PART II

GUIDANCE MANUAL

Part II of *NCHRP Report 483* (the Guidance Manual) is essentially the original text as submitted by the research agency and has not been edited by TRB. Page numbering for Part II will restart with page 1.

The Guidance Manual is also installed with the software on *CRP-CD-26* and can be accessed from the software as Help files. To view these files when not in the software, double click on Helpfile.hlp or Guidance.hlp. This will load the files into the standard Microsoft help system format. The files are also available as Word 97 documents.

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Foreword

This guidance manual describes principles and practices for analyzing the life-cycle costs of highway bridges, as a tool to assist transportation-agency personnel and others concerned with making decisions about planning, design, operation, maintenance, and possibly retirement or replacement of these structures. The manual, written as an independent primer within the context of current U.S. highway practice and policy, will be useful to anyone seeking background understanding of the principles of engineering economics applied to bridges and how economic uncertainty may be characterized and accommodated in bridge-management decision making.

This manual was written as part of NCHRP Project 12-43, a study to develop a comprehensive methodology for life-cycle cost analysis of bridges implemented as a software package for PC-style computers. The Bridge Life-Cycle Cost Analysis (BLCCA) package is designed for application to individual bridges. This bridge-level focus distinguishes the BLCCA from other currently available bridge-management tools such as PONTIS and BRIDGIT, which were developed under FHWA and NCHRP projects respectively. National Engineering Technology Corporation (NET), of Arlington Heights, IL, conducted research on current life-cycle cost analysis practices, availability and quality of data to support bridge life-cycle cost estimation, and computer-based facilities-management tools usable within government transportation agencies. The results of this work are presented in a final report. A User's Guide that accompanies the BLCCA software presumes that users are familiar with the principles and practices described in this guidance manual.

Chapter 1 Introduction and Summary

Background and Motivation

Life-cycle cost analysis (LCCA) has received increasing attention as a tool to assist transportation agencies in making investment decisions as well as in managing assets (PIARC 1991, FHWA 1994). Bridges compose a significant class of assets for which these agencies are responsible.

Transportation agencies using federal funds often must conduct LCCA to justify their planning and design decisions, because the federal agencies providing funds must do so. Sections 1024 and 1025 of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) specified that consideration should be given to life-cycle costs in the design and engineering of bridges, tunnels, and pavements. The National Highway System Designation Act of 1995 requires that states conduct an LCCA for each proposed National Highway System (NHS) project segment costing $25 million or more. Federal Executive Order 12893 (*Principles* 1994), signed by President Clinton in January 1994, requires that all federal agencies use "systematic analysis of expected benefits and costs... appropriately discounted over the full life cycle of each project" in making major infrastructure investment decisions; the Federal Highway Administration (FHWA) and other executive-branch agencies have issued more detailed guidance for implementing this Executive Order and been more explicit in adopting the terms of LCCA in describing their requirements, ("Life-Cycle" 1996).

The Transportation Equity Act for the Twenty-First Century, TEA-21, authorizes transportation funding for a six year period (1998 – 2003). In a broad sense TEA-21 has relaxed the requirements for life-cycle analysis but 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 where the cost of the analysis is warranted. The FHWA does require the consideration of life-cycle analysis in a broad sense for Congressionally mandated studies, generally highway corridors that contain bridges.

Despite such requirements, LCCA is not universally used in U. S. transportation agencies. There is currently no commonly accepted methodology for LCCA, particularly as it might be applied to bridge management. In an attempt to standardize the terminology used in this Guidance Manual, terms requiring definition are shown in italics and their definitions presented in the glossary, Appendix A. In drafting this guidance manual, the authors have sought to highlight aspects of LCCA practice that may vary from one jurisdiction to another or which entail elements of controversy. Users of LCCA must recognize the technique's limitations as well as its advantages as a decision-making tool.

In particular, this guidance manual recommends that explicit recognition must be given to the uncertainties of LCCA for bridges and other complex engineered systems. The analyses depend on estimates of costs and future behavior of structures and their users, and of the likelihood of storms and other future events. While the basic principles and computational procedures used in LCCA are relatively few and often straightforward in their presentation, the practice of LCCA under uncertainty quickly becomes complicated. This guidance manual presumes the reader will undertake bridge life-cycle analysis with computer-based computational tools.

Life-cycle Cost Analysis (LCCA) Defined

The challenge facing bridge managers–and the purpose of LCCA–is to specify an economically efficient set of actions and their timing during the bridge's life cycle to achieve the 50- to 100-year service life that many bridge-management professionals feel is an appropriate target for this major public investment. It also assists decision makers in comparing alternative strategies for managing a bridge.

The cost to an agency for a bridge is never a one-time expenditure. A bridge represents a long-term, multi-year investment. Following its planning, design, and construction, a bridge requires periodic maintenance and possibly repair or rehabilitation actions to ensure its continued function and safety. Responsible managers may eventually decide that a bridge must be replaced, effectively designating the end of its useful life. This end typically comes decades and sometimes even centuries after the initial construction was completed.

In simplest terms, the time between a bridge's construction and its replacement or removal from service is its *service life*. The sequence of *actions* and *events* and their *outcomes*–e.g., construction, usage, aging, damage, repair, renewal–that lead to the end of the service life and the condition of the bridge during its life compose the *life cycle*. Responsible managers must make decisions about what *management strategy* to follow, what materials and designs to use, what repairs to make and when they should be made, based on their expectations about what the subsequent costs and outcomes will be. LCCA is a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge will provide the services for which it was intended.

LCCA is essentially a technique for considering the economic efficiency of expenditures. Given a certain set of requirements that a bridge must meet–e.g., traffic volumes to be carried, maximum vehicle loads, geotechnical and climate conditions–the lowest-cost set of actions meeting those requirements is preferable to other sets of actions. The bridge resulting from those actions represents a more efficient use of scarce resources–i.e., public funds and time–than other alternatives. It is this consideration of all resources used to produce the bridge's services that distinguishes LCCA from discounted cash-flow analysis, a computationally similar technique used by financial analysts to compare streams of revenue and expenditure. The principle and computational practices of discounting to compare costs incurred at different times are discussed in Chapter 2.

In this guidance manual, resource "flows" of all types are termed "costs." In LCCA computations, revenue such as toll receipts, savings such as reduced maintenance spending enabled by more durable materials, and benefits such as users' time saved by avoiding lane closures are simply costs with negative values.

Section 303 of the National Highway System Designation Act defines LCCA as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment." The Act defines a usable project segment as a portion of the highway that could be opened to traffic independent of some larger project of which the segment is a part.

While LCCA has been known and used in management decision making since the 19th century, the earliest full articulation of the method in the highway field seems to be the computer-based models developed initially for the World Bank in the 1960s (the Highway Cost Model - HCM). This model considered both agency and user costs. This work is the basis for much of the thinking about pavement-management and now bridge-management programs in the United States.

When indirect user costs such as those relating to ride quality are considered, the use of LCCA is actually an expansion of the method's basic principles to encompass aspects of another decision-making tool, benefit-cost analysis (BCA). While LCCA is largely a consideration of current and future costs, BCA aims more broadly to assess a range of benefits and costs that go beyond the immediate reasons for undertaking a project. For example, BCA methods have been developed and widely used in dam-building assessments, where credit is taken, for example, of the recreational benefits of a lake formed by a dam that is proposed for purposes of irrigating farmland or generating electricity. A key metric of BCA, the benefit-cost ratio, requires that careful distinctions be made between what are "benefits" and what are "costs"; cost savings are often ambiguously treated. The "net present value" metric used in LCCA simply adds all "costs," positive and negative, to reach a conclusion.

Because of this ambiguity of the benefit-cost ratio, some analysts recommend that this metric should not be used; the net present value of benefits and costs, they say, is the only completely reliable indicator of efficiency. The internal rate of return, another widely used LCCA metric, suffers from some ambiguities as well: for certain cash-flow patterns, the calculations will yield multiple internal rates of return.

This guidance manual seeks to present a limited perspective on LCCA. Costs considered in the LCCA should be restricted to those that can be considered as representing economic resources invested by highway agencies, road users, and the tax-paying public (i.e., the highway bridge's owners) for the purpose of obtaining the services of a bridge. The broad range of benefits that a highway and its bridges may bring to a region should be considered in LCCA only to the extent that a particular management strategy will appropriate some portion of those benefits. The principal aim of LCCA is to calculate the Net Present Value, but at the same time any cost - whether agency, user or vulnerability - which distinguishes one alternative from another should be addressed. If the exercise is simply to determine the best new structure to twin an existing facility then only that bridge need be considered in the analysis. If the exercise is to determine whether a bridge should be strengthened versus detouring traffic onto adjacent roadways, then the effects on those adjacent facilities should be examined in order to arrive at a proper conclusions.

Uses of Bridge Life-Cycle Cost Analysis (BLCCA) in Bridge Management

"Bridge management" refers to the various activities of planning, design, operation, and maintenance that determine how a bridge is configured throughout its service life. The underlying motivation for using LCCA in bridge management is an understanding that tradeoffs are possible, e.g., spending to install more durable coatings of steel elements during initial construction in order to reduce the anticipated frequency of future repainting, or adopting a somewhat more costly design detail to make future maintenance easier and less costly.

Many of the applications of LCCA deal with such design issues. However, the principles apply equally well to questions posed by existing bridges, e.g., when is the best time to schedule a deck overlay, or how much of a premium might reasonably be paid as an incentive to a contractor for rapid completion of that overlay's installation?

LCCA presumes that a particular facility, e.g., a bridge, is warranted and will be provided by some means. The technique also includes the idea that there are minimally acceptable conditions that will trigger, if they are not met, corrective action, e.g., repainting, deck replacement. For these reasons, LCCA is useful for comparing alternative management strategies; the method cannot be used to justify construction of a new bridge where none exists. This latter problem requires application of BCA.

As will be described in Chapter 2, the basic principles of LCCA are few and relatively straightforward. The specific application of LCCA to bridge management, however, depends on the specific character of bridges and on availability of data for estimating values of key parameters influencing the life-cycle cost of a particular bridge. In contrast to pavements, for example, a bridge is spatially compact and generally has a high proportion of its life-cycle cost bound up in its initial construction. In comparison to tunnels, bridges are exposed to greater vagaries of climate and live load. A management tool designed to assist bridge-management decision makers will be most useful if it highlights the principal tradeoffs available to achieve a more efficient bridge life cycle. The term "bridge life-cycle cost analysis" (BLCCA) is used throughout this manual to designate the particular application of LCCA principles and procedures to bridge management.

Bridge-Management Decision Tools

Many agencies have adopted bridge-management decision tools that operate at the system level to assist in budget allocation and prioritization within an agency's total inventory of bridges. PONTIS, one such system-level tool, was developed under an FHWA project and is available to agencies through the American Association of State Highway and Transportation Officials' (AASHTO) AASHTOware program. BRIDGIT is another such tool developed under the NCHRP and available from the developer, National Engineering Technology.

In contrast to these tools, the BLCCA discussed in this manual focuses on the analysis of individual bridges, what is sometimes termed a "project level" analysis. BLCCA will be most useful to bridge engineering professionals concerned with selecting the most appropriate course of action for bridge design and improvements. These professionals will presumably seek to minimize the total costs likely to be incurred during a bridge's complete life cycle. BLCCA is concerned with projecting these costs and comparing costs for alternative courses of action.

These costs are paid by either the "agency" or "users." The agency is typically a government entity; its costs are direct expenditures of funds for planning, design, construction, operation, and maintenance of a bridge. "Users" is a broader category that includes vehicles using the bridge and possibly the businesses and residents of nearby areas that rely on the bridge for access. The specific elements of agency and user costs considered in a BLCCA will depend on the bridge under consideration and the purpose for which the analysis is being made. Chapters 3 and 4 of this manual address these matters.

Regardless of who pays, costs fall conceptually into two categories of "routine" or "extraordinary." Routine costs are those which spring from normal development and use of a bridge. Most people will understand that normal costs include at least some periodic spending for maintenance and repair, even if that spending is deferred because of tight budgets. Periodic cleaning of drains, inspections of structural condition, and the value of time lost to congestion when these cleanings and inspections block traffic are similarly included among routine costs.

Extraordinary costs are incurred when unusual events happen. A severe flood, an earthquake, a chemical-transport vehicle colliding with the structure, and the like can cause substantial bridge damage and high recovery costs. Users are delayed and inconvenienced while repairs are made and may even suffer direct damages from the event itself. Even though the events are rare, the costs when they do occur are so high that they may represent a significant factor in BLCCA. The *expected value* of these costs is termed in this guidance manual the “vulnerability cost,” because they result from a bridge’s vulnerability to extraordinary events.

Uncertainty and the Stochastic Approach to BLCCA

The basic principles of BLCCA are applied using estimates of future outcomes of actions taken to manage a bridge–e.g., crack-sealing for the deck will improve corrosion resistance and avoid severe structural damage–and the costs of those actions and outcomes. Even for extraordinary or “vulnerability” costs, the analysis must rely on such estimates.

Because they are estimates, these figures are always uncertain. Once an action is taken and its outcome observed, the actual value recorded as an indication of the outcome–e.g., cost, traffic level, deck spalling–may vary from the estimate, sometimes substantially. A *deterministic approach* to BLCCA relies on outcome and cost estimates initially without regard for their potential variability. A single set of estimated costs, deterioration rates, and the like are used to compute a single estimated life-cycle cost for a particular bridge-management strategy. After this estimate is made, the calculations may be repeated with different estimates to address the questions of what the life-cycle cost would be if the outcomes differ from the initial estimates. This *sensitivity analysis* explores the degree to which the life-cycle cost depends on initial assumptions.

An alternative to the deterministic approach is to give explicit recognition to the uncertainties of estimated costs and outcomes. Uncertain parameters are represented by probability distributions rather than single-number estimates. A *stochastic approach* to BLCCA computes the life-cycle cost of a particular management strategy as a probabilistic distribution, based on the uncertainty of these input parameters. Even the input distributions are uncertain, so a sensitivity analysis may still be conducted following the initial life-cycle cost computations.

This guidance manual presents a stochastic approach to BLCCA. This approach is computationally more complex and intensive than a deterministic approach and is made practical primarily by the availability of powerful and low-cost computers and bridge-performance databases that enable the analyst to make meaningful estimates of the probability distributions used in the analysis.

Organization of the Guidance Manual and its Relationship to Other Documents

This guidance manual is written as an independent primer on BLCCA, to provide background understanding of the principles of engineering economics applied to bridges and how economic uncertainty may be characterized and accommodated in bridge-management decision making. Chapter 2 presents the basic concepts of BLCCA. Chapter 3 then presents the step-by-step process of computing the life-cycle cost of a particular bridge-management strategy. These chapters together represent the core of the manual.

Chapter 4 describes the various parameters that may be used to describe bridge-management strategies, their outcomes, and their costs and to compute strategies' life-cycle cost. The description is structured to emphasize those parameters that are more likely to be important to decision makers facing typical highway-bridge management problems. However, the discussion seeks to be comprehensive as well, because the specific characteristics of a particular bridge may represent unusual problems where "typical" answers are questionable.

Chapter 5 describes data sources to support BLCCA. The National Bridge Inventory (NBI) and its program of periodic inspections has done much to build an extensive database for bridge-performance analysis, but not enough to enable fully reliable project-level BLCCA. More detailed studies by individual state agencies and researchers provide a basis for developing deterioration models to project the outcomes of bridge-management actions and events, and a great deal more work is needed. Information on bridge performance following rare events is, of course, scarce; more work is needed to improve our abilities to forecast the life-cycle cost consequences of flood-induced scour, seismic strains and other extraordinary conditions with which a highway bridge may contend. In the absence of good relevant data, a BLCCA user may have to rely on default values of various parameters, values derived from available data.

This manual is one of several products of NCHRP Project 12-43, a study to develop a comprehensive methodology for life-cycle cost analysis of bridges implemented as a software package for PC-style computers. The software package is designed to assist users seeking to make a stochastic analysis of management strategies for individual bridges. A User's Guide that accompanies the BLCCA software presumes that users are familiar with the principles and practices described in this guidance manual, but this manual avoids reliance on the User's Guide or the software itself. A final report of the project describes all work done and incorporates, by reference, this manual, the BLCCA software, and the User's Guide.

Chapter 2 Basic BLCCA Concepts

Condition, Service Life and Life Cycle

As a long-term, multi-year investment, a bridge is the product of decisions made and actions taken during its planning, design, construction, use and maintenance over the course of many years. Possibly the most basic issue in BLCCA is the determination of how long a bridge's service life is likely to be. In practice, the end of a bridge's useful life often comes decades or even centuries after its initial construction.

In practice, this end comes because the bridge is determined to be either (1) no longer needed or (2) unsafe, obsolete, or otherwise unable to provide the services expected of it even with repairs. Unacceptable safety and obsolescence are conditions judged by professionals who rely on currently applicable criteria and standards and best available information. Experience suggests that current expectations of the practical service lives of highway bridges in North America may be approximately 30 to 50 years. However, AASHTO specifies, for example, that the service life of new bridges should be 75 years, and other agencies use other values. In principle, and in the particular case of its use in BLCCA, the service life is a not-quite-arbitrarily chosen value denoting the anticipated time period from the end of construction until conditions reach an unacceptably low level.

The service lives of a bridge and its components are uncertain. BLCCA typically designates a *planning* or *time horizon* as the period of time over which all costs are to be estimated. The planning horizon and service life are not necessarily equal. An existing bridge, for example, will always have a service life greater than the planning horizon used in a BLCCA; the bridge will have provided years of service before the analysis is made and is assumed by convention to remain in service at least to the end of the planning horizon (subject of course to uncertainty, e.g., the possibility of an early failure).

Figure 2.1 Models of bridge-element and bridge deterioration (time scales not necessarily the same)

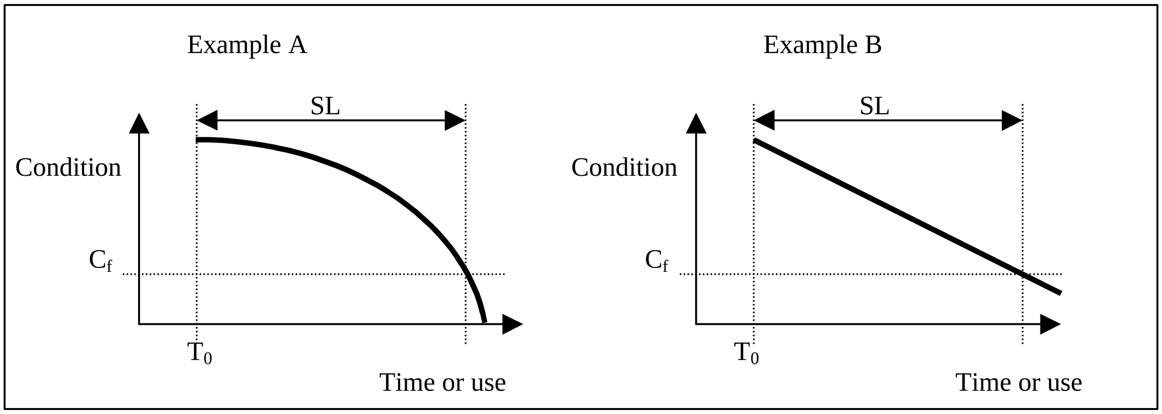


Figure 2.1 illustrates typical representations of a how the condition of a bridge or its elements deteriorate and define the service life, in the absence of any particular action to make repairs or otherwise change conditions. This basic model applies to a bridge as a whole or to any of its *elements*, e.g., deck, substructure, bearings, columns. If a bridge is placed in service following its construction (at time T0), the deterioration curve represents the bridge's condition as it declines with wear and aging, from its initially high level to a level considered unacceptable (Cf) . Example A might represent a concrete deck where the damage of gradual cracking accumulates and then begins to accelerate as water and chemicals penetrate more deeply beneath the surface. Example B might be more representative of a bridge as a whole where

the overall condition progresses through a series of defined states. The shape of the deterioration curve, of course, is dependant of the definition of the various condition states. Regardless of the deterioration curve's shape, the service life (SL) represents the length of time until unacceptable conditions prevail.

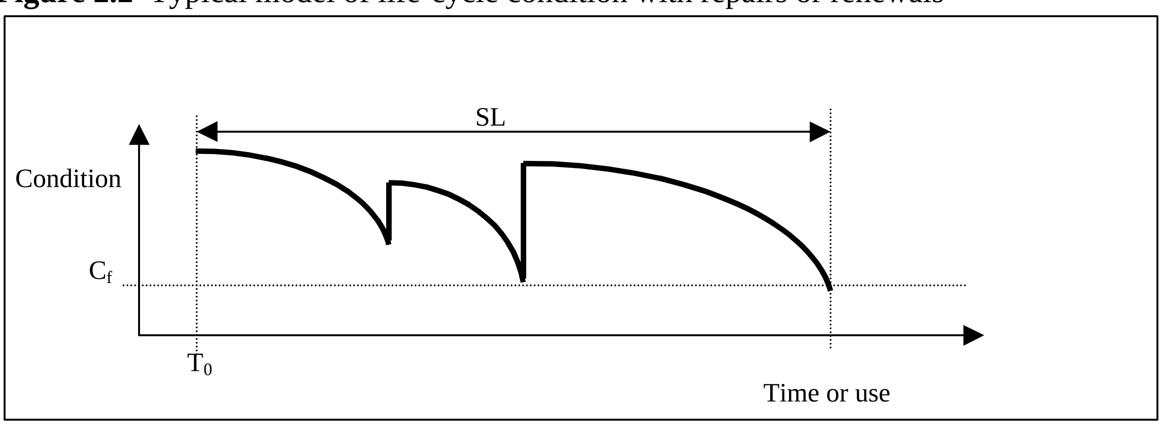
These typical deterioration models are generally understood to include at least some *normal* or *routine maintenance* effort during the service life. Such maintenance influences the rate of deterioration. Its neglect can reduce the service life. Under conditions of normal maintenance only, without more substantial repair or rehabilitation of elements, a typical highway bridge's service life can be substantially less than the often quoted 75 to 100 years.

Regardless of the progress of wear and aging, obsolescence may hasten the end of the service life. Obsolescence results when there is a change in the requirements or expectations. Such a change in effect increases the condition or functional level judged to be unacceptable. (Cf in Figure 2.1). A change in maximum-allowable vehicle load, for example, may impose on highway bridges greater maximum stresses or more frequent repetitions of critical stress levels or both. These changes, in turn, render some older structures effectively *obsolete* since the higher anticipated loads may exceed their design limits. 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 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 substantially 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 auto travel spurred removal of street railways in most urban areas. As a result, some heavily congested bridges now carry fewer people (albeit in more vehicles) than they did when they were first built.

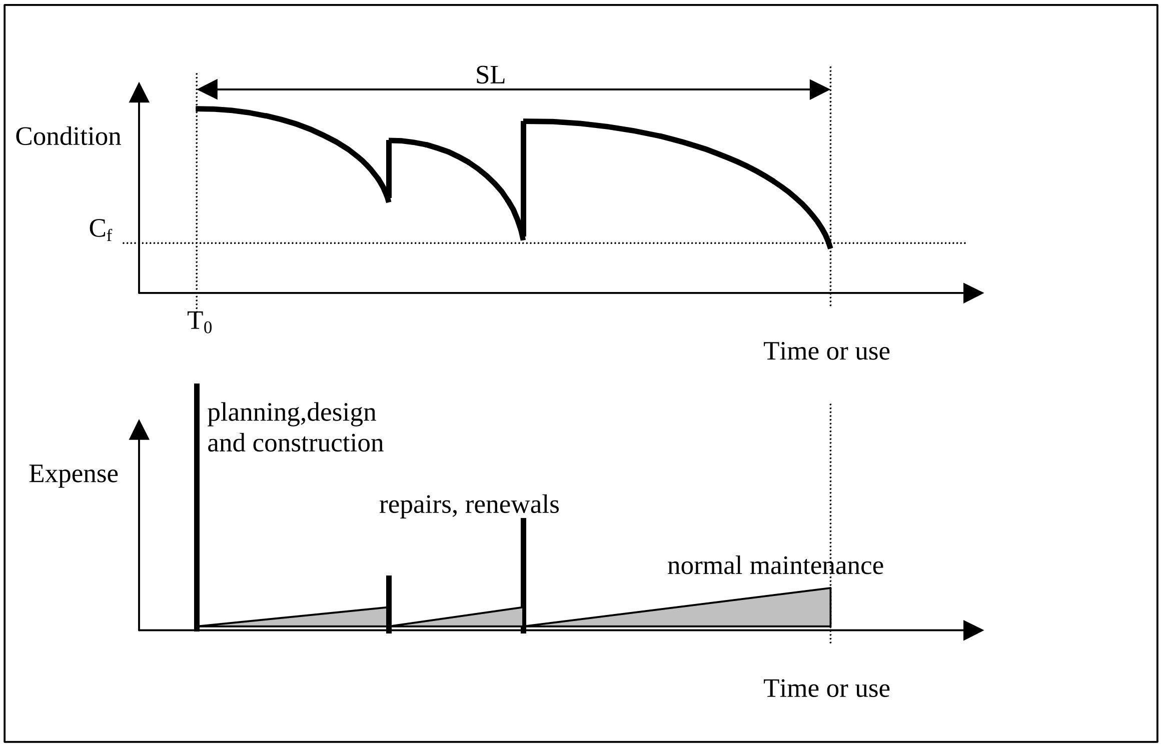
In most cases things that are obsolete continue to function but at levels below contemporary standards. A bridge that cannot carry the heaviest loads may be posted and kept open for lighter-duty use.

Figure 2.2 Typical model of life-cycle condition with repairs or renewals



In most cases a bridge is not left to follow the basic deterioration path and reach an unacceptable condition without interruption. Instead, the responsible agency will from time to time undertake *repairs*, *rehabilitations*, or *renewals* that return conditions to a higher level and extend the service life, as Figure 2.2 illustrates. The challenge facing bridge managers is to specify an economically efficient set of actions and their timing during the bridge's life cycle to achieve the 50- to 100-year service life.

Figure 2.3 Expenditure accompanying the life cycle



The sequence of actions and events that determine the bridge-element's condition throughout its life cycle is sometimes referred to as the "life-cycle activity profile." Actions will typically have associated expenditures and, as Figure 2.3 illustrates, these expenditures may be plotted as a function of the time when the expenditures are made. This plot, sometimes termed a "cash-flow diagram" even when it includes commitments of non-cash resources (e.g., user costs for time in congestion), shows the magnitude of the expenditure or receipt and when it occurs. (Receipts or revenues would be shown as lines extending below the x-axis.) To simplify computations, all resource flows generally are by convention represented as occurring at the beginning or end of the time period in which they in fact do occur. Resource flows extending over several periods, e.g., a multi-year construction project, are represented as a series of lines, one for each period in the multi-period set.

At the end of its service life, a bridge will have some value that must be taken into account in the BLCCA. That value, termed the *terminal value*, may be positive (e.g., if the materials can be sold for recycling) or negative (e.g., if demolition costs will exceed the resale amount). In many cases the BLCCA time horizon may not coincide with the technical service life of a particular bridge-maintenance strategy, and a bridge may have *residual value* or "serviceable life" value attributable to the years of service it will continue to provide before its condition becomes unacceptable. This residual value is not necessarily the same as the bridge's terminal value. Both parameters may have a role in a BLCCA. These values are treated the same as other costs in the BLCCA.

Time-Value and Equivalence of Economic Resources

The various actions taken during a bridge's life cycle entail use of economic resources. An agency spends money for construction, normal maintenance and repairs. Bridge users sacrifice time and out-of-pocket expenses (e.g., extra fuel) while repairs are being made, for the sake of the improved conditions and extended service life gained thereby. These uses of resources occur at times throughout the service life.

A basic principle of economics used in BLCCA is that economic resources have a *time value*. The principle derives from the premise that resources can always be put to productive use, yielding some return over time. A dollar placed in a savings account, for example, accrues interest because the bank can use the dollar in its lending programs. After one year, for example, the saver will be able to withdraw $1.06 to spend on food or clothing. In principle, one would then view an offer of one dollar paid today as equivalent to an offer of $1.06 to be paid one year from today. The *discount rate* is a parameter used in BLCCA to calculate the equivalent worth of economic resources used or received now or in the future. The question as to whether an agency can actually invest surplus funds is irrelevant. In essence the discounting of future costs is an attempt to place a worth on the funds being spent.

The relationship between the amount of a future expenditure and its equivalent present worth or value is then calculated using the discount rate [*DR*]:

$$PV = FV_N / (1 + DR)^N$$

where:

PV = *present value of the expenditure*
FV_N = *future value of an expenditure made at time N*
N = *# of periods (generally years) between the present and future times*

As will be described in Chapter 3, there are several standard formulas derived from this basic relationship, for computing the present values of certain frequently encountered expenditure patterns. The periodic expenditure for normal maintenance shown in Figure 2.3, for example, may be expressed in terms of its equivalent single-value present worth. Similarly, a single-value expenditure, now or at some future time, may be expressed in terms of its equivalent periodic value, the magnitude of a constant-valued periodic expenditure over a set number of periods that has the same present value as the single-value amount. This is often referred to as the equivalent uniform annual cost (EUAC).

While discounting is widely used and is an essential feature of all LCCA, it is not without problems. The discount rate itself, typically expressed on an annual basis, is generally understood to represent a measure of the "opportunity cost" or time-value of money. The principle that uncommitted funds can always be used productively is the basis for assuming a positive discount rate, e.g., $(1+DR) > 1$. The validity of this assumption is not always clear. A bridge-management professional, for example, does not generally have the choice of investing a portion of his or her capital budget to produce additional revenue instead of spending the budget on bridge construction or repairs.

Selecting an appropriate discount rate for public funds is not at all clear. However, we can draw upon experience in the private sector where profitability and return on investment drive decisions. The discount rate really serves two purposes; to reflect the opportunity cost of money, similar to the private sector and a method by which to quantify the benefits or dis-benefits of delaying actions. A zero discount rate implies, given equal conditions, that timing of repairs is irrelevant, only the total cost of repairs is important. This certainly seems to contradict current thought. Large discount rates, on the other hand, ensure that low up-front-cost alternatives are more desirable. Reality is somewhere between these two extremes.

Some analysts argue that this comparison of private spending and public spending warrants public-agency use of discount rates at least as high as those used in the private sector. Others suggest that public-sector spending is a special situation that justifies low discount rates, certainly no more than the interest- rate at which government can borrow funds in the open market. U. S. government agencies must apply the guidelines issued by the Office of Management and Budget (*Guidelines* 1992), which are updated by occasional revisions of Appendix C. As of 2002, agencies were instructed to use a current discount rate of 5.8% per annum, based on the nominal interest rate on 30-year Treasury Notes and Bonds. An up-to-date Appendix C can be found at the web site http://www.whitehouse.gov/omb/ by searching for “discount rate.”

The exponential relationship of present and future values means that higher discount rates have a dramatic impact in reducing the consequence of expenditures to be made in the more remote future. BLCCA with higher discount rates is thus less favorable to long-lived projects with initial costs that are large in comparison with future savings to be gained. Proponents of large capital-intensive projects may argue that discount rates should be low, or even zero. Others argue that inappropriately low discount rates encourage over-building and “gold-plated” design.

The discount rate generally is described as having three components measuring (1) the “real” opportunity-cost of capital [*cc*], (2) the required premium for financial risk associated with investments to be analyzed [*fr*], and (3) the anticipated rate of inflation in prices [*pi*]. Each component is typically stated as a percentage representing the rate of annual increase (or decrease, in the event of economic deflation), and the “current” discount rate is calculated as

$$DR = [1 + cc][1 + fr][1 + pi] - 1$$

The opportunity-cost of capital is sometimes termed the “real” discount rate. Historical trends suggest that the real time-value of money is typically in the range of 2 to 4 percent per year. The U. S. Treasury Department in the Spring of 1997 introduced a new debt instrument, Inflation-Protected Securities, which promised to pay investors a basic interest amount plus an additional amount based on changes in the consumer price index. Backed by the full faith and credit of the U. S. government, these securities are viewed by the financial markets as virtually free of financial risk as well as protected from inflation. The securities offering was oversubscribed at a base interest rate of just over 3.5 percent. Specific discount-rate values appropriate for use in BLCCA are discussed in Chapter 5.

Because the three components of the discount rate are typically small fractions, the second- and third-order terms in the discount-rate equation above are sometimes neglected to yield a frequently used approximation

$$DR = cc + fr + pi$$

As long as inflation rates and required risk premiums are low, errors associated with this approximation remain relatively small. The federal-agency discount rate (6.3 percent as noted above) may then be understood to represent a "real" cost of capital of about 4 percent and an anticipated inflation rate of just over 2 percent; U. S. government debt is widely judged to be "risk-free," i.e., to warrant no risk premium. Financial intermediaries such as mortgage lenders may charge 2 to 4 percent over this risk-free level, to cover their costs of doing business and the risks of non-payment and higher-than-expected inflation. A transportation agency might do likewise when considering substantial capital investments that effectively divert public funds from other potentially productive opportunities.

Uncertainty

Because the various parameters used in BLCCA–e.g., costs, condition, time when actions or events are likely to occur–are uncertain, a stochastic approach to BLCCA is needed. At the core of this stochastic approach is the principle that key parameters will be specified not as single numbers but rather as probability distributions.

Figure 2.4 Typical probability density functions

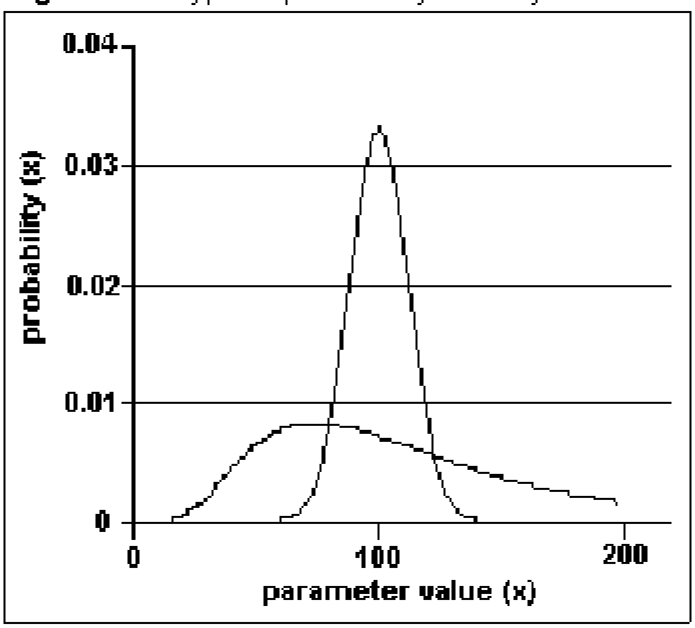
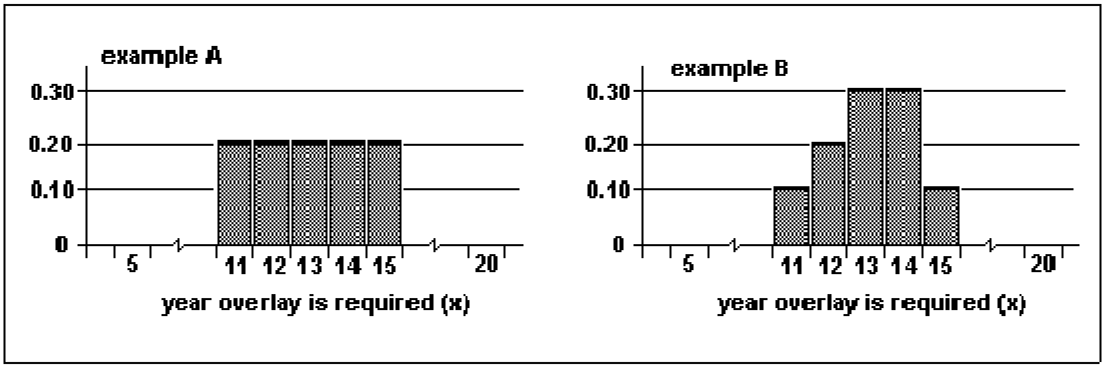


Figure 2.4 illustrates the shape of mathematical functions typically used to represent stochastic variables in engineering and financial analysis. The "probability (x)" is in these cases an estimate of the probability that a parameter "x" will occur in the range around a specific value "a," [a ±], where " " is very small. Because "x" will always have some value, the area under these probability density functions is always equal to unity.

Figure 2.5 Examples of discrete probability density distributions



A simpler form of probability distribution will often be used to represent many uncertain parameters in BLCCA, formed from a few specific values assumed to be plausible for the parameter in question (see Figure 2.5). For example, the time required for a bridge-deck's surface condition to deteriorate from its value at the end of construction to a low level that warrants a deck overlay might be estimated as 11 to 15 years (assuming normal maintenance). If the analyst feels the need for the overlay is equally likely to occur in any one of the five one-year periods of this range (example A), the probability of its occurring in any particular year is 20 percent for years 11 through 15, and 0 otherwise. If he or she has some reason to assume otherwise, greater probability may be assigned to one or another period (e.g., example B), as long as the total probability assignments total to 1.0 or 100 percent.

Regardless of the specific form used for a probability function, three characteristics of the function warrant particular consideration. The "mean" is that value E1 of the parameter "x" such that P[x E1] = 0.50; i.e., "x" is equally likely to be greater than or less than the mean. The mean of the distribution in Figure 2.5, example A, is 13.0 years; in example B, it is 13.1. (The means of the two distributions shown in Figure 2.4 are the same value, 100.) The "median" is that value E2 of the parameter "x" that is the halfway point when all observations or measurements are listed according to magnitude; i.e., half of all observations of "x" will be less than E2. Because all values of "x" must equal one of five values within the range of 11 to 15 years, the median in both example A and example B is 13.0. Finally, the "mode" is that value E3 with maximum probability of occurrence. In Figure 2.4 the mode is the value of "x" where the distribution curve peaks. In Figure 2.5, example B, the mode is the values 13 and 14; for a uniform distribution (e.g., Figure 2.5, example A) or a distribution with multiple peaks, the idea of "mode" is not particularly useful.

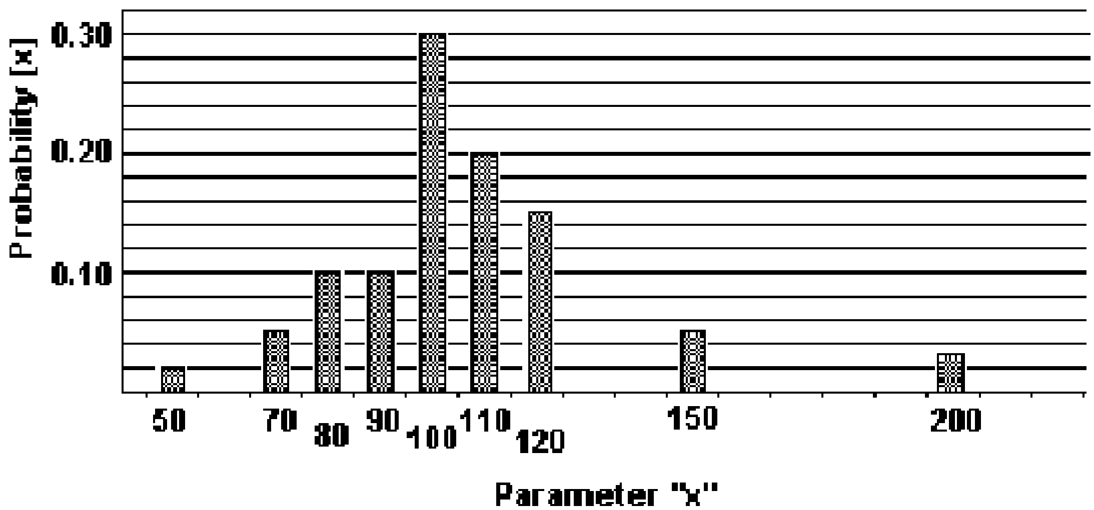
BLCCA may often be conducted using a *best estimate* of an uncertain parameter as a basis for estimating (in turn) a probability function for the likely range of that parameter. The analyst bases the initial "best estimate" on limited available data, his or her judgement, or perhaps default values suggested in a guidance manual. Considering whether the best estimate represents a mean, median, or mode is useful in developing a distribution to be used subsequently in the BLCCA, such as that illustrated in Figure 2.6.

Figure 2.6 Probability density distributed on “best estimate”

Example distribution on a “best estimate”

Variation from best estimate value (%)	-50	-30	-20	-10	0	10	20	50	100	Sum
Probability	0.02	0.05	0.10	0.10	0.30	0.20	0.15	0.05	0.03	1.00

Suppose “best estimate” = 100



In this example, the “best estimate” is both the mode and the median of the distribution; the mean is 105.

When an analysis includes many uncertain parameters described by various probability distributions, the BLCCA computation becomes very complex. *Monte Carlo simulation* is a widely used computer-based method for dealing with these computations. The computer uses each probability distribution to randomly select a value for each parameter in the analysis and then uses the specific sampled values to compute the desired outcome parameter, e.g., total present value of a bridge and its management strategy. Successive repetitions of the process yields a set of output computations that is then used to calculate the probability distribution for the outcome parameter. Complex, multi-parameter models such as those encountered in BLCCA typically require several thousand computation repetitions to produce a usable result.

The form of this result, the probability distribution of the outcome parameter, depends on the form of the input or independent parameters and the computational relationship of these inputs to the outcome parameter. For the types of relationships typically encountered in BLCCA–e.g., deterioration models and discounting of future values–and “well-behaved” input parameters–e.g., with distributions such as those in Figures 2.4, 2.5, and 2.6–the resulting outcome distributions are likely to have a form similar to the curves illustrated in Figure 2.4. The analyst may then use the mean, median, or mode of the distribution as a “best estimate” of the outcome, corresponding to the estimates used as inputs to the BLCCA.

The use of Monte Carlo simulation poses a particular problem in the treatment of very rare, low-probability events. The occurrence of such events, e.g., severe storm-induced flooding, is unlikely to be sampled adequately with only 1,000 computational repetitions. For example, the probability of a 100-year storm occurring in any given year is 1 percent; the expected number of computations involving this storm over the course of simulating, for example, a 50-year planning period, is then 0.5 (i.e., 50 computation repetitions for each year at one percent probability of occurrence). However, the estimated costs incurred if the storm does occur are likely to be very large; the expected value of these storm-related costs will then be a significant factor in a BLCCA. Assessing the consequences of low-probability, high-cost events–what was termed "vulnerability costs" in Chapter 1, therefore requires either a much larger number of computational repetitions or analysis by other means than the full-scale Monte Carlo simulation used for routine costs.

Deterioration Models

The relationships between condition and time indicated in Figures 2.1 and 2.2 are represented by *deterioration models* that predict the level of a specific condition measure (e.g., fraction of a bridge-deck's area that is spalled) as a function of a bridge-element's use or wear (e.g., number of passes of the critical axle load or simply time). While lack of data, lack of knowledge of the underlying physical and chemical deterioration mechanisms, and the complexity of bridge-element behavior have hindered development of realistic behavioral deterioration models, several approaches have proven useful in BLCCA.

In one such approach, the condition of a bridge or an element is characterized in terms of a distinct set of possible "states" (e.g., good, acceptable, marginal and unacceptable) and possible transitions from one state to another. An element's aging or wear is then represented as the successive occurrence of transitions from one state to another. The probabilities of transition during a defined period of time depend on anticipated loadings, environmental conditions, management actions, and other important factors and can in some instances be estimated with models similar to conventional decay, wear, or fatigue functions. Repair actions undertaken by a bridge-management agency may cause a transition to a better condition state, or at least change the probabilities of several inter-state transitions. A particularly popular representation for engineering LCCA applications uses *Markov process* assumptions in estimating transition probabilities; a key assumption is that transition probabilities are independent of the element's previous states.

Figure 2.7 A simple state-space deterioration model

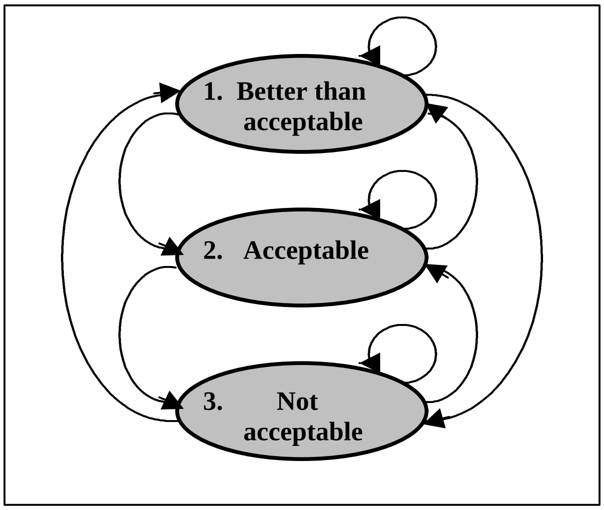


Figure 2.7 illustrates a basic state-space deterioration model. The three states might correspond, for example, to the conclusion drawn from a visual inspection of a bridge. The arrows represent transitions that could occur during a unit of time on which the analysis is based, e.g., one year. Associated with each arrow is a probability of the transition occurring within a single time period. The probabilities for all arrows out of a state will always (by definition) total to unity, i.e., the bridge will always be in some state at the next time period. Arrows from a higher to a lower condition represent wear, aging, or other deterioration. Arrows from lower to higher states represent the outcome of repair or rehabilitation actions. The estimated probability of remaining in the same state, acceptable or better, is typically contingent on normal maintenance being carried out. If, in each acceptable state, the sum of probabilities of transition to a lower state are greater than the sum of probabilities of remaining in the same state or moving to a higher state, the "process" will eventually reach the "not acceptable" state; the mean "service life" is the expected value of the number of periods required for the system to reach this terminal state.

Another generic approach uses statistical regression to develop relationships between condition measures and parameters presumed to have a causal influence on condition. These relationships maximize the likelihood that the output parameter (i.e., condition) will be in the particular range calculated if the causal parameters are in their particular assumed range. Such regression equations may be developed for transition probabilities in a state-space deterioration model as well.

One of the significant advantages of the state-space representation is that it can be applied to both bridge elements and a bridge taken as a whole. From the point of view of the decision-makers who determine design, construction, and maintenance budgets, the less-detailed perspective is generally adequate. It will not matter that particular elements of the bridge have deteriorated more than others, as long as overall performance remains adequate and maintenance crews can deal with whatever problems they encounter. Generalized bridge-level estimates of transition probabilities are then sufficient to support a meaningful BLCCA.

However, if data are available or the specific situation warrants collection of data to support a more detailed analysis, transition probabilities may be estimated at the element level. For example, if inspection reveals that deck cracking and road salt may have caused serious corrosion of reinforcing steel, a specific study may be warranted, to estimate the probability that the bridge will require substantial repairs within the next two years.

Level of Detail

In general, BLCCA may consider the condition of all of the distinct elements of a bridge at a very detailed level, e.g., foundation, columns, bearings, beams, deck, riding surface, drainage structures, expansion joints, and so on. In practice, limitations on data availability and computational resources as well as basic understanding of the physical and chemical processes at work in element aging and wear place limits on the reasonable level of detail for life-cycle cost analysis of an individual bridge.

Each element explicitly recognized in the BLCCA must be represented by a deterioration model that forecasts the element's condition as a function of time, use, management actions, and other events. Some analysts suggest that no more than three elements compose an adequately detailed description of most highway bridges: substructure, deck, and superstructure. Generally the types of bridge-management actions being considered in a particular BLCCA–e.g., painting, deck overlay, subsurface inspection for scour–will suggest the appropriate level of detail to be used.

A great deal of inspection detail is now available with modern bridge management systems, but current practice does not generally concern itself with element-level decision making. Work programs consider the bridge as a whole. Element-level deterioration modeling can suggest repairs but it cannot provide the accuracy required for project-level work plans. That must still be determined by the engineer.

Economic Efficiency, Marginal Analysis, and Bases for Decision Making

BLCCA addresses the issue of efficient use of resources to build, operate, and maintain a bridge in an acceptable condition for a selected period of time. Efficiency is indicated by low total life-cycle cost. The problem of bridge management is to find a management strategy with the lowest possible total life-cycle cost. BLCCA does not deal directly with the distribution of costs between the transportation agency and users or among groups of users. Economists refer to issues raised by the distribution of costs as matters of "equity."

BLCCA is used to measure relative efficiency; i.e, one management strategy may be judged more efficient that another because its expected life-cycle cost is lower. The comparison necessarily assumes that the two strategies will deliver outcomes that are comparable other than with regard to their costs. More particularly, the element-condition levels that trigger management actions must be similar for all management strategies if the BLCCA is to be valid.

The reliance on comparisons gives rise to the need to define a *base case* for each BLCCA. The present and forecast future conditions of traffic, physical condition, and the like that may be expected in the absence of any particular agency initiative provides the basis for defining management-strategy alternatives. Costs of the strategy alternatives are most appropriately measured as marginal changes from the base case. The base case represents "business as usual" and has no marginal costs. The base case is thus sometimes termed a "*do-nothing alternative*," although seldom does the base case involve absolutely no action on the part of the responsible bridge-management agency. Definition of the base case and consequent measurement of costs can be contentious. Even if the management agency simply stands by and watches a bridge deteriorate, salary and other administrative costs are likely to be incurred; eliminating the agency and all overhead expenses is not really an option. Allocating some portion of an agency's unavoidable fixed costs to the marginal increases in expenditures being considered under alternative bridge-maintenance strategies can in some circumstances mask the potential value of repair and renewal actions.

The point is particularly important for defining user costs. The base case will necessarily include assumptions (at least implicitly) regarding vehicle volumes and loads. The users' "investment" in a bridge-repair or renewal action–i.e., the user-cost component of the action's cost–will result primarily from work-zone congestion and safety hazards. It is certainly plausible and sometimes important that following the work's completion, users will have a safer and smoother ride than they might have had if the repairs were not made; these effects can yield savings (i.e., negative user costs) as compared with the base case. The computations involved in BLCCA and the resulting conclusions will generally be the same, whether costs are measured such that the base case is defined as the "no-cost" alternative or not, as long as all alternatives are described in a consistent manner. However, the amount of work required to conduct the BLCCA may be reduced by focusing sharply on the marginal differences from the base case that a proposed bridge-management strategy represents.

Future traffic levels, vehicle loads, climate, seismicity, cost levels, and other characteristics of the situation within which a bridge is to be managed compose the *analysis scenario* for a BLCCA. Taken as a whole, the analysis scenario includes all underlying assumptions–e.g., about materials, economics, construction methods, events that may entail vulnerability costs, and the like–on which the BLCCA depends. It may sometimes be important to conduct the BLCCA under several different scenarios before selecting a preferred management strategy. Price inflation, for example, has frequently been cited (with hindsight) as the reason why a more costly construction project should have been undertaken and why (today) the lesson of the past teaches that money spent to avoid future repairs is money well spent.

As a practical tool, the purpose of BLCCA is to assist decision-makers in comparing alternative strategies for managing a bridge. Generally the alternative with the lowest expected present value of all costs–i.e., the sum of routine agency, routine user, and extreme event agency and user costs–will be considered the "best" choice. For a number of reasons, however, this may not always be the case. An agency decision-maker faced with budgetary constraints, for example, may sometimes focus on alternatives with the lowest expected present value of agency costs only, i.e., the sum of only those costs representing actual expenditures of agency budgets, without regard for user costs. Sometimes priority may be given to alternatives that promise favorable user savings for agency costs, e.g., the greatest ratio of reductions in user costs to increased agency costs, as compared with the "least agency cost" option. Sometimes the consequences of making a mistake are so undesirable (e.g., having to close a high-volume bridge if a new material fails to be as durable as promised) that the low-cost alternative is not preferred. Many of these possibilities represent "risk aversion" and may be analyzed using techniques that rely on utility theory.

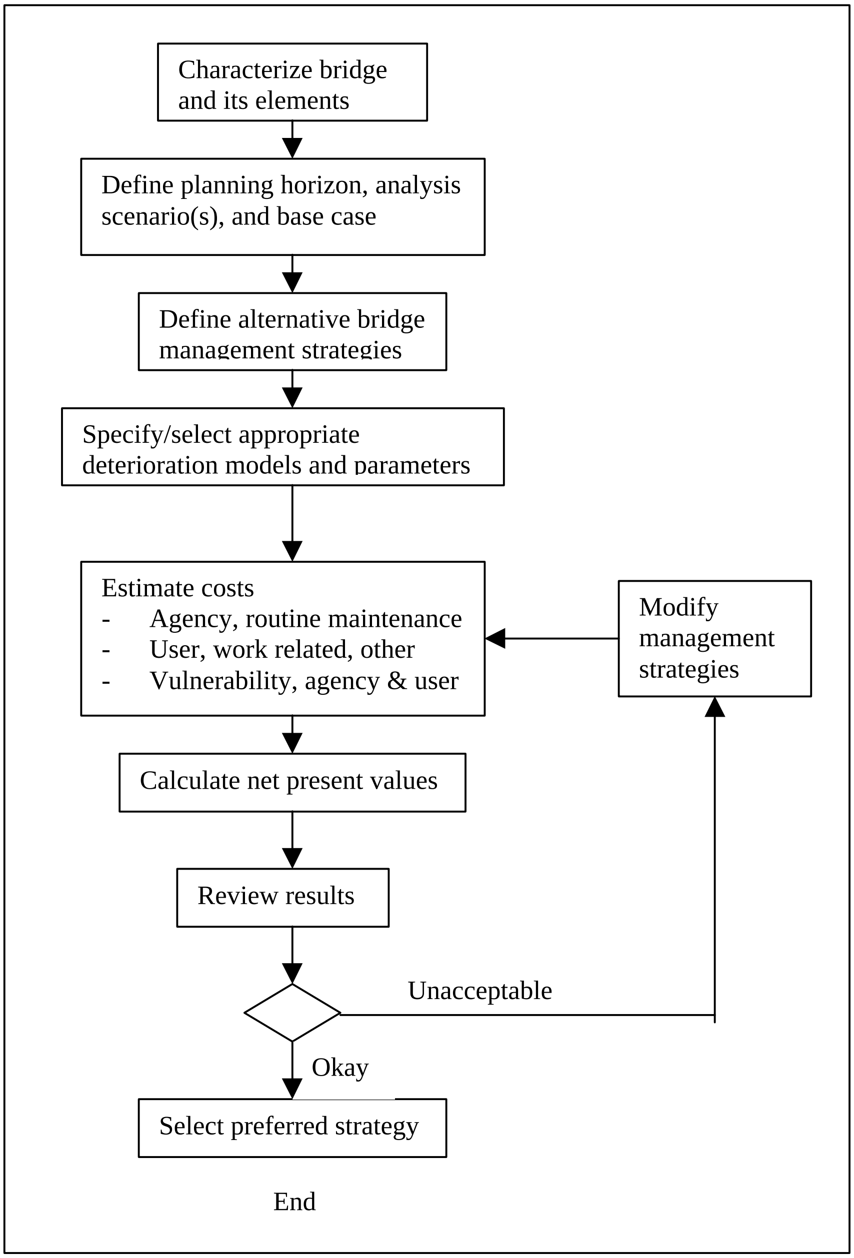
This guidance manual nevertheless focuses on "least total present value" as the primary measure of relative merit for comparing alternative bridge-management strategies.

Chapter 3 Process and Procedures

The Basic Steps in a BLCCA

Figure 3.1 illustrates the process and basic steps of a BLCCA. Each of these steps will be discussed in the following paragraphs. A simple example to illustrate the computations is included to accompanying this discussion. Other more complex examples are presented in Appendix C. More complete descriptions of the key parameters used in BLCCA computations may be found in Chapter 4.

Figure 3.1 The BLCCA process



<u>Characterize bridge and its elements</u> The bridge to be analyzed is described in terms of the characteristics relevant to its life-cycle cost. NBI and other inventory data, traffic information, inspection reports, and design information typically will be assembled. If information is available and the scale of analysis anticipated warrants it, specific elements may be addressed, either exclusively (e.g., if the analysis is undertaken to schedule a deck replacement only) or within the context of the bridge as a whole.

Bridge information is not the only data required for a BLCCA. As will be described in the context of subsequent steps, descriptions of analysis scenarios, the BLCCA base case, deterioration models, management strategies, and likely outcomes rely on available data and the analyst's judgement.

<u>Define planning horizon, analysis scenario(s), and base case</u> The framework of the BLCCA next is laid out; the planning horizon is a key variable. This time period should be selected on the basis of both the physical elements to be analyzed and the type of decision to be made. For example, a relatively short period–e.g., five to ten years–may be adequate for determining when a deck overlay should be scheduled for a standard-design highway overpass, while a longer period of two to three decades is more likely to be appropriate for developing a re-painting strategy for a large bridge. If the issue is possible use of new structural materials, the analysis period might extend to a century or more. Generally the planning horizon should be at least as long as the best-estimate service life of the element (under normal maintenance) that is the primary focus of analysis; this element will then have a very low expected residual value in the base case at the end of the analysis period.

The principal analysis scenario includes a description of what level of activity (and, at least implicitly, the annual cost) that will be defined as "normal maintenance," the condition levels that will be considered unacceptable or that will otherwise trigger maintenance or repair actions, hazard conditions that will influence vulnerability costs, forecast traffic and vehicle-load and climatic parameters that influence element deterioration, discount rate and aspects of agency policy that will influence action-timing or cost. The discount rate in particular may be estimated using current financial-market conditions or set by agency policy.

The base case is then described. Typically, the base case includes simply normal maintenance and vulnerability costs. If the analyst chooses to compute costs of all alternatives relative to the base case, the base-case total life-cycle cost is, by definition, zero. However, except for those parameters that are set by policy (e.g., discount rate), it is generally appropriate to specify even base-case parameters as stochastic variables, described by probabilities of occurrence. In that case, it is likely to be less confusing to the BLCCA's users if the base-case total life-cycle cost is computed in the same fashion as for other management-strategy alternatives.

<u>Define alternative bridge-management strategies</u> A management strategy will be described by the set of actions an agency plans to take to ensure the bridge remains in acceptable condition throughout the analysis period. Each action is scheduled to be taken at a particular time, although the precise year in which that action is taken may be uncertain (e.g., because of other priorities, budget limitations, or contracting difficulties).

Associated with each action will be a series of outcomes that must also be specified. The bridge's condition may improve, for example, and condition-deterioration rates may decline below those of the base case. Hazard-vulnerability risks may change also, as reflected by changes in the probabilities and cost consequences of hazard-related events. Each action will have estimated agency and user costs as well, also subject to uncertainty, but estimation of these costs is a later step in the BLCCA.

As described in Chapter 2, a valid analysis of several alternative management strategies requires that a single analysis period be used. Strategies must be defined to provide acceptable service throughout this analysis period. Some strategies may then have a residual value at the end of the analysis period.

<u>Specify/select appropriate deterioration models and parameters</u> The bridge elements and alternative management strategies will determine the deterioration models to be used in the BLCCA. Analysis of a deck might use a relatively detailed model of the fatigue and cracking processes at work under repeated heavy loadings, for example, while analysis of a complete bridge might rely on a simple model of condition states and probabilities of transitions between states. As described in Chapter 2, the Markov process is a simple model of this latter type frequently used in deterioration modeling.

The deterioration models will require parameters to describe the specific rates of deterioration anticipated for the bridge elements under analysis. These parameters may be estimated from available data, adopted from similar situations or other default values, or based on the analyst’s judgement.

<u>Estimate costs</u> Each of the actions that together compose a management strategy will entail agency and user costs. Estimates of these costs, a crucial component of the BLCCA, may depend on how deterioration is modeled as well as on the details of the actions themselves and the analysis scenario. For example, if a bridge-deck replacement is being analyzed and the deterioration model used yields an estimate of the percentage of the deck’s surface exhibiting severe damage, a parametric cost estimate based on a similar measure might be used, rather than developing a bid-quantities-based estimate. Each cost will typically be represented as a distribution of values and their probabilities of occurrence; the distribution may be constructed around a “best estimate.” The estimated costs of particular action and the associated deterioration models will also be the basis for estimating the residual values of strategies with service lives not conforming to the analysis period.

Each action will be identified as occurring at a future time period, and its costs may be estimated with constant prices or taking consideration of possible price inflation. The estimates must be consistent with the discount rate specified for the BLCCA, i.e., with inflation excluded (a “real discount rate”) or included. The former approach is simpler and generally acceptable unless differential inflation is anticipated, e.g., if wage rates are expected to rise much faster than materials prices. Such differential inflation may have a relatively small impact on agency costs, but much greater consequence for user costs involving time.

<u>Calculate net present values</u> The estimated costs of all actions are discounted to compute their equivalent present values, using the basic equation presented in Chapter 2 or other relationships derived from that basic equation (Appendix B). The net present value of each management strategy can then be calculated as the sum of all costs associated with that strategy including the residual value and terminal cost. If a stochastic approach is being used, each net present value will be represented by a probability distribution of its expected value. The calculation may require Monte Carlo simulation.

<u>Review results</u> The complexity of BLCCA using a stochastic approach requires that care be taken in using the results. Over-reliance on computer-based computational tools and data bases–together treated as a

"black box" that forecasts the results of an analyst's assumptions–can make these results misleading or simply erroneous. The analyst should review the net present value distributions to ensure they "make sense" in light of expectations and experience. Sometimes the BLCCA will yield unanticipated results that reveal important relationships; for example, road-users' time savings may justify paying substantial premiums for early completion of bridge-rehabilitation work. However, such results should be accepted only after careful review.

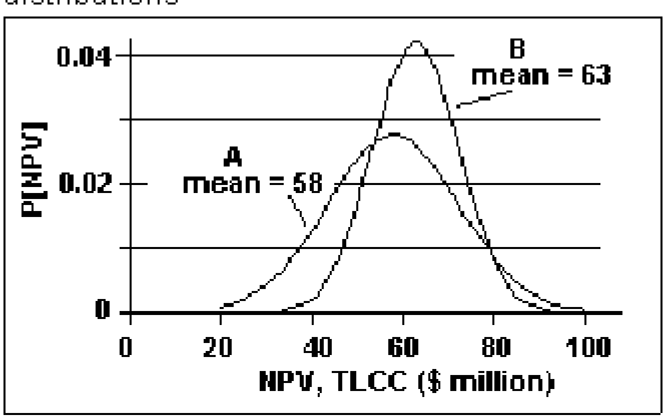
Part of that review may include sensitivity analyses. The stochastic approach to BLCCA inherently tests sensitivity of the results to uncertainty in many input parameters, but in some cases explicit testing of assumptions is warranted. Such testing is especially appropriate when two or more alternative management strategies have approximately the same expected total life-cycle cost (TLCC) but very different distributions of cost, e.g., agency versus user costs, or when the consequences of making the wrong choice are adverse and severe. Analyses of investments proposed to enhance a bridge's resistance to seismic damage, for example, may be very sensitive to the estimated risk of damage (probability and cost) with and without the investment.

<u>Modify management strategies</u> Initial results may suggest that modifying one or more of the management strategies may reduce TLCC. Such modification can be made and the results computed with relative ease using computer-based BLCCA tools.

<u>Select preferred strategy</u> The primary purpose of the BLCCA is to identify a management strategy with least TLCC. However, as noted in Chapter 2, because of the uncertainty of estimating TLCC, there are several ways that the several indicators identify a "best" alternative, e.g., least total present value of all costs, least agency cost, and others. In addition, the analyst may use the expected value (mean) of such a parameter or a value associated with another probability level (e.g., the value of TLCC such that there is estimated to be only a 20-percent probability that a lower value will occur; the mean represents the 50-percent level).

BLCCA may be used to assess a single strategy compared with the base case. In that application, the principle concern is whether the defined strategy represents a net saving relative to the base case: does it have a lower TLCC? When there are several strategies under consideration, the decision-maker may wish to choose, for example, a strategy most likely to have the lowest TLCC.

Figure 3.2 Example of expected TLCC distributions



As Figure 3.2 illustrates, the expected values of TLCC may not tell the whole story. In this illustration, the analysis shows (see Appendix D - Calculations) that there is approximately a 40-percent probability that alternative A, if implemented, will turn out to have a higher TLCC than would alternative B, despite the latter's larger mean expected TLCC. While the analysis indicates the chances are six out of ten that alternative A is a better choice, a particularly risk-averse decision-maker might wish to study the matter further, e.g., conduct sensitivity analyses or consider other aspects of the two choices before making a final selection. Despite the likelihood that many of the variables used in a complex BLCCA will be represented by probability distributions that are not themselves normally distributed, the distributions of expected TLCC resulting from a Monte Carlo simulation will frequently approximate normal distributions.

A Simple Example of BLCCA Assumptions and Calculations

The bridge The question is whether, and if so when, to replace the deck of a certain reinforced-concrete bridge crossing a large stream in a region with moderate seismic activity. The new deck, if installed, is anticipated to have a service life of about 20 years, at which time the question may again be faced. The bridge presently is usable and anticipated to remain so, but is judged to be susceptible to problems (e.g., corrosion, loss of structural integrity) that warrant frequent inspections. These problems, if found, could require the bridge's closure; if not found, they could cause substantial damage.

Analysis scenario and base case A continuing state-wide economic recession has effectively placed constraints on agency budgets; the state may have to borrow against future revenues to fund the replacement. A market-based discount rate will therefore be used, equal to the interest rate likely to be charged for general-obligation (GO) bonds, 5.5%. If we assume that 1.5% represents the long-term inflation rate, then the real discount rate is 5.5-1.5 or 4.0%. The agency estimates that monthly inspections and normal maintenance of the bridge, both conducted as part of the local district's in-house work, cost about $12,000 annually, but vary with materials prices. Traffic levels average about 22,000 vehicles per day (Average Annual Daily Traffic, two-way) with 15% heavy trucks. A 25-year planning horizon is chosen. The following conditions are estimated to represent likely bridge performance if no major action is taken.

Table 3.1 Real Discount rate

Variation from best estimate of 4%	-0.50%	-0.25%	0	+0.25%	+0.50%
Probability of rate	0.1	0.2	0.4	0.2	0.1

Table 3.2 Annual normal maintenance expenditure

Variation from best estimate of $12000	-15%	-10%	0	+10%	+20%
Probability of cost	0.1	0.2	0.4	0.2	0.1

Table 3.3 Annual hazard-vulnerability risk

Event	Risk measure (1 year)	Estimated risk			
Load-related structural failure	Probability of event Cost, per event	0.79 $0	0.15 $200,000	0.05 $1,000,000	0.01 $3,000,000
Severe traffic accident attributable to deck condition	Probability of event Cost, per event	0.89 $0	0.10 $40,000	0.01 $1,000,000	
Seismic damage	Probability of event Cost, per event	0.91 $0	0.05 $400,000	0.03 $2,000,000	0.01 $5,000,000

In Table 3.3, the event probability and cost columns, for seismic damage, for example, may represent the probability and expected damage from an earthquake of magnitude 0-4, 5, 6 and 7. For load-related failure, the columns could represent no damage, secondary damage, damage to primary members and collapse.

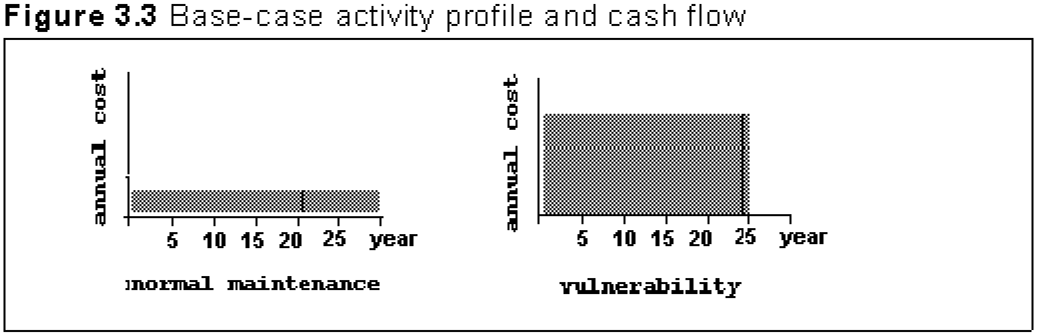
The expected costs shown in Table 3.4 are simply the sum of the products of costs and related probabilities of occurrence.

Table 3.4 Expected annual vulnerability cost computation

Event	Expected cost calculation	Expected cost
Load-related structural failure	0.79x$0 + 0.15x$200,000 + 0.05x$1,000,000 + 0.01x$3,000,000	$110,000
Severe traffic accident attributable to deck condition	0.89x$0 + 0.10x$40,000 + 0.01x$1,600,000	20,000
Seismic damage	0.91x$0 + 0.05x$400,000 + 0.03x$2,000,000 + 0.01x$5,000,000	130,000
Expected annual vulnerability cost, base case		$260,000

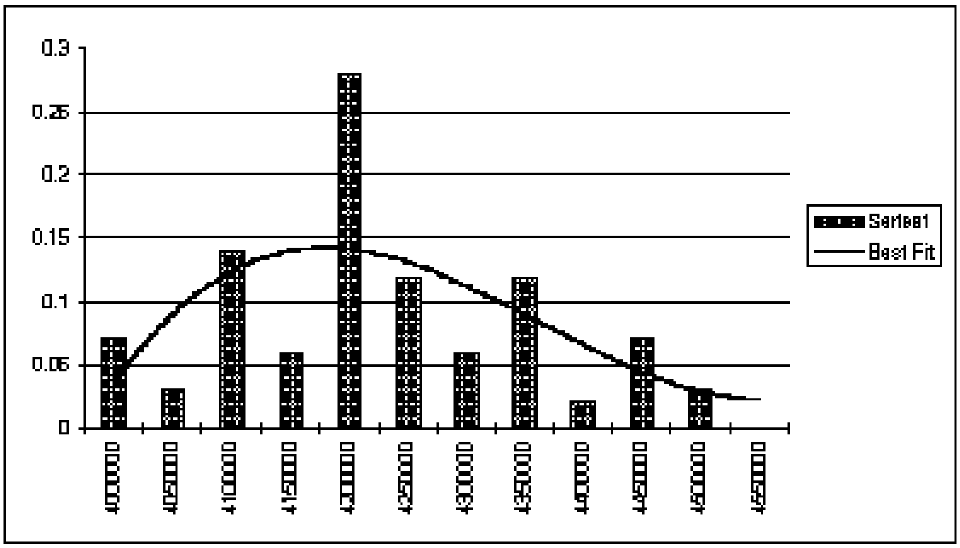
For computation of present values, normal maintenance costs are assumed to be incurred at the start of each year in the analysis period, vulnerability costs at the end of each year.

Figure 3.3 Base-case activity profile and cash flow



The probability density function (Figure 3.4) is the joint probability of annual normal maintenance costs and discount rate.

Figure 3.4 Expected base-case life-cycle normal-maintenance and vulnerability costs



The mean expected present value is $4,252,818. The distribution is derived by assembling a table of all expected outcomes with their associated joint probabilities, ranking them in ascending order of cost and then summing the associated probabilities for all outcomes which fall within a specified interval. The joint probabilities are equal to the probability of value 1 (discount rate) times the probability of value 2 (cost). Because the uncertainty in discount rate and maintenance cost are expressed as discrete values and probabilities rather than continuous probability density functions, it can be difficult to express the results as a probability density function rather than a cumulative function. This is because the shape of the curve is dependent on the intervals chosen for the horizontal axis and the shape of the curve can be very erratic. Figure 3.4 has results grouped into intervals of $50,000. The best fit curve represents the approximate continuous curve, which fits the discrete values. It should be noted that the vertical axis values are dependant on the “interval.” Thus even the continuous curve must be interpreted as the probability that a value is within $25000 of the value on the horizontal axis.

Vulnerability costs are much greater than normal maintenance costs (compare $12,000 per annum with $260,000), indicating that the agency is risking substantial losses (for the agency and the public) if no action is taken. This “conclusion” is consistent with the basic premise under which the BLCCA is being performed.

<u>Deck-replacement alternative</u> Designing, bidding, and reconstruction of the deck are likely to require about 18 months. Traffic on the bridge will be disrupted to some degree during the actual construction. Once

construction is complete, normal maintenance cost may be expected to decline substantially; the best estimate is $4,000 annually (Table 3.6). Vulnerability risk declines generally, although less so for seismic risk than other sources (Table 3.7 and Table 3.8). Because the bridge is likely to remain in service well beyond this period, terminal value will not be an important aspect of the calculations.

Table 3.6 Annual normal maintenance expenditure with new deck

Variation from best estimate of $4000	-10%	0	+10%
Probability of cost	0.2	0.7	0.1

Table 3.7 Annual hazard-vulnerability risk

Event	Risk measure (1 year)	Estimated risk			
Load-related structural failure	Probability of event Cost, per event	0.95 $0	0.03 $200,000	0.01 $1,000,000	0.01 $3,000,000
Severe traffic accident attributable to deck condition	Probability of event Cost, per event	0.989 $0	0.010 $40,000	0.001 $1,000,000	
Seismic damage	Probability of event Cost, per event	0.91 $0	0.05 $400,000	0.03 $1,500,000	0.01 $5,000,000

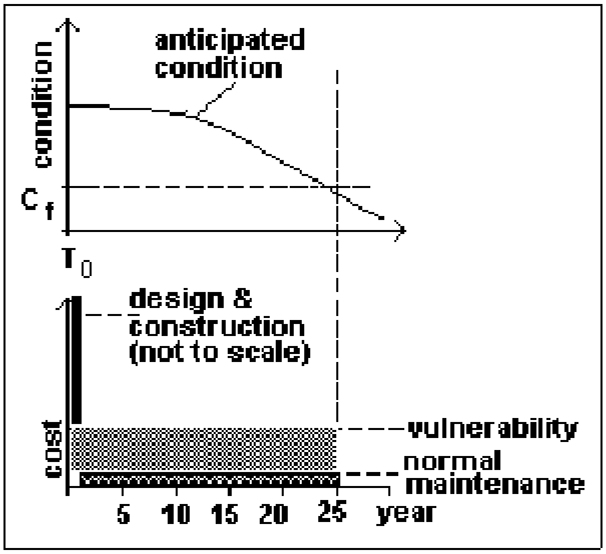
Table 3.8 Expected annual vulnerability cost computation

Event	Expected cost calculation	Expected cost
Load-related structural failure	0.97x$0 + 002x$200,000 + 0.005x$1,000,000 + 0.001x$3,000,000	$12,000
Severe traffic accident attributable to deck condition	0.989x$0 + 0.010x$40,000 + 0.001x$1,600,000	2,000
Seismic damage	0.91x$0 + 0.05x$400,000 + 0.03x$1,500,000 + 0.01x$5,000,000	105,000
	Expected annual vulnerability cost, base case	$119,000

Deck-reconstruction life-cycle cash-flow diagram and condition projection

The design-and-construction period, scheduled to begin immediately, will entail agency expenditures and user costs during actual construction. Normal maintenance will not occur during that period; necessary maintenance is included in the estimated agency costs of design and construction. Vulnerability costs are still appropriately charged, although work-zone restrictions on traffic may justify assuming these costs to be at the lower level anticipated after construction. These agency costs are anticipated to total $900,000, with 30 percent to be spent in the first year (Table 3.9). These costs are uncertain, as is the likelihood that the project will be completed as scheduled, but these uncertainties are assumed in this example to be insignificant.

Figure 3.5 Deck-reconstruction cash flow and condition estimates



Users will be exposed to congestion and delays during the construction period. Methods for estimating these costs can themselves be quite involved, as will be discussed in Chapter 4, and may depend on assumptions about construction scheduling and work-zone controls. For this example, 40 percent of vehicles are assumed to be delayed by the construction, incurring an average delay of three minutes. The value of this lost time is assumed to be $11/hr. The best estimate of user cost for the 22,000 AADT is then [0.4 x 22,000 veh x (3/60) hr/veh x 11$/hr] = $4,840 /day of construction. The best estimate of duration for traffic disruption is 10 months all in the second year, so that user costs for delay could be [10 mo x 30 d/mo x 4,840 $/day] = $1.452 million. These estimates are all uncertain.

Table 3.9 Best estimates of costs of deck reconstruction

Cost	Annual costs			
	Year 1	Year 2	Years 1-25	Years 3-25
Agency	270,000	630,000		4,000
User		1,452,000		
Vulnerability			119,000	

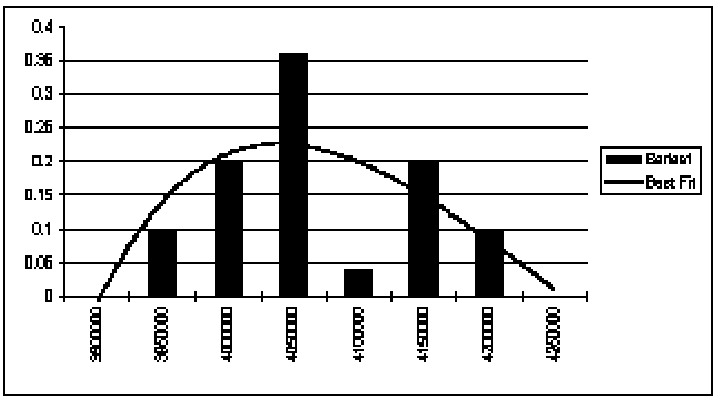
Expected present values

Discount rates remain the same as for the base case. The mean expected present value of normal maintenance is approximately $54,000. The mean expected present value of vulnerability costs is approximately $1.860 million. Agency and user costs in years 1 and 2, when discounted, have a total mean expected value of $2.136 million. The mean expected TLCC is then

Mean expected TLCC = 54,000 + 2,136,000 + 1,860,000 = $4,050,000

which is slightly less than the similar estimate for the base case. The probability density distribution for the expected TLCC is shown in Figure 3.6.

Figure 3.6 Expected TLCC with deck reconstruction



Reviewing results and reaching a decision While the proposed deck reconstruction has a lower mean expected TLCC, the small difference between the two alternatives warrants attention. The result depends primarily on the tradeoff between user costs incurred and vulnerability costs avoided by undertaking the reconstruction.

Note that the agency's deck reconstruction "front-end" costs, $900,000 in total, will be somewhat offset by savings in normal maintenance costs. The mean expected net present value of the deck reconstruction less the savings in maintenance costs is approximately $700,000; this net investment yields an estimated reduction in vulnerability costs–i.e., agency and public risk exposure–of more than $2 million (Net Present Value) over the life of the new deck. If the analyst feels reasonable confidence in the various cost and probability estimates incorporated in the BLCCA, then project planning and design should perhaps include an aggressive effort to reduce traffic disruptions during construction and reduce project duration.

Computational Approaches to BLCCA

This example illustrates how involved a BLCCA can become, even for a simple case. Computer software designed to support BLCCA can be extremely effective in allowing an analysis to be completed within an acceptable time and cost, while considering the full range of uncertainties and detail in the analysis.

In the absence of software tailored to the task, basic spreadsheet programs may be used quite effectively. These programs typically include a range of standard probability functions that represent uncertain parameters, as well as discounting equations. For small problems (e.g., such as the example presented in this chapter), the life-cycle-cost computations may simply be repeated for all appropriate combinations of the ranges of parameters in the analysis and the probability of occurrence of each resulting value calculated. The joint distributions of TLCC may then be constructed within the spreadsheet and graphed for easy review.

For more complex problems, "add-in" programs can enable the user to conduct a true Monte Carlo simulation using a spreadsheet model. Modifications of the Monte Carlo approach may be made by stratifying the sampling of probability distributions to increase the likelihood that lower-probability outcomes are represented in the results. Stratified sampling is widely used in experimental and survey design. The "Latin Hypercube" method is one particular approach sometimes used in highway LCCA (FHWA 1998). As explained in earlier chapters, hazard events and their vulnerability costs are typical of these low-probability outcomes; as shown in the example, these outcomes may also be represented as an average annual risk exposure.

Chapter 4 Parameters and Their Estimation

Parameters, Categories, and Their Significance

This chapter catalogs the principal components of cost and other parameters that may be used in the BLCCA of a particular bridge. Each parameter is defined, and its importance and applicability as a component of life-cycle cost are discussed. In contrast to preceding chapters, mathematical notation is used more extensively here to facilitate the discussion. Mathematical notation in this discussion has been simplified, however, to enhance clarity at the possible expense of precision.

This discussion presents essentially a stochastic approach to BLCCA, and many of the parameters are specified as probability density or distribution functions. The term "probability distribution," as used here, may refer to either a frequency or density distribution (i.e., for discrete-valued or continuous variables) or a cumulative distribution. Histograms and frequency curves are most typically used to represent the types of variables used in BLCCA. The discussion of each parameter includes consideration of the sources of uncertainty in the particular values that parameter may assume, e.g., statistical variation, lack of data, poor quality of data, contingency on management policy. The potential sources of data for specifying values of the parameter and likely quality of these data are also briefly addressed. Chapter 5 reviews a number of specific studies that may be helpful for estimating BLCCA parameters.

All of the parameters used in BLCCA can influence the outcome of the analysis and hence the bridge-management decisions based on that analysis. However, certain parameters are more pervasive in their influence or more basic to the principles of BLCCA and therefore perhaps warrant greater attention. The following descriptions are presented in an order intended to convey this relative significance:

- Total bridge life-cycle cost metrics and parameters influencing computation of life-cycle cost;
- Parameters describing actions, deterioration, hazards, and consequences;
- Parameters describing agency costs;
- Parameters describing user costs;
- Parameters describing vulnerability costs; and
- Value metrics for decision making.

Total Bridge Life-Cycle Cost Metrics and Parameters Influencing TLCC Computation

<u>Discount rate (*DR*)</u> The discount rate, discussed in Chapter 2, is perhaps the single most significant parameter in BLCCA because of its pervasive influence in computing equivalent present values of future costs. While a number of important factors may influence the appropriate level of the discount rate to be used in a BLCCA, in many cases agency policy will determine what rate must be used. In such cases, the analysts should conduct sensitivity analyses to determine whether the rate used has a decisive influence on the results of the analysis. The choice of a discount rate can sometimes affect the ranking of various alternatives. In particular, decisions about controversial projects that hinge on the particular value assumed for the discount rate may be difficult to defend in a public forum.

The discount rate is not nearly as important for new bridges because, after the initial cost, most future costs are heavily discounted and rather insignificant in the TLCC.

Service life (*SL*) and analysis period (*TA*) For each bridge and each of its elements, there is in principle a time period called its service life that represents the estimated time required for the element to deteriorate from its present condition *C0* to a level defined as unacceptable *Cf* (Figure 2.1). The deterioration occurs because of physical and chemical processes associated with wear and aging, subject to climate, geotechnical forces, and other factors. The service life may be shorter than these physical and chemical processes would suggest when economic or social forces raise *Cf* to a higher standard and obsolescence sets in. A great deal of research is devoted to improving ability to forecast *SL*; deterioration models represent stress fatigue, corrosion, and other underlying processes.

However, the precise value of *SL* often depends as much on policy or convention as on scientific data. Raising or lowering the limit of acceptable condition *Cf*, for example, effectively reduces or extends the service life; the relationship is routinely applied when bridge managers judge that an otherwise appropriate rehabilitation can be deferred when funds are limited and other problems have higher priority. Current bridge-management practice sets *SL* in the range of 70 to 100 years for most of a bridge's sub- and superstructure, and the current AASHTO design code sets a design life of 75 years. At another extreme, election cycles and budgeting cycles provide bases for proposals that decisions should be made with no more than a four- to five-year perspective. In practice, *SL* is a target, typically assumed to be 20 to 60 years. Agency experience with bridge rehabilitation and replacement can provide a statistical basis for assuming an initial service-life value. In general, there is no particular reason to assume that *SL* is equal to or different from the "design lifetime" that designers use for making component-size calculations.

The period over which all costs are assessed in a BLCCA, the analysis period *TA*, may be shorter than *SL* for the bridge as a whole and can be defined to encompass any meaningful period of years.. However, *TA* should generally be set to equal the best estimate of *SL* for the bridge element that is the focus of the BLCCA. Analysis of an existing bridge or one for which planning and design expenditures have been made is useful, however, primarily for exploring the relative costs of future courses of action. All past expenditures–i.e., "sunk" costs–can be neglected in such analyses. By convention, time typically is measured from the start of the analysis period.

TLCC and other metrics A bridge's TLCC and similar terms used in the previous section are computed as the total *present value* [*PV*], the sum of all costs anticipated during the service life, discounted to their equivalent value at the beginning of the analysis period. In general,

$$TLCC = PV\left\{\left[\ _{y}\ _{c}\ CC(c,y)\right] - RV(T_A)\right\}$$

where:

$CC(c,y)$ = *cost of type c incurred in year y*
$RV(T_A)$ = *residual value at the end of the analysis period,* $y = T_A$
$_y$ *sum over all years [y] in the analysis period,* $y\ \ T_A$
$_c$ *sum over all categories [c] of costs*

By convention, present value refers to the equivalent value at the start of the analysis period (e.g., $y = T_0 = 0$) and includes only costs incurred during the analysis period (T_0 y T_A). The calculation of present value depends on assumptions about discount rates and the length of the service life.

Basic principles of engineering economics provide mechanisms for presenting the equivalence of costs incurred at different times, in terms of not only their present value *PV*, but also their future value *FV* at some defined time. This guidance manual generally uses present value as the principal metric for *TLCC*. The relationship between *PV* and *FV* was stated in Chapter 2:

$$PV = FV_N / (1 + DR)^N$$

where:

PV	=	*present value of the expenditure*
FV_N	=	*future value of an expenditure made at time N, typically a discrete unit of the analysis period*
N	=	*number of time units (generally years) between the present and future times*

The concept of discounting may be applied with very small analysis periods, reducing the relationship of present and future value to a continuous–rather than discrete–equation. The continuous form is not typically used in life-cycle cost analysis and will not be discussed further in this manual.

A single-amount cost may also be expressed in terms of an equivalent periodic series of costs. For example, an agency can expect to incur costs for routine maintenance of a bridge; these costs might be estimated as a series of uniform amounts *AV* incurred annually over a period of years. The uniform series of costs may be expressed in terms of an equivalent single lump-sum *PV* amount using the relationship

$$PV = AV \times \left[(1 + DR)^N - 1\right] / \left[DR(1 + DR)^N\right]$$

where:

AV	=	*uniform payment or equivalent average value of the expenditure*

As previously explained, “costs” $CC(c,y)$ may be positive or negative to represent expenditures or receipts of funds and, unless otherwise specified, are valued at the time they are recorded or incurred; i.e., they are future values (for y 0). As was discussed in Chapter 2 with regard to the discount rate, general price inflation or deflation may increase or decrease costs, so costs may be expressed in terms of “current” prices valued at the time the cost is incurred, or “constant” prices adjusted to a specific date. By convention, present values *PV* of costs are generally stated in constant dollars referenced to the start of the analysis period.

Cost categories The costs *CC(c,y)* are of many different types, but may be grouped into three principle categories: *agency costs [AC]*, *user costs [UC]*, and *vulnerability costs [VC]*. That is *CC(c,y)*} for all years [*y* £ *TA*] in the analysis period and all types [*c*] of costs defined as "vulnerability costs."

TLCC	=	$PV[AC] + PV[UC] + PV[VC] - PV[RV(T_A)]$
where:		
PV[AC]	=	*PV{ y c CC(c,y)} for all years [y T A] in the analysis period and all types [c] of costs defined as "agency costs"*
PV[UC]	=	*PV{ y c CC(c,y)} for all years [y T A] in the analysis period and all types [c] of costs defined as "user costs"*
PV[VC]	=	*PV{ y c CC(c,y)} for all years [y T A] in the analysis period and all types [c] of costs defined as "vulnerability costs"*
$RV(T_A)$	=	*residual value at the end of the analysis period,* $y = T_A$

Some analysts make a distinction between costs that are directly observable and measurable and those that must be inferred from other observations. A distinction may also be made between those costs associated with the routine business of bridge use and maintenance, as opposed to costs incurred as a consequence of extraordinary events (e.g., earthquake, major storm, vehicular collisions). The former distinction is important primarily for understanding the sources and levels of uncertainty in cost estimates. The latter distinction is the basis for defining "vulnerability costs." These distinctions are considered again later in this Chapter.

Residual value (*RV*) What remains at the end of the analysis period has a residual value that reflects the remaining useful life left to the bridge (a "residual value"). There can also be a terminal value of its constituents *BCV* (e.g., recyclable steel, land) put to an alternate use. If the bridge has no remaining useful life and the cost of abandonment or removal is higher than what the agency can get selling the parts, the residual value is 0 and the terminal value is negative. Generally, residual and terminal values are computed as

RV+TV	=	$PV(SL) - PV(T_A) + BCV$
where:		
PV(SL)	=	*present value of all costs for time y SL, the end of the servic e life*
PV(TA)	=	*present value of all costs for time y T A, the end of the analysis period*
BCV	=	*opportunity cost of the bridge structure and land including decommissioning*

The quantity $PV(SL) - PV(T_A)$ is the residual value at time $y = T_A$.

A typical approach to developing an independent measure of residual value is based on an estimate of the bridge's current replacement cost,

$$RV(T_A) \quad = \quad RC\left\{\left[BCR(T_A) - BCR(U)\right] / \left[BCR(0) - BCR(U)\right]\right\}^d$$

where:

RC	=	*estimated replacement cost for the structure*
$BCR(T_A)$	=	*estimated bridge condition rating at the end of the analysis period*
BCR(0)	=	*estimated bridge condition rating at the beginning of the service life*
BCR(U)	=	*bridge condition rating at which the service life is expended*
d	=	*an exponent 1, typically 2*

Some agencies have developed methods for computing residual value or the "depreciation" factor $\{[BCR(x)-BCR(U)] / [BCR(0)-BCR(U)]\}^d$, where *x* is an indicator of planned and cumulative service usage. This parameter [*x*] typically may be elapsed time (e.g., years), cumulative total traffic volume, cumulative number of standard axle-loads, or some other indicator of likely level of deterioration or wear since the bridge entered service or was last reconstructed.

Actions, Deterioration, Hazards, and Consequences

Bridge costs are incurred generally as a consequence of specific actions taken by a transportation agency to facilitate road users' activities and by road users (including the general public at large). These actions are taken during the course of the bridge's life cycle, which extends in principle from the first time the development of a bridge structure is considered until that structure is removed from service. For analysis purposes, the individual costs themselves are assumed to be identifiably linked to specific actions and to occur at a specific time, as will be discussed in subsequent sections.

Sometimes these cost-causing actions respond to events not directly under the control of either the agency or users. These events may occur routinely, such as the development of congestion when traffic demand is high, or they may be extraordinary, such as scouring and other flood-damage associated with a major storm. The distinction between actions and events as the cause of costs–a distinction that may be carried over to the costs themselves, as noted previously–is useful primarily as an organizing concept for BLCCA. Once the costs and their timing *CC(c, y)* are specified, all types are treated the same in the BLCCA computations.

Figure 4.1 Major categories of routine agency actions or events

Design, engineering and regulatory
Acquisitions and takings and other compensation
Construction
Maintenance and repair
- Force account versus contracted
- Scheduled versus responsive

Contract incentives and disincentives
Demolition, removal and remediation
Inspections
- Scheduled
- Special

Site and administrative services
Replacements and rehabilitations
Miscellaneous routine agency actions

Figure 4.1 illustrates the types of agency actions that can entail costs included in a BLCCA.

Figure 4.2 Major categories of routine user actions or events

Traffic congestion delays
Accidents
Traffic detours and delay-induced diversions
- Caused by load
- Caused by clearance restrictions
- Caused by congestion

Highway vehicle damage
Environmental damage
Miscellaneous routine user actions

Figure 4.2 lists the types of routine user actions. All of the costs likely to be incurred because of these actions are termed "routine."

Figure 4.3 Events contributing to vulnerability costs

Load-related structural damage
- Overload
- Fatigue

Collision damage
- Traffic collisions
- Motor vehicle with structure (vertical, horizontal)
- Other collisions with structure (barge, rail, etc)

Earthquake-related damage
Flood-related damage
Scour-related damage
Obsolescence

Extraordinary events, typically hazard-related (see Figure 4.3), may substantially increase costs or require specific agency actions to avoid such extraordinary costs. The costs that may be incurred by the agency and users because of these events are described later in this Chapter.

Deterioration results more or less continuously from routine actions (i.e., agency and user) or in response to extraordinary hazard-related events. The measures of deterioration and consequent costs depend on the bridge-element and actions or events of interest.

Agency Costs

Agency costs are for the most part directly observable, with unambiguously measurable monetary values. A key exception is those costs that may be assigned by some agencies as "overhead" on design and construction contracts or maintenance spending. Unless there is a reason to do otherwise, agency costs are typically assumed to be incurred at the end of the period in which expenditures actually will occur. Design and construction costs for new facilities and the like, which are incurred prior to the beginning of the bridge element's use, are assumed to occur at the end of the preparatory period, which is then the beginning of the analysis period and service life.

<u>Design, engineering, and regulatory</u> This type includes all studies, environmental and other reviews, and consultant contracts prior to solicitation of construction bids for a new bridge or a major rehabilitation of an existing bridge. Each study or contract may be designated by its costs, allocated to the agency's fiscal years during which funds are budgeted or the years in which disbursements are likely to be made.

The estimated costs in each year are uncertain; that uncertainty is reflected in a probability distribution of cost variance. Uncertainties arise from changing competitive conditions that influence consultants' fees, administrative matters and general price changes that can influence both agency and consultant costs, and possibilities of public controversy or other unforeseeable events. User judgement and agency experience are thus the best bases for developing both best-guess cost estimates and the probability distribution. Many agencies develop best-guess estimates of these costs as a percentage of estimated construction costs, and such estimates may be used as best-guess cost default values when no other information is available.

<u>Acquisitions, takings, and other compensation</u> These costs include expenditures for both land and compensation for reductions in land value associated with reduced access, environmental impact or restrictions, and the like. Compensation for losses of business may be required when bridge closure or maintenance activities separate an establishment from its customers or suppliers. Agencies may also incur costs of litigation and compensation when bridge conditions are claimed to cause traffic accidents or damage to vehicles using the facility, e.g., because of pavement irregularities. The agency's overall experience is a primary source of default estimates for the anticipated level of these costs for a particular bridge; these costs are generally a function of the bridge's condition and length of maintenance activities.

<u>Construction</u> This type includes administrative and contract costs for development of the bridge and ancillary facilities, e.g., river-bank revetments, approach roads, or compensation for real-estate partial takings. Agencies may also include interest expenses and other costs caused by delays in project execution. However, such costs may be included in the "Contract incentives and disincentives" type discussed below.

Similarly, administrative costs may be isolated from contract costs by placing the former in the type "site and administration services."

Costs of each construction project are allocated to the agency's fiscal year during which funds are budgeted or the year in which disbursements are likely to be made. As a default, the best estimate of these costs may be distributed uniformly over the period of construction (although the computations treat each year's costs as occurring at the year's end). Uncertainties in the overall estimated costs–and hence the costs in each year–arise from changing competitive conditions that influence bid prices, unknown site conditions, weather, and administrative matters and general price changes that can influence both agency and contract costs. Hazard events, possibilities of public controversy and other unforeseeable occurrences also contribute to uncertainty. Analyst judgement and agency experience are the best bases for estimating the probability distribution.

Unit costs and bills of quantities are the most widely used basis for developing construction cost estimates when at least design studies have been completed. In the absence of such studies, parametric cost-estimating models may be used to develop the best-guess estimate and sometimes a basis for estimating the cost-variance probability distribution. These models are constructed using statistical correlations (e.g., linear regression) of observed costs and characteristics of bridges in an inventory, e.g., superstructure type (steel or concrete), maximum span-length, span height, number of spans, deck area, and the like. Such a parametric model, developed through regression analysis, typically will have the following form:

$$\text{Best-estimate cost} = A + b_1p_1 + b_2p_2 + \ldots + b_np_n + å$$

where:

p_1 *through* p_n	=	*characteristic parameters, e.g., length, deck area*
A, b_1 *through* b_n	=	*constants determined by regression*
å	=	*error term in the regression*

Any construction-cost estimate is uncertain. Analyst judgement and agency experience are sometimes the only bases for developing both best estimates and probability distributions for these costs.

<u>Maintenance and repair</u> This type includes (a) periodic activities required to maintain a bridge's condition at or above acceptable levels, often termed "normal maintenance or "routine maintenance," and (b) more substantial actions to repair or replace elements that threaten bridge condition but do not by themselves represent an unacceptable condition. These activities may be undertaken by the agency's own forces or contracted out under a variety of contractual arrangements.

Unusual or aperiodic activities such as repairs following a hazard-related event (e.g., flood damage) or major rehabilitation necessitated by the accumulated damage of deferred maintenance or overloading are treated as "construction" or "rehabilitation and replacement" events. Some agencies consider upgrading activities, e.g., approach and deck widening, to be "rehabilitations" as well.

Periodic maintenance activities may be regularly scheduled–e.g., normal, protective, or preventive maintenance–or undertaken in response to observed conditions. Maintenance of the latter type could include painting, deck overlays, and other items warranted by inspections or reports of condition deterioration. Normal or preventive maintenance activities typically are specified by agency policy.

Costs of these activities are best determined from agency experience. As with construction costs, some agencies have developed parametric models to predict periodic maintenance costs as a function of bridge-design and operating conditions.

A more sophisticated approach to projecting both normal and remedial maintenance activity costs relies on mathematical deterioration models that compute expected bridge condition as a function of traffic-loading, climatic conditions, age, and other characteristics of the bridge's service history. These deterioration models typically are developed for particular bridge elements, e.g., steel girders or reinforced-concrete stringers. A typical form for these models predicts bridge-component condition *BCC(y)* at a particular time *y* as

$$BCC(y) = ICC - d_1 \left[TLR(y) \right]^b - d_2\, y^{\,c}$$

where:

ICC	=	*initial condition when the component was placed in service or at its last major rehabilitation*
TLR(y)	=	*critical traffic-load repetitions to which the component has been exposed since it was placed in service or since its last major rehabilitation*
d_1, d_2	=	*component deterioration rates for wear and aging*
b, c	=	*exponents determined by theory or observation, typically recognizing that fatigue and other wear and aging damage mechanisms accelerate*

Traffic-load repetitions typically used are those specified in AASHTO or state design guides, e.g., HS20 rating-vehicle (36 tons) or 18K axle-load equivalents. Condition measures for *BCC(y)* and *ICC* may include overall load or generalized condition rating or characteristics directly observable on inspection, such as degree of steel corrosion or concrete crack and spalling depths (e.g., FHWA 1979).

As a default approach to estimating maintenance costs, parametric equations predicting overall bridge rating may be used. Bridge-rating indices–e.g., the FHWA Sufficiency Rating formula–are widely used to determine network-level priorities for maintenance of bridges in a statewide inventory. These indices, often a function of rated load capacity, importance in the network, and other factors, typically rate a bridge in a few steps such as "desirable," "satisfactory," or "unacceptable." The "component" in the preceding equation is then the bridge overall or its superstructure and the condition measure *BCC(y)* indicates the bridge rating. Agencies that have developed data for network-level bridge management tools such as PONTIS or BRIDGIT may then use that data to produce initial estimates of appropriate scheduled maintenance costs for the individual bridge being analyzed.

Contract incentives and disincentives Some state transportation agencies have begun to use financial incentives or disincentives in contracts to encourage faster completion of construction and major rehabilitation repair projects, discourage roadway obstruction, and thereby reduce the duration or severity of traffic disruptions. These instruments typically take the form of penalties for each day of delay beyond the contract completion date, charges to the contractor for each hour that a travel lane is blocked ("lane rent"), or bonus payments for each day that the actual project completion precedes the contract completion date. These actions may be considered as components of a construction action and the likely costs estimated from agency policy. Experience with such contracting mechanisms is too limited to derive default cost models, although the Florida Department of Transportation has undertaken to document the impact of that agency's experience in the form of an *Alternative Contracting User's Guide* for its personnel and has conducted extensive reviews of the agency's experience with "A+B" bidding, design-build, and liquidated savings, as well as lane rental and mechanisms for reducing traffic disruption and user costs.

Demolition, removal, and remediation This type of actions refers to bridges that are taken out of service and partially or totally demolished. In many cases only the bridge's superstructure is removed, although sometimes reconstruction of "natural" landscape and environmental conditions may be included in a project's scope. While they may be considered as "routine" agency actions, costs associated with these actions are generally incurred only following extraordinary deterioration. These costs are generally handled in exactly the same manner as those for construction or rehabilitation or replacement. Agency experience is the only practical source for cost estimates. These estimates may be generalized or based on unit prices and bills of quantities.

Inspections This type includes both regularly scheduled inspections and "special" inspections made in response to observed deterioration, extraordinary events (e.g., severe flood), or particular characteristics of the bridge (e.g. those with fracture-critical members, vulnerable to scour, posted as load-restricted or carrying loads close to the design levels). Some agencies include regularly scheduled inspections in their "normal" or "preventive" maintenance costs. Agency experience or budgets are the only practical source for cost estimates. In general, inspection costs are not that significant unless the analysis is trying to isolate a specific decision such as inspect versus repairing fatigue prone details.

Site and administration services This type refers to agency administrative activities for quality assurance and payment verification during contracted construction, rehabilitation, and repair work. Agencies may include these costs with "construction." Agency experience or budgets are the only practical source for cost estimates.

Replacement and rehabilitation Bridge replacements may include superstructure only or complete replacement of foundation, substructure and superstructure. The former action may be termed a "partial replacement" or a "rehabilitation." The latter term also is used for large-scale repairs that may include replacement of elements. In any case, the actions and costs are similar to those discussed previously in the categories of "construction" and "demolition, removal, and remediation."

Miscellaneous agency actions This type is included to accommodate items unique to a specific bridge or analysis situation. For example, surveys required to document historic structures or provision for archeological or special studies in environmentally sensitive areas will typically represent significant costs beyond those required for routine "design, engineering, and regulatory" categories.

User Costs

User costs typically must be inferred, e.g., from observations of increased fuel consumption and time lost due to increased congestion and assumed values of that time. Some of these costs may be incurred as monetary expenses, e.g., increased vehicle fuel consumption, but most are not.

<u>Traffic congestion delays</u> This type includes delays imposed on road users (1) by temporary closures of bridge lanes for routine maintenance, repair, and rehabilitation; (2) by the congestion that develops when such closures slow traffic and create secondary queuing delays; and (3) by the traffic-impeding effects of poor roadway conditions. The delays imposed on road users required to detour to other routes during longer-term closures are included in the “traffic detours” category. The costs include time lost and increased vehicle-operating costs due primarily to excess fuel consumption. The traffic delay costs due to congestion and closure TDC_C are often estimated by using unit costs, e.g.,

$$TDC_C = \left[tdc_1\, v_1 + tdc_2\, v_2 + \ldots + tdc_n\, v_n \right] DT_c$$

where:

$tdc_1, tdc_2, \ldots tdc_n$	=	*delay cost per vehicle per unit time for vehicle type 1, 2, …n*
$v_1, v_2, \ldots v_n$	=	*number of vehicles of type 1, 2, … n delayed by the action*
DT_c	=	*average delay time per vehicle due to congestion and closure*

Costs generally increase as a function of the duration of lane closure and traffic volume. Traffic volume, a key parameter in estimating user costs, is generally stated as vehicles per unit time per travel lane, e.g., vehicles per hour per lane (*vphpl*). Traffic often is measured in terms of passenger-car [*pc*] units, a measure computed by using “passenger-car equivalency” factors to convert the numbers of trucks and other slow or oversized vehicles in the traffic stream to an equivalent number of passenger vehicles that would be associated with similar traffic conditions. The actual number or percentage of trucks in the traffic stream is a second key parameter in estimating user costs; i.e., “passenger cars” and “trucks” generally compose the minimum number of vehicle types for estimating user costs. In the absence of specific estimates of traffic volumes on a particular bridge, average two-way traffic flow [average daily traffic, *ADT*] may be multiplied by the maintenance-action’s duration (number of days) to estimate numbers of vehicles likely to be delayed.

Traffic flow and queuing models may be employed to make relatively precise estimates of the numbers of vehicles likely to be delayed and the likely lengths of delay during partial and complete temporary closures. For relatively short-duration complete closures when traffic volumes are low–e.g., 1,200 to 1,800 vphpl– queues are unlikely to grow beyond those that form during the closure. In this case, actual closure time may be used as a default estimate of delay. These volumes represent typical “saturation flow” rate observed, for example at signalized intersections, operating under a wide range of conditions (e.g., see *Highway Capacity Manual* 1994).

Similarly, the estimated change in roadway level of service [*LOS*] and travel speed associated with channeling all traffic through a reduced number of lanes may be used as a default for estimating delay during partial closures. Relationships among traffic volume, *LOS* and travel-speed may be available from local data or taken from the *Highway Capacity Manual* (1994).

The delay costs per vehicle per unit time [tdc_n] typically include at least two components, time value and direct costs of vehicle operation. Time costs are found through economic studies and will depend on such factors as industrial base of the region, population income statistics, and the like; a frequently-used default value for automobiles is some fraction of the mean hourly wage of employed persons in the region; 50 percent or 100 percent are commonly used. Time value for truck delays will typically be greater because of estimated consequences of delayed cargo deliveries. Vehicle operating costs will include primarily fuel consumption during idling; local transportation-planning agencies and the U. S. Department of Energy typically have available estimates for a variety of vehicle types. Because time costs typically are substantially greater than vehicle operating costs for traffic delays, average wage rates are frequently used as a default for unit delay costs. Many analysts continue to rely on outdated information, not infrequently referring to decades-old work published by Robley Winfrey (1969).

Under normal operating conditions, bridge-deck riding surfaces become rough (e.g., rutted, cracked, spalled, potholed) in the absence of corrective maintenance. Increased roughness slows traffic and imposes delays and costs on the bridge's users. The average delay associated with deck-surface pavement condition [DT_P] is typically estimated as a function of a pavement-condition index, for example

$$DT_P = A\left[CI_t / CI_F\right]^Z$$

where:

CI_t	=	*condition deterioration index (increasing with roughness) during the period considered (e.g., one month or one year)*
CI_F	=	*condition index level considered failure and warranting resurfacing*
Z	=	*empirical or judgmental exponent typically greater than 2.0 (e.g., Purvis et al 1994 sets z = 4)*
A	=	*unit-delay calibration factor*

<u>Traffic detours and delay-induced diversions</u> This category includes costs imposed on road users required to detour to other routes because a bridge cannot accommodate a vehicle's weight or size dimensions or because of bridge closures or severe congestion. The traffic delay costs due to diversion [*TDCD*] are estimated in the same manner as those due to congestion, e.g.,

$$TDC_D = \left[tdc_1 v_1 + tdc_2 v_2 + \ldots + tdc_n v_n \right] DT_D$$

where:

$tdc_1, tdc_2, \ldots tdc_n$	=	*delay cost per vehicle per unit time for vehicle type 1, 2, …n*
$v_1, v_2, \ldots v_n$	=	*number of vehicles of type 1, 2, … n diverted to another route*
DT_D	=	*average delay time per vehicle diverted*

In many cases, an adequate estimate of the detour costs may be calculated as twice the distance between the bridge under analysis and the closest alternate crossing [D_D]; i.e., for each type of vehicle [n] diverted,

$$TDC_D = 2\left[(FP / FC_n) + (TV_n / S_n) \right] D_D v_n$$

where:

FP	=	*prevailing average price of fuel*
FC_n	=	*average fuel consumption rate for vehicle type n*
TV_n	=	*unit value of time for vehicle type n, e.g., average wage rate*
S_n	=	*average speed of vehicle n*
v_n	=	*number of diverted vehicles of type n*

<u>Highway vehicle damage</u> Bridge-deck or work-zone conditions may increase the likelihood that vehicles traversing a bridge will be damaged, e.g., by rough or uneven pavement, obstructions, and the like. These costs may be estimated as proportional to traffic levels. To the extent that these costs are repaid to the user as agency settlements, they will be included in agency costs and should not be double-counted.

<u>Environmental damage</u> Users–i.e., the public at large–may incur costs of environmental damage associated with bridge management if land is disturbed or altered, pollutants or waste products are permitted to enter adjacent waters or air, or waste materials are produced and require disposal. These costs arise from incremental damage greater than that caused by the road system operating under normal conditions. For example, traffic congestion and diversions increase air-pollution emissions. Bridge painting may deposit particulate materials (e.g., sand) in surface waters and possibly lead-paint debris as well. While agencies may pay direct costs for environmental impact-prevention and remediation activities, agency officials will typically judge many environmental-damage costs to be unavoidable.

Part of this judgement rests on the difficulty of attributing economic values to environmental damage. Recently conducted environmental impact studies may contain estimates that can be adopted for bridge-management analyses.

<u>Business effects</u> This category is similar to environmental damage in that it represents uncompensated costs imposed on road users and the public at large by disruptions of normal business activity. Enterprises whose customers, suppliers, or delivery vehicles encounter delays, diversions, or other disruptions of their normal

activity patterns may suffer loss of business, increased production costs, or both. These losses are directly measurable in monetary terms, but their estimation is difficult unless a small number of establishments may be pinpointed as bearing the greatest impact (e.g., all the heavy vehicles that are diverted by a load posting serve a single concrete plant). Recently conducted environmental impact studies and "major investment studies" for road projects may contain estimates that can be adopted for bridge-management analyses. In general, it can be said that business effects are a zero sum game where there is no net effect but merely a redistribution of costs and revenue. However, costs should be included if compensation is paid.

<u>Miscellaneous routine user actions</u> Other user costs that may be incurred as a result of routine bridge-management activities include nuisance effects of noise and dust during major repairs and reductions of access to schools, and health-care, recreational and community facilities. The levels and value of these costs must be inferred from information about road users and communities served by the bridge under study. Recently conducted environmental impact studies and "major investment studies" for road projects may contain estimates that can be adopted for bridge-management analyses.

Vulnerability Costs

Bridges are sometimes exposed to extraordinary circumstances involving hazards such as flooding, seismic events, or traffic occurrences that may or may not cause disruption and damage, but that must be considered by the agency responsible for a bridge's management. The agency's costs to repair damage sustained because of a hazard event might have been avoided if the bridge had been designed, constructed or maintained differently. The costs users incur travelling a circuitous route because a bridge is out of service similarly have been avoided. These hazard-vulnerability, or simply "vulnerability," costs may be very large, but the probability that they will indeed be incurred is typically very small. Because of these small probabilities of occurrence, Monte Carlo simulation generally is not an effective tool for dealing with these vulnerability costs in a BLCCA. As previously noted, the problem is the number of trials required for the simulation to exhibit an occurrence of a rare event. In 1,000 simulation runs intended to model a 50-year analysis period, for example, there is only a 50-percent chance that any damages associated with a scour-producing 100-year storm will be simulated.

The hazard-exposed bridge faces the potential for damage throughout its service life. An expected annual vulnerability cost *VC(H)* may be computed for each potential hazard *H*; i.e.,

$VC(H)$	=	*$E(c\|H)$, the expected cost given that the hazard H has some impact*
	=	${}_i \left[c(h_i)\ x\ p(h_i) \right]$
where:		
$c(h_i)$	=	*estimated cost associated with a hazard event h_i of intensity i (e.g. damage repairs caused by an eathquake of magnitude 5.7)*
$p(h_i)$	=	*probability of hazard event h_i occurring in any single analysis period, typically expressed on an annual basis*
i	=	*the set of estimated intensities {i} for hazard H*

Figure 4.3 lists the types of hazards *H* that may typically be included in a BLCCA; climate, geology, traffic, and other local factors will determine which hazards are in fact included in a particular analysis. Only those hazards that are likely to be relevant to the bridge-management strategies under consideration need be included in the BLCCA. Even in an area subject to substantial seismic risk, for example, the analysts might reasonably determine that earthquake hazard has little to do with scheduling repainting of a steel bridge's superstructure.

Several simplifying assumptions are typically made in estimating values for hazard probabilities. For example, hazard events are typically assumed to be independent with respect to types and severity, i.e., for example

p(earthquake occurs | flood occurs)	=	*p(earthquake occurs), and*
$p(h_1) + p(h_2) + \ldots + p(h_i) + \ldots + p(h_s)$	=	*p(H), where hazard H may occur with severity levels i = 1 through S*

In other words, the probability that an earthquake of a particular magnitude occurs in any one year is not dependant on whether a flood has occurred in the same year.

The probabilities of occurrence [$p(h_1), p(h_2)... p(h_S), p(H)$] are often assumed to be independent of the bridge's condition but may change with traffic levels or other time-related parameters. The anticipated costs [$C(h_i)$] are generally dependent on the bridge's current condition and design characteristics.

<u>Load-related structural damage</u> This type of costs includes losses of structural integrity (or sharply increased risk of such losses) due to overloading or excessive fatigue in key structural members. The likelihood of such occurrences is, generally speaking, a complex, time-varying function of past and current loading patterns, environmental conditions, material characteristics, and structural configuration.

The precipitating event for load-related structural damage is the bridge's use by vehicles that exceed the design loading either in absolute terms or in terms of numbers of repetitions of loads likely to cause fatigue damage. Models that predict bridge rating-factors or condition indices have been developed for a number of bridge types–e.g., design geometry and materials (Purvis *et al*. 1994). The probability of an occurrence of load-related structural damage [$p_L(t)$] at time *t* is then estimated as the joint probability of a loading (intensity for overload or number and intensity for fatigue) and susceptible condition for that loading. A conservative default estimate of this probability may be computed as

$p_L(t)$	=	*p(overload damage) + p(fatigue damage)*
	=	$[p_{OL} + p_{FL}]\{1 - [BCC(t) / ICC]\}$
where:		
p_{OL}	=	*probability of a vehicle of critical load for overload*
p_{FL}	=	*probability of a vehicle of critical load for fatigue*
BCC(t), ICC	=	*present and initial condition index for the critical component*

The probabilities of critical loads may be estimated from highway-traffic or vehicle-registration statistics.

Currently used bridge-design standards (e.g., AASHTO standards) have been developed to minimize the risk of fatigue failure during the recommended design service life of a new bridge. An analyst might reasonably assume that a BLCCA of a new or recently constructed bridge need not consider fatigue separately from overload. In any case, the anticipated cost of repairing service-related structural damages will be a function of bridge type and the specific actions needed to reinforce or replace damaged components. These costs will likely include a special inspection to determine levels of damage.

<u>Collision damage</u> This hazard includes events in which oversized or out-of-control vehicles strike the bridge with sufficient force or cause fire or chemical-spill damage that threaten structural integrity. Bridges crossing rail lines or navigable waterways may be vulnerable to collision damage from trains or barges and ships as well highway vehicles. The probability of these occurrences may be estimated from agency experience and is typically assumed to be uniform from year to year. A conservative default estimate of this probability may be computed as

$$P_C \quad = \quad p(\text{collision sources})$$

Sometimes, bridge design or condition and construction or maintenance work-zone conditions may pose hazards to vehicles and contribute to occurrence and severity of traffic collisions. User costs associated with property damage, injuries, and loss of life are likely to exceed any compensation that may be paid from agency expenditures. Traffic accident costs [*TAC*] are frequently estimated as a function of traffic volume,

$$TAC \quad = \quad AC_k \times ADT$$

where:
AC_k = *accident cost factor for bridge with characteristic k*
ADT = *average daily traffic on the bridge*

Statistics collected by the insurance industry and accident records maintained by state transportation agencies, police departments, and national agencies such as the National Highway Transportation Safety Administration may be used to develop accident cost-factors. The anticipated cost of repairing collision damages will be a function of bridge type and the specific actions needed to reinforce or replace damaged components. Fire and chemical spills may cause extensive superficial damage, and expenses for load tests to determine damage may be part of the anticipated costs.

<u>Earthquake-related damage</u> Bridges located in areas of high seismic risk are susceptible to damages that may warrant adoption of more stringent design standards for moment- and lateral-force resistance. As experience has shown, damages due to earthquake are often quite extensive for bridges not appropriately designed and constructed. For example, California's moderately severe (7.1 on the Richter Scale) Loma Prieta earthquake in 1989 damaged only 1 of the 800 bridges designed since 1972 in the jurisdictions

designated disaster areas. Standards introduced in 1971 required substantial increases in confinement and shear reinforcing in bridge columns, as compared with earlier designs. Older bridges that had been retrofitted with hinge-joint restrainers also fared well; engineers agreed afterwards that many of these bridges would have experienced collapse of spans had these restrainers not been in place (Roberts 1994).

The damage likely to be experienced by a specific bridge will depend on the characteristics of the bridge and its immediate surroundings, as well as the regional likelihood of an earthquake of a particular severity and the bridge's design and construction characteristics. Local geology and soils conditions may influence ground motion and accelerations, thereby shifting dramatically the forces a given earthquake imposes on otherwise similar structures. Estimates of the probability that an earthquake will impose forces of given intensity and duration, typically assumed to be uniform from year to year, may be based on probabilistic analysis of earthquake experience in the area, e.g., using U. S. Geological Survey and Federal Emergency Management Administration statistics. Estimated probable hazard levels may then include assessed likelihood that soil conditions will exacerbate accelerations.

Figure 4.4 Hazard and vulnerability criteria used in CALTRANS bridge assessments

	Weighting factors
Hazard attributes	
Peak rock acceleration	38.0%
Seismic duration	29.0%
Soil conditions	33.0%
	100.0%
Vulnerability attributes	
Year designed (constructed)	25.0%
Hinges (drop type failure)	16.5%
Outriggers, shared columns	22.0%
Bent redundancy	16.5%
Skew	12.0%
Abutment type	8.0%
	100.0%

Source Roberts 1994

For example, the California Department of Transportation (CALTRANS) uses a weighting scheme (Figure 4.4) to rate the hazard level (e.g., probability of occurrence of damaging earthquake) and the vulnerability of a bridge to damage (e.g., level of cost for repair). The initial estimates of probability of peak rock accelerations and seismic duration typically are based on a return period of 1000 to 2000 years (Roberts 1994). However, Division I-A of the AASHTO Standard Specifications for Highway Bridges assigns an Acceleration Coefficient [A] that is multiplied by the acceleration due to gravity [g], such that the product [Ag] represents the likely peak horizontal ground acceleration that will occur due to an earthquake sometime within a 475-year period. This acceleration has a 10-percent probability of being exceeded within a 50-year time frame (Buckle and Friedland 1994).

Regardless of the return period used, the occurrence of a damaging earthquake will cause costs for both agency (e.g., special inspection, repair, or demolition and replacement) and users (e.g., traffic detours and congestion delays, accident costs). These costs typically may be estimated for a prototypical earthquake event of a particular severity, based on the bridge's location, functional role in the network, and traffic levels. While the earthquake hazard for any bridge includes a range of earthquake intensities, conservative default estimates of probability of earthquake occurrence [*PE*] may be derived as

$$P_E \quad = \quad \textit{Probability(earthquake severity} \quad \textit{minimum intensity to cause damage)}$$

This representation enables use of the Poisson distribution to compute probabilities of severities. A similarly conservative default estimate of earthquake vulnerability costs [*VC(E)*] will be based on the agency and user costs expected if the bridge must be inspected, repaired or completely replaced.

<u>Flood-related damage</u> This hazard is very similar to earthquake, with structural damage due to lateral forces imposed by high-water flows and impact of flood-borne debris on a bridge's superstructure and supports. (Loss of foundation support due to scour is discussed here as a distinct category of hazard.) Extreme flooding may also cause erosion of bridge approaches. The hazard is restricted, of course, to bridges that cross flood-prone watercourses or are located downstream from dams that might fail. However, if the bridge and its approaches are the source of the flow constriction that causes flooding, then any flood damage to adjacent lands, buildings, etc. should be attributed to the bridge.

Hydrological data provide the basis for estimating frequency and severity of storm-related flood events. The flood hazard for any bridge may include a range of storm intensities; a conservative default estimate of probability of flood-damage occurrence [*PF*] may be derived as

$$P_F \quad = \quad \textit{Probability(flood-event severity} \quad \textit{minimum intensity to cause damage)}$$

The occurrence of a damaging event will cause costs for both agency (e.g., special inspection and repair) and users (e.g., congestion delays and possibly traffic detours). These costs typically may be estimated for a prototypical flood event of a particular severity, based on the bridge's location, functional role in the network, and traffic levels. Assuming that total replacement would be required will give a conservative default estimate of flood-damage vulnerability costs [*VC(F)*].

<u>Scour-related damage</u> Bridge-pier scour, the erosion of foundation materials (i.e., soil and rock) under bridges crossing water, is a dynamic phenomenon that varies with water depth and angle of flow, pier shape and width, soil characteristics, and other factors. The mechanisms of scour are not well understood and are currently the object of active research. The problem is sufficiently widespread and severe–the vast majority of bridge failures over water are said to be due to the effects of scour–that the Federal Highway Administration has mandated the evaluation of all highway bridges for scour vulnerability and a nationwide effort by state and federal agencies is underway to evaluate actual and predicted scour depths. As reported by the Transportation Research Board and contractors under the National Cooperative Highway Research Program, the total budgets of currently active research projects on bridge scour exceed $4 million. The survey of vulnerable bridges was mandated for completion in 1997. The agency and user costs of scour-related damage can be comparable with those of earthquake: instability can lead ultimately to catastrophic failure, possible loss of human life and facility replacement.

Bridge scour and stream stability inspections are performed to monitor conditions that may result in critical scour conditions and then provide guidance on appropriate action. The assessment of probability of scour damage [*PS*] and likely costs in the event of damage depend on the expertise and experience of inspectors. Generally, the costs and probability will both depend on the frequency and effectiveness of bridge inspections. A computer-based "expert system" currently being developed by researchers at the University of Washington (named CAESAR, from Cataloguing *A*nd *E*xpert Evaluation of *S*cour Risk *A*nd *R*iver Stability at Bridge Sites) to aid in the scour evaluation of bridges, based on case studies at 25 U. S. sites, may assist the assessment of these parameters. The *BRI*dge *S*tream *T*ube model for *A*lluvial *R*iver *S*imulation and sediment transport (BRI- Stars), another expert system microcomputer program that provides design criteria for highway stream crossings and flood-plain encroachments, includes a stream-classification system that may be used to judge probabilities of scour. ("BRI- STARS ..." 1994) Research projects in a number of states have produced other models that may be used to make default estimates (e.g., Sheppard 1992).

<u>Obsolescence</u> A number of factors can cause bridge obsolescence, including technological changes (e.g., shippers using larger trucks), regulatory changes (e.g., wider travel lanes or shoulder widths), and economic or social changes that substantially alter the demands placed on the bridge (e.g., higher-than-planned traffic volumes and percentage of heavy vehicles). An obsolete bridge is not necessarily unable to carry traffic or be otherwise dysfunctional, although these conditions may underscore its obsolescence. Rather, the bridge simply does not measure up to current needs or expectations. For example, low clearances made many Federal-aid-system highway overpasses obsolete when the higher Interstate-system standards were adopted. In each such case, obsolescence imposes agency and user costs or reduces the service life or both. Agency costs are likely to include expenses related to load posting, special inspections, and use-request permitting. (e.g., the Texas Department of Transportation issues special permits for heavy trucks to use bridges on the state's Farm-to-Market system). User costs may include detour and business effects.

The National Bridge Inventory includes statistics on bridges classified as "functionally obsolete" because they do not meet current standards. The FHWA's Coding Guide (FHWA 1995) defines the class as bridges having one or more deficiencies in roadway alignment, vertical clearance, bridge-deck width, underclearance, or structural load-bearing capacity. The large number of existing bridges on the Federal-aid system that fall into the category of "functionally obsolete" illustrates the potential severity of this hazard. However, there are no generally applicable statistics to support forecasting of future changes in standards that would cause obsolescence of a currently acceptable bridge. Generally, a bridge with greater difference between the bridge's current condition and the minimum-acceptable condition will have a lower probability of obsolescence in subsequent time periods (Lemer 1996). The latest version of the coding guide and errata can be found at the web site: http://www.fhwa.dot.gov/bridge/bripub.htm .

Summary Considerations on Best Estimates of Costs

Estimating costs and the probabilities that these costs will be incurred is a crucial component of BLCCA, regardless of the specific types of costs defined and included in a particular management analysis.

Figure 4.5 Guidance on treatment of cost categories in BLCCA

	Agency Costs incurred by the bridge owner/operator, typically as actual cash expenditures	**User** Direct cash expenses (e.g., increased fuel use), in-kind losses (e.g., time spent in congestion caused by lane closure), and other losses (e.g., reduced sales for a business) incurred by bridge users
Normal Costs incurred as a result of agency-planned or normally-occurring events, e.g., overlay construction, traffic using a bridge	1. Event timing is scheduled and may vary around scheduled time as result of scheduling uncertainty 2. Cost level is estimated and may vary around estimated amount as result of cost-estimating uncertainty 3. Cost in given year is computed from joint probability distribution of occurrence and level	1. Cost accrual is contingent on event occurring 2. Cost level is estimated and may vary around estimated amount as result of cost-estimating uncertainty 3. Cost in given year is computed from joint probability distribution of occurrence and level
Vulnerability Costs associated with rare and unplanned events, e.g., floods, earthquakes, traffic accidents; costs when an event occurs are typically high	1. Uniform annual probability of event occurrence is estimated 2. Cost level is estimated as function of event severity 3. Expected value of cost given range of severities is computed and may vary around estimated amount as result of cost-estimating uncertainty 4. Uniform expected annual cost of event is computed from probability of occurrence and probability distribution of level	

Figure 4.5 summarizes comments from the preceding sections, regarding how this guidance manual recommends that costs in the three principal categories should be addressed. The implication of the guidance presented here is that "routine" aspects of bridge management and related costs may be addressed using Monte Carlo simulation or other discrete-event simulation methods, while hazard-related risks require a different approach, e.g., estimation of expected annual vulnerability costs associated with a particular management strategy. The discounted present value of vulnerability costs is then one of the three principal components of a bridge's TLCC.

Other Parameters Influencing Computation of TLCC

Several other parameters may warrant special attention in the computation of a bridge's TLCC. However, in most cases, these parameters will have been addressed within the context of parameters described in preceding sections.

<u>Timing of actions</u> Unless the discount rate is assumed to be zero, the specific period in which an action is initiated and its cost incurred will influence the computation of present value of TLCC. When the discount rate is zero, $PV = FV$. Some analysts argue that a zero discount rate is appropriate for analysis of environment-related resources such as clean air and water. Higher discount rates, these analysts assert, sacrifice the interests of future generations to suit those of present decision-makers. However, others argue that the uncertainties of the future demand that future costs and benefits be given less weight in decision making, as is accomplished with discounting. Budgetary crises, political priorities, and other factors unrelated to the bridge itself may delay or accelerate the timing of particular actions. The consequences of shifting the timing of actions entailing high costs–e.g., major reconstruction–should be explored during the sensitivity-analysis stage of the BLCCA.

Another issue that can arise with timing is time-dependence of actions. For example, one may expect that the average service life of a deck overlay will be perhaps 12 years. A BLCCA involving a broad range of management actions and spanning a 75-year analysis period could then include several successive overlays. The analysts might wish to specify that the service life of each overlay is measured from the time period during which the previous overlay's surface is anticipated to reach an unacceptably poor condition. Because this time period is uncertain, the timing of the subsequent overlay is uncertain as well. In such cases, the action's timing may be treated as a stochastic variable. A distribution of probability would then be used to represent the start as well as the duration of the element's service life.

Maintenance quality The estimated condition of a bridge influences scheduling of inspections, scheduling and anticipated costs of routine maintenance activities, and likely vulnerability costs. Projected future condition depends, in turn, on assumptions that necessary maintenance is adequately performed. Failure to clear obstructed storm drains or expansion joints, for example, can increase probabilities of corrosion and localized stresses that lead to concrete spalling.

Estimated probabilities of occurrence in virtually all categories may depend on the probability that routine maintenance actions are completed effectively and on schedule, throughout the bridge's service life. This relationship is a basis for assessing the life-cycle-cost consequences of agency maintenance quality assurance (QA) expenditures and adoption of explicit maintenance quality control (QC) procedures. Neglect of routine maintenance and consequently accelerated condition deterioration may be represented in the BLCCA as a "shifting" of (1) the probabilities of routine agency and user costs from the "best guess" estimate based on presumed maintenance effectiveness and (2) the probabilities of occurrence of hazard-vulnerability costs. In general, assuming maintenance either is or is not effective,

$$
\begin{aligned}
P(cost) = {} & P(cost \mid effective\ maintenance)\, P(effective\ maintenance) \\
& + P(cost \mid not\ effective\ maintenance)\, [1 - P(effective\ maintenance)]
\end{aligned}
$$

In the absence of specific concern for this parameter–"maintenance effectiveness"–one assumes the probability of effective maintenance, P(effective maintenance) = 1. If an agency has adequate data on bridge costs, this assumption may be tested, e.g., to compare the relative effectiveness of maintenance in several management districts. In this case, BLCCA becomes the basis for an application of quality assessment and statistical decision theory.

Availability of special funds Certain government programs that make funds available for special purposes ("earmarked" funds) or for only limited periods of time may encourage agencies to undertake some actions sooner than they otherwise might or to defer other actions. For example, the U. S. Interstate Highways program's early provision that federal funds were available to cover 90 percent of the costs of new construction and substantial reconstruction but not recurring maintenance costs is now generally recognized to have encouraged rapid system expansion, high initial pavement-durability standards, and neglect of maintenance. The TLCC of a project or a program may not be minimized when such strategies are pursued. For example, some state transportation agencies use computer-based analysis programs to identify highway project priorities to maximize the federal contribution to state programs, i.e., to "stretch" state dollars to buy the largest possible amount of new construction. This strategy has longer-term consequences of increasing either the likely total system-wide costs of maintenance or the likelihood that otherwise unacceptable service conditions will have to be tolerated, or both. The impact of special-funds availability will typically be to shift the timing of certain actions in the analysis-period activity profile and cash flow schedule. These shifts will change the TLCC from what might otherwise have been estimated;

the magnitude of the change should be estimated with a sensitivity analysis that compares the activity profiles anticipated with and without the special-funds restrictions.

Chapter 5 Sources of Cost and Deterioration Information

Data Requirements and Likely Sources

BLCCA can place substantial demands on an agency's data resources. It has been generally acknowledged that statistics collected for the National Bridge Inventory compose an inadequate data base for effective life-cycle cost estimation and bridge management (Thompson and Markow 1996). The NBI was never intended to supply the level of information required to conduct life-cycle cost analysis but there are few other generally available sources of useful data. Researchers are therefore often restricted to using data of the sort collected for the NBI to develop element deterioration models, e.g., Sherer and Glagola (1994), Madanat *et al.* (1997). The analyst's judgement will often be a useful source of "best estimates" for BLCCA parameters until a comprehensive and directly relevant cost and deterioration database is assembled.

Parameter values found in other bridge-management situations may be a valuable basis for or supplement to this judgement. Agencies that use bridge-management tools, for example, will have inventory-wide average values for many parameters that may be used as initial default estimates of appropriate parameters for BLCCA of an individual bridge. Many states have in fact collected data for network-level bridge management and developed unit-cost estimates (Turner and Richardson 1994, Thompson and Markow 1996). Similarly, highway cost-allocation studies sponsored by the Federal Highway Administration are producing a data set that may be useful in calculating default values for many parameters (e.g., see Laman *et al.* 1997). These cost-allocation studies seek to develop tools to apportion damage due to fatigue in steel bridges and cumulative damage to concrete decks as a function of truck class, weight group, and highway class; e.g., current models consider the impact of 20 vehicle classes and 30 weight groups on each of 12 functional classes of highway.

Figure 5.1 Agencies reporting ability to estimate agency costs, of 33 survey respondents

Land acquisition	19
Mobilization	23
Traffic control	23
Environmental	16
Planning	14
Design	29

Source Thompsom and Markow 1996

Although many states have collected bridge-cost data, the scope of that data varies widely. Agency costs are most easily assembled and are most widely available; all agencies, of course, maintain records of their costs and have some capability to estimate construction costs. Thompson and Markow (1996) reported that 33 state agencies responding to a 1994 survey indicated they had available at least some maintenance cost data for their state-owned bridges. However, some states have only force-account and day labor cost data while others have only contract-maintenance records. Few states have made the effort to assemble historic data and develop unit-cost estimates. Only 29 states of the 33 responding in the 1994 survey reported the ability to estimate design costs for state-owned bridges (see Figure 5.1). An additional complexity is that agency costs should be all-inclusive and include items such as administration, overheads and the like. Not including these cost components underestimates the total agency cost. Even "do-nothing" alternatives can have these costs. Fixed costs can be ignored when comparing alternatives if those costs are the same for all alternatives being considered.

User-cost data are even scarcer. Ten states indicated use of vehicle-operating costs in their management analyses, and fewer considered travel-time costs, crash costs, or pollution costs. Only six states reported using user-cost models specifically for bridge studies (i.e., as compared with safety programs or pavements).

Of the states reporting any applications of user-cost data, North Carolina, Washington, and Utah appear to have the most extensive databases. North Carolina, in particular, has assembled an extensive database on some 14,000 bridges in that state's inventory (e.g., see Isa-Al-Subhi *et al*. 1989, Johnston 1993, and Johnston and Lee 1994). Indiana, Iowa, and other states have assembled data that may be useful but generally are less comprehensive or unavailable (e.g., Fanous *et al*. 1990 and 1991; Saito and Sinha 1990, Sinha *et al*. 1991; Green and Richardson 1993; Ruinen and Bell 1993; *Pennsylvania* 1987). Pennsylvania's data, for example, have not been made available to researchers because of the state-agency's concerns over pending litigation.

Studies of vehicle fuel-consumption behavior provide bases for estimating vehicle operating costs (e.g., Waters 1992, *Automotive* 1992), and data from less-developed regions may be adapted to U.S. bridge applications (e.g., Archando-Callao and Faiz 1994, Watanatada *et al.* 1987). In the absence of other information, user-cost estimates may be based on the average vehicle-operating costs estimated by the Internal Revenue Service and used in federal-government cost-reimbursement contracts (e.g., $0.325/mile in 1997) and the average per capita income level of the region to which the analysis refers.

Information on local climate, geology and soils conditions is required for assessment of vulnerability costs. Local conditions may have dramatic influence on flooding, seismic-related ground motion and accelerations. Estimates of the probability that an earthquake or storm will impose forces of given intensity and duration, typically assumed to be uniform from year to year, may be based on probabilistic analysis of experience in the area, e.g., using U. S. Geological Survey and Federal Emergency Management Administration statistics. Estimated probable hazard levels may then include assessed likelihood that soil conditions will exacerbate accelerations.

General Guidance on Assumptions

Raw data is not particularly useful in BLCCA. Research and analysis are required to produce estimates of key parameters such as service lives, deterioration rates, and monetary values of user costs. The AASHTO *Manual on User Benefit Analysis...* (1977, the "AASHTO Red Book"), for example, continues to be widely used as a source of information for dealing with inferred user costs, despite the substantial changes that the U. S. economy and transportation system have undergone since that document's publication. The *MicroBENCOST* computer software package automates many of the manual's procedures. Researchers at the Texas Transportation Institute (TTI) developed MicroBENCOST under a National Cooperative Highway Research Program project to revise and update the 1977 AASHTO Manual. The two-piece software package includes a main program that performs economic analyses and an update program that can be used to customize and update portions of the default values of unit operating costs, maintenance costs and other parameters (McFarland, *et al*. 1993). Much of the updating in the project involved conversion of traffic relationships to conform to those in the *1985 Highway Capacity Manual*. Researchers have been working to develop more up-to-date and easily-used benefit-estimation methods, although many methods stop short of assigning monetary values to such factors as commitment of environmental resources (e.g., wetlands) (*Guidance for Estimating* 1998). Contingent valuation methods–which use surveys of individuals' responses to hypothetical situations that explore their willingness to pay or be compensated for changes in a particular "good," e.g., time spent in traffic–show considerable promise in dealing with this problem (see, e.g., *Contingent Valuation* 1993)

Estimates of the consequences of bridge-management actions, e.g., work-zone congestion during pedestrian walkway repairs, that underlie subsequent costs often can be made using generally accepted relationships or studies of analogous situations. The *Highway Capacity Manual* (1994), for example, is widely used to estimated changes in roadway level of service, travel speed, and possible queue formation associated with channeling all traffic through a reduced number of lanes; time lost may subsequently be estimated. The HCM has recently been updated (at the end of 1997) and a software package released that automates many of the procedures for speed and delay estimation. The University of Florida's Center for Microcomputers in Transportation (McTrans) maintains a catalog and distributes this and other software (see <http://mctrans.ce.uf.edu/>). The FHWA has sponsored studies (e.g., FHWA 1989) that may be used to estimate crash costs and other consequences of work-zone management. The U. S. Department of Energy and Environmental Protection Agency have sponsored studies on the relationships of fuel consumption and air pollution emissions to motor-vehicle speed and idle time (e.g., Duleep 1995, EPA 1992).

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Appendix A Glossary

Glossary Introduction

Bridge life-cycle cost analysis (BLCCA) is a specialized application of the principles and practices of engineering economics. BLCCA also employs concepts adapted from civil and environmental engineering, other fields of economics, finance, and the social sciences. Each discipline uses terminology that may have precise and generally accepted meaning among specialists in that field, which may differ from the terminology of other fields and common use. The following terms are defined as they are used in this guidance manual. (Terms shown in *italics* are themselves defined in this glossary. Symbols or acronyms follow those terms that are so identified frequently in the text.)

Action

The application of resources to accomplish something related to a bridge; the basic unit of a *management strategy*, typically identified by its description and timing (e.g., apply a four-inch asphalt deck overlay in year 12); actions have anticipated *costs* and *outcomes*.

Agency Cost (AC)

Cost incurred by an agency responsible for bridge management; typically an actual expenditure of money (e.g., a *monetary cost*) for construction, maintenance and operation of a bridge; *actions* entailing agency costs include inspections, *normal maintenance*, construction, *repairs*, and land acquisition.

Analysis Period

The time period, typically measured in years, over which *costs* of a *bridge-management strategy* are evaluated; same as *time horizon*, *planning horizon*, but not necessarily the same as *service life*.

Analysis Scenario

Conditions–e.g., of traffic, climate, agency budget allocations, regional economy–assumed to hold during the *analysis period*, that influence the BLCCA; characterized by such parameters as *discount rate*, estimated probabilities of severity and cost of seismic events, unit costs for *normal maintenance*, and the like; a BLCCA may employ several analysis scenarios, especially as part of the *sensitivity analysis*.

Base Case

The *management strategy* and *analysis scenario* assumed to apply in the absence of any particular agency initiative, sometimes termed the *do-nothing alternative*, although the base case will generally include at least *normal maintenance* at historical levels.

Best Estimate

The anticipated value of a parameter–e.g., *cost* of an *action*, *service life* of an *element*–based on available data, judgement, or current policy; may or may not represent a specifically defined statistical measure such as *expected value* or mode.

Bridge Element

See *element*.

Bridge-Management Strategy

A *management strategy* for a bridge or group of bridges; the object of BLCCA.

Bridge-Management System (BMS)

A set of rules, guidelines, and procedures used to identify a *management strategy*; the term has usually been used to refer to computer programs such as PONTIS or BRIDGIT that organize and automate these rules, guidelines, and procedures; often include storage and organization of inventory and inspection information, maintenance scheduling, and work-program optimization.

Condition

A concept characterizing how well a bridge is suited to fulfill its function at a particular instant, typically measured in terms of specific parameters such as allowable load level, quantity of deck cracking, or an inspector's judgement.

Consequence

An *outcome* of a particular *action* or *event*, possibly modified by subsequent actions and events, that may or may not be directly and functionally related to the particular action or event; e.g., a consequence of not sealing bridge-deck cracks may be extensive spalling of the Portland-cement concrete surface.

Cost

A measure of resources used in planning, design, construction, operations, maintenance, and other activities that provide a bridge and its services to a highway network; see also *direct cost*, *indirect cost*, *inferred cost*, *non-monetary cost, agency cost, user cost, vulnerability cost*.

Deterioration Model

An abstract representation, typically expressed as a mathematical relationship of time or use and *condition*, of how a bridge *element* will respond to wear and aging; commonly used techniques for formulating bridge-element deterioration models employ theory of *Markov processes* or regression analysis.

Deterministic Approach

Computation of a BLCCA using a single set of input values assumed to be to only likely values and therefore producing a single estimated value of total life-cycle cost for a management strategy; compare *stochastic approach*.

Direct Cost

A *cost* incurred explicitly for and as a consequence of a bridge-management action; see also *indirect costs*.

Discount Rate (DR)

The exponent value used to compute the equivalent *present value* of a *future cost*; the effective discount rate accounts for inflation, the relative financial risk of an investment, and the *time value of money*; compare *interest rate, inflation rate, real discount rate*.

Do-Nothing Alternative

The *base case*, typically implying a bridge receives little or no agency funding in the near future.

Element

A portion of a bridge for which a deterioration model is at least implicitly adopted in a BLCCA; elements are generally identifiable as unique parts of the bridge system, defined by differing function and deterioration characteristics, e.g., decks, railing, beams, bearings, joints, piers, abutments; may be the bridge as a whole.

Event

An occurrence during the BLCCA *analysis period* that has one or more *consequences* for a bridge's *total life-cycle cost*; typically characterized by its description and probability of occurrence (e.g., the "100-year storm," a traffic collision involving fatality); may be rare, periodic, extraordinary, or routine.

Expected Value

A mathematical parameter used in probability and statistical computations, the quantity "A" such that the probability that a continuous random variable "x" is less than or equal to A is P[x   A] = 0.50.

Extraordinary Cost

A *cost* incurred as a *consequence* of a rare *event*.

Finite Service Life

An anticipated *service life* of definite length, assuming no maintenance or *normal maintenance*; compare *infinite service life*.

Future Cost

A cost anticipated to be incurred in the future; may be estimated at constant prices, neglecting potential price *inflation*, or at prices anticipated to be "current" when the cost is incurred.

Hazard

A source of *risk*, e.g., seismicity, flooding, soil instability, fire, vehicle collisions; typically characterized by probabilities of occurrence and anticipated severity of events.

Indirect Cost

A *cost* associated with bridge-management action, either an *agency cost* or *user cost*; see also *direct costs*, *inferred costs*.

Inferred Cost

A cost whose value cannot be directly determined from a market transaction, involving no identifiable exchange of funds, e.g., the value of road-users' time lost as a consequence of bridge-repair actions.

Infinite Service Life

A concept associated with defining a *management strategy* that will, if continued indefinitely, prevent a bridge's *condition* from ever reaching an unacceptable level; not the same as an infinite *analysis period*, in which an entire bridge may be assumed to be replaced upon reaching the end of its *service life*.

Inflation

Increase of the general price level of goods and services used in bridge management; typically measured as a annual percentage rate; compare *discount rate* and *interest rate*.

Interest Rate

The *cost* of funds used by an agency or enterprise, typically representing the current financial-markets' assessment of the opportunity cost of capital; not necessarily the same as the *discount rate* used in BLCCA.

Internal Rate of Return

The *discount rate* such that the net present value of a stream of present and discounted future costs and savings or revenues is exactly zero.

Lane Rental

An amount established by contractual agreement that a construction contractor will pay or have deducted from payments for work done, payable for occupancy of a highway traffic lane to facilitate construction progress; also the concept of using such an incentive to complete construction sooner than the contract period.

Life Cycle

The sequence of *actions*, *outcomes*, *events*, and *consequences* that characterize a bridge's design, construction, and use through its *service life*.

Life-Cycle Activity Profile (LCAP)

A graphical representation of the *life cycle*, typically shown as points along a horizontal axis indicating the time of an action of event's occurrence and one or more lines perpendicular to the axis indicating the magnitude of consequent costs and times these costs are incurred.

Life-Cycle Cost Analysis (LCCA)

A mathematical procedure for evaluating the economic efficiency of a *management strategy*.

Management Strategy

A set of *actions* and their timing for developing, deploying, operating, and possibly disposing of a bridge or other major asset; typically stated within the context of certain experience-based rules or standards of professional practice.

Markov Process

A mathematical representation of wear, aging, or other processes, frequently used to represent highway pavement and bridges, comprising a set of two or more condition states (e.g., acceptable, not acceptable) and the probabilities that the *element* represented (e.g., bridge deck), will remain in its present state or have changed to another state in the next time period; in the classic Markov model, transition probabilities are independent of the element's condition history and constant with time.

Monetary Process

A cost whose value is determined or determinable from a market transaction, e.g., purchase or bid; compare *non-monetary cost*.

Monte Carlo Simulation

A numerical method for estimating the probability distribution of a parameter that depends on several stochastic variables, whereby repeated computations are made using randomly sampled values of the independent variables.

Network-Level Analysis

BLCCA for a group of bridges linked in a highway network rather than individual bridges; generally based on system-wide average cost estimates and deterioration models, although results may be presented on a bridge by bridge basis, e.g., PONTIS; compare *project-level analysis*.

Non-Monetary Cost

A cost incurred through a means other than a market transaction, whose value must be inferred; see *inferred cost*.

Normal Maintenance

The actions routinely undertaken by an agency to inspect and care for its bridges; may be sensitive to changes in policy or budgetary constraints.

Obsolete

A condition of being antiquated, old-fashioned, or out-of-date, not meeting current needs, expectations, or standards; not necessarily broken, worn out, or otherwise dysfunctional; e.g., an obsolete bridge may still carry traffic.

Outcome

The result or effect of an *action*, possibly influenced by subsequent actions and *events*; e.g., the expected outcome of painting a particular bridge is that the *service life* will be extended by 10 years; see also *consequence*.

Planning Horizon

The BLCCA *analysis period*.

Present Value (PV)

The value of a cost incurred at some future time expressed as the amount that would be equivalent if that cost were incurred now, computed as a function of the *discount rate* and time period between now and the anticipated time when the cost will be incurred.

Project-Level Analysis

BLCCA for a specific bridge, including site-specific variables and constraints.

Real Discount Rate

The value *discount rate* excluding inflation but allowing for anticipated financial risk and *time value of money*; compare *interest rate, inflation rate*.

Rehabilitation

Action that returns a bridge to a condition approximating that of a newly constructed bridge; *renewal*.

Renewal

See *rehabilitation*.

Repair

Action that corrects a fault or flaw in an *element* threatening to make a bridge's *condition* unacceptable.

Residual Value

The *present value* of the *total bridge life-cycle cost* computed for an analysis period equal to the *service life*, less the present value of the bridge for an analysis period shorter than the service life, under the same *management strategy*; the value of the bridge's remaining lifetime at the end of the BLCCA analysis period. Where appropriate the present values should include the costs of decommissioning the bridge.

Risk

A concept entailing a specific *hazard* and the *consequences* of exposure to that hazard; e.g., an agency adopting particular inspection policies may increase or lower the risk that a seismic event (hazard) will cause substantial damage to structural members with unseen corrosion damage.

Routine Cost

A *cost* incurred as a *consequence* of normal activities of a bridge's use.

Routine Maintenance

Normal maintenance.

Scenario

See *analysis scenario*.

Sensitivity Analysis

A computational technique for considering the significance of uncertainty in assumptions underlying the BLCCA, by systematically varying one or another of these assumptions by a predetermined amount and calculating the outcome, e.g., total bridge life-cycle cost; changes in outcome that are proportionateley larger than changes in assumptions indicate assumptions to which the outcome–an hence the decision to be made–are relatively sensitive.

Service Life (SL)

The period of time from a defined instant, typically the end of construction or the beginning of the *analysis period*, until a bridge's service *condition* declines to an unacceptable level; AASHTO recommends that new bridges be designed for a 75-year service life; specific values of service life depend on specification of a *management strategy*.

Stochastic Approach

Recognizing uncertainty in the bridge-management problem by computing the BLCCA using probabilistic distributions of input values and thereby producing an estimated distribution of values of total life-cycle cost for a management strategy; compare *deterministic approach*.

Terminal Value

The value of a bridge, associated land, etc. at the end of its service life less the cost of decommissioning.

Time Horizon

See *analysis period, planning horizon.*

Time Value of Money

A concept attributing greater value to funds now available, as compared with an otherwise equal amount not available until some future time, based on a proposition that the funds in hand may be productively used; the opportunity cost of capital.

Total Bridge Life-Cycle Cost (TLCC)

The sum of all *costs* anticipated during the *service life*, discounted to their equivalent *present value* at the beginning of the *analysis period*; as presented in this guidance manual, the sum of all routine *agency costs*, routine *user costs*, and the *vulnerability cost* (see also *routine cost*).

User Cost (UC)

A *cost* borne by bridge users, for example, increased fuel consumption and time lost due to congestion during *repairs*.

Vulnerability Cost (VC)

An amount representing the *expected value* of annual *extraordinary costs* anticipated under a particular bridge-management strategy, typically including both *agency costs* and *user costs*.

Appendix B Standard Present-Value Equations

Standard Present-Value Equations Introduction

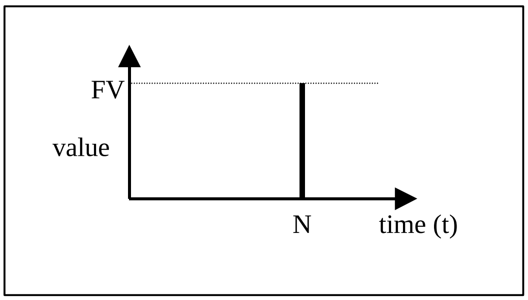
The following equations are frequently used in BLCCA. The initial equation, relating the value of costs as measured at the future time they are incurred to an equivalent present value, is the basis for all other relationships. Uniform- and increasing-series resource flows starting in a future year, for example, can be converted to an equivalent single future value and then that single future value converted to an equivalent present value at the start of the analysis period.

One-Time Future Event

$$PV = \frac{FV_N}{(1 + DR)^N}$$

where

PV	=	present value (e.g., at the beginning of year 1, $t = 0$)
FV_N	=	future value at year N (e.g., for resource flow occurring at the end of year N, $t = N$)
DR	=	discount rate

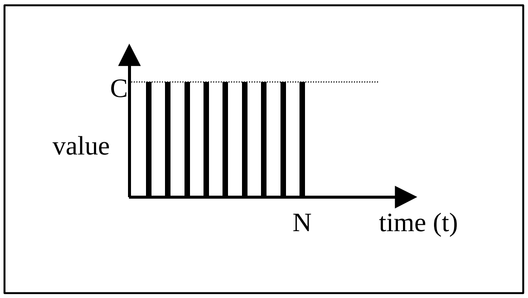


Equal Annual Events

$$PV = C\frac{(1 + DR)^N - 1}{DR(1 + DR)^N}$$

where

C	=	value (e.g., future, at the end of the year resource flow occurs) of uniform periodic resource flows commencing at the end of year 1 ($t = 1$) and concluding with a final flow at the end of year N ($t = N$)



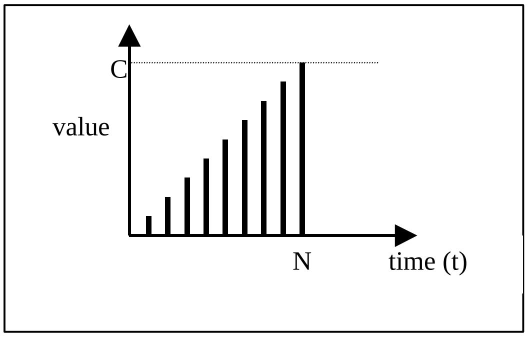
This equation is useful, for example, for representing periodic maintenance expenditures.

Linearly Increasing Annual Events

$$PV = C\left[\frac{1}{DR(1+DR)^N}\right]\left[\frac{(1+DR)^N - 1}{DR} - N\right]$$

where

C = value (e.g., future, at the end of the year the final resource flow occurs) of periodic resource flows *tC/N*, increasing linearly in steps *C/N*, commencing at the end of year 1 (*t* = *1*) and concluding with a final flow of C at the end of year *N* (*t* = *N*)



This equation is useful, for example, for representing user costs that are a function of a linearly increasing traffic volume.

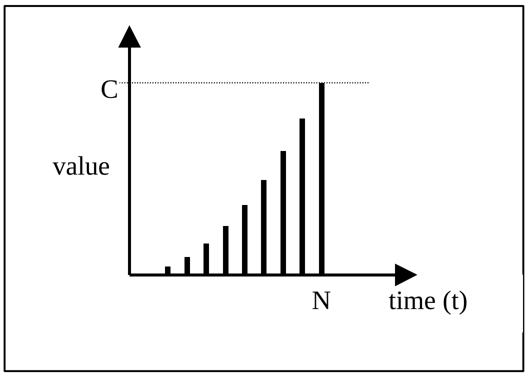
Exponentially Increasing Annual Events

The proceeding formula may be used for this situation, if the discount rate is replaced with a composite factor *PDR.*

$$PDR = \frac{(1+\ DR)}{(1+GR)} - 1$$

where

GR = growth rate of the exponentially-increasing amount.



For example, user costs are sometimes projected to be a function of traffic level,

$$UC_n = A \times ADT_0 \times (1 + GR)^n$$

where

UC_n	=	total annual user costs in year *n*
A	=	constant unit user cost, e.g., per vehicle per day
ADT_0	=	base-year traffic, average vehicles per day

and traffic is growing at the exponential rate *GR.* The composite factor *PDR* is sometimes referred to as a "pseudo discount rate."

Appendix C Computational Example

Computational Example Introduction

The following computational example is more complex than the example presented in the main body of this report but is nevertheless presented for illustrative purposes only. The example and the assumptions it includes are not intended to represent actual bridges or to recommend one type of management strategy over another. The strategy alternatives have been defined to make hand calculations feasible and uncertainties have in some cases been exaggerated to more clearly illustrate the BLCCA methodology. In the following discussion, expected values will be computed to illustrate hand calculations; a spreadsheet analysis is the basis for discussions of values other than these expected values.

The choices of appropriate deterioration models, user-cost relationships, and the like in a particular BLCCA are the responsibility of agency personnel performing the analysis. The number of uncertain variables in practical situations can be rather large, necessitating the use of computer-based solution methods.

The Problem

The problem posed for this analysis is selection of a design for a new 100-m-long bridge likely to have the lowest total life-cycle cost over the bridge's lifetime. A new "high-performance" design has been proposed, which its proponents assert will offer both extended service life and higher load capacity than the standard 36-tonnes capacity of "conventional" designs, a potentially valuable characteristic because there is a definite possibility that the legal truck load limit will be increased in the jurisdiction. Three alternatives are defined for analysis:

1. Conventional steel design;
2. Conventional concrete design; and
3. High-performance design, transverse-deck post-tensioned concrete with high-performance concrete deck.

Traffic volume upon opening is projected to be 3,500 vpd, with 15 percent trucks in the traffic stream, and is projected to grow at 1.5 percent annually. The peak-hour traffic represents 15% of the average daily flow and 60% of the peak-hour traffic travels in the peak direction. Maximum demand is then 315 vph/lane; two travel lanes will likely be adequate for all traffic until perhaps 95 years in the future, when peak demand will reach a level of approximately 1,320 vph/lane, the estimated capacity of a single travel lane. The bridge width is then estimated to be 11 m, out-to-out. In the event that the bridge is not available to traffic, the shortest detour route will add 20 km to the average trip of bridge users.

Agency policy requires that an 80-year analysis period should be used for decisions involving new construction. Agency policy also specifies that inflation should generally be neglected and a "real" discount rate of 6 percent should be used in the analysis. The agency's legislative liaison staff recommend estimate a 40% probability that the increase in legal load limits will occur; if it does, the new limit will become effective approximately ten years in the future.

Alternative 1 Conventional Steel

Agency costs Studies and design work prior to construction are estimated to cost $100,000. The estimate is judged to be relatively reliable, so no probability values will be assigned; i.e, the probability that these costs will be $100,000 is assumed to be 100 percent.

Construction cost is estimated at $2,000,000 total, including final design work; construction is scheduled to take two years following a one-year final design period. It should be noted that initial costs for an alternative are often the largest cost component in the total life-cycle cost since they receive the least discounting and thus their estimate and distribution in time can be very important. For simplicity, the cost is assumed to be paid half in year 2 and half in year 3. This alternative would open for service at the start of year 4. Because this is a new bridge, to be constructed under “greenfield” conditions and with minimum need to work within existing roadways, we neglect user costs, e.g., for traffic delays, during construction.

Using the basic one-time-event discounting equation, the present value of the best estimate of construction cost is

$$PV = \$1,000,000 / (1.06)^2 + \$1,000,000 / (1.06)^3$$
$$= \$1,729,616.$$

However, competition among bidders, changes in material prices, or other cost variances could influence the final construction cost, so the cost will be treated as uncertain:

Contract/final cost	10% below estimate	At estimate of $2,000,000	10% above estimate	20% above estimate
PV of cost	$1,556,654	$1,729,616	$1,902,577	$2,075,539
Probability	0.10	0.60	0.20	0.10

The expected value of the final construction cost discounted to time zero can be calculated as,

$$EV_0 = \$1,556,654x0.10 + \$1,729,616x0.60 + \$1,802,577x0.20 + \$2,075,539x0.10$$
$$= \$1,781,504.$$

The expected value is generally a better value to use than the best estimate since it reflects the “average” or mean cost rather than the median cost. In general, uncertain costs can be represented by a distribution that is skewed to the left: i.e., there is more cost uncertainty to the up-side that to the down-side. For this case the best estimate is less than the expected value.

If we were conducing an analysis including uncertainty, the individual PVs and probabilities would be used instead of the expected value.

We will assume that the bridge is inspected every two years at a cost of $1,000 per occurrence. This can be treated as a uniform annual payment of $500 per year for 80 years using the standard uniform-annual-payment formula.

$$PV_{80} = \$500 \times [(1.06)^{80} - 1] / [0.06 \times (1.06)^{80}]$$
$$= \$8{,}255.$$

However, the inspections will not start until year 6, two years following the completion of construction. The present value of the first four payments is then deducted (i.e., $500 are accrued in years 5 and 6 for the first inspection):

$$PV_{4} = \$500 \times [(1.06)^{4} - 1] / [0.06 \times (1.06)^{4}]$$
$$= \$1{,}733.$$

The estimated present value of inspections then is $8,255 - $1,733 = $6,522; we will treat this number as relatively certain.

This is a steel bridge and will require periodic repainting. We will assume that these painting projects can be carried out from beneath the bridge and do not involve any disruption to traffic; i.e., there are no painting-related user costs.

The likely agency cost is uncertain, as repainting methods could reduce future repainting costs and new paints may last longer; on the other hand, environmental regulations may become more stringent. To model these uncertainties individually would be excessive for hand calculation, so we will make simplifying assumptions: the paint-job's service life is estimated to be 15 years, with a 10% chance of being only 12 years and a 20% chance of being 18 years; estimated cost is $150,000, with a 20% chance of being 20% less and a 20% chance of being 30% more. The following table summarizes these assumptions.

Service life	12 years	15 years (best est.)	18 years
Probability	0.10	0.70	0.20
Cost	$120,000	$150,000	$195,000
Probability	0.20	0.60	0.20
Expected cost	0.20 x $120,000 + 0.60 x $150,000 + 0.20 x $195,000 = $153,000.		

The best estimate is that repainting will be required in years 15, 30, 45, 60, and 75. The best estimate of the expected present value of repainting costs is then computed as

$$PV_E = \$153{,}000 / (1.06)^{15} + \ldots + \$153{,}000 / (1.06)^{75} = \$108{,}169.$$

This can be considered the median value. If we assume that costs and timing are independant, a better value can be calculated by considering all possible combinations:

$$\begin{aligned} PV = \; & 0.10 \times [153{,}000 \times (1.06^{-12} + 1.06^{-24} + 1.06^{-36} + 1.06^{-48} + 1.06^{-60} + 1.06^{-72})] \\ & + 0.70 \times [153{,}000 \times (1.06^{-15} + 1.06^{-30} + 1.06^{-45} + 1.06^{-60} + 1.06^{-75})] \\ & + 0.20 \times [153{,}000 \times (1.06^{-18} + 1.06^{-36} + 1.06^{-54} + 1.06^{-72})] \\ = \; & \$106{,}860. \end{aligned}$$

Another recurring maintenance item will be replacing the asphaltic deck overlay every 10 years. Assuming that the overlay costs $\$25/m^2$ to replace and that the deck area is $1000m^2$, the cost of each replacement overlay is $25,000. We will assume that the timing and cost are not uncertain; the present value of overlay costs is then

$$\begin{aligned} PV = \; & \$25{,}000 \times (1.06^{-12} + 1.06^{-22} + 1.06^{-32} + 1.06^{-42} + 1.06^{-52} \\ & + 1.06^{-62} + 1.06^{-72}) \\ = \; & \$27{,}658. \end{aligned}$$

The table summarizes the agency costs estimated for Alternative A. The expected present value of agency costs is approximately *ACA* = $2,076,000.

User costs The deck-overlay replacements will clearly produce traffic delays and road-user costs. Assume that one lane of the two-lane bridge will be closed to traffic for a 5-day period each time the deck is resurfaced. Using the *Highway Capacity Manual*, the one-lane capacity is estimated to be 1,340 vph, which is not expected to be exceeded until after year 80. We will assume that until that time delays are incurred only during periods when both lanes are blocked, which we estimate to occur 6 times each day during replacement, for approximately 30 minutes each time.

Alternate A Cost item	Timing	Best estimate cost ($)	Expected PV ($)
Plans and studies	year 0	100,000	100,000
Design & construction	years 1–2	2,000,000	1,781,504
Inspections	every 2nd year in service	1,000 per inspection	6,522
Painting	12 to 18 year intervals	153,000 per project	106,860
Deck overlay replacement	10 year intervals	25,000 per project	27,658
Total agency cost for Alternative A			**$2,022,544**

Assume that hourly traffic demand during closures is 6% of ADT, equal to 210 vph initially and grown to 240 in year 12. During the closure, vehicles form a queue that we estimate will clear at a rate of 2 veh/min. once the lane is reopened. The number of vehicles delayed in each direction is then estimated to be approximately 40 per closure, or 240 vehicles total per day. Over the 5-day reconstruction period, the total vehicles delayed is 1,200 in year 12. The number will increase proportionally to total traffic volume.

We estimate the unit time costs of delay, including both time and vehicle-operating cost, to be $25.00/hour for trucks and $5.00/hour for other vehicles. With trucks accounting for 15% of the traffic stream, the best-estimate unit cost is computed as $25 x 0.15 + $5 x 0.85 = $8.00/hr.

User costs associated with the first resurfacing (at year 12) are then calculated as

$$UC = (\text{vehicles delayed}) \times (\text{average delay}) \times (\text{cost per unit delay time})$$

$$UC_{12} = 1{,}200 \times 0.50 \times \$8.00 = \$4{,}800.$$

This cost will increase proportionally to traffic levels in subsequent years when the deck overlay is replaced. Total discounted expected user cost is calculated as

$$PV[UC_T] = (4{,}800 \text{ x } 1.06^{-12}) + (5{,}571 \text{ x } 1.06^{-22}) + (8{,}465 \text{ x } 1.06^{-32}) + (7{,}503 \text{ x } 1.06^{-42}) + (8{,}707 \text{ x } 1.06^{-52}) + (10{,}105 \text{ x } 1.06^{-62}) + (11{,}727 \text{ x } 1.06^{-72})$$

$$= \$6{,}452$$

<u>Strengthening</u> If the legal load limit is increased, some trucks will have to be diverted or the bridge will have to be strengthened. If the increase occurs in year 10 and we assume that 20% of future truck traffic will have to be diverted over a 20-km detour, then the number of equivalent vehicles diverted during the remaining analysis period will be potentially substantial:

$$\text{heavy trucks} = 365 \text{ x } 3{,}500 \text{ x } 15\% \text{ x } 20\% \text{ x } {}_{n=10 \text{ to } 80} (1.015)^n$$

$$= 365 \text{ x } 14{,}590$$

$$= 5.325 \text{ million vehicles}$$

We estimate the diversion cost will include added travel time of 0.4 hr/veh and vehicle operating cost of \$0.65/km. The unit user cost will then be

$$\text{UC/veh diverted} = 0.4 \text{ hr x } \$25/\text{hr} + 20 \text{ km x } \$0.65/\text{km}$$

$$= \$23$$

The total user cost in each year *n* is

$$UC_n = \$23 \text{ x } 365 \text{ x } 15\% \text{ x } 20\% \text{ x } 3{,}500 \text{ x } (1.015)^n$$

Calculated for the years 10 through 80, discounted to their equivalent present value and summed, these annual user costs add up to an estimated total user cost of

$$PV[UC_T] = \$12{,}276{,}500.$$

Alternatively, the agency may choose to strengthen the bridge when the load limit is raised. We estimate the total cost of this strengthening will be \$350,000, incurred in year 11, and that the strengthening will occur only after the load limit requirement is increased and that strengthening will take 4 months. The present value of this expenditure is \$184,376. In addition, there will be four months of user-diversion cost, in year 11, computed to be

$$= \$23 \times 365/3 \times 15\% \times 20\% \times 3{,}500 \times (1.015)^{11}$$
$$= \$881{,}198$$

and the discounted present value is $464,204. Note that even 4 months of diversion costs far exceed the cost of the strengthening. The agency may want to consider strengthening before the load limit is raised. It could also be argued that the overload vehicles are not there now and won't use the bridge until it is strengthened, thus making their user costs very indirect.

We assume the agency will choose to strengthen the bridge if the load limit is increased and that the strengthening can be accomplished with no major disruption to normal traffic using the bridge. We use the agency's legislative liaison estimate of a 40% probability that this increase will be enacted (with the cost of strengthening then incurred) to estimate that the expected present value of costs for this action is

$$AC = (0.4 \times \$184{,}376) + (0.6 \times 0)$$
$$= \$73{,}750.$$

$$UC = (0.4 \times \$464{,}204) + (0.6 \times 0)$$
$$= \$185{,}682$$

<u>Vulnerability Costs</u> The bridge is in a moderate earthquake zone and will be damaged during a severe earthquake. It is assumed that this vulnerability is constant throughout the life of the structure and is defined as follows:

Intensity	0-3	4	5	6	7
Agency cost	0	$500	$4,000	$100,000	$2,000,000
User cost	0	0	$10,000	$500,000	$2,000,000
Probability	0.738	0.20	0.05	0.01	0.002

Costs vary from a cursory visual inspection at low earthquake intensities to potential collapse in a severe earthquake. The annual expected value can be calculated by multiplying the costs by the probabilities.

Agency portion	=	*0.738(0) + 0.20(500) + 0.05(4,000) + 0.01(100,000) + 0.002(2,000,000)*
	=	*$5,300.*

User portion	=	*0.738(0) + 0.20(0) + 0.05(10,000) + 0.01(500,000) + 0.002(2,000,000)*
	=	*$9,500.*

$$EV = \$5,300 + \$9,500 = \$14,800.$$

and using the annual payment formula the present value of the annual vulnerability cost of $14,800 is:

$$VC = \$14,800 / 0.06 \times (1.06^{80} - 1) / (1.06)^{80} = \$244,335.$$

Residual value We have implicitly assumed in the analysis so far that the overall bridge will remain safe and serviceable–subject to adequate completion of the inspection and maintenance actions included in the management strategy we have assumed–for the entire 80-year analysis period. We further have assumed that the overall condition will reach an unacceptable level approximately in year 80. In this case there would be no residual value assumed for the structure.

However, we recognize such an assumption may be unreasonable; our experience with the deterioration models included in PONTIS and BRIDGIT lead us to estimate that the bridge's overall condition, as measured by the NBI rating, could decline to an unacceptable level (an NBI rating value of 3) as early as year 60, requiring a major rehabilitation or replacement. If the bridge must be replaced at year 60, we estimate that the replacement cost would be similar to initial construction plus a significant premium to maintain traffic flow during the reconstruction period. We estimate that user costs will be insignificant if contract incentives to maintain traffic service levels are used, but the agency's costs would total $2,400,000, net of any savings on painting and deck resurfacing that will be avoided. The new bridge will then almost certainly have a service life extending well beyond year 80; assuming deterioration occurs in equal annual decrements in rating index over a 60-year period, from an initial level of 9 to the unacceptable level of 3, the replacement construction cost, incurred in year 60, will be only one-third "used up" by year 80. We therefore estimate the value of the bridge in year 80 to be $1,600,000; discounting to present values gives $\$2,400,000 / (1.06)^{60} = \$72,754$ for the replacement and $\$1,600,000 / (1.06)^{80} = \$15,123$ as the residual value.

On the other hand, we estimate the bridge's overall service life could extend well beyond year 80, in which case the condition at year 80 could be rated as acceptable; we estimate the rating at year 80 could be 4. In this case the accumulated wear and aging of the bridge will have "consumed" approximately 83% of the original investment in structure, based on the change in rating over the 80-year period, (9-4)/(9-3). The "remaining" 17% of the service life implies a best-estimate Residual value of $340,000 at year 80; discounted to its present value, this figure is $3,214.

	SL = 60 years	SL = 80 years	SL > 80 years (NBI rating)$_{80}$ = 4
Replacement, year 60	$72,754	0	0
Replacement value, year 80	$15,123	0	$3,214
Probability	0.40	0.50	0.10

We estimate the probabilities of the three outcomes, and then compute the expected present value of the residual value, RV and the agency costs.

$$AC_A = 0.40 \times \$72{,}754 = \$29{,}102.$$

$$RV_A = (0.40 \times \$15{,}123) + (0.50 \times \$0) + (0.10 \times \$3{,}214) = \$6{,}371.$$

<u>Total life-cycle cost</u> The expected present value of TLCC of Alternative A, "conventional steel," is then estimated to be approximately *TLCCA* = $2,555,494:

$$TLVVA = ACA + UCA + VCA - RVA$$
$$= (\$2{,}022{,}544 + \$73{,}750 + \$29{,}102) + (\$6{,}452 + \$185{,}682) + \$244{,}335 - \$6{,}371$$
$$= \$2{,}555{,}494.$$

Alternative 2 Conventional Concrete

Agency costs As with Alternative A, studies and design prior to construction are estimated to be $100,000 and relatively certain. Construction costs have been estimated at $2,200,000 with greater uncertainty than a conventional steel design. Design and construction are estimated to take three years with the construction cost distributed equally in years 2 and 3.

Contract/final cost	20% below estimate	At estimate of $2,200,000	105 above estimate	25% above estimate
PV of cost	$1,552.062	$1,902,578	$2,187,964	$2,378,222
Probability	0.10	0.60	0.20	0.10

The computation of present values and expected value of design and construction costs is then exactly similar to the computations for Alternative A. The expected value of final construction costs is

$$
\begin{aligned}
EV &= \$1,760,000 \times 0.10 + \$2,200,000 \times 0.60 + \$2,530,000 \times 0.20 + \$2,750,000 \times 0.10 \\
&= \$2,277,000.
\end{aligned}
$$

or expensed over years 2 and 3 and discounted to present value

$$
\begin{aligned}
EV_0 &= \$1,138,500 / (1.06)^2 + \$1,138,500 / (1.06)^3 \\
&= \$1,969,168.
\end{aligned}
$$

This alternative would also have an inspection program estimated to be identical to that for Alternative A. The discounted present value of that program's cost is then the same as that for Alternative A, $6,522. No painting program is required, and we estimate the needs for deck resurfacing to be the same as those for Alternative A.

Alt. B, Cost Item	Timing	Best-estimate cost ($)	Expected PV ($)
Plans and studies	year 0	100,000	100,000
Design & construction	years 1-2	2,200,000	1,969,168
Inspections	every 2nd year in service	1,000/inspection	6,522
Deck-overlay replacement	10-yr intervals	25,000/project	27,658
Total agency cost, Alt. B			**$2,103,348**

The agency costs for Alternative B are then similar to those for Alternative A, as the table summarizes. The expected present value of agency costs is approximately *ACB* = $2,103,000.

User costs The deck-overlay replacement schedule is anticipated to be similar in cost and uncertainty to that for Alternative A. The expected present value of user costs associated with these overlays is then equal to that of Alternative A, $6,452.

Strengthening costs The issue of truck-diversion versus strengthening the bridge will apply to Alternative B as well. We estimate the total cost of strengthening in this case will be $440,000, incurred in year 11. This amount is still well below the estimated user costs if the strengthening is not done; we assume the agency will choose to make the expenditure. The present value of this expenditure is $231,787. In addition, as for Alternative A, there will be four months of user-diversion cost, computed to be $881,198; the discounted present value is $464,204. Using the agency's legislative liaison estimate of a 40% probability that the load-limit increase will be enacted and the cost of strengthening incurred, we estimate that the expected present value of vulnerability cost for Alternative B is

$$AC = 0.4 \times (\$231{,}787) + 0.6 \times (0) = \$92{,}715$$

$$UC = 0.4 \times (\$464{,}204) + 0.6 \times (0) = \$185{,}682$$

Vulnerability Costs The bridge is in a moderate earthquake zone and will be damaged during a severe earthquake. Costs are expected to be similar to the steel bridge. It is assumed that this vulnerability is constant throughout the life of the structure and is defined as follows:

Intensity	0 - 3	4	5	6	7
Agency Cost	0	$500	$4,000	$100,000	$2,000,000
User Cost	0	0	$10,000	$500,000	$2,000,000
Probability	**0.738**	**0.20**	**0.05**	**0.01**	**0.002**

Costs vary from a cursory visual inspection at low earthquake intensities to potential collapse in a severe earthquake. The annual expected value can be calculated by multiplying the costs by the probabilities

$$EV = 0.738(0) + 0.20(500) + 0.05(4000+10000) + 0.01(100000+500000) + 0.002(2000000+2000000) = \$14{,}800$$

and using the annual payment formula the present value of the annual vulnerability cost of $14,800 is:

$$VC = \$14800 / 0.06 * (1.06^{80} - 1)/(1.06)^{80}$$
$$= \$244,335.$$

Residual value As with Alternative A, we have implicitly assumed in this analysis that the overall bridge will remain safe and serviceable–subject to adequate completion of the inspection and maintenance actions included in the management strategy we have assumed–for the entire 80-year analysis period. We further have assumed that the overall condition will reach an unacceptable level approximately in year 80, implying there would be no residual value for the structure.

However, again such an assumption may be unreasonable; our experience with the deterioration models included in PONTIS and BRIDGIT lead us to estimate that the bridge's overall condition, as measured by the NBI rating, could decline to an unacceptable level (an NBI rating value of 3) as early as year 60, requiring a major rehabilitation or replacement. If the bridge must be replaced at year 60, we assume a lower-initial-cost superstructure replacement might be used; we estimate the agency's costs (including a significant premium to maintain traffic flow during the reconstruction period) would total $1,800,000, net of any savings on deck resurfacing that will be avoided. We then assume that deterioration progresses as was described for Alternative A: equal annual decrements in rating index over a 60-year period, from an initial level of 9 to the unacceptable level of 3. The superstructure replacement construction cost, incurred in year 60, will be one-third "used up" by year 80. We therefore estimate the value of the bridge in year 80 to be $1,200,000; discounting to present values gives $\$1,800,000 / (1.06)^{60} = \$54,566$ for the replacement and $\$1,200,000 / (1.06)^{80} = \$11,343$ as the residual value.

On the other hand, we estimate the bridge's overall service life could extend well beyond year 80, in which case the condition at year 80 could be rated as acceptable; we estimate the rating at year 80 could be 5. In this case, the accumulated wear and aging of the bridge will have "consumed" approximately 67% of the original investment in structure, based on the change in rating over the 80-year period, (9-5)/(9-3). The "remaining" 33% of the service life implies a best-estimate residual value of $600,000 at year 80; discounted to its present value, this figure is $5,671.

	SL = 60 yrs	SL = 80 yrs	SL > 80 yrs $(\text{NBI rating})_{80} = 5$
Superstructure, year 60	$54,566	0	0
Residual value, year 80	$11,343	0	$5,671
Probability	0.20	0.70	0.10

We estimate the probabilities of the three outcomes and then compute the expected present value of the residual value, RV and the agency costs.

$$AC_B = 0.20 \times \$54{,}566 = \$10{,}913$$

$$RV_B = 0.20 \times \$15{,}123 + 0.70 \times \$0 + 0.10 \times \$5{,}671 = \$3{,}592$$

Total life-cycle cost The expected present value of TLCC of Alternative B, "conventional concrete," is then estimated to be approximately *TLCCB* = $2,487,788:

$$\begin{aligned} TLCC_B &= AC_B + UC_B + VC_B - RV_B \\ &= (\$2{,}103{,}348 + \$92{,}715 + \$10{,}913) + (\$6{,}452 + \$185{,}682) + (\$244{,}335) - \$3{,}592 \\ &= \$2{,}639{,}853 \end{aligned}$$

Alternative 3 High Performance

Agency costs This alternative is based on the use of transverse deck post-tensioning, high strength concrete, a high performance overlay, galvanized steel and a higher design-load capacity. We anticipate this design will age and wear well, offering an extended service life for the bridge overall and certain of its components. We anticipate that studies and preliminary design costs prior to construction will be higher than the conventional alternatives, a likely total of $150,000. Final design and construction costs also will be higher, estimated at $2,500,000 and with some uncertainty. As with the other two alternatives, final design and construction are estimated to take three years with the cost distributed equally in years 2 and 3.

Contract/final cost	15% below estimate	$2,500,000	10% above estimate	20% above estimate
PV of cost	$1,837,717	$2,162,020	$2,378,222	$ 2,594,424
Probability	0. 10	0.60	0.20	0.10

The computation of present values and expected value of design and construction costs is then exactly similar to the computations for Alternative A. The expected value of final construction costs is

$$EV = \$2{,}500{,}000 \times (0.85 \times 0.10 + 1.0 \times 0.60 + 1.10 \times 0.20 + 1.2 \times 0.10) = \$2{,}562{,}500$$

or expensed over years 2 and 3 and discounted to present value

$$EV_0 = \$1{,}281{,}250 / (1.06)^2 + \$1{,}281{,}250 / (1.06)^3 = \$2{,}216{,}070.$$

This alternative would also have an inspection program estimated to be identical to that for Alternatives A and B. The discounted present value of that program's cost is then the same as that for these other two Alternatives, $6,522. No painting program is required.

We estimate that the epoxy-concrete deck overlays used in this design will require replacement only once every 25 to 30 years. We estimate the agency's costs for these replacements will be $100,000. We estimate that two overlay cycles will be required, at years 30 and 57. Even though the $200,000 investment to be made over the analysis period apparently exceeds that for the conventional asphaltic concrete overlay, deferring the need to make investment yields savings: the discounted value of the overlay costs is

$$\begin{aligned} PV &= \$100{,}000 \times [(1/1.06^{30}) + (1/1.06^{57})] \\ &= \$21{,}022 \end{aligned}$$

Variation from "best estimate" ($12,000)	-15%	-10%	0	+10%	+20%
Probability of cost	0.10	0.20	0.40	0.20	0.10

The agency costs for Alternative C are then summarized in the table. The expected present value of agency costs is *ACC* = $2,393,614.

<u>User costs</u> Each deck-overlay replacement will have user costs similar to those incurred for a conventional alternative, but there are only two occurrences. The estimated costs are calculated in a manner similar to that for Alternative A, based on anticipated traffic levels in the years when replacements are anticipated. Total discounted expected user cost is calculated as

$$\begin{aligned} PV[UC_T] &= 6{,}275/1.06^{30} + 9{,}380/1.06^{57} \\ &= \$1{,}431. \end{aligned}$$

<u>Strengthening costs</u> This alternative will have a load-capacity rating that will remain adequate if the legal load limit is increased. There are therefore no strengthening costs estimated for Alternative C.

<u>Vulnerability costs</u> The bridge is in a moderate earthquake zone and will be damaged during a severe earthquake. Costs are expected to be less than for a conventional design due to the incorporation of energy dissapators at the abutments and other considerations. It is assumed that this vulnerability is constant throughout the life of the structure and is defined as follows:

Intensity	**0 - 3**	**4**	**5**	**6**	**7**
Agency Cost	0	0	$500	$4,000	$100,000
User Cost	0	0	0	$10,000	$500,000
Probability	**0.738**	**0.20**	**0.05**	**0.01**	**0.002**

Costs vary from a cursory visual inspection for a level 5 earthquake to plastic hinge formation in a severe earthquake. The annual expected value can be calculated by multiplying the costs by the probabilities.

$$EV = 0.738(0) + 0.20(0) + 0.05(500) + 0.01(4{,}000+10{,}000) + 0.002(100{,}000+500{,}000) = \$1{,}365$$

and using the annual payment formula the present value of the annual vulnerability cost of $1,365 is

$$VC = \$1365 / 0.06 * (1.06^{80} - 1)/(1.06)^{80} = \$22{,}535$$

Residual value Alternative C is an extended-life design; we anticipate the overall bridge will not only remain safe and serviceable–subject to adequate completion of the inspection and maintenance actions included in the management strategy we have assumed–for the entire 80-year analysis period, but also that the overall condition will be higher than a just-acceptable level in year 80.

Deterioration models included in PONTIS and BRIDGIT are less helpful for unusual designs. We rely instead on research studies and the designer's judgement to estimate that the bridge's overall condition, as measured by the NBI rating, at year 80 be at least 5 and possibly 6. Estimating the effects of accumulated wear and aging as in our analyses of Alternatives A and B, we anticipate the bridge will have 33% to 50% "remaining" service life, a best-estimate residual value of approximately $833,000 to $1,250,000 at year 80. We estimate the probabilities of these two outcomes to be equally likely and compute the expected present value of the residual value,

$$RV_C = (0.50 \times \$833{,}000 + 0.50 \times \$1{,}250{,}000)/(1.06)^{80} = \$9{,}840$$

Total life-cycle cost The expected present value of TLCC of Alternative C, "high performance," is then estimated to be approximately $TLCC_C$ = $2,407,740:

$$TLCC_C = AC_C + UC_C + VC_C - RV_C = \$2{,}393{,}614 + \$1{,}431 + \$22{,}535 - \$9{,}840 = \$2{,}407{,}740.$$

Reviewing the Results

The table summarizes the expected total life-cycle costs of the three alternatives.

Cost components	Expected PV of costs		
	Alt. A "conventional steel"	Alt. B "conventional concrete"	Alt. C "high performance"
Agency cost (AC)	2,125,396	2,206,976	2,393,614
User cost (UC)	192,134	192,134	1,431
Vulnerability cost (VC)	244,335	244,335	22,535
Residual value (RV,credit)	6,371	3592	9,840
Expected TLCC, rounded	$2,555,494	$2,639,853	$2,407,740

Alternative C, the "high performance" design, offers the lowest total life-cycle cost but also the highest agency cost. This conclusion depends rather critically, however, on the assumptions that (1) actual agency costs and construction costs in particular, the largest component of TLCC, will be close to their expected values; (2) maintenance activities are carried out as specified; and (3) the bridge-strengthening occurs four months after vehicle-load limits are increased. The sensitivity of our preference for Alternative C (based on its low TLCC) to these three sets of assumptions should be considered. For example, if the user costs associated with the strengthening are avoided by having the strengthening in place before the load limit is increased, both alternatives A and B are reduced by $185,682.

Referring back to the estimates of design and construction costs, we can use the predicted construction costs and probabilities instead of the expected value. By adjusting the Total Present Values accordingly, the following table results.

Cost estimate used	Probability	Total PV with Initial Construction Treated as Uncertain		
		A	B	C
Expected value		2,555,494	2,639,853	2,407,740
lower	0.10	2,330,644	2,192,747	2,029,387
best estimate	0.60	2,503,606	2,573,263	2,353,690
higher	0.20	2,676,567	2,858,649	2,569,892
much higher	0.10	2,849,529	3,048,907	2,786,094

If the cost of Alternative B "comes in" at the lower cost estimate, for example, it's PV is clearly lower than the PV for Alternative C. It would therefore be useful to predict the confidence level of alternative A being better than A or B. The probability that Alternative C will have the lowest PV can be calculated as

$$
\begin{aligned}
P[PV_C < PV_A \text{ and } PV_C < PV_B] &= 0.10 \times (0.1+0.6+0.2+0.1) \times (0.1+0.6+0.2+0.1) \\
&\quad + 0.60 \times (0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&\quad + 0.20 \times (0.2+0.1) \times (0.6+0.2+0.1) \\
&\quad + 0.10 \times (0.1) \times (0.2+0.1) \\
&= 64.3\%
\end{aligned}
$$

We make a similar calculation for Alternatives A and B to find

$$
\begin{aligned}
P[PV_A < PV_B \text{ and } PV_A < PV_C] &= 0.10 \times (0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&+ 0.60 \times (0.6+0.2+0.1) \times (0.2+0.1) \\
&+ 0.20 \times (0.2+0.1) \times (0.1) \\
&+ 0.10 \times (0.2+0.1) \times (0) \\
&= 24.9\%
\end{aligned}
$$

$$
\begin{aligned}
P[PV_B < PV_A \text{ and } PV_B < PV_C] &= 0.10 \times (0.1+0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&+ 0.60 \times (0.2+0.1) \times (0.1) \\
&+ 0.20 \times (0) \times (0) \\
&+ 0.10 \times (0) \times (0) \\
&= 10.8\%
\end{aligned}
$$

Thus Alternative C has the least PV with a probability of 64.3%, Alternative A 24.9%, and Alternative B 10.8%. Alternative C is a fairly clear winner. But what if we now eliminate the load capacity detour user costs as mentioned previously. This changes the results to the following:

Cost estimate used	Probability	Total PV with Initial Construction Treated as Uncertain		
		A	B	C
Expected value		2,369,812	2,454,171	2,407,740
lower	0.10	2,144,962	2,007,065	2,029,387
best estimate	0.60	2,317,924	2,387,581	2,353,690
higher	0.20	2,490,885	2,672,967	2,569,892
much higher	0.10	2,663,847	2,863,225	2,786,094

If the cost of Alternative B "comes in" at the lower cost estimate for example, it's PV is clearly lower than the PV for Alternative C. It would therefore be useful to predict the confidence level of alternative A being better than A or B. The probability that Alternative C will have the lowest PV can be calculated as

$$
\begin{aligned}
P[PV_C < PV_A \text{ and } PV_C < PV_B] &= 0.10 \times (0.1+0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&+ 0.60 \times (0.2+0.1) \times (0.6+0.2+0.1) \\
&+ 0.20 \times (0.1) \times (0.2+0.1) \\
&+ 0.10 \times (0) \times (0.1) \\
&= 26.8\%
\end{aligned}
$$

We make a similar calculation for Alternatives A and B to find

$$
\begin{aligned}
P[PV_A < PV_B \text{ and } PV_A < PV_C] &= 0.10 \times (0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&\quad + 0.60 \times (0.6+0.2+0.1) \times (0.6+0.2+0.1) \\
&\quad + 0.20 \times (0.2+0.1) \times (0.2+0.1) \\
&\quad + 0.10 \times (0.2+0.1) \times (0.1) \\
&= 58.8\%
\end{aligned}
$$

$$
\begin{aligned}
P[PV_B < PV_A \text{ and } PV_B < PV_C] &= 0.10 \times (0.1+0.6+0.2+0.1) \times (0.1+0.6+0.2+0.1) \\
&\quad + 0.60 \times (0.2+0.1) \times (0.2+0.1) \\
&\quad + 0.20 \times (0) \times (0.1) \\
&\quad + 0.10 \times (0) \times (0) \\
&= 15.4\%
\end{aligned}
$$

Under this assumption, Alternative A at 58.8% is the most likely to be the least PV. As you can see, the assumption are important. In both cases Alternative B is the loser.

Next, we consider the effects on agency costs only

Agency costs	PV of agency costs		
	Alternative A	Alternative B	Alternative C
Normal costs	$2,022,544	$2,103,398	$2,393,614
Strengthening	$73,750	$92,715	$0
Future Replacement	$29,102	$10,913	$0
Vulnerability - Agency Portion	$87,498	$87,498	$4,375
Total	**$2,212,894**	**$2,294,524**	**$2,397,989**

When comparing the alternatives on the basis of agency costs only, we see that Alternative A is the best choice although all alternatives are within about 5% of the average. We may still lean toward Alternative C if we are not certain of the magnitude of the vulnerability costs. If we are concerned that future painting of the steel bridge (Alternative A) may be deferred too long, leading to corrosion damage and costly repairs, or that the likelihood of a 60-year service life is greater than assumed in the computations, our preference for Alternative B or C might be stronger. In developing the concrete alternative (Alternative B), however, we might choose to put extra effort into cost control in design and construction to ensure that actual final costs do not exceed our best estimate.

Finally, we consider the problem of load capacity and the “high performance” alternative. If additional funds are available, perhaps for demonstrating new technology, we might wish to make the extra investment to build Alternative C and avoid with certainty the problems of strengthening an obsolete bridge if legal load limits are increased. Also Alternative C would gain more favor if the chance of the load capacity requirements being increased is more than the assumed 40%.

On balance, the analysis indicates that a conventional steel bridge design is likely to be a good choice for this situation if we only consider agency costs and the high performance design should be considered if user costs are also considered.

Appendix D Probability Calculations

Determining Probability That Value 1 is Less Than Value 2

$m_1 =$	63
$COEF_1 =$	0.15
$s_1 =$	9.45

$m_2 =$	58
$COEF_2 =$	0.25
$s_2 =$	14.5

X1	f (x1)	X2	f (x2)	Sum(f (x2) | x1< x2)	f (x1) * sum
0	1.8859E-11	1	2.4265E-05	0.999968072	1.88584E-11
2	7.5606E-11	3	4.1337E-05	0.999943807	7.56015E-11
4	2.8983E-10	5	6.9091E-05	0.99990247	2.89797E-10
6	1.0623E-09	7	0.0001133	0.999833379	1.06217E-09
8	3.7234E-09	9	0.00018231	0.999720074	3.72238E-09
10	1.2479E-08	11	0.00028781	0.999537766	1.24728E-08
12	3.9989E-08	13	0.0004458	0.999249956	3.99587E-08
14	1.2253E-07	15	0.00067751	0.998804154	1.22387E-07
16	3.5902E-07	17	0.00101025	0.998126644	3.5835E-07
18	1.0059E-06	19	0.001478	0.997116398	1.00295E-06
20	2.6946E-06	21	0.00212159	0.995638394	2.68285E-06
22	6.9024E-06	23	0.00298804	0.993516801	6.85768E-06
24	1.6907E-05	25	0.00412902	0.990528764	1.67465E-05
26	3.9597E-05	27	0.00559818	0.986399739	3.90582E-05
28	8.8676E-05	29	0.00744703	0.980801564	8.6974E-05
30	0.00018989	31	0.0097198	0.973354534	0.000184831
32	0.00038882	33	0.01244712	0.963634735	0.00037468
34	0.00076127	35	0.01563933	0.951187613	0.000724112
36	0.00142521	37	0.01927991	0.935548279	0.001333349
38	0.00255131	39	0.02332005	0.916268366	0.002337685
40	0.00436713	41	0.02767524	0.892948316	0.003899621
42	0.00714786	43	0.03222485	0.865273074	0.006184853
44	0.01118674	45	0.03681527	0.833048221	0.009319094
46	0.01674088	47	0.04126698	0.796232949	0.013329637
48	0.02395521	49	0.04538526	0.754965971	0.018085372
50	0.032777	51	0.04897389	0.709580708	0.023257927
52	0.04288305	53	0.05185038	0.660606816	0.028328832
54	0.05364748	55	0.0538613	0.608756437	0.032658247
56	0.06417417	57	0.05489582	0.554895139	0.035609934
58	0.07340378	59	0.05489582	0.499999322	0.036701843
60	0.08028306	61	0.0538613	0.445103505	0.035734272
62	0.08396082	63	0.05185038	0.391242207	0.032849016
64	0.08396082	65	0.04897389	0.339391828	0.028495615
66	0.08028306	67	0.04538526	0.290417936	0.023315641
68	0.07340378	69	0.04126698	0.245032673	0.017986326
70	0.06417417	71	0.03681527	0.203765696	0.013076494

72	0.05364748	73	0.03222485	0.166950423	0.008956469
74	0.04288305	75	0.02767524	0.13472557	0.005777443
76	0.032777	77	0.02332005	0.107050328	0.003508789
78	0.02395521	79	0.01927991	0.083730278	0.002005777
80	0.01674088	81	0.01563933	0.064450365	0.001078956
82	0.01118674	83	0.01244712	0.048811031	0.000546036
84	0.00714786	85	0.0097198	0.036363909	0.000259924
86	0.00436713	87	0.00744703	0.026644111	0.000116358
88	0.00255131	89	0.00559818	0.019197081	4.89777E-05
90	0.00142521	91	0.00412902	0.013598905	1.93812E-05
92	0.00076127	93	0.00298804	0.009469881	7.20915E-06
94	0.00038882	95	0.00212159	0.006481844	2.52027E-06
96	0.00018989	97	0.001478	0.004360251	8.27973E-07
98	8.8676E-05	99	0.00101025	0.002882246	2.55587E-07
100	3.9597E-05	101	0.00067751	0.001872001	7.4125E-08
102	1.6907E-05	103	0.0004458	0.001194491	2.01948E-08
104	6.9024E-06	105	0.00028781	0.000748689	5.16777E-09
106	2.6946E-06	107	0.00018231	0.000460879	1.24188E-09
108	1.0059E-06	109	0.0001133	0.00027857	2.802E-10
110	3.5902E-07	111	6.9091E-05	0.000165266	5.93341E-11
112	1.2253E-07	113	4.1337E-05	9.61744E-05	1.17846E-11
114	3.9989E-08	115	2.4265E-05	5.48375E-05	2.19288E-12
116	1.2479E-08	117	1.3976E-05	3.05721E-5	3.81497E-13
118	3.7234E-09	119	7.8978E-06	1.65962E-05	6.17948E-14
120	1.0623E-09	121	4.3789E-06	8.69845E-06	9.24077E-15
122	2.8983E-10	123	2.3822E-06	4.31951E-06	
124	7.5606E-11	125	1.2715E-06	1.93735E-06	1.46475E-16
126	1.8859E-11	127	6.6587E-07	6.65867E-07	1.25576E-17
	1.000		**1.000**		**0.386**

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation