

PART I

REPORT

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Transportation officials consider life-cycle cost analysis an important technique for assisting with investment decisions. Several recent legislative and regulatory requirements recognize the potential benefits of life-cycle cost analysis and call for consideration of such analyses for infrastructure investments, including investments in highway bridge programs. However, a commonly accepted, comprehensive methodology for bridge life-cycle cost analysis (BLCCA) currently does not exist. Research is needed, therefore, to provide bridge engineering professionals with a methodology for the determination of life-cycle costs of bridges to aid them in selecting the most appropriate bridge improvement alternatives.

RESEARCH OBJECTIVES

The objective of this research was to develop a methodology for BLCCA for use by transportation agencies. This methodology was augmented by practical tools, including a guidance manual for carrying out BLCCA (Part II) and a software package (with appropriate documentation) that automates the methodology (CRP-CD-26). The following three points, in particular, received special attention throughout the course of the research:

1. Obsolescence and the design service life,
2. Risk and vulnerability, and
3. Information displays for decision makers.

Obsolescence and the Design Service Life

The calculation of life-cycle costs depends on the choice of a distinct time period over which operations and maintenance costs are accrued, discounted, and compared with capital costs. This time period is often termed the “planning time horizon” or “design service life.” The specific time period selection—typically made with consideration for wear and aging of materials and sometimes the customary practices of financial markets—is generally decades long. Over the course of as little as 10 to 30 years, obsolescence may reduce substantially the value of a bridge.

Obsolescence is a condition of being antiquated, old-fashioned, or out of date. An obsolete item is not necessarily broken, worn out, or otherwise dysfunctional, although these conditions may underscore its obsolescence; rather, the item simply does not measure up to current needs or expectations. Obsolescence results when there is a change in the requirements or expectations—for example, the danger of earthquakes motivates changes in structural design standards to reduce the risks of failure and to mitigate the consequences of such a disaster. These changes, in turn, render many older structures effectively obsolete because they no longer comply with the most recent safety requirements. In most cases, things that are obsolete continue to function, but at levels below contemporary standards.

A number of factors can cause obsolescence:

- *Technological changes influence the scope or levels of services a bridge is to provide*—for example, when heavier loads are permitted than those loads for which the bridge was initially designed.
- *Regulatory changes impose new requirements on infrastructure*—for example, when safety requirements change the lane or shoulder widths required.
- *Economic or social changes can alter the demands placed on infrastructure*—for example, when suburban development generates traffic substantially above levels envisioned in design.
- *Changes in values or behavior can similarly alter demands but are more difficult to foresee*—for example, when a societal commitment to private automobile travel spurred removal of street railways in most urban areas, the result was that some heavily congested bridges carry fewer people than they did when they were first built.

Forecasting of obsolescence is difficult at best and is certainly beyond the realm of current life-cycle cost-analysis models. However, effective life-cycle cost management should include explicit consideration of obsolescence. The user of cost-analysis software should be given the tools to explore varying design service life assumptions. In addition, guidance material accompanying the software should present cases that illustrate the sources and consequences of obsolescence so that software users can assess the technical and financial uncertainties in their decision making.

Risk and Vulnerability

A major component that is missing in current bridge life-cycle costing is the assessment of risk and vulnerability in economic terms—for example, a bridge with attributes contributing to seismic vulnerability has a risk cost relating to the probability of damage or failure and the consequences of that damage or failure. This assessment should form part of the decision process when evaluating competing life-cycle alternatives.

Engineering risks and uncertainty are related to the interaction of environmental factors and bridge characteristics causing partial or complete loss of functionality, collateral damage, or both. The most easily recognized sources of engineering risks and uncertainty are condition-related reduction in load capacity, life, or both; seismic vulnerability; bridge scour; and overloads. In addition, there are other areas of risk.

Condition-Related Reduction in Load Capacity, Life, or Both

As a bridge deteriorates, undergoes repeated load cycles, or both, the travelling public is exposed to increasing risk and potential inconvenience. A bridge in poor condition may require posting, which has a direct effect on user costs or may be at a higher risk of failure. A partial or total bridge failure can cause substantial hardship—thus, increasing the risk of failure must carry a cost and be considered in the BLCCA. An increased risk of failure, therefore, carries with it the potential of increased cost attributed to that failure. These direct and indirect costs could include replacement of the bridge, detouring of traffic and associated traffic congestion, loss of life and substantial liability, effects on area businesses serviced by the facility, and so forth.

Seismic Vulnerability

Particular types of structures carry a higher risk of damage caused by seismic events. A structure's seismic vulnerability and the uncertainty in seismic events need to be addressed. The risk of damage from a seismic event needs to be evaluated against the cost of mitigating that damage. Seismic events also tend to be unusual in that a single event can cause damage to many structures and can compromise the entire road network. The value of providing at least some post-disaster emergency routes must be recognized. The user costs associated with earthquake damage are difficult to assign to individual structures—it is an entire road network or even an economy-based issue. Seismic vulnerability is a high-profile issue; yet, engineers are ill equipped to evaluate their decisions. For example, the double-decked Nimitz Freeway in San Francisco may have been designed to a normal reliability index; yet, the consequence of failure proved to be far beyond that of a typical bridge structure. Would the original designers have

accepted a 10^{-4} risk of failure if they knew the consequences of such a failure?

Bridge Scour

A recent study in New York State has shown that scour is, by far, the primary cause of bridge structural failure in that state. Engineers need a systematic way of evaluating the susceptibility of a bridge to scour, the probability of events causing scour, and the consequences (i.e., damage or failure). These consequences of scour need to be balanced against the cost of mitigating measures. In some cases, it may be warranted to replace a particularly scour-susceptible bridge even if the structure is in good condition if the consequences of failure are severe, if the risk of failure is unacceptably high, and if no other mitigating measures are available.

Overloads

Live loads for which bridges are designed are upperbound representations of typical traffic found on the nation's roads. Changing trucking regulations, unscrupulous operators, and steadily increasing loads are putting the nation's bridges at a greater risk of being overloaded. Overloads can cause direct damage, changes to structural behavior (e.g., through plastic-hinge formation causing permanent moment redistribution, deck cracking, connection slippage, etc.), or cumulative damage (e.g., fatigue). Similar to the condition-related reduction in load capacity or life (discussed above), this overloading can lead to direct agency and user costs as well as to an increased risk of future damage or failure.

Other Areas of Risk

Another area of risk concerns public safety and agency liability. Substandard bridge railing, guiderails, transitions, end treatments, and so forth can expose the agency to litigation even if the design of such appurtenances was appropriate when the bridge was constructed. Even a policy that is as seemingly benign as "all new bridges shall have concrete barriers" may, by inference, condemn all steel railing as being deficient in the eyes of the court. Exposure to litigation is obviously an issue that must be addressed.

Uncertainties can contribute to the risk of making the wrong preservation decision for a particular bridge. Uncertainties can apply to many parameters such as the short-term and long-term discount rates, rates of traffic growth, changes to road usage, value of litigation awards, costs of repair, effectiveness of repairs, timing of repairs, construction of competing facilities, changes to load permits, definition of "substandard" geometry, and so forth. Generally, these uncertainties are twofold: the current value is uncertain and the future trends are uncertain. For example, it may be appropriate to express

the current cost of a particular deck repair as being a standard normal function with a mean of \$100 per square meter and a standard deviation of \$20 per square meter and to assume that the cost of a similar repair in the future will increase by, on average, 5% per year with a standard deviation of 1%. In other words, the compounding of uncertainty makes the value more and more uncertain with time.

Information Displays for Decision Makers

Bridges, like other civil infrastructure facilities, are notoriously subject to maintenance neglect. The aging and wear that reduce bridge performance are slow processes and are often invisible to the untrained eye. In the face of competing demands for limited government budgets, political forces may persuade decision makers to defer maintenance spending. Over time, such deferrals can have dire consequences, as many notable cases have illustrated.

The analysis of life-cycle cost and design of bridges on the basis of minimizing that cost makes good sense only to the extent that the assumptions on which design decisions are based remain valid throughout the facility's service life. Deferral of maintenance invalidates an important set of assumptions and is sometimes argued to be the result of lack of understanding—on the parts of both the public at large and political decision makers—of what those assumptions are. If the public is made fully aware of the degree to which maintenance deferral represents a diversion of public assets, one may argue that it will become difficult for political decision makers to use the public's capital as an unrestricted source of borrowed funds. Life-cycle cost-analysis models should therefore be designed to enable presentation of results in ways that are understandable to the broad range of decision makers, including the public at large.

Legislative and Regulatory Requirements

While the basic principles were articulated more than 100 years ago, the systematic approaches to life-cycle cost analysis appeared only 25 to 30 years ago in the United States. Several recent legislative and regulatory requirements have called for greater consideration of life-cycle costs in the highway program. Sections 1024 and 1025 of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required the consideration of life-cycle cost analysis in the design and engineering of bridges, tunnels, and pavements. The rule on implementation of ISTEA management systems required that life-cycle costs be analyzed in pavement and bridge management systems. Executive Order 12893, "Principles of Federal Infrastructure Investment," required that the benefits and costs of infrastructure investment be measured and appropriately discounted over the full life cycle of the project (1). The life-cycle cost analysis has now begun to be used in

transportation facility management systems, especially for pavement and bridge management systems (2).

The Transportation Equity Act for the 21st (TEA-21) authorizes transportation funding for a 6-year period (1998–2003). In a broad sense, TEA-21 has expanded the types of benefits and costs to be considered as factors in transportation investment decision making. Although these considerations are not in the form of regulations and formal benefit-cost analysis is still the exception for most bridge projects in the United States, the use of life-cycle analysis and benefit-cost comparisons are encouraged. This is particularly true of large projects for which the cost of the analysis is warranted. FHWA does require the consideration of life-cycle analysis in a broad sense for congressionally mandated studies—generally, highway corridors that contain bridges.

STUDY SCOPE

This section identifies the various tasks and subtasks that were involved throughout NCHRP Project 12-43.

Phase 1

Task 1: Review Relevant Domestic and International Practice, Research Findings, and Other Information Related to BLCCA

National Engineering Technology Corporation (NET Corp.) has key contacts in most state agencies and has also provided consulting services to review current bridge-management practices and optimization techniques for Wyoming and Florida. A comprehensive review of current state DOT bridge management system practices was compiled from studies that NET Corp. has already undertaken. The review of state practices was focused specifically on life-cycle costing issues through the use of a questionnaire that pointedly asked decision makers which issues are important, which are not, and whether they currently account for each issue. The questionnaire was distributed to the state departments of transportation (DOTs); approximately 25 states responded. Eight international agencies and several non-bridge agencies were also contacted. A literature search was carried out.

Task 2: Describe Specific Parameters and Variables Associated with BLCCA, Including Both Agency and User Costs

The research team met during the week of September 23, 1996, to discuss the specific variables and parameters that should be considered in developing a BLCCA methodology. The results of the Task 1 questionnaire were correlated to the list of parameters and variables with respect to the issues of applicability, availability, quality, and uncertainty. The issues of applicability, availability, quality, and uncertainty for each

parameter and variable as well as a definition of each parameter and variable were compiled and presented in an interim report.

Task 3: Develop Framework for the Minimum Life-Cycle Cost Methodology

The research team met in September 1996 to discuss the framework for carrying out bridge life-cycle costing. Based on the responses to the questionnaire, it appeared that there was almost universal agreement that the system should be developed for the personal-computer (PC) environment in Windows. Approximately one-third of the respondents preferred a client-server solution while the other two-thirds preferred a file server-based or stand-alone system.

Although a classical minimum life-cycle cost methodology is relatively straightforward, methods of introducing such concepts as vulnerability and uncertainty were not well defined. As part of Task 3, it was necessary to evaluate the merits of methodologies such as fuzzy set theory for uncertainty in the variables, or a Bayesian approach, or, perhaps, a probabilistic approach to vulnerability. It was also necessary to determine a suitable methodology to handle long-term innovation and changes over time to the functional requirements such as load capacity, traffic capacity, and clearance requirements.

Each parameter and variable in Task 2 was evaluated as to whether it was applicable to the chosen methodology, could be defined as a default value, was user input, should be part of an automated sensitivity analysis, required reference tables in the system, or required its uncertainty to be evaluated.

A summary of the proposed methodology was compiled and submitted as part of the Interim Report. This summary formed the conceptual basis for Task 4 and became part of the core of the Guidance Manual produced in Task 6.

Task 4: Provide a Functional Specification for Software to Automate Task 3

A review of hardware requirements was carried out to develop a recommended hardware configuration for BLCCA. At the time, a Pentium PC was identified as the recommended workstation platform. A review of available operating systems and software languages was carried out. It was concluded that the BLCCA should run in Windows 95/98/NT. It was further concluded that Visual Basic was the recommended software package for developing the BLCCA. It became evident later in the project that Visual Basic was too slow for some of the more intensive data-manipulation functions, so Visual FoxPro routines were interfaced with the Visual Basic core package to increase performance. Although some of the speed enhancement could be attributed to programming technique, the 100-fold increase in calculation speed made integrating the Visual FoxPro code well worth while.

Based on the information gathered in Tasks 1, 2, and 3, basic BLCCA features were defined, and an outline of the scope and architecture of the proposed system was produced. A BLCCA demonstration package was produced to present the BLCCA “shell” using Visual FoxPro. Sample mock-ups of the screens and various objects were included to demonstrate how the BLCCA would actually look and operate. The BLCCA produces hardcopy reports in text and graphical format. As part of Task 4, the basic report types and contents were defined.

Task 5: Submit an Interim Report

NET Corp. prepared an interim report summarizing the data collected and evaluated in Task 1, the parameters and variables defined in Task 2, the draft framework for the BLCCA developed in Task 3, and the functional specification for the software developed in Task 4. The Interim Report provided the detailed work plan for the remaining tasks, including the beta test plan. The Interim Report was delivered to NCHRP for review.

Task 6: Develop Complete Methodology for the BLCCA and Develop the BLCCA Software

Once the Interim Report received approval from the NCHRP Project Panel, detailed design of the BLCCA methodology was undertaken and the software was developed. The following subtasks show the various milestones that were achieved during this phase of the project.

Subtask 6.1: Develop Guidance Manual Fully Describing the BLCCA Methodology. The Guidance Manual, which will provide bridge engineering professionals with guidance and a methodology to determine and evaluate life-cycle costs for bridges, was produced. The Guidance Manual addresses the major issues, discusses the important parameters and variables, and also provides guidance in the selection of appropriate values for the variables (see Part II: Guidance Manual). The Guidance Manual is in a format suitable for adoption by the AASHTO Highway Subcommittee on Bridges and Structures and, as such, is tailored as a stand-alone document that is not specifically linked to the use of the software.

Subtask 6.2: Produce Final Software Scope. The BLCCA software scope—as defined in the Interim Report, the detailed work plan, and the User’s Manual (which is on *CRP-CD-26*)—served as the primary roadmap for specifying the philosophy, concepts, models, and algorithms to be incorporated into the BLCCA. In order to meet the project objectives, the scope and architecture of the BLCCA software encompassed the following system features:

- Compliance with FHWA’s recommendations and long-term requirements for bridge management;
- Flexibility of the BLCCA to be easily modified to accommodate changing requirements by FHWA and to accommodate other advances in bridge-management and computer technology;
- An easily accessible computerized bridge database;
- User-friendly system features allowing staff to operate the BLCCA without specialized training in computer technology;
- Authoritative computer-generated reports, both tabular and graphical;
- The ability to establish life-cycle maintenance and rehabilitation strategies that ensure the satisfactory long-term performance of bridges;
- The ability to evaluate the short- and long-term impacts of various alternatives based on a least-present-value analysis;
- A means of forecasting future trends to make cost-effective investments in current rehabilitation works; and
- A printable User’s Manual to supplement the BLCCA on-screen User’s Manual for training and reference purposes.

Subtask 6.3: Produce a User’s Manual. The User’s Manual was developed to present the different modules and submodules that make up the system and the format for data input and output. The User’s Manual also contains the Technical Manual, which details the algorithms and methodologies used (the User’s Manual is included on *CRP-CD-26*). The preparation of the preliminary User’s Manual involved an evaluation of user operation needs and an assessment of the level of user-friendliness to which the BLCCA should be designed. Based on the progress and results of the software development and testing, the User’s Manual was expanded, upgraded, and finalized.

Subtask 6.4: Produce Data-Entry Screens. NET Corp. produced data-entry screens in accordance with the input-screen mockups produced under Subtask 4.4 and the preliminary User’s Manual.

Subtask 6.5: Program Tables Containing System Data and Calibration Data. These tables constituted the “knowledge-based” portion of the BLCCA. The information and data contained in these tables was identified in Tasks 2, 3, and 4.

Subtask 6.6: Produce Report Formats. Reports were produced using two third-party applications—dGE Pro Essentials and Crystal Reports—and were based on the reports identified in Subtask 4.5 in the outline of the project.

Subtask 6.7: Program the BLCCA Software Source Code. Development was carried out in accordance with the detailed work plan and the preliminary User’s Manual. The

BLCCA source code is of modular architecture to facilitate both current and future programming, compiling, revision, addition, and deletion. An object-oriented approach was used. Most programming was done in Visual Basic, with database-intensive operations programmed in Visual FoxPro.

Subtask 6.8: System Validation (Alpha Testing). System validation and testing accounted for a significant portion of the development effort for this project.

Task 7: Discuss Available Data Sources for Information on the Significant Parameters and Variables

When Task 6 was sufficiently advanced for the final set of parameters and variables to be well known and their usage within the software program well defined, a summary of available data sources was developed and added to the Guidance Manual. The summary included comments on the reliability of the available data, the currency of the data, variation in values from different sources, and the proper application of raw data to the BLCCA methodology.

Task 8: Beta Test Software

The objectives of the beta testing were as follows:

- Uncover any source coding errors and inaccuracies or inconsistencies that may exist;
- Evaluate the use and reliability of the system;
- Evaluate the accuracy of the results obtained from the analysis module;
- Evaluate the various types of reports produced by the system;
- Evaluate the user interface of the system;
- Evaluate the accuracy and clarity of information provided in the User’s Manual (and within the User’s Manual, in the Technical Manual) and in the Guidance Manual;
- Identify possible improvements to the system; and
- Identify additional information that would be beneficial to agencies in implementing the BLCCA.

Beta testing indicated the need for additional testing, enhancements to the user-friendliness of the software, and improvements to the reports produced. A need for training and for more worked examples was also identified.

Task 9: Finalize Documentation and Submit All Deliverables

At the end of the defined timetable for Phase 1, NET Corp. delivered the following, with the exception of the Final Report,

to NCHRP. The Final Report was delayed until the completion of Phase 2.

1. The Final Report, which documented the entire research effort—including updated sections of the Interim Report, where applicable—and an implementation plan;
2. The Guidance Manual;
3. The source code for the BLCCA software;
4. A compiled and executable software package;
5. A software package installation routine;
6. The User's Manual, in the form of an online help system;
7. The Technical Manual (incorporated into the User's Manual) for material that is necessary to the understanding of the operation of the software; and
8. Software documentation, including definitions of data tables, program structure, and basic architecture.

All textual materials, with the exception of the source code, were delivered in WordPerfect 5.1/5.2 format. The source code was provided in an ASC II—file format. The source code was submitted as a compilation of all objects necessary to modify or review the software.

Phase 2

Phase 2 involved developing enhancements to make the system more user-friendly. The following activities were included in the overall scope of the enhancements.

Task 1: Produce Additional Examples to Illustrate Key Software Applications

The developed software contained many concepts that were new to practicing engineers and that required the user of the software to understand the consequences of various decisions made when developing scenarios and alternatives. Several simple example problems illustrating situations such as linked events, uncertain versus certain costs and timing, decision points, and how to apply the condition and load predictors were added to the system.

Task 2: Undertake Additional Testing of the Existing System

The developed system turned out to be much more complex than was originally envisioned, and additional testing on the accuracy of the results was required. The system was also difficult to use in its original form. The menu structure was revised to make the system more intuitive, and a data-input wizard was added.

Task 3: Conduct On-Site User Training

Again, because the developed system turned out to be much more complex than was originally envisioned, more formal training of potential users of the software was required. This training was conducted as a workshop in Wisconsin and as a presentation at the TRB Annual Meeting in Washington, D.C.

Task 4: Improve Textual and Graphic Reports

Testing and evaluation of the system revealed shortcomings in the textual and graphical reports. The types of analysis and reports seemed to be appropriate, but some of the reports were lacking in content. The existing reports were augmented with additional useful information such as the data point tables used to draw the graphs and curve statistics (e.g., mean, standard deviation, and the like).

Task 5: Modify Help System to Make It Context Sensitive

Originally, the help system was a hypertext-style document with topics and links; topics were found by navigating through the equivalent of a table of contents. To this original help system, a new level of user help was added by introducing Info buttons on most of the data-input forms to provide the user with context-sensitive help.

Task 6: Produce a Hardcopy Version of the User's Manual

The modified online help system—a hypertext-style document with topics and links, navigable through a table of contents and capable of providing context-sensitive help—was not amenable to printing the User's Manual (i.e., was not amenable to producing a hardcopy) because the user had to print out each topic in the help system one topic at a time; there are several hundred topics. The help system was compiled into a printable Word document, which the user can print as a whole or by chapter.

RESEARCH APPROACH

Life-Cycle Cost Analysis and Its Application to Bridges

Life-cycle cost analysis has received increased attention as a tool to assist transportation agencies in making investment decisions and in managing assets (2,3). While the basic principles of life-cycle cost analysis were articulated more than 100 years ago, the systematic approaches to life-cycle cost analysis appeared only 25 to 30 years ago in the United States.

Bridges last much longer than do pavements. For a highway agency, bridges are a long-term investment. Throughout its useful life, a bridge requires both routine and periodic maintenance and occasional rehabilitation and replacement work. Thus, bridges require a series of expenditures for various activities during their life cycles. A life-cycle activity profile of a bridge can be represented by a series of future bridge activities laid out in a cash-flow diagram (4–6). It is necessary to make economic decisions with these future expenses in mind. Selection of projects only in terms of initial investments fails to reflect future funding needs. Some of the examples of life-cycle cost analysis can be found in pavement management (7) as well as in bridge management (4–6, 8). This section gives an overview of the various aspects of life-cycle cost analysis, with special reference to bridge management.

Identification of Alternatives

There are different alternatives for bridge maintenance and improvement for a given set of distress characteristics and other factors. These specific alternatives vary from state to state, based on experience and local practices. It is desirable to identify a list of promising alternatives for various combinations of distress and bridge traffic and geometric factors. Each alternative is then analyzed with the alternative's activity profiles and cash flows for project-level decisions or with promising alternatives of other bridge projects for network-level decisions.

Agency Costs

For a complete life-cycle cost analysis, both agency and user costs need to be included. Agency costs consist of maintenance, rehabilitation, and replacement costs. Most routine maintenance activities are performed by an agency's own workforce. Rehabilitation works consist of minor and major repair activities that may require the assistance of design engineers and are let to contractors for construction. Most rehabilitation work is deck related. A major rehabilitation activity may involve deck replacement. The term "bridge replacement" is, on the other hand, reserved for a complete replacement of the entire bridge structure. New bridge constructions caused by the construction of a new road or a new alignment are also included in this category.

Agency costs include materials, personnel, and equipment costs. To estimate the costs of the different activities, a good cost-accounting system is essential. The type of action performed on each bridge element, the costs incurred for the bridge element, the condition of the bridge element before and after the activity, and other relevant data should be recorded and used in the future for estimating various agency and user costs (9).

Routine Maintenance Costs

The costs associated with the routine maintenance of bridge elements can be estimated in the following ways. First, these costs can be developed as a function of the material type, condition, location, average daily traffic (ADT), highway classification, and other important factors for each bridge element. Second, these costs can also be estimated by first estimating the quantity of different routine maintenance activities performed on a type of element per year as a function of element condition, material type, ADT, highway classification, environment, and other factors. The unit cost of each type of maintenance activity is also estimated as a function of the above mentioned factors. Together, the quantity of routine maintenance activities and the unit cost of each type of activity give an estimate of the routine maintenance costs.

Element Rehabilitation Costs

The costs associated with the rehabilitation of bridge elements should be estimated for different types of elements and the different rehabilitation alternatives applicable for each element type. Together, elements and alternatives give estimates of the costs for element rehabilitation corresponding to different rehabilitation alternatives.

Element Replacement Costs

The costs associated with element replacement are estimated in the same way as element rehabilitation costs; however, they are distinguished from element rehabilitation because the funding options may be different for each.

Bridge Replacement Costs

Bridge replacement costs depend on the length, width, and height of a bridge; the number and length of individual spans; the superstructure and substructure material; and structural type; the bridge location; and the feature being crossed (e.g., road, rail, or river). The estimation of bridge replacement costs is done by breaking the entire project into different cost items and then using historical contract costs for similar items on similar projects to estimate the costs.

User Costs

User costs are primarily attributable to the functional deficiency of a bridge such as a load posting, clearance restriction, and closure. These functional deficiencies may cause higher vehicle-operating costs because of such factors as detours, lost travel time, and higher accident rates.

Detour Costs

User costs are incurred because vehicles must take detours caused by narrow deck width or inadequate vertical clearance or load capacity. The costs consist of additional vehicle-operating costs and the value of the time lost. Load capacity can be predicted using regression analysis or Markov chains (10). The estimation of future traffic can be done using the present traffic flow and the traffic growth rate. A comparison of the future load capacity and the predicted traffic land distribution gives an estimate of the expected detoured traffic. If the lengths of detours associated with individual bridges are known, user costs caused by detours can be estimated.

Crash Costs

Crashes also contribute to user costs caused by bridge deficiencies. For each bridge, the expected rates of each type of accident can be estimated as a function of the deficiencies. The costs associated with each type of crash may also be estimated. Together, the rates of each crash type and the costs associated with each of them gives the total crash costs for a bridge.

Bridge Work Costs

Bridge work—whether routine maintenance, rehabilitation, or replacement—usually influences traffic flow both across the bridge and on surrounding roads. The congestion caused by each of the alternatives, however, may be different. The congestion caused on the surrounding roads and on the bridge results in additional costs. These additional user costs are experienced by the users of the bridge and the users of the surrounding roads. Moreover, the increased use of alternative routes during construction may cause accelerated deterioration of the roads and bridges along the alternative routes, adding to additional agency costs.

Agency and User Cost Models

Regression analysis is generally used for estimating agency and user costs as a function of various factors on which the costs are dependent. The costs may be listed as follows:

- Initial cost;
- Operation and maintenance costs;
- Rehabilitation and replacement costs;
- Salvage value or terminal cost, energy costs (particularly for equipment), and user costs (particularly for pavement and bridge management systems); and
- Associated costs, including other identifiable costs associated with life-cycle cost analysis but not previously mentioned, such as costs for staffing, downtime, tax implications, and so forth (11).

The costs listed above serve as the input to life-cycle cost-analysis models. The life-cycle models used in transportation decision making may be classified into two categories: general and specific. The general models are applicable to all types of infrastructure; the specific models are customized for specific systems such as bridge or pavement management systems.

General Models

A generalized life-cycle cost model can be expressed as the following (12):

$$LCC = C_1 + C_2 \quad (1)$$

where

LCC = life-cycle cost,
 C_1 = nonrecurring costs, and
 C_2 = recurring costs.

It may be noted that the salvage value or terminal value may be regarded as a nonrecurring cost if the analysis period equals the life of the project.

The risk and vulnerability of a system can be included in a life-cycle cost model, as follows:

$$LCC = IC + OP + FC \quad (2)$$

where

LCC = life-cycle cost,
 IC = initial cost,
 OP = operating cost, and
 FC = failure cost.

This model refers to the failure cost as those costs incurred when the system is not in its normal state of performance. This type of model is important for those facilities that are located in areas particularly vulnerable to earthquakes and other natural disasters. Failure cost will include not only appropriate agency costs for repair, rehabilitation, or replacement, but also user costs.

Specific Models

Specific models are used to analyze specific systems. Several models for pavement and bridge management systems are discussed as examples.

Pavement Models. The most frequent use of life-cycle cost analysis in transportation projects occurs in highway pavement projects (13–15). Life-cycle cost analysis is used in the selection of pavement type, pavement design, pavement-

rehabilitation options, and other related actions. The most common form of a pavement life-cycle cost model is given below:

$$LCC = DC + CC + MC + RC + UC + SV \quad (3)$$

where

LCC = life-cycle cost,
 DC = design cost,
 CC = construction cost,
 MC = maintenance cost,
 RC = rehabilitation cost,
 UC = user cost, and
 SV = salvage value.

It should be mentioned that some of the cost items are recurring while other items are only one-time costs. The user costs are those accumulated by the users of the facility according to different pavement type, condition, maintenance activities, or rehabilitation work. These costs could be in the form of delay costs, operating costs, and denial-of-use costs. Salvage values can be either positive or negative, depending on whether the material has some economic value or would necessitate cost for removal (13).

Another form of a pavement life-cycle cost model, used for pavement-type selection (16), can be expressed as

$$LCC = CC + MC + RC + SC \quad (4)$$

where

LCC = life-cycle cost;
 CC = construction cost, the tendered amount plus any administration costs; the unit rate is obtained by dividing the tendered price by the area of the pavement;
 MC = maintenance costs, including minor patching, crack sealing, and so forth;
 RC = rehabilitation costs, including any structural overlays, periodic reseals, removal and replacement of open-graded friction course asphalt, and so forth; and
 SC = salvage value at the end of the analysis period.

An example of the use of life-cycle cost analysis in pavement-rehabilitation project selection is given below (15):

$$LCC = CC + MC + RC + IV \quad (5)$$

where

LCC = life-cycle cost of a rehabilitation alternative;
 CC = construction cost of rehabilitation;
 MC = routine maintenance cost after rehabilitation;
 RC = rehabilitation cost (if required before the end of the analysis period); and

IV = initial value (the initial condition of each pavement is converted to a dollar value and all pavements are brought to a common starting point).

Also, in this model, an index called the “Service Cost Index” (SCI) was used to determine the relative benefits derived from each rehabilitation action. This index was defined as

SCI = total number of equivalent 18-kip single-axle loads served by the pavement during the analysis period / total life-cycle cost.

By using the IV and the SCI, alternatives with different initial conditions and different future traffic can be compared on an equitable basis.

Bridge Models. Bridges are unique structures in transportation systems, and they require frequent and substantial maintenance, rehabilitation, and replacement. Consequently, maintenance and rehabilitation costs are a significant part of the total costs in BLCCAs. Similar to the pavement model presented in Equation 3, a bridge life-cycle cost model can be expressed as follows:

$$LCC = DC + CC + MC + RC + UC + SV \quad (6)$$

where

LCC = life-cycle cost,
 DC = design cost,
 CC = construction cost,
 MC = maintenance cost,
 RC = rehabilitation cost,
 UC = user cost, and
 SV = salvage value.

Although this model has a format similar to the model format in Equation 3, the actual interpretations for some items are different. In the bridge model, the user operating cost is negligible, and the primary user costs are denial-of-use costs. Denial-of-use costs include the extra costs occurring during bridge congestion and repair, rehabilitation, and replacement. The major elements of denial-of-use costs are value of time lost by the users because of delay, detours, and so forth. Moreover, in the evaluation of the alternatives for a bridge, crash costs of users seem significant because bridge structures correlate with crash rates (17).

The life-cycle cost analysis has been used in determining optimal timing of bridge activities (18). In a recent research study, Mohammadi et al. (19) used a single parameter to quantify the bridge decision-making process in an optimal scheduling scheme. Three major elements for the BLCCA were combined to estimate the parameter: (1) bridge condition rating, (2) costs associated with various bridge works, and (3) bridge service life expectancy. Equation 7 demonstrates as follows:

$$VI = F(r, c, t) \quad (7)$$

where

VI = bridge value index,
 F = objective function,
 r = condition rating,
 c = costs, and
 t = time or bridge service life expectancy.

The proposed form for F is

$$VI = r \cdot t / c = A_s / c \quad (8)$$

where

A_s = area under the bridge deterioration curve.

The Equation 7 (with Equation 8) can be used as the objective function in a mathematical-optimization scheme in which various constraints on the three parameters and on time can be imposed. It should be noted that Jiang and Sinha (18) earlier proposed the concept of maximizing the area under the deterioration curve in bridge decision making. However, condition rating cannot be used as the sole determinant of a particular activity.

Other Transportation-Related Models

A host of life-cycle cost models is available in the literature. For transportation-related applications, life-cycle cost models have been developed for equipment management (12), steel-bridge corrosion-protection systems (20), lane-marking (21), rural advanced traveler information systems (22), and transit fleet management (23, 24).

Activity Profiles and Cash Flows

Activity profiles and associated cash flows are necessary to conduct life-cycle cost analyses. The activity profile provides a good estimate of expected future costs, although it is unlikely that the amount and timing of future expenditures will follow exactly the projected profile. Three basic pieces of information must accompany each bridge activity profile: cost, starting time of bridge work, and duration of bridge work. The construction of life-cycle activity profiles can be done either by default assignment from a set of predetermined profiles, given some selection criteria such as type and timing of the next recommended bridge work, or by the bridge manager, based on his or her engineering judgements. Once the proposed bridge management system is started and bridge activities are clearly defined, unique identification codes are assigned to the bridge activities so that their cost information can be readily extracted from the cost data file in the future.

It should be noted that condition prediction models are used to predict future conditions of various bridge elements or components. These models, along with models for agency and user costs, are used to estimate the costs associated with each activity profile and thereby to derive each associated cash flow (25).

Interest Formulas

Life-cycle costs are expressed as equivalent present worth of costs or as equivalent uniform annual costs, using compound interest formulas. Several interest formulas may be needed to convert future cash flows to the equivalent present worth or uniform annual costs. The first factor is the single payment present worth factor (SPPWF). This factor is used to convert single-payment capital outlays in the future—such as rehabilitation and replacement of a bridge at a future date—into a present worth. When a constant sum of money is spent at the end of each year for n years, the total amount of the individual payments can be converted to a single present sum by using the uniform series present worth factor (USPWF). If the uniform series payment does not start at the beginning of the project analysis period, its present worth obtained by using the USPWF needs to be discounted to the base year of the program period by using the SPPWF. If expenditures would increase every year with a uniform arithmetic rate (G) (e.g., deck patching work), this uniform gradient series can be converted to the present by the gradient series present worth factor (GSPWF). Again, if the start of the gradient series does not match the beginning of the analysis period, its present worth needs to be discounted to the beginning of the base year of the analysis period. By using the above three interest formulas, future life-cycle cash flows can be discounted to the present worth, and the total present worth of an alternate option can be determined.

The equivalent uniform annual cost (EUAC) over the service life is computed by multiplying the capital recovery factor (CRF) by the total present worth of costs of a project. This factor converts a present amount based on some discount rate into a series of uniform annual payments for an n -year service life. The salvage value of a bridge can also be included, if desired. The salvage value can be converted to the present worth by using the SPPWF. Of course, the salvage value may be either a negative or a positive cost, depending upon the situation. In some cases, the salvage may be an income for the agency. In other cases, the agency may have to incur expenses to remove the salvage.

In general, bridges provide service to the traveling public in perpetuity; therefore, it is necessary to compute EUAC for perpetual service. In this case, m payments of an amount A are paid at n -year intervals beginning in year 0 (zero date). The amount A is the present worth of all costs incurred in one life cycle, and n is the service life. This cash-flow series becomes a geometric-power series that is convergent for i greater than 0. For a perpetual-series case, m is an infinite

number. This factor is the perpetual series present worth factor (PSPWF).

The formulas needed to compute the appropriate factors are summarized as follows:

$$SPPWF_{i,n} = \frac{1}{(1+i)^n} \quad (9)$$

$$USPWF_{i,n} = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (10)$$

$$GSPWF_{i,n} = \frac{1}{i(1+i)^n} \left[\frac{(1+i)^n - 1}{i} - n \right] \quad (11)$$

$$CRF_{i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

$$PSPWF_{i,n} = \frac{(1+i)^n}{(1+i)^n - 1} \quad (13)$$

where

$SPPWF_{i,n}$ = single-payment present worth factor at discount rate i (in decimals), for a single payment in year n ;

$USPWF_{i,n}$ = uniform series present worth factor at discount rate i , over a period of n years;

$GSPWF_{i,n}$ = gradient series present worth factor at discount rate i , over a period of n years;

$CRF_{i,n}$ = capital recovery factor at discount rate i , over an analysis period of n years; and

$PSPWF_{i,n}$ = perpetual series present worth factor at discount rate i , with n equal payment intervals.

Repeatability and Perpetuity

When a bridge is replaced or rehabilitated, it comes to the end of its service life and needs to be replaced again. It is impractical to try to determine precisely what type of bridge work would be needed in the distant future—say, 30 to 40 years ahead; therefore, it is a common practice in life-cycle cost analysis to assume a certain sequence of maintenance and rehabilitation work. After the first replacement, the same work sequence is assumed to repeat itself in perpetuity. Even if rehabilitation work is performed, the bridge is eventually replaced, and its life-cycle activity profile is repeated. In such a case, the rehabilitation cost is considered to be capitalized—that is, the present worth of rehabilitation-related expenditures is amortized in perpetuity. The EUAC in perpetuity is thus computed by multiplying the present worth of all costs by the interest rate in decimals. The use of perpetual service of a bridge is based on the fact that bridge sites are normally used for a long period of time (e.g., 50 years or more).

In choosing among alternative investment proposals, it is desirable in principle to make an analysis in units of constant

purchasing power. Usually, inflation is excluded from the prevailing discount rate. Cost inputs estimated at present prices are used for life-cycle cost analysis, and all monetary items are given in constant dollars.

In case the rate of inflation outgrows the rate of income in the program funding, the effect of inflation may affect investment decisions because the effective discount rate would be different. The interest rate under this situation can be expressed in the following interest formula (26):

$$i^* = \frac{(1+i)(1+q)}{(1+f)} \quad (14)$$

where

i^* = “true” discount rate that incorporates the effect of inflation,

i = prevailing discount rate,

q = rate of increase in funding, and

f = expected rate of inflation.

If the rate of increase in funding is expected to keep pace with the rate of inflation, the discount rate can be taken equal to the prevailing discount rate.

The equivalent uniform annual cost of an option in perpetuity may be expressed as follows:

$$EUAC_{OC} = \left[\begin{array}{l} I - E(SPPWF_{i,N}) \\ + G(GSPWF_{i,h+1}) \\ + F(SPPWF_{i,g-1}) \\ + A(USPWF_{i,n_1}) \\ + (A(USPWF)_{i,N}) \end{array} \right] (PSPWF_{i,N}) i \quad (15)$$

where

I = initial cost,

F = future rehabilitation cost,

A = annual maintenance cost,

G = gradient series of maintenance cost increase,

E = salvage value of existing structure,

g = time passed before the beginning of uniform gradient series of maintenance cost increase,

h = duration of uniform gradient series maintenance cost increase,

n_1 = time passed before the future rehabilitation,

N = service life of the option, and

i = discount rate.

Criteria for Project Selection

Commonly used criteria for selecting or ranking alternatives are net present value, equivalent uniform annual cost, incremental benefit-cost ratio, and incremental rate of return (27, 28). If the analysis is done correctly, these criteria should

lead to the same preferences of alternatives relative to each other. The higher the net present value, the lower the equivalent uniform annual cost, the higher the benefit-cost ratio, or the higher the incremental rate of return, the better ranked is the alternative. A number of references describe the application of these techniques (29, 30).

A minimum acceptable rate of return must be chosen to use these techniques. Theoretically, the chosen rate should be the rate of return that can be earned on projects or investments with a similar level of risk. The yield rate on an applicable type of long-term government bond, adjusted for inflation, can be used.

Conclusions

A vast body of literature exists on life-cycle cost analysis. There are several methods of incorporating a life-cycle cost approach in making bridge-related decisions. Traditional life-cycle cost-analysis methodology has a framework that

aims to produce both “deterministic” and “static” schedules of treatment. A state increment method has been developed to model uncertainty and to allow scheduling of treatments dynamically (31).

Although life-cycle cost analysis has been in use in transportation for several decades, there is still disagreement as to the appropriate cost items to be included, for example, delay costs, vehicle operating costs, fuel costs, and quality-related costs (2). Furthermore, external costs such as environmental costs and other nonagency costs are generally not included. It is difficult to anticipate fuel costs, deterioration rates, expected life, salvage value, changes in traffic patterns, and environmental effects. It would be unrealistic to expect that the current knowledge would be applicable toward the end of the life-cycle period (2, 16). However, it must be recognized that once the framework for a life-cycle cost analysis is developed, the specific cost and other input parameters must be continuously updated as more data are available. In that sense, life-cycle cost analysis is a dynamic process.

CHAPTER 2

FINDINGS

STATE-OF-THE-ART STUDY SUMMARY

BLCCA Needs

Currently, most states do not use life-cycle cost analysis. Those states that do use qualitative rather than quantitative analysis methods. Analysis is most commonly applied to the selection of the overall bridge design, timing of bridge repair, and network-level bridge management. There is a noticeable shift in the planned use of life-cycle cost analysis to quantitative analysis from qualitative analysis, in particular for overall bridge design, timing of bridge repair, and network-level bridge management. To support this shift to quantitative analysis, certain elements are needed; these elements have been identified and are listed as follows in order of priority:

1. Develop a uniformly accepted methodology,
2. Obtain access to reliable cost and service-life data,
3. Rectify the lack of user-friendly computer software,
4. Train personnel, and
5. Resolve the conflict with “least first cost” method of contract administration.

To satisfy these needs, the following activities have been identified and are listed in order of preference:

1. Obtain better data,
2. Get commitment from senior management,
3. Develop an accepted methodology,
4. Compare predictive life-cycle costs with actual values,
5. Develop supporting user-friendly software tools, and
6. Improve research and training.

International BLCCA Practices

Overseas it was found that life-cycle cost analysis is often discussed under the term “whole life costing” but is not widely used. British, French, and Danish practices include apparently routine applications of benefit-cost analysis for major investments, but none of the respondents reported the application of life-cycle cost analysis. Japanese adoption of life-cycle cost-analysis principles is reported to be less advanced; in Australian, it is less so still.

AVAILABLE COST MODELS

BLCCA uses two types of models in the life-cycle cost analysis: primary and cost. A primary model is used to forecast the physical condition of a bridge; a cost model is used to predict the actual expenses expected during the life of the structure. This chapter contains a basic description of and a guide on how to define and modify all the model types used in BLCCA. The actual model calculation methodology is shown on *CRP-CD-26* (see Chapter 6 of the User’s Manual).

Primary Models

Primary models describe external bridge conditions. At installation, the BLCCA software contains two models for each of the three primary conditions:

1. For ADT, the Generic Model and the NBI Growth Model;
2. For the Condition Index, the Generic Model and the Markov Chain Model; and
3. For load capacity, the Generic Model and the BRIDGIT Model.

Cost Models

Cost models describe the expenses anticipated to occur during the length of the analysis. There are two basic categories of these costs:

- **During-event costs:** costs that occur during events, such as traffic control, lane rentals, detours, and other costs associated with the event. These costs are in addition to the repair costs incurred by the agency and include the user costs and vulnerability costs.
- **After-event costs:** costs expected to occur because of normal operation of the structure. These costs are defined initially in the scenario definition and can be redefined after each event. The three main categories are the user costs, vulnerability costs, and distributed agency costs.

The BLCCA program allows the user to select different model types for different problem scenarios. For consistency

within the scenario, however, all alternatives must have only one globally selected model type for each of the primary conditions and costs. Available models are outlined in detail on *CRP-CD-26* (see Chapter 5 of the User's Manual). Currently, there is a lack of good models for use in life-cycle costing.

CLOSED-FORM SOLUTIONS

This section introduces the details of the calculation methodology used to develop total life-cycle costs in the BLCCA software. It deals with the following issues:

- Defining uncertainty in the BLCCA software;
- Dealing with value uncertainty (e.g., addition and multiplication of costs);
- Dealing with timing uncertainty (e.g., simplification procedure, related events, discounting, etc.);
- Dealing with after-effect costs (e.g., manipulation of curves with uncertain time, value, and boundaries); and
- Generating probability distribution curves for the final present values.

Historically, analyses with uncertainty have relied on Monte Carlo simulation. Such analyses, however, have their short-

comings: the need to sample data for all to be combined cost curves and the calculation of all the resulting combinations. This process leads to a large number of calculations and possibly significant errors, if the cost sampling is inappropriate. It is also difficult to obtain smooth curves, and curve shapes are dependent on the sampling interval. To avoid the shortcomings of Monte Carlo simulation, BLCCA restricts the representation of uncertainty to smooth continuous curves that make it possible to formulate closed-form solutions. This process has many advantages:

- Significantly faster calculations;
- Smooth curve shape that is independent of the sampling interval;
- Unlimited number of uncertainties;
- Final solution that can be fully expressed by mean (x), standard deviation (σ), skew (q), and kurtosis (k); and
- Separate solutions for each of the three cost types—agency costs, user costs, and vulnerability costs.

Three types of uncertainty representation have been incorporated in the BLCCA: smooth curve, general curve, and probability table. The treatment of uncertainty is explained in detail on *CRP-CD-26* (see Chapter 6 of the User's Manual).

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

GENERAL RECOMMENDATIONS

Application of life-cycle costing to bridges is not a straightforward procedure. The professional performing the analysis must have a working knowledge of economic principles; be acquainted with bridge repair techniques, costs, and effectiveness; have access to a good costing database; know the most likely alternatives to be pursued; and have a good knowledge of how a bridge behaves over the long term. No computer package can contain all of the subtle variations and knowledge that an expert relies on. It is therefore paramount that professionals who are well trained and skilled in this area of expertise undertake life-cycle costing. Poor decisions can result if the user applies the wrong assumptions. The BLCCA software is a complex tool—it must be used with care.

APPLICATIONS

Assessment of New Bridges

One of the main uses of life-cycle costing is in the determination of the most effective new bridge configuration. The methodologies outlined in this report and in the provided software can be used (1) to assess the trade-offs between initial costs and long-term maintenance and (2) to determine whether it is cost effective to prebuild to a future standard or to widen and strengthen in the future. The software contains sample analyses that deal with these issues.

Decision Points

In the context of life-cycle costing, a decision point is a point in the future at which the analyst can choose two or more courses of action—for example, there may be a need to accommodate heavier trucks on a bridge in the future. At that point in time, the analyst may need to evaluate the likelihood of the strengthening actually being required at that time and, if it is required, to decide whether to strengthen the structure or post the structure for reduced loading. At this point in time, the alternative is splitting into subalternatives that each follow independent paths into the future. These subalternatives

can then be recombined by assigning each one a probability of occurrence and blending the results together. The software contains a sample analysis to illustrate this point.

Assessment of Uncertainty

One of the key components of the BLCCA methodology is the incorporation of uncertainty into the analysis. Although this makes the analysis much more complex, it results in a more real-life solution and allows the user to evaluate his or her confidence in whether he or she has chosen the correct solution. Uncertainty allows the user to define the variability both in the cost of repairs and in the timing of those repairs. This is dealt with in detail on *CRP-CD-26* (see Chapter 6 of the User's Manual) and is also examined in several of the sample analyses contained in the software.

Assessment of New Materials

One of the primary uses of the life-cycle cost-analysis methodology can be in the assessment of new materials or components. When new materials or components are first used, they have a limited track record and no history on how they perform over the long term. This lack of historical observation can be modeled in the software by applying a high level of uncertainty to the performance of the new material over time. For example, when using a new type of deck overlay that shows promise and appears to be cheaper, it would be prudent to apply a high level of uncertainty to the cost of the overlay and also to the amount of time until the next overlay is required. The user can then examine the results of the analysis and decide whether the high degree of uncertainty is outweighed by the potential short- and long-term cost savings.

REPORTS

Reports are detailed on *CRP-CD-26* (see Chapters 7 and 8 of the User's Manual). Analysis reports provide the basis by which the alternatives can be quantified and compared. Under this heading, the BLCCA offers two types of analysis:

1. Distributions and comparisons and
2. Sensitivity.

The results of the BLCCA are strongly influenced by several variables:

1. Discount rate,
2. Event timing, and
3. Event value.

To address the significance of the choices made throughout the data input, the BLCCA allows the user to run sensitivity analysis on these three parameters. All the relationships and uncertainties defined during the data input are accounted for.

Figure 1 shows the organization of the sensitivity analysis process. Most reports, other than sensitivity reports, are calculation intensive and may take several minutes to run.

Discount-Rate Report

The discount-rate report displays the results of a discount-rate sensitivity analysis for the specified bridge, scenario, and alternative. When this report is selected, a form appears that allows the user to specify the discount-rate range for which the sensitivity analysis is to be performed. Enter the discount-rate range and select the Calculate button to carry out the analysis. The graphic report appears once the calculations are complete.

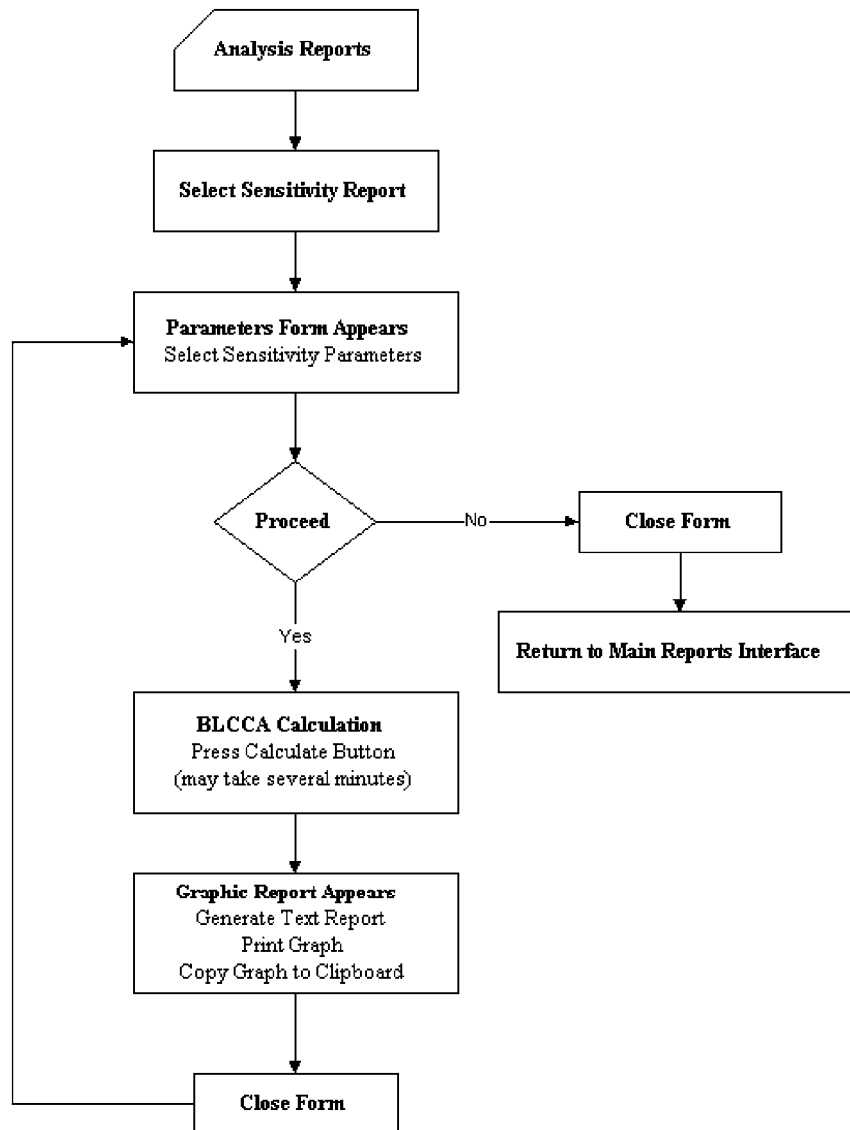


Figure 1. Organization of the sensitivity analysis process.

Event-Timing Report

The event-timing report displays the results of an event-timing sensitivity analysis for the specified bridge, scenario, and alternative. When this report is selected, a form appears that allows the user to select the event in question and to specify the range in years for which the sensitivity analysis is to be performed. The graphic report appears once the calculations are complete (see Figure 2).

Event-Cost Report

The event-cost report displays the results of an event cost sensitivity analysis for the current bridge, scenario, and alternative. When this report is selected, a form appears that allows the user to select the event in question and to specify the range in % cost for which the sensitivity analysis is to be performed. See Figure 3.

Distributions and Comparison Report

When this option is selected, the user is notified that calculations for the related reports are about to begin. These calculations can take a few minutes. After the calculations are complete, the form for probability distributions and comparisons appears. This form has a pull-down menu that allows the user to access all probability distribution and comparison reports.

Process Report

Figure 4 shows the steps required to complete the distribution and comparisons analysis.

Probabilistic Distribution Report

The probabilistic distribution report shows the probability distributions for present values for the specified combination of alternatives. When this report is selected, the BLCCA carries out operations to devolve the results into plottable curves. These curves are then smoothed so that alternatives can be combined. This process can take several minutes. When these calculations are complete, the alternatives combination form appears. To specify a combination of alternatives, each alternative is given a weight. The total weighting of all alternatives must equal 1.0. The BLCCA combines the alternatives as specified and produces the graphic report showing the probability distribution. See Figure 5.

Comparisons Report

The comparisons report shows the probability distributions for present values for the specified combination of alternatives and compares them. When this report is selected, the BLCCA carries out operations to devolve the results into plot-

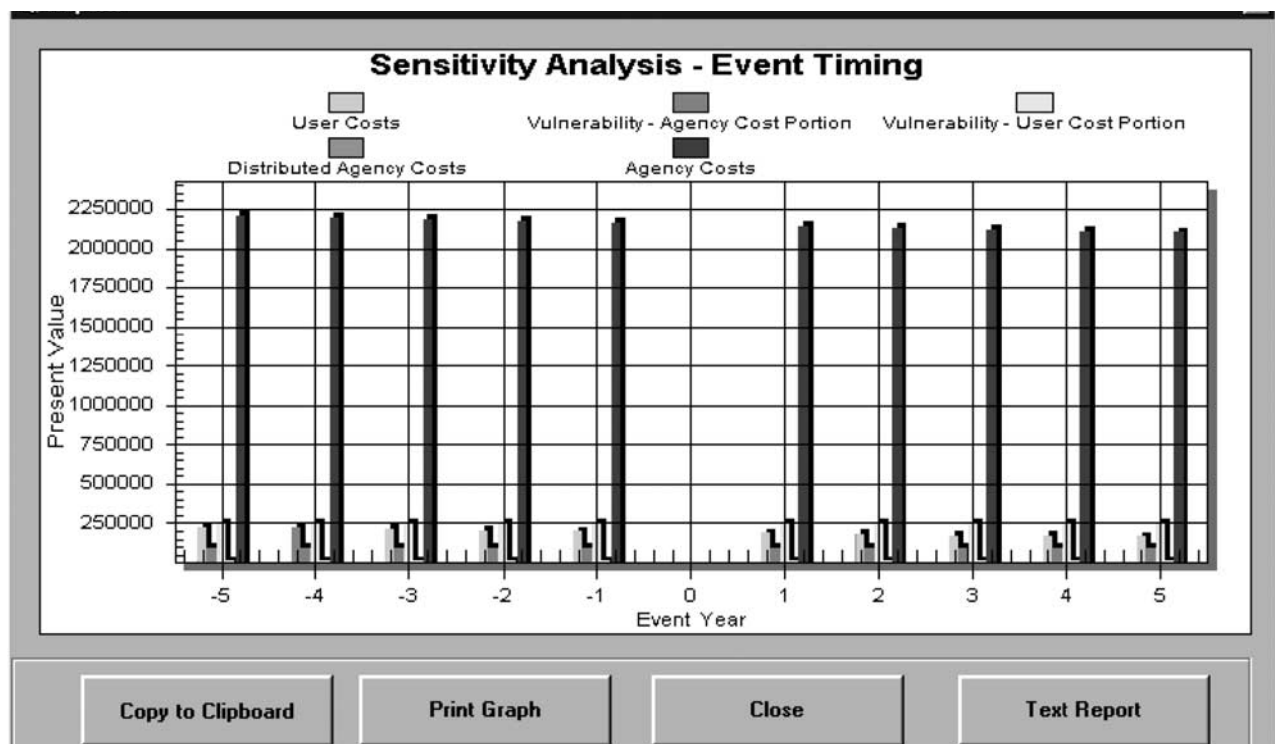


Figure 2. Graphics report for event-timing sensitivity analysis.

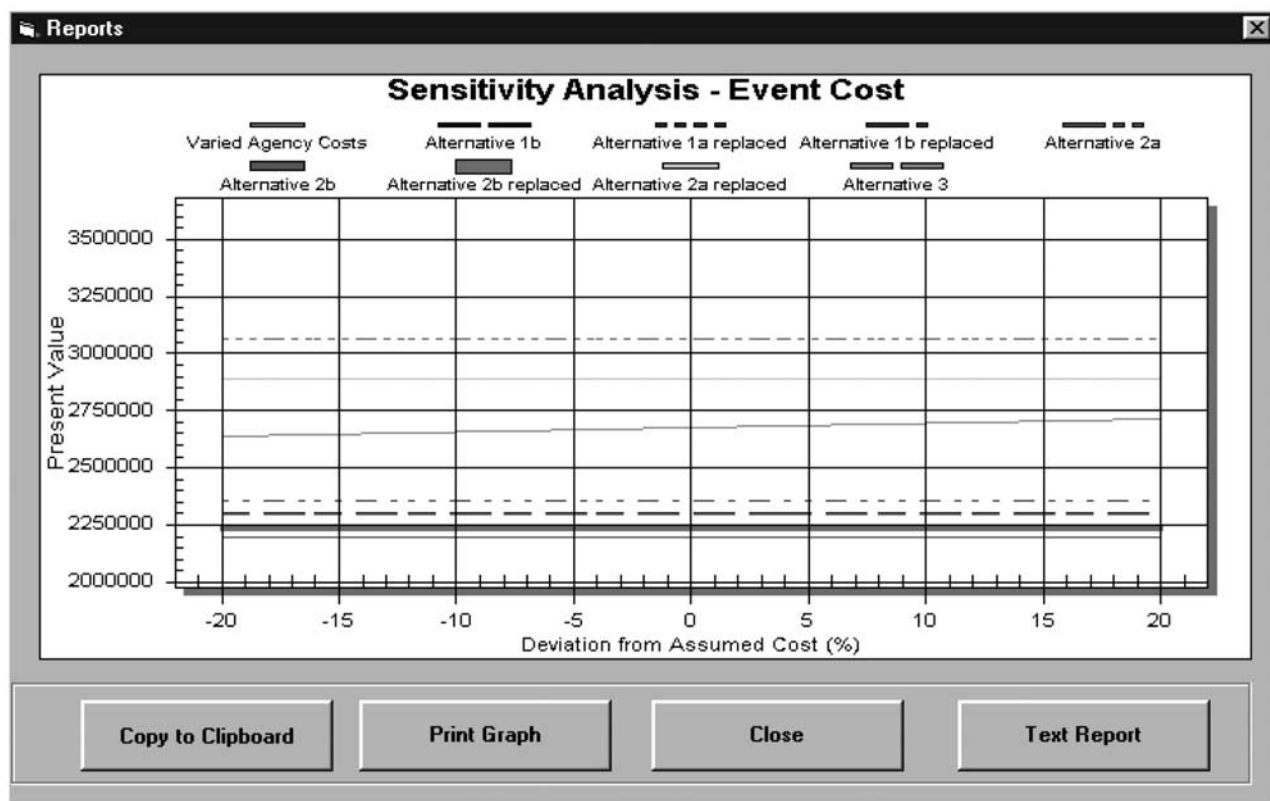


Figure 3. Graphics report for event-cost sensitivity analysis.

table curves. These curves are then smoothed so that alternatives can be combined. This process can take several minutes. When these calculations are complete, the alternatives combination form appears. To specify up to five combinations of alternatives, each alternative is given a weight. The total weighting of all alternatives for a particular combination must equal 1.0. The BLCCA combines the alternatives as specified

and produces the graphics report showing the probability distribution for each combination and a final graph overlaying all of the combinations (see Figure 6).

When you click on the Text Report button, the BLCCA calculates the probability of each combination being the least present value and produces the following comparison text report (see Figure 7).

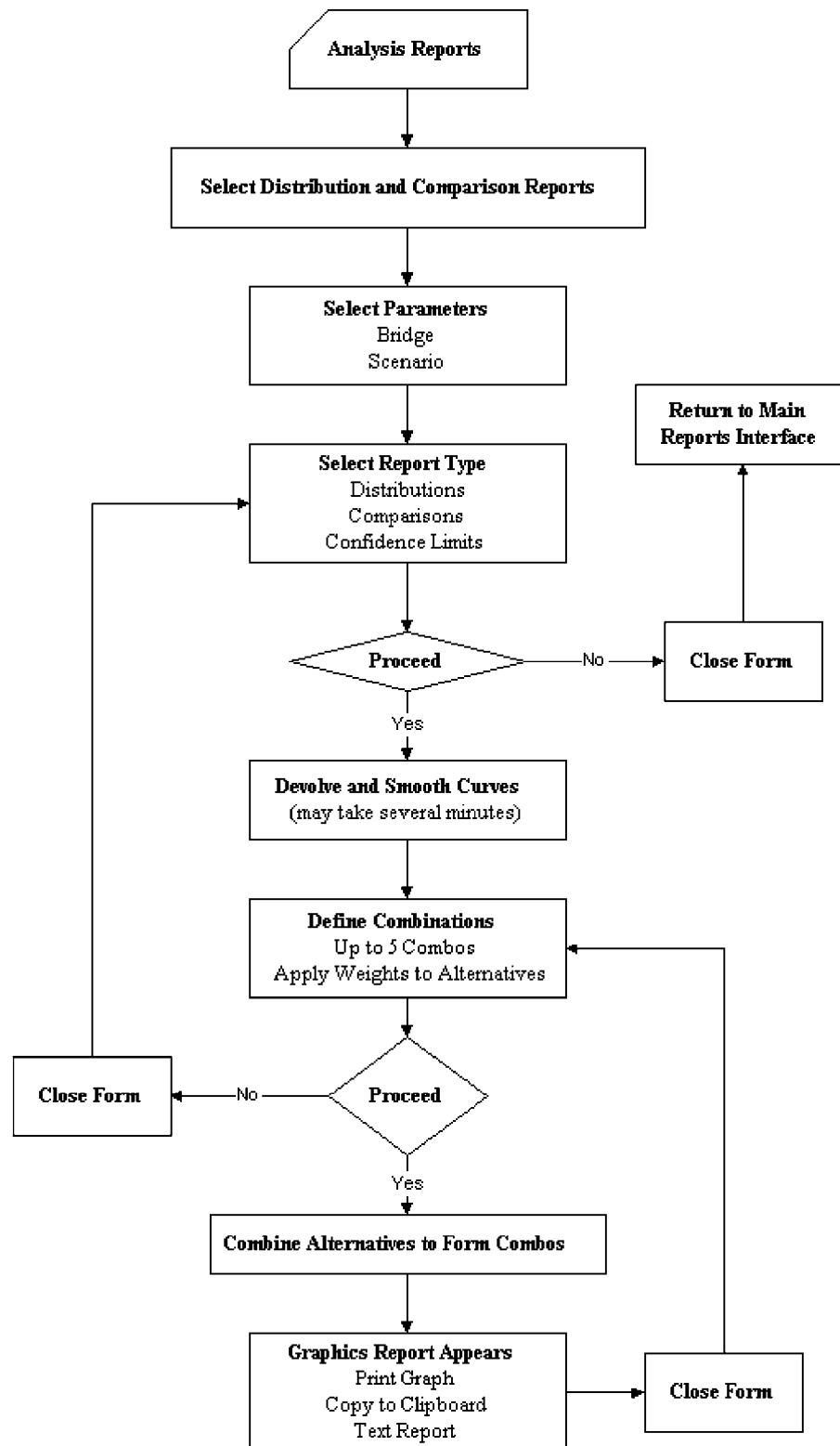


Figure 4. Steps for the distribution and comparison analysis.

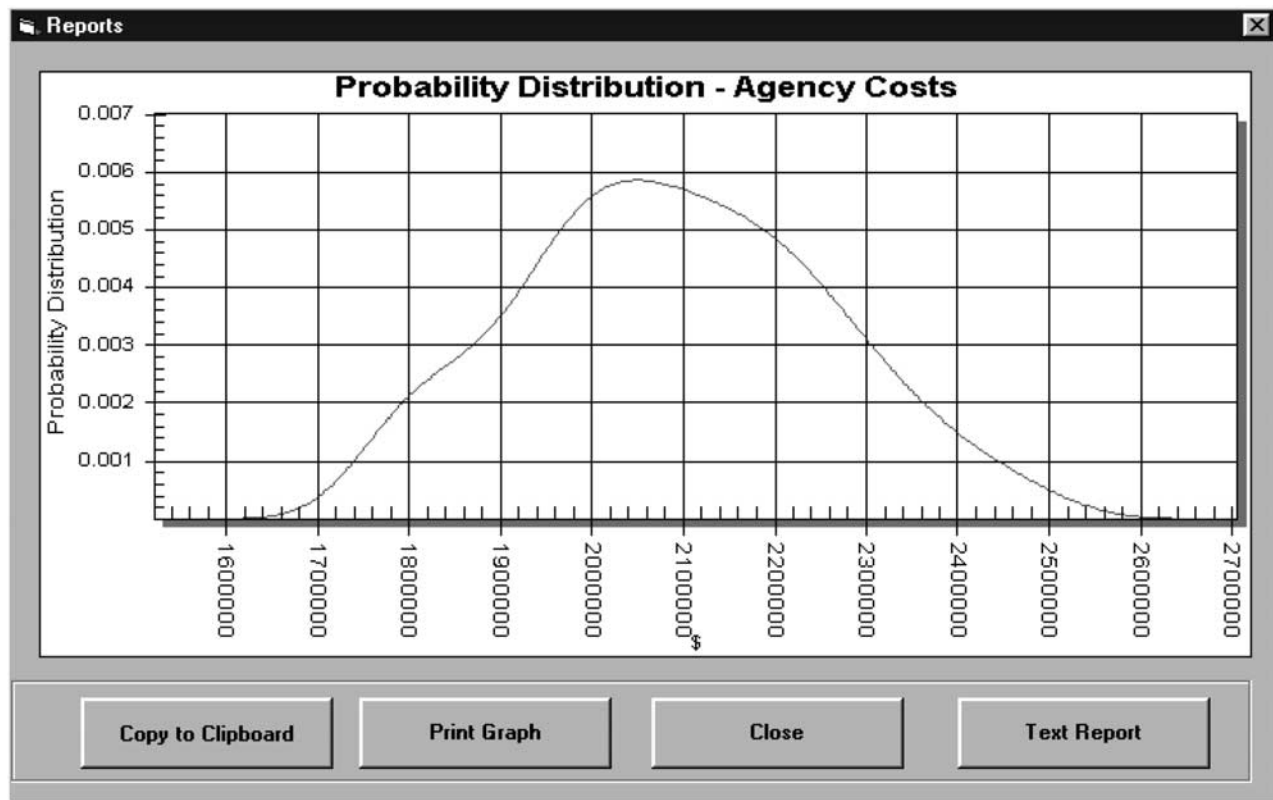


Figure 5. Graphics report for a probabilistic distribution.

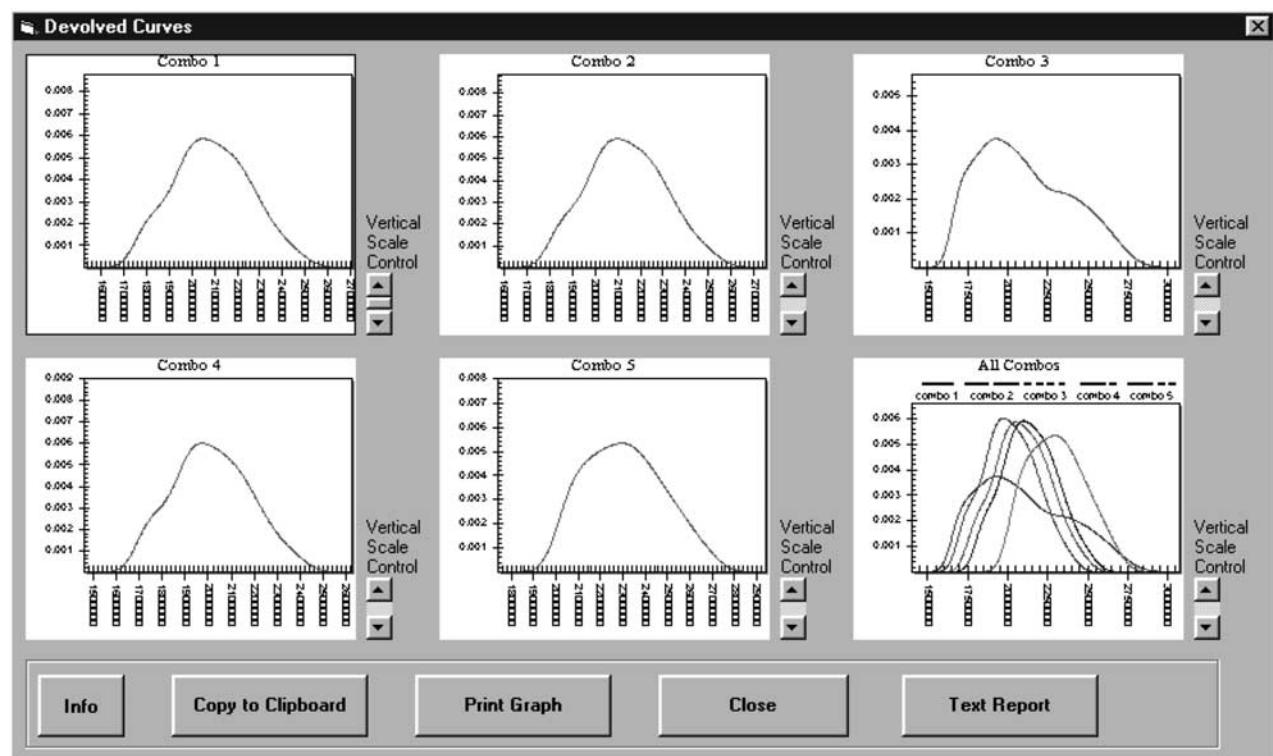


Figure 6. Graphics report for a comparison of probability distribution combinations.

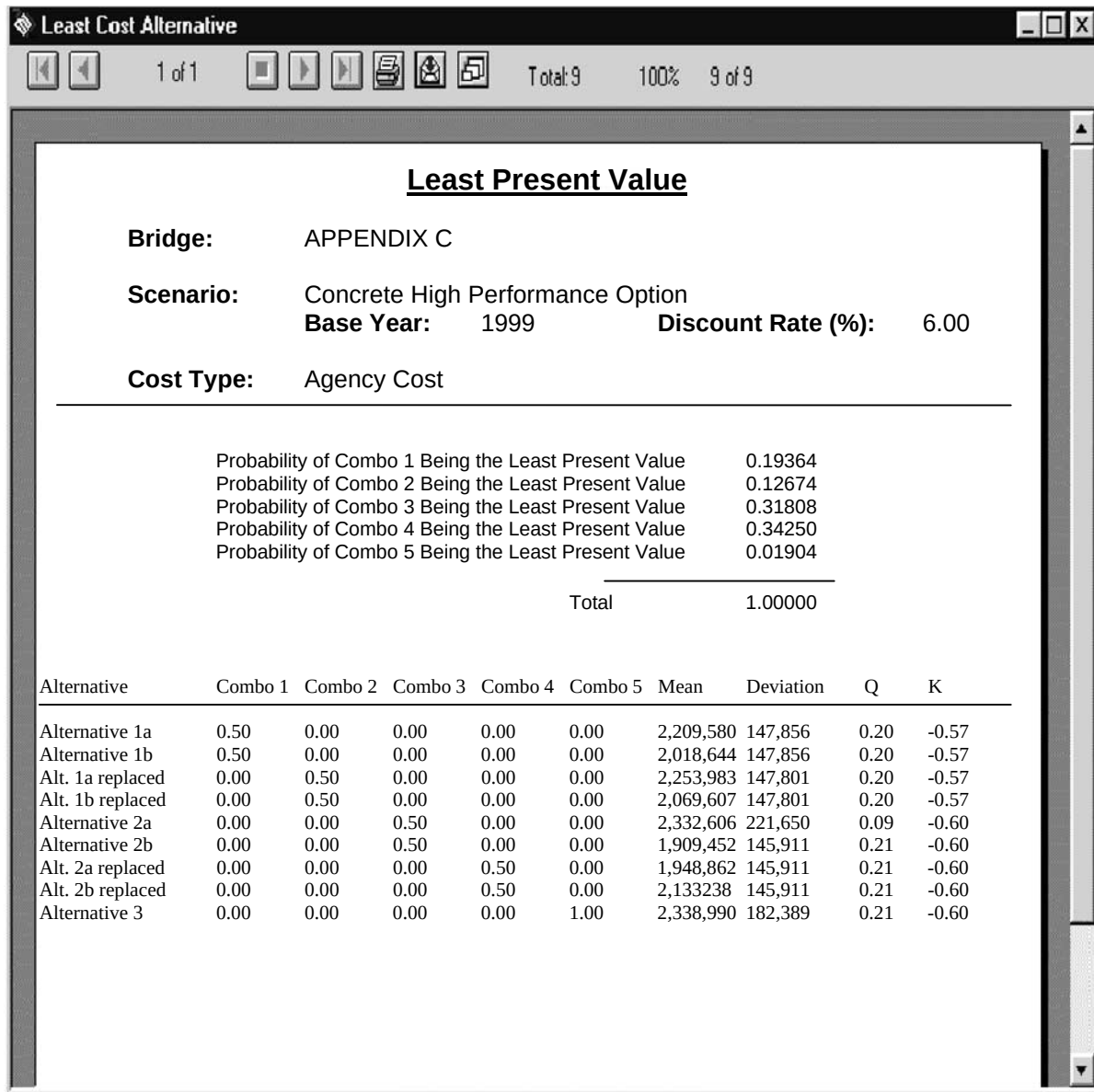


Figure 7. Comparison text report of least present value.

CHAPTER 4

CONCLUSIONS, SUGGESTED RESEARCH, AND SUGGESTED IMPLEMENTATION

CONCLUSIONS

NCHRP Project 12-43 has identified various modular elements required in a model BLCCA methodology and has developed some of the engineering concepts necessary to adopt such a methodology. The project has also included the development of an IBM PC-based computer program. Subsequent testing and evaluation of the software identified a number of deficiencies in the system that needed to be corrected before the system could be accepted for use by state agencies.

A great deal of research work is required in the areas of vulnerability, work-zone user costs, load and condition deterioration models, and prediction of future needs. Much research in this area is ongoing. As a result, there is a need to periodically review this information and to evaluate the possibility of incorporating applicable results into the BLCCA program.

The initial system was constructed using only models that are currently available. There is a need to develop simple interim models for vulnerability and other costs until the ongoing research results in usable models. There is also a need for additional computational aids.

Transportation officials consider life-cycle cost analysis an important technique for assisting with investment decisions. Several recent legislative actions recognize the potential benefits of life-cycle cost analysis and call for consideration of such analyses for infrastructure investments, including investments in highway bridge programs. The current research has provided bridge engineering professionals with a methodology for the determination of life-cycle costs, but the software cannot be considered complete.

SUGGESTED RESEARCH

A great deal of research is still required in the area of life-cycle costing. The methodologies are now well established, but there is a lack of background data. There is a need to establish guidelines for repair costs and the expected life span of various repairs under specific environmental conditions. Distributions of costs are also required to establish the uncertainty in repair costs. Vulnerability to earthquakes and scour needs to be quantified. Currently, only an instinctual feel for the costs is available. Costing models need to be refined to include more specific bridge parameters. The current software

relies heavily on the use of generic models in which the real calculations are done off system and the summary data is brought into the software as a curve definition.

SUGGESTED IMPLEMENTATION

For this project to succeed, it is essential to move the results of this research into practice. The following draft implementation plan outlines the issues and steps necessary to develop the formal implementation plan.

Issues

The implementation plan must address the following four issues.

1. *Do state DOTs have adequate resources to implement the BLCCA?*

Although the BLCCA is designed to be user-friendly and efficient, there is a considerable amount of effort required to use it properly and to collect project-specific data. This proficient use of software may require staff dedicated to conducting life-cycle costing as their primary job description.

2. *Do state DOTs have access to reliable and useful cost data to obtain accurate and meaningful results?*

The results of the questionnaire made it very clear that virtually all states consider the accuracy and availability of cost data and other information required to run the BLCCA to be inadequate. Traffic data is an exception because it is already collected for other purposes. Data quality needs to be improved.

3. *Can industry be brought onboard?*

Effective use of life-cycle costing requires that many state practices be modified to accommodate the concepts of whole life costing versus initial cost and to consider user and risk costs. There may be resistance to these types of changes unless the benefits are clearly identified and there is support from senior management.

4. *How will the BLCCA integrate with other efforts and with AASHTOWare products?*

There is obviously a significant overlap in both concepts and data requirements between the BLCCA and

bridge management systems. It is therefore important that both systems use common data consistently and unambiguously. Also, many modern software systems are moving into the client-server paradigm in which there is a central data source. This sharing of data should be accommodated in a straightforward manner.

Steps

The following steps are suggested for the implementation.

AASHTO Support

Contractor. The role of the contractor is to develop the BLCCA according to AASHTO's requirements to facilitate the eventual transfer of the BLCCA into AASHTOWare. The BLCCA should be capable of integrating with other AASHTO-Ware products to the extent practical.

AASHTO. AASHTOWare is viewed by many as the clearinghouse for products that can be applied countrywide, generally at the state level. As such, AASHTOWare carries a great deal of credibility with state DOTs and can effectively market developed products for use by DOTs. The research team feels, therefore, that it is essential to pursue acceptance of the product by AASHTOWare so that there is a very well-defined, long-term marketing and support mechanism in place as soon as the software is released.

Other. AASHTOWare may require sponsorship by one or several states for the software to be considered. Forward-looking candidate states should be identified.

Conferences and Papers

Contractor. At appropriate points during this study, the principal investigator presented the research findings and recommendations at relevant conferences and meetings (including to the AASHTO Highway Subcommittee on Bridges and Structures and at the TRB Annual Meeting).

Other. Presentations by users carry much more credibility than do presentations by the contractor in that the users are end-users of the developed software and guidelines. A well-respected state DOT or consultant who is considered a leader in life-cycle cost analysis or in a related field should be encouraged to apply the software to real-life use.

Formal Training Courses

Contractor. The contractor must be considered the expert in the developed methodologies and software and, therefore,

has played a key role in the development of training materials that will promote the use of and understanding of the concepts. This should be expanded through a federally supported formal training strategy that, by its nature, will ensure widespread acceptance.

FHWA. The National Highway Institute (NHI) should be contacted to see how such a training course should be funded and structured. It may be appropriate to include training on life-cycle costing and value engineering as part of NHI's bridge engineering training course.

Other. AASHTOWare may also sponsor formal training if the BLCCA moves into its domain.

System Support and Marketing

Contractor. The contractor must be considered the expert in the developed methodologies and software and, therefore, must play a key role in the system maintenance and support. If this support is not provided through AASHTOWare, then another source of support must be found. Software products must evolve over time.

AASHTO. AASHTOWare has a well-established software support and marketing mechanism—it would be wise to make use of that infrastructure.

Other. The formation of a BLCCA users group would enable end-users to share knowledge on the use of the BLCCA, provide feedback, and propose future enhancements. Such groups have been very successful—for example, the Bridge Rating Analysis of Structural Systems (the BRASS) Users Group.

Data Clearinghouse

AASHTO. Currently, at AASHTO there is a movement to create data clearinghouses that enable state DOTs to share experiences with various standards, products, and product experiences. Although a data clearinghouse was not selected as a high priority by the questionnaire respondents, it might be beneficial to establish a tracking system for new structures designed and costed out using the BLCCA so that long-term tracking of the structures' performances and fine tuning of BLCCA can occur.

Contractor. To encourage widespread participation, the contractor could include within the BLCCA routines that automatically upload reference cost data; the data would be provided in the future by the data clearinghouse.

Other. In order for the data clearinghouse to accumulate data, it would be necessary for participating transportation agencies to submit data to the clearinghouse periodically.

and, perhaps, to follow up with future updates on individual projects.

Trial Use by a State DOT

State DOTs. The design of any new tool and associated documentation is based on the involved parties' perceptions of how the tool will actually be applied in day-to-day practice. Often, until the tool sees extensive use in practice, its shortcomings and weaknesses are not evident. The only way

to ensure that the tool is truly useful and that its implementation is straightforward is to use it for an extended period of time. The end result of this trial use would be a formal report on the state DOTs' findings with respect to the software's usefulness, shortcomings, and weaknesses.

Contractor. For a trial installation, the contractor would need to educate the participating state DOT in life-cycle concepts, in how the BLCCA actually applies the concepts, and as to what the consequences would be if the state DOT's method of operation were to change.

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APPENDIXES

Appendix C to this report is the Guidance Manual, which is published herein as Part II. Appendixes A, B, D, and E of this report are included on *CRP-CD-26*. The appendixes, which are unedited, are as follows:

- Appendix A: State of the Art,
 - Appendix B: Questionnaire,
 - Appendix D: User's Manual, and
 - Appendix E: BLCCA Software.
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