contractor experience, traffic control, and availability of materials, to make the final determination. A number of states, including Ohio, Kentucky, Louisiana, Michigan, Maryland, and Missouri, have reported using alternate bidding procedures to select pavement type under the FHWA's Special Experimental Projects (SEP) No. 14 – Alternate Contracting.

A summary of LCCA policies and practices is provided in the paragraphs below and in table 3. The information is derived from a 2003 pavement type selection study performed for Ohio DOT

(ARA, 2003), and from update information included in a recent LCCA study performed for Ministry of Transportation of Quebec (MTQ) (ARA, 2008).

LCCA Procedure: All highway agencies use an LCCA procedure that consists of the sum of initial construction costs and discounted future costs. Most highway agencies use the NPW method to calculate life cycle costs, although the equivalent uniform annual cost (EUAC) method also is used.

Analysis Period: Analysis period ranges from 35 to 60 years, with most agencies using 40 years.

Discount Rate: Discount rates range from 3 to 6 percent, with most using 4 or 5 percent. The FHWA recommends discount rates of 2 to 4 percent. One-fourth of the agencies use the annual rate posted in the US Office of Management and Budget (OMB) Circular A-94. Currently, that rate is about 3 percent, based on the 30-year Treasury rate.

Sensitivity Analysis: Sensitivity analysis of the discount rate is performed by five highway agencies.

Initial Costs: Five agencies have centrally developed cost data for LCCA. The other agencies have project-specific costs or are centrally developed with discretionary adjustments for the LCCA. While there is a similarity in the general practice, several agencies have addressed life cycle cost issues more rigorously. For example, Wisconsin, Michigan, and Ontario complete a statistical analysis of their unit cost data. If sufficient cost data are not available in a specific project area, the data included in the analysis are expanded until sufficient information is available to develop a confident estimate of the costs. In Minnesota, cost estimates are based on site-specific factors such as materials costs.

LCCA Quantity Adjustment: No agencies reviewed develop or use any adjustment factors to account for the difference between estimated and as-built quantities.

Routine Maintenance: Only three agencies include the cost of annual routine maintenance in the LCCA.

Scheduled Maintenance: Nine agencies include the cost of regularly scheduled maintenance, such as crack sealing, joint resealing, and seal coats.

Table 3. Summary of selected highway agency LCCA practices.

Practices	**IL**	**IN**	**MD**	**MI**	**MN**	**NY**	**ON**	**OH**	**PA**	**WA**	**WI**	**QEB**
Use LCCA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes[2]	Yes	Yes	Yes	Yes
Analysis period (years)	40	40	40	var.[1]	35	50[2]	50[2]	35	40	60	50	50[3]
Discount rate (%)	3	4	4	OMB[4]	4.5[5]	OMB[4]	5[6]	OMB[4]	6	4	5[7]	5
Sensitivity analysis	No	0-10%	3-5%	No	No	No	±2%	No	No	2-5%[8]	No	±0.5
Initial cost												
Centrally developed	Yes	No	Yes	Yes[9]	No	No	No	Yes	No	No	No	Yes
Project-discretionary	No	Yes	No	No	Yes[10]	Yes	Yes	No	Yes	Yes	Yes	No
Adjust LCCA for as-built quantities	No	No	No	No	No	No	No	No	No	No	No	No
Routine maintenance ($/lane-km)	Yes[11]	No	No	No	No	No	No	No	Yes	No	No	Yes[11]
Scheduled maintenance	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes
How estimated	Com[12]	MM[13]	n/a	Hist[14]	Com[12]	Est[15]	Est[15]	n/a	MM[13]	n/a	MM[13]	Hist[14]
Rehabilitation cost	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
How estimated	Est[15]	PM[16]	PM[16]	PM[16]	Est[15]	Est[15]	Est[15]	Est[15]	PM[16]	PM[16]	PM[16]	Est[15]
Hot mix asphalt (HMA)												
1st rehab (years)	var.[17]	Proj[18]	Proj[18]	10[19]	15	15	19	12	10	15	18	12
2nd rehab (years)	var.[17]	Proj[18]	Proj[18]	13[19]	27	27	31	22	20	30	Proj[18]	23
PCC												
1st rehab (years)	20	Proj[18]	Proj[18]	9[19]	17	15	18	22	20	20	25	19
2nd rehab (years)	none	Proj[18]	Proj[18]	15[19]	27	30	28	32	30	40	Proj[18]	29

Salvage value (method)	No	Yes (RL[20])	Yes (RL[20])	No	No	Yes (RL[20])	Yes (RL[20])	No	No	Yes (RL[20])	Yes (RL[20])	Yes (RL[20])
Const. traffic control												
Initial	No	No	Yes	No	Yes	No	No	No	No	Yes	No	No
Rehabilitation	No	No	No	Yes	No	No	No	Yes	Yes	Yes	No	Yes
Engineering and admin.												
Initial	No	No	No	No	No	No	No	No	No	Yes	No	No
Rehabilitation	No	No	No	Yes	No	27%	No	Yes	Yes	Yes	No	Yes
User delay	No	No	Yes	Yes	Fut[21]	Fut[21]	Fut[21]	Fut[21]	Yes	Yes	No	Fut[22]
Spread of LCCA considered equal	10%	10%	10%	0%	0%	0%	0%	15%	10%	15%	5%	N/A

Notes:

1. 50 years typically used, recommendation for at least 40 years.
2. Consider and weigh initial cost and future cost separately.
3. Analysis period varies to match pavement service life.
4. OMB Circular A-94.
5. Use OMB Circular A94.
6. Ministry of Finance social discount rate.
7. Set by long standing policy.
8. Use a probabilistic analysis.
9. Regionally adjusted.
10. Not unit cost-based. Based on materials/construction costs at specific site.
11. Includes lane marking, for Québec may also include winter salt usage.
12. Developed by committee.
13. Maintenance management system.
14. Past history.
15. Best estimate.
16. Pavement management system.
17. Four categories, based on traffic.
18. Project specific.
19. Strategies reflect overall maintenance approach used network wide for a specific fix, based on historical maintenance and pavement management records.
20. Remaining life.
21. Plan to incorporate user delay costs into the LCCA in the near future.
22. Consider user delay days in type selection process.

Rehabilitation: All agencies include the cost of rehabilitation activities, such as overlays and concrete pavement restoration.

Time for First Rehabilitation: The year of the first rehabilitation for flexible pavements varies considerably, from 10 to 19 years, with a median of 15 years. The year of the first rehabilitation for rigid pavements is highly variable, ranging from 9 to 25 years, with a median value of about 18 years.

Second Rehabilitation: The year of the second rehabilitation for flexible pavements varies considerably, from 13 to 30 years, with a median of 27 years. The year of the second rehabilitation for rigid pavements is highly variable, ranging from 15 to 40 years, with a median value of about 30 years.

Method for Rehab Schedule: Six agencies use pavement management data as the basis for the rehabilitation schedule used in the LCCA and four agencies use engineering estimates.

Salvage Value: Seven highway agencies consider salvage value in the LCCA. Each uses the remaining life method; none use the residual/recyclable value method. Michigan's analysis period equals their service life.

Traffic Control Costs: Only three of the highway agencies include the cost of initial construction traffic control costs in their analysis. Three of the highway agencies consider cost of future rehabilitation construction traffic control costs in their analysis.

Engineering and Admin: Only one agency includes the cost of engineering and administration costs in its initial construction cost estimate for LCCA. Four agencies account for the costs of engineering and administration in their cost estimate for future rehabilitation activities.

User Delay: Four highway agencies consider user delay in their LCCA, and five others are considering including user delay in the future.

LCCA Spread Equivalency: Four highway agencies consider life cycle costs within ±10 percent to be statistically equivalent, thereby enabling other factors or agency preference to factor into the selection. One agency uses 15 percent and another uses 5 percent. Four highway agencies use 0 percent.

At least three national surveys on LCCA practices have been conducted in the last 3 years. A South Carolina DOT survey in 2005 (SCDOT, 2005) generated responses from 33 SHAs and two Canadian provincial highway agencies. A 2007 AASHTO Research Advisory Committee (RAC) member survey yielded responses from 18 states and 3 provinces (Mississippi DOT, 2007). And a 2008 NCHRP survey on pavement type selection and LCCA (NCHRP Project 10-75) (Hallin and Smith, 2008) produced responses from 32 SHAs to date. Table 4 summarizes some of the key findings from these surveys.

Table 4. Summary of highway agency LCCA practices based on recent national surveys.

Item	2005 SCDOT Survey	2007 MSDOT Survey	2008 NCHRP Survey
Use of LCCA as part of pavement type selection process	Yes—32/35[a] (91%)	Yes—17/21[a] (81%)	Yes (new/reconstruction)—27/33[a] (82%) Yes (rehabilitation)—11/33[a] (37%)
Economic formula used in LCCA			NPW—22/27[a] (81%) EUAC—9/27[a] (33%)
Analysis period used for new/reconstruction projects	Range = 20 to 60 years (70% of respondents specify 30 to 50 years)	Range = 28 to 50 years (40 or 50 years typical)	Mean = 38.5 years Std Dev = 9.7 years Range = 20 to 60 years (based on 26 responses)
Analysis period used for rehabilitation projects			Mean = 28.5 years Std Dev = 10.0 years Range = 10 to 45 years (based on 11 responses)
Discount rate used	SHA Range = 3 to 5% OMB-recommended rate used by 2 agencies	SHA Range = 3 to 4.5% OMB-recommended rate used by some agencies	Mean = 3.74% Std Dev = 0.72% Range = 2.8 to 6.0% (based on 26 responses) (8/25 use OMB Circular A-94)
Inclusion of user costs	Yes—13/32[a] (41%)	Yes—5/21[a] (24%) (2 agencies working on implementing user costs in the process)	Yes—12/30[a] (40%)
Use of salvage value	Yes—19/32[a] (59%)		Yes—13/26[a] (50%) (10 agencies use prorated life method, 5 use residual/recyclable value)
Basis for establishing the type and frequency of M&R treatments		History only—8/17[a] (47%) History & Theory—5/17[a] (29%) Theory only—3/17[a] (18%) History & Eng Judgment—1/17[a] (6%)	Historical Data Analysis—19/30[a] Design Analysis (theory)—7/30[a] Expert Analysis—2/30[a]
LCCA software used	RealCost—5/15[a] (33%) DARWin—1/15[a] (7%)		RealCost (or modified)—11/30[a] Proprietary—2/30[a] AASHTO DARWin—

	In-house Spreadsheet—4/15[a] (27%)		4/30[a] In-house Spreadsheet—17/30[a]
Statistical computation approach			Deterministic—21/24[a] Probabilistic—5/24[a]
LCCA utilized in developing pavement alternate bidding procedures		Yes—2/21[a] (10%)	Yes (on fairly routine basis)—3/30[a] (10%)
Age at which total reconstruction of flexible pavements is assumed to occur			Mean = 40.0 years Std Dev = 9.0 years Range = 20 to 50 years (based on 18 responses) (2 agencies report never/not anticipated)
Age at which total reconstruction of rigid pavements is assumed to occur			Mean = 40.8 years Std Dev = 8.9 years Range = 26 to 50 years (based on 20 responses) (1 agency reports never/not anticipated)

[a] Number of affirmative responses out of total number of responses.

Pavement Alternate Bidding Procedures

Pavement alternate bidding is a process by which transportation agencies let bids on pavement projects with the option for contractors to propose either asphalt or concrete as the material to be used (CTC & Associates, 2006). Alternate bidding puts the burden of choice on potential contractors rather than the transportation agency. Provided below is a summary of some of the alternate bidding practices identified in this study.

Airport Sponsor/Consultant Procedures

Although no applications of pavement alternate bidding on airport projects were identified in the literature search/review, one such project was unearthed in the airport sponsor/consultant interviews. This project was the 2005 Runway 17-35 reconstruction project at Pensacola Regional Airport. Details of this application are provided in the next section.

FHWA and Other Highway Agency Procedures

Historically, the FHWA discouraged the use of contractor selection of pavement type through an alternate bidding process. The Federal-Aid Policy Guide, Transmittal 25 23 CFR 500B, dated April 8, 1999, contains the following non-regulatory guidance:

> 1) The FHWA does not encourage the use of alternate bids to determine the mainline pavement type, primarily due to the difficulties in developing truly equivalent pavement designs.
> 2) In those rare instances where the use of alternate bids is considered, the SHA's engineering and economic analysis of the pavement type selection process should clearly demonstrate that there is no clear cut choice between two or more alternatives having equivalent designs. Equivalent design implies that each alternative will be designed to perform equally over the same performance period and have similar life-cycle costs.

However, since 1990, the FHWA has allowed highway agencies to evaluate non-traditional contracting techniques under SEP No. 14 – Innovative Contracting. At least six states (Ohio, Kentucky, Louisiana, Michigan, Maryland, and Missouri) have used alternate bidding procedures under SEP-14 to select pavement type. The province of Ontario has awarded 6 projects using the alternate bidding process.

Typically, highway alternate bidding projects use an A+C approach to evaluating the contractor's bid, where A is the contractor's bid for the initial construction of the pavement and C is the life cycle cost of a pavement excluding initial cost. The C cost typically is computed by the agency and included in the bidding documents. There are variations of this process that include B and D bid items reflecting construction time costs and pavement warranty costs, respectively.

The FHWA recently provided policy clarification through a memorandum on the use of pavement alternate bidding procedures on National Highway System (NHS) projects (Stephanos, 2008). The policy indicates that consideration should be given to various factors prior to and after deciding to use alternate bidding procedures. The factors to be considered prior to determining to use alternate bidding procedures include:

- Equivalent designs—Alternatives should perform equally, provide the same level of service over the same performance period, and have similar life cycle costs (i.e., NPW of higher cost alternative is within 10 percent of NPW of lowest cost alternative). Engineering judgment is required in determining what is and what is not "equivalent design."
- Realistic discount rate—The selected discount rate should be consistent with OMB Circular A-94. A discount rate in the range of 2 to 4 percent is reasonable based on recent trends.
- Consideration of uncertainty—The impact of uncertainty in factors such as performance life, material costs, and construction duration, should be considered using sensitivity analysis or probabilistic LCCA.
- Realistic rehabilitation strategy—The rehabilitation strategy established for each alternative design should accurately reflect current or anticipated agency pavement management practices.
- Subjective considerations—Despite the outcome of objective engineering and economic analysis, agencies should consider non-economic factors, such as constructability, type of adjacent pavements, recycling, and conservation of materials.
- Appropriate application—Alternate bidding should only be used where pavement items impacted by the alternate bid are likely to influence the final determination of the lowest responsive bidder. Projects with substantial bridge or earthwork items or with potentially substantial differences in equipment mobilization costs are not suited for alternate bidding.

The factors to be considered once a decision has been made to bid alternate pavement types include:

- Commodity price adjustments—Price adjustment clauses should not be used when using alternate bidding procedures, due to the difficulty in administering equal treatment of the factors to the alternate materials.
- Incentive/disincentive (I/D) provisions for quality—I/D provisions should provide comparable opportunity for each alternate.
- Specifications of material quantities—Agencies should consider approaches that balance materials quantity risk between the alternate pavement types.
- SEP-14 approval needed if using adjustment factors—If life cycle cost adjustment factors are to be used, approval under SEP-14 is required. Moreover, it is recommended that the appropriate stakeholders be provided an opportunity to provide input into development of the adjustment factors.
- Approval requirements—FHWA division administrator shall review the analysis and concur in the finding of equivalency, when bidding alternate pavement types, and no adjustment factors are used.

In short, the clarified FHWA policy instructs highway agencies interested in using alternate bidding procedures to perform a complete LCCA (i.e., initial and future costs) to confirm that the alternative designs are "equivalent" and are acceptable for alternate bidding. Consideration of non-cost factors and the composition of pay items to be included in the bid is suggested in helping determine the acceptability of alternate bidding techniques. After the decision has been made to use alternate bidding, life cycle cost adjustment factors may be developed but are subject to approval under SEP-14.

Louisiana DOTD

In 1998, the Louisiana DOTD developed an alternate design/alternate bid (AD/AB) procedure that uses LCCA to estimate the long-term costs of asphalt and concrete pavements (Temple, et al., 2004). The procedure enables pavement type selection through the bid process, which purportedly enhances fair competition among paving industries and promotes a more cost-effective use of highway construction funds. The AD/AB bid model uses an A+B+C approach, where A is the contractor's bid for the initial construction of the pavement, B is the construction time-based bid component, and C is the life cycle cost adjustment factor assigned to each pavement design alternate by the DOTD. The bidder with the lowest total A+B+C is selected.

The C component in the model represents the total future rehabilitation and user delay cost expected for a particular project. It is computed following the FHWA LCCA methodology (Walls and Smith, 1998), with deterministic NPW based on a 40-year analysis period for new construction (30 years for overlays), a 4 percent discount rate, historical-based and new technology-adjusted (e.g., Superpave, polymer-modified asphalt, material transfer devices for asphalt pavements; larger-diameter coated dowel bars, reduced joint spacing, and widened lanes for concrete pavements) rehabilitation schedules, and inclusion of work zone user costs only. Only differential costs are considered between alternates (i.e., common costs, such as mobilization, signing, and utilities are not included) and the total structure thickness for each alternate is held constant to avoid differential earthwork quantities. Salvage value is avoided by adjusting the design life of overlays to match the remaining time for the analysis period and residual value of materials is not considered.

In determining pavement design alternates to be put to bid, Louisiana uses a 20 percent threshold evaluation criterion. If the difference in total NPW (initial plus discounted future costs) of competing pavement types is larger than 20 percent, the alternate with the lower total NPW is selected for bidding. Otherwise, alternate pavement designs are included in the plans, with life cycle cost adjustment factors assigned to each alternate. An example of the bid form provided to contractors is shown in figure 1. The AD/AB process has been implemented on several projects to date.

Contractor's Informational Bid
It is agreed that the total bid(s) shown below, determined by the bidder, are for informational purposes and that the low bidder for this project will be determined in accordance with the special provision entitled "Cost-Plus-Time-Plus Life Cycle Cost Bidding Procedure (A+B+C Method), as determined by the Department.
A_1=Summation of products of quantities shown in Schedule of Items (Base Bid plus PCC Pavement, Alternate A1) multiplied by unit prices.
A_1=______________________________
B_1=Bidders proposed contract time for Base Bid and Alternate A1 items multiplied by the Daily User Cost ($1,000)
B_1=______________________________ Working Days × $1,000
B_1=______________________________
C_1=Life Cycle Cost Adjustment Factor for PCC Pavement, determined by the Department
C_1=$728,100
Contractor's Total Bid (A_1+B_1+C_1)=_______________

OR

A_2=Summation of products of quantities shown in Schedule of Items (Base Bid plus Superpave AC Pavement, Alternate A2) multiplied by unit prices.
A_2=______________________________
B_2=Bidders proposed contract time for Base Bid and Alternate A2 items multiplied by the Daily User Cost ($1,000)
B_2=______________________________ Working Days × $1,000
B_2=______________________________
C_2=Life Cycle Cost Adjustment Factor for Superpave AC Pavement, determined by the Department
C_2=$2,108,000
Contractor's Total Bid (A_2+B_2+C_2)=___

Figure 1. Example of Louisiana DOTD A+B+C bid form.

Missouri DOT

In 2004, as the first of a two-phased, integrated effort between Missouri DOT and industry stakeholders, a consensus set of LCCA procedures was sought that would provide a fair and accurate assessment of life cycle costs for the agency's pavement type selection process (Missouri DOT, 2004). Although an in-house cost-estimating spreadsheet ("Estimating 2000") was determined to be adequate for use in life cycle costing, agreement on design life assumptions for different rehabilitation treatments could not be reached. As a result, Missouri instituted a policy to reinstate alternate pavement design bidding.

Under this process, LCCAs are performed primarily to determine adjustment factors for use in new full-depth pavement projects over 2 lane-miles in length (Missouri DOT, 2004). The adjustment factors represent the C component of an A+C bid model, with the C values for each pavement alternate assigned by the DOT (typically, C for the alternate with the lower life cycle cost is assigned a value of zero and the alternate with the higher life cycle cost is assigned a C value reflecting the difference in life cycle costs). Key aspects of the LCCA include:

- Discount rate based on OMB rates (currently 3.2% for 30-year forecast).
- Maintenance costs, salvage values, and user costs not included.
- Incidental construction, engineering, and mobilization costs included as various percentages of construction cost.

Phase II of Missouri's pavement design and type selection process study was to seek enhancements/improvements in the alternative bidding process, such as inclusion of salvage and residual values, incorporation of maintenance costs, and consideration of certain user costs. It also was to assess the appropriateness of extending the process to rehabilitation projects and including friction and noise performance impacts. Through 2007, a total of 95 alternate bid projects have been let in Missouri (Missouri DOT, 2008). Of the 89 full-depth pavement projects, 37 were awarded to asphalt bids and 52 to concrete bids. Of the 6 rehabilitated pavement projects, 1 was awarded to an asphalt bid and 5 to concrete bids.

Other Agencies

Kentucky allows for use of alternate bidding on selected projects. Typically, A+C bidding models are followed, but if alternate bidding is used and the user costs during initial construction are calculated to be greater than $2,000,000 for either alternate, the time component B may be added for bidding purposes (KTC, 2006).

Summary of Experiences with Alternate Bidding

Noted advantages of alternative bidding include the following:

- Inclusion/involvement of paving industries in process development has increased chances of developing a consensus process that all stakeholders perceive as fair and reasonable.
- Increased competition and lower bid prices because of increased competition.
- Reflect truer material and construction costs than conventional pavement type selection procedures which occur as much as 3 to 5 years prior to project letting.

Noted disadvantages of alternative bidding include the following:

- Disagreement among paving industries regarding pavement life and rehabilitation performance estimates, and rehabilitation type/extent assumptions.
- Extra work to design plans and compute bid quantities for pavement design alternates.
- Short time allotted for designers to add the alternate designs to project bid documents.
- Not applicable to all situations/projects.
- Inability to model surface characteristics (smoothness, noise, friction) as part of the LCCA and thus quantify benefits associated with one design over another.

LCCA Software Programs

Airport Sponsor/Consultant Programs

No formal programs specifically developed for airport project-level LCCA were identified in the literature search/review. However, as noted earlier, participants in the airport sponsor/consultant interviews provided some sample LCCA spreadsheets for examination in this study. Summary descriptions and illustrations of these spreadsheets are provided in appendix A. Although some differences existed in the manner in which the LCCAs were carried out, the basic structure and format of the spreadsheets were the same. Figure 2 shows the typical layout, representative of one design alternative for a particular airport pavement improvement project.

FHWA and Other Highway Agency Programs

On the highways side, various project-level LCCA programs have been developed and used over the years, most of which have consisted of in-house customized spreadsheets. In 1993, AASHTO developed the DARWin pavement design software program, which included a project-level LCCA module. Some states began utilizing the program in the years following its release, but in recent years its usage has decreased, primarily as a result of the development of the FHWA RealCost program.

Construct Unbonded PCC Overlay of R/W 18L-36R

Section:	10" PCC	Shoulder area (2 @ 25 ft) ft^2	500,000
Pavement area (8 lanes @ 25 ft/ln) ft^2	2,000,000	Analysis period, years	20
Longitudinal joints, ft	110,000	Initial year of construction	2004
Transverse joints, ft	100,000	Discount rate, %	3.00
Length of runway, ft	10,000		

CONSTRUCTION ITEMS	YEAR	QUANTITY	UNIT	UNIT PRICE	COST	PRESENT WORTH
INITIAL CONSTRUCTION						
Apply Tack Coat on Runway	0	33,333	gal	$1.00	$33,333	$33,333
Place 2" AC Bond Breaker on Runway (145lb/ft3)	0	24,167	ton	$40.00	$966,667	$966,667
Place 10" PCC Unbonded Overlay	0	222,222	yd^2	$32.00	$7,111,111	$7,111,111
Apply Tack Coat on Shoulders	0	8,333	gal	$1.00	$8,333	$8,333
Place 9" AC Binder on Shoulders (145lb/ft3)	0	27,188	ton	$40.00	$1,087,500	$1,087,500
Apply Tack Coat on Shoulders	0	8,333	gal	$1.00	$8,333	$8,333
Place 3" AC Surface on Shoulders (145lb/ft3)	0	9,063	ton	$40.00	$362,500	$362,500
Construct Transitions at Intersections	0	1	ea	$700,000.00	$700,000	$700,000
Restripe Runway	0	1	ea	$35,000.00	$35,000	$35,000
Electrical	0	1	LS	$937,595.00	$937,595	$937,595
Design Costs at 8%	0		Subtotal	$10,312,778	$825,022	$825,022
Inspection Services at 9%	0		Subtotal	$10,312,778	$928,150	$928,150
FUTURE MAINTENANCE & REHABILITATION						
Rout & Seal Joints	6	110,000	ft	$1.95	$214,500	$179,640
Apply Seal Coat to Shoulder Surfaces	6	8,333	gal	$1.50	$12,500	$10,469
Restripe Runway	6	1	ea		$0	$0
Rout & Seal Joints	12	110,000	ft	$1.95	$214,500	$150,446
Apply Seal Coat to Shoulder Surfaces	12	8,333	gal	$1.50	$12,500	$8,767
Restripe Runway	12	1	ea	$35,000.00	$35,000	$24,548
Rout & Seal Joints	18	110,000	ft	$1.95	$214,500	$125,996
Apply Seal Coat to Shoulder Surfaces	18	8,333	gal	$1.50	$12,500	$7,342
Restripe Runway	18	1	ea	$35,000.00	$35,000	$20,559
				TOTAL INITIAL COST:	$13,003,545	$13,003,545
				TOTAL MAINTENANCE AND REHABILITATION COST (year 0 to 20):	$751,000	$527,768
				SALVAGE VALUE:	($4,334,515)	($2,399,916)
				PRESENT WORTH:		**$11,131,397**
				EQUIVALENT UNIFORM ANNUAL COST:		$748,205

Figure 2. Example of a deterministic-based LCCA for an airport pavement project.

Brief descriptions of RealCost and two proprietary LCCA programs reviewed in this study are provided in the sections below. Additional details and illustrations of each program are provided in appendix B.

- FHWA RealCost (current version 2.5)—RealCost is a Microsoft Excel-based probabilistic program that utilizes the principles and procedures contained in the FHWA *Interim Technical Bulletin on LCCA.* The program was developed by the FHWA in 2002/2003, based on the DP 115 prototype program used in the FHWA-sponsored LCCA workshops/demonstrations. The program performs deterministic and probabilistic LCCA for two alternative design strategies. Visual Basic programming functions are utilized for probabilistic (Monte Carlo method) simulations. Both agency and user costs (delay costs and vehicle operating costs associated with construction and rehabilitation activities) can be computed, with separate display of results.

RealCost has two interface mechanisms—the form graphical user interface (GUI) and the worksheet interface. While the form GUI is the primary means of interacting with the software, all of the entered data are stored in worksheet cells, as are all outputs (calculation results, analysis results, etc.).

At least 11 states have adopted and/or customized RealCost for use in conducting highway pavement LCCAs. One of these states, Indiana, has developed its own stand-alone, PC-based Windows program, called RealCost-IN.

- APA LCCA (version 3.1)— The APA LCCA program is based on the procedures contained in the FHWA *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998). It has the ability to perform LCCA in either a probabilistic or deterministic mode for up to four alternatives, with probabilistic variables consisting of discount rate, traffic growth, and construction duration (Ozbay et al., 2003). It allows for the inclusion of user costs resulting from delay time during work zones and generates the resulting detailed analysis graphically and in Excel format.

- NLA Asphalt LCCA (version 1.3)—The NLA LCCA software package is a Microsoft Windows-based application that was developed to perform economic analyses of two pavement alternatives (asphalt only) subject to future M&R activities (Hicks and Scholz, 2003). The methodology is based on the approach presented in the FHWA *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998). The software allows analyses for both new construction and rehabilitation projects and supports both deterministic and probabilistic analyses.

CHAPTER 3. GUIDELINES FOR CONDUCTING AIRPORT PAVEMENT LCCA

Introduction

The process of planning, designing, contracting, and constructing airport pavement projects often takes several years to complete. Typically, once a particular project is identified as needing to be built or improved, it is assigned a general scope and cost and is scheduled with other airport projects as part of a proposed multi-year improvement plan. After funding has been secured for the project, preliminary design plans are developed based on the latest information concerning the goals, needs, and constraints of the project. It is during this stage of the process that the issue of which pavement type or rehabilitation type to use on the project usually is addressed.

Regardless of whether a traditional or an alternate bidding approach will be used for contractor selection, two or more feasible pavement design strategies should be developed for consideration. The alternative strategies generally will consist of those that have been used successfully in the past to satisfy the regional and/or local conditions (traffic, climate, and subgrade characteristics, materials and equipment availability, contractor experience, etc.). However, they also may include revised (design and/or material modifications) and/or innovative strategies that have shown improved and/or promising performance characteristics.

Pavement type or rehabilitation type selection for airport pavement projects requires the collection and meticulous evaluation of a large amount of data. Such data pertain to both the project at hand and past projects having at least some degree of relevance in terms of the various factors considered in the selection process (pavement structure design, costs, performance, traffic characteristics, climate, materials, subgrade, etc.). The past project data may consist of direct source data or could be manifest as practical experience information held by the airport sponsor, its engineering consultants, paving contractors, or various other project stakeholders (FAA, state aeronautics agency, Air Force, etc.).

LCCA Applications

LCCA is a key part of both traditional and alternate bid contracting approaches, and LCCA is a major component in the pavement type or rehabilitation type selection process undertaken for airport projects. The exact application of LCCA will depend primarily on the type of contracting approach (traditional or alternate bid) desired or planned for the project, the availability of data to support the analysis, and the level of detail that can be afforded for the analysis. For projects in which traditional bidding procedures will be used, it is recommended that either a deterministic LCCA with sensitivity testing or a probabilistic LCCA be performed. If sufficient data exist to define the variation or uncertainty of each of the inputs (e.g., discount rate, pay item unit costs, pavement service lives), then probabilistic LCCA should be used. If not, then a deterministic LCCA should be performed along with sensitivity testing to determine the effects of varying key inputs, such as the discount rate, initial pavement service life, and the analysis period.

For projects in which alternate bidding procedures may be sought, it is important to ensure that the alternative strategies are considered "equivalent"—that is, their initial structures are based on the same design life (with same reliability level) and will be maintained to the same levels of serviceability over the same chosen analysis period (the analysis period being substantially longer than the design life). In addition, it should be ensured that there will be no initial construction factors or non-economic factors that would dictate an advantage for any one of the alternatives.

Once the equivalent alternative strategies have been established, a preliminary deterministic LCCA should be performed that includes both the initial and future costs of each alternative. The results of this LCCA should be examined and acted on as follows:

- If the difference between the alternative with the lowest NPW and the alternative with the next highest NPW is greater than 10 percent, it is recommended that alternate bid contracting not be pursued and that type selection be made using a more detailed LCCA (i.e., a final LCCA consisting of either deterministic procedures with sensitivity testing or probabilistic procedures).

- If the difference is 10 percent or less, then alternate bidding should be considered a viable option, with the strategy alternatives consisting of (a) the one with the lowest NPW and (b) all others within 10 percent of the lowest alternative. A final deterministic LCCA should then be performed in which the NPW of only the future costs of each alternative is computed. The resulting values can then be used as life cycle cost adjustment factors (i.e., the C component in the A+C or A+B+C bidding structures) to be applied in the alternate bid form. Subsequently, the bid with the lowest life cycle cost (initial cost bid plus life cycle cost adjustment factor) will be awarded.

While choosing a strategy based solely on initial costs allows for more to be accomplished with a specified annual budget, it does not account for the long-term costs that are paid by taxpayers and facility users. LCCA is the ideal vehicle for taking into consideration initial and future costs and weighing them against non-economic factors (e.g., constructability, continuity of pavement type, conservation of materials/energy, safety) to identify the preferred pavement alternative.

Recommended LCCA Practice

Overview

Chapter 1 presented an 8-step procedure for conducting project-level highway pavement LCCA. A similar, slightly expanded version of this procedure is recommended for use in the airports arena. It entails 10 steps, as shown in figure 3. Descriptions of and guidance for completing each step are provided in the sections below. Although experience-based estimates can be used in quantifying the many LCCA inputs, it is highly recommended that all available, applicable, and reliable data be used in this effort. The quality of LCCA results is only as good as the quality of the inputs.

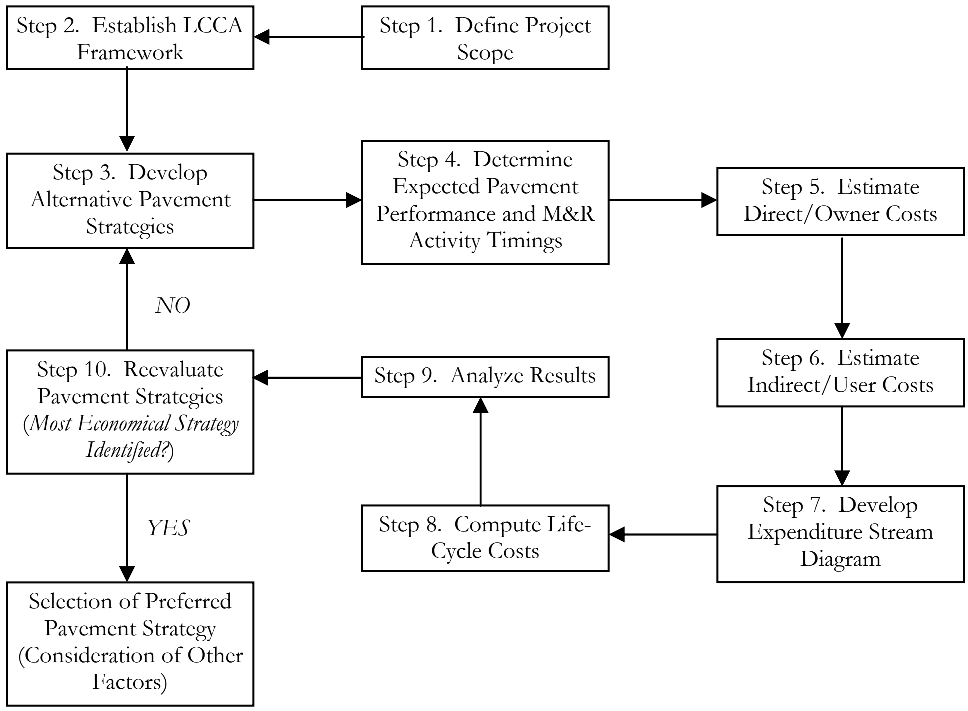

Figure 3. Process for conducting airport pavement LCCA (Walls and Smith, 1998).

The process described herein is conducive to both traditional and alternate bidding approaches. In alternate bidding, all of the steps used in traditional bidding are followed, except that the initial cost in the LCCA is substituted by the actual bid price. Thus, there is no need to estimate this cost for each of the alternative strategies. Also, since alternate bidding uses a discrete life cycle cost adjustment factor for each alternative strategy, only a deterministic computation of the life cycle costs associated with future expenditures is needed.

Successful application of alternate bidding requires that the LCCA process be totally transparent and largely acceptable to both pavement industries. Its use generally is recommended in situations where there are no primary or secondary factors that would foster an advantage for the use of one pavement strategy over the others.

Step 1—Define Project Scope

The first step in conducting an airport pavement LCCA involves defining the physical scope of the LCCA. Airport pavement projects vary greatly in terms of the type of facility (runway, taxiway, or apron), the specific branch(es) (e.g., Runway 12-24, Taxiway D), and specific section(s) that are to be constructed or rehabilitated. While defining the LCCA scope for a project consisting of just one section is easy, projects that include work on multiple branches or facilities require thoughtful consideration of whether all the sections involved can be lumped into one LCCA or if two or more separate LCCAs are warranted. In traditional bidding, the focus is on "differential" costs. In alternate bidding, all pay items in the project need to be included (lighting, drainage structures, etc.). Bid costs received from contractors need to be examined carefully to ensure they are within reason.

In general, it is good practice to perform separate LCCAs for sections located on different facilities. In addition, if there are significant design differences and/or forecasted traffic applications between sections located on the same branch, separate LCCAs should be performed for those sections. Exceptions to this guidance are sure to exist, such as when one section is much smaller in size than another section. An LCCA for the smaller section may not be warranted, given the mobilization and other advantages of using the same material type for both sections (as determined via the LCCA for the larger section).

In the highways arena, LCCA often is performed on the basis of a unit representative of the project limits. The quantities and costs for multi-mile and divided-lane projects are developed for a short representative segment (usually 1 mile) and sometimes for the lanes in one direction, rather than for the entire project length and width. Although this approach can be used in airport pavement LCCA, the shorter lengths of airport projects and some of the unique design characteristics that occur throughout the project (transition sections, electrical/lighting issues) make the LCCA more conducive to a full representation of quantities and costs.

Step 2—Establish LCCA Framework

Analysis Period

The analysis period for LCCA must be sufficiently long such that each alternative pavement strategy includes at least one future rehabilitation event. FAA pavement design practice requires using a 20-year design life, but recent research has found that airport pavements largely exceed this design life value, indicating that the FAA-recommended analysis period is too short (Garg, Guo, and McQueen, 2004). This is further supported by the current practices of SHAs, which on average use analysis periods of 38.5 and 28.5 years for new/reconstruction and rehabilitation projects, respectively. Typical design lives for new/reconstructed highway pavements surfaces range from 10 to 20 years for asphalt structures and 20 to 30 years for concrete structures.

Therefore, it is recommended that the analysis period for airport pavement LCCA be increased. For new/reconstruction projects, an analysis period of 40 years or more is considered appropriate. For rehabilitation projects, an analysis period of at least 30 years is considered appropriate. While longer analysis periods may be warranted for long-life pavement designs, it is cautioned that the LCCA should not extend beyond the period of reliable forecasts. One reasonable approach is to use an analysis period of one of the alternatives that results in zero salvage for that alternative, and apply that period to the other alternatives. Salvage for the others would then be linearly adjusted.

Finally, it must be emphasized that the chosen analysis period is to be applied to all pavement strategies being considered in the LCCA. No alternative should be analyzed over a time period that is different from the other alternatives.

Economic Analysis Technique

Current FAA guidance on using NPW is adequate. The NPW should be applied using constant/real dollars and a discount rate selected in accordance with the procedure described below. The formula for NPW is as follows (note that the variable designations have been modified from those given in AC 150/5320-6D, appendix 1, but the formula is the same):

$$NPW = IC + \sum_{j=1}^{k} M\&R_j \times \left[\frac{1}{1 + i_{dis}}\right]^{n_j} - SV \times \left[\frac{1}{1 + i_{dis}}\right]^{AP} \qquad \text{Eq. 1}$$

where: NPW = Net present worth, \$.

IC = Present cost of initial construction or rehabilitation activity, \$.

k = Number of future M&R activities.

$M\&R_j$ = Cost of j^th future M&R activity in terms of present costs (i.e., constant/real dollars), \$.

i_{dis} = Discount rate.

n_j = Number of years from the present of the j^th future M&R activity.

SV = Salvage value, \$

AP = Analysis period length, years.

As an alternative to NPW, EUAC can be used. However, since the same analysis period is used for each pavement alternative, the EUAC values are simply NPW values that are extrapolated out over the chosen analysis period. The formula for EUAC is as follows:

$$EUAC = NPW \times \left[\frac{i_{dis}(1 + i_{dis})^{AP}}{(1 + i_{dis})^{AP} - 1}\right] \qquad \text{Eq. 2}$$

Discount Rate

The discount rate is a very important and often controversial piece of the LCCA framework, because it can influence the results of the analysis significantly. It represents the real value of money over time and is used to convert future costs to present-day costs (in EUAC analysis, it is used to convert NPW to annualized costs).

The discount rate is a function of both the interest rate and the inflation rate. In general, the interest rate (often referred to as the market interest rate) is associated with the cost of borrowing money and represents the earning power of money. Low interest rates favor those alternatives that combine large capital investments with low maintenance or user costs, whereas high interest rates favor smaller capital investments with higher maintenance or user costs.

The inflation rate is the rate of increase in the prices of goods and services (construction and upkeep of highways) and represents changes in the purchasing power of money. The discount rate is approximately the difference of the interest and inflation rates, representing the real value of money over time. The exact mathematical relationship between PW, the interest rate, and the inflation rate is as follows:

$$PW = C * [(1 + i_{inf}) / (1 + i_{int})]^n \quad \text{Eq. 3}$$

where: PW = Present-worth cost, $.
C = Future cost in present-day terms, $.
i_{inf} = Annual inflation rate, decimal.
i_{int} = Annual interest rate, decimal.
n = Time until cost C is incurred, years.

For practical purposes, however, the discount rate often is approximated as the difference between the interest rate and the inflation rate. As a result, a close approximation of *PW* is calculated as follows:

$$PW = C * [1 / (1 + i_{dis})]^n \quad \text{Eq. 4}$$

where:

$$i_{dis} = i_{int} - i_{inf} \quad \text{(decimal)} \quad \text{Eq. 5}$$

As discussed previously, the literature search/review and airport sponsor/consultant interviews indicate the predominant use of discount rates in the 3 to 5 percent range. In its *Interim Technical Bulletin on LCCA* (Walls and Smith, 1998), FHWA stated that “LCCA should use a reasonable discount rate that reflects historical trends over long periods of time.” It illustrated the discount rate trends published in OMB Circular A-94 and, based in part on those trends, recommended using a rate of 3 to 5 percent (FHWA recently changed this range from 2 to 4 percent).

This study recommends the same for the application of LCCA for airport pavements. However, it is further suggested that the discount rate values provided in OMB Circular A-94 be utilized when possible, particularly for probabilistic LCCA. Specifically, the most current annual real discount rate based on a long-term (10-, 20-, or 30-year) Treasury rate should be used for deterministic LCCA and as the mean value for probabilistic normal-distribution LCCA. In addition, the standard deviation of the daily Treasury real long-term rate for the most current year should be used as the standard deviation value for probabilistic normal-distribution LCCA.

OMB Circular A-94 is available on the Internet at the address below. The 2009 long-term real discount rates posted at this site are 2.2 percent (10-year), 2.7 percent (20-year), and 2.7 percent (30-year).

www.whitehouse.gov/omb/circulars/a094/a094.html

Daily Treasury real long-term rate information can be accessed at the Internet address below. Computations of the standard deviation discount rate for years 2000 through 2010 show this parameter as ranging between 0.12 and 0.42 percent.

www.treasury.gov/offices/domestic-finance/debt-management/interest-rate/real_ltcompositeindex.shtml

Cost Factors

Cost factors are subdivided into two basic categories: direct/owner costs and indirect/user costs.

Direct/owner costs are the costs forecasted to be incurred by the transportation facility owner/operator for a given pavement strategy over the chosen analysis period. They are embodied by the initial construction/rehabilitation event, the sequence of future M&R events, and the salvage value of the pavement strategy at the end of the analysis period.

Direct/owner costs include the physical cost of the pavement structure/treatment associated with an event and may include certain supplemental costs, such as engineering costs and materials testing costs. In both cases (physical and supplemental costs), only the differential costs between pavement alternatives are considered in the LCCA; costs common to all alternatives cancel out and are excluded from LCCA calculations (Walls and Smith, 1998).

Indirect/user costs are defined as the long-term costs incurred by the users of a transportation facility as a result of choosing and implementing a particular pavement strategy. The indirect/user costs of concern in pavement LCCA are the differential or extra costs incurred as a result of one investment strategy being used instead of another. Although user costs are not borne directly by the facility owner/operator, they affect the owner/operator's customers and the customers' perceptions of the owner/operator's performance (FHWA, 2002). Moreover, since the owner/operator acts as the proxy for public benefit, the impetus should exist to maximize taxpayer dollars used in the construction and upkeep of facilities, as well as minimize the expenses incurred by those who use the facilities.

In the airports arena, there are a variety of users—the aircraft crew and passengers, the airline, air cargo, and air charter companies, the airport owner/operator, and the community of businesses tied to airport operations (vendors/concessionaires, rental car companies, hotels, etc.). Costs incurred by these users as a result of choosing one pavement strategy over another can be evaluated in terms of the following components:

- Normal operating conditions.
  - Aircraft operating costs due to added fatigue damage caused by rough pavements. Pavement alternatives with more rehabilitation events could have a longer cumulative period of being in a "rough" condition, resulting in additional upkeep costs.
- Construction zone operating conditions.
  - Aircraft time delay costs due to partial or full pavement facility closures associated with construction and M&R activities. Pavement strategies with more and/or longer interventions could result in greater lost time/productivity of crew and passengers.

- Aircraft operating costs due to the same. Pavement strategies with more and/or longer interventions could result in increased business costs (fuel, maintenance, crew, upkeep, etc.) for airlines, air cargo, and air charter companies.
- Aircraft crash/accident costs due to the same. Pavement alternatives with more and/or longer interventions yield greater risk for crashes.
- Environmental costs due to the same. Pavement alternatives with more and/or longer interventions could result in increased air pollution and energy consumption.

Although standardized procedures for estimating these costs have not been developed, there have been some preliminary evaluations and work in recent years to correlate runway roughness/profile with aircraft fatigue damage, and estimating amounts of air pollution and energy consumption associated with construction operations. For instance, the Air Transport Association (ATA) recently projected the overall cost of delay to be $72.13/minute, based on airport system delay data (138 million delay minutes) and corresponding airline operating cost data ($10 billion) for 77 airports in 2008 (ATA, 2009). Other evaluations of user costs are expected in the near future, such as one outlined in a Transportation Research Board research needs statement pertaining to the effects of rough airfield pavements on aircraft operations (TRB, 2008).

When normal airport operations are altered because of construction or M&R activities, the business cycles of the airport and the aircraft operators are affected. Partial or full closures of any of the airside pavement facilities for any duration can result in significant rescheduling of aircraft operations and/or re-routing of flights to alternate airports. Airlines, air cargo companies, etc. are the first to experience cost impacts; airport owner/operators are next.

While it is very difficult to estimate the added costs incurred by the various aircraft operators as a result of airfield construction and M&R activities, a more tangible estimate can be made of the airport owner/operator's costs in terms of reduced daily operating revenues. Pavement alternatives entailing more intensive and/or longer restrictions on airport operations, particularly when a runway is involved, are sure to result in greater losses of daily revenue due to reduced passengers and/or cargo, and possibly fewer aircraft operations.

As an example, ATA estimated the cost of closing runway 18R/36L at Dallas Fort Worth International Airport (DFW) in 1990 at $131,000 per day in bad weather and $110,000 per day in good weather, based upon the delay to the airlines. This estimate was used to compare block paving construction of taxiways versus conventional construction. DFW engineers estimated that $4.3 million in potential delay costs were avoided by choosing construction with concrete block pavers, which allowed the runway to be open an additional 2 hours daily for 114 days (McNerney, 1995). This shows that it is possible calculate or estimate to potential delay costs and use those numbers in developing rehabilitation and maintenance strategies.

The loss-of-daily-operating-revenue approach is recommended as one form of user cost that a pavement designer/analyst can consider including in an airport pavement LCCA. Other user cost components, such as passenger delay costs and airline delay and operating costs, appear to be relevant to LCCA but require further development before they can be adapted to the process outlined in this report.

Statistical Computation Approach

As discussed earlier, there are two basic approaches for computing life cycle costs—deterministic and probabilistic. In deterministic LCCA, a single value is selected for each input parameter (usually the value considered most likely to occur, based on historical evidence or professional experience), and the group of selected values is then used to compute a single projected life cycle cost. Because each input parameter is represented by only one value, the uncertainties and variations known to exist in these variables in the real world are not fully accounted for.

To some degree, the variability associated with input estimates, projections, and assumptions can be accounted for through a deterministic sensitivity analysis. In this process, a given input parameter is varied over a practical range while holding all other inputs at their chosen value, and a series of projected life cycle costs are computed. Figure 4 shows an example of a sensitivity analysis performed on the discount rate. The projected costs are plotted as a function of the variable input parameter, to reveal the relative impact of input parameter variation on life cycle costs.

Probabilistic LCCA simulates and accounts for the inherent variability of the input parameters. As illustrated in figure 5, for a given pavement strategy, sample input values are randomly drawn from the defined frequency distributions and the selected values are used to compute one forecasted life cycle cost value. The sampling process is repeated hundreds or even thousands of times, thereby generating many forecasted life cycle cost values for the pavement strategy. The resulting forecasted costs can then be analyzed and compared with the forecasted results of competing alternatives to identify the most economical strategy.

For airport pavement LCCA, it is recommended that the probabilistic computation approach be used when reliable historical data exist to model one or more of the input parameters. If such data do not exist, then a deterministic approach should be used, supplemented with sensitivity testing of key input parameters, such as the discount rate, major unit costs associated with the initial pavement structures, and the service life estimates of the initial structures. For alternate bidding applications, the deterministic computation approach should be used.

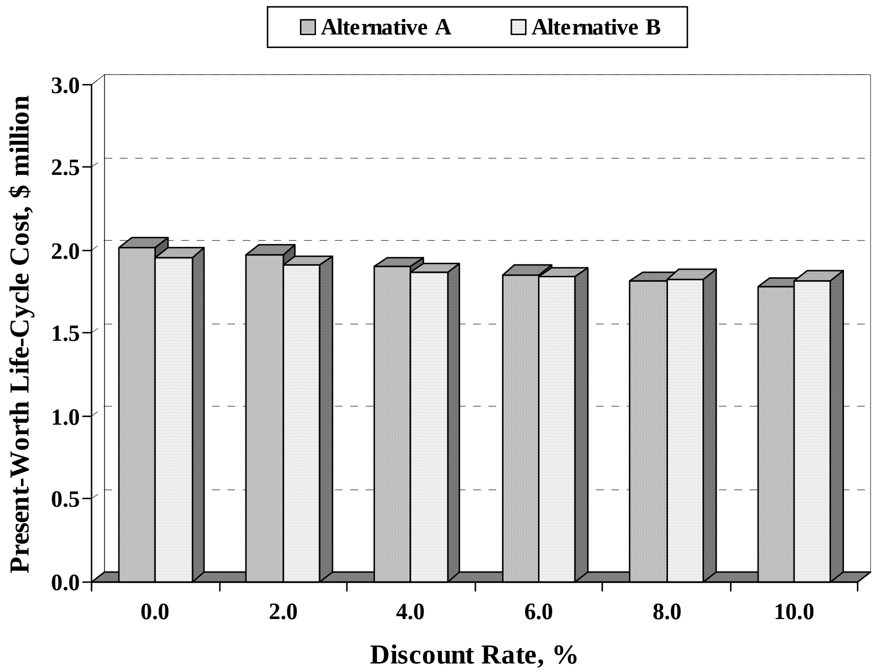

Figure 4. Example illustration of deterministic sensitivity analysis.

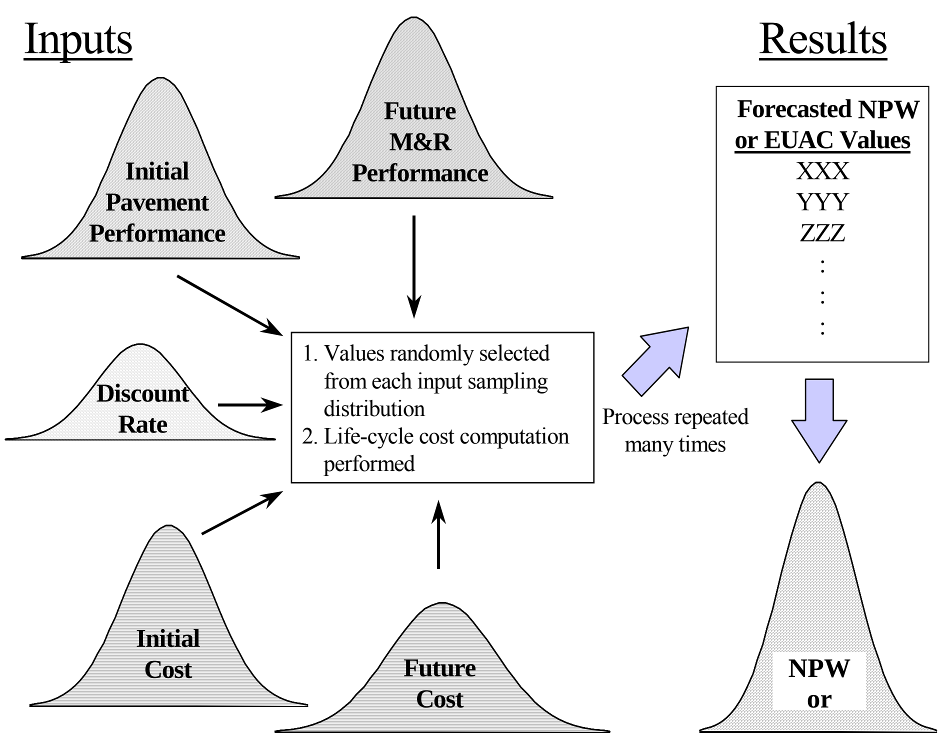

Figure 5. Illustration of the probabilistic LCCA process (ARA, 2004).

Step 3—Develop Alternative Pavement Strategies

For a given project, at least two feasible pavement alternatives should be identified for evaluation in the LCCA. In this step, each alternative is assigned a strategy consisting of the initial structure (whether new or rehabilitated) and the probable M&R activities covering the selected analysis period.

The traditional approach of establishing M&R activities is to make use of historical experience and/or airport M&R policies. Most civil and military airports have pavement management systems in place to record and track important historical pavement information. Such information usually includes year of original construction, years and types of M&R treatments, structural composition (material layers and thicknesses), historical traffic applications (number of operations and types of aircraft), and historical pavement conditions (PCI or other pavement condition/distress indicators). The airport pavement management system should provide at least a general indication of the types of M&R treatments that have been applied to specific types of pavement. If individual distress data are available, then critical forms of distress and modes of failure may be identified, allowing for greater perspective on appropriate M&R treatments (i.e., are current and/or past M&R practices acceptable or are deviations needed?).

Step 4—Determine Pavement Performance and M&R Activity Timing

New/reconstructed pavements and rehabilitated pavements deteriorate due to a combination of traffic- and environmental-related stresses. The deterioration prompts the need for various forms of upkeep over a long time period to sustain the structural integrity and capacity of the pavement, as well as its functional characteristics (smoothness, friction). Step 4 involves determining, for each alternative pavement strategy, the expected performance life of the initial pavement structure and each future rehabilitation treatment projected to occur over the chosen analysis period. It also entails identifying the timings and extents of anticipated maintenance treatments. The resulting information can then be used to establish the sequence and timings of future M&R activities treatments, as illustrated by the life cycle model in figure 6.

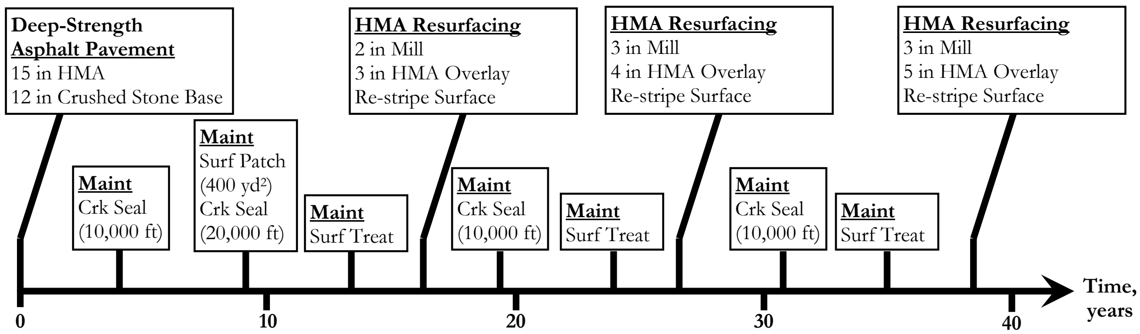

Figure 6. Example pavement life cycle model.

Service Lives of Initial Pavement and Future Rehabilitation Treatments

A pavement's service life is defined as that period of time from completion of construction until the structural integrity of the pavement is considered to be unacceptable and structural rehabilitation or replacement is required. In the example in figure 6, the service life of the initial asphalt pavement structure is about 17 years, corresponding to the timing of the first HMA resurfacing activity. Similarly, the service life of the first resurfacing is about 10 years, corresponding to the timing of the second HMA resurfacing. It should be noted that, in LCCA, service life generally is taken to mean the average or median life of the pavement (i.e., the time associated with 50 percent probability of the need for structural rehabilitation). This is different than the design life, which represents a time period with a relatively low probability of the need for structural rehabilitation or reconstruction.

Pavement service life can be estimated in various ways, ranging from expert modeling using the opinions of experienced engineers to detailed performance prediction modeling using historical pavement performance data. Because of the potential for bias, the only time the former approach should be considered is when reliable historical performance data are not available or are greatly limited (for instance, if the pavement or rehabilitation types being considered are substantially different, due to changes in traffic or use of new materials or technologies). Experience-based estimates often can be made in conjunction with data trends from other locations.

The airport's pavement management system should be the first and foremost source for developing service life estimates of the pavement structures and rehabilitation treatments anticipated for each strategy. Depending on the data available, a variety of analyses can be performed to develop service life estimates. For both techniques, the reliability and accuracy of results depend greatly on the number of data points available for analysis. The more pavement sections representative of a particular pavement type, the better. And, in the case of performance trend analysis, the more time-series condition measurements, the better.

Performance Trend Analysis

In performance trend analysis, historical condition data for pavements similar to those comprising each pavement strategy are compiled and plotted as a function of time. A best-fit regression curve is then fitted through the data and projected out to a threshold condition level representative of the need to perform structural rehabilitation. The corresponding time at which the threshold level is reached reflects the average age at time of rehabilitation or the estimated service life of the pavement.

Performance trend analysis is essentially a four-step process. In step 1, existing pavement sections with structural designs, traffic loadings, and functional purposes (runway, taxiway, apron) that are similar to the pavement alternatives being considered (i.e., same pavement family) are identified, and their historical data are extracted from the pavement management system or other records. Ideally, these pavement sections will be located at the subject airport, but if insufficient sections exist, then assistance should be sought from the appropriate Government agency to identify sections at other airports with similar climatic conditions.

As part of the first step, careful attention should be given to the acceptability of the pavement sections. Were they built with drastically different materials than the pavement alternatives currently being evaluated? Were there design and/or construction issues that substantially influenced performance? Was traffic loadings significantly altered, thereby influencing performance? Sections with these kinds of issues may warrant removal from the analysis.

Step 2 entails creating time-series plots of pavement performance using the available condition data for each group or family of pavements, and developing best-fit linear or non-linear models relating pavement condition to age. The condition data will most likely consist of PCI data, but SCI data also may be available. Most pavement management programs have the ability to develop customized performance/condition models for a family of pavements, but there may be limitations on use of the surface condition data for prediction of pavement life, since other modes of failure may be ignored. Therefore, these programs cannot be used readily for decisions relating to reconstruction and rehabilitation.

In creating the time-series condition plots, some filtering of the data may be needed, such as when a significant increase is observed in PCI from one year to the next. Such increases likely indicate a rehabilitation or significant maintenance intervention. To negate their influence, the post-treatment PCI data should be removed.

Figure 7 illustrates PCI deterioration data for asphalt taxiway pavements located at a large commercial airport. The data points represent the PCI values recorded for individual pavement sections with similar design and traffic characteristics. Fourth-order polynomial trend lines have been fit through the dataset reflecting the central tendency for the deterioration of PCI over time.

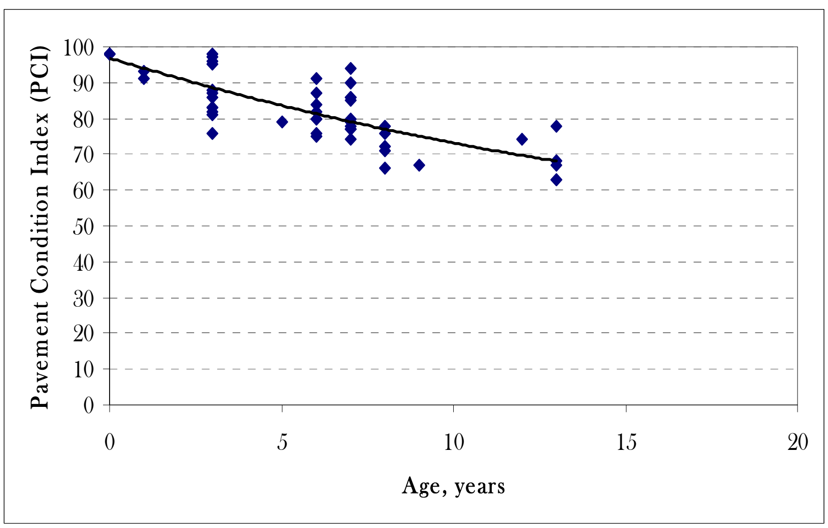

Figure 7. PCI deterioration curve for a family of pavements.

In step 3, an acceptable threshold condition level must be identified to serve as the trigger for structural rehabilitation. PCI levels of 60 to 70 are fairly typical when airport pavements receive some form of structural rehabilitation—the higher end of this range being more suitable for runways and the lower end for aprons. Alternatively, based on a recent study of the FAA's thickness design procedure and 20-year design life requirement (Garg, Guo, and McQueen, 2004), SCI values of 75 to 80 appear to be suitable threshold condition levels for estimating pavement service life. If sufficient pre-rehabilitation PCI data exist (i.e., PCI measurements made within the year preceding a rehabilitation event), they should be examined to help identify the appropriate threshold condition level.

With the development of pavement performance/condition trends and the establishment of a specific condition threshold, an estimate of service life can be made for each pavement family (step 4). Depending on the nature of each performance/condition model, there may be a need to project the model forward so that it reaches the threshold condition level. Figure 8 illustrates this step utilizing the PCI deterioration curve shown in the previous figure and a threshold PCI value of 65. Projection of the PCI deterioration trendline to the threshold value results in an estimated service life of 15 years.

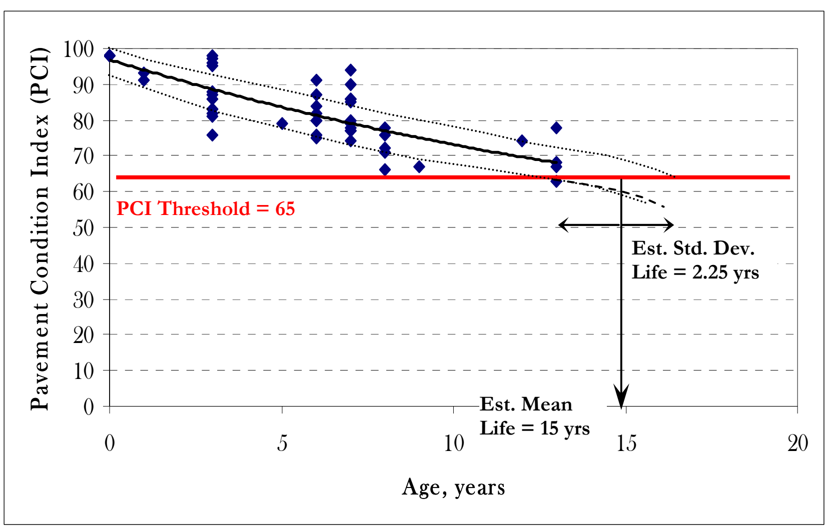

Figure 8. Service life estimation for a family of pavements.

If a probabilistic LCCA will be conducted, then an estimate of the variation in expected pavement life will be needed. In the development of the performance/condition model, a confidence level can be defined that allows for the development of confidence bands around the model trend line. In the above figure, the estimated standard deviation for service life is 2.25 years.

Survival Analysis

A procedure successfully used in the highways arena for estimating pavement service life is survival analysis (alternatively known as failure analysis). This technique uses historical construction and rehabilitation data for a family of pavements to construct a survival curve that depicts the probability of survival with time (or traffic loadings). In survival analysis, "survival" of a pavement section is defined as the non-occurrence of "failure" or, in other words, the non-occurrence of structural rehabilitation, such as a substantive overlay or extensive concrete pavement restoration.

Survival analysis begins with an assessment of the survival or failure status of each pavement family section at the time of the analysis. As illustrated in table 5, the age of each family pavement section that has failed is determined by subtracting the construction year from the rehabilitation year.

Table 5. Performance history of a selected pavement family.

Section	Year Constructed	Year Rehabilitated	Age at Failure	Age in 2008
RW 14L-22R / 001	1995	—	—	13
RW 14L-22R / 002	1995	—	—	13
RW 14L-22R / 003	1998	—	—	10
RW 14L-22R / 004	2000	—	—	8
RW 14R-22L / 001	1988	2007	19	—
RW 14R-22L /	1988	—	—	20

002				
RW 14R-22L / 003	1988	2005	17	—
RW 14R-22L / 004	1990	2005	15	—
RW 14R-22L / 005	1994	—	—	14
RW 7-29 / 001	1990	2006	16	—
RW 7-29 / 002	1990	2008	18	—
RW 7-29 / 003	1996	1993	19	—
RW 7-29 / 004	1997	—	—	11
RW 7-29 / 005	1999	—	—	9
		Mean (Standard Deviation)	17.3 (1.6)	

Using the age data from table 5, a life table like the one shown in table 6 can be produced. These data can then be used to construct a survival curve like the one shown in figure 9. Using a value of 50 percent pavement sections surviving, an estimate of the median life (and standard deviation) for a pavement with similar features and loading conditions can be developed and used in LCCA.

Table 6. Pavement survival analysis life table.

Pavement Section Age, years	Cumulative No. of Failed Pavement Segments	Cumulative No. of Censored Pavement Sections[a]	Number of Pavement Sections Left in Study	Proportion of Pavement Sections Failed	Proportion of Pavement Sections Surviving
0	0	0	14	0.000	1.000
8	0	1	13	0.000	1.000
9	0	2	12	0.000	1.000
10	0	3	11	0.000	1.000
11	0	4	10	0.000	1.000
13	0	6	8	0.000	1.000
14	0	7	7	0.000	1.000
15	1	7	6	0.143	0.857
16	2	7	5	0.286	0.714
17	3	7	4	0.429	0.571
18	4	7	3	0.571	0.429
19	6	7	1	0.857	0.143
20	6	8	0	1.000	0.000

[a] Censored pavements are those that are still in-service at time of analysis.

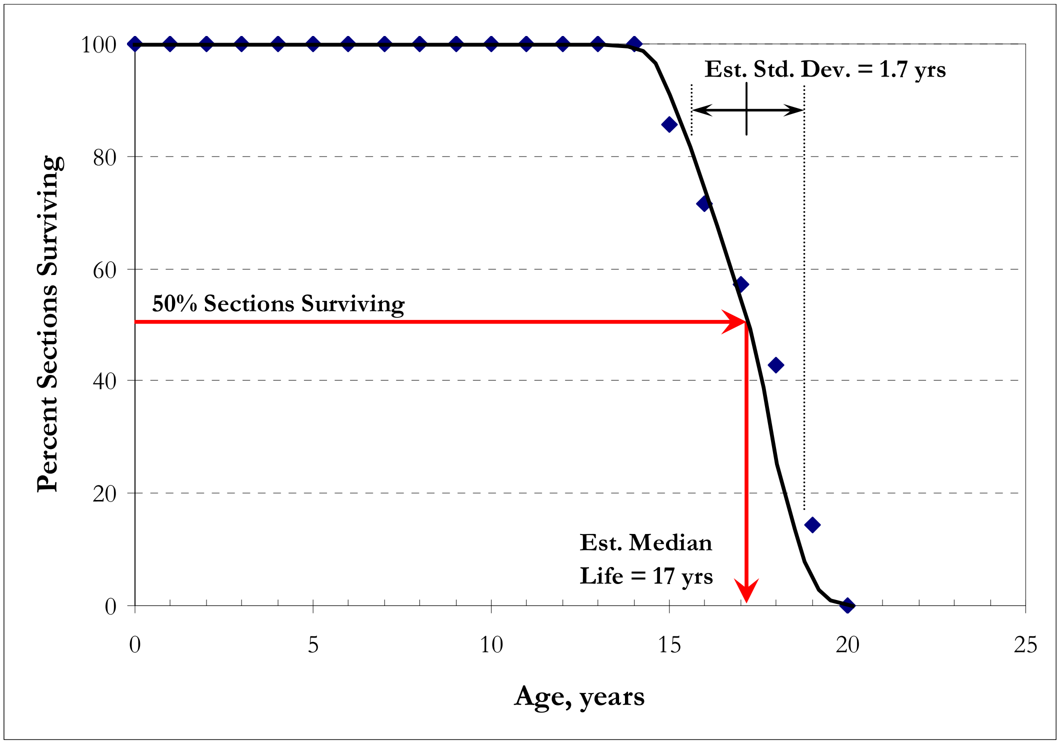

Figure 9. Pavement survival curve for selected pavement family.

One drawback to the survival analysis approach is the potential inability to identify a sufficient number of sections at a given airport from which to develop a pavement family survival curve. There may or may not be enough sections at medium to large-sized airports, and there definitely will not be enough at small airports. In such cases, pavement sections from other airports with similar conditions should be utilized, if available, or performance trend or other types of analysis should be used.

Timing and Extent of M&R Treatments

Occasionally, airports are faced with the need to improve only the functional characteristics of pavements (e.g., thin overlays to address smoothness and/or friction deficiencies or transverse grooving to restore texture for improved friction). As with structural rehabilitation treatments, pavement management and/or history records should be consulted to identify the expected timings and extents of these actions, if needed.

Between the time a pavement is originally constructed and the time it is rehabilitated (or rehabilitated and then rehabilitated again), there are sure to occur multiple maintenance interventions. Such maintenance may range from routine activities (pothole/spall repairs, removal of foreign objects) to preventive activities (crack sealing, joint resealing, surface treatments) to major repairs (slab replacements, full-depth repairs, localized skin patching). Unlike on highways, many of the routine maintenance items performed at airports are considered extremely important and are done very frequently to maintain high levels of safety. Airport maintenance is much more preventive in nature than highway maintenance. Typically, the pavement management system includes maintenance activities geared to particular distresses and these treatments may vary as a function of the distress severity level.

The ideal airport pavement LCCA captures all forms of maintenance costs, since the types, timings, and extents of maintenance activities will be different for each pavement alternative. However, because routine reactive-type maintenance costs generally are not very high and not substantially different between pavement types, they usually can be ignored. Thus, the focus of maintenance costs should be on the timing and extent of preventive and major forms of maintenance. Again, pavement management and/or history records should be consulted to develop this information.

Step 5—Estimate Direct/Owner Costs

The costs of building, maintaining, and rehabilitating pavements as part of each alternative pavement strategy are an important element of LCCA. Using reliable, up-to-date unit price estimates for each activity/material pay item associated with the initial structure (whether new/reconstructed or rehabilitated) and future M&R treatments will ensure a fair and accurate computation of life cycle costs. Step 5 involves estimating these unit costs and combining them with estimated pay item quantities to develop the physical costs of pavement activities for use in the LCCA. It also entails determining whether to account for the salvage value of the pavement structure at the end of the analysis period and, if so, developing an estimate of that benefit (or cost).

A third aspect of direct/owner costs is the supplemental costs associated with construction and M&R activities. These costs can be categorized into administrative, engineering, and traffic control costs. Their inclusion in the LCCA depends on whether substantive differences can be identified among the alternative pavement strategies.

Physical Costs of Pavement Activities

The key to estimating physical costs is identifying and obtaining sufficient and reliable unit cost data for the pay items that will go into the initial structure and individual M&R treatments. The best sources for these data are the historical bid tabulations for projects undertaken in recent years (preferably, within the last 5 to 7 years) at the subject airport or at other airports in the region. These data often are compiled and summarized on a regular basis for project estimating purposes, and in some cases they are included in the airport pavement management system. Other good sources for unit cost data are the local highway agencies, such as the district office of the state DOT or nearby city/county governments. Since these agencies may use different specifications and/or pay item designations, care must be taken to ensure that the pay items represent the same work activities as those of the subject airport.

Unit cost estimates can be developed using the unit price data from the lowest bid or three lowest bids tendered on projects of comparable nature. Each average unit price must be adjusted to present day to account for the effects of inflation, and consideration should be given to filtering out prices biased by projects that included small quantities of a particular pay item. Using inflation-adjusted and quantity-filtered unit price data, the mean cost of each pay item, as well as key variability parameters (standard deviation, range), can be computed for use in the LCCA. Figures 10 and 11 illustrate the process of normalizing unit cost data and developing best estimates for both deterministic and probabilistic LCCA applications.

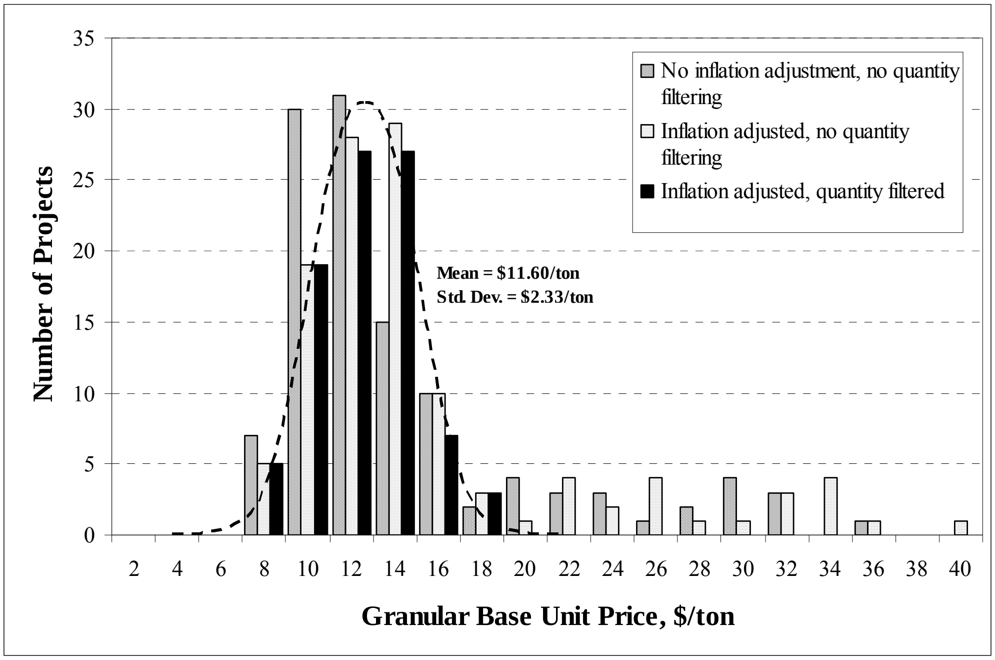

Figure 10. Example of pay item unit price development.

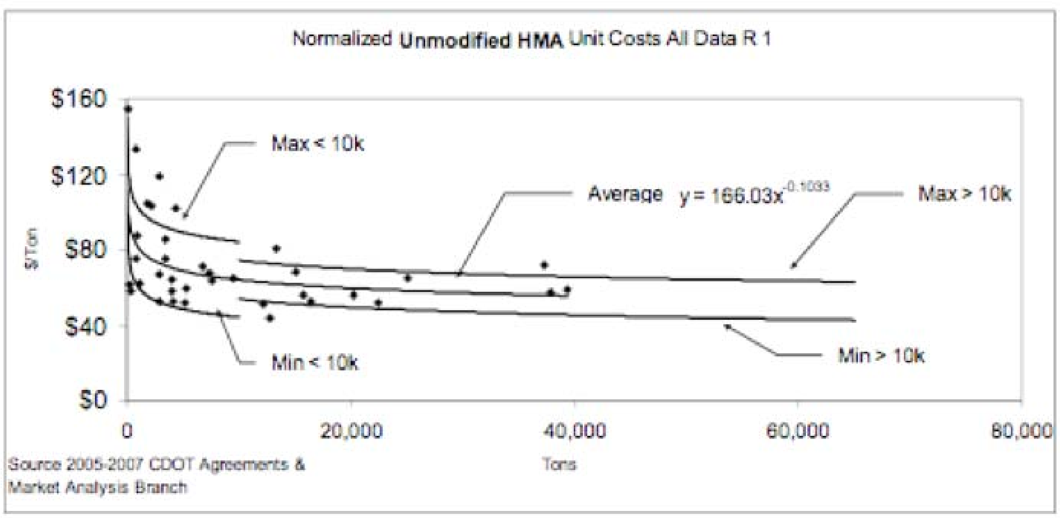

Figure 11. Colorado DOT's process for estimating initial costs (Colorado DOT, 2009).

In cases where new materials/technologies are expected to be used and little or no regional cost information is available, estimates should be derived using data available from other sources. Pavement industry groups can be consulted to help identify appropriate sources.

Unit cost data obtained from other sources may need to be adjusted to account for geographical differences in construction costs. The US Air Force has developed adjustment factors on a state-by-state basis that can serve this purpose (AFCESA, 2007). The most recent listing of adjustment factors is shown in table 7.

Table 7. Construction cost location adjustment factors (AFCESA, 2007).

State	Factor	State	Factor	State	Factor	State	Factor
Alabama	0.82	Indiana	0.96	Nebraska	0.94	Rhode Island	1.11
Alaska	1.90	Iowa	0.98	Nevada	1.24	South Carolina	0.88
Arizona	0.97	Kansas	0.93	New Hampshire	1.06	South Dakota	0.96
Arkansas	0.85	Kentucky	0.91	New Jersey	1.17	Tennessee	0.85
California	1.18	Louisiana	0.94	New Mexico	0.98	Texas	0.85
Colorado	1.04	Maine	1.06	New York	1.07	Utah	1.02
Connecticut	1.13	Maryland	1.02	North Carolina	0.84	Vermont	1.00
Delaware	1.02	Massachusetts	1.12	North Dakota	1.04	Virginia	0.93
Florida	0.86	Michigan	1.12	Ohio	0.96	Washington	1.06
Georgia	0.84	Minnesota	1.12	Oklahoma	0.91	West Virginia	0.95
Hawaii	1.74	Mississippi	0.88	Oregon	1.06	Wisconsin	1.08
Idaho	1.03	Missouri	0.97	Pennsylvania	1.04	Wyoming	0.98
Illinois	1.20	Montana	1.14				

Salvage Value

Salvage value reflects any remaining worth of a pavement alternative at the end of the analysis period (Grogg et al., 2001). Salvage value may be either positive or negative: a positive value represents useful, salvageable material, whereas a negative value represents a cost to remove and dispose of the material that exceeds any possible positive salvage value (Peterson, 1985).

There are two components to salvage value: serviceable life (commonly referred to as remaining life) and residual value. As previously discussed, current FAA guidance is for salvage value to be based solely on serviceable life. In the highways arena, a few state DOTs use the residual value method, but many more use the remaining life method. As illustrated in figure 12, the remaining life method prorates the cost of the last pavement rehabilitation event using the ratio of its remaining life at the end of the analysis period to its total expected life.

Residual value is the actual revenue that could be generated from the sale or recycling of the existing pavement at the end of the analysis period (Grogg et al., 2001). While usually positive, residual value can be negative if removal, hauling, and disposal costs exceed the revenue its sale generates. Several project-specific factors, such as age, durability, quantity, and location of existing materials, must be considered in estimating this component of salvage and, therefore, it requires extensive input data and very detailed analyses. The differential residual value between pavement alternatives generally is not very large and, when discounted over long periods of time, tends to have little effect on LCCA results.

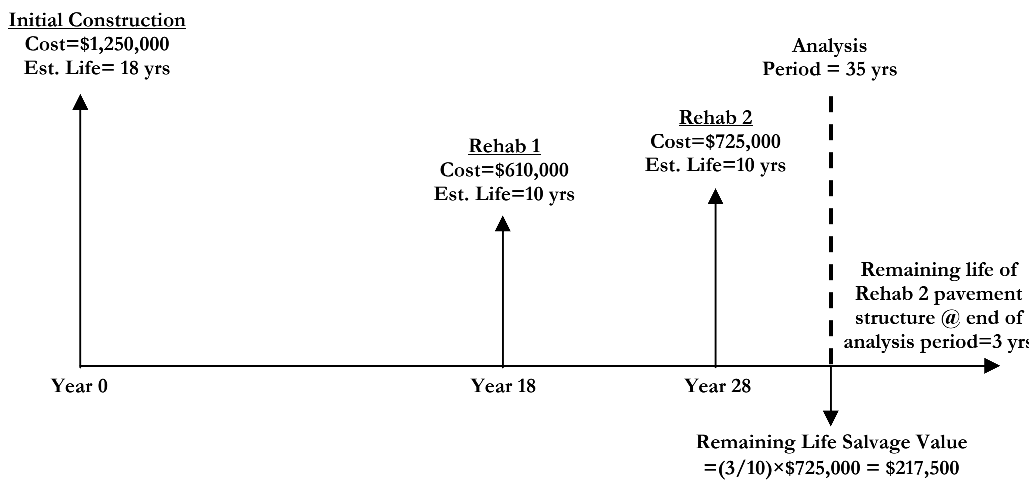

Figure 12. Illustration of remaining life salvage value.

It is recommended that salvage value be considered in the airport LCCA, particularly when shorter analysis periods (30 to 40 years) are used. Because of the complexity in evaluating the recyclable value of a pavement structure at the end of the analysis period, it is recommended that only the remaining life component be considered when including salvage value in the LCCA.

Supplemental Costs

Brief descriptions of supplemental costs are provided below. Each category is applicable only to the series of anticipated future M&R events.

- Administrative costs—Contract management and administrative overhead.
- Engineering costs—Design and construction engineering, construction supervision, and materials testing and analysis.
- Ground traffic control costs—Traffic control setup and communications.

If the supplemental costs of the different alternatives are approximately the same, then these costs can be ignored and only the physical costs should be considered. If there are significant differences, the process of developing estimates for all events should proceed. Because estimating these costs can be difficult and time-consuming, an alternative method to consider is to specify them as a percentage of the total project-level pavement costs. Table 8 illustrates this simple and straightforward application using a value of 5 percent to represent engineering costs. As can be seen, the percentage is applied equally to each event in each alternative strategy.

Table 8. Example application of estimating supplemental costs.

Event	Cost Item	Pavement Alternative 1	Pavement Alternative 2
Rehabilitation No. 1	Total Pavement Cost	$1,250,000	$1,560,000
	5% Engineering Cost	$62,500	$78,000
	Total	$1,312,500	$1,638,000
Rehabilitation No. 2	Total Pavement Cost	$575,000	$350,000
	5% Engineering	$28,750	$17,500
	Total	$603,750	$367,500

Step 6—Estimate Indirect/User Costs

This step should be performed if it is decided in step 2 that indirect/user costs should be included in the airport pavement LCCA. In this step, estimates of the reduction in airport daily revenue are developed for each event (initial construction/rehabilitation and future M&R treatments) in the life cycle of each pavement alternative. Key aspects include defining the following:

- Type and duration of pavement facility restrictions—Because each airport is unique in terms of its airfield pavement system layout, how it manages air and ground traffic operations, and how it facilitates construction and M&R practices, each event in the life cycle of a pavement alternative must be examined carefully to identify the most probable construction zone scenario. For each scenario, it must be determined if daily capacity will be exceeded and, if so, for how long.
- Reductions in aircraft operations, passengers, and/or cargo—If capacity is expected to be exceeded for a given construction zone scenario, then estimates of the daily reduction in aircraft operations, passengers, and/or cargo must be developed. These estimates should reflect what would most likely occur in terms of how aircraft operators might alter their services. If capacity is not expected to be exceeded, but the construction zone is such that airlines and/or air cargo companies must reduce their operational loads due to shortened runways, then estimates of reduced passengers and/or reduced landing weights must be developed.
- Loss of daily operating revenue—Commercial airport owner/operators derive most of their revenues either directly or indirectly from aeronautical activities. These include passenger, cargo, and fuel taxes/fees collected through the Airport Improvement Program (AIP), passenger facility charges (PFCs), and aircraft take-off/landing fees. Computation of the loss of daily operating revenue for a given construction zone scenario entails (a) multiplying the appropriate fee or tax rates by the daily reductions in aircraft, passengers, and cargo, (b) summing the individual daily revenue losses, and (c) multiplying the overall daily revenue loss by the number of days the construction zone scenario is expected to be in-place.

As an example illustration, consider the following runway construction scenario for a major commercial airport:

<u>Initial Year (Year 0) Data</u>

- Daily Operations = 1,250 (625 arrival flights and 625 departing flights)
- Average Number of Passengers/Flight: 80

- Daily Total Passengers = 1,250 × 80 = 100,000
    - Daily Passenger Enplanements = 625 × 80 = 50,000
    - Daily Passenger Deplanements = 625 × 80 = 50,000
- Average Aircraft Fuel Usage: 320 gal/flight
- Daily Fuel Flowage = 320 × 625 = 200,000 gal
- Average Landing Fee = $750/aircraft
- Passenger Facility Charge (PFC) = $4.50/enplaned passenger
- Fuel Flowage Fee = $0.10/gal
- Landing Fee Daily Revenue = 625 aircraft * $750/aircraft = $468,750
- PFC Daily Revenue = 50,000 passengers * $4.50/enplaned passenger = $225,000
- Fuel Flowage Daily Revenue = 200,000 gal * $0.10/gal = $20,000
- Total Daily Revenue = $468,750 + $225,000 + $20,000 = $713,750

Two different pavement alternatives are being considered for the project, which is being evaluated for life cycle costs covering a 30-year analysis period. The first alternative consists of initial construction followed by rehabilitation activities after 15 and 25 years. The second alternative consists of initial construction followed by a rehabilitation treatment after 20 years. Each event for each pavement alternative entails a partial runway closure that will limit the runway length and therefore reduce the operational loads of some aircraft. These load reductions will cause the average landing fee to decrease from $750/aircraft to a specified value corresponding to the events of each alternative. For simplicity, it has been assumed that aircraft operations will remain the same over the 30-year analysis period.

Table 9 lists the anticipated reductions in flight associated with each construction and rehabilitation event, as well as the corresponding reductions in passenger movements and fuel usage. Based on these reductions and the various fees listed above, reductions in daily airport operating revenues are computed for each event, along with the total lost revenue corresponding to the estimated duration of the event. A summation of lost revenues for each pavement alternative is also given. However, it should be noted that as part of an LCCA, the lost revenues associated with future rehabilitation treatments would be discounted using the selected discount rate. These values also assume that work is performed during peak hours. Should construction activities be scheduled at night or during other off-peak hours such that peak-hour operations are less impacted, reduction factors should be adjusted accordingly to reflect the reduced impact of construction activities.

Table 9. Estimate of airport operating revenue losses due to construction/rehabilitation activities.

Year	Pavement Alternative #1	Pavement Alternative #2
0	Initial Construction Duration: 50 days Avg Landing Fee: $700 Passenger Reduction: 2,000 passengers Fuel Reduction: 8,000 gal Daily Lost Revenue: ($750−$700)×(625) + (2,000×$4.50) + (8,000×$0.10) = $41,050 Total Lost Revenue: 50 days × $41,050/day = $2,052,500	Initial Construction Duration: 90 days Avg Landing Fee: $700 Passenger Reduction: 2,000 passengers Fuel Reduction: 8,000 gal Daily Lost Revenue: ($750−$700)×(625) + (2,000×$4.50) + (8,000×$0.10) = $41,050 Total Lost Revenue: 90 days × $41,050/day = $3,694,500
15	Rehab #1 Duration: 25 days Avg Landing Fee: $685 Passenger Reduction: 4,000 passengers Fuel Reduction: 16,000 gal Daily Lost Revenue: ($750−$685)×(625) + (4,000×$4.50) + (16,000×$0.10) = $60,225 Total Lost Revenue: 25 days × $60,225/day = $1,505,625	—
20	—	Rehab #1 Duration: 25 days Avg Landing Fee: $725 Passenger Reduction: 1,200 passengers Fuel Reduction: 4,800 gal Daily Lost Revenue: ($750−$725)×(625) + (1,200×$4.50) + (4,800×$0.10) = $21,505 Total Lost Revenue: 25 days × $21,505/day = $537,625
25	Rehab #2 Duration: 30 days Avg Landing Fee: $725 Passenger Reduction: 1,200 passengers Fuel Reduction: 4,800 gal Daily Lost Revenue: ($750−$725)×(625) + (1,200×$4.50) + (4,800×$0.10) = $21,505 Total Lost Revenue: 30 days × $21,505/day = $645,150	—
Total Lost Revenue*	$2,052,500 + $1,505,625 + $645,150 = **$4,203,275**	$3,694,500 + $537,625 = **$4,232,125**

* Does not account for discounting of future rehab costs.

Step 7—Develop Expenditure Stream Diagrams

Expenditure stream diagrams are graphical or tabular representations of expenditures over time. They are developed for each alternative pavement strategy to help the designer/analyst visualize the magnitudes and timings of all expenditures projected for the analysis period. As shown in figure 13, costs normally are depicted by upward arrows and benefits (e.g., salvage value) by downward arrows.

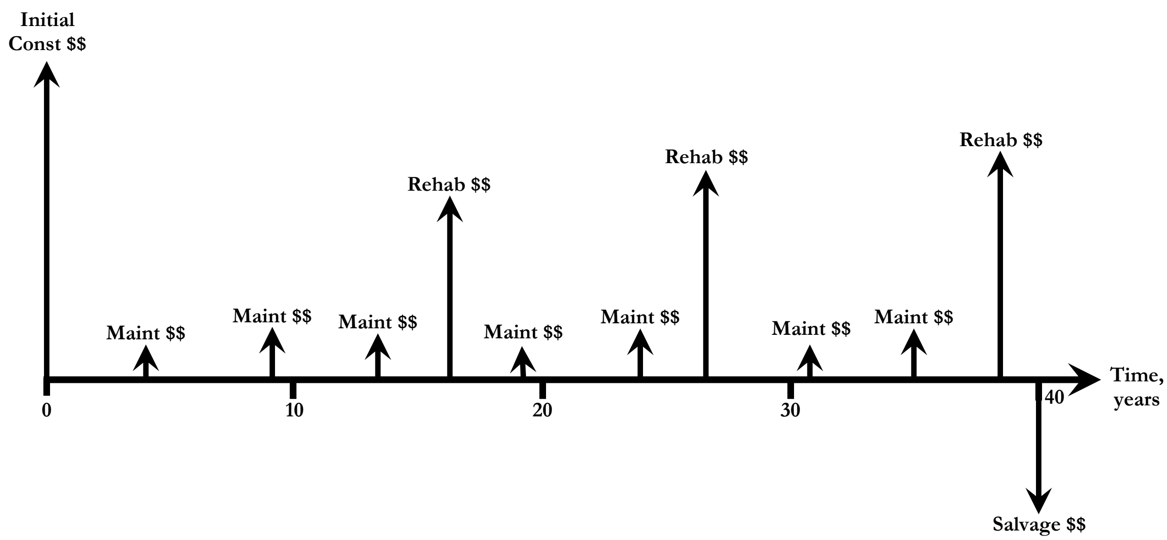

Figure 13. Example expenditure stream diagram.

Step 8—Compute Life Cycle Costs

Once the expenditure stream for each alternative pavement strategy has been developed, the task of computing projected life cycle costs is undertaken. For deterministic analysis, this is a simple matter of converting all future costs (including salvage, if appropriate) projected to occur over the chosen analysis period to present worth values using a specified discount rate. The initial construction cost and all converted costs are then summed together to produce the NPW (see equation 1). If desired, this cost can then be converted to EUAC using the discount rate and analysis period (see equation 2). Sensitivity testing of selected inputs, such as the discount rate or key unit costs, can also be performed to examine the effects on life cycle costs of varying these inputs.

As described earlier, probabilistic LCCA involves randomly selecting a value from each input parameter's sampling distribution, using the selected values and the NPW/EUAC formula to compute a single life cycle cost, and repeating these steps through hundreds or thousands of iterations to generate an array of forecasted costs. These costs are then analyzed and compared with the forecasted costs of the alternative pavement strategies to identify the most economical strategy. Probabilistic simulation requires the use of either a computerized spreadsheet program equipped with the necessary probabilistic distribution functions or a stand-alone computer program that is properly hard-coded to perform the simulation.

When performing a probabilistic simulation, it is important to make sure that each iteration represents a scenario that can actually occur. Two particular modeling errors with the potential to create unrealistic scenarios are as follows (FHWA, 1998):

- Lack of appropriate pre-defined relationships between input parameters—Although each randomly selected value for a given iteration may be legitimate on its own, reality may dictate that certain relationships exist between the input parameters. For example, since higher traffic volume generally is linked with shorter pavement life for a given design cross-section, it is important to establish an appropriate sampling correlation between these two inputs. Such a correlation would ensure that, for each iteration, a sample from the high side of the traffic probability distribution is countered with a sample on the low side of the pavement life probability distribution, and vice versa.
- Lack of fixed limits on input sampling distributions—For some types of sampling distributions, the limits for sampling are not among the criteria used to define the distribution (e.g., in defining a normal sampling distribution, only the mean and standard deviation are needed). However, it is important to know the minimum and maximum values for sampling, so that reasonable values are used in the probabilistic simulation. Misleading simulation results can be expected, for instance, if the distribution for a cost or pavement service life parameter allows negative values to be selected.

Step 9—Analyze/Interpret Results

Regardless of whether deterministic or probabilistic life cycle costs are computed, the results must be analyzed and interpreted carefully to identify the most economical pavement strategy. Because the outputs of each computational approach are different (deterministic yields a single NPW/EUAC value, probabilistic yields a distribution of NPW/EUAC values), the ways in which they are evaluated and interpreted are different.

In the analysis of deterministic results, it is common practice to compute the percent difference in life cycle costs of the alternative strategies. If the percent difference between the two lowest cost strategies is greater than some established minimum requirement—usually set according to the tolerance for risk (5 and 10 percent are common)—then the lowest cost strategy is accepted as the most economical one. If, on the other hand, the percent difference is less than the established minimum requirement, then the life cycle costs of the two strategies are deemed equivalent, thereby leaving the analyst with the option of reevaluating the strategies or allowing other factors to drive the strategy selection process.

The results of probabilistic LCCA simulation can be analyzed and interpreted in different ways. One straightforward, comprehensive approach recommended for use involves carrying out the following evaluations in sequence:

1. Trial-by-trial comparisons of forecasted NPW/EUAC values.
2. Statistical analysis—differences between mean values.
3. Risk assessment of forecasted NPW/EUAC distributions.

Discussions of each evaluation are provided in the sections below.

Evaluation 1—Trial-By-Trial Comparisons

A preliminary indication of the most economical pavement strategy can be obtained by examining the life cycle cost results associated with each iteration or trial computation (ARA, 2004). By tallying the number of "wins" for each alternative (i.e., trials in which one strategy had the lowest life cycle cost compared to all other strategies), dividing the respective wins by the total number of trials performed in the simulation, and multiplying by 100, the overall probabilities for each alternative to have the lowest life cycle cost are determined. The pavement strategy with the highest overall probability becomes the favored strategy, but additional evaluation is needed to determine if it is the most economical one.

Table 10 shows the NPW results for three alternative strategies and 1,000 trials in columns 2 through 4. In columns 5 through 10, the outcomes as to whether a particular strategy had a lower cost than one or all other alternatives for a given trial are indicated by values of 0 or 1—0 meaning that the cost was not lower, 1 meaning that the cost was lower. At the bottom of the table, the results of all trials are tallied, and it can be seen that alternative C had the lowest life cycle cost in 538 of the 1,000 total trials. Table 11 summarizes these results in terms of a probability matrix. In the case of alternative C having the lowest life cycle cost of all three alternatives, the probability of 53.8 percent is simply the quotient of 538 divided by 1,000, multiplied by 100 percent.

Table 10. Process for tallying life cycle cost results on a trial-by-trial basis (ARA, 2004).

Iteration/ Trial No.	**NPW, $1000**			**Alt. A < Alt. B**	**Alt. A < Alt. C**	**Alt. B < Alt. C**	**Alt. A Lowest?**	**Alt. B Lowest?**	**Alt. C Lowest?**
	Alt. A	**Alt. B**	**Alt. C**						
1	1,692	1,511	1,501	0	0	0	0	0	1
2	1,570	1,646	1,608	1	1	0	1	0	0
3	1,535	1,472	1,515	0	0	1	0	1	0
4	1,425	1,418	1,536	0	1	1	0	1	0
5	1,705	1,677	1,639	0	0	0	0	0	1
.	.	.	.	.	.	.	.	.	.
1,000	1,492	1,541	1,476	0	0	0	0	0	1
			TOTAL	302	244	386	152	310	538

Table 11. Life cycle cost probability matrix for trial-by-trial comparison example (ARA, 2004).

Pavement Strategy Alternative	Probability of LCC of:			Overall Probability of Having the Lowest LCC, %
	Alt. A Less Than LCC of:	Alt. B Less Than LCC of:	Alt. C Less Than LCC of:	
A	X	69.8	75.6	15.2
B	30.2	X	61.4	31.0
C	24.4	38.6	X	53.8

Evaluation 2—Statistical Analysis

In this generally straightforward exercise, the mean and standard deviation life cycle cost values computed for each alternative pavement strategy are used to determine if significant differences exist between the means of each strategy (ARA, 2004). If the strategy with the lowest mean life cycle cost is shown to be statistically significantly lower than all other alternatives, then it can be accepted as the most economical strategy. Otherwise, the third and final evaluation option must be investigated.

For the evaluation of two competing alternatives, the difference in means is investigated using the t-test. For three or more competing alternatives, an analysis of variance (ANOVA) can be performed or, if appropriate, the LCCA can be narrowed down to the two seemingly lowest cost alternatives. Because of the complexity of ANOVA, it is not discussed here.

In the t-test, the null hypothesis is that the mean life cycle cost values of the alternative strategies are equal (e.g., $LCC_{AltA} = LCC_{AltB}$) at some prescribed confidence level (typically 90 percent). To reject the null hypothesis and conclude that the mean life cycle costs are statistically significantly different, the calculated t-value must fall in a critical range, defined by the chosen confidence level and the sample size n (i.e., number of trials in the simulation). The critical range can be determined by referring to a t-distribution table. For simulations with the recommended minimum of 500 trials, the following critical ranges apply:

Confidence Level	Critical Range
90%	$t \geq +1.65$ or $t \leq -1.65$
95%	$t \geq +1.96$ or $t \leq -1.96$
99%	$t \geq +2.58$ or $t \leq -2.58$

The t-value is calculated using the following equation:

$$t = (LCC_{AltA} - LCC_{AltB}) / [(s_{\mathrm{AltA}}^2 + s_{\mathrm{AltB}}^2)/n]^{0.5} \qquad \text{Eq. 6}$$

where: LCC_{AltA} = Mean life cycle cost (NPW or EUAC) for alternative strategy A, $.

LCC_{AltB} = Mean life cycle cost for alternative strategy B, $.

s_{AltA} = Standard deviation of life cycle cost for alternative strategy A, $.

s_{AltB} = Standard deviation of life cycle cost for alternative strategy B, $.

n = Number of simulation trials.

As an example application of the t-test, figure 14 shows the NPW distributions of two alternative strategies, along with their respective mean and standard deviation values. Previous trial-by-trial comparison indicated that the favored strategy is alternative B (lowest NPW in 56.3 percent of the 1,000 trials). Based on a confidence level of 95 percent, the critical range is established at $t \geq +1.96$ or $t \leq -1.96$. Entering the respective mean and standard deviation costs into the above equation yields the following result:

$$t = (\$1{,}611{,}702 - \$1{,}600{,}344) / [(\$100{,}190^2 + \$89{,}996^2)/1000]^{0.5}$$

$$t = \$11{,}358 / \$4{,}259$$

$$t = 2.67$$

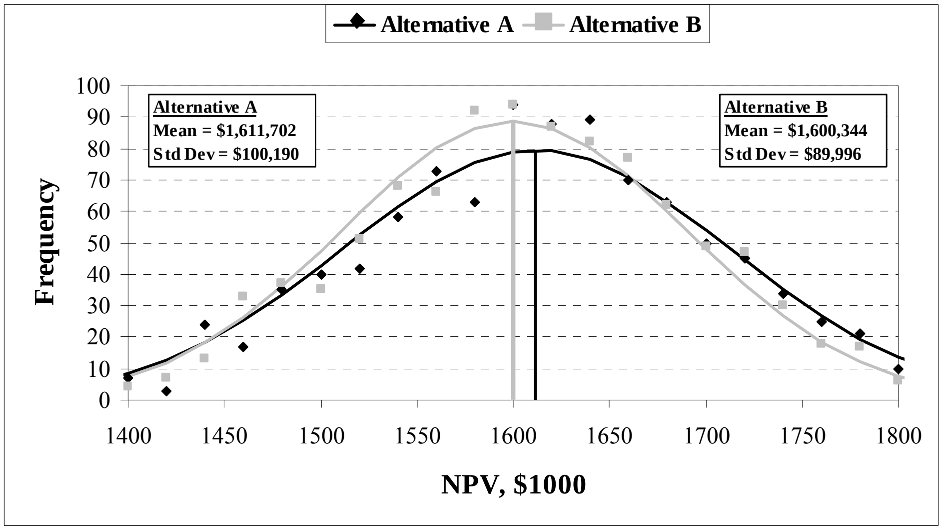

Figure 14. NPW frequency distributions for alternative strategies A and B.

Since the t-value falls within one part of the critical range (i.e., ≥ +1.96), the null hypothesis is rejected and the mean NPW of alternative strategy B is shown to be statistically significantly lower than that of alternative A. Although there is a potential for savings in selecting alternative A, that potential is outweighed by alternative B over the range of most probable NPW outcomes—$1.51 to $1.7 million—as illustrated in figure 15.

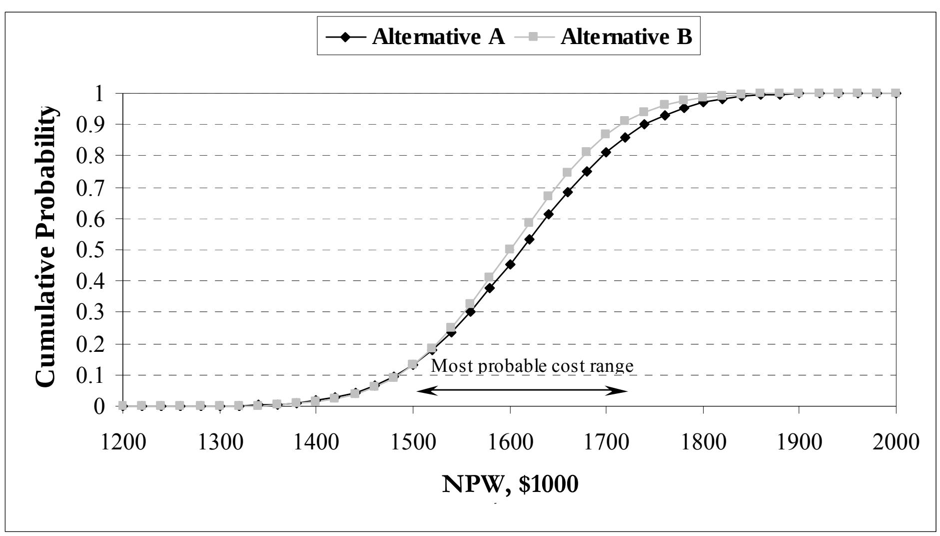

Figure 15. NPW cumulative distributions for alternative strategies A and B.

Evaluation 3—Risk Assessment

If the results of the statistical analysis are not definitive with respect to identifying the most economical strategy, then risk assessment should be performed. The goal of this evaluation is to identify any distinguishing probability characteristics that play to or against an agency's propensity for risk-taking. Since statistical analysis will have revealed no statistically significant difference between the expected means of the lowest-cost alternatives, such distinguishing characteristics may be looked for in the tails of the frequency distribution curves.

Suppose that alternative A from the previous illustration had a slightly lower mean NPW ($1.608 million instead of $1.611 million) and a more dispersed distribution, such that a t-test showed no statistically significant difference between it and alternative B. The frequency distribution curves for the two alternatives would resemble those shown in figure 16. At the tails of these two distributions, there are clear differences in the forecasted NPWs. In the case of alternative A, there is potential for a cost under run if the true NPW is low, say less than $1.45 million. This opportunity for cost savings is termed upside risk. If, on the other hand, the true NPW is high, say greater than $1.75 million, there is potential for a cost overrun associated with alternative A. This chance for financial loss is termed downside risk.

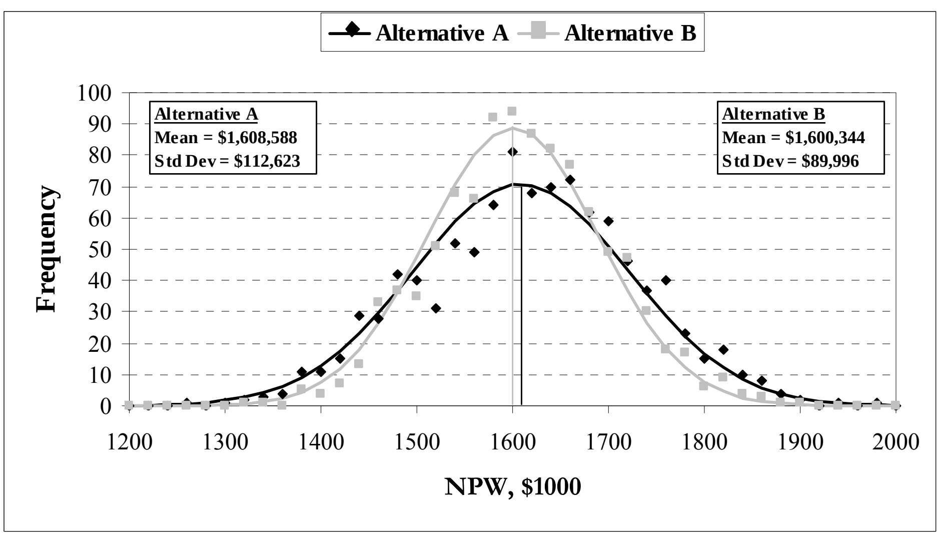

Figure 16. Risk assessment—NPW frequency distributions.

In the cumulative distributions shown in figure 17, it can be seen that there is a 10 percent probability that the NPW of alternative A will be less than alternative B by as much as $26,000. At the other end of the spectrum, there is a 10 percent probability that alternative A will exceed the cost of alternative B by up to $41,000. Although to many agencies this information may be insufficient for identifying the most economical strategy, to some risk-averse agencies it may provide enough assurance that the allocated budget is best served by choosing alternative B. In other words, there is a greater risk of the true cost of alternative A exceeding the cost of alternative B than vice versa.

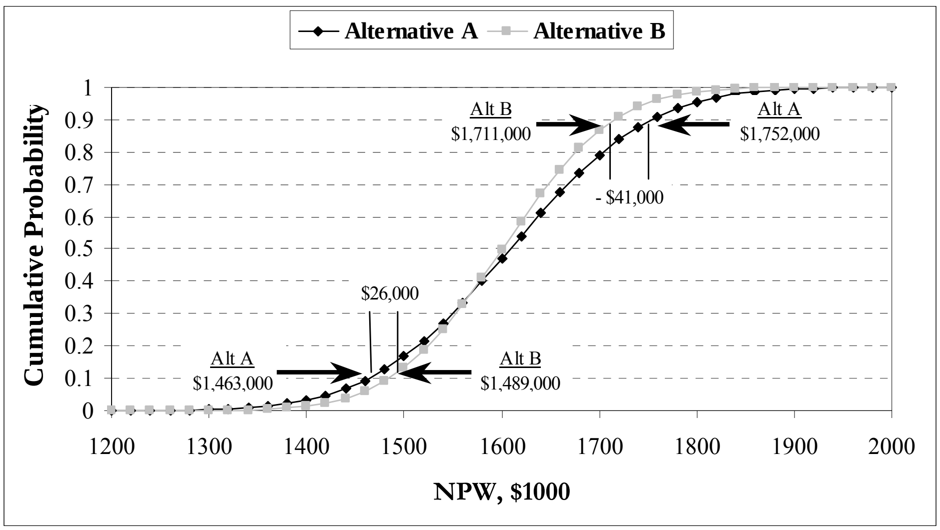

Figure 17. Risk assessment—NPW cumulative distributions.

Step 10—Reevaluate Strategies

In the final step of the LCCA process, information resulting from the LCCA is reevaluated to determine if any modifications to the alternative strategies are warranted, prior to making a final decision on which alternative to use (ARA, 2004). Such adjustments may entail changes to the original structure or rehabilitation treatment, revisions to the maintenance of traffic plans, reductions in construction periods, or changes in future M&R activities.

Probabilistic sensitivity analysis is one technique that can provide insight on the refinement of strategies. This technique uses correlation analysis and tornado plots (figure 18) to show the impacts of key input parameters on life cycle costs. Inputs found to be driving the LCCA results can be looked at more closely to determine if certain actions can be taken to improve cost-effectiveness.

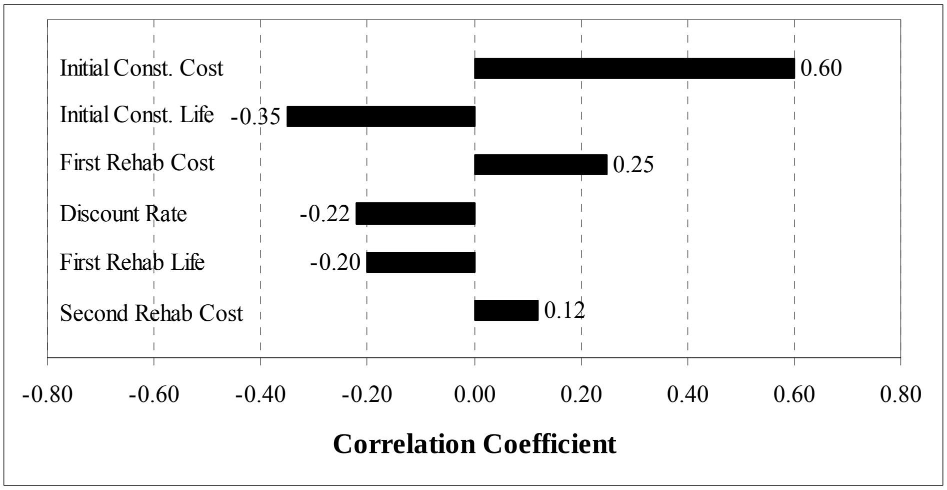

Figure 18. Sensitivity of factors affecting the NPW of a particular pavement strategy.

CHAPTER 4. DEVELOPMENT OF THE LCCA PROGRAM FOR AIRPORT PAVEMENTS

The LCCA program developed in this project is called AirCost. It has been modeled after the FHWA RealCost program and the other highway pavement LCCA programs reviewed in the first phase of the study. In addition, to retain a connection with the structure and layout of past airport pavement LCCAs (e.g., Pensacola, Tulsa), the new program uses the basic computational template utilized in those spreadsheet-based LCCAs.

AirCost is a Microsoft Excel-based program capable of performing both deterministic and probabilistic LCCA for use in traditional and alternate-bid (deterministic only) contracting situations. The program utilizes Visual for Basic Applications (VBA) programming tools to provide a user-friendly GUI and navigational tools to perform probabilistic life cycle cost computations for up to four alternative pavement strategies. Listed below are brief descriptions of some of the key features of the program:

- Main switchboard for navigating to the various input and output screens.
- FAA-based pay item library with default unit costs (mean and standard deviation) that can be modified by the user.
- Input screen for user-defined material/activity pay items and corresponding unit costs (mean and standard deviation).
- Input screen for user to define the LCCA parameters, including:
    - Analysis period.
    - Economic formula—NPW or EUAC.
    - Remaining life salvage value—to include or exclude.
    - Simulation mode (deterministic or probabilistic) for discount rate, pay item unit costs, and pavement service lives.
    - Discount rate value (mean for deterministic, mean and standard deviation for probabilistic).
    - Other direct costs—administrative, engineering, maintenance of traffic expressed as percentages of construction cost.
    - User costs—to include or exclude, total airport daily revenue.

- Ability to analyze up to four different pavement strategy alternatives for a given airport pavement project. For each strategy, the user has the ability to:
  - Assign the pavement strategy name.
  - Define the initial construction/rehabilitation event in terms of the specific pay items and quantities comprising the event, the estimated service life (mean value for deterministic LCCA, mean and standard deviation for probabilistic LCCA) of the event, the duration of the event and the percent reduction in airport daily revenues (if user costs are considered), and the scheduled maintenance activities (types, timings, and quantities) for the pavement associated with the event.
  - Define up to six future rehabilitation events in terms of the specific pay items and quantities comprising each event, the estimated service lives (mean value for deterministic LCCA, mean and standard deviation for probabilistic LCCA) of each event, the duration of each event and the corresponding percent reduction in airport daily revenues (if user costs are considered), and the scheduled maintenance activities (types, timings, and quantities) for the pavement associated with each event.
- Input screen for user-defined simulation parameters, including number of iterations, convergence monitoring, and probabilistic reporting levels.
- Deterministic and probabilistic simulation output tables.
- File management capabilities, including saving and exiting the workbook.

Appendix C includes the AirCost user manual.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

Summary

This study utilized information gathered through a comprehensive literature review and through surveys with airport sponsor/consultant representatives to develop guidance and recommendations for performing airport pavement LCCA. It also evaluated several LCCA spreadsheets and software programs to help guide the development of a spreadsheet-based probabilistic LCCA program for use by airport sponsors and/or their consultants.

The recommended LCCA practice involves the following process:

1. Define project scope.
2. Establish LCCA framework.
3. Develop alternative pavement strategies.
4. Determine expected pavement performance and M&R activity timings.
5. Estimate direct/owner costs.
6. Estimate indirect/user costs.
7. Develop expenditure stream diagram.
8. Compute life cycle costs.
9. Analyze results.
10. Reevaluate pavement strategies.

The process is conducive to both traditional and alternate bidding approaches. However, since alternate bidding uses a discrete life cycle cost adjustment factor for each alternative strategy, only a deterministic computation of the life cycle costs associated with future expenditures is needed for projects utilizing the alternate bidding approach.

Key recommendations made concerning airport pavement LCCA include the following:

- Selection of discount rate in accordance with the long-term (10-, 20-, or 30-year) Treasury rate values provided in OMB Circular A-94 (appendix C).

- Use of a longer analysis period than the 20-year analysis period currently recommended by FAA. For new/reconstruction projects, an analysis period of at least 40 years is considered appropriate, while for rehabilitation projects, an analysis period of at least 30 years is considered appropriate.
- Continued use of the NPW economic formula, using constant/real dollars and a discount rate selected in accordance with OMB Circular A-94.
- Consideration of the inclusion of indirect/user costs in the form of reduced daily operating revenue for the airport due to cancellations and delays caused by partial or full pavement facility closures.
- Use of probabilistic LCCA procedures when reliable historical data exist to model one or more of the input parameters (e.g., discount rate, unit costs, pavement service lives). Use of deterministic LCCA with sensitivity testing of key input parameters (discount rate, major unit costs associated with the initial pavement structures, service life estimates of the initial structures) when probabilistic LCCA is not appropriate.
- Estimation of pavement service life using performance trend analysis or survival analysis techniques, when sufficient and reliable pavement history (construction and M&R activities and dates) and performance (time-series pavement condition data) data exist.
- Development of expected future M&R treatment types and extents based on pavement history and pavement management records.
- Inclusion of remaining life salvage value component, particularly when shorter analysis periods (30 to 40 years) are used.
- Analysis and interpretation of probabilistic LCCA results using the following three-step process:
    1. Trial-by-trial comparisons of forecasted NPW/EUAC values.
    2. Statistical analysis—differences between mean values.
    3. Risk assessment of forecasted NPW/EUAC distributions.

The recommended LCCA practices were incorporated into a new Microsoft Excel-based program, AirCost. AirCost is modeled after the FHWA RealCost program and other highway pavement LCCA programs, but it retains the basic computational template utilized in current airport sponsor/consultant LCCA spreadsheets. The program utilizes VBA programming tools to provide a user-friendly GUI and navigational tools to perform probabilistic life cycle cost computations for up to four alternative pavement strategies.

Recommendations

The LCCA guidelines and recommended practices presented in this report are a significant step toward a more transparent and fair process in the economic evaluation of alternative pavement strategies for airport pavement projects. The process is built upon principles and procedures that are regarded as successful in both the airports and highways arenas. Options are provided that allow airport sponsors/consultants some flexibility in the application of LCCA, based on the availability of cost and performance data and the desire to capture indirect/user costs.

Pavement technologies will continue to advance, prompting the need to revisit and update the airport pavement LCCA process. A substantial amount of research related to pavement type selection and LCCA is ongoing in the highways area, including NCHRP Project 10-75 (Guide for Pavement Type Selection) and the FHWA LCCA for Asset Management project. Findings from these and other studies undoubtedly will provide ideas for improvements to the process described in this report.

Additional suggestions for future improvements to the airport LCCA process include the investigation and possible development of methods for:

- Considering other forms of indirect/user costs, such as airline and passenger delay costs.
- Quantifying the costs of different pavement types based on a cost-to-own concept.
- Estimating pavement performance using FAARFIELD, PCASE, and other pavement design software.
- Estimating construction and M&R costs that are more reflective of the costs at the time the project is let (traditional LCCA often involves a 1- to 3-year gap between the time a pavement type is selected and the time it is put to bid).

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APPENDICES

APPENDIX A. AIRPORT SPONSOR/CONSULTANT LCCA SPREADSHEETS

Pensacola Regional Airport, 2005 Runway Reconstruction

In this unique alternate bidding project, the City of Pensacola provided an addendum to the contract documents and specifications that specified how the LCCA was to be performed by each responsive bidder for the Runway 17-35 reconstruction project. The City did this to ensure a competitive environment so that both asphalt and concrete would be evaluated fairly. The City also provided a Microsoft Excel spreadsheet that bidders were to use to enter their bid prices, determine their level of competitiveness based on the projected life cycle costs, and adjust their bids, as desired. Bidders were given the option of bidding on either pavement type or both.

The deterministic LCCA behind the alternate bidding process used an analysis period of 20 years and an inflation factor of 5 percent. Expected asphalt life was 30 years, and expected concrete life was 40 years. Maintenance schedules were specified as shown in table A-1.

Table A-1. Maintenance schedules and unit costs for Pensacola Airport Runway 17-35 project.

Concrete Runway (17 in)	Asphalt Runway (12 in)
Yr 15 - Joint seal replacement, \$1.70/ft	Yr 6 - Pavement preservation system, \$2.00/yd^2
Yr 19 - Crack seal, \$1.30/yd^2	Yr 13 - Pavement preservation system, \$2.00/yd^2
Yr 20 - 5% slab replacement, \$16.00/yd^2	Yr 15 - Mill & overlay (3 in), \$15.12/yd^2

1 in = 25.4 mm   1 yd^2 = 0.84 m^2

Unit costs for the various maintenance items were provided by either the ACPA or the AI. The salvage value for both alternatives was based on straight-line depreciation of the expected life of the last major rehabilitation activity (i.e., prorated life method). The salvage value was calculated after the mill and overlay at year 15 for the asphalt runway and from year 0 for the concrete runway.

Figure A-1 shows the LCCA computation sheet for one of the alternatives. The bidding resulted in the selection of concrete pavement for the new runway.

Runway 17-35 Reconstruction
Pensacola Regional Airport
Life Cycle Cost Analysis Evaluation
Asphaltic Concrete Runway

DESIGN LIFE (N):	20
EXPECTED LIFE:	30
INFLATION FACTOR: (%)	5

SCHEDULE "B" ASPHALTIC CONCRETE RUNWAY

YEAR (N)	ACTIVITY	ITEM DESCRIPTION	UNIT	COST	QUANTITY	TOTAL COST	PERSENT WORTH FACTOR	PRESENT WORTH
0	INITIAL CONSTRUCTION	12" ASPHALT/5" SUBBASE	SYD	$ 182.17	130,309	23,737,899	1.0000	$ 23,737,899.05
1							0.9524	$ -
2							0.9070	$ -
3							0.8638	$ -
4							0.8227	$ -
5							0.7835	$ -
6	MAINTENANCE	PAVEMENT PRESERVATION SYSTEM	SYD	$ 2.00	130,309	260,618	0.7462	$ 194,477.16
7							0.7107	$ -
8							0.6768	$ -
9							0.6446	$ -
10							0.6139	$ -
11							0.5847	$ -
12							0.5568	$ -
13	MAINTENANCE	PAVEMENT PRESERVATION SYSTEM	SYD	$ 2.00	130,309	260,618	0.5303	$ 138,211.29
14							0.5051	$ -
15	REHABILITATION	MILL AND OVERLAY	SYD	$ 15.12	130,309	1,970,272	0.4810	$ 947,734.56
16							0.4581	$ -
17							0.4363	$ -
18							0.4155	$ -
19							0.3957	$ -
20							0.3769	$ -
SUBTOTAL								$ 25,018,322.06
LESS: SALAVAGE VALUE								$ (495,049.88)
PRESENT WORTH				$ 188.19				$ 24,523,272.18

Notes: Salvage value is based on straight-line depreciation of the expected life of the last rehabilitation item.
Rehabilitation cost based on mill & 3" overlay including paving, mobilization, repainting, (includes transition areas)

Figure A-1. Example of alternate bid LCCA for Pensacola Regional Runway 17-35 project.

Tulsa International Airport, 2004 Runway Rehabilitation

Four alternatives were considered for the rehabilitation of Runway 18L-36R at Tulsa International, which was experiencing significant D-cracking. These included:

- Removal of existing pavement and reconstruction with 17 in (406 mm) PCC and 8-in (203-mm) drainable base.
- 10-in (254-mm) unbonded PCC overlay (includes 2-in [51-mm] AC bond breaker).
- 5-in (127-mm) bonded PCC overlay (includes wedge-milling and repair at joints).
- 4-in (102-mm) HMA overlay.

A discount rate of 3 percent and analysis period of 20 years were utilized in the deterministic LCCA. Maintenance activities included routing and sealing joints and cracks, applying seal coats to the asphalt runway surface and shoulders, and restriping the runway. Major rehabilitation activities included mill-and-overlay efforts for the asphalt runway and shoulders. Unit costs and schedules for the M&R activities are shown in tables A-2 and A-3, respectively. The salvage value for all alternatives was based on the prorated life method.

Figure A-2 illustrates the LCCA worksheet for one of the alternatives. Based on the LCCA results for each alternative, the consultant recommended to the Tulsa Airport Authority that the bonded PCC overlay be given the strongest consideration.

Table A-2. Initial and future M&R unit costs for Tulsa International Runway 18L-36R project.

Reconstruction	Bonded PCC Overlay	Unbonded PCC Overlay	Asphalt Overlay
Initial Costs	Initial Costs	Initial Costs	Initial Costs
Removal of PCC and base, $9.00/yd^2 17-in PCC, $55.00/yd^2 8-in granular base, $8.00/yd^2	Mill longitudinal & transverse ejoints, $2.50/ft Prepare surface, $1.00/yd^2 5-in bonded PCC, $16.00/yd^2 Shoulder tack coat, $1.00/gal AC on shoulders, $40.00/ton	Tack coat, $1.00/gal AC - Shoulders and bond breaker, $40.00/ton 10-in Unbonded PCC, $32.00/yd^2	Tack coat, $1.00/gal Runway AC, $60.00/ton Shoulder AC, $40.00/ton Saw & seal matching joints, $2.75/ft
M&R Costs	M&R Costs	M&R Costs	M&R Costs
Rout & seal joints, $0.87/ft	Rout & seal joints, $0.87/ft Shoulder seal coat, $1.50/gal	Rout & seal joints, $0.87/ft Shoulder seal coat, $1.50/gal	Rout & seal joints, $1.00/ft Seal coat, $1.50/gal Mill 2-in AC, $2.50/yd^2 Tack coat, $1.00/gal Overlay 2-in AC, $60.00/ton Overlay 2-in shoulder, $40.00/yd^2

1 in = 25.4 mm   1 yd^2 = 0.84 m^2 1 gal = 3.785 L   1 ton = 0.91 Mton

Table A-3. M&R schedules for Tulsa International Runway 18L-36R project.

Reconstruction	**Bonded PCC Overlay**	**Unbonded PCC Overlay**	**Asphalt Overlay**
Yr 6 – Route and seal joints, restripe runway	Yr 6 – Route and seal joints, shoulder seal coat, restripe runway	Yr 6 – Route and seal joints, shoulder seal coat, restripe runway	Yr 3 – Route and seal joints, runway and should seal coat, restripe runway
Yr 12 – Route and seal joints, restripe runway	Yr 12 – route and seal joints, shoulder seal coat, restripe runway	Yr 12 – Route and seal joints, shoulder seal coat, restripe runway	Yr 6 – Route and seal joints, runway and should seal coat, restripe runway
Yr 18 – Route and seal joints, restripe runway	Yr 18 – Route and seal joints, shoulder seal coat, restripe runway	Yr 18 – Route and seal joints, shoulder seal coat, restripe runway	Yr 9 – Mill and overlay runway and shoulders (2 in)
			Yr 12 – Route and seal joints, runway and should seal coat, restripe runway
			Yr 15 – Route and seal joints, runway and should seal coat, restripe runway
			Yr 18 – Mill and overlay runway and shoulders (2 in)

1 in = 25.4 mm

Construct Unbonded PCC Overlay of R/W 18L-36R

Section:	10" PCC	Shoulder area (2 @ 25 ft) ft^2	500,000
Pavement area (8 lanes @ 25 ft/ln) ft^2	2,000,000	Analysis period, years	20
Longitudinal joints, ft	110,000	Initial year of construction	2004
Transverse joints, ft	100,000	Discount rate, %	3.00
Length of runway, ft	10,000		

CONSTRUCTION ITEMS	YEAR	QUANTITY	UNIT	UNIT PRICE	COST	PRESENT WORTH
INITIAL CONSTRUCTION						
Apply Tack Coat on Runway	0	33,333	gal	$1.00	$33,333	$33,333
Place 2" AC Bond Breaker on Runway (145lb/ft3)	0	24,167	ton	$40.00	$966,667	$966,667
Place 10" PCC Unbonded Overlay	0	222,222	yd^2	$32.00	$7,111,111	$7,111,111
Apply Tack Coat on Shoulders	0	8,333	gal	$1.00	$8,333	$8,333
Place 9" AC Binder on Shoulders (145lb/ft3)	0	27,188	ton	$40.00	$1,087,500	$1,087,500
Apply Tack Coat on Shoulders	0	8,333	gal	$1.00	$8,333	$8,333
Place 3" AC Surface on Shoulders (145lb/ft3)	0	9,063	ton	$40.00	$362,500	$362,500
Construct Transitions at Intersections	0	1	ea	$700,000.00	$700,000	$700,000
Restripe Runway	0	1	ea	$35,000.00	$35,000	$35,000
Electrical	0	1	LS	$937,595.00	$937,595	$937,595
Design Costs at 8%	0		Subtotal	$10,312,778	$825,022	$825,022
Inspection Services at 9%	0		Subtotal	$10,312,778	$928,150	$928,150
FUTURE MAINTENANCE & REHABILITATION						
Rout & Seal Joints	6	110,000	ft	$1.95	$214,500	$179,640
Apply Seal Coat to Shoulder Surfaces	6	8,333	gal	$1.50	$12,500	$10,469
Restripe Runway	6	1	ea		$0	$0
Rout & Seal Joints	12	110,000	ft	$1.95	$214,500	$150,446
Apply Seal Coat to Shoulder Surfaces	12	8,333	gal	$1.50	$12,500	$8,767
Restripe Runway	12	1	ea	$35,000.00	$35,000	$24,548
Rout & Seal Joints	18	110,000	ft	$1.95	$214,500	$125,996
Apply Seal Coat to Shoulder Surfaces	18	8,333	gal	$1.50	$12,500	$7,342
Restripe Runway	18	1	ea	$35,000.00	$35,000	$20,559
				TOTAL INITIAL COST:	$13,003,545	$13,003,545
				TOTAL MAINTENANCE AND REHABILITATION COST (year 0 to 20):	$751,000	$527,768
				SALVAGE VALUE:	($4,334,515)	($2,399,916)
				PRESENT WORTH:		**$11,131,397**
				EQUIVALENT UNIFORM ANNUAL COST:		$748,205

Figure A-2. Example of deterministic LCCA for Tulsa International Runway 18L-36R project.

George Bush Intercontinental Airport, 2005 Runway 9-27 Rehabilitation

Two major alternative types were considered for this project:

- 12-in (305-mm) unbonded PCC overlay (includes 1.5-in [38-mm] HMA bond-breaker).
- 7-in (178-mm) mill-and-replace with polymer-modified asphalt (Novophalt) (includes 0.5-in [13-mm] stress absorbing membrane interlayer [SAMI]).

The LCCA report delivered to the project team for review was considered preliminary at the time it was written, so a 20 percent contingency was incorporated into all costs. Unit rates were based on average cost of like items in the Houston Airport System bid tabs from 1997 to 2005. All costs were adjusted to 2005 rates. In addition, local contractors and suppliers were contacted to provide comparison rates, which were used to further refine the unit rates. The variables utilized in the deterministic LCCA included an annual inflation rate of 2 percent, a discount rate of 5 percent, and an analysis period of 25 years. The rate of inflation was estimated over the period of analysis and the discount rate was used to establish the NPW. The M&R schedule used for each alternative in the LCCA are summarized in table A-4. Unit cost information was not available.

Table A-4. M&R schedules for George Bush Intercontinental Runway 9-27 project

Concrete Runway (12 in)	Asphalt Runway (7 in)
Longitudinal repair, 1% of total quantity per year	Years 11 and 21, Mill and overlay
Transverse joint repair, 1% total quantity per year	
Spall repair, 0.01% per year	

1 in = 25.4 mm

The results of the preliminary LCCA showed the concrete alternative as having the lower NPW, primarily because of the difference in the number of future major interventions projected for each (2 for the asphalt alternative, 0 for the concrete alternative). A more detailed analysis was planned that would include more up-to-date and accurate information, as well as information on electrical circuitry requirements.

JFK International Airport, 2007 Runway 13R-31L Construction

Two major alternatives were considered for the JFK Runway 13R-31L construction project:

- 18-in (457-mm) PCC.
- 9-in (229-mm) HMA.

Each alternative included sub-alternatives in terms of full-closure, partial-closure, and night work scenarios.

A discount rate of 3.5 percent and an analysis period of 40 years were used in the LCCA. A detailed M&R schedule was utilized as shown in table A-5. Unit costs used for this project were not available. Salvage costs for the concrete and asphalt alternatives were included, but the exact basis for their derivation was not given.

Table A-5. M&R schedules for JFK International Runway 13R-31L project.

Concrete Runway (18 in)	Asphalt Runway (9 in)
Yr 8 – Shoulder/erosion/fillets seal coat, PCC repair (1% of initial cost), regroove, repaint	Yr 8 – Mill and overlay, PCC repair (1% of initial cost), regroove, repaint
Yr 16, Joint seal replacement, shoulder/erosion/fillets mill and overlay, PCC repair (2% of initial cost), regroove, repaint	Yr 16 – Mill and overlay, PCC repair (2% of initial cost), shoulder/erosion mill and overlay, regroove, repaint
Yr 24 – Shoulder/erosion/fillets seal coat, PCC repair (2% of initial cost), regroove, repaint	Yr 24 – Mill and overlay, PCC repair (2% of initial cost), regroove, repaint
Yr 32, Joint seal replacement, shoulder/erosion/fillets mill and overlay, PCC repair (2% of initial cost), regroove, repaint	Yr 16 – Mill and overlay, PCC repair (4% of initial cost), shoulder/erosion mill and overlay, regroove, repaint

1 in = 25.4 mm

Figure A-3 illustrates the LCCA template established for one of the alternatives, with dummy values inserted instead of the actual values. Figure A-4 shows the LCCA comparison template, equipped for discount rate sensitivity analysis.

Runway 13R-31L Reconstruction
John F. Kennedy International Airport
Life Cycle Cost Analysis Evaluation

Asphalt Approach, Option - 3A "Full Closure"

Discount Rate - BASED ON 2007 (%) 3.5%

YEAR (N)	ACTIVITY	ITEM DESCRIPTION	TOTAL COST	PRESENT WORTH FACTOR	PRESENT WORTH
0	INITIAL CONSTRUCTION	SEE NOTE	**$ 1,000,000**	1.0000	$ 1,000,000
1				0.9662	$ -
2				0.9335	$ -
3				0.9019	$ -
4				0.8714	$ -
5				0.8420	$ -
6				0.8135	$ -
7				0.7860	$ -
8	REHABILITATION - 1A	SEE NOTE	$ 1,000,000	0.7594	$ 759,412
9				0.7337	$ -
10				0.7089	$ -
11				0.6849	$ -
12				0.6618	$ -
13				0.6394	$ -
14				0.6178	$ -
15				0.5969	$ -
16	REHABILITATION - 2A	SEE NOTE	$ 1,000,000	0.5767	$ 576,706
17				0.5572	$ -
18				0.5384	$ -
19				0.5202	$ -
20				0.5026	$ -
21				0.4856	$ -
22				0.4692	$ -
23				0.4533	$ -
24	REHABILITATION - 3A	SEE NOTE	$ 1,000,000	0.4380	$ 437,957
25				0.4231	$ -
26				0.4088	$ -
27				0.3950	$ -
28				0.3817	$ -
29				0.3687	$ -
30				0.3563	$ -
31				0.3442	$ -
32	REHABILITATION - 4A	SEE NOTE	$ 1,000,000	0.3326	$ 332,590
33				0.3213	$ -
34				0.3105	$ -
35				0.3000	$ -
36				0.2898	$ -
37				0.2800	$ -
38				0.2706	$ -
39				0.2614	$ -
40	SALVAGE VALUE	SEE NOTE	$ 99,754,350	0.2526	$ 25,195,202
PRESENT WORTH IN 2007 DOLLARS					**$ 28,302,000**

Note:

INITIAL CONSTRUCTION	9" AC, AC SHOULDERS/EROSION/FILLETS, SAFETY AREA REGARDING, NEW ELECTRICAL
REHABILITATION - 1A	MILL & OVERLAY, (3"-M, 4"-O), PCC REPAIR (1% OF INITIAL COST OF CONCRETE), REPAINT
REHABILITATION - 2A	MILL & OVERLAY, (6"-M, 7"-O), PCC REPAIR (2% OF INITIAL COST OF CONCRETE), SHOULDER/ EROSION M&O (3"-M, 4"-O), REPAINT
REHABILITATION - 3A	MILL & OVERLAY, (3"-M, 4"-O), PCC REPAIR (2% OF INITIAL COST OF CONCRETE), REPAINT
REHABILITATION - 4A	MILL & OVERLAY, (6"-M, 7"-O), PCC REPAIR (4% OF INITIAL COST OF CONCRETE), SHOULDER/ EROSION M&O (3"-M, 4"-O), REPAINT
SALVAGE VALUE	40" AC FULL DEPTH ASPHALT CONCRETE CONSTRUCTION MINUS ASPHALT RUNWAY

Figure A-3. Deterministic LCCA template for JFK International Runway 13R-31L project.

Comparison of alternative options NPVs ($1,000,000) to discount rate.

Activity	Net Present Value (NPV)				
	2%	3%	4%	5%	6%
ASPHALT - Option Plan 1A "Night Work"	1	1	1	1	1
ASPHALT - Option Plan 2A "Partial Use"	1	1	1	1	1
ASPHALT - Option Plan 3A "Full Closure"	1	1	1	1	1
Concrete - Option Plan 2C "Partial Use"	1	1	1	1	1
Concrete - Option Plan 3C "Full Closure"	1	1	1	1	1
Cost Advantage Alt. 2C vs Alt. 1A	-	-	-	-	-
Cost Advantage Alt. 2C vs Alt. 2A	-	-	-	-	-

Note:
** Cost in "Year - 0" dollars.*

Figure A-4. Deterministic LCCA alternative comparison template for JFK Runway 13R-31L.

Jefferson County (Colorado) Airport, Taxiway A and Apron Construction

Two alternative pavement types were considered for the Jefferson County Airport construction project:

- 12-in (305-mm) PCC placed on 6-in (152-mm) stabilized permeable base.
- 6-in (152-mm) HMA placed on 6-in (152-mm) stabilized permeable base and 12-in (305-mm) lime-stabilized subgrade.

A discount rate of 4 percent and an analysis period of 40 years were used in the deterministic LCCA. The unit costs and M&R schedules for each pavement alternative are shown in tables A-6 and A-7, respectively. A salvage value was not used in either analysis, although the spreadsheet provided by the consultant contained a placeholder for this value.

An example of the LCCA computation worksheet used for one of the alternatives is provided in figure A-5. The asphalt alternative resulted in the lowest NPW and is assumed to have been selected for use.

Table A-6. Initial and future M&R unit costs for Jefferson County Taxiway A and Apron project.

Concrete Pavement (12 in)	**Asphalt Pavement (6 in)**
Initial Costs	Initial Costs
12 in PCC, $40.00/yd^2	6 in Asphalt, $18.50/yd^2
6 in Stabilized base, $14.50/yd^2	6 in Stabilized base, $14.50/yd^2
12 in Stabilized subgrade, $4.75/yd^2	Geotextile, $1.50/yd^2
	12 in lime-stabilized subgrade, $4.75/yd^2
M&R Costs	M&R Costs
Joint seal, spall repair, slab replacement, $3.20/yd^2	Crack sealing, $1.25/yd^2 Seal coat, $0.35/yd^2 4-in Mill and overlay, $14.50/yd^2 Full-depth mill and new AC, $24.50/yd^2

1 in = 25.4 mm

Table A-7. M&R schedules for Jefferson County Taxiway A and Apron project

Concrete Pavement (12 in)	**Asphalt Pavement (6 in)**
Yr 20, Joint seal, spall repair, slab replacement	Yr 4, Crack sealing
Yr 40, Joint seal, spall repair, slab replacement	Yr 8, Crack sealing
	Yr 9, Seal coat
	Yr 12, Crack sealing
	Yr 15, 4 in Mill and overlay
	Yr 19, Crack sealing
	Yr 23, Crack sealing
	Yr 24, Seal coat
	Yr 28, Crack sealing
	Yr 30, Full-depth mill and new AC
	Yr 34, Crack sealing
	Yr 38, Crack sealing
	Yr 39, Seal coat

1 in = 25.4 mm

PORTLAND CEMENT CONCRETE				
Year	Action	Cost ($/SY)	Present Worth Factor (4%)	Present Worth ($)
0	New Pavement	$59.25	1.0000	$59.25
1			0.9615	$0.00
2			0.9246	$0.00
3			0.8890	$0.00
4			0.8548	$0.00
5			0.8219	$0.00
6			0.7903	$0.00
7			0.7599	$0.00
8			0.7307	$0.00
9			0.7026	$0.00
10			0.6756	$0.00
11			0.6496	$0.00
12			0.6246	$0.00
13			0.6006	$0.00
14			0.5775	$0.00
15			0.5553	$0.00
16			0.5339	$0.00
17			0.5134	$0.00
18			0.4936	$0.00
19			0.4746	$0.00
20	Joint Seal, Spall Repair, Slab Replacement	$3.20	0.4564	$1.46
21			0.4388	$0.00
22			0.4220	$0.00
23			0.4057	$0.00
24			0.3901	$0.00
25			0.3751	$0.00
26			0.3607	$0.00
27			0.3468	$0.00
28			0.3335	$0.00
29			0.3207	$0.00
30			0.3083	$0.00
31			0.2965	$0.00
32			0.2851	$0.00
33			0.2741	$0.00
34			0.2636	$0.00
35			0.2534	$0.00
36			0.2437	$0.00
37			0.2343	$0.00
38			0.2253	$0.00
39			0.2166	$0.00
20	Joint Seal, Spall Repair, Slab Replacement	$3.20	0.4564	$1.46
	Sub Total	$62.45		
	Salvage Value	$0.00	0.2083	$0.00
	TOTAL	$62.45		***$60.71***

Figure A-5. Deterministic LCCA template for Jefferson County Taxiway A and Apron project.

APPENDIX B. HIGHWAY AGENCY LCCA PROGRAMS

FHWA RealCost

FHWA's RealCost is a Microsoft Excel-based probabilistic program that utilizes the principles and procedures contained in the FHWA *Interim Technical Bulletin on LCCA*. The program was developed by the FHWA in 2002/2003, based on the DP 115 prototype program used in the FHWA-sponsored LCCA workshops/demonstrations. The RealCost program includes VBA programming functions instead of the @Risk add-in program to perform the probabilistic simulations.

RealCost applies a simulation technique that entails defining individual input parameters by either a frequency (or probability) distribution or by a discrete value, as is done typically in deterministic LCCA, and computing life cycle costs (using an iterative sampling of the pre-defined frequency distributions of each input variable for the probabilistic approach). The resulting life cycle costs (NPW as a discrete average cost or a probability distribution of costs), can then be examined and compared with the cost or cost distribution of a competing design alternatives. The technique utilized by RealCost for probability simulation is the Monte Carlo method and is illustrated in figure B-1 (Walls and Smith, 1998). Both agency and user costs (delay costs and vehicle operating costs associated with construction and rehabilitation activities) can be computed, with separate display of results.

The RealCost program generally is user-friendly and straightforward in its application. It has two interface mechanisms—the form GUI and the worksheet interface (FHWA, 2004). While the form GUI is the primary means of interacting with the software, all of the entered data are stored in worksheet cells, as are all outputs (calculation results, analysis results, etc.).

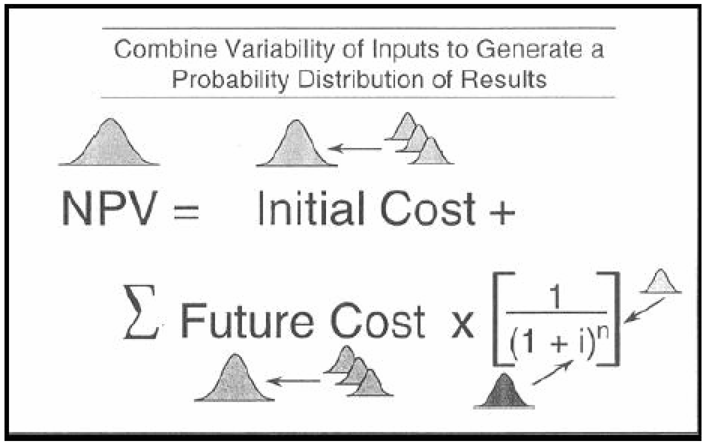


Figure B-1. NPW distribution generation (Walls and Smith, 1998).

Figure B-2 shows the program layout (i.e., the main switchboard) for RealCost. The layout shows the various function and inputs of the program and inputs required for analysis. Figures B-3 through B-8 show various GUI screen shots associated with input information, such as project details, LCCA analysis options, traffic, initial and subsequent rehabilitation costs and service lives, and probabilistic simulation. Figures B-9 and B-10 illustrate some of the LCCA outputs.

In addition to tabular and graphical outputs, RealCost supports deterministic sensitivity analyses and probabilistic risk analyses (FHWA, 2004). Input files for each pavement alternative being considered can be saved and brought in, as needed, for comparing any number of alternatives.

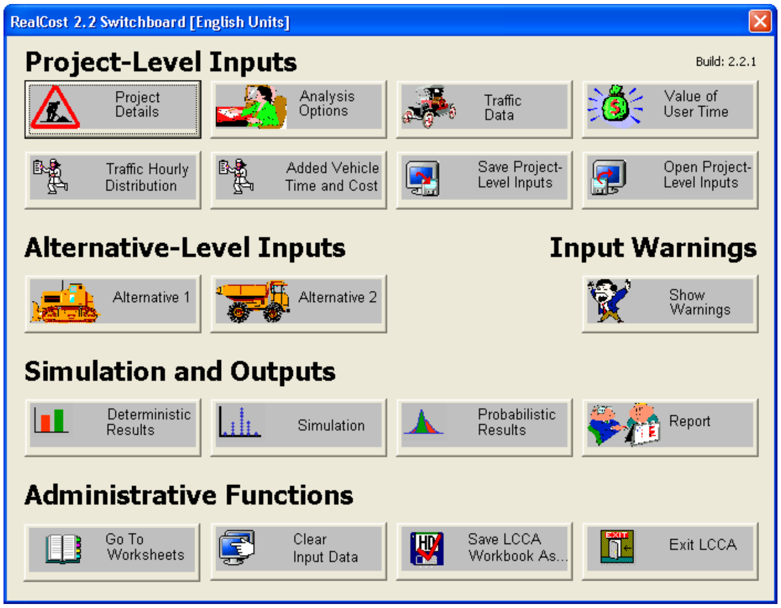


Figure B-2. Overall program layout for RealCost.

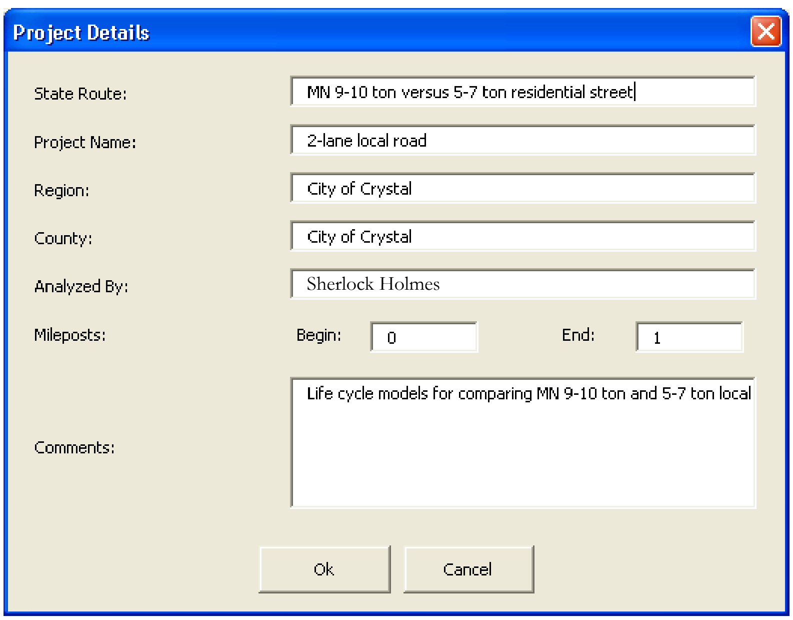


Figure B-3. Project details screen shot.

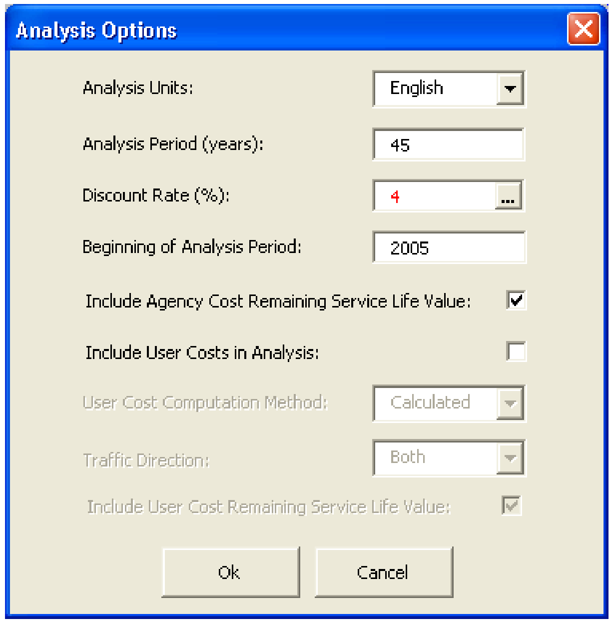


Figure B-4. Screen shot of analysis options for computing life cycle costs.

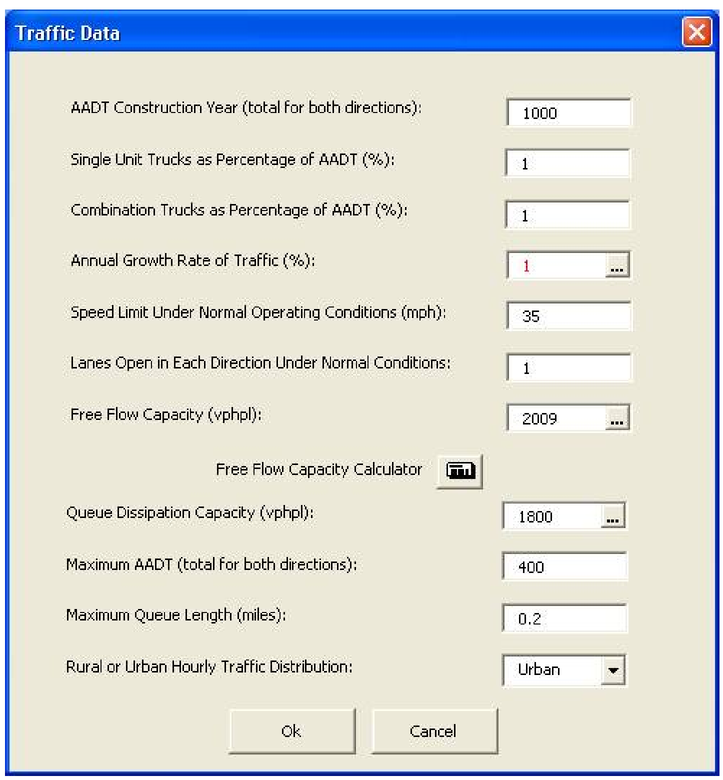


Figure B-5. Traffic data screen shot.

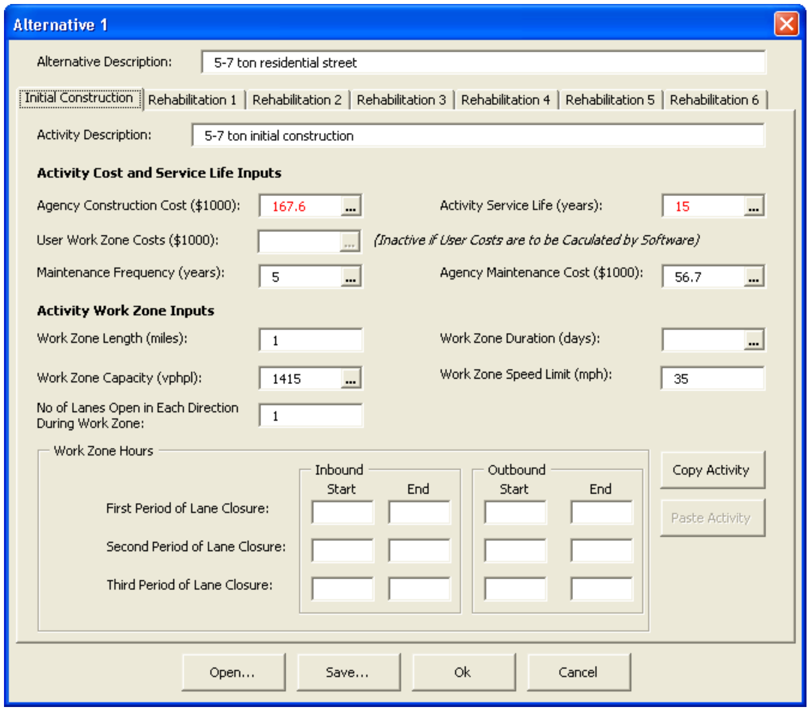


Figure B-6. Activity cost, service life, and activity work zone inputs associated with initial construction for a particular pavement alternative.

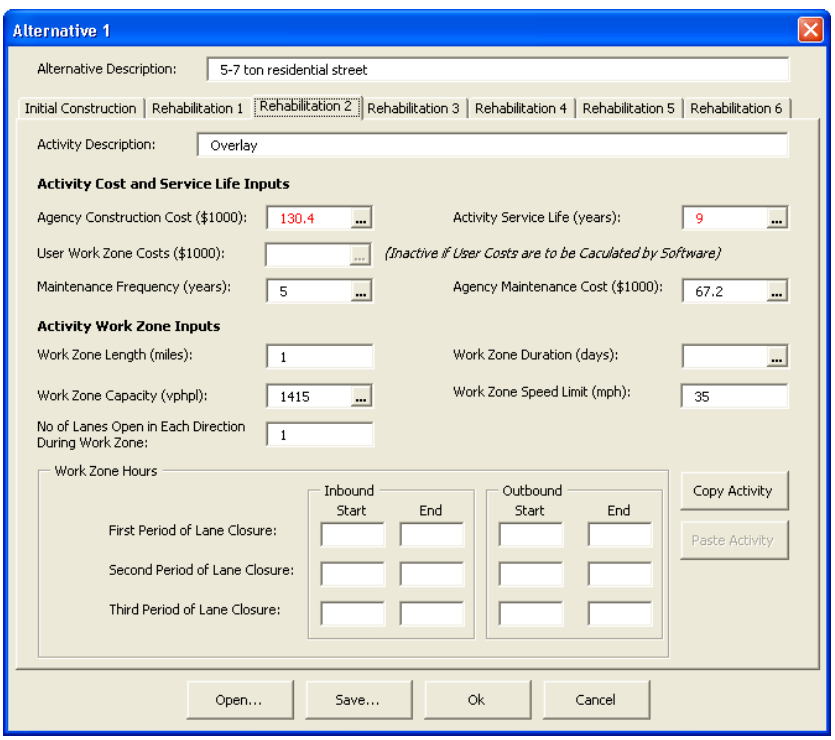


Figure B-7. Activity cost, service life, and activity work zone inputs associated with second rehabilitation for a particular pavement alternative.

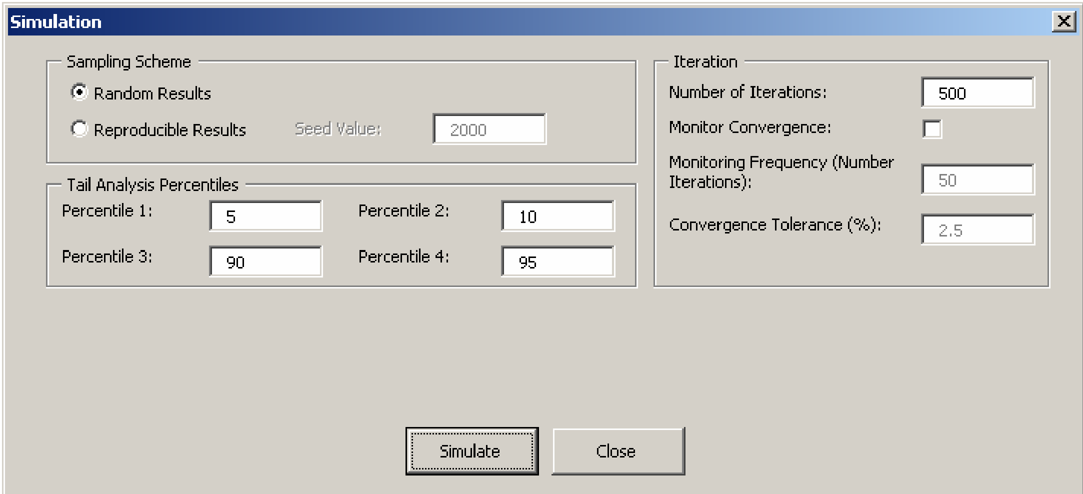
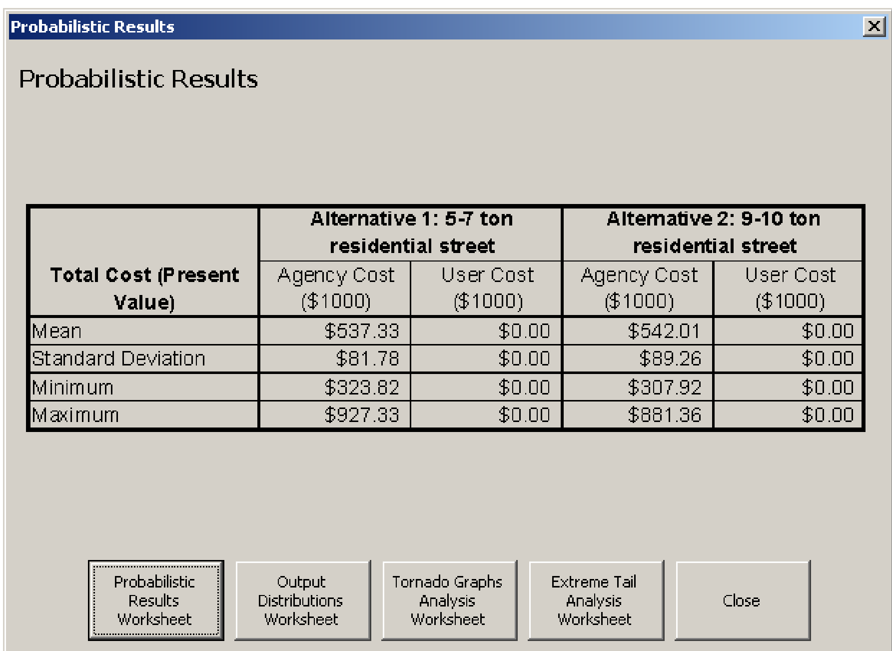


Figure B-8. Input screen showing sampling scheme, number of iterations, and convergence tolerance for LCCA.



Total Cost (Present Value)	Alternative 1: 5-7 ton residential street		Alternative 2: 9-10 ton residential street	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Mean	$537.33	$0.00	$542.01	$0.00
Standard Deviation	$81.78	$0.00	$89.26	$0.00
Minimum	$323.82	$0.00	$307.92	$0.00
Maximum	$927.33	$0.00	$881.36	$0.00

Figure B-9. Output screen showing computed life cycle costs for a particular pavement alternative, along with basic descriptive statistics.

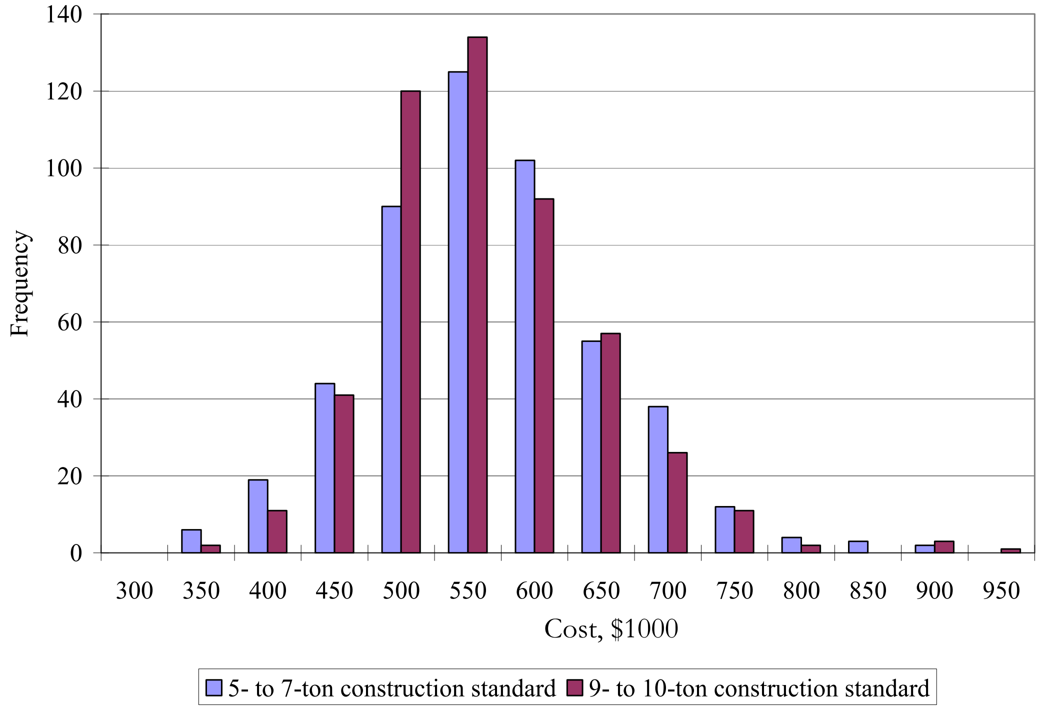


Figure B-10. Histogram distribution of life cycle costs for two alternative designs using probabilistic simulation.

Minimum system requirements for RealCost include Excel 2000 and Windows 98 operating from a computer with a 350 MHz Pentium processor, 128 MB of RAM, and 100 MB of hard drive space. Noted shortcomings of the program include the following (Lamptey et al., 2005):

- The current version is not flexible to accommodate different overall analysis periods for different alternatives.
- Software can handle only two alternatives at a time.
- Value of some inputs, such as travel time, are not updated automatically to future years using appropriate consumer price index.
- Trigger values (an alternative to "activity life") are not considered for use as an alternative treatment timing criteria in the formulation of M&R strategies.
- User is not provided a default or modifiable set of pavement design alternatives that are typical of a given agency's practice.
- User is not provided a set of pavement M&R strategies (over a life cycle) that are typical of an agency's practice.

- User is not provided an automated method to compute agency costs on the basis of line items and their unit rates based on reliable data of such contractual work activities

State DOT Adaptations of RealCost

Based on a recent survey by the South Carolina DOT (South Carolina DOT, 2005), eight SHAs have adopted and/or customized the RealCost program for conducting LCCAs:

- Caltrans—Chose RealCost as the official software for evaluating the cost-effectiveness of alternative pavement designs for new roadways and for existing roadways requiring capital preventive maintenance or rehabilitation/reconstruction (Caltrans, 2007). Because probability distribution functions for individual LCCA input variables are still under development, Caltrans only uses the deterministic approach at this time.
- Colorado DOT—In 2004, formed a task force to investigate which probabilistic LCCA software to use, and RealCost was selected unanimously (Demos, 2006).
- Indiana DOT—Modified and enhanced RealCost software package to suit Indiana's pavement design and maintenance practices (Lamptey et al., 2003). The program, called RealCost-IN, was written using Microsoft Visual Basic.NET and SQL. It is a PC-based Windows program and can run in either the Windows 9X or XP environments. Modifications and enhancements made to the existing RealCost program included:
  - Mechanism for estimating costs of construction and M&R activities based on pay items and their unit costs.
  - Ability to simultaneously carry out analysis for more than two alternatives.
  - The form of menus of default M&R strategies, such that they are modifiable by the user.
  - Improved GUI data input forms and output displays/reporting.
  - Ability of user to specify the percentage of user cost to be used in the analysis.

APA LCCA (version 3.1)

APA's LCCA program is based on the procedures contained in the FHWA *Interim Technical Bulletin on LCCA*. It has the ability to perform LCCA in either a probabilistic or deterministic mode for up to four alternatives, with probabilistic variables consisting of discount rate, traffic growth, and construction duration (Ozbay, 2003). It allows for the inclusion of user costs resulting from delay time during work zones and generates the resulting detailed analysis graphically and in Excel format. Figure B-11 shows the main screen for the program.

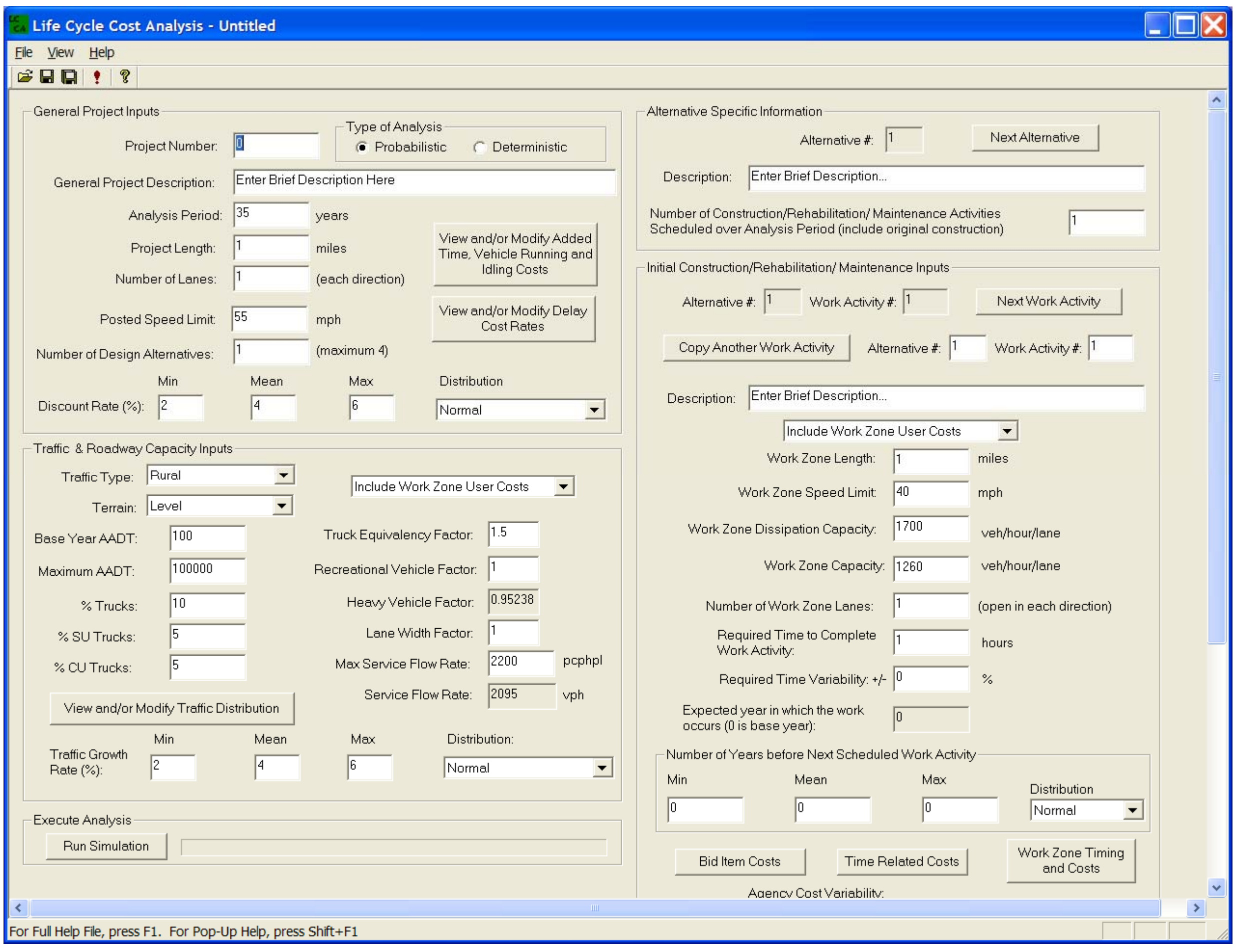


Figure B-11. Main screen of APA LCCA software program.

The APA program has been noted to be more user-friendly than other LCCA programs and has an elaborate module for work zone user cost computation (one that optimizes work zone timing to minimize user costs based on the hourly traffic distribution and the work-zone duration)

(Lamptey et al., 2005). Noted shortcomings include limited analysis capacity (only four alternatives can be considered at once, not flexible to accommodate different analysis periods for different alternatives) and inability to compute user costs during normal traffic operation (Lamptey et al., 2005). Also, the program is handicapped by the large number of variables and assumptions that have to be considered to run the analysis, thus making it almost impossible to justify the results generated for each pavement type selection (Missouri DOT, 2004).

NLA Asphalt LCCA (version 1.3)

The NLA LCCA software package is a Windows-based application that was developed to perform economic analyses of two asphalt pavement alternatives subject to future M&R activities (Hicks and Scholz, 2003). The methodology is based on the approach developed by the FHWA (Walls and Smith, 1998). The software allows analyses for both new construction and rehabilitation projects and supports both deterministic and probabilistic analyses.

Figures B-12 through B-15 illustrate some of the primary input screens of the NLA LCCA program. The program's GUI interacts with a 32-bit Microsoft Access 97 database. All data utilized by the LCCA software package are contained in the database. System operating requirements include Windows 98, 200, or NT 4.0, Pentium central processing unit (CPU), 20 MB of hard disk space, and 16 MB RAM.

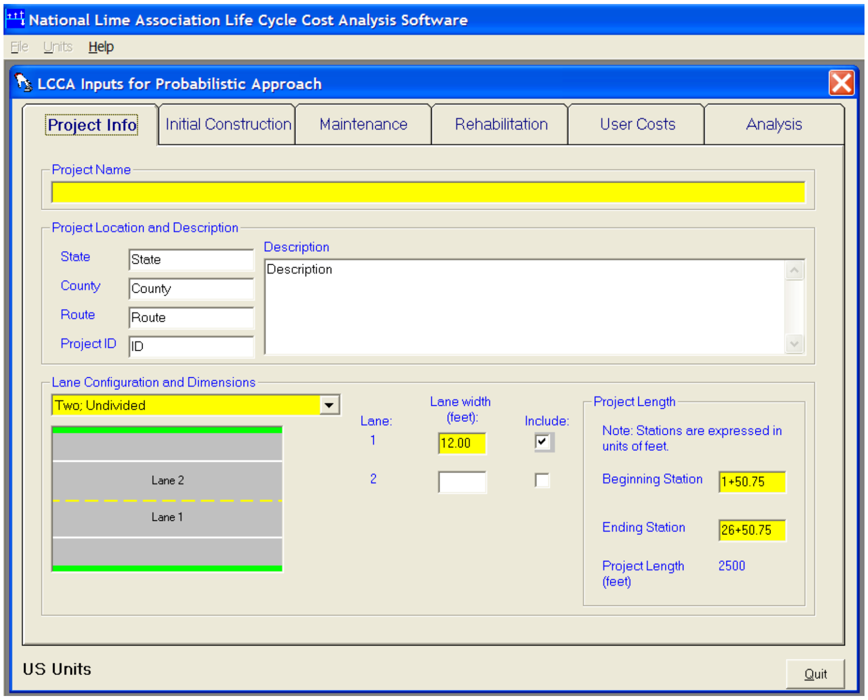


Figure B-12. NLA LCCA project information screen.

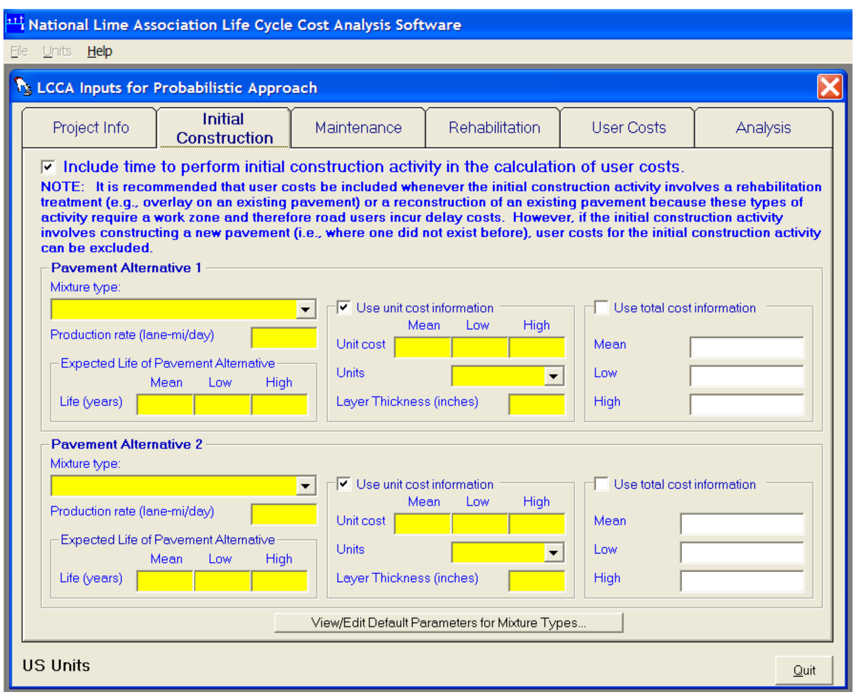


Figure B-13. NLA LCCA initial construction screen.

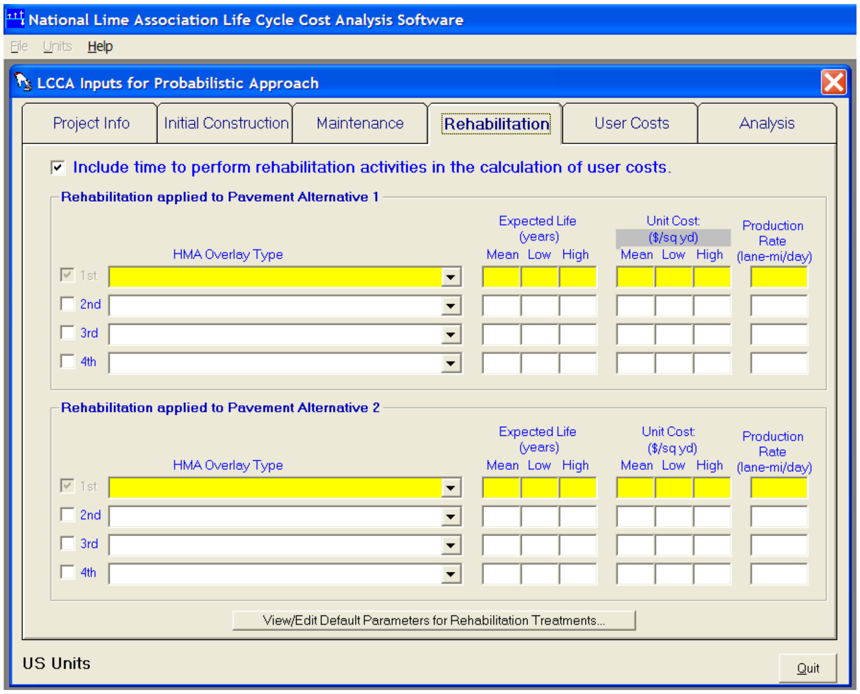


Figure B-14. NLA LCCA rehabilitation screen.

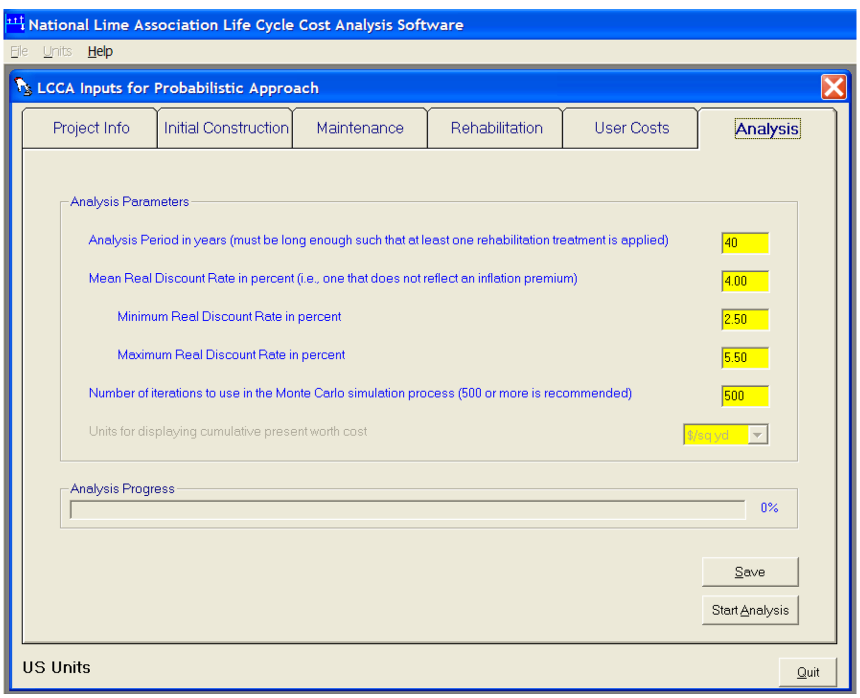


Figure B-15. NLA LCCA analysis screen.

Key assumptions and features of the program include equal VOCs and crash costs, lane rental fees used as a surrogate for user delay costs, prorated life method used in computing salvage value, and normal (Gaussian) distributions for the probabilistic variables (i.e., treatment lives, treatment costs, and discount rate) (Hicks and Scholz, 2003). Noted limitations of the program include the fact that 1) only one type of maintenance treatment can be applied to a pavement alternative, and future costs are in real (constant) dollars and the discount rate is a real discount rate (one that does not reflect an inflation premium).

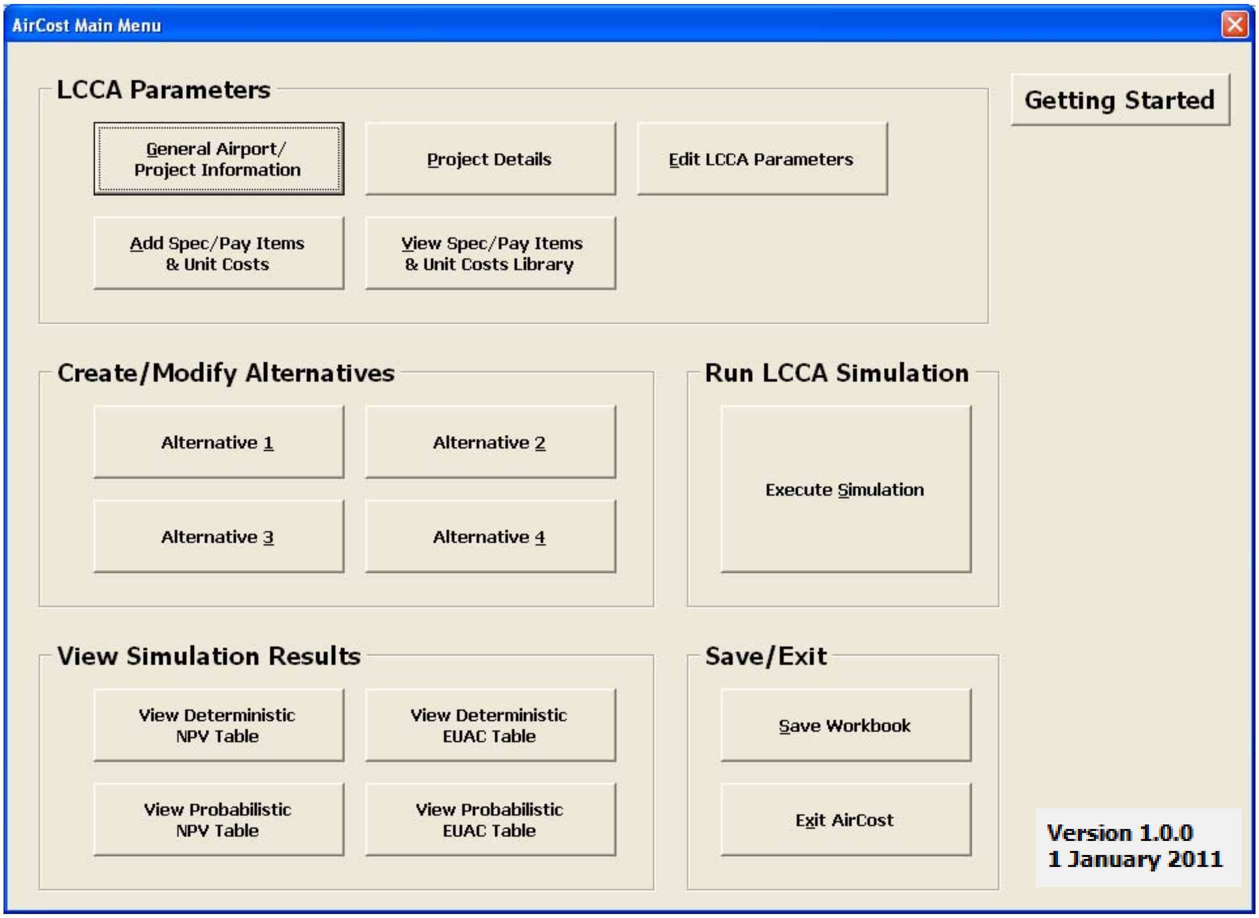
APPENDIX C. AIRCOST USER MANUAL

Introduction

AirCost® is a life cycle analysis tool for airport pavement maintenance. AirCost allows users to analyze and document airport pavement cost activities as well as perform scenario analysis for future needs and cost requirements. AirCost is built as an application with Microsoft Excel. This provides an easy-to-use tool with the benefits of the standard Excel features, functionality, and familiarity.

AirCost Application Interface

Below is an example of the main AirCost interface, showing the component modules of the application.



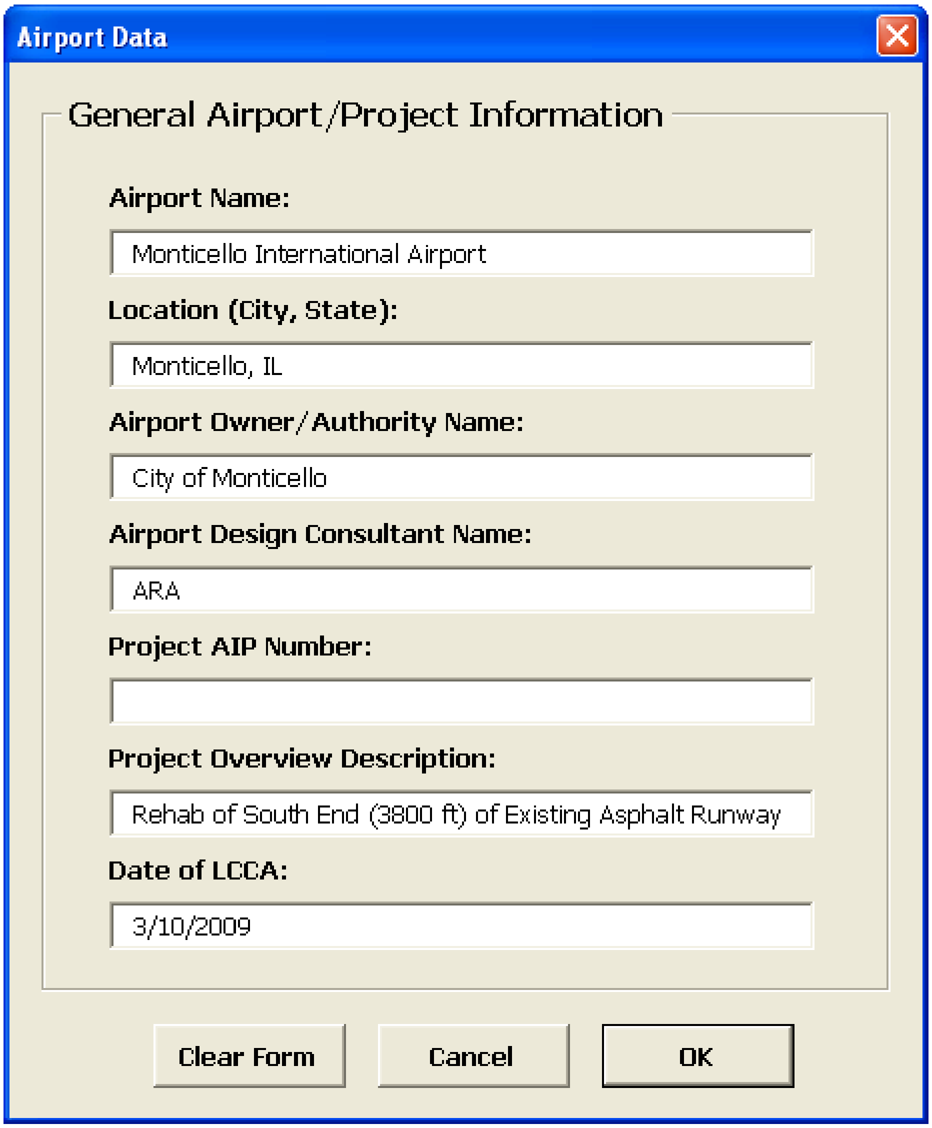
LCCA Parameters

The LCCA Parameters module allows the user to input information into the system for subsequent analysis. As shown in the screen above, this module includes five elements:

- General Airport/Project Information.
- Project Details.
- Edit LCCA Parameters.
- Add Spec/Pay Items & Unit Costs.
- View Spec/Pay Items & Unit Costs Library.

General Airport/Project Information

Click on General Airport/Project Information to input details for the airport project.



1. Click the Clear Form button to clear the current data from the form.

2. Enter the correct data in the corresponding fields:

   i. Airport Name – Specify the name of the airport where work is performed.

   ii. Location (City, state) – Specify the city and the state for the airport.

iii. Airport Owner/Authority – Specify the owner/authority for the airport.

iv. Airport Design Consultant Name – Specify the organization that is performing the work at the airport.

v. Project AIP Number - Specify the Airport Improvement Program (AIP) project number.

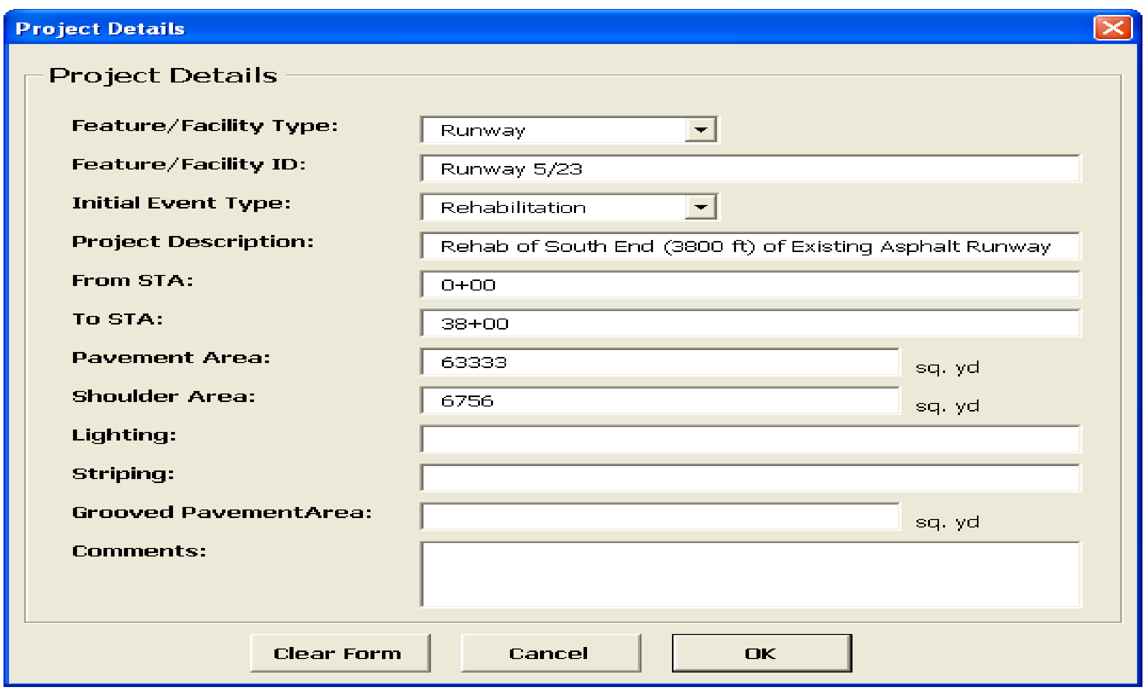
vi. Project Overview Description – Provide a brief description of the project and the work to be performed.

vii. Date of LCCA – Specify the date when the LCCA assessment was performed.

3. Click OK to save the data and return to the main screen.

Project Details

The Project Details screen allows the user to input specific details regarding the category of work to be performed at the airport.



1. Click the Clear Form button to clear the current data from the form.

2. Enter the correct data in the corresponding fields:

   i. Feature/Facility Type – Specify the airport feature (e.g, runway, taxiway, ramp, apron).

ii. Feature/Facility ID – Specify the feature/facility identification value.

iii. Initial Event Type – Specify the type of task event (e.g., rehabilitation, new construction).

iv. Project Description – Specify a brief description of the project (i.e, the event and activity).

v. From STA – Enter beginning station.

vi. To STA – Enter ending station.

vii. Pavement Area – Specify the area of pavement.

viii. Shoulder Area – Specify the area of the shoulder.

ix. Lighting.

x. Striping.

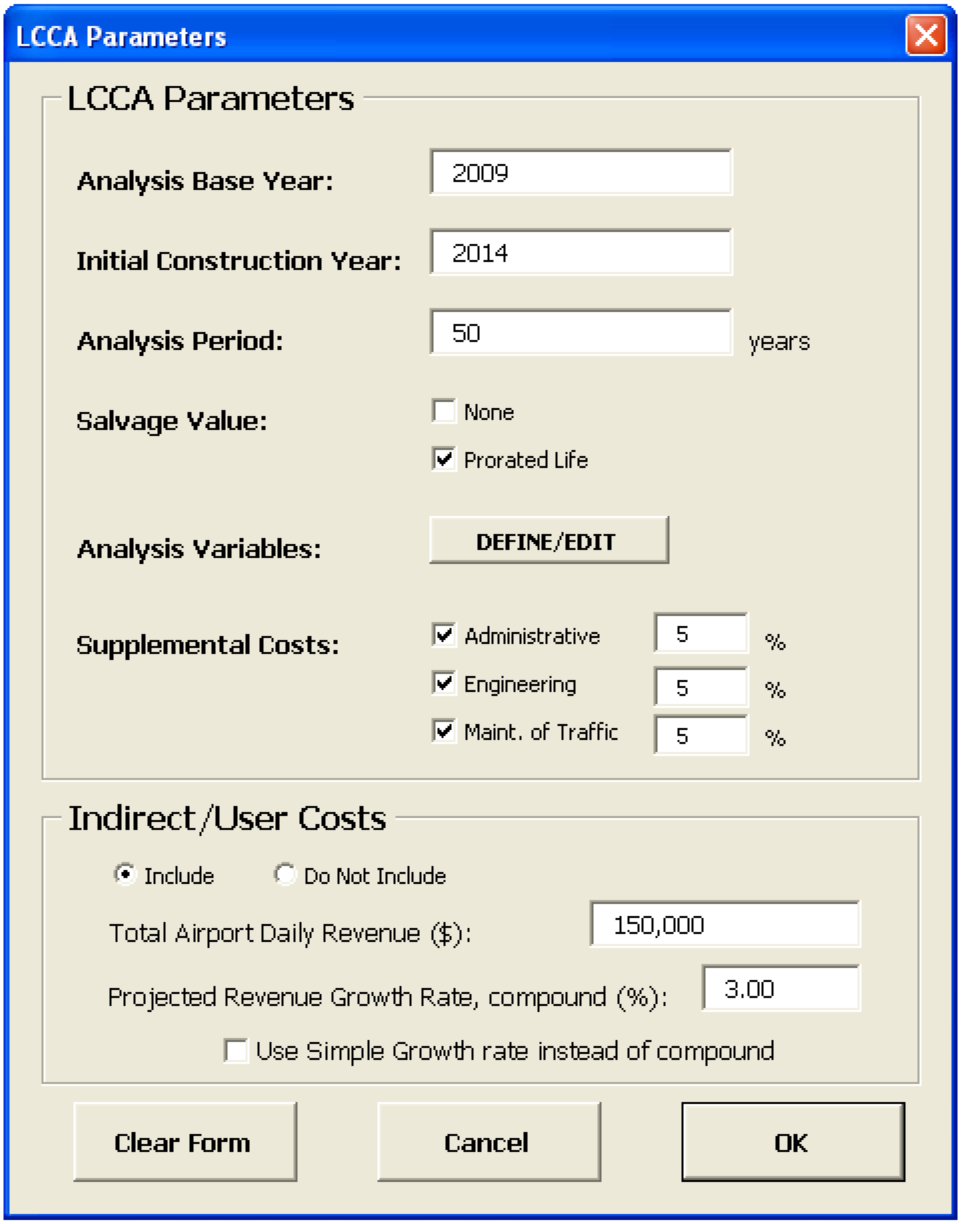
xi. Grooved Pavement Area – Specify the area of the grooved pavement.

xii. Comments – Specify any desired comments about the projects and/or tasks.

3. Click OK to submit the data.

Edit LCCA Parameters

The Edit LCCA Parameters screen allows the user to modify the LCCA input parameters that will be used during the simulation.



1. Click the Clear Form button to clear the current data from the form.

2. Enter the correct data in the corresponding fields:

   i. Analysis Base Year – Specify the base year for which all the NPV values are calculated (typically, the year in which the analysis is performed).

   ii. Initial Construction Year – Specify the year when initial construction begins. This value should not be confused with the analysis base year. The year of initial construction typically is later than the analysis base year by a couple years.

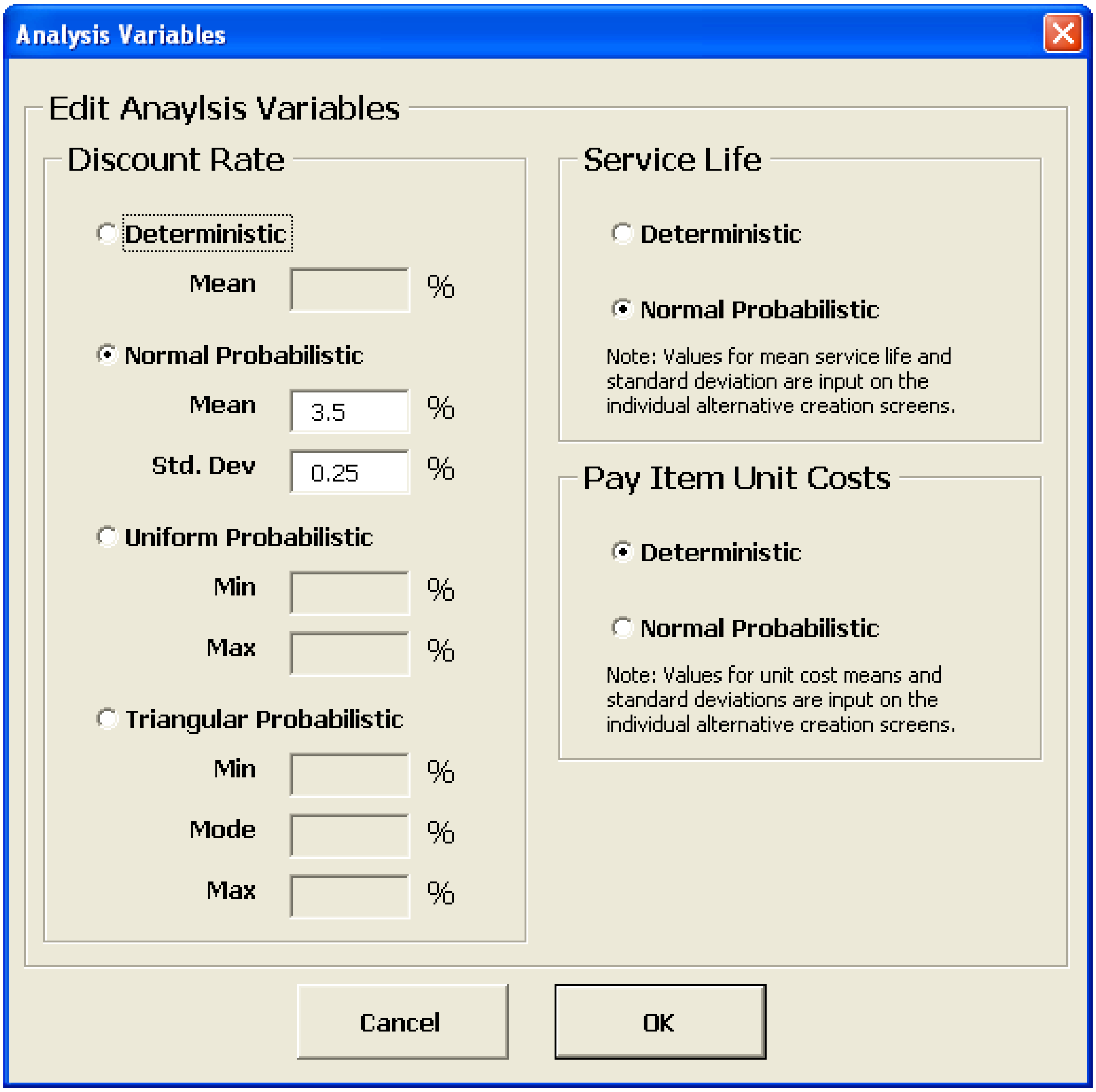
iii. Analysis Period – Specify the number of years to include in the simulation. The analysis period should be sufficiently long that each alternative includes at least one rehabilitation event. For new construction or reconstruction projects, analysis periods of 35 to 50 years are typical. For rehabilitation project, analysis periods of 25 to 30 years are appropriate.

iv. Salvage Value – Specify a method of calculation for the salvage value for the asset:

a. None – The analysis assumes that there is no value of the existing pavement or final rehabilitation event at the end of the analysis period.

b. Prorated – The prorated salvage value linearly depreciates the final rehabilitation event until the end of the analysis period. Note that only those line items that are specified to be included in the salvage value will be included in the calculation.

v. Analysis Variables – Specify the desired parameters for discount rate, service life, and pay item unit costs (see the following figure). Each analysis variable can be modeled as either deterministic or probabilistic. If any variable is specified as probabilistic, the simulation will update that parameter in a probabilistic manner during the simulation. The application will proceed through the iteration for that variable if or until convergence is realized.



a. Discount Rate – The annually updated 30-year discount rate can be found in OMB Circular A-95A. This value typically is around 3 percent. If the user wishes to use a probabilistic discount rate, professional judgment should be used to determine an appropriate standard deviation. A standard deviation of 0.25 percent would be a good starting point.

b. Service Life – Service lives for each rehabilitation should be based on experience and knowledge of similar rehabilitations, preferably on pavements that are subject to similar loading and environmental conditions.

c. Pay Item Unit Costs – Unit costs should be representative of products purchased and used in the same geographic region, as the costs of materials can vary significantly throughout different geographic regions.

vi. Supplemental Costs – Specify additional percentage cost to the project for administration, engineering, and maintenance of traffic. These cost factors cover other costs associated with the construction activities. Line items such as quality testing, construction supervision, traffic control, and preliminary engineering often are not included in the cost of purchasing and placing materials. If these values are not appreciably different between competing alternatives, the user may omit these supplement costs from the analysis.

vii. Indirect/User Costs – The user can decide whether to include the cost that considers the airport daily revenue. This computation considers the:

a. Daily airport revenue ($).

b. Revenue growth rate:

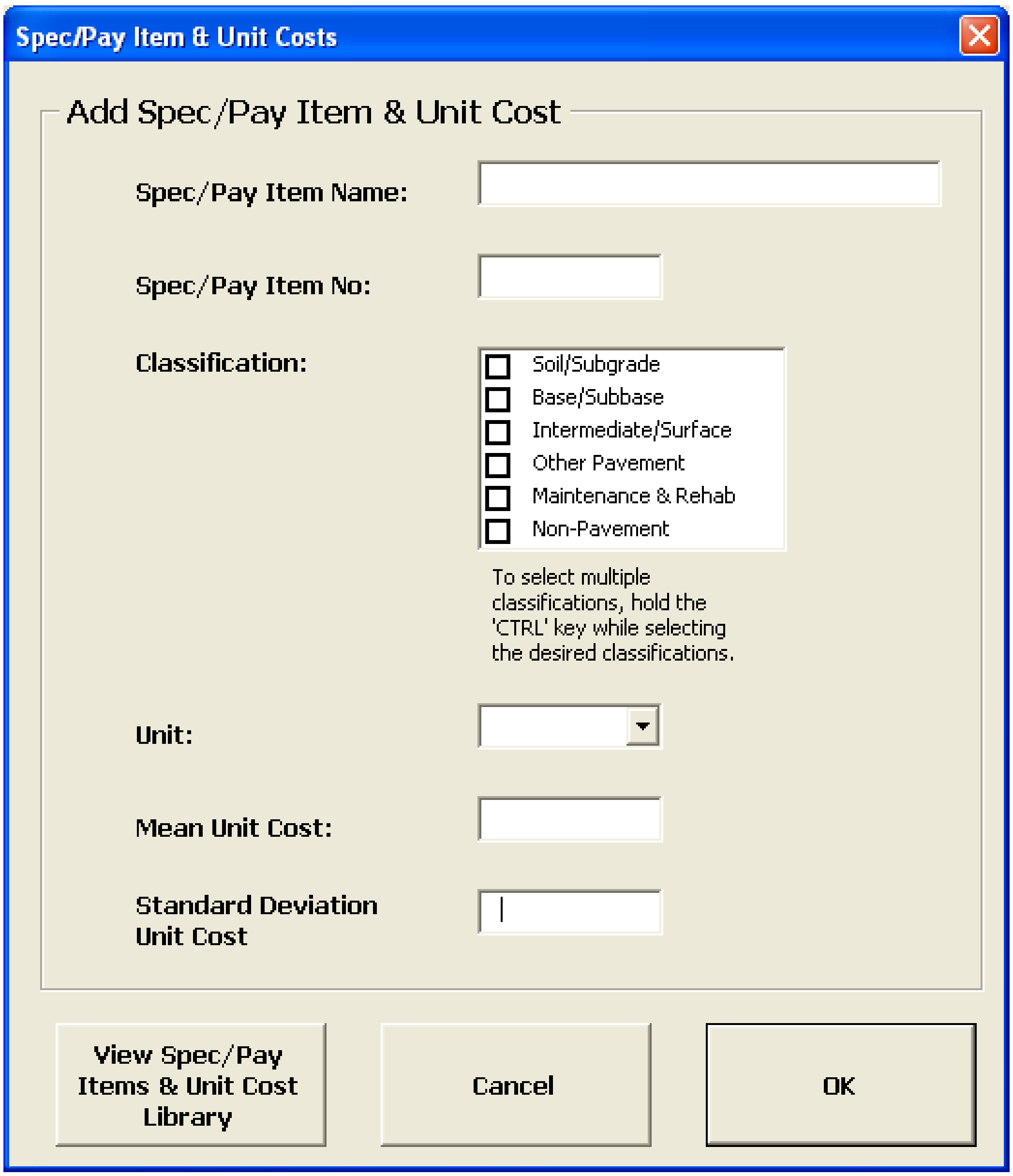
- Compound – Long range revenue projection. Apply the growth rate based on the previous year's revenue. This represents exponential growth.

- Simple – Short period revenue projection. Apply the growth rate at a uniform value over the years. This represents linear growth.

3. Click OK to submit the data.

Add Spec/Pay Items & Unit Costs

The Add Spec/Pay Items & Unit Costs screen allows users to add line items to the material library for inclusion in events and alternatives. Each pay item must be input into the material library before it can be added to an event.



1. Click the Clear Form button to clear the current data from the form.

2. Enter the correct data in the corresponding fields:

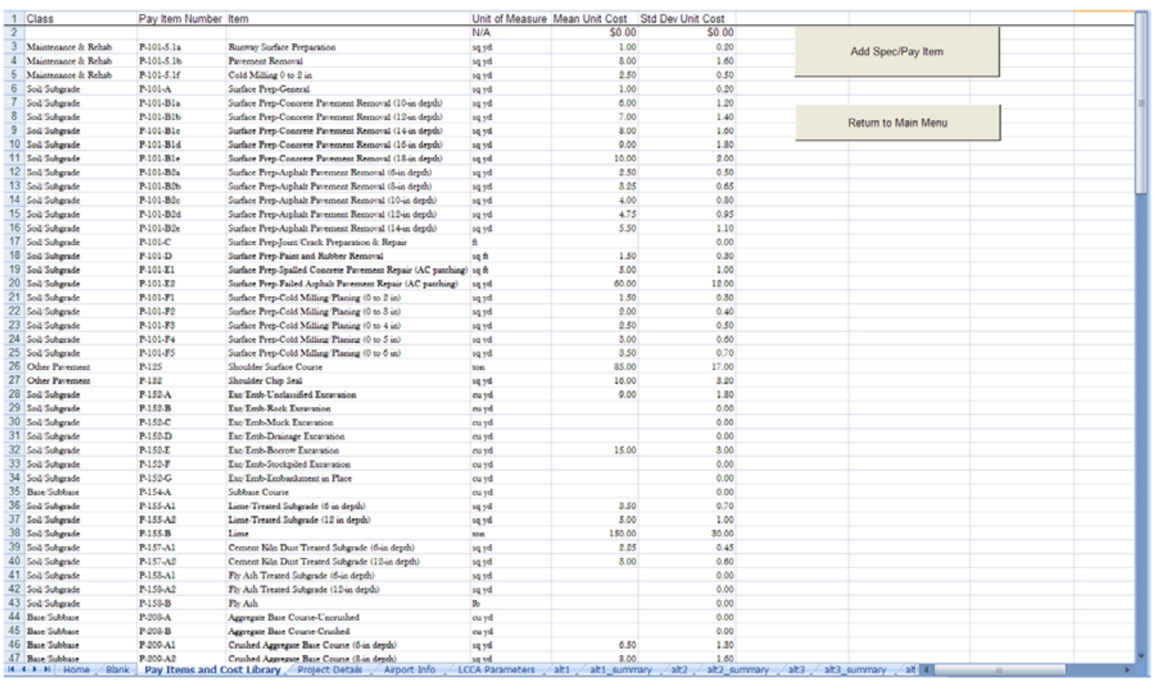
   i. Spec/Pay Item Name – Specify the desired pay item name.
   ii. Spec/Pay Item No. – Specify the number for the given pay item.
   iii. Classification – Specific the details for the pay item.
      a. Soil/Subgrade.
      b. Base/Subbase.
      c. Intermediate/Surface.
      d. Other Pavement.
      e. Maintenance & Rehab.
      f. Non-Pavement.
   iv. Unit – Specify the measurement units.
   v. Mean Unit Cost – Specify mean cost for a pay item unit.
   vi. Standard Deviation Unit Costs – Specify the standard deviation of the pay items unit cost.
   vii. View Spec/Pay Items & Unit Cost Library – When you select this option, it opens a standard Excel Spreadsheet populated with the pay item details:
      a. Classification.
      b. Number.
      c. Unit of Measurement.
      d. Mean Unit Cost.
      e. Std. Deviation of Unit Cost.
3. Click OK to submit the data.

<u>View Spec/Pay Items & Unit Costs Library</u>

The View Spec/Pay Items & Unit Cost Library allows the user to view current pay items and their details. The values shown in the default Pay Items and Costs Library are not representative of a particular geographical region and should not be assumed to be accurate for any particular project. The user should ensure that values in the library accurately reflect the costs of pay items used in the LCCA. Users can edit unit costs and standard deviations on this page but should not use this page to add pay items. Doing so may cause the line item to be unavailable for selection on the alternative creation page.

To use this module, click on the View Spec/Pay Items & Unit Costs Library button on the main menu. This opens a standard Excel Spreadsheet populated with pay items currently saved in AirCost:

- Classification.
- Number.
- Unit of Measurement.
- Mean Unit Cost.
- Std. Deviation of Unit Cost.



1	Class	Pay Item Number	Item	Unit of Measure	Mean Unit Cost	Std Dev Unit Cost
2				N/A	$0.00	$0.00
3	Maintenance & Rehab	P-101-5.1a	Runway Surface Preparation	sq yd	1.00	0.20
4	Maintenance & Rehab	P-101-5.1b	Pavement Removal	sq yd	8.00	1.60
5	Maintenance & Rehab	P-101-5.1f	Cold Milling 0 to 2 in	sq yd	2.50	0.50
6	Soil/Subgrade	P-101-A	Surface Prep-General	sq yd	1.00	0.20
7	Soil/Subgrade	P-101-B1a	Surface Prep-Concrete Pavement Removal (10-in depth)	sq yd	6.00	1.20
8	Soil/Subgrade	P-101-B1b	Surface Prep-Concrete Pavement Removal (12-in depth)	sq yd	7.00	1.40
9	Soil/Subgrade	P-101-B1c	Surface Prep-Concrete Pavement Removal (14-in depth)	sq yd	8.00	1.60
10	Soil/Subgrade	P-101-B1d	Surface Prep-Concrete Pavement Removal (16-in depth)	sq yd	9.00	1.80
11	Soil/Subgrade	P-101-B1e	Surface Prep-Concrete Pavement Removal (18-in depth)	sq yd	10.00	2.00
12	Soil/Subgrade	P-101-B2a	Surface Prep-Asphalt Pavement Removal (6-in depth)	sq yd	2.50	0.50
13	Soil/Subgrade	P-101-B2b	Surface Prep-Asphalt Pavement Removal (8-in depth)	sq yd	3.25	0.65
14	Soil/Subgrade	P-101-B2c	Surface Prep-Asphalt Pavement Removal (10-in depth)	sq yd	4.00	0.80
15	Soil/Subgrade	P-101-B2d	Surface Prep-Asphalt Pavement Removal (12-in depth)	sq yd	4.75	0.95
16	Soil/Subgrade	P-101-B2e	Surface Prep-Asphalt Pavement Removal (14-in depth)	sq yd	5.50	1.10
17	Soil/Subgrade	P-101-C	Surface Prep-Joint/Crack Preparation & Repair	ft		0.00
18	Soil/Subgrade	P-101-D	Surface Prep-Paint and Rubber Removal	sq ft	1.50	0.30
19	Soil/Subgrade	P-101-E1	Surface Prep-Spalled Concrete Pavement Repair (AC patching)	sq ft	5.00	1.00
20	Soil/Subgrade	P-101-E2	Surface Prep-Failed Asphalt Pavement Repair (AC patching)	sq yd	60.00	12.00
21	Soil/Subgrade	P-101-F1	Surface Prep-Cold Milling/Planing (0 to 2 in)	sq yd	1.50	0.30
22	Soil/Subgrade	P-101-F2	Surface Prep-Cold Milling/Planing (0 to 3 in)	sq yd	2.00	0.40
23	Soil/Subgrade	P-101-F3	Surface Prep-Cold Milling/Planing (0 to 4 in)	sq yd	2.50	0.50
24	Soil/Subgrade	P-101-F4	Surface Prep-Cold Milling/Planing (0 to 5 in)	sq yd	3.00	0.60
25	Soil/Subgrade	P-101-F5	Surface Prep-Cold Milling/Planing (0 to 6 in)	sq yd	3.50	0.70
26	Other Pavement	P-125	Shoulder Surface Course	ton	85.00	17.00
27	Other Pavement	P-132	Shoulder Chip Seal	sq yd	16.00	3.20
28	Soil/Subgrade	P-152-A	Exc/Emb-Unclassified Excavation	cu yd	9.00	1.80
29	Soil/Subgrade	P-152-B	Exc/Emb-Rock Excavation	cu yd		0.00
30	Soil/Subgrade	P-152-C	Exc/Emb-Muck Excavation	cu yd		0.00
31	Soil/Subgrade	P-152-D	Exc/Emb-Drainage Excavation	cu yd		0.00
32	Soil/Subgrade	P-152-E	Exc/Emb-Borrow Excavation	cu yd	15.00	3.00
33	Soil/Subgrade	P-152-F	Exc/Emb-Stockpiled Excavation	cu yd		0.00
34	Soil/Subgrade	P-152-G	Exc/Emb-Embankment in Place	cu yd		0.00
35	Base/Subbase	P-154-A	Subbase Course	cu yd		0.00
36	Soil/Subgrade	P-155-A1	Lime-Treated Subgrade (6 in depth)	sq yd	3.50	0.70
37	Soil/Subgrade	P-155-A2	Lime-Treated Subgrade (12 in depth)	sq yd	5.00	1.00
38	Soil/Subgrade	P-155-B	Lime	ton	150.00	30.00
39	Soil/Subgrade	P-157-A1	Cement Kiln Dust Treated Subgrade (6-in depth)	sq yd	2.25	0.45
40	Soil/Subgrade	P-157-A2	Cement Kiln Dust Treated Subgrade (12-in depth)	sq yd	3.00	0.60
41	Soil/Subgrade	P-158-A1	Fly Ash Treated Subgrade (6-in depth)	sq yd		0.00
42	Soil/Subgrade	P-158-A2	Fly Ash Treated Subgrade (12-in depth)	sq yd		0.00
43	Soil/Subgrade	P-158-B	Fly Ash	lb		0.00
44	Base/Subbase	P-208-A	Aggregate Base Course-Uncrushed	cu yd		0.00
45	Base/Subbase	P-208-B	Aggregate Base Course-Crushed	cu yd		0.00
46	Base/Subbase	P-209-A1	Crushed Aggregate Base Course (6-in depth)	sq yd	6.50	1.30
47	Base/Subbase	P-209-A2	Crushed Aggregate Base Course (8-in depth)	sq yd	8.00	1.60

This spreadsheet includes two buttons:

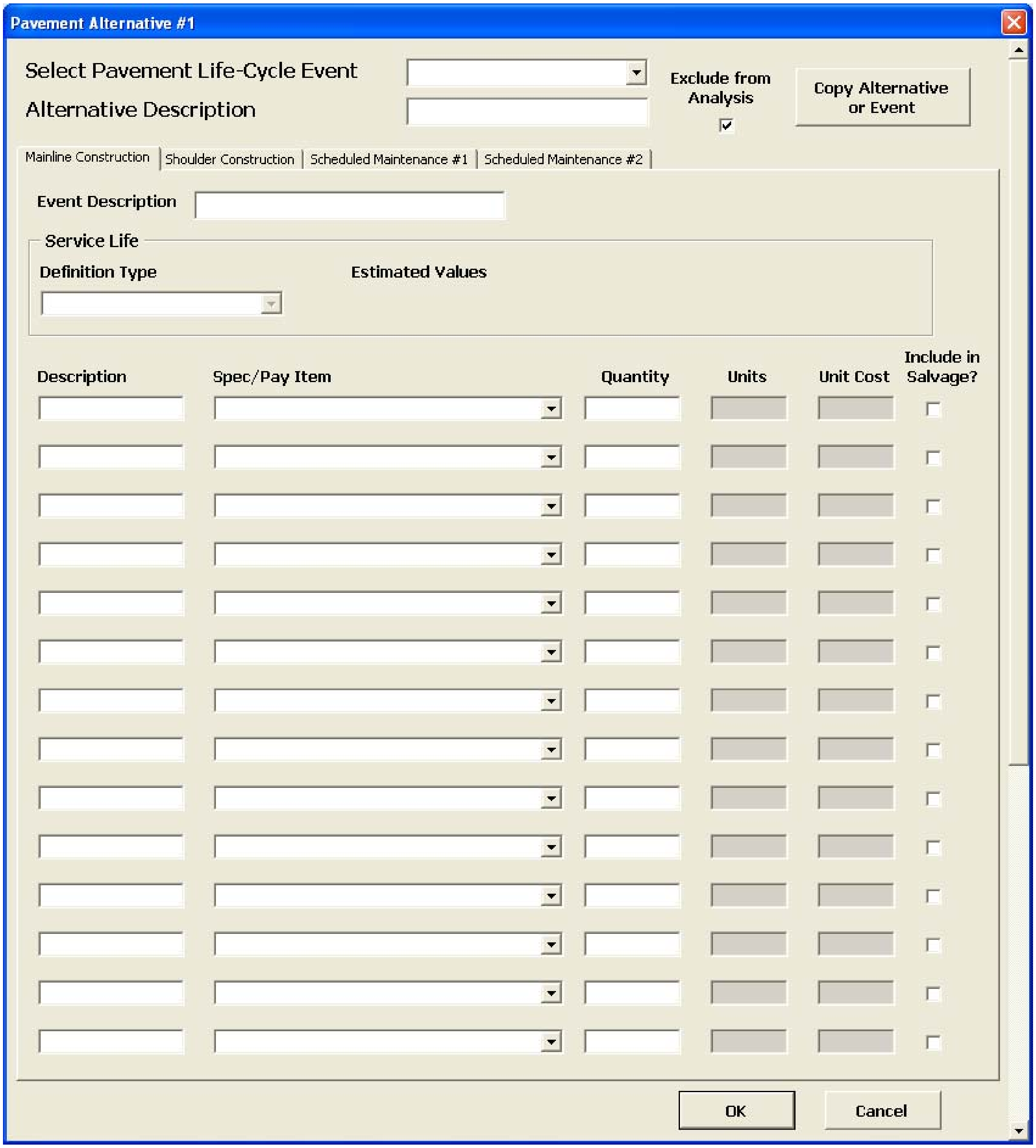
- Return to the Main Menu – Clicking this button will open the AirCost main menu.
- Add Spec/Pay Items – Clicking this button will return the user to the Add Spec/Pay Items & Unit Cost screen. Click on the OK button on that screen to save data and return to the main menu.

Create/Modify Alternatives

The Create/Modify Alternatives module allows the user to add up to four different scenarios for analysis, providing the opportunity to perform and compare analysis of alternative decisions.

On the main menu screen, the Create/Modify Alternatives options are displayed as shown below.

The same procedure is used for creating/modifying each of the four alternatives. Click on the Alternative 1 button to begin.



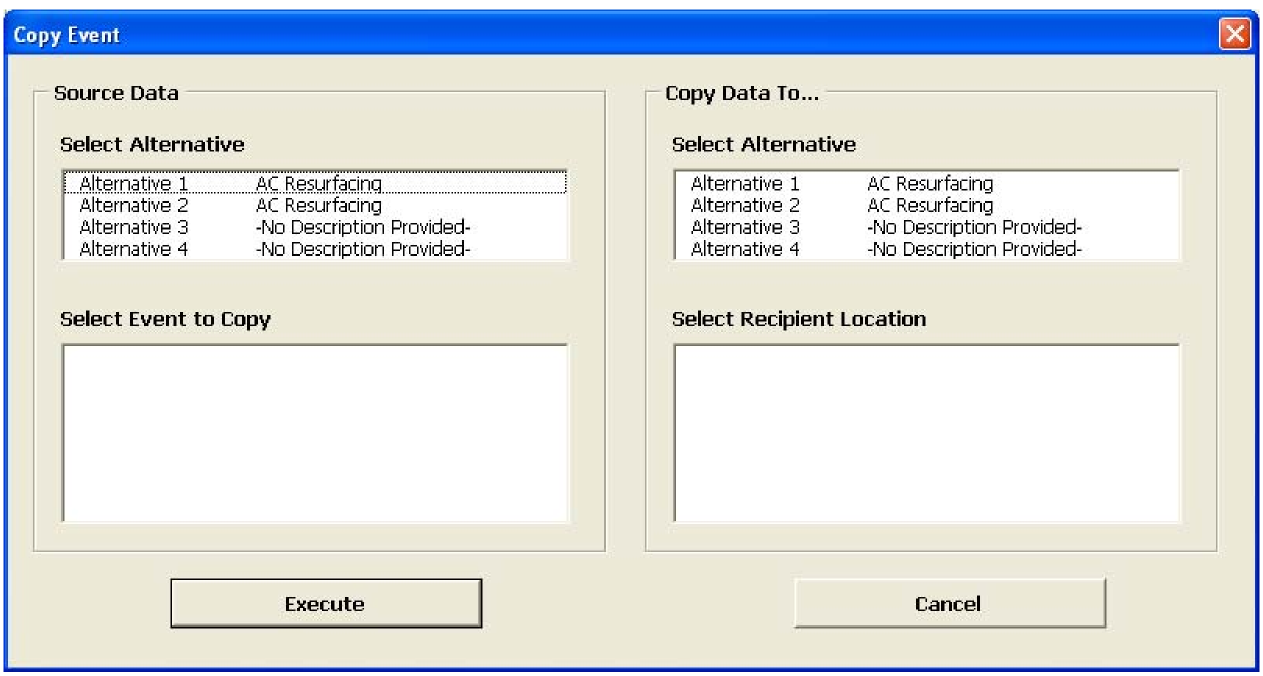
On this screen, enter the following information:

1. Select Pavement Life-Cycle Event – Specify a life cycle event (e.g., initial construction, rehabilitation).
2. Alternative Description – Assign a description to the alternative, ideally self-explanatory.

3. Exclude from analysis – Check the box to exclude an alternative from the analysis, if desired. Note that it is necessary to toggle on alternatives in sequence. In other words, if you would like to run Alternative 1 and Alternative 3, you must include Alternative 2 as well.

The Copy the Alternatives and/or Event feature is available if the user is running Excel 2007 or later. This allows the user to copy events from one alternative to another using the following steps:.

1. Select the desired alternatives (Source Data). The event box will be populated with the events associated with the alternative.
2. Click on the event in the Select Event to Copy box.
3. Select the alternative to which you would like to copy the events (Copy Data To...).
4. Click on the recipient location in the Select Recipient Location box.
5. Click Execute (or click Cancel to return to the previous screen without copying data).



Mainline Construction

Enter mainline construction data on this tab

1. Select a pavement life cycle event to activate the mainline construction data entry form.

2. Enter the correct data in the corresponding fields:

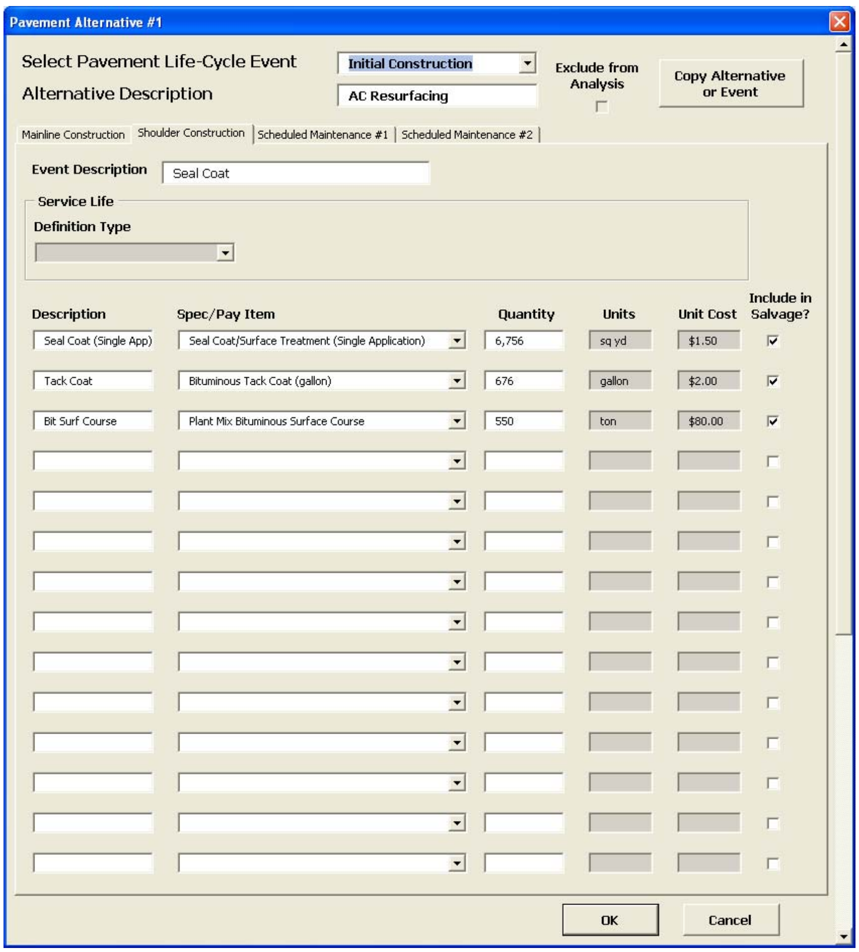
   i. Event Description – Specify a self-explanatory description.
   ii. Service Life – Specify the mean service life of the event (and standard deviation if using probabilistic analysis). Ideally, the service is based on projects of similar scope at locations with similar traffic and environmental considerations.
   iii. Description – Specify a task description.
   iv. Spec/Pay Item – Select the spec/pay item from the drop-down options.
   v. Quantity – Specify the quantity of the spec/pay item needed for the task.
   vi. Units – Automatically populated with pay item data from the pay item library.
   vii. Unit Cost – Automatically populated with pay item data from the pay item library.
   viii. Click the Salvage checkbox to include salvage value analysis for this project.

3. Click OK to submit the data.

Shoulder Construction

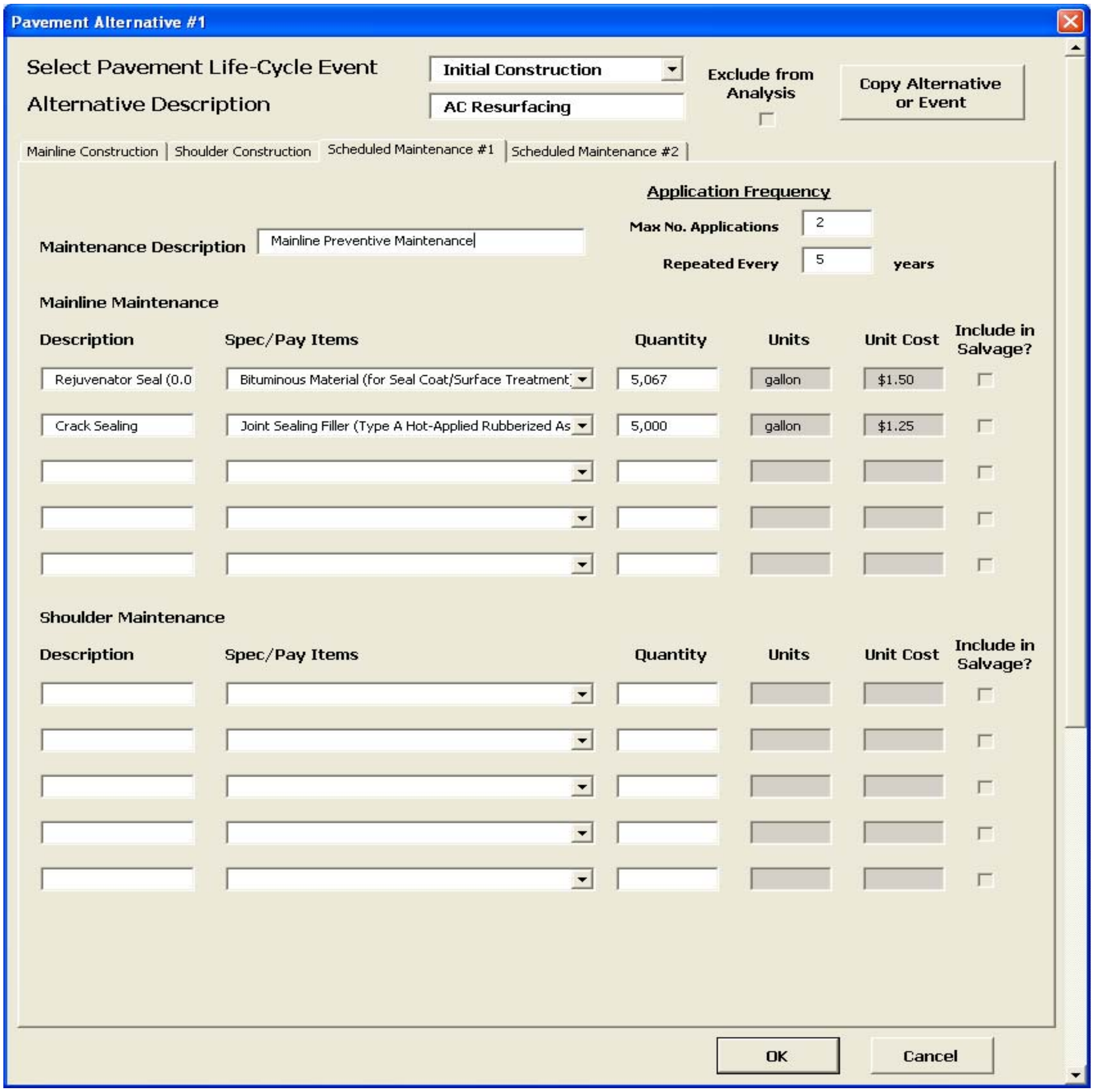
Click the Shoulder Construction tab to input analysis data for shoulder construction projects. The data entry screen appears identical to the Mainline Construction screen, as shown in the following figure. Enter data as described under Mainline Construction. However, note that Service Life is not applicable on the Shoulder Construction tab. The service life entered for mainline construction applies to all aspects of the event.

After entering the data on this tab, click the OK button.



Scheduled Maintenance #1

Click the Schedule Maintenance #1 tab to specify analysis data for both mainline and shoulder maintenance. The data entry screen is shown below.



Enter the following data:

1. Maintenance Description – Specify a self-explanatory description of the maintenance project.
2. Application Frequency. – Maintenance applications are always deterministic and applied at specified intervals.
    a. Max No. Applications – Enter the maximum number of times a maintenance activity can be repeated for the given rehabilitation.
    b. Repeated Every … Years – Enter the frequency of maintenance applications. The maintenance activity will be repeated every "X" years until the end of the service life is reached or the maximum number of applications is attained

For mainline maintenance and shoulder maintenance, enter the following:

1. Description – Specify a task description.
2. Spec/Pay Item – Select the spec/pay item from the drop down options.
3. Quantity – Specify the quantity of the spec/pay item need for the task.
4. Units – Automatically populated with pay item data from the pay item library.
5. Unit Cost – Automatically populated with pay item data from the pay item library.

Note that the checkbox for including or excluding a line item in the salvage value is deactivated on the maintenance activity page. All maintenance activities are excluded from salvage value and given no credit at the end of the analysis period.

After entering the desired data, click OK to submit data.

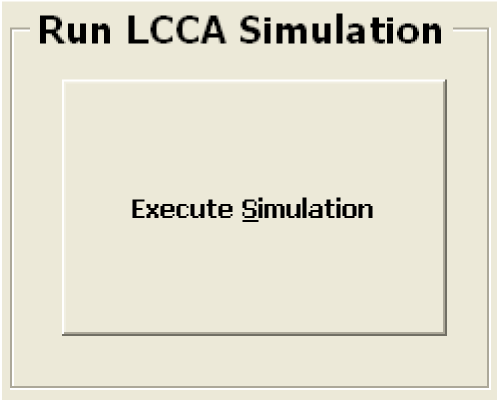
Scheduled Maintenance #2

Follow the same procedure as for scheduled maintenance #1.

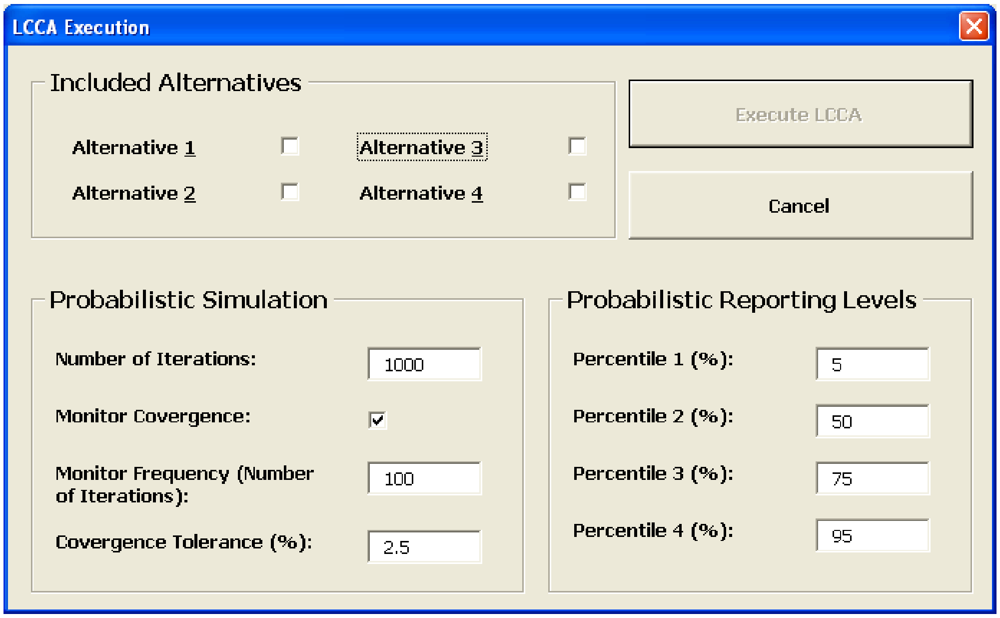
Run LCCA Simulation

The Run LCCA Simulation module allows the user to run a simulation based on the alternatives specified in the Create/Modify Alternatives module.

Access the Run Simulation module by clicking on the Execute Simulation button on the main menu screen.



This will open the following data entry screen.



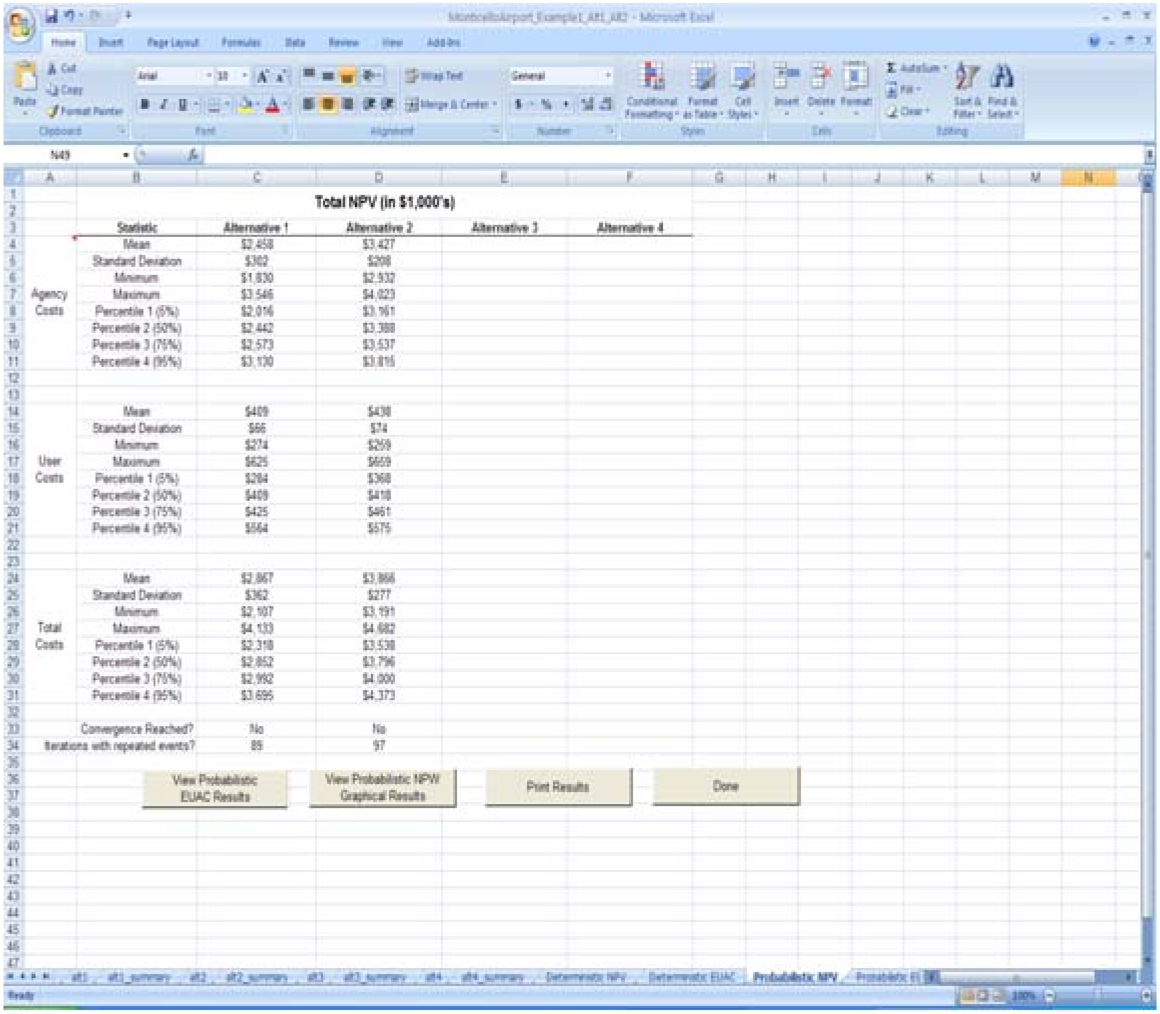
1. Included Alternatives – Specify which alternatives to use in the simulation (you can

chose multiple alternatives). At least one alternative must be selected to activate the Execute LCCA button.

2. Probabilistic Simulation (only active if running in probabilistic mode):
    i. Number of Iterations – The number of iterations to perform during the simulation. A minimum of 1,000 iterations should be run if convergence is not desired.
    ii. Monitor Convergence – Check this box to terminate the simulation upon convergence. If convergence is reached, the software has determined that no further iterations are necessary, as the result from more iterations will be statistically insignificant. Convergence is based on changes in average NPW, as well as the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles and the standard deviation.
    iii. Monitor Frequency (Number of Iterations) – Specify the frequency of checking convergence. Larger intervals generally will take longer to converge. A monitoring frequency of 100 iterations is typical.
    iv. Convergence Tolerance – Specify the acceptable level of tolerance for the convergence of the simulation. The tolerance is the criterion which all factors listed above must meet to ensure that convergence has been attained. A tolerance of 2.5 percent is typical and ensures that a representative probabilistic solution has been found.
3. Probabilistic Reporting Levels (only active if running in probabilistic mode) – Specify the distribution of values in the report by percentile. These four fields can be used to evaluate the statistical distribution of the iterative results.

After entering data, click the Execute LCCA button to start the simulation. After the simulation is completed, AirCost will display the following message:

Click OK to view the simulation results in an Excel spreadsheet.



Total NPV (in $1,000's)

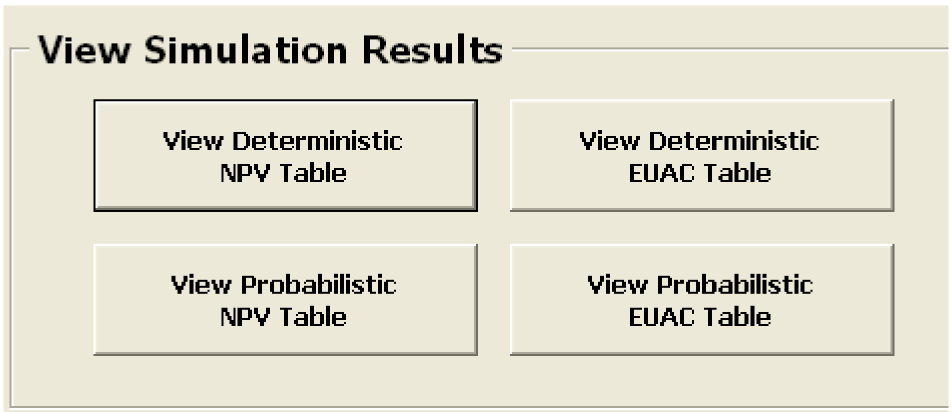
	Statistic	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Agency Costs	Mean	$2,458	$3,427		
	Standard Deviation	$302	$208		
	Minimum	$1,830	$2,932		
	Maximum	$3,546	$4,023		
	Percentile 1 (5%)	$2,016	$3,161		
	Percentile 2 (50%)	$2,442	$3,388		
	Percentile 3 (75%)	$2,573	$3,537		
	Percentile 4 (95%)	$3,130	$3,815		
User Costs	Mean	$409	$438		
	Standard Deviation	$66	$74		
	Minimum	$274	$259		
	Maximum	$625	$659		
	Percentile 1 (5%)	$284	$368		
	Percentile 2 (50%)	$409	$418		
	Percentile 3 (75%)	$425	$461		
	Percentile 4 (95%)	$564	$575		
Total Costs	Mean	$2,867	$3,866		
	Standard Deviation	$362	$277		
	Minimum	$2,107	$3,191		
	Maximum	$4,133	$4,682		
	Percentile 1 (5%)	$2,318	$3,538		
	Percentile 2 (50%)	$2,852	$3,796		
	Percentile 3 (75%)	$2,992	$4,000		
	Percentile 4 (95%)	$3,695	$4,373		
	Convergence Reached?	No	No		
	Iterations with repeated events?	89	97		

In addition to these tabular NPW results, the user can view EUAC results by clicking the appropriate button at the bottom of the spreadsheet. There also is a button to print the analysis results.

When you have finished reviewing the simulation results, click the Done button to return to the main menu screen.

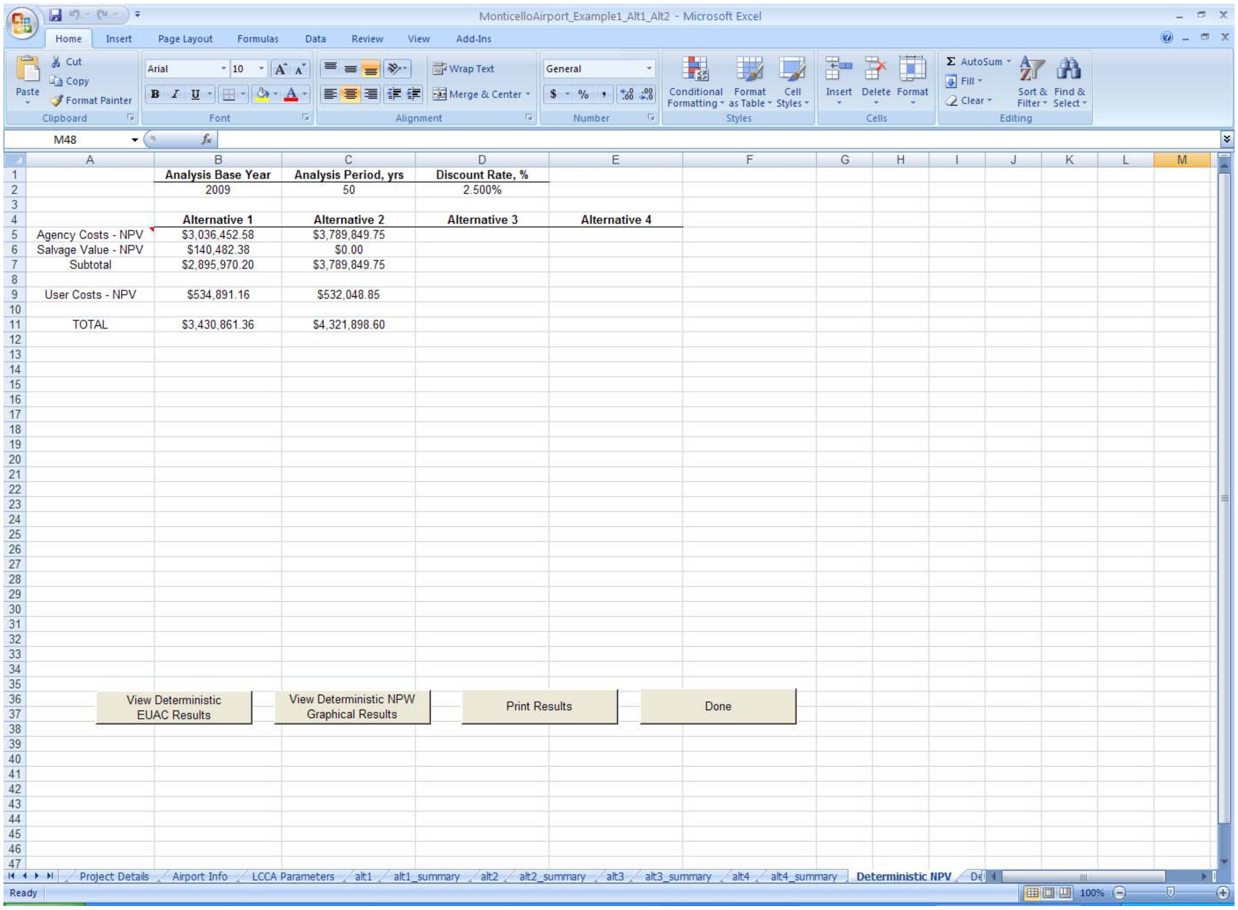
View Simulation Results

The View Simulation Results module allows the user to view the results after executing the simulation. These results include both probabilistic and deterministic values for NPV and EUAC.



View Deterministic NPV Table

Clicking this button opens a spreadsheet similar to the one shown below.



:

The selected analysis base year, analysis period, and discount rate are shown at the top. Then, for each alternative selected for the analysis, the following are displayed:

- Agency Costs NPV – The agency costs consider only the cost of construction and maintenance activities during the analysis period. The salvage costs and user costs are considered separately. The NPV of the alternative assumes that costs are constant (relative to inflation) over the duration of the analysis and uses the discount rate to determine the investment required during the base year to cover the cost of the entire alternative. In essence, the NPV represents the current, up-front costs that must be invested in the base year and that are assumed to grow at a rate equal to the discount rate, to cover the entire cost of the alternative.
- Salvage Costs NPV – The salvage value is the value of the pavement assumed to exist at the end of the analysis period. If the salvage value is included in the analysis, the value will represent a linear depreciation of the final rehabilitation event from the beginning to the end of the analysis period. For example, if a $5 million overlay with an expected

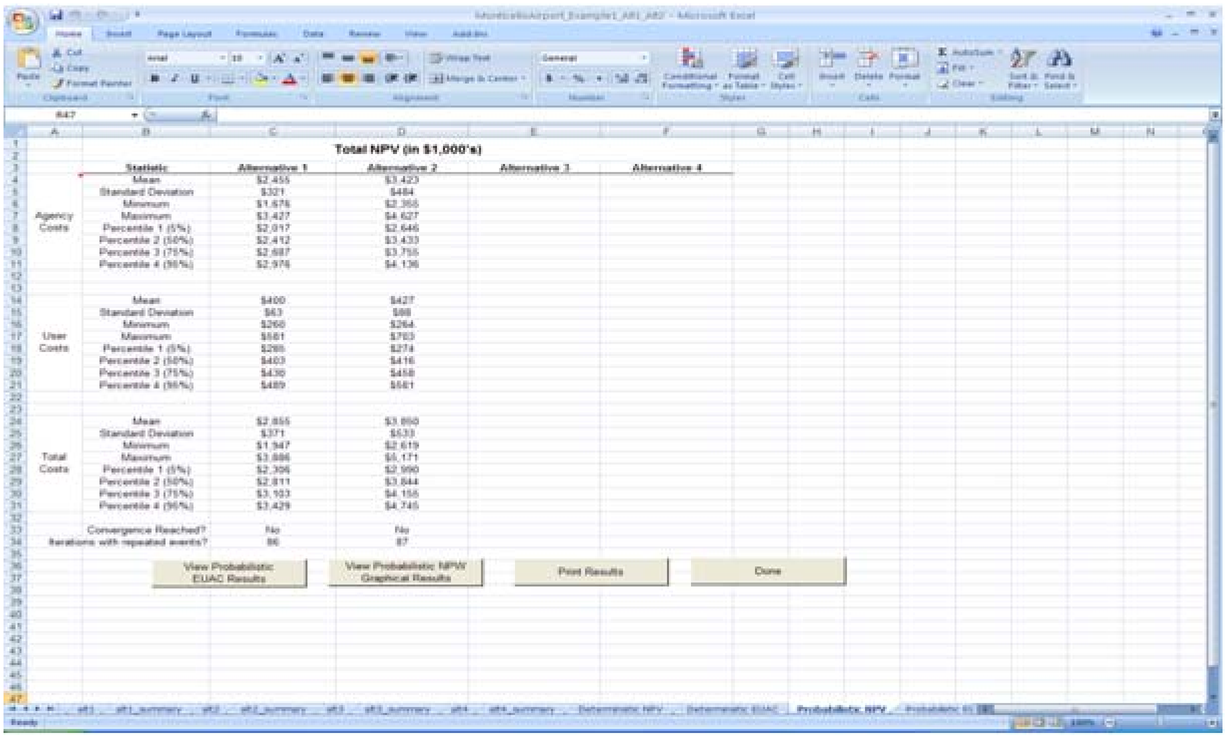
service life of 10 years was placed in year 36 of a 40-year analysis, the salvage value would be roughly equal to 60 percent of the $5 million rehabilitation cost, or $3 million, as only 40 percent of the anticipated service life was used. This value will be decreased substantially as a result of the discount rate and backcasting the value in year 40 to the base year of the analysis. As a result, that same $3 million salvage value in year 40 would have a NPV of only $129,800, assuming a discount rate of 3 percent.

- User Costs – The user costs are those costs incurred as a result of the disruption to full pavement access. In the AirCost analysis, this cost represents lost daily airport revenue. To determine the user cost, the daily revenue is projected based on the initial daily revenue, the annual revenue growth factor (either compound or simple growth), the percentage reduction in daily revenue, and the assumed duration of the rehabilitation event. For each event, the disruption to revenue is determined and backcasted to the base year. These values are then totaled for a total user cost.
- Total Cost – The total cost of an alternative is the summation of the agency costs and the user cost, with the salvage costs applied as a credit. In a deterministic model, the alternative with the lower NPV is considered to be the best alternative, all other factors being equal. In a probabilistic model, the mean NPV is a factor in choosing the best alternative, but the standard deviation also must be considered to assess the amount of risk inherent in a given alternative. An alternative with a higher standard deviation indicates that cost estimates are more variable and, therefore, more risky.

Click the Done button to return to the main menu screen.

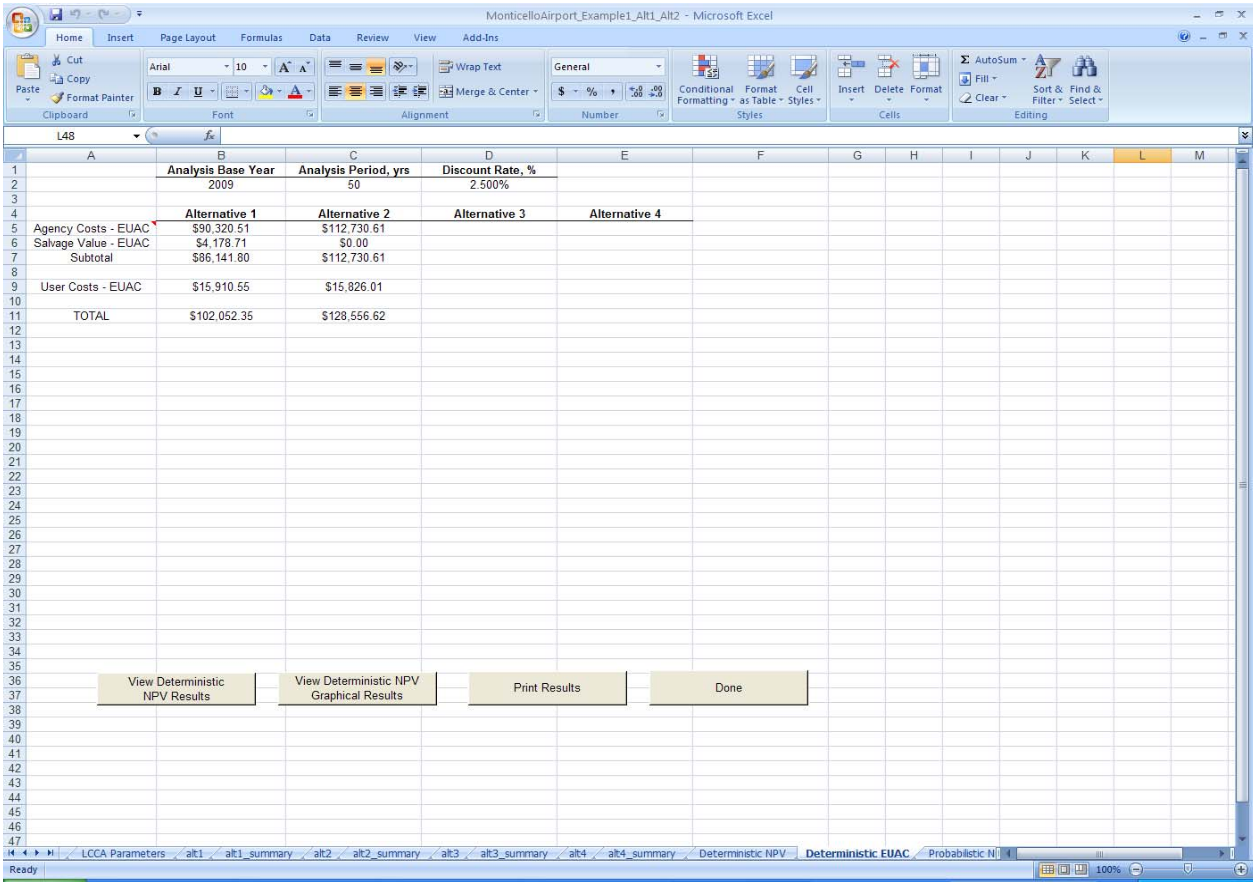
<u>View Probabilistic NPV Table</u>

A sample probabilistic NPV table is shown in the figure below. Most of the data elements and navigation buttons are similar to those described previously. However, this table also displays the percentile analysis results based on the simulation iterations.



<u>View Deterministic EUAC Table</u>

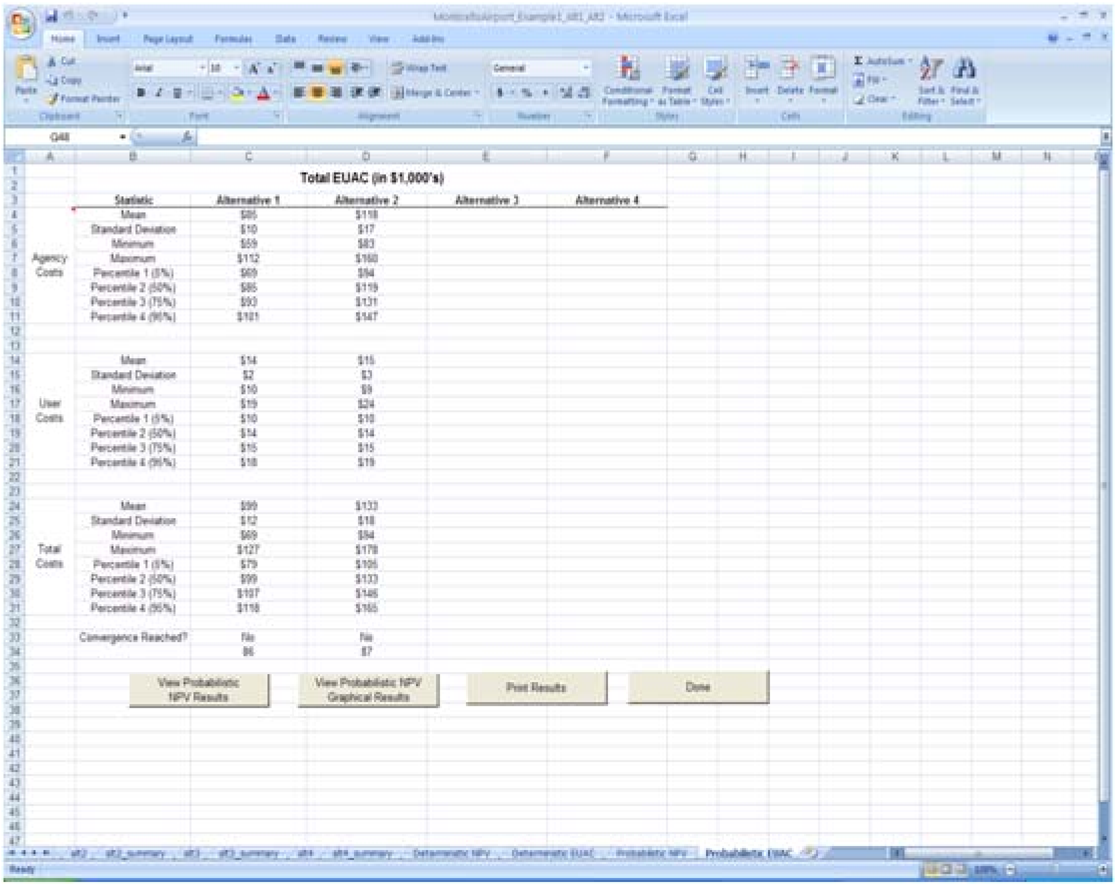
A sample deterministic EUAC table is shown in the figure below. The data elements and navigation buttons are similar to those described previously.



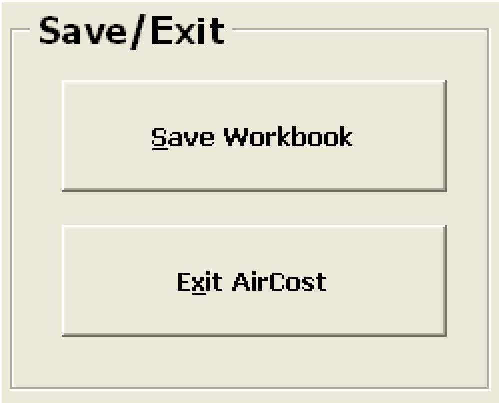
i.

View Probabilistic EUAC Table

A sample probabilistic EUAC table is shown in the figure below.



Save & Exit



The Save Workbook option on the main menu screen allow the user to save the current LCCA analysis in an Excel workbook. The user has the option to save to the current file or save as a new file name.

The Exit AirCost button closes the application. Before exiting, AirCost displays the following message:

Click Yes to save changes to the current file. Click No to exit AirCost without saving changes. Or click Cancel to continue working in the program or to save as a different file name.