

# Guide for Mechanistic-Empirical Design

## OF NEW AND REHABILITATED PAVEMENT STRUCTURES

### FINAL REPORT APPENDIX C



Prepared for  
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## **APPENDIX C—LIFE CYCLE COST ANALYSIS GUIDELINES**

### **C.1 INTRODUCTION**

The application of principles of engineering economy to highway pavement projects generally occurs at two levels—the network level and the project level. At the network level, the feasibility and programming of many pavement projects must be determined as part of a multi-year capital improvement program. Pavement management data, including inventory, condition, and cost data, are evaluated to prioritize network needs and develop listings of recommended projects and preservation treatments, based on anticipated budgets.

At the project level, the most economical design strategy capable of satisfying the overall project requirements must be determined. Whether the project is to be new construction or rehabilitation, the goal of project-level analysis is to select the most appropriate strategy, given various cost, engineering, and other constraints associated with the project. Ideally, network and project asset management should be accomplished simultaneously, but analytical tools are not available. Thus, they are often performed independently.

An important tool to both the network and project levels is life cycle cost analysis (LCCA). LCCA has been used in transportation engineering for well over a century, but it is only in the last couple decades that its use has become more widespread, largely due to the increased accountability placed on highway agencies. Not only has LCCA helped many agencies make wiser use of limited capital improvement funds, it has strengthened the competitiveness of the road building industry.

#### **C.1.1 Definition and Makeup of LCCA**

LCCA allows comparisons of investment alternatives having different cost streams. In the highway arena, it is a formal, systematic approach for considering most of the factors that go into making a pavement investment decision. Such factors include the initial cost of building or renovating a pavement facility, all significant upkeep costs anticipated over the pavement's life, and the value of the pavement at the end of its life. Other factors can include engineering costs, traffic control costs associated with construction work zones, and costs incurred by users of the highway as a result of travel delays and/or increased vehicle operating costs. Accident costs due to lane closures may also be significant.

There are four components of LCCA—the LCCA framework, the input parameters, the analysis process, and the outputs/results. The LCCA framework represents the governing criteria and principles by which a comparison of costs of alternative design strategies is made.

Input parameters include the specified costs and the anticipated timings of the specified costs. Estimated values of each input parameter are needed in order to conduct the LCCA.

The LCCA process is the sequence of steps taken to successfully complete a LCCA. It begins with the formulation of alternative design strategies and concludes with the analysis and

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

The outputs or results of a LCCA represent important decision-making information for the pavement designer/analyst. Combined with engineering and other feasibility information, the projected economic implications of alternative design strategies can be used to identify the preferred pavement strategy.

### C.1.2 Basic Concepts and Principles

As illustrated in figure C.1, upon identifying different investment strategy options, the differential upkeep costs (i.e., maintenance/rehabilitation costs not shared equally by all options) associated with each strategy option are determined and converted into present worth dollars (i.e., costs adjusted to properly reflect the time value of money). The individual present worth dollars are then summed with the differential initial cost and the total cost is compared with the total costs of the other strategy options, so as to identify the most economical investment option. Although other factors, such as the agency budget and traffic control, environment, and construction considerations, may ultimately override life cycle cost results, LCCA provides a crucial piece of decision-making information.

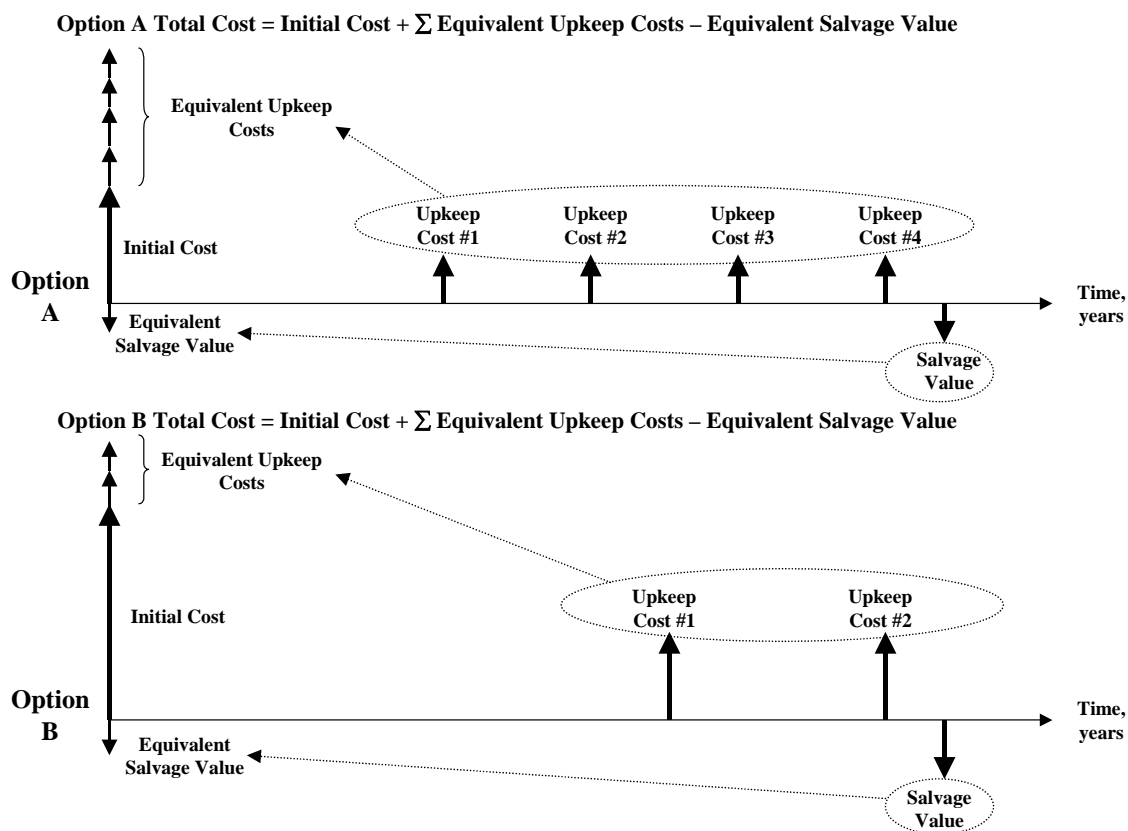


Figure C.1. Determining life cycle costs for alternative investment strategies.

The accuracy of LCCA results depends on the accuracy of each of the inputs, which typically include the following:

- Initial construction (or rehabilitation) cost.
- Expected service life of initial pavement structure.
- Future maintenance and rehabilitation (M&R) costs.
- Expected timings/performance characteristics of future M&R treatments.
- Economic discount rate.
- Expected salvage value.
- User costs, as a result of extra time delay, increased vehicle operating costs, or increased accidents.
- Expected timings of user costs.

### **C.1.3 Applications of LCCA in Design**

Although LCCA is occasionally used at the network level for project programming purposes, its predominant application is for comparing and judging the efficiency of different design alternatives at the project level. This includes both new and rehabilitation designs having different pavement surface types (i.e., AC versus PCC) or other different design features, such as surface mix design and thickness, subsurface and shoulder design, and in the case of PCC surfaces, joint and reinforcement design.

Nearly two-thirds of 52 United States (U.S.) highway agencies (including all 50 States) surveyed by the Federal Highway Administration (FHWA) in 1997 reported using formal LCCA procedures for determining the type of pavement to use in a new construction or reconstruction project (1). Most of the remaining one-third use informal procedures or plan to develop a set of procedures in the near future.

Although the concepts and principles of LCCA are fairly uniform, the application of LCCA in design varies considerably. 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 FHWA 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. Specifically, the development of the Interim Technical Bulletin on LCCA in 1998 (2) and the conduct of Demonstration Project (DP) 115 training sessions between 1997 and 2001 have greatly helped advance the application of LCCA in the U.S.

### **C.1.4 LCCA and the Design Guide Pavement Design Methodology**

The LCCA principles and process outlined in the FHWA Interim Technical Bulletin (2) and promoted under the DP 115 project largely represent the state of the technology at the design level. For this reason, they have been adopted for use with the Design Guide methodology.

A computerized LCCA program that incorporates the FHWA procedures and various functional enhancements has been developed and is provided on the CD-ROM included with the Design Guide. The program, titled “LCCA2002,” is a Microsoft® Excel-based spreadsheet that can perform deterministic and probabilistic analysis of life cycle costs (including certain user costs) for a minimum of two alternative designs. Developed primarily by the FHWA, LCCA2002 is completely separate from the Design Guide software, but uses the same database administrator (Excel) as the Design Guide software outputs (e.g., performance prediction data).

### **C.1.5 Organization and Use of the LCCA Guide**

This appendix presents up-to-date guidelines for performing pavement LCCA at the project level. It is intended for State and local highway agency personnel with responsibility for conducting or reviewing new pavement or pavement rehabilitation design alternatives (1,2).

The guidelines presented embody the principles and practices contained in the 1998 FHWA Interim Technical Bulletin and feature a few supplementary considerations and techniques. The guidelines are detailed and comprehensive, covering all actions necessary for a highway agency to do a full and fair assessment of the economic implications of alternative design strategies.

This appendix consists of four sections, including this introductory section. Section C.2 provides guidance in establishing the LCCA framework, so that projects within an agency are evaluated in a consistent fashion. Section C.3 describes the LCCA process, addressing in detail both the selection of input values and the interpretation of analysis results. Finally, section C.4 provides an overview of the LCCA2002 spreadsheet program, followed by two example applications of the project-level LCCA methodology.

## **C.2 LCCA FRAMEWORK**

As mentioned previously, the LCCA framework represents the governing criteria and principles by which a comparison of costs of alternative design strategies is made. Facets of the LCCA framework include the following:

- Economic analysis technique.
- Real versus nominal dollars.
- Discount rate.
- Analysis period.
- Cost factors.
- Approach to risk and uncertainty in LCCA.

Detailed discussions on these facets and guidance in addressing them as part of a project-level LCCA are provided below.

### C.2.1 Economic Analysis Technique

LCCA is a form of economic analysis used to evaluate the long-term economic efficiency between alternative investment options. Several types of economic models/formulas exist and are used by transportation agencies throughout the world for planning and designing pavement projects. The models fall under various decision-making-system categories, the most common of which is a cost–benefit analysis (CBA), which simply measures the costs and benefits of a strategy or action.

The present-worth (PW) method is the economic indicator or formula of choice for the Design Guide. The PW method is also referred to as the net present value (NPV). The other economic indicator of choice by many State highway agencies in the U.S. is the equivalent uniform annual cost (EUAC) method. EUAC represents the NPV of all discounted cost and benefits of an alternative as if they occur uniformly throughout the analysis period. Both are briefly defined and discussed below.

- **Present Worth Analysis**—The PW analysis transforms future expenditures or costs into present worth dollars. In comparing two or more alternatives, future payments or a series of payments for each case are converted to present values. The alternative with the lowest present value is considered (at least from an economic standpoint) the most attractive.

The NPV is the discounted monetary value of expected net benefits (i.e., the benefits minus the costs). It is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits.

Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement. If it is assumed that the benefits of keeping a roadway above some pre-established condition or ride quality level are the same for all design alternatives, the benefits component drops out and the formula for computing NPV is:

$$NPV = \text{Initial Cost} + \sum \text{Upkeep Cost}_k * [1 / (1 + i_{dis})^n_k] \quad (C.1)$$

where:

$$\begin{array}{lll} i_{dis} & = & \text{discount rate} \\ n & = & \text{year of expenditure} \\ k & = & \text{individual maintenance/rehabilitation activity} \end{array}$$

The most important assumption for the PW analysis is that the alternatives are equal in all respects, except cost. However, most pavement design options under consideration have different services lives. For example, most State highway agencies use different design

lives for HMA and PCC pavements. Techniques have been developed to overcome this difficulty of unequal service lives; the most common method is to assume that an alternative can be considered a sequence of identical work activities. That is, each alternative will be replaced with an “identical successor” at the end of its service life, and this process will continue until all alternatives reach the end of their service lives at the same time.

- **Equivalent Uniform Annual Cost Analysis**—In this method of comparing multiple alternatives, all present and future values are converted to EUAC (simply termed annual cost). In comparing multiple alternatives, that which has the lowest annual cost is the most attractive. For the annual cost comparison, no assumption is made concerning equal service lives. Alternatives may be directly compared with no sequential repetition of alternatives. In other words, the EUAC represents the NPV of all discounted costs and benefits of an alternative as if they were to occur uniformly throughout the analysis period. The preferred method of determining EUAC is first to determine the NPV, and then use the following formula to convert it to EUAC.

$$EUAC = NPV * [(i_{dis} * (1 + i_{dis})^n) / ((1 + i_{dis})^n - 1)] \quad (C.2)$$

where:

$$\begin{array}{ll} n & = \text{number of years into the future} \\ i_{dis} & = \text{discount rate} \end{array}$$

The obvious difference between the two methods is that the NPV analysis requires equal service lives of alternatives for direct comparison with unequal service lives requiring special treatment. The special treatment requires sequential repetition of alternatives until all alternatives reach the end of their service life at the same time. It should be noted that from a mathematical standpoint, both methods are exact and, thus, always predict the same alternative as the most attractive. In fact, if the sequential alternative repetition technique is used, the computed present costs can be converted into annual costs that are numerically equal to those obtained from a conventional annual cost comparison.

It should be noted that the basic benefits (excluding salvage value) of providing and maintaining some pre-established pavement condition level on any given roadway are outside the scope of this LCCA. The benefits of providing a specified level of pavement condition are considered to be the same for all pavement design strategies. Hence, under these conditions, the LCCA objective is to determine the alternative design strategy that meets the minimum performance requirements with the lowest life cycle costs.

LCCA includes long-term cost parameters that represent future activities needed to maintain the pavement’s surface at some pre-defined condition or performance requirement. Some of the long-term costs are very difficult, if not impossible, to predict. For example, an extended surplus of material, economic embargos, or international conflicts that may deplete the supply or increase the demand of a material can greatly affect long-term costs.



### C.2.2 Real Versus Nominal Dollars

When evaluating future costs and benefits as part of a LCCA, a decision must be made whether to use real or nominal dollars in the calculation process. Real (or constant) dollars reflect dollars with the same or constant purchasing power over time), whereas nominal (or inflated) dollars reflect dollars that fluctuate in purchasing power as a function of time (2).

For example, in the case of real dollars, if the current estimated unit cost of a full-depth PCC patch is \$100/yd<sup>2</sup>, then the same \$100/yd<sup>2</sup> cost should be used for future-year patching cost estimates. Although the projected quantities of patching may vary from year to year, the same unit cost is used over time.

When using nominal dollars, on the other hand, the estimated cost of patching would change as a function of the year in which it is accomplished. Thus, if inflation were estimated at 4 percent, the unit cost of the full-depth PCC patching at Year 0 would be \$100/yd<sup>2</sup>, whereas 1 year later the unit cost would increase to \$104/yd<sup>2</sup> (i.e., \$100/yd<sup>2</sup> \* 1.04).

Although LCCA can be conducted using either real or nominal dollars, the analyst must be sure not to mix the two types of dollars in any given LCCA (2). All costs must either be in real dollars or nominal dollars. Because of its simplicity, it is recommended that LCCA be conducted using real dollars and the “real” discount rate formula presented in the next section.

### C.2.3 Discount Rate

The discount rate is a very important and often controversial piece of the LCCA framework, because it can significantly influence the results of the analysis. As noted earlier, 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 subsequently used to convert NPV to annualized costs).

The discount rate is a function of both the interest rate and 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 reverse combinations.

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 the discount rate, the interest rate, and the inflation rate is as follows:

$$i_{dis} = [(1 + i_{int}) / (1 + i_{inf})] - 1 \quad (C.3)$$

where:

$$i_{dis} \quad = \quad \text{discount rate, decimal}$$

$$\begin{aligned} i_{inf} &= \text{inflation rate, decimal} \\ i_{int} &= \text{interest rate, decimal} \end{aligned}$$

For practical purposes, however, the discount rate is often approximated as the difference between the interest rate and the inflation rate. As a result, close approximation of present worth (PW) is determined as follows:

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

where:

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

Selection of an appropriate discount rate is highly debatable. The FHWA Office of Engineering, Pavement Division, conducted a pavement design review and found that the discount rates currently used by SHAs to conduct LCCA in pavement design showed a distribution of values clustering in the 3 to 5 percent range (2). Some agencies consider the sensitivity (using a range of discount rates) to determine if the selected design strategy will change with a reasonable range of discount rates, because of the uncertainty and importance of this input parameter in LCCA. As such, a range of discount rates is recommended for use in the LCCA2002 procedure to determine the effect or sensitivity of the discount rate on the life cycle costs of a project. This range is between 3 and 5 percent and corresponds with the use of real/constant dollars (i.e., future estimated costs not adjusted for inflation).

#### C.2.4 Analysis Period

The analysis period is defined as the time period over which the initial and future costs are evaluated for different design alternatives. As a rule of thumb, the analysis period should be long enough to incorporate the cost of at least one rehabilitation activity for all design alternatives, but no longer than the period for making reasonable forecasts. The suggested minimum analysis period for major high-volume roadways (e.g., urban expressways) is 35 years.

There are two exceptions to the general guideline note above. The first exception is for paving projects that are considered short-term or temporary fixes to roadways. For example, widening or rehabilitating a roadway that will be rebuilt in high-development or changing social-economical areas, or the structural-geometrical improvement of roadways to provide temporary access/capacity while adjacent roadways are being rebuilt or rehabilitated. For these cases, the analysis period should equal the expected life of the temporary pavement.

The second exception is for the long-life pavement design. Long-life pavements are those that are designed to an endurance limit (i.e., no structural damage from wheel loads) and only require surface repairs as a result of surface deterioration from environmental and wheel loads. For this case, an analysis period of 50 years is recommended. Table C.1 summarizes the default values recommended for the analysis period for the different design strategies.

Table C.1. Recommended minimum values for the analysis period.

Design Strategy/Condition	Recommended Minimum Analysis Period
Short-term or temporary designs	Analysis period = Minimum of expected life of temporary pavement
Standard design; design period of 10+ years	Minimum of 30 to 40 years, depending on level of traffic and roadway functional class. Analysis period should include at least one rehabilitation activity
Long-life pavement designs	Minimum of 50 years

### C.2.5 Cost Factors

Some of the most critical aspects of LCCA for pavement type selection are the costs of building, maintaining, and rehabilitating the various design alternatives. Having the best unit price estimates possible for the various pay items associated with initial construction and periodic M&R goes a long way toward ensuring a fair assessment of life cycle costs.

Cost factors are subdivided into two basic categories: direct or agency costs and indirect or user costs. Descriptions of each are provided in the paragraphs below.

**Agency Costs.** Agency costs include all costs incurred directly by the agency over the life of the project. These costs are generally subdivided into three groups: initial cost, future costs, and salvage value. The initial costs include preliminary engineering, material testing, contract administration, construction supervision and quality assurance testing, and traffic control supervision, as well as the construction costs of a project. Future costs include routine and preventive maintenance activities, rehabilitation design and construction costs, as well as the administration costs of these activities, and traffic control costs for both preventive maintenance and rehabilitation activities. Both the initial and future costs to the agency should include overhead or operating costs of the agency to support those activities.

**User Costs.** Users costs are a key ingredient in any LCCA of competing pavement design alternatives. Although borne by the highway user, these costs must be given serious consideration by the highway agency, since the agency acts as the proxy for public benefit.

User costs are the costs incurred by the highway user over the life of the project. The user costs of concern in a LCCA are the differential or extra costs incurred by the traveling public as a result of one design being used instead of another. For instance, a design that requires more frequent and/or longer lane closures in the future (to satisfy upkeep needs) will inevitably lead to added user costs due to increased delay, greater fuel consumption, and so on. Also, a design that provides a lower overall level of serviceability during normal operating conditions will yield increased vehicle operating costs (VOCs) as a result of exposure to more pavement roughness.

User costs can be incurred through various mechanisms and at any time over the life of a project. As presented by McFarland in 1972, there are four primary mechanisms or components of user costs and they are as follows (3):

- Time delay costs—Motorist delay costs spurred by detours, work zones, or closures associated with construction, maintenance, and rehabilitation activities.
- Vehicle operating costs (VOCs)—Costs associated with fuel and oil consumption, tire wear, emissions, maintenance and repair, and depreciation due to pavement roughness.
- Accident costs—Costs associated with accidents due to rough or slippery roads and with the increased rate of accidents in construction zones.
- Discomfort costs—Costs associated with rough roads.

User cost components recommended for consideration in the Design Guide include time delay costs and VOCs. These components can be estimated reasonably well and comprise a large portion of the total user costs. Accident costs can be a significant portion of total user cost, however they are difficult to estimate because the value of a human life and the cost of a debilitating injury are very controversial. Discomfort costs are probably the most difficult to estimate and generally provide a relatively low contribution to total user costs. A fifth user-cost component, which requires much more research before practical application can occur, is environmental costs. These costs include traffic noise, as well as the pollution created and energy expended in the construction and upkeep of a pavement facility.

As described below, user costs can be incurred during the operation of a work zone or during normal (non-restricted) highway operating conditions.

- Work Zone Costs—This category of user costs deals with costs brought about by the establishment of a work zone. A work zone is defined in the 2000 Highway Capacity Manual (HCM) (NCHRP) as an area of a highway where maintenance, rehabilitation, or construction operations are taking place, which impinge on the number of lanes available to moving traffic or affect the operational characteristics of traffic flowing through the area (4). A work zone disrupts normal traffic flow, drastically reduces the capacity of the roadway, and leads to specific changes in roadway use patterns that affect the nature of user costs.
- Normal Operating Condition Costs—In between work zone periods, users costs are still incurred during normal operating conditions. These include highway user costs associated with using a facility during periods free of construction, repair, rehabilitation or any work zone activity that restricts the capacity of the facility.

Although normal operating condition user costs are comprised of similar components as work zone user costs, they are of a different nature and are chiefly a function of the differential pavement performance between alternatives. Under the normal operating condition user cost precept, a pavement reaching a severely distressed state sooner or more frequently over the analysis period than another pavement, will result in additional user costs for that pavement, primarily in the form of extra time delay costs and VOCs (figure C.2). However, based on the latest research, today's highways are typically not allowed to get rough enough (i.e., IRI > 3 m/km) to generate significant normal operating condition user costs. Therefore, they

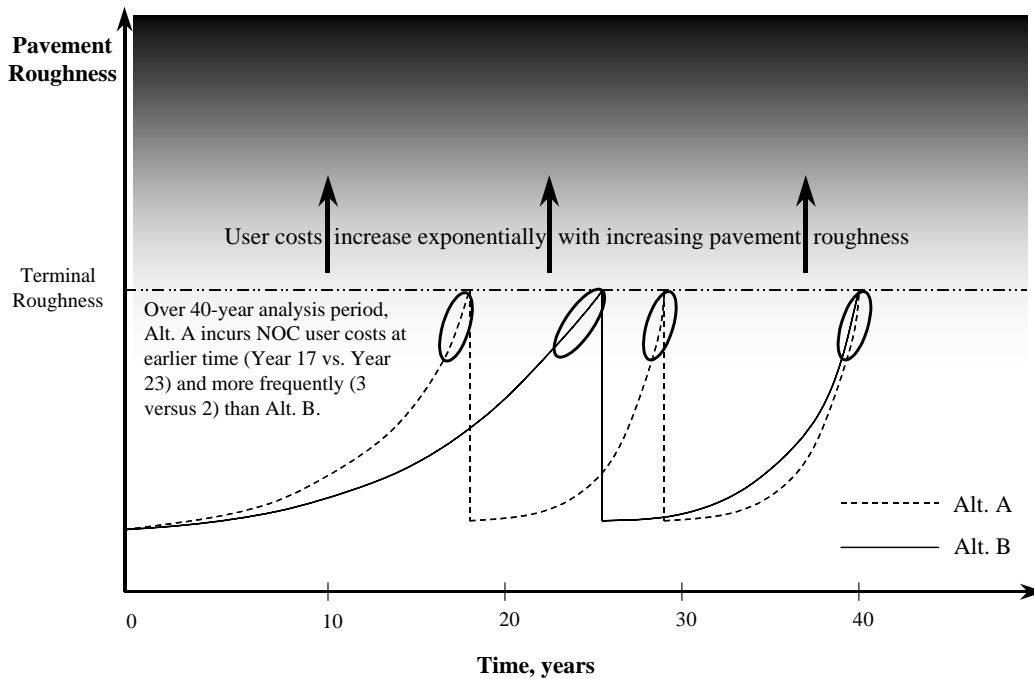


Figure C.2. Illustration of normal operating condition user costs.

are not recommended for consideration in the Design Guide; only the time delay and vehicle operating costs associated with work zones are recommended.

### C.2.6 Approach to Risk and Uncertainty in LCCA

Much uncertainty exists in LCCA. This can be directly considered through probabilistic analysis. Traditionally, LCCA procedures have been deterministic, whereby, as pointed out by the FHWA (2), “the analysis treats all inputs, estimates, projections, and assumptions as discrete values and computes a discrete NPV.” In other words, in deterministic LCCA, a single value is selected (usually the value considered most likely to occur, based on historical evidence or professional experience) for each input parameter (e.g., costs, pavement life) and the group of selected values are 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 properly accounted for in deterministic LCCA. As such, the LCCA results provide only a partial glimpse of the expected life cycle costs.

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. As illustrated in figure C.3 with the discount rate, the projected costs are then plotted as a function of the variable input parameter, so as to reveal the relative impact of input parameter variation on life cycle costs.

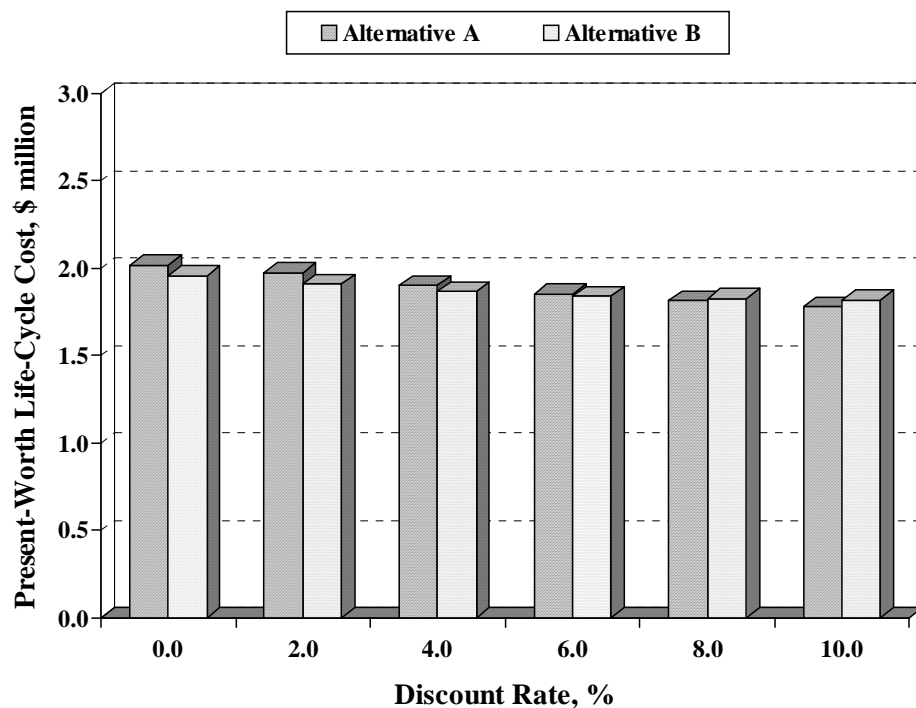


Figure C.3. Example illustration of deterministic sensitivity analysis.

Although a deterministic sensitivity analysis is easy to perform and shows the effect of a changing input variable on LCCA outcome, it does not account for the simultaneous change of all inputs on the LCCA outcome. Moreover, it does not account for the likelihood of a particular input value actually occurring. Thus, while deterministic sensitivity analysis does represent a major step in the right direction of a full, impartial analysis of costs, it is limited in its ability to reflect reality.

Probabilistic LCCA is a relatively new concept that utilizes the processing capabilities of today's computers to simulate and subsequently account for the simultaneous changes of input parameters. The probabilistic approach entails defining individual input parameters by a frequency (or probability) distribution, rather than by discrete values. It represents a risk analysis of the life cycle costs of a particular design alternative.

As illustrated in figure C.4, for a given design 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, which is commonly performed using Monte Carlo or Latin Hypercube techniques (details of these techniques are provided in the 1998 FHWA Interim Technical Bulletin), is then repeated hundreds or even thousands of times, thereby generating many forecasted life cycle cost values for the design strategy. The resulting forecasted costs can then be analyzed and compared with the forecasted results of competing strategies, so as to identify the most economical design.

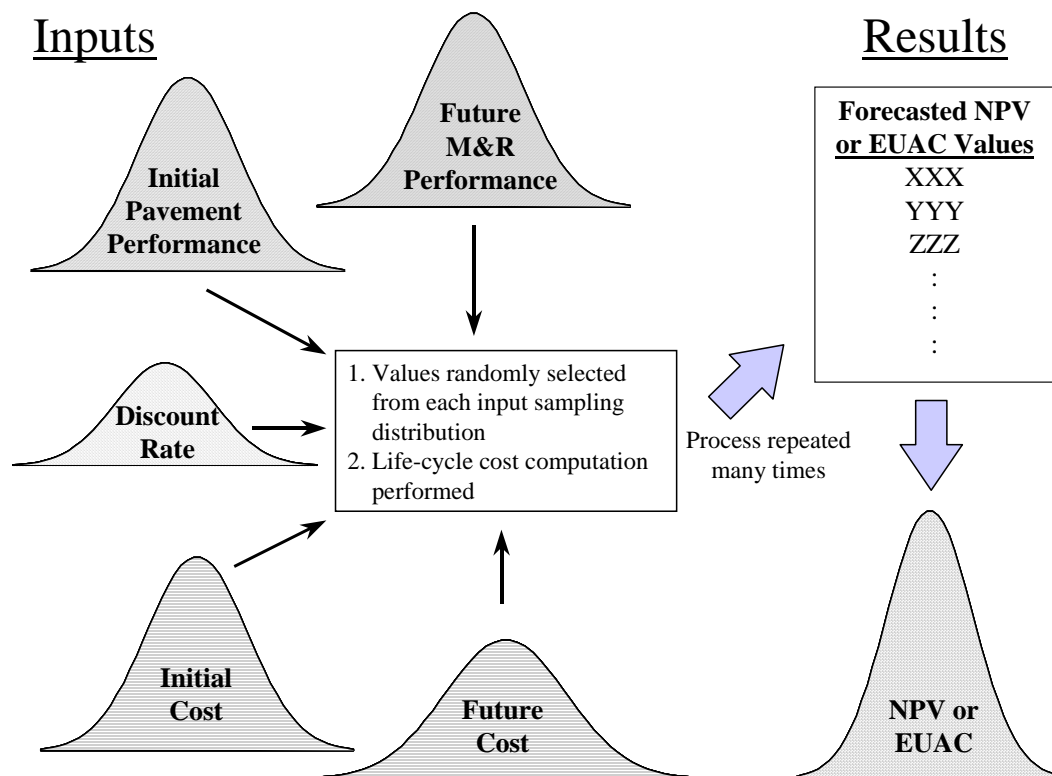


Figure C.4. Illustration of the probabilistic LCCA process.

The type and range of each input sampling distribution are user-defined, and may be developed using either objective or subjective methods (2). The objective method uses hard data, such as bid price history or pavement survival distributions, to formulate the distribution, whereas the subjective method uses expert opinion. In most cases, a combination of the two must be used. For example, in the case of pavement performance, past service life information might be supplemented with expert opinion about the effects of incorporating new materials or technologies.

Although many different types of frequency distributions exist, the most commonly used in probabilistic LCCA are the normal and triangular distributions, with related variations (e.g., truncated ends). These distribution types are fairly simple to apply and generally provide an adequate level of accuracy. Values needed to define the normal distribution include the mean and standard deviation, whereas those needed to define the triangular distribution include the minimum, maximum, and most likely values.

As a minimum, LCCA should be performed deterministically with sensitivity analysis of key variables. However, the preferred approach to LCCA is the probabilistic approach. When properly applied, probabilistic LCCA provides a full view of the expected life cycle costs, because it takes into consideration the real-world tendencies of uncertainty and variation. In

addition, it accounts for the simultaneous change of all input parameters and for the likelihood of a particular input value occurring. Every input into the LCCA is uncertain and may vary from the most expected value.

### C.3 LCCA PROCESS

As outlined in the FHWA Interim Technical Bulletin (2) and shown in figure C.5, the LCCA process consists of the following eight steps:

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

Steps 2 through 6 are performed for each alternative strategy. At the conclusion of the eighth and final step, the pavement designer/analyst will have either identified the most economical design or identified appropriate adjustments to be made to the design alternatives. Details on these steps and guidelines in properly administering them are provided below.

#### C.3.1 Step 1—Establish Alternative Pavement Design Strategies

In this step, each alternative design is assigned a strategy, consisting of the initial structure (new or rehabilitation) and the probable M&R activities covering the chosen analysis period. For a

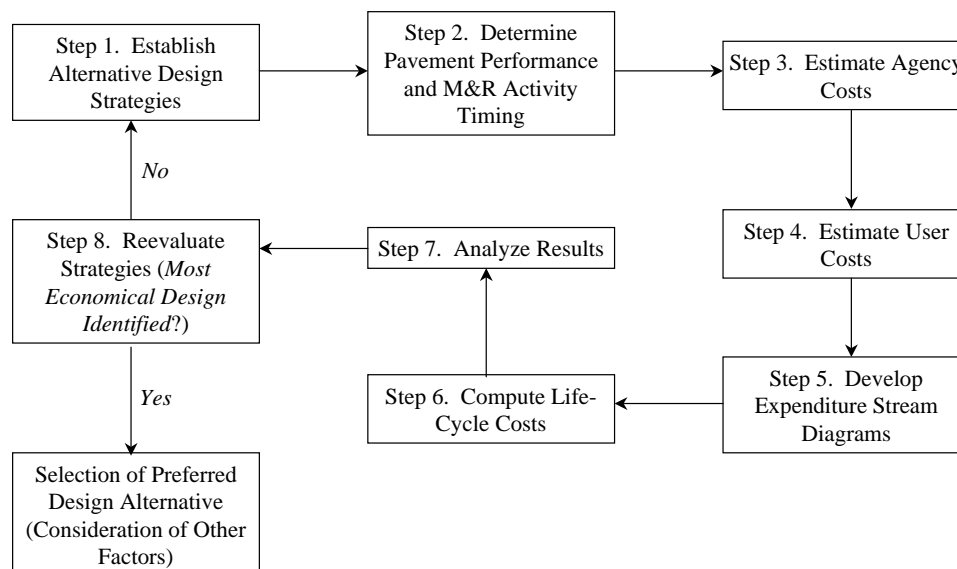


Figure C.5. LCCA process flowchart.



given project, at least two different initial structure types should be evaluated, however LCCA allows several alternatives to be analyzed simultaneously. By the time the LCCA process is reached, the design details of each structure type have been formulated.

Though it is not important at this point to have estimates of expected pavement life, it is essential that the expected critical distresses and modes of failure be identified, so that the probable types of M&R activities can be established. The traditional approach of establishing M&R activities is to make use of historical experience, detailed research, and/or agency policies. Such information generally reflects how an agency will act in preserving or restoring the pavement in the future. This is an acceptable procedure, but consideration should be given to site-related factors, such as traffic, climate, and the incorporation of new materials/technologies.

Use of the Design Guide procedure provides an alternative approach to establishing M&R activities. Performance prediction output, in the form of predicted key distress types and roughness over time, provides valuable insight as to the appropriateness of particular M&R treatments. For instance, in the case of a concrete pavement design, if a prototype strategy calls for asphalt overlay at Year 20, but the Design Guide model suggests that only joint spalling has reached significant levels at that time, then the designer/analyst might consider specifying a concrete pavement restoration (CPR) activity instead of the overlay.

### **C.3.2 Step 2—Determine Pavement Performance and M&R Activity Timing**

Newly constructed, reconstructed, and rehabilitated pavements undergo deterioration due to a combination of environmental and traffic-related loads. The deterioration prompts the need for various forms of upkeep over a long time span to secure the structural capacity of the pavement and to retain the safety and comfort characteristics desired by highway users. It is essential that the series of M&R activities projected for each pavement alternative be as realistic as possible, because the timing and frequency of upkeep activities can result in a sizeable percentage of the total life cycle cost of a particular pavement type.

Step 2 involves the determination of the performance life for each design alternative and the timings of subsequent M&R treatments. This step requires a clear sense of objectivity, so that each design alternative is accorded a fair analysis of life cycle costs. As described below, there are three parts to this step.

#### **Determine Initial Performance Life of Design Option**

A pavement's service life is defined as that period of time from completion of construction until the condition of the pavement is considered to be unacceptable and rehabilitation or replacement is required. Pavement performance and the occurrence of distress must be estimated as accurately as possible for the LCCA procedure to provide meaningful results.

The condition of the pavement surface with time and initial service life should be determined using the Design Guide distress and ride quality prediction models. The Design Guide prediction models have been calibrated with the LTPP monitoring data or performance

measurements. As such, the design life and initial service life should be equal as long as the failure criteria used in design equals the threshold criteria for major rehabilitation. Calibration of the performance prediction models to local or regional conditions (specific materials, climate, construction specifications and maintenance decisions and strategies) is important to ensure that the design and initial service lives are equal and to improve on the accuracy of the NPV costs calculated from the LCCA procedure for an agency. As such, a user agency should confirm these predictions through the use of their own pavement performance database by completing a local calibration of each performance prediction model.

One of the following approaches can be used when a technology or design strategy is not reflected in past observations and performance data that were not included in the calibration of the Design Guide performance prediction models:

- Analyzing data from the agency pavement management system.
- Utilizing results of research performed by the agency or applicable research performed by others at the local, regional, or national level.
- Seeking the collective estimates of experienced engineers within the agency when actual performance data are unavailable. The estimate of the service life for each action from experienced engineers should only be used when no other data exists because of potential bias and the differences that can be caused by regional and climatic differences within a State. However, experienced engineers can be used in addressing the potential effects of new technologies.

A procedure successfully used in the past for estimating pavement service life is failure analysis (alternatively known as survival analysis). This technique uses historical construction and rehabilitation data for a family of pavements (i.e., sections with similar designs and subjected to similar traffic and environmental loadings) to construct a failure curve that depicts the probability of failure with time (or traffic loadings). In failure analysis, “failure” of a pavement section is defined as the occurrence of a major rehabilitation, such as a structural overlay or extensive CPR.

As illustrated in table C.2, the age of each family pavement section that has failed is determined by subtracting the construction year from the rehabilitation year (e.g., 1996–1978 for the first section). Then, by dividing the number of sections failed after each year by the total number of sections in the family (failed and unfailed), a failure curve like the one shown in figure C.6 can be constructed. Using a value of 50 percent projects failed, 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.

**Determine Repair or Maintenance Requirements.** Highway agencies should establish decision criteria and/or functions (even though they may be subjective) that are used to define the type of repair. Decision criteria are applied to select a type of repair option appropriate to the predicted physical condition of the pavement at time  $t$ . Time  $t$  is defined as the time at which the calculated distress value or performance measure exceeds the critical level (amount and/or area) that causes the pavement to be repaired or maintained.

Table C.2. Performance history of a selected pavement family.

Section	Year Constructed	Year Rehabilitated	Age at Failure	Age in 2001
US 51 (MP 112.25 - 118.89)	1978	1996	18	—
US 51 (MP 140.51 - 145.69)	1978	1997	19	—
US 69 (MP 18.65 - 26.33)	1976	1993	17	—
US 60 (MP 26.33 - 31.54)	1977	1997	20	—
US 60 (MP 50.87 - 59.32)	1977	1996	19	—
US 281 (MP 0.00 - 4.92)	1980	1998	18	—
US 281 (MP 18.63 - 27.72)	1980	1998	18	—
US 281 (MP 54.32 - 62.26)	1981	—	—	20
US 281 (MP 62.26 - 69.44)	1981	1996	15	—
Rt 27 (MP 11.66 - 19.34)	1974	1991	17	—
Rt 27 (MP 30.02 - 35.21)	1974	1993	19	—
Rt 64 (MP 0.00 - 8.84)	1983	—	—	18
Rt 89 (MP 45.33 - 53.71)	1982	2000	18	—
Rt 89 (MP 53.71 - 60.07)	1983	—	—	18
Rt 115 (MP 6.22 - 10.65)	1976	1989	13	—
Rt 133 (MP 45.92 - 49.77)	1983	2000	17	—
Rt 133 (MP 49.77 - 58.23)	1982	—	—	19
Rt 205 (MP 7.40 - 14.36)	1977	1993	16	—
Rt 456 (MP 78.84 - 89.75)	1979	1996	17	—
Rt 456 (MP 96.28 - 104.47)	1980	2000	20	—
Mean (Standard Deviation)			17.6 (1.8)	

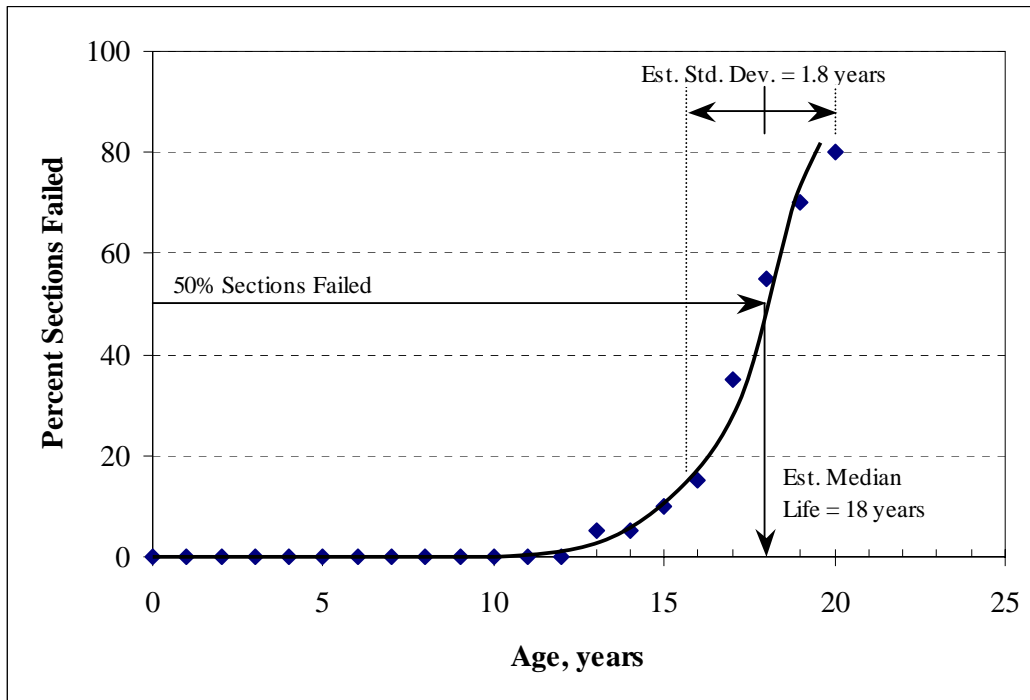


Figure C.6. Age and ESAL failure curves for selected pavement family.

Selection of a repair option implicitly establishes a repair cost at time  $t$ . As stated above, the distress or ride quality prediction models are used to predict time  $t$ .

A standard set of M&R guidelines should be developed based on the performance indicators that are considered important to the structural integrity and/or surface condition of the roadway. Single or multiple criteria can be used to specify different levels of distress or performance measures as critical levels for triggering a specific maintenance or rehabilitation action to be taken. These criteria can be communicated through the use of decision trees or tables that have been developed to relate or identify typical rehabilitation techniques and those actions to be taken for different surface distresses and conditions. The decision tree identifies the key distress types or a combination of distresses and trigger values associated with those distresses, and relates them to appropriate repair techniques.

Pavement M&R techniques should be divided into the following three levels:

- Routine maintenance—where the pavement distress and frequency are such that only local repair is involved and can generally be completed by district maintenance staff.
- Major maintenance—where localized repairs alone may not cost-effectively address pavement problems and a more comprehensive approach is required, perhaps at the regional level.
- Rehabilitation—where the pavement problems are severe and extensive, typically requiring overlays, restoration, and/or reconstruction.

**Determine the Expected Life of M&R Activities.** The amount and cost of routine maintenance should be considered to determine the significance of routine maintenance on total life cycle costs. The timing of maintenance activities should be confirmed through an analysis of performance records. Among the suggested approaches are the following:

- Analyzing data from the agency pavement management system.
- Utilizing results of research performed by the agency or applicable research performed by others at the local, regional, or national level. As an example, these data can be obtained from the Long Term Pavement Performance (LTPP) database.
- Seeking the collective estimates of experienced engineers within the agency when actual performance data are unavailable. However, the estimate of the service life for each action from experienced engineers should only be used when no other data exists because of potential bias and the differences that can be caused by regional and climatic differences within a State.

Agencies that lack sufficient and reliable M&R performance data must usually rely on experienced opinions, whereas those more data fortunate can generally supplement experienced opinions with, or fully base projections on, actual pavement performance data.

NCHRP Synthesis 223 (5) contains a summary of published information on the performance of preventive maintenance treatments, as researched by various highway agencies. Information for this report was obtained through a comprehensive review of literature and current research, and through a questionnaire survey of many highway agencies on their current practices. Also

included in this report are summary statistics (minimum, maximum, and mode) of the highway agency survey respondents' estimates of pavement age at the time of first application of the maintenance treatment, frequency of application of the maintenance treatment, and observed increase in pavement life as a result of applying the maintenance treatment.

### **C.3.3 Step 3—Estimate Direct/Agency Costs**

The costs of building, maintaining, and rehabilitating the different design alternatives is an important element of LCCA. Using current unit price estimates for each pay item associated with the initial construction and periodic M&R will ensure a fair and accurate computation of life cycle costs. Step 3 involves estimating the agency costs for each design alternative. The agency costs are separated into the following five categories:

- Design costs
- Initial construction costs
- Maintenance costs
- Rehabilitation costs
- Salvage value

**Design Costs.** Design costs should be included in the LCCA procedure when evaluating the effectiveness or accuracy of the different input levels and for completeness of the procedure. The design costs include preliminary engineering, preparation of environmental impact statements, materials testing and analyses, site investigations, traffic and climatic analyses, pavement design, and preparation of plans and specifications. Most of these costs are engineering and administrative in nature. The significance of the design costs depends on if there are any significant differences between alternatives and whether this difference can even be estimated.

The determination of accurate and real design costs can be estimated only if the agency maintains adequate accounting records. The agency should also account for real operating or overhead costs for each option in a LCCA.

**Initial Construction Costs.** Initial construction costs are the costs associated with building a new section of pavement or reconstructing or rehabilitating an existing pavement. Though quantifying construction costs is fairly straightforward, key considerations include the following:

- Including in the LCCA only the components of construction that are unique to each design alternative—commonly the travel lane pavement structure and shoulder pavement structure—and omitting incidentals that are identical in each alternative.
- Using an appropriate source for construction costs. Common sources for construction costs include historical projects and bids, and current bids.
- Using great care in generating costs for designs that incorporate new materials or techniques for which historical cost data are unavailable.
- Identifying project-specific aspects that might affect costs, particularly traffic control requirements and project size (i.e., amount of pavement to be constructed).
- Estimation of actual project construction costs involves risk and is highly probabilistic.

Unit costs will vary substantially based on the size of the project, and will vary from agency-to-agency. These costs are also dependent on an agency's materials and construction specifications and enforcement policy. The unit costs can be calculated and consist of the average and standard deviation unit costs computed using either the "low-bid" price for asphalt and concrete projects or the three "lowest bid" prices for asphalt and concrete projects.

The typical procedure for establishing initial construction costs is to compile, for each pay item, the average unit price of the three lowest bids for all similar contracts over the last 3 to 5 years. 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, as illustrated in figure C.7.

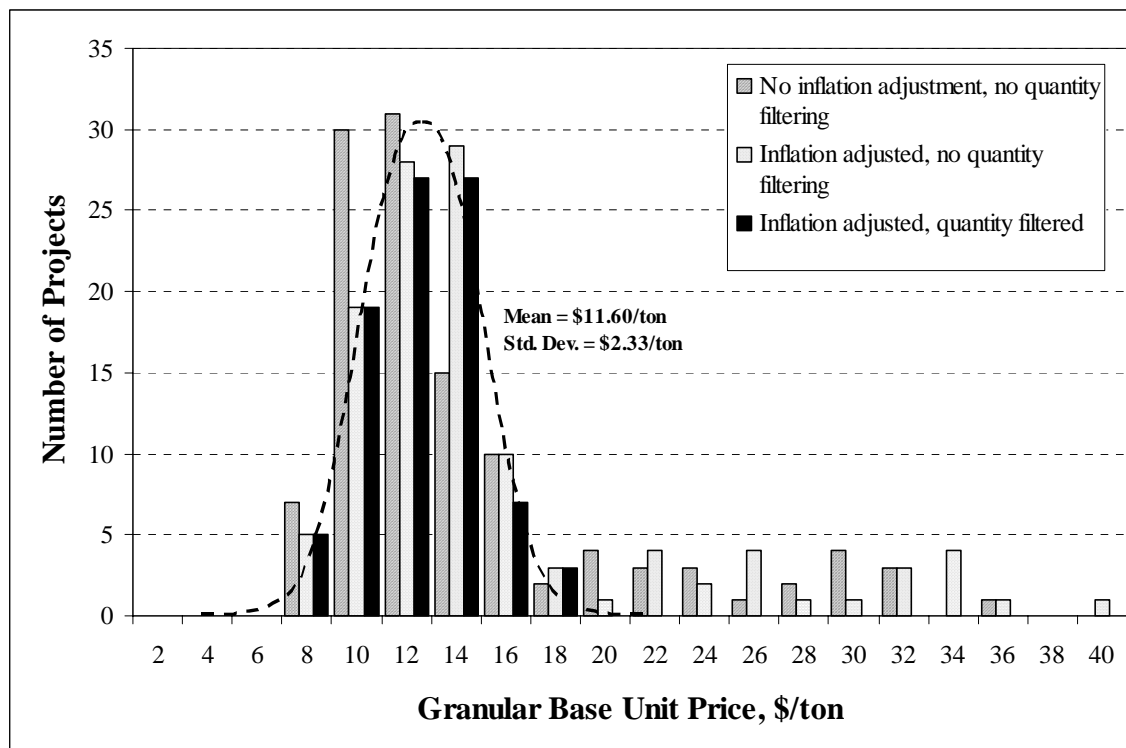


Figure C.7. Example of pay item unit price development.

In general, this procedure is quite appropriate, because it reflects the most recent costs of the various pavement features. However, because each project put to bid is unique in terms of design, location, and other factors, the bid prices submitted on the various pay items are certain to vary by both contractor and project. Paving equipment, materials, and technology also change rapidly, increasing productivity. This same approach can be used in determining pay item unit prices associated with M&R activities.

The LCCA procedure incorporated into the Design Guide uses the total construction costs or total unit construction costs for the paving project. These costs can be determined within the LCCA2002 program, as it includes a unit cost library and a template for multiplying the projected quantities of individual pay items by the appropriate unit costs.

**Maintenance Costs.** Maintenance costs are those costs associated with maintaining a pavement at or above some predetermined performance level. This normally includes maintenance of the pavement surface, shoulders, and related drainage, and all associated costs (e.g., administrative costs, operating or overhead costs, traffic control costs, and any testing and contract administration costs, if the agency contracts the maintenance work). Typical maintenance costs that should not be included in LCCA for pavement design and strategy selection include those that are equal between all alternatives, such as guardrail repair, sign repair, vegetation mowing, and tree/shrub maintenance.

Maintenance costs should be subdivided into costs for preventive maintenance (carefully planned activities intended to extend pavement life) and routine maintenance (day-to-day activities performed to address safety and operational concerns). These costs can be projected to occur at certain periods over the life of a pavement or on an annual basis that are based on real performance data.

Though maintenance costs can be estimated based on previous experience and historical cost data, the estimates should be modified for any differences that may exist between the proposed alternative and the projects from which the experience was derived (e.g., traffic levels, materials, reflection crack control). Maintenance costs depend on pavement deterioration and operational factors that are all highly variable. The determination of accurate and real design costs can be estimated only if the agency maintains adequate accounting records. The timing of these costs was determined under step 2.

**Rehabilitation Costs.** Rehabilitation costs cover the types of activities performed as part of resurfacing or restoring the pavement. Like design and maintenance costs, rehabilitation costs must be determined for each design alternative by identifying the most appropriate or most likely rehabilitation activities and their timing, and using the best estimates of costs and service lives. These costs should also include construction/materials costs, testing of materials, traffic control, contract administration, pavement evaluation and rehabilitation design costs, and other operating or overhead costs. All of these estimates are subject to variation and are, thus, probabilistic in nature. The determination of accurate and real design costs can be estimated only if the agency maintains adequate accounting records. The timing of these costs was determined under step 2.

**Salvage Value.** Salvage value represents the economic worth of the pavement at the end of the analysis period. It is comprised of two components: residual value and serviceable life. Residual value refers to the net value from recycling the pavement at the end of the analysis period, whereas serviceable life represents the value associated with the remaining life of the pavement at the end of the analysis period. The latter component is generally much more significant than the former.

Since salvage value may vary among different design alternatives, it should be accounted for in LCCA. However, it should be recognized that even substantial differences in computed salvage values will be reduced when converted to PW, particularly if a very long analysis period is used.

For those cases where there is some residual life remaining for some of the pavement alternatives, that value of residual life should be accounted for in the life cycle cost comparison and is a positive value (i.e., a benefit). The corollary to this statement would be that some pavements at the end of their design life have a negative salvage value (i.e., a cost). This situation may arise if it costs more to remove and dispose of the pavement than it is actually worth.

Salvage value can be estimated using various methods, however, two particular methods recommended for use are the prorated life method and the reusable material value method. Descriptions of these techniques are provided in the paragraphs below.

Prorated Life Method. The prorated life method should be used to calculate the salvage value for pavements that have remaining life at the end of the analysis period (provided that the pavement expected service life is determined accurately). In this method, salvage value is determined by multiplying the ratio of the remaining life to expected life of the pavement (original construction or rehabilitation) in-place at the end of analysis period by the most recent cost of that pavement. The basic equation used is as follows:

$$SV = (L_{rem}/L_{exp}) * C_{pvt} \quad (C.6)$$

where:

$SV$	=	salvage value, \$
$L_{rem}$	=	remaining life of subject pavement, years
$L_{exp}$	=	expected life of subject pavement, years
$C_{pvt}$	=	cost of subject pavement, \$

The prorated life method does not directly estimate the economic value of the existing pavement. However, it is a fairly logical approach and can provide a reasonable estimate of salvage if the pavement expected service life is determined accurately and the roadway is expected to remain in service.

Reusable Material Value Method. The reusable material value method should be used when the pavement has no remaining life or extensive levels of distress. This method can provide a more accurate estimation of the economic value of the pavement structure, but often requires more extensive input data to make that assessment. Salvage value is calculated external to the LCCA procedure. It is computed as the actual value of the existing materials if they were recycled minus the cost of reclamation. Several project-specific factors, such as age, durability, quantity, and location of existing materials, must typically be considered in this method and therefore it requires extensive input data. If all input parameters are available, this method is expected to provide a reasonable estimation of salvage value.

Summary. The expected condition of the in-place material at the end of the analysis period is used to determine how the salvage value is calculated. If the surface material is expected to have



minimal structural distress and some remaining life, then the prorated life method is used. However, if it is expected that considerable distress or no remaining life exists at the end of the analysis period, then, certain percentages of the original materials cost are applied.

### **C.3.4 Step 4—Estimate Indirect/User Costs**

In this section of the Design Guide, the recommended models and model inputs for calculating the work zone user costs of alternative designs are presented. These models should be used to calculate the life cycle costs of alternative designs with the same initial performance requirements (i.e., equal initial smoothness for a particular project).

**User Cost Components.** As discussed previously, only the work zone user costs of time delay and vehicle operation are recommended for consideration in the Design Guide. Though various models have been developed and are available for estimating other user cost components (e.g., work zone accident costs, normal operating condition VOCs), such models are not deemed sufficiently accurate at this time for use at the national level. Nonetheless, agencies are highly encouraged to develop or investigate reliable ways of accounting for other user cost components.

**Time Delay Costs.** Time delay costs are the opportunity costs incurred as a result of additional time spent completing a journey because of work zone delays. The opportunity cost represents the value associated with other activities that cannot be completed because of the extra time that is normally spent completing a journey.

**Vehicle Operating Costs.** VOCs are the most recognized of highway user costs because they typically involve the out-of-pocket expense associated with owning, operating, and maintaining a vehicle. Unit VOCs are highly related to the road roughness (smoothness) and operating conditions (free flow versus forced flow). Five cost components associated with operating a vehicle are fuel consumption, oil consumption, maintenance and repairs, tire wear, and roadway related vehicle depreciation. Measuring VOCs involves identifying the following:

- Quantity of each type of resource consumed in the productions of transportation services (resources necessary to drive a vehicle from one point to another).
- The unit cost of consumption of the resource, which are marginal costs, taxes, subsidies, and other transfer payments.

**User Cost Model.** To develop a framework for a user cost model that addresses work zone user costs, a number of existing procedures were evaluated (2, 6-8). Based on the information obtained, a comprehensive model was selected for calculating both components of work zone user costs as part of the Design Guide's LCCA procedure. The recommended model is based on principles outlined in the FHWA's 1998 Interim Technical Bulletin. Details of this procedure are provided in the sections below.

**Methods of Establishing Work Zone Traffic Control.** Different types of work zones can be established to control traffic during maintenance, rehabilitation, or construction that require the shifting or closure of one or more lanes. Specific guidance on establishing temporary traffic control when normal operations on a roadway are suspended is provided in Part 6 (Temporary

Traffic Control) of the 2000 *Manual on Uniform Traffic Control Devices* (MUTCD) (9). By definition a work zone should extend from the first sign that warns of the impending traffic control change to the point on the roadway past the last traffic control device where traffic resumes normal operations. A work zone can be stationary or movable and can be for any desirable duration.

Work zone types can be grouped into two general categories. The first category includes work zones that involve the restriction of travel in only one direction of travel with no or minimal interruption of normal traffic operations in the opposing lane. The other category consists of work zones that result in traffic control changes in both directions of travel simultaneously. The work zone possibilities within each category are identified below.

- **Traffic Control in One Direction**—This type of work zone involves closure of one or more lanes in a given direction of travel with the traffic routed to adjacent roadway lane elements in the same direction. Possible adjacent roadway lane elements include the inner or outer shoulder, detours, and adjacent travel lanes. Figure C.8 shows typical examples of this type of work zone that are applicable to two or more lanes, undivided or divided roadways. Note that, as shown in figure C.8(d), this may involve work zones in both directions that are independent of each other and are therefore distinguished for the bi-directional traffic control described next.

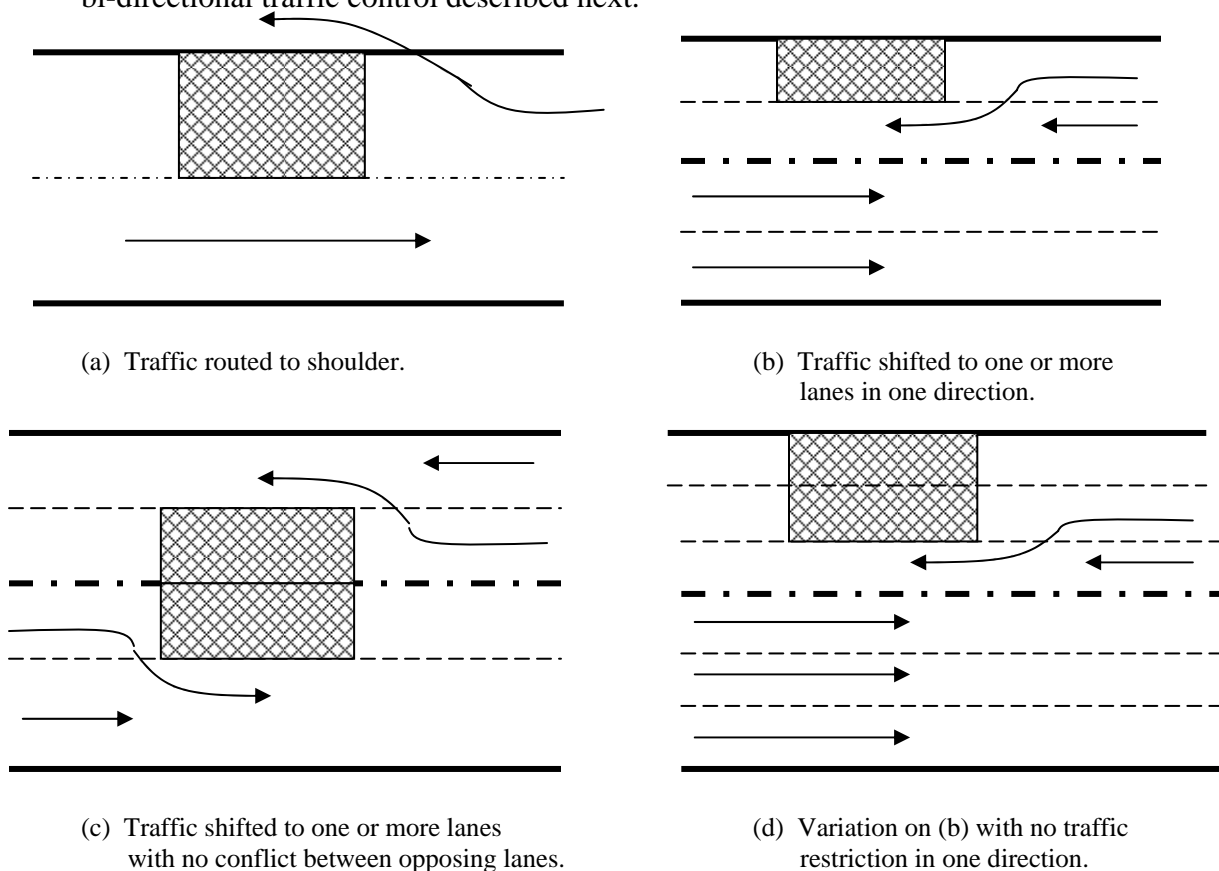
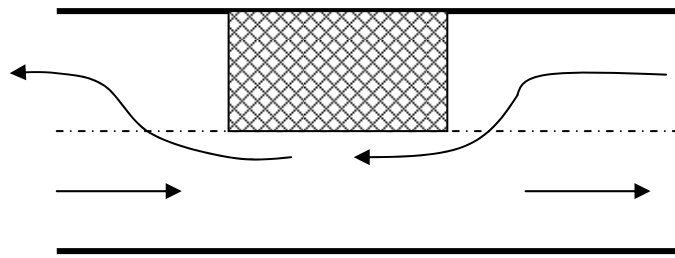
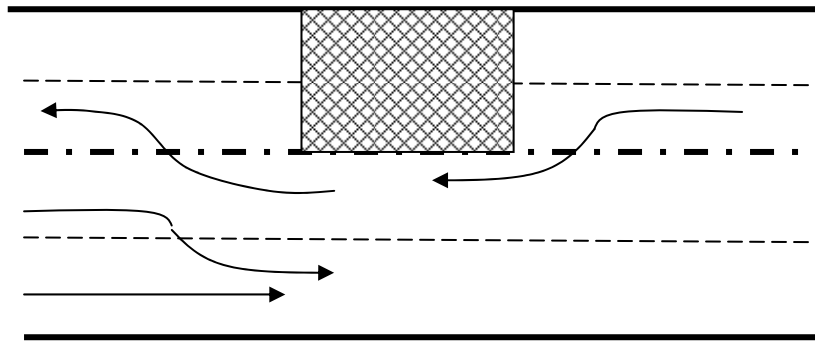


Figure C.8. Uni-directional traffic control changes.

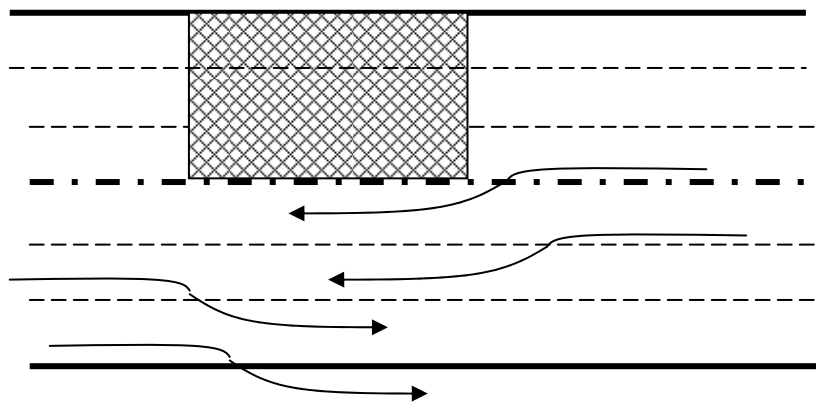
- **Bi-Directional Traffic Control**—This alternative involves traffic control changes in an opposing direction of travel as a direct consequence of the work zone established in a particular direction of travel. Typically, the work zone established in one direction will require that all or part of the traffic be moved to lanes in the opposing direction. Several variations of this arrangement are possible depending on the number of lanes in each direction. For two-lane undivided roadways this may result in alternating traffic in one lane, as shown in figure C.9(a).



(a) Alternating traffic in one lane.



(b) Closure of lanes in one direction with traffic shifted to opposing direction.



(c) Variation of (b) involving use of shoulder.

Figure C.9. Bi-directional traffic control changes.

Work Zone User Cost Components. Seven specific user cost components that are important to work zone activities are identified in the FHWA model (2). They include three user cost components that are also associated with normal operations when traffic operates under free-flow conditions. The four other user cost components are associated with the queue that develops when traffic operates under forced-flow conditions brought on by a work zone. Descriptions of these seven different components are as follows:

- Free Flow—The costs associated with free-flow conditions arise from speed change and result in three work zone related user cost components: speed change delay, speed change VOC, and reduced speed delay (1).
  - Reduced Speed Delay is the additional time necessary to traverse the work zone at the lower posted speed. It depends on the upstream and work zone speed differential and length of work zone.
  - Speed Change Delay is the additional time necessary to decelerate from the upstream approach speed to the work zone speed and then to accelerate back to the initial approach speed after traversing the work zone.
  - Speed Change VOC is the additional vehicle operating cost associated with decelerating from the upstream approach speed to the work zone speed and then accelerating back to the approach speed after leaving the work zone.
- Forced Flow (Level of Service F)—When instantaneous traffic demand exceeds work zone capacity, traffic flow breaks down and a queue develops (2). Queuing situations impose four work zone-related user costs that only apply to vehicles that encounter a physical queue.
  - Stopping Delay is the additional time necessary to come to a complete stop from the upstream approach speed (instead of just slowing to the work zone speed) and the additional time to accelerate back to the approach speed after traversing the work zone.
  - Stopping VOC is the additional vehicle operating cost associated with stopping from the upstream approach speed and accelerating back up to the approach speed after traversing work zone.
  - Idling VOC is the additional vehicle operating cost associated with stop-and-go driving in the queue. The idling cost rate multiplied by the additional time spent in the queue is an approximation of actual VOC associated with stop-and-go conditions. When a queue exists, stopping delay and VOC replace the free-flow speed change delay and VOC.
  - Queue Delay is the additional time necessary to creep through the queue under forced-flow conditions.

Computation of Work Zone User Costs. Once the individual work zones have been identified, each is evaluated separately. This is the point at which individual user cost components are quantified and converted to dollar cost values. The method for calculating work zone user costs involves 12 different steps, as described below.

1. Project Future Year Traffic Demand—The first step of the procedure involves projecting the hourly traffic demand volumes for the years in which a work zone will be in place (2). This is determined by applying appropriate growth factors for the different vehicle classes to the respective current year or base year AADT, as given by the following equation:

$$FutYear\ AADT = BaseYear\ AADT * VehClass\% * (1 + i_{AADT})^{(FutYear - BaseYear)} \quad (C.7)$$

where:

<i>FutYear AADT</i>	=	AADT for future year, veh/day
<i>BaseYear AADT</i>	=	AADT for base or current year, veh/day
<i>VehClass%</i>	=	percentage of AADT comprised by specified vehicle class
<i>i<sub>AADT</sub></i>	=	traffic growth rate, decimal

For example, if the base year AADT is 45,000 veh/day and passenger cars comprise 90 percent of the AADT and are expected to grow compoundly by 2 percent, then the projected AADT in Year 10 would be 49,369 veh/day ( $45,000 * 0.90 * [1+0.02]^{10}$ ).

2. Calculate Directional Hourly Demand—The directional hourly traffic distribution should be determined from appropriate agency traffic data (2). However, if no such data exist, the default values from the MicroBENCOST user cost program developed under NCHRP Project 7-12 (10) can be used. These are listed in table C.3.
3. Determine Roadway Capacities—Three capacities are important for analyzing work zone user costs. They include the following:
  - Free-flow capacity—maximum capacity a facility can handle under free-flow conditions. The approach described in the 2000 HCM is used to estimate the capacity. It involves adjustment of the maximum capacity per lane to account for factors such as restricted lane widths, reduced lateral clearances, the presence of trucks and recreational vehicles, and the presence of a driver population unfamiliar with an area. Typically, the maximum capacities under ideal conditions are 2,200 passenger cars per hour per lane (pcphpl) for a 2-lane directional freeway and 2,300 pcphpl for a three or more lane directional freeway. The free-flow capacity equation is as follows:

$$SF_i = MSF_i * N * f_w * f_{hv} * f_p \quad (C.8)$$

Table C.3. Default hourly distributions for all functional levels from MicroBENCOST (2).

Hour (24-hr Clock)	Rural			Urban		
	% ADT	Direction %		% ADT	Direction %	
		In	Out		In	Out
0 - 1	1.8	48	52	1.2	47	53
1 - 2	1.5	48	52	0.8	43	57
2 - 3	1.3	45	55	0.7	46	54
3 - 4	1.3	53	47	0.5	48	52
4 - 5	1.5	53	47	0.7	57	43
5 - 6	1.8	53	47	1.7	58	42
6 - 7	2.5	57	43	5.1	63	37
7 - 8	3.5	56	44	7.8	60	40
8 - 9	4.2	56	44	6.3	59	41
9 - 10	5.0	54	46	5.2	55	45
10 - 11	5.4	51	49	4.7	46	54
11 - 12	5.6	51	49	5.3	49	51
12 - 13	5.7	50	50	5.6	50	50
13 - 14	6.4	52	48	5.7	50	50
14 - 15	6.8	51	49	5.9	49	51
15 - 16	7.3	53	47	6.5	46	54
16 - 17	9.3	49	51	7.9	45	55
17 - 18	7.0	43	57	8.5	40	60
18 - 19	5.5	47	53	5.9	46	54
19 - 20	4.7	47	53	3.9	48	52
20 - 21	3.8	46	54	3.3	47	53
21 - 22	3.2	48	52	2.8	47	53
22 - 23	2.6	48	52	2.3	48	52
23 - 24	2.3	47	53	1.7	45	55

where:

- $SF_{fi}$  = service flow rate for LOS I under prevailing roadway and traffic conditions for N lanes in one direction, veh/hr
- $MSF_i$  = maximum service flow rate for LOS I for N lanes in one direction, veh/hr
- $N$  = number of lanes in one direction of the freeway
- $f_w$  = factor to adjust for the effects of restricted lane widths and lateral clearances
- $f_{hv}$  = factor to adjust for the effect of heavy vehicles on the traffic stream
- $f_p$  = factor to adjust for the effect of recreational or unfamiliar driver populations

- Work zone capacity—estimated from results obtained from research on the capacity associated with various multilane facilities. Table C-4 shows observed mixed vehicle flow capacities at several real-world work zones under several lane closure scenarios.

Table C.4. Measured average work zone capacities (2).

Directional Lanes		Number of Studies	Average Capacity	
Normal Operations	Work Zone Operations		Vehicles/hour	Vehicles/lane/hour
3	1	7	1,170	1,170
2	1	8	1,340	1,340
5	2	8	2,740	1,370
4	2	4	2,960	1,480
3	2	9	2,980	1,490
4	3	4	4,560	1,520

- Queue dissipation capacity is less than the capacity for free-flow conditions, even though the lanes are unrestricted. A reduction of as much as 200 vehicles per hour (vph) has been observed. According to the 1994 HCM, “various observations of freeway queue departure rates range from as low as 1,500 pcphpl to as high as 2,000 pcphpl.” This implies that a separate and distinct temporary dissipation capacity rate exists after a work zone is removed. This rate comes into play when work zones are only in place for certain hours of the day (i.e., when work zones are removed during peak traffic flow periods).
4. Quantify Traffic Affected By Each Cost Component—With the hourly demand and capacities determined, the next step is to quantify the traffic that is affected by the relevant user cost components. Depending on the hourly demand and capacities, there can be vehicles that traverse the work zone without having to go through a queue or those that have to go through a queue that forms because of the work zone. The work zone related cost components applicable to vehicles that traverse a section of roadway under consideration include the following:
- Free flow, work zone in place with no queue.
    - work zone reduced speed delay costs.
    - work zone speed change delay costs.
    - work zone speed change VOC.
  - Forced flow, work zone in place with queue.
    - work zone reduced speed delay cost.
    - queue reduced speed delay costs.
    - queue stopping delay costs.
    - queue stopping VOC.
    - queue idling VOC.
  - Forced flow, no work zone in place with queue.
    - queue reduced speed delay costs.
    - queue stopping delay costs.
    - queue stopping VOC.
    - queue idling VOC.

The recommended approach for determining the number of vehicles to apply these costs to is to set up a spreadsheet that, for each hour of the day, shows the number of vehicles traversing the work zone, vehicles traversing a queue, vehicles that come to a stop and accelerate back to free-flow speed, and vehicles that slow down but do not stop and accelerate back to free-flow speed. While accounting of costs on an hourly basis is recommended for most purposes, costs in less than 1-hour increments can be considered, as long as the corresponding demand and capacity data are available. Table C.5 is an example showing the number of vehicles in each of these categories for a particular case.

Table C.5. Number of vehicles affected by each cost component (2).

AADT 134,615			Queue Rate	No. of Queued Vehicles	Number of Vehicles that			
Hour (24-Hr Clock)	Demand	Capacity			Traverse WZ	Traverse Queue	Stop 88-0-88 (km/h)	Slow down 88-64-88 (km/h)
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
0 - 1	856	2,830	-1,974	0	856	0	0	856
1 - 2	614	2,830	-2,216	0	614	0	0	614
2 - 3	509	2,830	-2,321	0	509	0	0	509
3 - 4	350	2,830	-2,480	0	350	0	0	350
4 - 5	405	2,830	-2,425	0	405	0	0	405
0 - 5					2,734			2,734
5 - 6	961	6,540	-5,579	0	0	0	0	0
6 - 7	2,540	6,540	-4,000	0	0	0	0	0
7 - 8	4,200	6,540	-2,340	0	0	0	0	0
8 - 9	3,477	6,540	-3,063	0	0	0	0	0
5 - 9				0	0	0	0	0
9 - 10	3,150	2,830	320	320	2,830	2,830	3,150	0
10 - 11	3,417	2,830	587	907	2,830	2,830	3,417	0
11 - 12	3,639	2,830	809	1,715	2,830	2,830	3,639	0
12 - 13	3,769	2,830	939	2,654	2,830	2,830	3,769	0
13 - 14	3,837	2,830	1,007	3,661	2,830	2,830	3,837	0
14 - 15	4,051	2,830	1,221	4,881	2,830	2,830	4,051	0
9 - 15					16,980	16,980	21,861	0
15 - 16	4,725	5,454	-729	4,152	0	5,454	4,725	0
16 - 17	5,849	5,454	395	4,548	0	5,454	5,849	0
17 - 18	6,865	5,454	1,411	5,959	0	5,454	6,865	0
18 - 19	4,289	5,454	-1,165	4,794	0	5,454	4,289	0
19 - 20	2,730	5,454	-2,724	2,070	0	5,454	2,730	0
15 - 20					0	27,270	24,458	0
20 - 21	2,354	2,830	-476	1,594	2,830	2,830	2,354	0
21 - 22	1,998	2,830	-832	762	2,830	2,830	1,998	0
22 - 23	1,610	2,830	-1,220	0	2,372 <sup>a</sup>	1,767 <sup>b</sup>	1,005 <sup>b</sup>	605 <sup>b</sup>
20 - 23					8,032	7,427	5,357	605
23 - 24	1,259	2,830	-1,571	0	1,259	0	0	1,259
24 hours	67,453				29,005	51,677	51,677	4,597

<sup>a</sup> Represents hourly demand and vehicles queued from the previous hour.

<sup>b</sup> Values shown are prorated based on the portion of the hour required to clear queue (762/1220).



Using a similar approach the number of vehicles that traverse the work zone, traverse a queue, slow down from the free flow speed and accelerate back up to the free flow speed, or come to a complete stop and accelerate back up to the free flow speed can be determined. The seven user cost components that apply to the vehicles within each of these four categories during each hour can be identified. In each case, the costs incurred in each hour are obtained by multiplying the number of vehicles affected by that cost component by the unit cost of the cost component.

For clarity, the procedures for calculating each of the cost components are described in the following steps. Depending on which of the three conditions identified above exist during any hour, the user can combine the relevant cost components to calculate the total work zone user costs. The conditions that each calculation step is applicable to are noted at the beginning of every step.

5. Calculate Work Zone Reduced Speed Delay Cost—The work zone reduced speed delay is applicable to these conditions:

- Free flow, work zone in place with no queue.
- Forced flow, work zone in place with queue (ahead of work zone).

It quantifies the cost of the delay incurred by vehicles that traverse the length of the work zone at the reduced posted work zone speed. The delay time through the work zone is calculated as the difference between the travel time when the work zone is in place and the travel time without the work zone.

$$d_{wz} = L_{wz} \left( \frac{1}{v_{wz}} - \frac{1}{v_u} \right) \quad (C.9)$$

where:

$d_{wz}$	=	work zone delay per vehicle, hours
$v_{wz}$	=	work zone speed, mph
$v_u$	=	upstream free flow speed, mph
$L_{wz}$	=	work zone length, mi

The upstream speed ( $v_u$ ), work zone speed ( $v_{wz}$ ), and work zone length ( $L_{wz}$ ) are the specific values for each of the alternative designs under consideration. The work zone delay ( $d_{wz}$ ) is the delay experienced by each vehicle since they all go through the work zone when it is in place. The value of time for the different vehicle classes is shown in table C.6. The work zone reduced speed delay cost is determined by vehicle class using the unit cost for each class.

Table C.6. Recommended values of travel time (\$/veh-hr) (Year 2000 dollars).<sup>a,b</sup>

Passenger Cars (average)	Single-Unit Trucks (average)	Combination Trucks (average)
\$11.25 to \$14.75 (\$13.08)	\$19.25 to \$22.50 (\$20.95)	\$23.75 to \$27.00 (\$25.21)

<sup>a</sup> Each cost should be converted to the current year cost by multiplying the cost by an escalation factor based on the consumer price index (CPI) computed as follows:

$$\text{Escalation Factor} = \frac{CPI_{CY}}{CPI_{OY}}$$

where:  $CPI_{CY}$  = CPI for current year.  
 $CPI_{OY}$  = CPI for original year of stated costs (e.g., Year 2000).

<sup>b</sup> CPI data are available from the Bureau of Labor Statistics, U.S. Department of Labor, Washington, D.C. 20212. Monthly CPI data from 1913 to the current year are available via the internet at the address <http://www.bls.gov/cpihome.htm>.

The work zone reduced speed cost during each hour is calculated as follows:

$$WZRSDC_H = \sum_{i=PC,CU,COMBO} VRSDC_i \quad (C.10)$$

where:  $WZRSDC_H$  = work zone reduced speed delay cost during the hour  
 $VRSDC_i$  = work zone reduced speed delay cost for vehicles in class  $i$  (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO], \$  
 $= d_{wz} * VOL_{wz} * \%AADT_i * TV_i$   
 $d_{wz}$  = work zone delay per vehicle, hours  
 $VOL_{wz}$  = number of vehicles that traverse work zone  
 $\%AADT_i$  = percent of AADT that is vehicle class  $i$   
 $TV_i$  = time value for vehicle class  $i$ , \$/veh-hour

6. Calculate Work Zone Speed Change Delay Cost—Work zone speed change delay cost is applicable when a work zone is in place but there is no queue. It accounts for the delay incurred by vehicles ahead of the work zone that occurs when the vehicles change speed from the upstream free flow speed to the work zone speed. The information presented in table C.7 is used to determine the work zone speed change delay. Table C. shows the delay in hours and VOC (2000 \$) associated with bringing 1,000 vehicles from a particular speed to a stop and then returning them to that speed. Delay and VOC data are provided for the three vehicle classes of passenger cars, single-unit trucks, and combination trucks. The VOC rates associated with idling of vehicles in a queue are also provided in the last row of the table.

Table C.7. Added time (hours) and vehicle operating cost (Year 2000 dollars) per 1,000 stops and idling cost per vehicle (11, 12).

Initial Speed (km/h)	Added Time (hr/1,000 Stops) (Excludes Idling Time)			Added Cost (hr/1,000 Stops) (Excludes Idling Time)		
	Passenger Cars	Trucks		Passenger Cars	Trucks	
		Single-Unit	Combination		Single-Unit	Combination
8	1.02	0.73	1.10	2.90	9.93	36.10
16	1.51	1.47	2.27	9.48	22.24	83.19
24	2.00	2.20	3.48	16.27	36.38	139.52
32	2.49	2.93	4.76	23.34	51.96	204.03
40	2.98	3.67	6.10	30.78	68.68	275.41
48	3.46	4.40	7.56	38.75	86.13	352.34
56	3.94	5.13	9.19	47.30	104.00	433.53
64	4.42	5.87	11.09	56.58	122.35	517.66
72	4.90	6.60	13.39	66.63	139.65	603.47
80	5.37	7.33	16.37	77.63	156.69	689.65
88	5.84	8.07	20.72	89.61	172.72	774.84
96	6.31	8.80	27.94	102.73	192.14	857.74
104	6.78	9.53	NA	117.04	210.25	NA
112	7.25	NA	NA	132.70	NA	NA
120	7.71	NA	NA	149.78	NA	NA
128	8.17	NA	NA	168.38	NA	NA
Idling Cost (\$Veh-Hr)				0.7436	0.5245	0.8855

Added Cost (\$/1,000 stops) includes fuel, tires, engine oil, maintenance, and depreciation. Idling cost (\$/veh-h) includes fuel, engine oil, maintenance, and depreciation.

Using this lookup table, the delay incurred by a vehicle that slows down from the higher upstream free flow speed  $v_u$  to a slower work zone speed  $v_{wz}$  can be determined as follows:

$$SCD_i = (D_{vu,i} - D_{vwz,i})/1000 \quad (C.11)$$

where:  $SCD_i$  = speed change delay per vehicle in class  $i$ , hours  
 $D_{vu,i}$  = added time per 1,000 stops for vehicle in class  $i$  with initial speed  $v_u$   
 $D_{vwz,i}$  = added time per 1,000 stops for vehicle in class  $i$  with initial speed  $v_{wz}$

The work zone speed change delay cost during each hour is calculated as follows:

$$WZSCDC_H = \sum_{i=PC,CU,COMBO} VSCDC_i \quad (C.12)$$

where:  $WZSCDC_H$  = work zone speed change delay cost during the hour, \$  
 $VSCDC_i$  = work zone speed change delay cost for vehicles in class  $i$  (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO]), \$  
=  $SCD_i * VOL_{wz} * \%AADT_i * TV_i$

$SCD_i$	= speed change delay per vehicle in class $i$ , hours
$VOL_{wz}$	= number of vehicles that traverse work zone
$\%AADT_i$	= percent of AADT that is vehicle class $i$
$TV_i$	= time value for vehicle class $i$ , \$/veh-hour

7. Calculate Work Zone Speed Change VOC—The VOC associated with the work zone speed change delay in step 6 is calculated here. The work zone speed change VOC is incurred when there is a work zone but no queue and vehicles slow down from the free flow speed to the work zone speed and accelerate back up to the former. The VOC data in table C.7 is used to calculate the work zone speed change VOC. Using table C.7, the VOC incurred by a vehicle that slows down from the higher upstream free flow speed  $v_u$  to a slower work zone speed  $v_{wz}$  can be determined as follows:

$$SCVOC_i = (VOC_{vu,i} - VOC_{vwz,i})/1000 \quad (C.13)$$

where:	$SCVOC_i$	= speed change VOC per vehicle in class $i$ , \$
	$VOC_{vu,i}$	= added time per 1,000 stops for vehicle in class $i$ with initial speed $v_u$
	$VOC_{vwz,i}$	= added time per 1,000 stops for vehicle in class $i$ with initial speed $v_{wz}$

The work zone speed change VOC during each hour is calculated as follows:

$$WZSCVOC_H = \sum_{i=PC,CU,COMBO} VSCVOC_i \quad (C.14)$$

where:	$WZSCVOC_H$	= work zone speed change VOC during the hour, \$
	$VSCVOC_i$	= work zone speed change VOC for vehicles in class $i$ (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO], \$
		= $SCVOC_i * VOL_{wz} * \%AADT_i * TV_i$
	$SCVOC_i$	= speed change VOC per vehicle in class $i$ , hour
	$VOL_{wz}$	= number of vehicles that traverse work zone
	$\%AADT_i$	= percent of AADT that is vehicle class $i$
	$TV_i$	= time value of vehicle class $i$ , \$/veh-hour

8. Calculate Queue Speed and Queue Length—The remaining calculations are necessary if a queue develops because of the work zone. Two important parameters that are required are the queue speed ( $v_{que}$ ) and queue length ( $L_{que}$ ) during each hour. The parameter  $v_{que}$  is determined from a relationship between average speed and the volume/capacity ( $V/C$ ) ratio at level of service F, which was obtained from the 2000 HCM and is reproduced in table C.8. For a work zone with a queue, the queue volume ( $V$ ) is the volume of vehicles

Table C.8. Average queue speed versus V/C ratio (level of service F).

V/C	$v_{que}$ , (km/h)
0.2	5.3
0.3	8.0
0.5	16.1
0.6	20.1
0.8	29.0
1.0	41.8

that moves out of the queue in a 1-hour period, while the free-flow capacity is the capacity ( $C$ ) of the roadway. The following equation closely matches the data in the table and can be used to estimate the average queue speed  $v_{que}$  for each hour:

$$v_{que} = 23.186 (V/C) + 12.361(V/C)^2 + 5.773(V/C)^3 \quad (C.15)$$

The queue length  $L_{que}$  is required for queue delay computations. Since the number of queued vehicles when there is a queue changes continually, an hour-by-hour analysis to determine the average number of vehicles queued and the average queue length is recommended. The average number of queued vehicles is simply the arithmetic average of the number of queued vehicles at the beginning and end of each hour. The average number of queued vehicles for each hour divided by the difference between the upstream and queue densities in that hour gives  $L_{que}$ . The difference between the upstream density and queue density represents the change in density. The densities are calculated as follows:

$$\text{Upstream density} = \text{Upstream Demand/Free flow speed} \quad (C.16)$$

$$\text{Queue density} = \text{Work zone capacity/Queue speed} \quad (C.17)$$

Alternatively, by assuming an average vehicle length, the hourly queue length can be calculated as follows:

$$L_{que} = \frac{N_{que} * L_{veh}}{1000 * N} \quad (C.18)$$

where:  $N_{que}$  = average number of queued vehicles, veh/km  
 $L_{veh}$  = average vehicle length (12.2 m according to HCM)  
 $N$  = number of lanes

For practical purposes, a maximum queue length is established and the average queue length during each hour is taken as the minimum of the calculated queue length and the established maximum queue length.

9. Calculate Queue Stopping Delay Cost—This cost is applicable when there is a queue that brings vehicles to a stop. It is the cost of the additional time it takes for vehicles to slow down from the free flow speed to a complete stop in a queue and then to accelerate (through the work zone) back to the free flow speed after traversing the work zone. Using table C-7, the delay incurred by a vehicle that slows down from the upstream free flow speed  $v_u$  to a stop in the queue and accelerates back up to  $v_u$  is determined as follows:

$$QSD_i = D_{vu,i}/1000 \quad (C.19)$$

where:  $QSD_i$  = queue stopping delay per vehicle in class  $i$ , hours  
 $D_{vu,i}$  = added time per 1,000 stops for vehicle in class  $i$  with initial speed  $v_u$

The queue stopping delay cost during each hour is calculated as follows:

$$QSDC_H = \sum_{i=PC,CU,COMBO} VQSDC_i \quad (C.20)$$

where:  $QSDC_H$  = queue stopping delay cost during the hour, \$  
 $VQSDC_i$  = queue stopping delay cost for vehicles in class  $i$  (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO]), \$  
 $= QSD_i * VOL_{que} * \%AADT_i * TV_i$   
 $VOL_{que}$  = number of stopped vehicles in queue  
 $\%AADT_i$  = percent of AADT that is vehicle class  $i$   
 $TV_i$  = time value of vehicle class  $i$ , \$/veh-hour

10. Calculate Queue Stopping VOC—This cost is also applicable when there is a queue that brings vehicles to a stop. It is the additional VOC for vehicle that slow down from the free flow speed to a complete stop in a queue and then accelerate (through the work zone) back to the free flow speed after traversing the work zone. Using table C.7, the VOC incurred by a vehicle that slows down from the upstream free flow speed  $v_u$  to a stop in the queue and accelerates back up to  $v_u$  is determined as follows:

$$QSVOC_i = D_{vu,i}/1000 \quad (C.21)$$

where:  $QSVOC_i$  = queue stopping VOC per vehicle in class  $i$ , hours  
 $D_{vu,i}$  = added VOC per 1,000 stops for vehicle in class  $i$  with initial speed  $v_u$

The queue stopping VOC during each hour is calculated as follows:

$$QSVOC_H = \sum_{i=PC,CU,COMBO} VQSVOC_i \quad (C.22)$$

where:

$QSVOC_H$	= queue stopping VOC during the hour, \$
$VQSVOC_i$	= queue stopping VOC for vehicles in class $i$ (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO]), \$
	= $QSVOC_i * VOL_{que} * \%AADT_i * TV_i$
$VOL_{que}$	= number of stopped vehicles in queue
$\%AADT_i$	= percent of AADT that is vehicle class $i$
$TV_i$	= time value of vehicle class $i$ , \$/veh-hour

11. Calculate Queue Idling VOC—This applies when there is a queue and accounts for the idling costs for vehicles in the queue. Table C.7 provides hourly idling costs per vehicle in the last row for passenger cars, single-unit trucks and combination trucks. The delay incurred by a vehicle that traverses the queue at the reduced queue speed instead of the upstream free flow speed is calculated as follows:

$$d_{que} = L_{que} \left( \frac{1}{v_{que}} - \frac{1}{v_u} \right) \quad (C.23)$$

where:

$d_{que}$	= queue delay, hours
$L_{que}$	= queue length, km
$v_{que}$	= queue speed, km/hour
$v_u$	= upstream free flow speed

The queue idling VOC associated with this additional delay during each hour is calculated as follows:

$$QIVOC_H = \sum_{i=PC,CU,COMBO} VQIVOC_i \quad (C.24)$$

where:

$QIVOC_H$	= queue idling VOC during the hour
$VQIVOC_i$	= queue idling VOC for vehicles in class $i$ , (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO]), \$
	= $d_{que} * VOL_{que} * \%AADT_i * IC_i$
$VOL_{wz}$	= number of vehicles affected by queue
$\%AADT_i$	= percent of AADT that is vehicle class $i$
$IC_i$	= idling cost for vehicle class $i$ , \$/veh-hour

12. Calculate Queue Reduced Speed Delay Cost—This also applies when there is a queue and accounts for the time value of the queue delay  $d_{que}$  calculated in step 12. The queue reduced speed delay cost during each hour is calculated as follows:

$$QRSDC_H = \sum_{i=PC,CU,COMBO} VQRSDC_i \quad (C.25)$$

where:

$QRSDC_H$	= queue reduced speed delay cost during the hour, \$
$VQRSDC_i$	= queue reduced speed delay cost for vehicles in class $i$ (i.e., passenger cars [PC], single-unit trucks [SU], or combination trucks [COMBO]), \$
	= $d_{que} * VOL_{que} * \%AADT_i * TV_i$
$VOL_{que}$	= number of queued vehicles
$\%AADT_i$	= percent of AADT that is vehicle class $i$
$TV_i$	= time value of vehicle class $i$ , \$/veh-hour

Aggregating Work Zone User Costs. Using the step-by-step approach described, the user costs that are applicable in each hour can be identified and calculated. As indicated previously, because of the repetitious nature of the calculation, it is advisable to use the LCCA2002 spreadsheet program for these calculations. For each work zone, the costs for the individual components are summed up to obtain the total cost for each of the seven cost components and the total work zone user costs, as shown in table C.9.

This should be repeated for every work zone established during the life cycle of each of the alternatives being considered to obtain the stream of work zone user costs during the analysis period under consideration. The appropriate discount rates can be used to bring back the costs associated with each work zone to current costs.

### C.3.5 Step 5—Develop Expenditure Stream Diagrams

Expenditure stream diagrams are graphical representations of expenditures over time (2). They are developed for each alternative design strategy to help the designer/analyst visualize the magnitudes and timings of all expenditures projected for the analysis period.

In the expenditure stream diagram, costs are normally depicted as upward arrows, whereas benefits are represented by downward arrows (see figure C.1). As pointed out in the FHWA Interim Technical Bulletin (2), under the NPV economic analysis approach, the benefits of providing and maintaining some pre-established pavement condition level on any given roadway are outside the scope of the analysis, as they are considered to be the same for all design strategies. This means that the only benefit that need be shown in the expenditure stream diagram is the salvage value at the end of the analysis period.

Table C.9. Summary of work zone user costs.

User Cost Component	Passenger Cars	Trucks		Totals, \$
		Single-Unit	Combination	
WZ reduced speed delay				
Speed change delay				
Speed change VOC				
Queue stopping delay				
Queue stopping VOC				
Queue idling VOC				
Queue reduced speed delay				



A slight variation of the expenditure stream diagram is the life cycle model, which can be created in graphical or tabular format. As seen in figure C.10, the life cycle model depicts the entire strategy of each design alternative, from the initial structure to the final M&R treatment. The type and timing of each anticipated activity are indicated (for probabilistic LCCA, these timings represent the mean or most likely value), along with the expected quantities.

### C.3.6 Step 6—Compute Life Cycle Cost

Once the expenditure stream (and variation, in the case of probabilistic LCCA) for each alternative design strategy has been developed, the task of computing projected life cycle costs must be undertaken. Regardless of the computation approach (deterministic or probabilistic), the selected economic formula (NPV or EUAC) must be applied using the established cost inputs and discount rate, so as to generate equivalent-dollar costs that can be summed together to yield NPV or total EUAC. In this step, it is important to individually compute and keep separate the projected agency life cycle costs and the projected user life cycle costs, as the two costs carry different weight and meaning.

**Deterministic LCCA.** Although deterministic life cycle cost computation can be carried out manually using a calculator, a more efficient approach is to use a computerized spreadsheet program. All of the input values and computational formulas can be keyed into the spreadsheet, and the projected life cycle costs are then calculated automatically. A spreadsheet is particularly useful when conducting a deterministic sensitivity analysis. By varying the values of the inputs chosen for sensitivity analysis, the life cycle cost corresponding to each value can be computed and saved for examination.

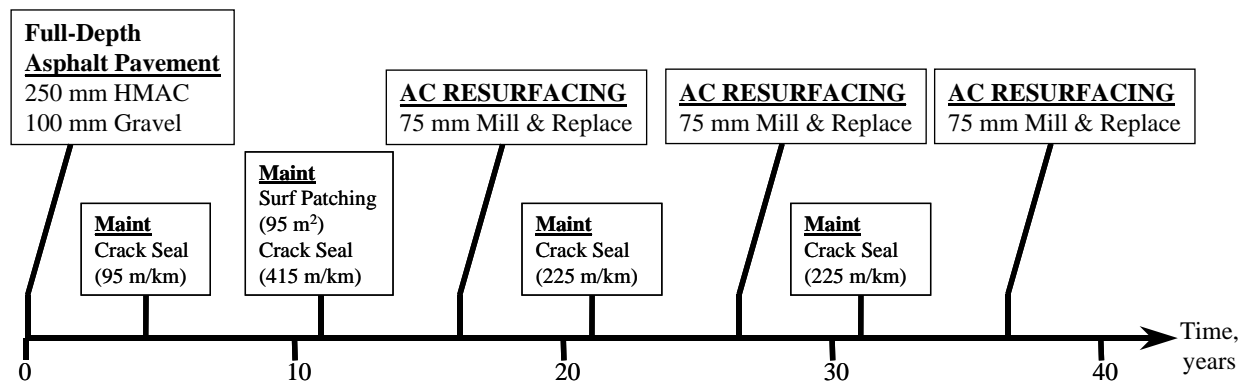


Figure C.10. Example illustration of pavement life cycle model.

Figure C.11 provides an example illustration of a deterministic life cycle cost computation. As can be seen, the example strategy involves an initial investment (resurfacing), three individual future expenditures (two resurfacings and a reconstruction), and the future one-time benefit (negative cost) of pavement salvage. The estimated mean agency cost of each activity is accompanied by an estimate of the activity's work zone user cost. All mean costs are given in real/constant dollars.

The calculation of NPV is performed using the NPV economic formula (equation C.1). The resulting agency- and user-cost mean NPV values are \$1,057,553 and \$56,661, respectively. Since there are no recurring annual costs, the total mean EUAC is simply the NPV extracted over the 35-year analysis period (use of equation C.2). The resulting agency- and user-cost mean EUAC values are \$320,403 and \$17,166, respectively.

**Probabilistic LCCA.** As described earlier, probabilistic LCCA or risk analysis involves randomly selecting a value from each input parameter's sampling distribution, using the selected values and the NPV/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 other design alternatives (step 7 in the LCCA process), so as to identify the most economical design.

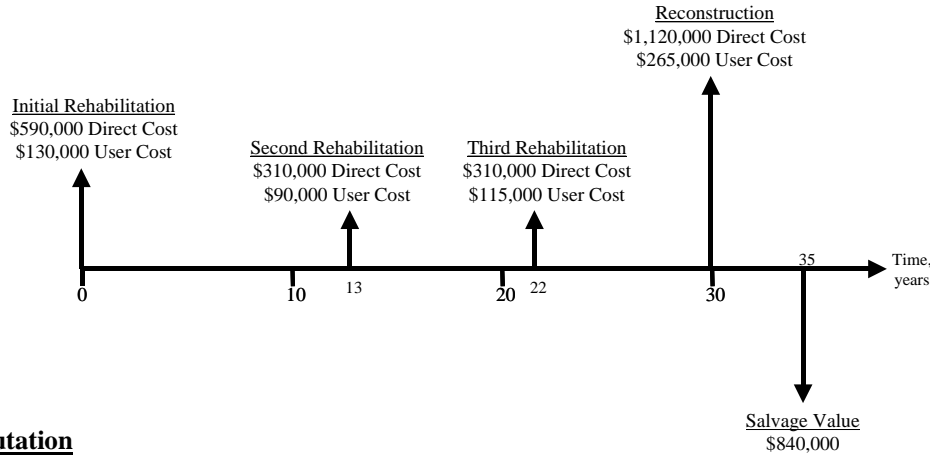
Probabilistic simulation requires the use of either a computerized spreadsheet program equipped with the necessary probabilistic distribution functions or a stand-alone computer program that is properly hard-coded to perform the simulation. In the case of spreadsheet-based programs, the probabilistic distribution functions can be either built-in to the program using the functions or programming tools available with the spreadsheet (as is the case with the LCCA2002 program), or added in through links with proprietary risk analysis programs, such as @RISK (Palisade Corporation) and Crystal Ball (Decisioneering Inc.).

When performing a probabilistic simulation, it is important to make sure that every iteration represents a scenario that can actually occur in real life. Two particular modeling errors with the potential to create unreal scenarios are as follows (2):

- Lack of appropriate pre-defined relationships between input parameters—Though 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 is generally 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 establish or know what the minimum and maximum values for sampling are, 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.

### Project Description

An existing 2-lane, rural highway is to undergo major rehabilitation. The existing pavement is a doweled jointed plain concrete pavement that is 18 years old. One particular rehabilitation design strategy involves a thick AC overlay (\$590,000) initially, followed by two subsequent overlays (Years 13 and 22, \$310,000 each) and then reconstruction (Year 30, \$1,120,000), as depicted in the expenditure stream diagram below. Associated work zone user costs are \$130,000 initially, \$90,000 in Year 13, \$115,000 in Year 22, and \$265,000 in Year 30. A discount rate of 4.0 percent has been selected and an analysis period of 35 years is used. The salvage value at the end of the analysis period, based on prorating the cost and 20-year expected life of the Year 30 reconstruction, will be \$840,000 (15/20 \* \$1,120,000).



### Cost Computation

Agency- and user-cost NPVs and EUACs are calculated as follows:

$$\begin{aligned}
 NPV_{agency} &= InitialCost + \sum (FutureCost_k * [1 / (1+i_{dis})^n_k]) \\
 &= \$590,000 + \$310,000 * [1 / (1+0.04)^{13}] + \$310,000 * [1 / (1+0.04)^{22}] + \$1,120,000 * [1 / (1+0.04)^{30}] \\
 &\quad - \$840,000 * [1 / (1+0.04)^{35}] \\
 &= \$590,000 + \$186,178 + \$130,806 + \$345,317 - \$212,869 \\
 &= \$1,039,432
 \end{aligned}$$

$$\begin{aligned}
 EUAC_{agency} &= NPV_{agency} * [(i_{dis} * (1+i_{dis})^n) / ((1+i_{dis})^n - 1)] \\
 &= \$1,039,432 * [(0.04 * (1+0.04)^{35}) / ((1+0.04)^{35} - 1)] \\
 &= \$1,039,432 * [(0.04 * (1+0.04)^{35}) / ((1+0.04)^{35} - 1)] \\
 &= \$55,690
 \end{aligned}$$

$$\begin{aligned}
 NPV_{user} &= InitialCost + \sum (FutureCost_k * [1 / (1+i_{dis})^n_k]) \\
 &= \$130,000 + \$90,000 * [1 / (1+0.04)^{13}] + \$115,000 * [1 / (1+0.04)^{22}] + \$265,000 * [1 / (1+0.04)^{30}] \\
 &= \$130,000 + \$54,052 + \$48,525 + \$81,704 \\
 &= \$314,281
 \end{aligned}$$

$$\begin{aligned}
 EUAC_{user} &= NPV_{user} * [(i_{dis} * (1+i_{dis})^n) / ((1+i_{dis})^n - 1)] \\
 &= \$314,281 * [(0.04 * (1+0.04)^{35}) / ((1+0.04)^{35} - 1)] \\
 &= \$314,281 * [(0.04 * (1+0.04)^{35}) / ((1+0.04)^{35} - 1)] \\
 &= \$16,838
 \end{aligned}$$

Figure C.11. Example illustration of deterministic life cycle cost computation.

The natural progression in generating forecasted life cycle costs is to summarize the data by constructing frequency and cumulative distributions and to compute key statistical measures that describe the resulting distributions. Both are easily accomplished using the data analysis functions typically available in spreadsheet programs.

Figure C.12 illustrates the application of probabilistic LCCA. The same example project outlined in figure C.11 is used; however, the discount rate, agency cost, user cost, and pavement performance input parameters are defined in terms of normal distributions (mean and standard deviation), rather than as discrete values. Again, all costs are given in real/constant dollars and a 35-year analysis period is used.

The probabilistic simulation is performed using 5,000 iterations (or “runs”) of the Monte Carlo sampling process and corresponding NPV/EUAC computation process. The resulting agency- and user-cost distributions are illustrated, along with a table summarizing various cost and pavement service life statistics. As can be seen, the projected agency-cost NPV has a mean of \$1,028,470, a standard deviation of \$193,396, and a range of \$506,288 to \$2,468,172.

The projected user-cost NPV has a mean of \$322,527, a standard deviation of \$59,928, and a range of \$151,190 to \$614,016. It should also be noted that the service life means and standard deviations projected for the first three pavement structures match their respective pre-defined performance inputs—13.0 and 2.9 years for initial rehabilitation, 9.0 and 2.3 years for the second rehabilitation, and 8.0 and 1.8 years for the third rehabilitation.

### C.3.7 Step 7—Analyze 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 design strategy. However, because the outputs of each computational approach are different (deterministic yields a single NPV/EUAC value, probabilistic yields a distribution of NPV/EUAC values), the ways in which they are evaluated and interpreted are also different.

**Analysis of Deterministic Life Cycle Cost Results.** In the analysis of deterministic results, it is common practice to compute the percent difference in life cycle costs of the competing designs. If the percent difference between the two lowest cost design alternatives is greater than some established minimum requirement—usually set according to an agency’s tolerance for risk (5 and 10 percent are common)—then the lowest cost alternative is accepted as the most economical design. If, on the other hand, the percent difference is less than the established minimum requirement, then the life cycle costs of the two alternatives are deemed equivalent, thereby leaving the options of reevaluating the designs or allowing other factors to drive the design selection process.

In the absence of a probabilistic LCCA, it is highly recommended that deterministic LCCA be accompanied with a sensitivity analysis, as it provides a far broader picture of the anticipated life cycle costs. As a minimum, deterministic sensitivity analysis should examine the effect of factors such as discount rate, initial costs, and initial performance on LCCA. Other factors shown to significantly affect LCC based on local experience should be included in sensitivity analysis.

The effects of other factors, such as the analysis period and pavement costs, can also be examined with minimal extra effort using any computerized spreadsheet programs (e.g., Microsoft® Excel, Lotus® 1-2-3, Corel® Quattro Pro). By varying the values of a given input parameter, the resulting NPV or EUAC for each design alternative can be recorded and displayed (in tabular or graphical form) as a function of the input parameter.

Although the results of a deterministic sensitivity analysis can be analyzed and interpreted in different ways, there are two ultimate goals for the process. The first goal is to determine the relative frequency with which a particular alternative has the lowest life cycle cost (frequency is defined as the percentage of the total range of all input parameters chosen for sensitivity analysis). The “favored” alternative should have the lowest life cycle cost for a majority of the circumstances tested. A good rule of thumb is twice the frequency of the next lowest cost alternative (e.g., at least 67 percent when comparing two alternatives).

Once a “favored” alternative is identified, the second goal is to affirm that it is the low-cost alternative under the “most likely” scenario. The “most likely” scenario is generally represented by mean values (based on objective data) or best estimates (based on subjective expert opinions) of the various inputs. Moreover, the ranges used in sensitivity analysis are often established around “most likely” values.

Figure C.13 contains an example application of deterministic sensitivity analysis. Two alternative designs are featured, with one of them being the design highlighted earlier in figures C.11 and C.12. The other design (alternative B) involves a comprehensive concrete pavement restoration (CPR) activity, followed by one additional CPR activity and reconstruction.

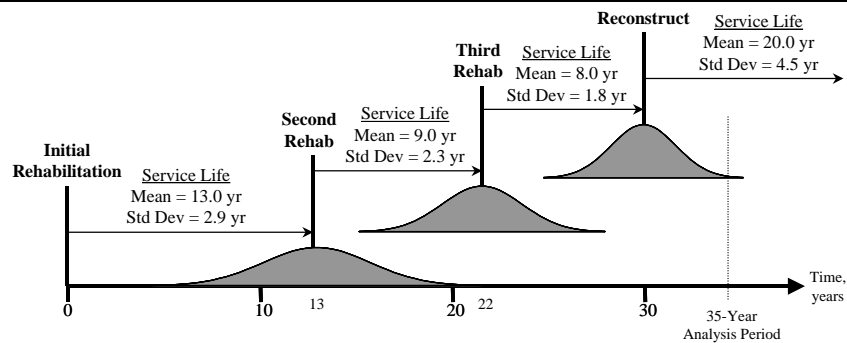
The computed present-worth agency costs for each alternative for three different analysis periods (30, 35, and 40 years) and a range of discount rates (2.0 to 6.0 percent) are tabularized. Plots of NPV as a function of discount rate and analysis period show that alternative B is a little more sensitive to the discount rate than alternative A, whereas the analysis period has about the same impact on both alternatives. In the case of the discount rate, since alternative B future costs are weighted more toward Year 0 than alternative A’s future costs, their conversion to present-worth is more largely magnified by smaller and smaller discount rates.

In terms of overall cost comparison between the two design alternatives, it can be seen that alternative B has the lowest life cycle cost over most of the discount rate range for each analysis period. In fact, it is only for a 30-year analysis period with discount rates of 2 and 3 percent that alternative A is the more economical strategy. Overall, alternative B is the least-cost design about 87 percent of the time, which makes it the favored strategy. Under the “most likely” scenario—35-year analysis period and discount rate of 4.0 percent—alternative B has the lowest life cycle cost, thereby qualifying it as the most economical design strategy.

### Project Description

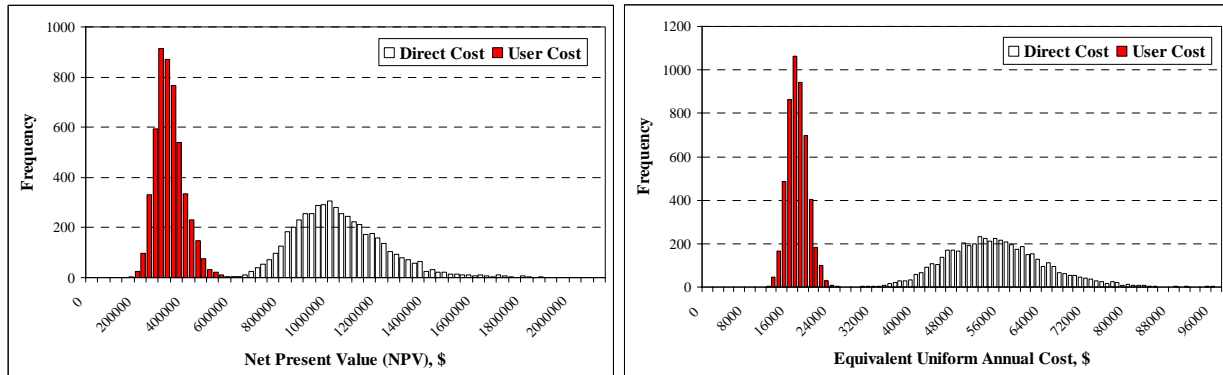
An aged 2-lane, rural highway pavement is to undergo major rehabilitation. One particular rehabilitation design strategy involves an overlay initially, followed by two subsequent overlays and then reconstruction. The service life and costs (both agency and user costs) associated with each activity are defined probabilistically, according to the means and standard deviations shown below. A probabilistic discount rate of  $4.0 \text{ (mean)} \pm 1.1 \text{ (standard deviation)}$  percent is specified for use, along with a 35-year analysis period.

Input Parameter	Mean	Standard Deviation
Agency Cost of Initial Rehabilitation, \$	590,000	87,000
Agency Cost of Second Rehabilitation, \$	310,000	46,500
Agency Cost of Third Rehabilitation, \$	310,000	46,500
Agency Cost of Reconstruction, \$	1,120,000	221,100
Work Zone User Cost of Initial Rehabilitation, \$	130,000	16,500
Work Zone User Cost of Second Rehabilitation, \$	90,000	15,200
Work Zone User Cost of Third Rehabilitation, \$	115,000	17,500
Work Zone User Cost of Reconstruction, \$	265,000	47,700



### Cost Computation

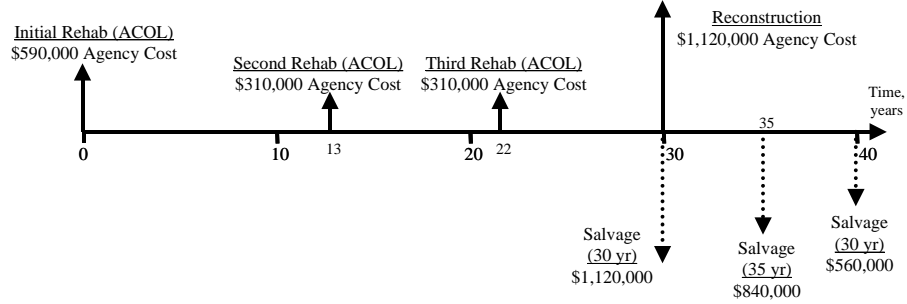
Probabilistic simulation, based on 5,000 runs, yields the following life cycle cost distributions and statistics:



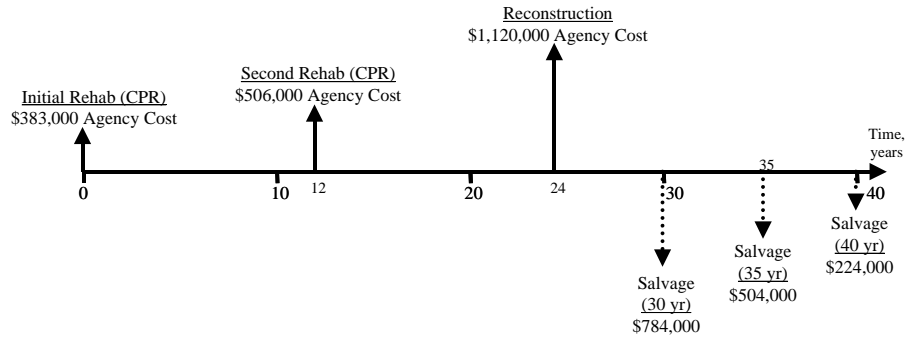
Statistical Parameter	Agency Cost NPV	User Cost NPV	Agency Cost EUAC	User Cost EUAC	Initial Rehab Life	Second Rehab Life	Third Rehab Life
Mean	\$1,028,470	\$322,527	\$54,709	\$17,004	13.0 years	9.0 years	8.0 years
Median	\$1,003,993	\$315,430	\$54,025	\$16,880	13.0 years	9.0 years	8.0 years
Standard Deviation	\$193,396	\$59,928	\$9,640	\$1,908	2.9 years	2.3 years	1.8 years
Variance	$\$37.4 \times 10^9$	$\$3.6 \times 10^9$	$\$92.9 \times 10^6$	$\$3.6 \times 10^6$	8.5 years	5.3 years	3.3 years
Skewness	0.96	0.74	0.59	0.38	-0.01	0.01	-0.01
Kurtosis	5.47	4.02	4.13	3.28	3.04	3.04	2.88
Coeff. of Variability	0.19	0.19	0.18	0.11	0.22	0.26	0.23
Range Minimum	\$506,288	\$151,190	\$25,103	\$11,313	1.6 years	0.4 years	1.4 years
Range Maximum	\$2,468,172	\$614,016	\$120,841	\$25,164	23.6 years	17.3 years	14.3 years
Range Width	\$1,961,884	\$462,827	\$95,738	\$13,851	22.0 years	16.9 years	12.9 years
Mean Standard Error	\$2,735	\$848	\$136	\$27	0.04 years	0.03 years	0.03 years

Figure C.12. Example illustration of probabilistic life cycle cost computation.

### Alternative A



### Alternative B



Activity	Cost, \$1000	Present-Worth Agency Cost, \$1000														
		30-Year Analysis Period					35-Year Analysis Period					40-Year Analysis Period				
		2%	3%	4%	5%	6%	2%	3%	4%	5%	6%	2%	3%	4%	5%	6%
Alternative A																
Initial Rehab	590	590	590	590	590	590	590	590	590	590	590	590	590	590	590	590
Rehab #2	310	240	211	186	164	145	240	211	186	164	145	240	211	186	164	145
Rehab #3	310	201	162	131	106	86	201	162	131	106	86	201	162	131	106	86
Reconstruct	1,120	1,120	1,120	1,120	1,120	1,120	618	461	345	259	195	618	461	345	259	195
Salvage	—	-1,120	-1,120	-1,120	-1,120	-1,120	-420	-299	-213	-152	-109	-254	-172	-117	-80	-54
TOTAL		1,031	963	907	860	821	1,229	1,125	1,039	967	907	1,395	1,252	1,135	1,039	962
Alternative B																
Initial Rehab	383	383	383	383	383	383	383	383	383	383	383	383	383	383	383	383
Rehab #2	506	399	355	316	282	251	399	355	316	282	251	399	355	316	282	251
Reconstruct	1,120	696	551	437	347	277	696	551	437	347	277	696	551	437	347	277
Salvage	—	-433	-323	-242	-181	-137	-252	-179	-128	-91	-66	-101	-69	-47	-32	-22
TOTAL		1,045	966	894	831	774	1,226	1,110	1,008	921	845	1,377	1,220	1,089	980	889

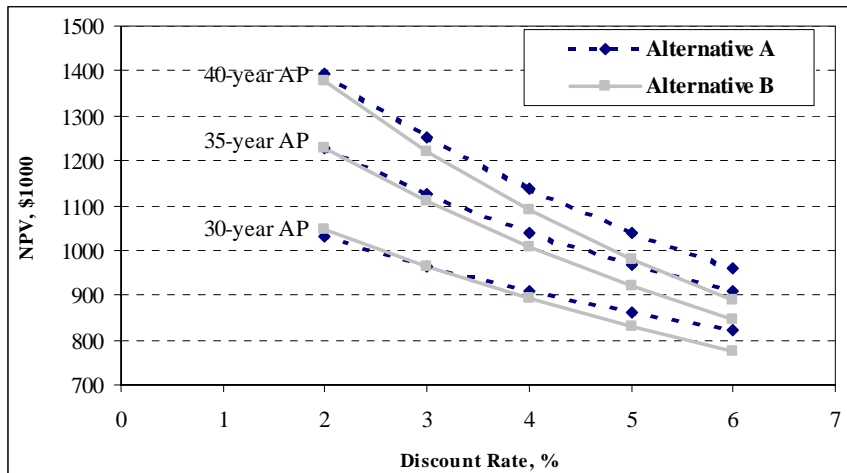


Figure C.13. Example illustration of deterministic sensitivity analysis.

**Analysis of Probabilistic LCCA Results.** 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 NPV/EUAC values.
2. Statistical analysis—differences between mean values (z-score, ANOVA).
3. Risk assessment of forecasted NPV/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 design alternative can be obtained by examining the life cycle cost results associated with each iteration or trial computation. By tallying the number of “wins” (i.e., trials in which an alternative had the lowest life cycle cost compared to all other alternatives) for each alternative, dividing the respective wins by the total number of trials performed in the simulation, and multiplying by 100 percent, the overall probabilities for each alternative to have the lowest life cycle cost are determined. The design with the highest overall probability becomes the favored alternative, yet additional evaluation is needed to determine if it is the most economical alternative.

Trial-by-trial comparisons can be made quickly and effectively using a computerized spreadsheet program. With the life cycle cost results of individual trials arrayed down the spreadsheet, logical functions can be created in the spreadsheet that identify whether a particular alternative had a lower life cycle cost than a competing alternative for each trial, and whether it had the lowest cost of all alternatives.

In the example in table C.10, the NPV results for three different alternative designs and 1,000 trials are provided in columns 2 through 4 (only the first five trials and the last trial are shown). In columns 5 through 10, the outcomes as to whether a particular alternative 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 table C.10, 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 C.10. Process for tallying life cycle cost results on a trial-by-trial basis.

Iteration/ Trial No.	NPV, \$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 C.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 C.11. Life cycle cost probability matrix for trial-by-trial comparison example.

Design	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:	
Alt. A	X	69.8	75.6	15.2
Alt. B	30.2	X	61.4	31.0
Alt. 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 (either in terms of NPV or EUAC) computed for each alternative in Step 6 of the LCCA process are used to determine if significant differences exist between the means of each alternative. If the alternative 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 alternative. 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. This simple statistical test can be carried out manually, as described below, or automatically using the data analysis functions available in most spreadsheet programs.

In the *t*-test, the null hypothesis is that the mean life cycle cost values of the two alternatives are equal ( $LCC_A = LCC_B$ ) at some prescribed confidence level (a minimum confidence level of 90 percent is recommended for use). 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:

$$t = (LCC_A - LCC_B) / [(s_A^2 + s_B^2)/n]^{0.5} \quad (C.26)$$

where:  $LCC_A$  = mean life cycle cost (NPV or EUAC) for design alternative A, \$  
 $LCC_B$  = mean life cycle cost for design alternative B, \$

$s_A$  = standard deviation of life cycle cost for design alternative A, \$  
 $s_B$  = standard deviation of life cycle cost for design alternative B, \$  
 $n$  = number of simulation trials

As an example application of the  $t$ -test, figure C.14 shows the NPV distributions of two design alternatives, along with their respective mean and standard deviation values. Trial-by-trial comparison indicated that the favored alternative is alternative B (lowest NPV 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 equation C.26 yields the following result:

$$\begin{aligned}
 t &= (\$1,611,702 - \$1,600,344) / [(\$100,190^2 + \$89,996^2)/1000]^{0.5} \\
 t &= \$11,358 / \$4,259 \\
 t &= 2.67
 \end{aligned}$$

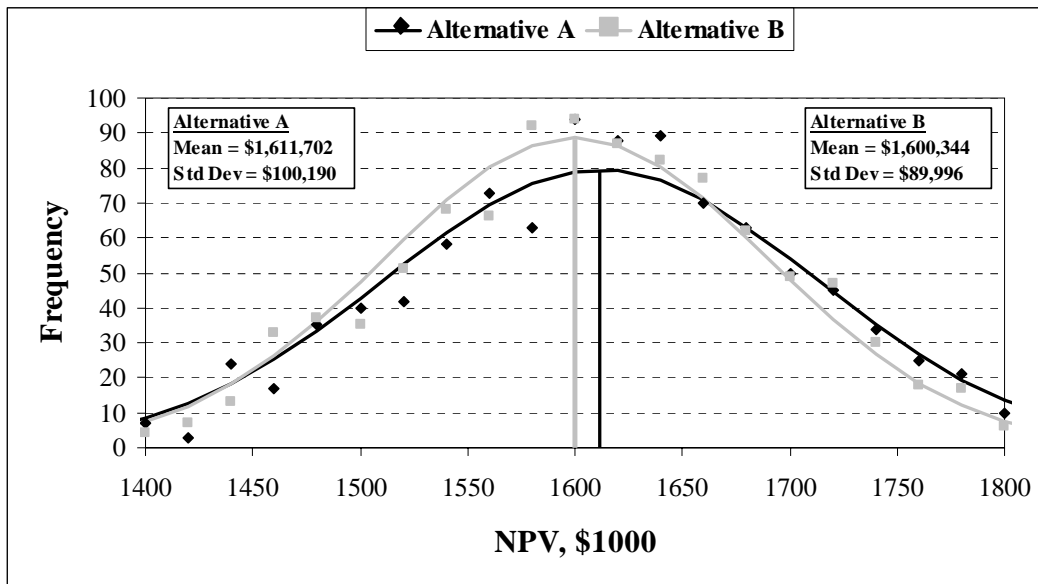


Figure C.14. NPV frequency distributions for alternatives A and B.

Since the  $t$ -value falls within one part of the critical range (i.e.,  $\geq +1.96$ ), the null hypothesis is rejected and the mean NPV of alternative 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 NPV outcomes—\$1.51 to \$1.7 million—as illustrated in figure C.15.

In general, if three or more alternatives are being evaluated for a particular project, then an analysis of variance (ANOVA) test should be conducted to determine if the mean life cycle cost of the favored design is statistically significantly lower than the mean life cycle cost of all other designs. This type of test requires the use of statistical grouping functions (e.g., Duncan, Scheffe, Tukey) available only in advanced statistical software packages, such as SAS<sup>®</sup> and

SPSS®. Because of the complexity of the ANOVA with groupings test procedure, it is not discussed here.

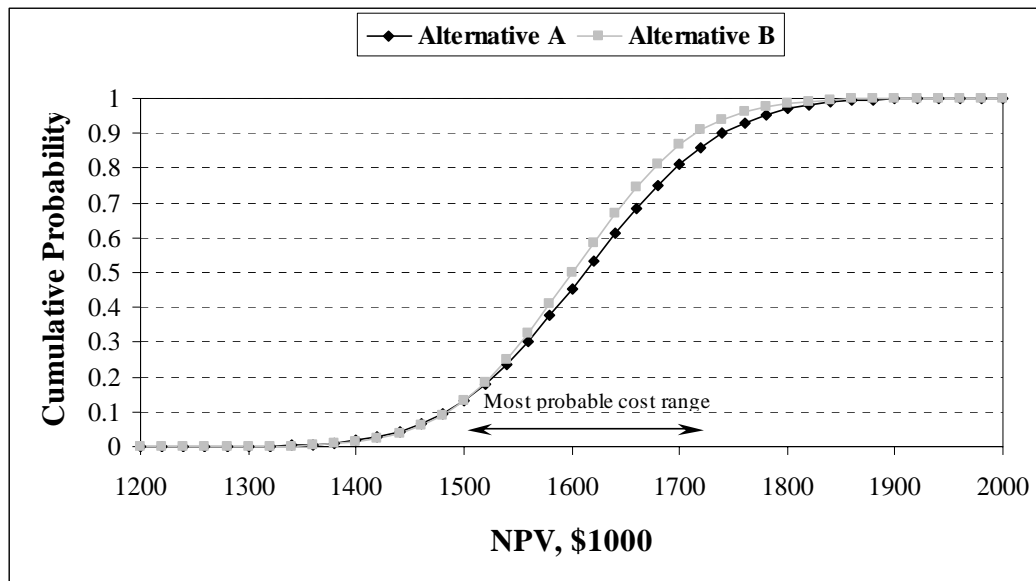


Figure C.15. NPV cumulative distributions for alternatives A and B.

On occasion, it may not be necessary to resort to the ANOVA test, when evaluating three or more alternatives. If it is readily apparent from the various constructed frequency distributions that only two of the alternatives are cost-competitive, then a *t*-test can be performed on those two alternatives.

**Evaluation 3—Risk Assessment.** If the results of the statistical analysis are not definitive with respect to identifying the most economical design, then the designer/analyst can seek a possible resolution through risk assessment. 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, for a minute, that alternative A from the previous illustration had a slightly lower mean NPV (\$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 C.16.

At the tails of these two distributions, there are clear differences in the forecasted NPVs. In the case of alternative A, there is potential for a cost underrun if the true NPV is low, say less than \$1.45 million. This opportunity for cost savings is termed upside risk. If, on the other hand, the true NPV 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.

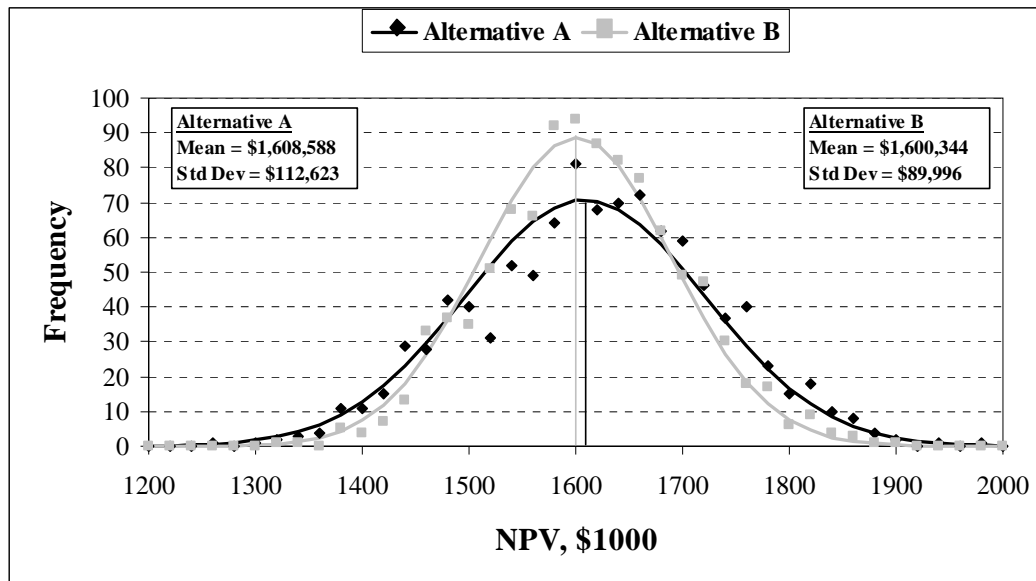


Figure C.16. Risk assessment—NPV frequency distributions.

In the cumulative distributions shown in figure C.17, it can be seen that there is a 10 percent probability that the NPV 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 design alternative, 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.

### C.3.8 Step 8—Reevaluate Strategies

In the final step of the LCCA process, the pavement designer/analyst uses the information resulting from the LCCA to determine if any adjustments or modifications to the design alternatives are warranted, prior to finalizing the design decision. Such adjustments may entail structural design changes to the mainline and/or shoulder pavements, revisions to the maintenance of traffic plans, reductions in construction periods (accompanied by increased pay item costs), or changes in rehabilitation designs or strategies.

One approach to reexamining the design strategies is to perform a probabilistic sensitivity analysis. In this analysis, correlations between individual input parameters and the life cycle cost output distribution are determined statistically, allowing one to identify which inputs have the greatest impact on total life cycle costs. Those inputs found to be driving the results can then be looked at closely to determine if certain actions can be taken to improve cost-effectiveness.

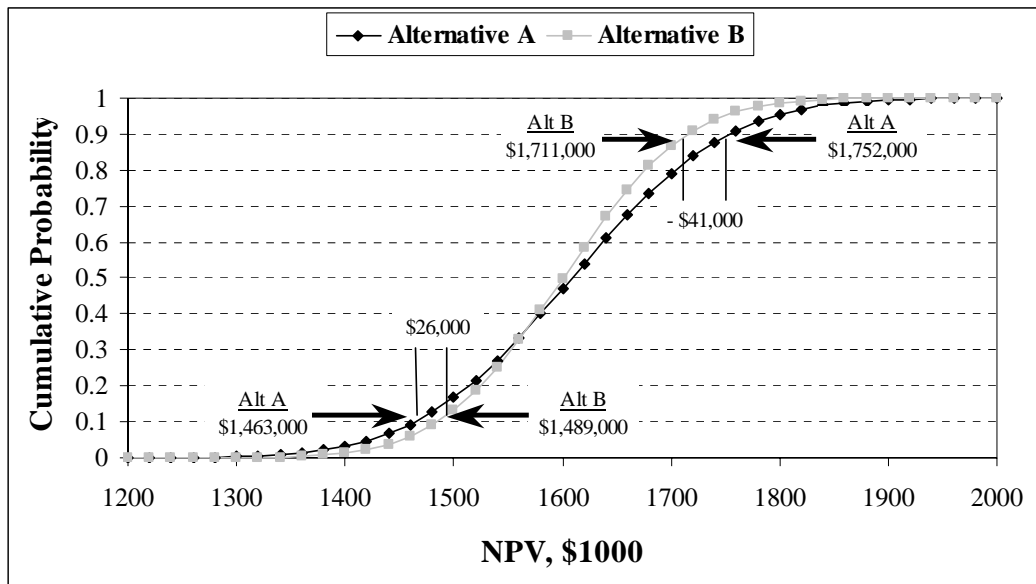


Figure C.17. Risk assessment—NPV cumulative distributions.

The strengths of the correlations are defined by the correlation coefficient, which can range from  $-1$  to  $+1$ . A coefficient value of  $-1$  indicates a very strong inverse relationship between an input variable and total life cycle cost, whereas a value of  $+1$  reflects a very strong direct relationship. A coefficient value of  $0$  indicates complete absence of a relationship.

The results of a probabilistic sensitivity analysis are often displayed in tornado plots, which are basically bar charts that show, in descending fashion, the correlation coefficients of individual input parameters. Figures C.18 and C.19 show the tornado plots associated with the alternative designs in the previous example (Evaluation 3—Risk Assessment). As can be seen, for both alternatives A and B, the input with the greatest impact on NPV is the initial pavement structure cost. If the cost of the alternative A's initial structure is decreased by one standard deviation, then the resulting NPV for alternative A is reduced by  $0.6$  of a standard deviation. Alternatively, if the cost of alternative B's initial structure is increased by one standard deviation, then the resulting NPV for alternative B is increased by  $0.72$  of a standard deviation.

A second approach to reexamining design strategies is to look at the balance between agency- and user-based life cycle costs. As pointed out in the 1998 Interim Technical Bulletin (2), if user costs overwhelm agency costs for all of the alternatives, the analysis may indicate that none of the alternatives analyzed are viable, and that changes must be made to drastically reduce work zone user costs. For instance, pavement structural designs might be increased to delay the timings and frequencies of rehabilitation and major maintenance activities, or geometric designs might be altered to provide for greater capacity and improved traffic flow through construction work zones.

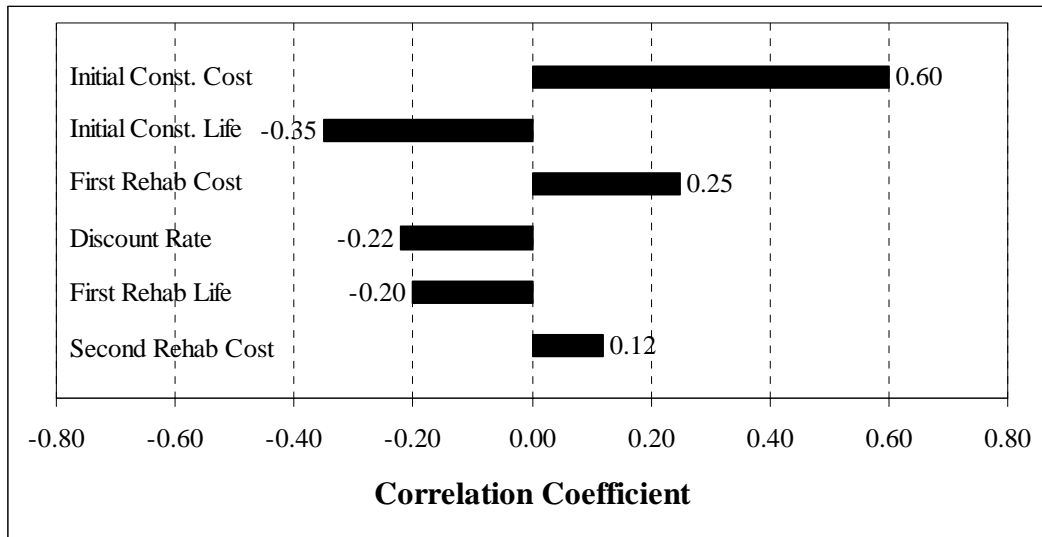


Figure C.18. Sensitivity of factors affecting the NPV of alternative A.

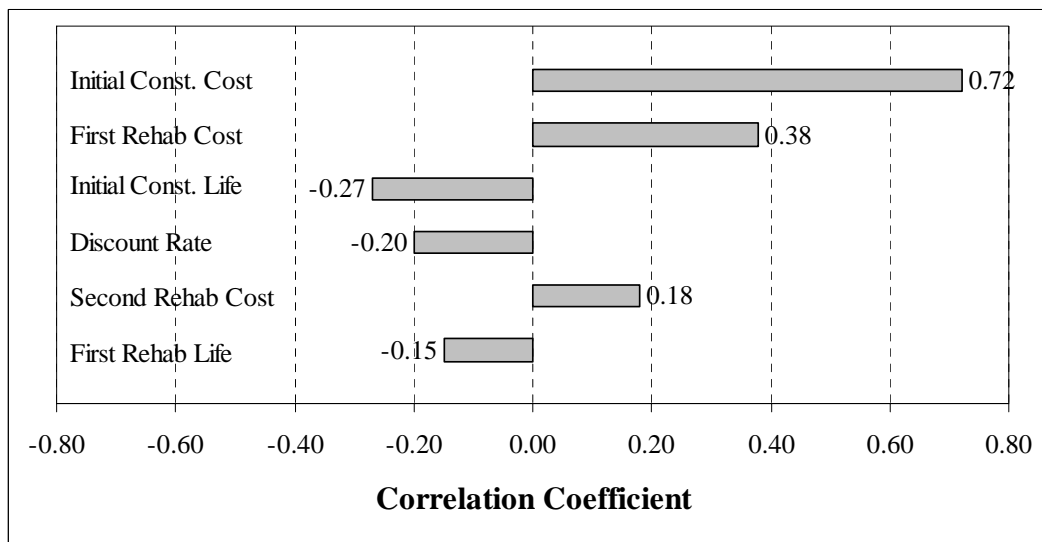


Figure C.19. Sensitivity of factors affecting the NPV of alternative B.

#### C.4 LCCA2002 SPREADSHEET PROGRAM

Included in this Guide is a deterministic/probabilistic LCCA spreadsheet program named LCCA2002. This program, which operates in Microsoft® Excel and uses Visual Basic programming functions, allows users to perform LCCA of both new construction (or reconstruction) projects and rehabilitation projects in accordance with the procedures described throughout this appendix.

LCCA2002 features a navigational switchboard that allows the user to move about the various data input, simulation and output, and administrative function screens. It also includes a pay item unit cost library and cost computation templates for estimating the overall agency costs (i.e., construction and subsequent M&R treatments) and work zone user costs (time delay and vehicle operating costs) associated with two competing design strategies.

The program allows the user to define the analysis period and LCCA approach (deterministic versus probabilistic LCCA), and to specify the inclusion or exclusion of user costs, agency-related salvage value, and user-related salvage value. Many of the inputs can be defined probabilistically, including the discount rate, traffic growth, initial construction cost and service life, rehabilitation cost and service life, maintenance cost and frequency, work zone duration and capacity, free flow capacity, and queue dissipation capacity. Eight different probabilistic distribution options are available, including the uniform, triangular, normal, and truncated log normal distributions.

Probabilistic simulation is performed using the Monte Carlo simulation procedure. Simulation controls established by the user include the number of iterative cost computations to be performed, the percentiles to be used in reporting life cycle cost statistics, the simulation output convergence settings, and whether a new sampling scheme is to be used or a repeat of the previous sampling scheme.

LCCA2002 displays results in tabular and graphical formats. Deterministic results for competing design alternatives are illustrated as expenditure streams and overall PW life cycle costs. Probabilistic results include key life cycle cost statistics (mean, standard deviation, range, percentiles), frequency and cumulative frequency distributions, and detailed data from individual simulations, such as the randomly selected input values and the computed agency- and user-related life cycle costs. They also include tornado charts and extreme tail analysis tables, that help the user identify which input variables most influence the magnitude and spread of the life cycle cost distribution.

## **C.5 EXAMPLE APPLICATIONS OF PROBABILISTIC LCCA**

This section presents two example exercises intended to familiarize the reader with the AASHTO LCCA process: a reconstruction project located in an urban setting with high traffic volume and a highway realignment project located in a rural setting on a moderately trafficked pavement. In each example, two alternative pavement designs (one flexible, one rigid) are featured for comparison. Although the examples were created to portray a realistic investigation into the identification of a preferred design alternative, they do not represent actual projects, and by no means should the results be construed as favoring one design over another.

The LCCA for both examples was performed using the LCCA2002 spreadsheet program (in actuality, the April 2002 version of the FHWA probabilistic model was used. Once LCCA2002 is done, it will be used for these examples). As mentioned previously, a copy of this program is available on the CD-Rom disk provided with the Design Guide.

### C.5.1 Urban Reconstruction Example

**Introduction.** The project featured in this example is set in an urban environment and involves the reconstruction of a 6-lane, high-volume pavement facility 4.0 miles long. The existing pavement structure, a 9.5-in concrete pavement overlain with 6 in of asphalt and bounded by asphalt shoulders, is to be completely removed and replaced with one of the following two pavement structures:

#### Alternative A—Flexible Design

- AC Surface and Binder Course: 3 in
- AC Base Course: 9 in
- Crushed Stone Base: 8 in
- Gravel Subbase: 8 in

#### Alternative B—Rigid Design

- Doweled Jointed Plain Concrete (JPC): 11 in
- Crushed Stone Base: 8 in

Both designs include 12-ft wide travel lanes (3 lanes in each direction) and 8- and 10-ft wide inside and outside shoulders constructed with 6 in of AC. Both structures are to be constructed atop a fully compacted subgrade.

The two design alternatives are to be evaluated on a probabilistic life cycle cost basis using a 40-year analysis period and a variable discount rate, having a mean of 4.0 percent and a standard deviation of 0.33 percent.

**LCCA Inputs.** The following are the inputs used in this example analysis.

Traffic. The traffic inputs include the base year average daily traffic (ADT), the traffic growth rate estimate, and the percent trucks and automobiles. A truck directional distribution factor of 0.5 has been assumed, along with a lane distribution factor of 0.7.

- Initial ADT (both directions): 60,000 vehicles/day
- Traffic Growth Rate: 2 percent
- Percent Automobiles: 80 percent
- Percent Trucks: 20 percent (8% single units, 12% combination)

Pavement Performance and Activity Timing. Based on historical performance data and a comprehensive pavement failure analysis, the estimated service lives of the various pavement structures were established in accordance with a normal probability distribution. Table C.12 lists the mean service life and corresponding standard deviation used for each structure in conducting the LCCA, and figure C.20 shows the life cycle models for the two design alternatives. Maintenance in the form of crack sealing of asphalt-surfaced pavement and joint resealing of concrete pavements are also included.



Agency Costs. Differential agency costs associated with initial construction include removal of the existing pavement (mainline and shoulder), construction of the new pavement structure (mainline and shoulder) as shown in figure C.20, and all associated traffic control costs, mobilization costs, and engineering costs. Because the flexible design is thicker than the rigid design (28 in versus 19 in), an extra 9 in of subgrade must be removed as part of this design option during reconstruction. In addition, the flexible design requires an extra 9 in of gravel beneath the asphalt shoulders.

Table C.12. Pavement service life input values for urban reconstruction example.

Pavement Structure	Service Life, years <sup>a</sup>	
	Mean	Standard Deviation
<i>Alternative A--Flexible Design</i>		
Initial Structure	16.0	2.7
Rehab 1: 3-in AC Overlay (mainline and shoulders)	11.0	2.2
Rehab 2: 3-in Mill and AC Replacement (mainline only)	10.0	1.8
Rehab 3: 3-in Mill and AC Replacement (mainline and shoulders)	9.0	1.7
Rehab 4: 3-in Mill and AC Replacement (mainline only)	8.0	1.3
Rehab 5: 3-in Mill and AC Replacement (mainline and shoulders)	7.0	1.1
<i>Alternative B--Rigid Design</i>		
Initial Structure	26.0	3.8
Rehab 1: CPR (patching/grinding/resealing, mainline only)	12.0	2.3
Rehab 2: 3-in AC Overlay (mainline and shoulders)	10.0	1.9
Rehab 3: 3-in Mill and AC Replacement (mainline only)	9.0	1.4
Rehab 4: 3-in Mill and AC Replacement (mainline and shoulders)	8.0	1.3
Rehab 5: 3-in Mill and AC Replacement (mainline only)	7.0	1.1

<sup>a</sup> Estimated through pavement failure analysis of existing pavements built by agency.

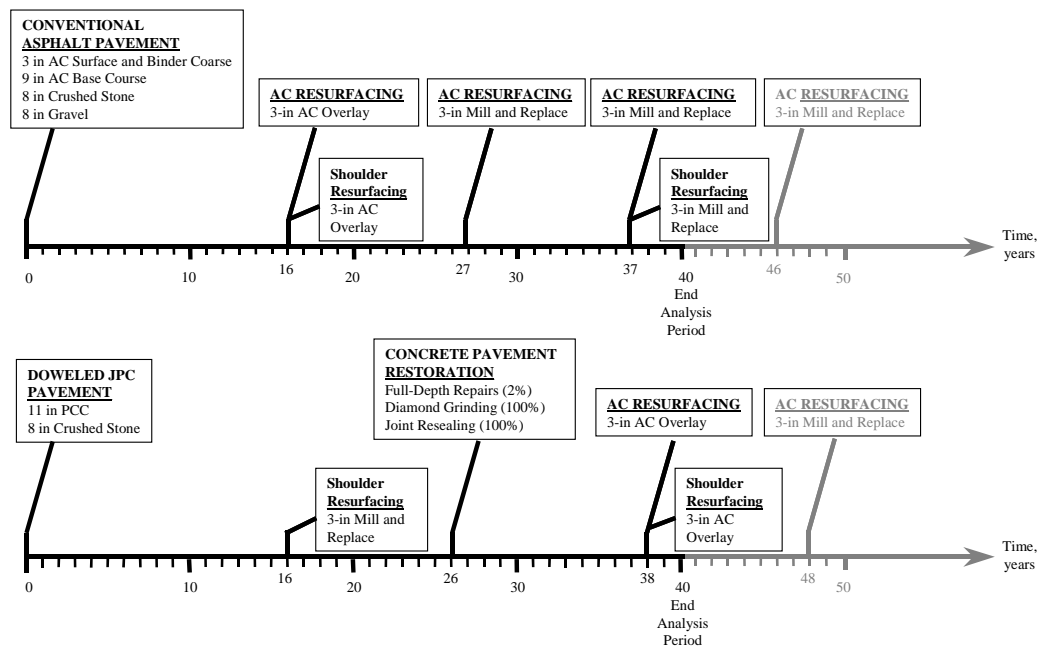


Figure C.20. Pavement life cycle models for urban reconstruction alternative designs.

Using estimated quantities of individual construction pay items and historical unit cost data for those items, the overall project cost for each initial structure was computed. These costs, expressed in terms of means and standard deviations, are listed in table C.13.

Future differential agency costs are based on the projected mainline and shoulder rehabilitations shown previously in figure C.20. As with initial construction costs, estimated quantities of individual rehabilitation pay items were multiplied by estimated unit costs to yield an overall project cost for each rehabilitated pavement structure. Table C.13 shows the mean and standard deviation cost values to be used as LCCA inputs.

Work Zone User Costs. For both design options, work zones will be required for the initial construction (i.e., reconstruction) and for each rehabilitation performed on the mainline. During reconstruction, the two inside lanes of a given direction will be closed and traffic will be diverted to the outside lane and outside shoulder. After the inside lanes (and inside shoulder) have been reconstructed, the outside lane will be closed and traffic will be diverted to the inside lanes. Work zone hours of operation will be 24 hours/day.

These same work zone setups will be used for future rehabilitations. However, the work zones will be in effect only during off-periods of rush-hour traffic; namely, from 9 a.m. to 3 p.m. and from 8 p.m. to 5 a.m. Table C.14 summarizes key aspects of each work zone and lists the values of time for the three vehicle types.

Table C.13. Agency cost input values for urban reconstruction example.

Pavement Structure	Overall Project Cost, \$ <sup>a</sup>	
	Mean	Standard Deviation
<i>Alternative A--Flexible Design</i>		
Initial Structure (mainline and shoulders)	\$10,869,500	\$1,195,600
Rehab 1: 3-in AC Overlay (mainline and shoulders)	\$2,181,400	\$250,900
Rehab 2: 3-in Mill and AC Replacement (mainline only)	\$1,824,500	\$218,900
Rehab 3: 3-in Mill and AC Replacement (mainline and shoulders)	\$2,614,000	\$326,700
Rehab 4: 3-in Mill and AC Replacement (mainline only)	\$1,824,500	\$237,200
Rehab 5: 3-in Mill and AC Replacement (mainline and shoulders)	\$2,614,000	\$352,900
<i>Alternative B--Rigid Design</i>		
Initial Structure (mainline and shoulders)	\$11,194,500	\$1,007,500
Rehab 1: CPR (mainline)	\$2,145,700	\$203,800
Rehab 2: 3-in AC Overlay (mainline and shoulders)	\$2,790,800	\$279,100
Rehab 3: 3-in Mill and AC Replacement (mainline only)	\$2,432,800	\$255,400
Rehab 4: 3-in Mill and AC Replacement (mainline and shoulders)	\$3,211,600	\$353,300
Rehab 5: 3-in Mill and AC Replacement (mainline only)	\$2,432,800	\$279,800

<sup>a</sup> Estimated through evaluation of previous bids on similar sized projects.

Table C.14. Work zone details for urban reconstruction example.

	Reconstruction	AC Overlay of AC	AC Overlay of PCC	AC Mill and Replace	CPR
Work zone operation (1 direction)	2 of 3 lanes open	2 of 3 lanes open	2 of 3 lanes open	2 of 3 lanes open	2 of 3 lanes open
Approach speed, mph	55	55	55	55	55
Work zone speed, mph	45	45	45	45	45
Work zone hours of operation	24 hours	9 a.m. – 3 p.m. 8 p.m. – 5 a.m.	9 a.m. – 3 p.m. 8 p.m. – 5 a.m.	9 a.m. – 3 p.m. 8 p.m. – 5 a.m.	9 a.m. – 3 p.m. 8 p.m. – 5 a.m.
Flexible construction duration, days	268 (mean) 50 (std. dev.)	25 (mean) <sup>a</sup> 3 (std. dev.)		34 (mean) <sup>a</sup> 5 (std. dev.)	
Rigid construction duration, days	250 (mean) 43 (std. dev.)		47 (mean) <sup>b</sup> 6 (std. dev.)	51 (mean) <sup>b</sup> 7 (std. dev.)	57 (mean) 7 (std. dev.)
Value of time for passenger vehicles, \$/hour/vehicle	13.08 (mean) 0.75 (std. dev.)				
Value of time for single-unit vehicles, \$/hour/vehicle	20.95 (mean) 1.00 (std. dev.)				
Value of time for combination vehicles, \$/hour/vehicle	25.21 (mean) 1.25 (std. dev.)				

<sup>a</sup> Includes limited pre-overlay repairs with AC.

<sup>b</sup> Includes considerable pre-overlay repairs with PCC.

**Life Cycle Cost Computation.** A probabilistic simulation was performed using 2,500 iterations. The resulting agency- and user-cost NPV statistics are summarized in table C.15, and the frequency and cumulative distribution curves are illustrated in figures C.21 through C.24. As can be seen, the mean projected agency-cost NPV is lowest for alternative B (PCC reconstruction)—\$12.529 million versus \$12.991 million for alternative A. Likewise, the mean projected user-cost NPV is lowest for alternative B—\$3.362 million versus \$3.528 million for alternative A.

The variation in both projected agency- and user-cost NPVs is highest for alternative A. The agency-cost NPV standard deviations are \$709,000 for alternative A and \$551,000 for alternative B. The user-cost NPV standard deviations are \$1.285 million for alternative A and \$1.110 million for alternative B.

**Analysis of Results.** The following sections describe the results of the LCCA.

Evaluation 1—Trial-By-Trial Comparison. Tables C.16 and C.17 show the resulting agency- and user-cost probability matrices for the two alternative designs. In both instances, the favored design is the rigid design. Of the 2,500 iterations, the rigid design had the lowest agency-cost NPV 1,536 times (61.4 percent) and the lowest user-cost NPV 1,528 times (61.1 percent).

Table C.15. Probabilistic simulation NPV statistics for urban reconstruction example.

Statistic	Alternative A—Flexible Design		Alternative B—Rigid Design	
	Agency NPV	User NPV	Agency NPV	User NPV
Simulation Trials	2,500	2,500	2,500	2,500
Mean, \$million	12.991	3.528	12.529	3.262
Median, \$million	12.971	3.546	12.511	3.262
Standard Deviation, \$million	1.285	0.619	1.110	0.737
Variance, \$million	1,652,369.680	383,526.600	1,233,002.630	542,523.820
Coefficient of Variability	0.099	0.175	0.089	0.226
Range Minimum, \$million	8.644	1.055	8.767	0.845
Range Maximum, \$million	17.032	5.585	17.195	5.637
Range Width, \$million	8.388	4.530	8.428	4.792

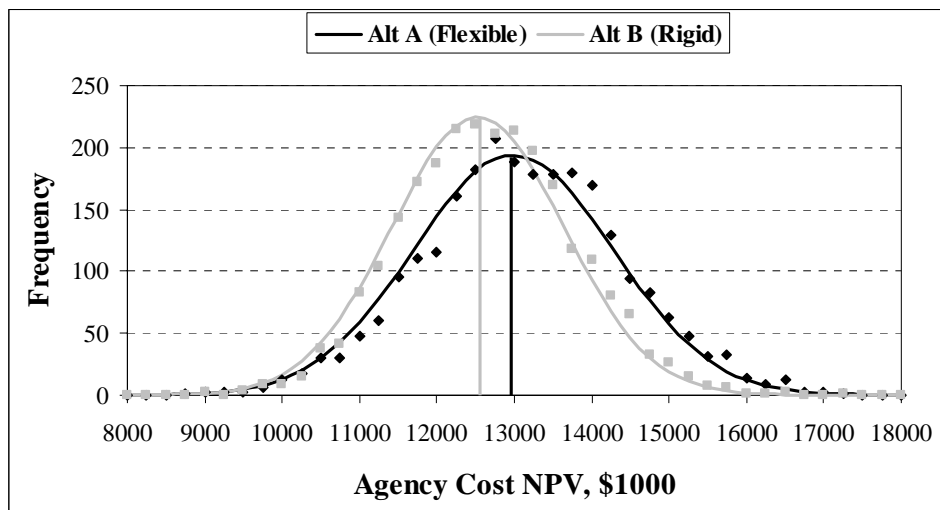


Figure C.21. Frequency distribution of forecasted agency costs for urban reconstruction example.

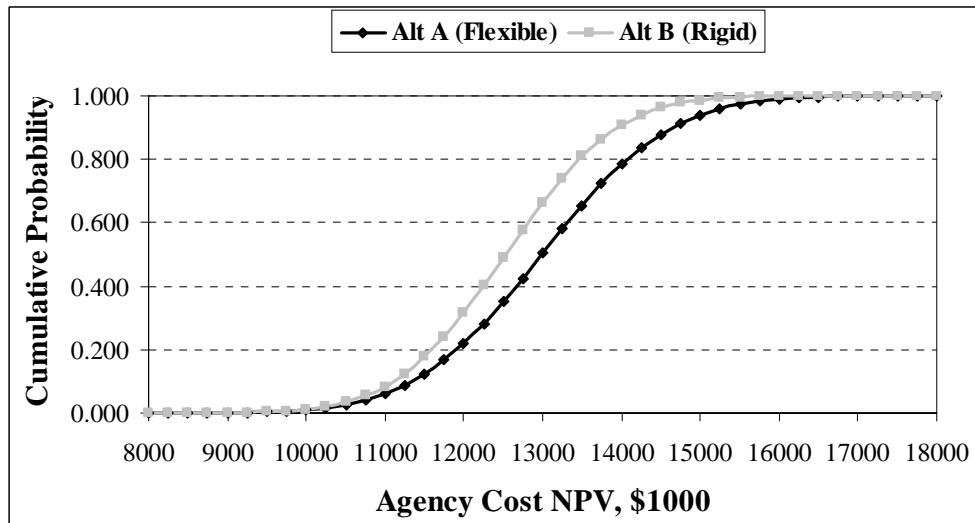


Figure C.22. Cumulative distribution of forecasted agency costs for urban reconstruction example.

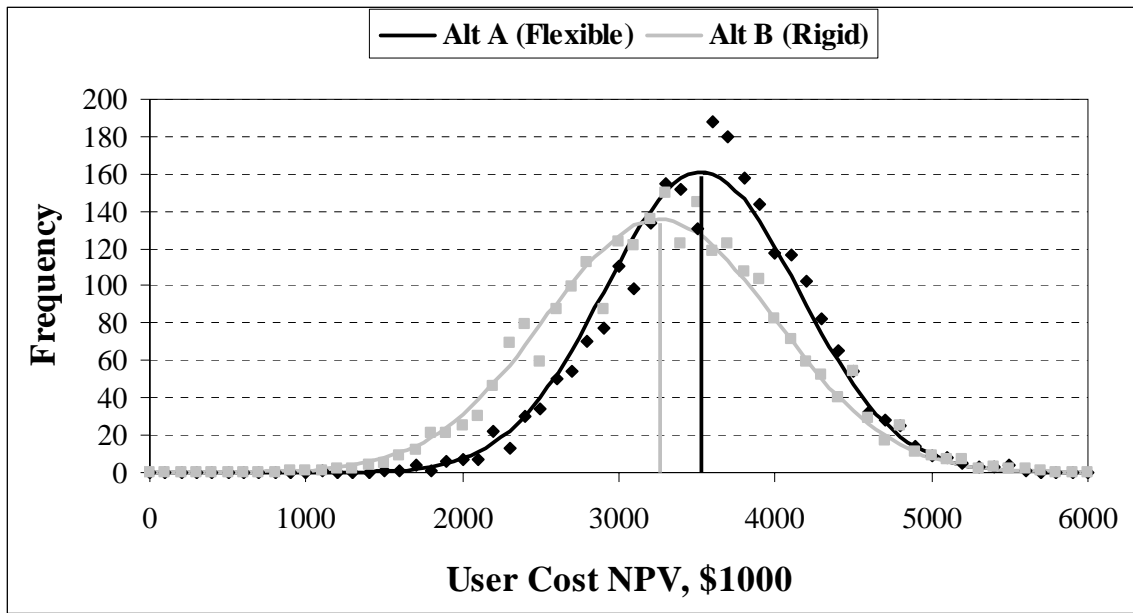


Figure C.23. Frequency distribution of user costs for urban reconstruction example.

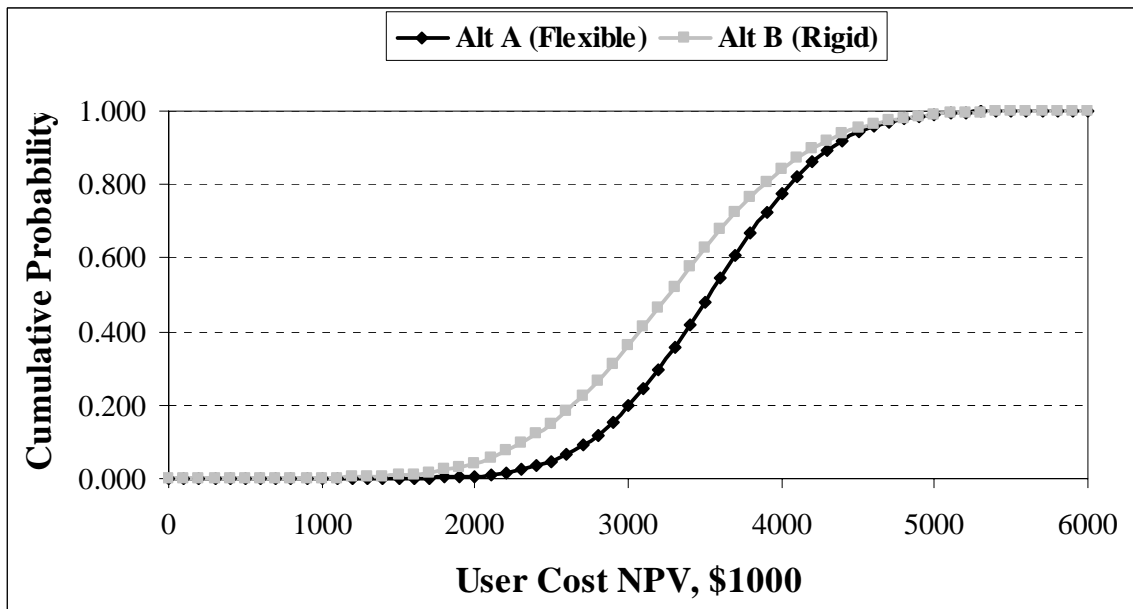


Figure C.24. Cumulative distribution of user costs for urban reconstruction example.

Table C.16. Agency-cost NPV probability matrix for urban reconstruction example.

Design	Probability of Agency-Cost NPV of:		Overall Probability of Having the Lowest LCC, %
	Alternative A Less Than NPV of:	Alternative B Less Than NPV of:	
Alternative A (flexible)	X	61.4	38.6
Alternative B (rigid)	38.6	X	61.4

Table C.17. User-cost NPV probability matrix for urban reconstruction example.

Design	Probability of User-Cost NPV of:		Overall Probability of Having the Lowest LCC, %
	Alternative A Less Than NPV of:	Alternative B Less Than NPV of:	
Alternative A (flexible)	X	61.1	38.9
Alternative B (rigid)	38.9	X	61.1

**Evaluation 2—Statistical Analysis.** To test for significant differences in the mean NPV values, the t-test formula given in equation C.26 was used. Results of the test as applied separately to agency and user-cost NPVs are as follows:

$$\begin{aligned}
 t_{\text{agency}} &= (\$12,991,000 - \$12,529,000) / [(\$1,285,000^2 + \$1,110,000^2)/2500]^{0.5} \\
 t_{\text{agency}} &= \$462,000 / \$33,961 \\
 t_{\text{agency}} &= 13.60 \\
 \\ 
 t_{\text{user}} &= (\$3,528,000 - \$3,262,000) / [(\$619,000^2 + \$737,000^2)/2500]^{0.5} \\
 t_{\text{user}} &= \$266,000 / \$19,249 \\
 t_{\text{user}} &= 13.82
 \end{aligned}$$

At the 95 percent confidence level ( $t \geq +1.96$  or  $t \leq -1.96$ ), both  $t$ -values fall within the critical range. Hence, the mean agency- and user-cost NPVs of alternative B (rigid design) are statistically significantly lower than those of alternative A (flexible design), making it the preferred economic alternative. Although there is a potential for agency-cost savings in selecting the flexible design, that potential is far outweighed by the rigid design over most of the range of probable NPV outcomes (i.e., >\$9.5 million). Similarly, the potential for the flexible design user-cost savings is outweighed by the rigid design over most of the range of probable NPV outcomes (i.e., <\$5.0 million).

## C.5.2 Rural Realignment Example

**Introduction.** The project featured in this example involves the upgrading of an existing 2-lane highway into a 4-lane divided highway facility. The upgrade requires rehabilitating the existing 2-lane asphalt pavement and constructing a new 2-lane structure along a shifted geometric alignment.

The 8.3-mile long facility is located in a rural setting and will carry moderate levels of traffic. The existing pavement structure consists of 8 in of AC on top of 6 in of dense-graded aggregate.

Its poor condition is the result of extensive fatigue and thermal cracking, as well as varying levels of rutting. The existing 6-ft wide shoulders are comprised of dense-graded aggregate.

Two different design strategies have been developed and are being considered for use in the project—a flexible pavement strategy and a rigid strategy. The structural cross-sections for each strategy are shown in table C.18.

Each strategy includes the provision of 12-ft wide travel lanes (2 lanes in each direction) and 6- and 8-ft wide inside and outside shoulders. The shoulders are to be constructed with 3.5 in of AC on top of dense-graded aggregate extending full-depth.

Table C.18. Pavement structural cross-sections for rural realignment example.

Design Strategy	Rehabilitation of Existing Structure	New Structure
Strategy A—Flexible Design	2.5 in AC surface and binder course 4.0 in asphalt treated base 8 in existing AC with top 1 in milled off 6 in existing dense aggregate base	2.5 in AC surface and binder course 7.5 in asphalt treated base 10 in dense aggregate subbase
Strategy B—Rigid Design	8 in continuously reinforced concrete (CRC) 8 in existing AC with top 3 in milled off 6 in existing dense aggregate base	8 in CRC 6 in dense aggregate base

The two design strategies are to be evaluated on a probabilistic life cycle cost basis using a 35-year analysis period. A triangular distribution is assumed for the discount rate, with the most likely value being 4.0 percent and the minimum and maximum values being 3.0 and 5.0 percent, respectively.

**LCCA Inputs.** The following are the inputs used in this LCCA example.

Traffic. The traffic data inputs to be used in the simulation include the base year average daily traffic (ADT), the traffic growth rate estimate, and the percent trucks and automobiles. A truck directional distribution factor of 0.5 has been assumed, along with a lane distribution factor of 0.9.

- Initial ADT (both directions): 22,000 vehicles/day
- Traffic Growth Rate: 2.0 percent
- Percent Automobiles: 85 percent
- Percent Trucks: 15 percent (5% single units, 10% combination)

Pavement Performance and Activity Timing. Using available distress and roughness prediction models, the service life of each initial pavement structure (new and rehabilitated) was estimated, and appropriate future M&R treatments and timings were identified. For both the flexible and rigid strategies, only slight differences in the M&R schedule for the new structure and the rehabilitated structure were projected. Hence, the same life cycle model was deemed applicable for both structures.

Table C.19 lists the mean service life and corresponding standard deviation used for each structure in conducting the LCCA, and figure C.25 shows the life cycle models for the two design strategies.

Table C.19. Pavement service life input values for rural realignment example.

Pavement Structure	Service Life, years <sup>a</sup>	
	Mean	Standard Deviation
<i>Strategy A--Flexible Design</i>		
Initial Structure (new and rehabilitated)	12.0	2.6
Rehab 1: 1.5-in Mill and AC Replacement (mainline only)	7.0	1.8
Rehab 2: 1.5-in Mill and AC Replacement (mainline and shoulders)	6.0	1.7
Rehab 3: 1.5-in Mill and 4.5-in AC Overlay (mainline); 3-in AC Overlay (shoulders)	10.0	2.1
Rehab 4: 1.5-in Mill and AC Replacement (mainline only)	6.0	1.7
Rehab 5: 1.5-in Mill and AC Replacement (mainline and shoulders)	5.0	1.3
Rehab 6: 1.5-in Mill and 4.5-in AC Overlay (mainline); 3-in AC Overlay (shoulders)	8.0	1.8
<i>Strategy B--Rigid Design</i>		
Initial Structure (new and rehabilitated)	23.0	2.4
Rehab 1: CPR—patching and joint resealing (mainline) 1.5-in Mill and AC Replacement (shoulders)	10.0	1.9
Rehab 2: CPR—patching and grinding (mainline)	10.0	1.4
Rehab 3: 2.5-in AC Overlay (mainline and shoulders)	10.0	1.5
Rehab 4: 1.5-in Mill and AC Replacement (mainline only)	7.0	1.7

<sup>a</sup> Estimated using locally calibrated distress and roughness prediction models.

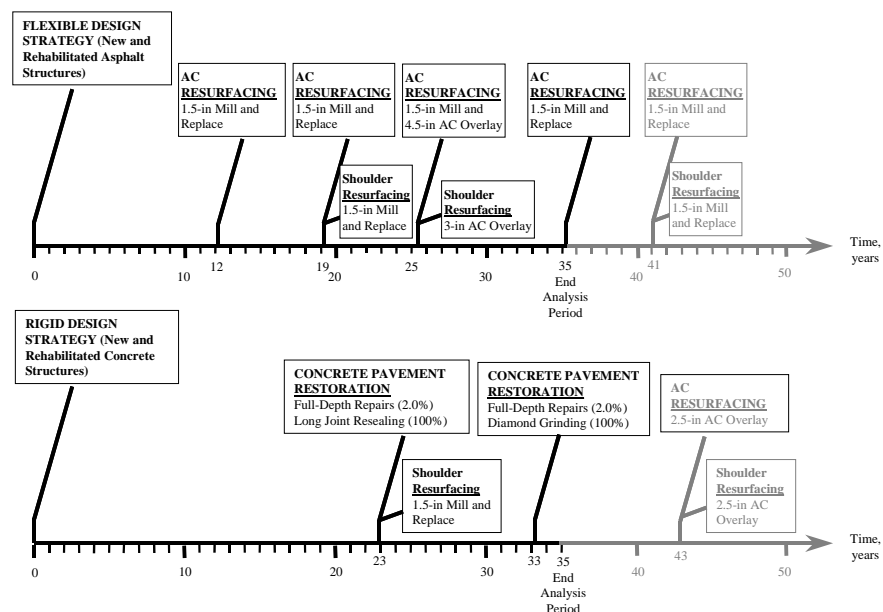


Figure C.25. Pavement life cycle models for rural realignment design strategies.



Agency Costs. Differential agency costs associated with initial construction include the mainline and shoulder pavement structures listed in table C.19 (including milling of the existing asphalt structure), as well as all associated traffic control costs, mobilization costs, and engineering costs. Using estimated quantities of individual construction pay items and historical unit cost data for those items, the overall project cost for each initial structure was computed. These costs, expressed in terms of means and standard deviations, are listed in table C.20.

Future differential agency costs are based on the projected mainline and shoulder rehabilitations shown previously in figure C.25. As with initial construction costs, estimated quantities of individual rehabilitation pay items were multiplied by estimated unit costs to yield an overall project cost for each rehabilitated pavement structure. Table C.20 shows the mean and standard deviation cost values to be used as LCCA inputs.

Work Zone User Costs. For both design options, work zones will be required for the initial construction and for each future rehabilitation performed on the mainline. During the initial construction, the existing 2-lane structure will remain open and will carry both directions of traffic, while the new 2-lane structure is built. Upon completion, traffic will be switched from the existing structure to the new structure, so that rehabilitation may commence on the existing structure. Work zone hours of operation in both cases will be 24 hours/day.

Future mainline resurfacing operations will involve daily (8 a.m. to 4 p.m.) work zone setups on one of the two lanes per direction. CPR operations will also require closing one of two lanes per direction; however, the work zone setups will be in effect 24 hours/day. Table C.21 summarizes key aspects of each work zone and lists the values of time for the three vehicle types.

**Life Cycle Cost Computation.** A probabilistic simulation was performed using 2,500 iterations. The resulting agency- and user-cost NPV statistics are summarized in table C.22, and the frequency and cumulative distribution curves are illustrated in figures C.26 through C.29. Clearly, the mean projected agency-cost NPV is lowest for alternative A (flexible pavement strategy)—\$10.611 million versus \$11.315 million for alternative B. However, the mean projected user-cost NPVs are much closer—\$0.763 million for alternative A versus \$0.779 million for alternative B.

The variation in projected agency-cost NPVs is highest for alternative A—standard deviation of \$1.116 million versus \$1.079 million for alternative B. However, alternative B has a slightly higher variation in projected user-cost NPVs—standard deviation of \$92,000 versus \$74,000 for alternative A.

Table C.20. Agency cost input values for rural realignment example.

Pavement Structure	Overall Project Cost, \$	
	Mean	Standard Deviation
<i>Strategy A--Flexible Design</i>		
Initial Structure (new and rehabilitated)	\$7,308,800	\$730,800
Rehab 1: 1.5-in Mill and AC Replacement (mainline only)	\$1,250,700	\$125,100
Rehab 2: 1.5-in Mill and AC Replacement (mainline and shoulders)	\$1,855,000	\$185,500
Rehab 3: 1.5-in Mill and 4.5-in AC Overlay (mainline); 3-in AC Overlay (shoulders)	\$4,266,000	\$426,600
Rehab 4: 1.5-in Mill and AC Replacement (mainline only)	\$1,250,700	\$125,100
Rehab 5: 1.5-in Mill and AC Replacement (mainline and shoulders)	\$1,855,000	\$185,500
Rehab 6: 1.5-in Mill and 4.5-in AC Overlay (mainline); 3-in AC Overlay (shoulders)	\$4,266,000	\$426,600
<i>Strategy B--Rigid Design</i>		
Initial Structure (new and rehabilitated)	\$10,175,600	\$1,017,600
Rehab 1: CPR—patching and joint resealing (mainline) 1.5-in Mill and AC Replacement (shoulders)	\$2,263,00	\$226,300
Rehab 2: CPR—patching and grinding (mainline)	\$2,530,300	\$253,300
Rehab 3: 2.5-in AC Overlay (mainline and shoulders)	\$3,747,800	\$374,900
Rehab 4: 1.5-in Mill and AC Replacement (mainline only)	\$1,905,900	\$190,600

<sup>a</sup> Estimated through evaluation of previous bids on similar sized projects.

Table C.21. Work zone details for rural realignment example.

	Initial Construction	AC Mill and Replace	AC Mill and Overlay	CPR-patching and sealing	CPR-patching and grinding	AC Overlay
Work zone operation (one direction)	1 of 2 lanes open	1 of 2 lanes open	1 of 2 lanes open	1 of 2 lanes open	1 of 2 lanes open	1 of 2 lanes open
Approach speed, mph	55	55	55	55	55	55
Work zone speed, mph	45	45	45	45	45	45
Work zone hours of operation	24 hours	8 a.m. – 4 p.m.	8 a.m. – 4 p.m.	24 hours	24 hours	8 a.m. – 4 p.m.
Flexible construction duration, days	147 (mean) 15 (std. dev.)	21 (mean) 2 (std. dev.)	54 (mean) 6 (std. dev.)			
Rigid construction duration, days	157 (mean) 18 (std. dev.)			45 (mean) 5 (std. dev.)	65 (mean) 7 (std. dev.)	58 (mean) 6 (std. dev.)
Value of time of passenger vehicles, \$/hour/vehicle	13.08 (mean) 0.75 (std. dev.)					
Value of time of single-unit trucks, \$/hour/vehicle	20.95 (mean) 1.00 (std. dev.)					
Value of time of combination trucks, \$/hour/vehicle	25.21 (mean) 1.25 (std. dev.)					

Table C.22. Probabilistic simulation NPV statistics for rural realignment example.

Statistic	Alternative A—Flexible Design		Alternative B—Rigid Design	
	Agency NPV	User NPV	Agency NPV	User NPV
Simulation Trials	2,500	2,500	2,500	2,500
Mean, \$million	10.611	0.763	11.315	0.779
Median, \$million	10.603	0.761	11.288	0.781
Standard Deviation, \$million	1.116	0.074	1.079	0.092
Variance, \$million	1,244,516.400	5,415.488	1,163,963.550	8,518.610
Coefficient of Variability	0.105	0.097	0.095	0.118
Range Minimum, \$million	7.133	0.522	7.467	0.467
Range Maximum, \$million	14.575	1.019	15.187	1.096
Range Width, \$million	7.442	0.497	7.720	0.629

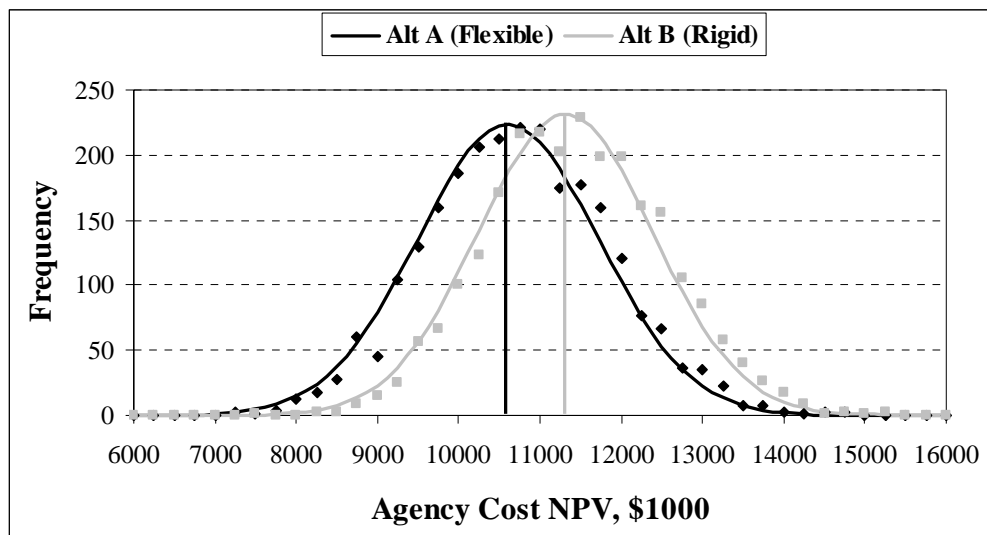


Figure C.26. Frequency distribution of forecasted agency costs for rural realignment example.

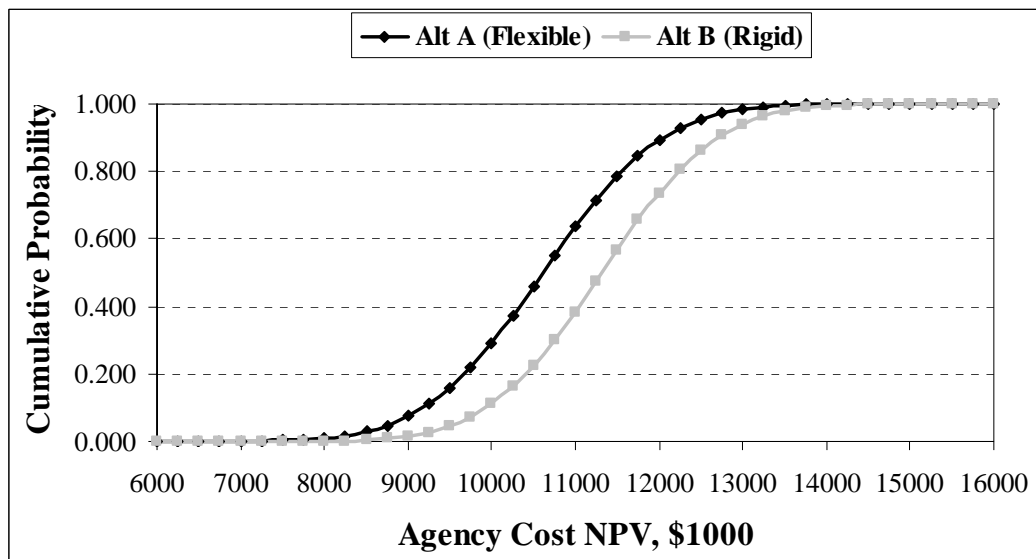


Figure C.27. Cumulative distribution of forecasted agency costs for rural realignment example.

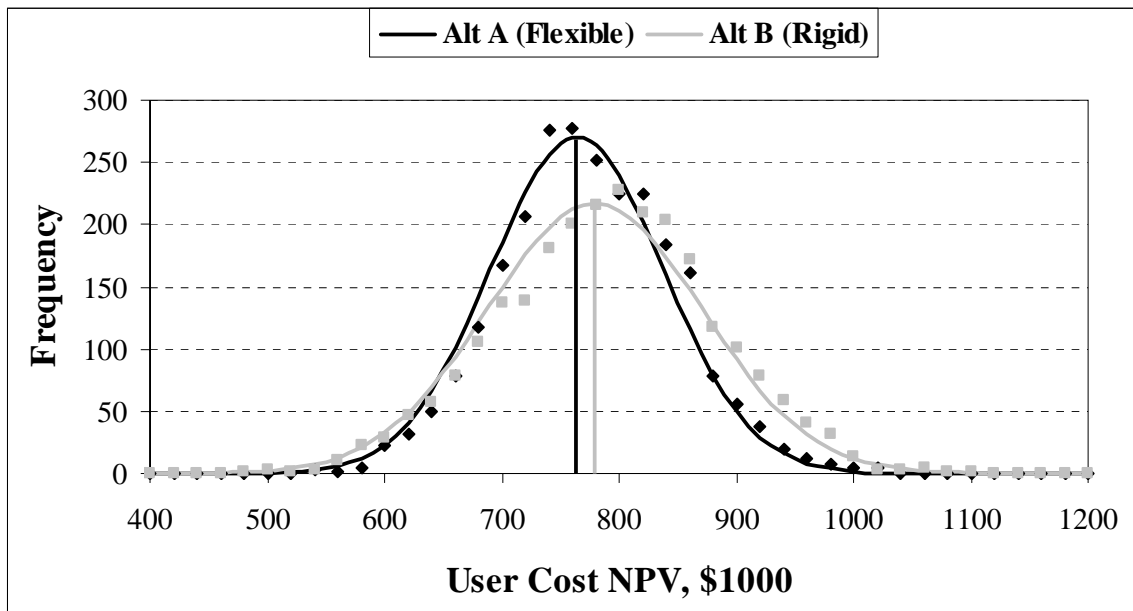


Figure C.28. Frequency distribution of user costs for rural realignment example.

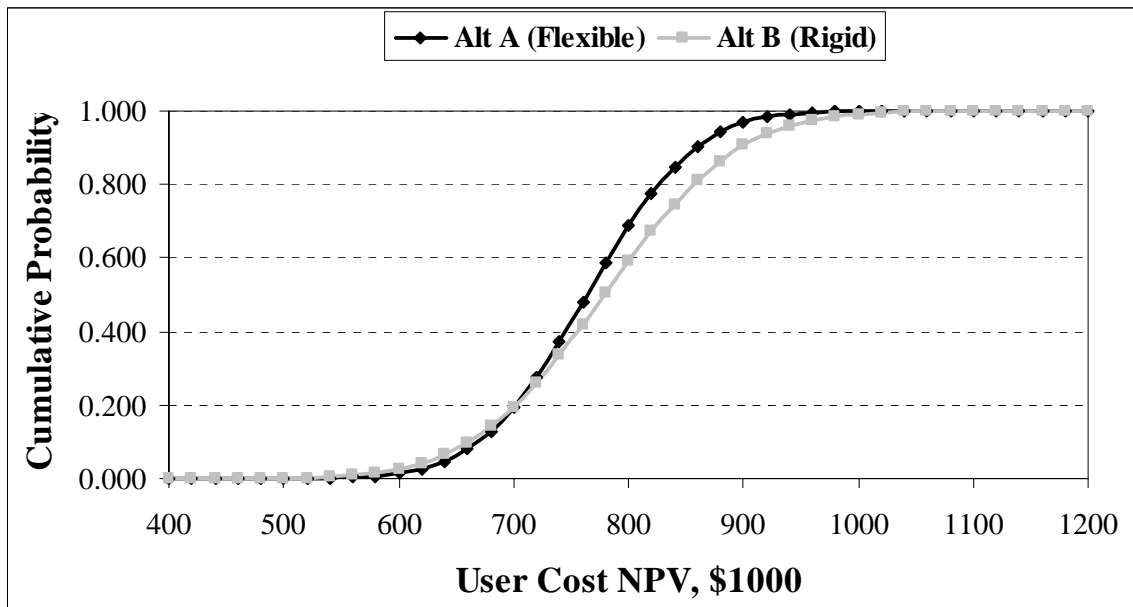


Figure C.29. Cumulative distribution of user costs for rural realignment example.

**Analysis of Results.** Following is an analysis of the results of this LCCA example.

Evaluation 1—Trial-By-Trial Comparison. Tables C.23 and C.24 show the resulting agency- and user-cost probability matrices for the two alternative design strategies. As can be seen, the favored strategy from an agency-cost standpoint is the flexible design. Of the 2,500 iterations, the flexible design had the lowest agency-cost NPV 1,696 times (67.8 percent).

In terms of the user-cost NPV, the flexible design is slightly favored. Of the 2,500 iterations, the flexible design had the lowest user-cost NPV 1,426 times (57.0 percent).

Evaluation 2—Statistical Analysis. To test for significant differences in the mean NPV values, the t-test formula given in equation C.26 was used. Results of the test as applied separately to agency and user-cost NPVs are as follows:

$$t_{\text{agency}} = (\$10,611,000 - \$11,315,000) / [(\$1,116,000^2 + \$1,079,000^2)/2500]^{0.5}$$

$$t_{\text{agency}} = -\$704,000 / \$31,046$$

$$t_{\text{agency}} = -22.68$$

Table C.23. Agency-cost NPV probability matrix for rural realignment example.

Design	Probability of Agency-Cost NPV of:		Overall Probability of Having the Lowest LCC, %
	Alternative A Less Than NPV of:	Alternative B Less Than NPV of:	
Alternative A (flexible)	X	32.2	67.8
Alternative B (rigid)	67.8	X	32.2

Table C.24. User-cost NPV probability matrix for rural realignment example.

Design	Probability of User-Cost NPV of:		Overall Probability of Having the Lowest LCC, %
	Alternative A Less Than NPV of:	Alternative B Less Than NPV of:	
Alternative A (flexible)	X	43.0	57.0
Alternative B (rigid)	57.0	X	43.0

$$t_{\text{user}} = (\$763,000 - \$779,000) / [(\$74,000^2 + \$92,000^2)/2500]^{0.5}$$

$$t_{\text{user}} = -\$16,000 / \$2,361$$

$$t_{\text{user}} = -6.78$$

At the 95 percent confidence level ( $t \geq +1.96$  or  $t \leq -1.96$ ), both the agency-cost  $t$ -value (-22.68) and the user-cost  $t$ -value (-6.78) fall within the critical range. This means that the mean agency-cost NPV of the flexible design strategy is statistically significantly lower than that of the rigid design strategy, and that the mean user-cost NPV of the flexible strategy is also statistically significantly lower than that of the rigid strategy. Based on these results, the preferred economic design strategy is the flexible design.

## C.6 GLOSSARY OF TERMS

(Design) Alternative—One of multiple feasible design options for a given pavement project, be it new construction, reconstruction, or rehabilitation.

Analysis Period—The period of time used in making economic comparisons between design alternatives. The analysis period should not be confused with the pavement design life (i.e., performance period).

Equivalent Uniform Annual Cost (EUAC) Method—Economic analysis method whereby all present and future costs and benefits are converted to an equivalent uniform annual cost that represents the amount that would have to be invested each year over the analysis period to match the total present worth of the project. Typically, EUAC is determined by first computing NPV and then multiplying NPV by the uniform capital recovery factor.

(Pavement) Corrective Maintenance—Maintenance operations performed to correct specific deficiencies in a pavement, such as potholes and localized deterioration.

(Pavement) Maintenance—Treatment activities intended to correct or preserve a roadway pavement for its safe and efficient utilization.

(Pavement) Preventive Maintenance—A planned strategy of cost-effective treatments that help preserve an existing pavement facility by retarding future deterioration and maintaining or improving functional condition. Preventive maintenance does not increase the structural capacity of a pavement.

(Pavement) Rehabilitation—Treatment activities undertaken to significantly enhance the structural or functional condition of a pavement, thereby greatly extending its service life. Rehabilitation can be subdivided into major rehabilitation, which includes structural AC overlays and extensive CPR (e.g., combination of full-depth repairs, retrofitted edge drains, and diamond grinding), and minor rehabilitation, which includes thin AC overlays and limited CPR (e.g., diamond grinding).

(Pavement) Strategy—A sequence of planned pavement work activities, consisting of the initial design (either new or rehabilitation) and all subsequent M&R treatments expected over the analysis period.

(Pavement) Upkeep—All maintenance and rehabilitation activities performed to keep a pavement in a safe and serviceable condition.

Performance Period—The period of time that an initially constructed or rehabilitated pavement structure will perform before reaching its terminal serviceability. Performance period is synonymous with design life.

Present Worth (PW) Method—Economic analysis method that requires converting all present and future costs and benefits to a single point in time (usually at or around the time of the first

expenditure), using a discount rate factor. (Also known as the Net Present Value [NPV] method).

**Serviceability**—The ability of a pavement to provide a safe and comfortable ride to its users.

**User Costs**—Costs incurred by highway users traveling on the facility and the excess costs incurred by those who cannot use the facility because of either agency or self-imposed detour requirements. User costs are typically comprised of vehicle operating costs, accident costs, and user delay costs.

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