The objectives of NCHRP Project 12-28(2)A were to develop a microcomputer-based bridge management system (BMS) that could be implemented by departments of transportation and local bridge authorities as well as satisfy the requirements for bridge management systems mandated in the interim final regulations for Intermodal Surface Transportation Efficiency Act management systems. Phase 2 of the project was completed in 1994 and resulted in the development of the BRIDGIT BMS. The various models used in BRIDGIT to produce life-cycle activity profiles (LCAPs) for each bridge in a network are discussed. In developing repair and functional improvement strategies for any selected group of bridges, it is necessary to identify and compare feasible alternatives. As part of its optimization analysis, BRIDGIT develops different LCAPs for individual bridges and determines the present value of life-cycle costs and benefits for each one. The costs considered include agency costs for the various repair or improvement actions as well as user costs associated with accidents or detours due to load capacity deficiencies, vertical clearance deficiencies, or bridge width deficiencies.

As part of the inventory data requirements in BRIDGIT, it is necessary to define the physical and geometric characteristics of each bridge in a network. Bridges can be divided into segments that can represent different bridge units such as approach spans, main spans, or spans of similar construction. Agencies are required to define the various elements and protection systems that make up each segment.

BRIDGIT uses a condition rating system similar to that used in the Pontis bridge management system (BMS) software, whereby inspectors must report the quantity of a bridge element that is in each of the condition states defined for that element. Up to five condition states can be identified for any element model, with the first state representing the best condition. The condition state definitions correspond to different types and severities of defects for the element. Protection systems such as deck overlays are reported separately from the underlying element by using the same condition rating format.

In order to produce accurate life-cycle costs, predict future deterioration of elements and protection systems, and define feasible repair or improvement alternatives for each bridge, agencies must provide cost and deterioration information for each of the element and protection system models. The following data are required for each model. Unless otherwise noted, any references to elements are also applicable to protection systems.

- Repair actions and associated costs. For each condition state a repair action and associated unit cost may be defined. BRIDGIT uses this information to calculate the costs associated with repair of the element on the
basis of the quantities of an element identified in each condition state.

- A/M/U factors and threshold value. The A/M/U factor is used to define the acceptability of each condition state. This factor indicates whether a condition state is considered to be acceptable (A), marginally acceptable (M), or unacceptable (U). For example, Condition State 1 usually represents a condition that would not require any repair actions and that would always be considered acceptable. Condition State 2 usually corresponds to only a small amount of deterioration and would necessitate, at most, carrying out minor preventive maintenance actions to those element quantities. Thus, it would also be considered an acceptable condition state. Condition State 3 is generally defined as having significant deterioration but with little loss of structural capacity or performance. An agency would usually consider this state to be marginally acceptable. In other words, repair actions would be performed only if sufficient funds were available. Condition State 4 is usually associated with significant deterioration and with the loss of structural capacity or performance. This would no doubt be considered unacceptable and would require repair if the quantity of element in this state exceeds some defined threshold value percentage.

As part of the element model information, BRIDGIT requires agencies to define this threshold value, which represents the maximum permissible quantity (in percent) of an element that may be present in any unacceptable condition state before a repair action should be triggered. As part of the development of individual bridge life-cycle activity profiles (LCAPs), the threshold value is therefore used to determine the timing of future repair actions.

- Element deterioration models. BRIDGIT has been initially loaded with deterioration information for four environments: benign, low, moderate, and severe. It is expected that agencies will customize these data to reflect their own experience and judgment. Because little information that can be used to assist agencies in initially defining deterioration model parameters is available, any BMS should assist agencies in improving the accuracy of this information in the future. To accomplish this, BRIDGIT provides a routine for automatically updating the deterioration models from an analysis of historical inspection data.

BRIDGIT also provides a means for agencies to specify additional factors that can be used to modulate the rate of deterioration of the average element deterioration models on the basis of average daily traffic (ADT). These factors are defined for each functional route classification and are applied to any element or protection system model that has been identified as being affected by ADT. In general, deck elements, joints, and overlays are affected by ADT.

**Development of Agency and User Costs**

Two types of costs are considered in any year of a bridge's life cycle: agency costs and user costs. Agency costs are incurred by bridge users as a result of functional deficiencies. The occurrence of accidents is higher on bridges with narrow deck widths or low vertical clearances than on bridges without these deficiencies. Bridges with low vertical clearances or insufficient load capacities will force a certain volume of truck traffic to be detoured to alternate routes, resulting in increased vehicle operating costs.

**Development of Agency Costs for Repair and Improvement Actions**

A number of repair or improvement cost alternatives are developed by BRIDGIT for any given year in a bridge's life cycle. These include

1. Scheduled actions,
2. Level 1 (U) repairs,
3. Level 2 (U-M) repairs,
4. Protection system replacement in a bridge segment,
5. Element replacement in a bridge segment,
6. Superstructure replacement in a bridge segment,
7. Segment replacement,
8. Load capacity improvements,
9. Bridge raising improvements,
10. Bridge widening improvements, and

**Scheduled Actions**

Scheduled actions are defined as repairs that form part of a scheduled maintenance program for bridges and that include such actions as repairing railings or joints as well as painting steel elements or overlaying decks. BRIDGIT considers scheduled actions for all protection systems as well as any minor unprotected elements. The term “scheduled actions” denotes that this level of maintenance is programmed and should be performed as required. It does not compete with other actions during optimization. Scheduled actions are initiated when the element or protection system deteriorates to the point at which the quantity of an element in an unacceptable state exceeds the threshold value defined for the model. At that time, all unacceptable marginally acceptable states are repaired and returned to Condition State 1. A scheduled action within 5 years of a selected
repair, rehabilitation, or replacement action will be deferred. For example, repainting of a steel girder element should not occur if the girders are to be repaired within 5 years. Painting would be deferred until the year of repair.

**Level 1 (U) Bridge Repairs**

Level 1 bridge repairs are defined as actions that remove only the quantities of elements in an unacceptable condition state. This is referred to as a “U” repair in BRIDGIT. Level 1 repairs do not remove functional deficiencies, with the possible exception of load-carrying capacity. This repair scenario would normally be applicable to situations in which it is desirable to extend the service life of the bridge until a more comprehensive action can be afforded (such as replacement of the entire bridge). Level 1 repairs can often be the most cost-effective bridge repair action, even though they do not completely restore the bridge to an acceptable condition level.

**Level 2 (U-M) Bridge Repairs**

Level 2 bridge repairs are defined as those repairs that are intended to remove all quantities of elements in unacceptable and marginally acceptable condition states. This is referred to as a “U-M” repair in BRIDGIT. Level 2 repairs do not remove functional deficiencies, with the possible exception of load-carrying capacity.

**Protection System Replacement in a Bridge Segment**

When a protection system receives a repair, BRIDGIT checks to see whether complete replacement of the protection system for that bridge segment may be a more economical choice. This verification is made by comparing the cost of repairing the protection system with the cost of replacing the protection system.

**Element Replacement in a Bridge Segment**

When an element receives a scheduled Level 1 or Level 2 repair, BRIDGIT checks to see whether complete replacement of that element and any associated protection system may be warranted. This check is made by comparing the cost of repairing the element and protection system for a particular bridge segment with the cost of replacing the entire element and protection system. BRIDGIT also recognizes the fact that a new element and associated protection system generally have longer lives and thus reduced life-cycle costs. Therefore, BRIDGIT selects an element and protection system replacement if the cost of repairs exceeds 70 percent of the cost of replacement. This value is based on evaluations of life-cycle costs associated with various types of bridge repairs and represents a conservative level. Element replacement is usually considered to be economical when the repair costs exceed 65 to 85 percent of the replacement costs.

**Superstructure Replacement in a Bridge Segment**

In the same way that the cost-effectiveness of element replacement is evaluated against element repairs, BRIDGIT also examines replacement of the entire superstructure including the deck, bearings, joints, and railing elements. This situation is difficult to evaluate because replacement of a superstructure for only one segment of the bridge usually involves a number of considerations:

1. Should the superstructure be replaced to the same dimensions that already exist when only a portion of the total bridge is being considered for replacement?
2. Should the bridge be locally widened in anticipation of a possible future widening of the remaining segments?
3. Does replacement of, say, one span remove a load capacity deficiency or does it still exist at another location?
4. Does a localized bridge raising, if possible, through a more slender superstructure design or adjustment of the vertical profile remove a vertical clearance deficiency, or does it still exist in another location? If there is at least a partial removal of a vertical deficiency, how much traffic under the bridge is affected?

BRIDGIT sidesteps these issues by not evaluating superstructure replacement as a bridge improvement alternative to be considered during the optimization analysis. Instead, BRIDGIT evaluates superstructure replacement after optimization is complete by notifying the user in the analysis work plan reports that superstructure replacement may be warranted for a particular bridge if the combined cost of repairs for a particular segment for the superstructure, deck, joints, bearings, and railing elements exceeds 70 percent of the cost of replacing the entire superstructure.

**Segment Replacement**

The issue of segment replacement is treated in the same way as superstructure replacement is (i.e., not during optimization). In the case in which both superstructure replacement and segment replacement may be warranted, only replacement of the segment is reported. The cost of segment replacement is calculated by using
the bridge replacement unit costs defined for the replacement bridge model identified for that segment.

**Load Capacity Improvements**

If a bridge has been identified as being posted, BRIDGIT assumes that Level 1 repair, Level 2 repair, and replacement actions to superstructure elements will result in increased load capacity for the bridge. The amount of increase is determined by the following rules:

1. A Level 1 repair restores the load capacity 85 percent of the way back to its load capacity in the new condition, provided that the percentage of the total quantity remaining in any marginally acceptable states after repairs for any critical superstructure element does not exceed 25 percent.
2. A Level 1 repair restores the bridge load capacity only 50 percent of the way back to its load capacity in the new condition if the percentage of the total quantity in any marginally acceptable states after repairs for any critical superstructure element exceeds 25 percent.
3. A Level 2 repair restores the bridge load capacity 85 percent of the way back to its load capacity in the new condition.
4. Bridge replacement results in a bridge load capacity 25 percent higher than the maximum legal load or nonposted single-vehicle capacity.

**Bridge Raising Improvements**

A bridge raising improvement is intended to remove functional deficiencies due to vertical clearance. As part of the inventory information required for each bridge, users are required to define whether each bridge segment can be raised (on the basis of physical as well as economic constraints). BRIDGIT will verify if all segments in the bridge can be raised. If this is possible, BRIDGIT will estimate the cost to remove the vertical deficiency.

BRIDGIT assumes that once bridge raising improvements have been performed, no future user costs due to vertical clearance deficiencies will be incurred over the remaining life of the bridge.

**Bridge Widening Improvements**

A bridge widening is intended to remove functional deficiencies due to clear deck width. As part of the inventory information required for each bridge, users are required to specify if each bridge segment can be widened. BRIDGIT will verify whether it is possible to widen all segments in a bridge. If so, BRIDGIT will consider widening the bridge to the desirable level-of-service goals for clear deck width defined by the agency for a projected level of traffic 20 years beyond the date of the widening. Widenings can be of two types:

1. Minor width adjustments to remove lane width and shoulder deficiencies and
2. Major width adjustments to add new lanes. This may be a twinning of an existing structure.

It is recognized that the unit costs of minor widenings are higher because of the difficulties of integrating new structural elements with existing ones. For this reason BRIDGIT permits agencies to define a multiplying factor that is used to increase the unit cost for widenings less than a prescribed width. For widenings greater than this prescribed value, the unit costs defined for the replacement bridge models identified for each segment of the bridge are used without modification.

**Bridge Replacement**

A bridge replacement removes all functional deficiencies and is designed to accommodate levels of traffic 20 years beyond the year of replacement being considered. The new bridge width will be based on the desirable level-of-service goals defined by the agency for vertical clearance, number of lanes, lane widths, and load capacity. The new length of the bridge is assumed to be longer than that of the structure being replaced and is calculated from an equation that is modifiable by the agency.

**Development of Agency Costs for Routine Maintenance**

BRIDGIT estimates the present value of annual costs associated with routine maintenance of a bridge over its service life. In BRIDGIT routine maintenance represents strictly preventive actions such as deck washing, drain cleaning, and bearing cleaning. Spot repairs to bridge elements and protection systems are considered scheduled actions. In order to calculate routine maintenance costs for all bridge elements of any bridge i, BRIDGIT multiplies the quantities of the element reported in each element condition state by the unit maintenance costs defined by the bridge agency for each corresponding element model. It is assumed that these costs increase as the conditions of the bridge elements deteriorate. Elements that have an associated protection system receive maintenance to the protection system only. This can be represented by the equation

\[
ARMC(i, t) = \sum_{c=1}^{NBE(i)} MCB(i, c, t) + \sum_{c=1}^{NPBE(i)} MCP(i, c, t) \tag{1}
\]
where

\[ t = \text{time; time is generally considered to be a continuum but is sometimes discretized to integer years; the first year is denoted as year 0 and year 1 is defined as being from } t = 1.0 \text{ to } 1.999; \]

\[ \text{ARMC}(i, t) = \text{annual routine maintenance cost for bridge } i \text{ at the beginning of year } t; \]

\[ \text{MCB}(i, c, t) = \text{maintenance cost for bare bridge element } c \text{ of bridge } i \text{ at the beginning of year } t; \]

\[ \text{MCP}(i, c, t) = \text{maintenance cost for bridge protection system } c \text{ of bridge } i \text{ at the beginning of year } t; \]

\[ \text{NB}(i) = \text{total number of bare bridge elements for bridge } i; \]

\[ \text{NP}(i) = \text{total number of protection systems for bridge } i. \]

The present value (PV) of routine maintenance (RM) costs from time \( T_1 \) to \( T_2 \) for bridge \( i \) can then be calculated as follows:

\[
\text{PV}_{\text{RM}}(i, T_1, T_2) = \sum_{t=T_1}^{T_2} \frac{\text{ARMC}(i, t)}{(1 + \text{RRRR})^t} \tag{2}
\]

where RRRR is real required rate of return or discount rate.

**Development of User Costs**

User costs are generated because of deficiencies associated with narrow deck width, insufficient load capacity, and low vertical clearance. The various concepts used in BRIDGIT for estimating these costs have been developed by Chen and Johnston (1), Aabed-Al-Rahim and Johnston (2), and Al-Subhi et al. (3) for use in the optimization portion of the OPBRIDGE program, developed for the North Carolina Department of Transportation.

The occurrence of accidents is higher on bridges with narrow deck widths, poor approach alignments, or low vertical clearances than on bridges without these deficiencies. Bridges with low vertical clearances or insufficient load capacities force a certain volume of truck traffic to be detoured to alternate routes, resulting in increased vehicle operating costs. As the volume of traffic increases the number of accidents or detoured vehicles also increases.

For each bridge in the network BRIDGIT determines if a geometric or load capacity deficiency exists by comparing the bridge's vertical clearance, deck width, and load capacity with the level-of-service goals defined by the agency. The calculation of annual user costs considers the following three terms:

- User costs associated with deficient deck width. User costs associated with deficient deck width are a function of traffic volume, structure length, acceptable deck width, and the actual deck width.

The present value of user costs for bridge \( i \) due to deck width deficiency within the time interval of \( T_1 \) to \( T_2 \) years can be expressed as

\[
\text{PV}_{\text{WIDTH}}(i, T_1, T_2) = \sum_{t=T_1}^{T_2} \frac{\text{COST}_{\text{WIDTH}}(i, t)}{(1 + \text{RRRR})^t} \tag{3}
\]

where \( \text{COST}_{\text{WIDTH}}(i, t) \) is user costs associated with width deficiency in year \( t \) for bridge \( i \).

- User costs associated with vertical clearance deficiencies. Vertical clearance deficiencies can generate user costs due to accidents that occur on the bridge (overhead deficiencies) or under the bridge (underpass deficiencies) as well as detour costs due to deficient clearance under or over the bridge. The following equation expresses these costs in any year \( t \) for bridge \( i \):

\[
\text{COST}_{\text{VERT}}(i, t) = \text{COST}_{\text{VERT AO}}(i, t) + \text{COST}_{\text{VERT AU}}(i, t) + \text{COST}_{\text{VERT DO}}(i, t) + \text{COST}_{\text{VERT DU}}(i, t) \tag{4}
\]

where

\[
\text{COST}_{\text{VERT}}(i, t) = \text{annual user cost due to vertical clearance deficiencies for bridge } i \text{ in year } t; \]

\[
\text{COST}_{\text{VERT AO}}(i, t) = \text{annual user cost due to accidents on the bridge attributed to vertical clearance over the bridge}; \]

\[
\text{COST}_{\text{VERT AU}}(i, t) = \text{annual user cost due to accidents under the bridge attributed to vertical clearance under the bridge}; \]

\[
\text{COST}_{\text{VERT DO}}(i, t) = \text{annual user cost due to detouring of traffic from on the bridge because of vertical clearance deficiency over the bridge}; \]

\[
\text{COST}_{\text{VERT DU}}(i, t) = \text{annual user cost due to detouring of traffic from under the bridge because of a vertical clearance deficiency under the bridge}. \]
The present value of accident and detour costs for bridge \( i \) due to vertical clearance deficiencies within the time interval of \( T_1 \) to \( T_2 \) years can be expressed as

\[
PV_{\text{VERT}}(i, T_1, T_2) = \sum_{t=T_1}^{T_2} \frac{\text{COST}_{\text{VERT}}(i, t)}{(1 + RRRR)^t}
\] (5)

- Annual user costs associated with load capacity deficiency. Reduced load capacity results in a percentage of the traffic being detoured, thus generating user costs. These user costs can be expressed as a function of traffic volume, detour length, and the percentage of trucks detoured at the reduced load capacity.

The present value of user costs for bridge \( i \) due to posting within the time interval of \( T_1 \) to \( T_2 \) can be expressed as

\[
PV_{\text{POST}}(i, T_1, T_2) = \sum_{t=T_1}^{T_2} \frac{\text{COST}_{\text{POST}}(i, t)}{(1 + RRRR)^t}
\] (6)

where \( \text{COST}_{\text{POST}}(i, t) \) is user cost due to reduced load capacity in year \( t \) for bridge \( i \).

- Calculation of total user costs. The total annual user cost associated with geometry and load capacity deficiencies of bridge \( i \) in year \( t \) is calculated as follows:

\[
\text{COST}_{\text{USER}}(i, t) = \text{COST}_{\text{WIDTH}}(i, t) + \text{COST}_{\text{VERT}}(i, t) + \text{COST}_{\text{POST}}(i, t)
\] (7)

and the present value of user costs for bridge \( i \) within the interval \( T_1 \) to \( T_2 \) years and discounted to year 0 is

\[
PV_{\text{USER}}(i, T_1, T_2) = PV_{\text{WIDTH}}(i, T_1, T_2) + PV_{\text{VERT}}(i, T_1, T_2) + PV_{\text{POST}}(i, T_1, T_2)
\] (8)

**Development of Life-Cycle Activity Profiles**

A life-cycle activity profile (LCAP) represents a series of repair and improvement actions expected to occur over the life of a structure. The cost to an agency for a bridge is seldom a one-time cost. It is a long-term, multiyear investment. Throughout its useful life, a bridge requires periodic maintenance and possibly repair or rehabilitation actions. At the end of its useful life, the bridge must be replaced.

As part of its optimization analysis, BRIDGIT compares the cost-effectiveness of different repair and improvement options for each bridge in the network by determining the present value of costs and benefits of each option by using a life-cycle approach. The various alternatives to be considered for economic analysis are selected from knowledge-based decision rules that examine overall strategies over the life cycle of each bridge. BRIDGIT calculates the present value of life-cycle costs for the following maintenance, rehabilitation, and replacement alternatives at each analysis period:

1. Replacement,
2. Rehabilitation (Level 2 repairs to all bridge elements and removal of all functional deficiencies),
3. Level 2 (U-M) repairs to all bridge elements, and
4. Level 1 (U) repairs to all bridge elements.

In addition, the present value cost of doing nothing except routine maintenance and scheduled actions until the end of the analysis horizon (year 20) is calculated; this is followed by an LCAP based on the bridge's condition and functionality at the end of the analysis horizon.

The development of the LCAPs includes the costs associated with immediate as well as future actions. BRIDGIT ages the bridge network to project the future conditions of elements and protection systems in order to calculate future repair or improvement costs. In addition, future ADT levels are predicted in order to determine future user costs. The LCAP models select feasible repair and functional improvement actions and determine the appropriate timing of such actions over the life cycle of each bridge.

**Replacement LCAP**

The replacement LCAP assumes that all bridges require complete replacement at some year \( t_g \) in the future. BRIDGIT permits bridge agencies to define replacement bridge models and associated unit construction costs for different road classifications and span length ranges. This information is used to develop the LCAP.

Agencies are required to supply all of the information necessary to calculate the replacement LCAP in the models section of BRIDGIT. It is therefore a "hard-wired" LCAP in that the calculated present values of present and future costs are fundamentally characteristic of the model and not site dependent. They depend only on the size of the new bridge.

**Initial Bridge Replacement Costs**

The estimated initial cost of a bridge replacement alternative for any existing bridge \( i \) at the beginning of year \( t \) can be expressed as a function of the existing bridge length, the width required to accommodate future traf-
fic volumes, the type of replacement bridge, and the cost per unit deck area for that replacement bridge type.

User Costs

When the bridge is replaced in year $t_R$ it is assumed that the design will meet all functional requirements over its service life. Therefore, no user costs associated with geometric deficiencies will be incurred over the life of the new structure. Load capacity is assumed to be related to the condition of the key bridge superstructure elements. Initially, the bridge does not have any load capacity deficiencies and therefore does not have any associated user costs. It is also assumed that the new bridge receives timely repairs that would ensure that the bridge would not require posting at any time. User costs are thus zero.

Routine Maintenance and Minor Repair Costs

The bridge replacement models defined by the agency in BRIDGIT include an average unit annual cost of maintenance over the life of the bridge model. This value represents both routine preventive maintenance as well as minor repair actions to the bridge. A new bridge is assumed to not require any maintenance repairs until a significant quantity of one of its bridge elements has deteriorated to Condition State 2 or 3. Costs then increase annually as the condition of the new bridge deteriorates and until the bridge is rehabilitated.

When elements have been improved by rehabilitation, the maintenance costs are reduced or eliminated, depending on the condition of other bridge elements at the time of rehabilitation. As the structure deteriorates, these costs again increase until the next rehabilitation and then again to the next replacement. The present value of the maintenance costs accumulated from the time of replacement until the next bridge replacement thus assumes that maintenance varies through time.

Major Repairs and Rehabilitation

The replacement LCAP includes up to two major repairs during the life of the bridge. The timing of these actions as well as their associated unit costs are taken from the replacement bridge model defined by the agency.

Calculation of Replacement Life-Cycle Costs

The present value of the replacement life-cycle costs for the replacement LCAP for bridge $i$ applied at the beginning of year $t_R$ and discounted to year 0 and assuming perpetual replacements every $t_{NB}$ years can be expressed as

$$PV_{REPL}(i, t_R) = \frac{ICNB(i, t_R)}{(1 + RRRR)^{t_R}} + \frac{COSTRH1(i)}{(1 + RRRR)^{(t_R + t_RHi)}}$$

$$+ \frac{COSTRH2(i)}{(1 + RRRR)^{(t_R + t_RHi + t_{Hi})}} + \sum_{j=t_R + t_{Hi}}^{t_R + t_{NB}} ARMC(i, t) \frac{1}{1 - (1 + RRRR)^{-t_{NB}}}$$

where

- $ICNB(i, t_R) =$ initial cost of a bridge replacement for bridge $i$ in year $t_R$;
- $COSTRH1(i) =$ initial cost of the first rehabilitation of bridge $i$ at the beginning of year $t_R + t_{Hi}$;
- $COSTRH2(i) =$ initial cost of the second rehabilitation of bridge $i$ at the beginning of year $t_R + t_{Hi} + t_{Hi} + t_{Hi} = t_R + 2t_{Hi}$;

Rehabilitation LCAP

The purpose of a major rehabilitation is to extend the service life of a bridge before replacement. Usually, a bridge receives one major rehabilitation in its lifetime involving the replacement or rehabilitation of all deficient bridge elements and the removal of all functional deficiencies. At the end of the extended service life $E$, BRIDGIT assumes that the rehabilitated bridge may receive one more repair cycle and then be replaced.

The rehabilitation LCAP assumes that the rehabilitated bridge is improved to meet all functional requirements established by the bridge agency for the remainder of its extended service life (i.e., the bridge is widened or vertical clearance is increased to the level-of-service standards defined by the agency). Therefore, no user costs due to geometric deficiencies are incurred during the extended life of the bridge. If a bridge's geometric deficiencies cannot be removed because of some constraint, then the rehabilitation alternative is rejected as infeasible.

Routine maintenance costs are generally reduced because of the rehabilitation but increase over the extended service life of the bridge as it deteriorates.

The present value of the life-cycle costs of the rehabilitation LCAP, $PV_{UMF}(i, t)$, is the sum of the dis-
counted initial cost of rehabilitation at year \( t \), the present value of annual routine maintenance and user costs during the extended service life period \( E \), and the minimum of the present value of the replacement LCAP applied at the end of the extended service life or the present value of another rehabilitation cycle. This can be expressed as

\[
PV_{UMF}(i, t) = \frac{COST_{UM}(i, t)}{(1 + RRRR)^t} + \frac{COST_{WIDEN}(i, t)}{(1 + RRRR)^t} + \frac{COST_{RAISE}(i, t)}{(1 + RRRR)^t} + PV_{SCHED}(i, t, t + E) + PV_{RM}(i, t, t + E) + PV_{USER}(i, t, t + E) + \min[PV_{REPL}(i, t + E), PV_{UMF}(i, t + E)]
\]  

where

\[
COST_{UM}(i, t) = \text{cost of a repair to remove all unacceptable and marginal states in year } t;
\]

\[
COST_{WIDEN}(i, t) = \text{cost of widening bridge};
\]

\[
COST_{RAISE}(i, t) = \text{cost of raising bridge};
\]

\[
PV_{SCHED}(i, t, t + E) = \text{present value of scheduled maintenance from year } t \text{ to } t + E;
\]

\[
PV_{RM}(i, t, t + E) = \text{present value of routine maintenance from year } t \text{ to } t + E;
\]

\[
PV_{USER}(i, t, t + E) = \text{present value of user costs from year } t \text{ to } t + E;
\]

\[
\min[\ldots] = \text{minimum value of the terms inside the brackets};
\]

\[
PV_{REPL}(i, t + E) = \text{present value of a replacement LCAP in year } t + E; \text{ and}
\]

\[
PV_{UM}(i, t + E) = \text{present value of a Level 2 repair LCAP in year } t + E.
\]

**Level 1 (U) or Level 2 (U-M) Repair LCAPs**

The third type of repair or improvement alternative to be considered during optimization is the Level 1 or Level 2 repair LCAP. The purpose of this level of action is to repair elements that are in unacceptable or marginally acceptable condition states without initiating any functional improvement such as widening or raising. At the end of the extended service life \( E \), it is assumed that either a rehabilitation or a replacement action takes place at year \( t + E \).

Two LCAP scenarios are possible:

1. Removal of all unacceptable condition states, a Level 1 (U) repair; and
2. Removal of all unacceptable and marginally acceptable condition states, a Level 2 (U-M) repair.

The Level 1/Level 2 repair LCAP does not involve removal of any geometric deficiencies that may be present. Therefore, user costs due to geometric deficiencies may be incurred until the year that a rehabilitation or replacement is carried out. Routine maintenance costs are calculated in the same way as for the rehabilitation LCAP.

The present values of the two life-cycle costs for the repair alternatives \( PV_U \) and \( PV_{UM} \) are calculated as the sum of the discounted initial cost of the repair alternative in year \( t \), the present value of annual routine maintenance and user costs during the extended service life period, and the present value of the rehabilitation or replacement LCAP applied at the end of the extended service life. This can be expressed as

\[
PV_U(i, t) = \frac{COST_U(i, t)}{(1 + RRRR)^t} + PV_{SCHED}(i, t, t + E_U) + PV_{RM}(i, t, t + E_U) + PV_{USER}(i, t, t + E_U) + \min[PV_{REPL}(i, t + E_U), PV_{UMF}(i, t + E_U)]
\]  

where \( COST_U(i, t) \) is the cost of a repair to remove all unacceptable states in year \( t \) for bridge \( i \) and \( E_U \) is extended service life due to a Level 1 repair; all other terms were defined earlier.

Similarly, the present value of the Level 2 repair LCAP can be expressed as

\[
PV_{UM}(i, t) = \frac{COST_{UM}(i, t)}{(1 + RRRR)^t} + PV_{SCHED}(i, t, t + E_{UM}) + PV_{RM}(i, t, t + E_{UM}) + PV_{USER}(i, t, t + E_{UM}) + \min[PV_{REPL}(i, t + E_{UM}), PV_{UMF}(i, t + E_{UM})]
\]  

where \( E_{UM} \) is the extended service life due to a Level 2 repair, and all other terms have been defined earlier.
Base Case—The “Do-Nothing” LCAP

As part of the optimization analysis, BRIDGIT compares the present value of costs associated with each of the feasible alternatives defined for replacement, rehabilitation, or Level 1/Level 2 repair of a bridge with the present value of the do-nothing LCAP. In developing this base case it is assumed that no bridge repair or improvement actions are performed on the bridge during the optimization analysis horizon of 20 years. Two different scenarios can result from this assumption:

- Case 1: Bridge becomes functionally deficient during the analysis horizon. At the end of the 20-year analysis horizon a functionally deficient bridge is assumed to require either rehabilitation or replacement. Level 1 and Level 2 LCAPs are not considered acceptable.
- Case 2: Bridge does not become functionally deficient during the analysis horizon. If by the end of the analysis horizon no “critical” bridge elements have deteriorated to the point that quantities in unacceptable condition states have exceeded the defined threshold values, the time beyond 20 years at which a critical threshold is reached is determined and the LCAP with the least present value of costs at that point is applied. If a critical bridge element has already exceeded the defined threshold, then the LCAPs are applied immediately after the 20-year analysis horizon.

The do-nothing LCAP forms the base case against which all other alternatives are evaluated. Since BRIDGIT assumes that scheduled actions can form part of the do-nothing alternative, it is not a zero-cost alternative. For each period all elements are deteriorated from their condition at the beginning of the period to their condition at the end of the period, suitably adjusted for ADT effects. This process may initiate scheduled actions to minor elements and to protection systems.

At this point all of the costs and associated present values for scheduled actions and for user costs up to year 20 have been calculated. It is now necessary to calculate the number of years from year 20 to the just-calculated year. This point an action is taken, namely, the most cost-effective life-cycle activity profile, based on the calculated present value of the Level 1 or Level 2 repair, rehabilitation, or replacement LCAPs.

We now have the total present value in year zero of doing no repair, rehabilitation, or replacement in the first 20 years followed by some action after 20 years, with proper account taken of user costs, routine maintenance, and scheduled actions within the first 20 years and beyond.

The present value of the life-cycle costs, $PV_{DN}(i)$, for the do-nothing alternative is thus the sum of the present value of routine maintenance, scheduled maintenance, and user costs during the analysis horizon of 20 years and the minimum of the present values for the replacement, rehabilitation, and Level 1 or Level 2 repair LCAPs applied after the 20-year analysis horizon. This can be expressed as

$$ PV_{DN}(i) = PV_{RM}(i, 0, YR(i)) + PV_{USER}(i, 0, YR(i)) + PV_{SCHED}(i, 0, yr(i)) + \min\{PV_{UM}(i, YR(i)), PV_{UMF}(i, YR(i)), PV_{REPL}(i, YR(i))\} $$

where $YR(i)$ is the year beyond the analysis horizon at which a repair is required for bridge $i$, and all other terms have been defined earlier.

Example: Calculation of a Level 2 Repair LCAP in Period 4

A Level 2 repair LCAP in Period 4 constitutes 1 of the 21 alternatives that BRIDGIT considers and has been selected to illustrate the basic methodology by which costs and present values are calculated for each alternative. Period 4 is defined as being from years 11 to 15 of the 20-year analysis horizon. BRIDGIT assumes that a Period 4 action will occur in year 13, approximately the median year for the period.

Up to year 13, the do-nothing LCAP is followed, except that scheduled actions in years 9 to 13 are dropped since they are within 5 years of the primary action. Thus, up to year 13

$$ PV(i, 0, 13) = PV_{USER}(i, 0, 13) + PV_{RM}(i, 0, 13) + PV_{SCHED}(i, 0, 8) $$

The number of years until a critical element reaches its threshold value is determined by deteriorating the elements of the bridge through time until the threshold value for any critical element is exceeded. It is then necessary to calculate the user costs and routine maintenance costs associated with the time period from year 20 to the just-calculated year. At this point an action is taken, namely, the most cost-effective life-cycle activity profile, based on the calculated present value of the Level 1 or Level 2 repair, rehabilitation, or replacement LCAPs.
where

\[ \text{PV}_{\text{USER}}(i, 0, 13) = \text{the present value of user costs from year 0 to 13 for bridge } i; \]
\[ \text{PV}_{\text{RM}}(i, 0, 13) = \text{the present value of routine maintenance costs from year 0 to 13 for bridge } i; \]
\[ \text{PV}_{\text{SCHED}}(i, 0, 8) = \text{the present value of scheduled maintenance from year 0 to 8 for bridge } i; \]
\[ \text{PV}(i, 0, 13) = \text{the present value of all user costs, scheduled maintenance, and routine maintenance up to year 13 for bridge } i. \]

In year 13 the Level 2 (UM) repair is undertaken. It should be noted that for the primary action the timing of the action is independent of the condition of the elements. Whether a critical element is under or over its threshold value has no influence on the timing of the principal action. It is simply a Period 4 repair option. Following the repair, the bridge elements are in an improved condition. It is now necessary to calculate the number of years that it takes for a critical element to deteriorate to the point at which its unacceptable condition quantity exceeds its defined threshold value.

This is done by deteriorating all of the elements of the bridge until one of the critical elements reaches its threshold (but not less than 10 years). As an example assume that superstructure steel box girders are deemed critical elements and that in year 29, 15 percent of the total element quantity is in Condition State 4 (and also that Condition State 4 is an unacceptable state with a defined threshold value of 15 percent). Year 29 thus becomes the year at which an action must be taken.

From year 13 to year 29 it is necessary to calculate the additional user costs, routine maintenance costs, and scheduled action costs to be included in the present value calculation. At year 29, according to the Level 2 repair LCAP, we have two choices: rehabilitate the structure or replace the structure. The least present value option will be selected. Thus,

\[ \text{PV}(i, 0, 29) = \text{PV}(i, 0, 13) + \frac{\text{COST}_{\text{UM}}(i, 29)}{1 + RRRR} + \frac{\text{COST}_{\text{WIDEN}}(i, 29)}{1 + RRRR} + \frac{\text{COST}_{\text{RAISE}}(i, 29)}{1 + RRRR} + \text{PV}_{\text{SCHED}}(i, 29, 57) + \text{PV}_{\text{RM}}(i, 29, 57) + \text{PV}_{\text{USER}}(i, 29, 57) + \text{PV}_{\text{REPL}}(i, 57) \]  

It should be noted that at each step of the way it is necessary to determine element condition state quantities and bridge load capacity before and after the repair or improvement actions have been implemented. In addition, ADT volumes and their effects on bridge width requirements and user costs must also be determined.

Thus, in year 29 the structure receives a rehabilitation action. If the bridge is now (i.e., year 29) width deficient relative to the acceptable level-of-service goals, BRIDGIT will assume that the bridge must be widened to satisfy the desirable width goals for ADT levels 20 years hence (i.e., year 49). If the bridge is vertical clearance deficient relative to the acceptable level-of-service goals, BRIDGIT will assume that the bridge must be raised to the desirable level-of-service goal.

If after the rehabilitation action (Level 2 repair and removal of all geometric deficiencies) the bridge is still load capacity deficient relative to the defined acceptable level-of-service goals, then BRIDGIT will not consider rehabilitation as a feasible alternative. Similarly, if widening is required and not possible or raising is required and not possible, then rehabilitation is not considered feasible. It should also be noted that if there are no functional deficiencies relative to acceptable standards, then the rehabilitation option is really no different than the Level 2 repair option. Again, assuming that the rehabilitation option in year 29 was the best choice and that the bridge requires widening and raising, BRIDGIT now continues with the development of the LCAP by again determining the future year when a critical element reaches its defined threshold value. At that time BRIDGIT considers only one feasible option: replacement. If it is assumed that this occurs in year 57, then it is necessary to calculate the additional user costs, routine maintenance costs, and scheduled action costs from years 29 to 57 for inclusion in the present value calculations. At year 57 BRIDGIT determines the present value cost of the replacement LCAP, which is completely defined by the replacement bridge model specified for that bridge. These models include all of the future costs that are associated with replacement (in perpetuity). Thus,

\[ \text{PV}(i, 0, \infty) = \text{PV}(i, 0, 29) + \frac{\text{COST}_{\text{UM}}(i, 29)}{1 + RRRR} + \frac{\text{COST}_{\text{WIDEN}}(i, 29)}{1 + RRRR} + \frac{\text{COST}_{\text{RAISE}}(i, 29)}{1 + RRRR} + \text{PV}_{\text{SCHED}}(i, 29, 57) + \text{PV}_{\text{RM}}(i, 29, 57) + \text{PV}_{\text{USER}}(i, 29, 57) + \text{PV}_{\text{REPL}}(i, 57) \]  

To simplify the discussion, assume that the rehabilitation option turns out to be the most economical.
**Cost-Effectiveness Index**

Once the present values for each of the 20 repair LCAPs (four alternatives per period by five periods) as well as the do-nothing LCAP have been determined for a given bridge, the benefits and costs of each of the alternatives can be compared. The benefits associated with a particular alternative are represented by the reduction in the present value of costs for that alternative compared with that for the do-nothing case. Thus, benefits are considered to be reductions in future maintenance, repair, or user costs. Costs are considered to be the discounted initial cost of the alternative. It would also be valid to consider all costs within the 20-year time horizon or all life-cycle costs. The decision as to which costs to include is dependent on whether future costs are considered to be true costs or disbenefits. Use of only the initial cost in a benefit-cost ratio tends to favor low-cost repairs, provided that user costs are low, over more extensive repairs or functional improvements. The benefit-cost ratio (expressed as a cost-effectiveness index) can be defined in a modified form as

\[
\text{CEI}(i, p, a) = \frac{\text{PV}_{\text{DN}}(i) - \text{PV}_{\text{ALT}}(i, p, a)}{\text{COST}_{\text{ALT}}(i, p, a)/(1 + \text{RRRR})^{t(p)}} + 1 \quad (17)
\]

where

- \(\text{CEI}(i, p, a)\) = cost-effectiveness index for alternative \(a\) in period \(p\) for bridge \(i\);
- \(\text{PV}_{\text{ALT}}(i, p', a)\) = present value of alternative \(a\) in period \(p\) for bridge \(i\);
- \(\text{COST}_{\text{ALT}}(i, p, a)\) = cost of alternative \(a\) in period \(p\) for bridge \(i\); and
- \(t(p)\) = median year for period \(p\).

Once the benefits and costs are determined, various optimization strategies can be used. BRIDGIT uses a multi-period modified incremental benefit-cost approach (4).

**Conclusion**

This paper discussed the models used in BRIDGIT to produce LCAPs for each bridge in the network as well as the methodology used to determine the cost-effectiveness of each option. For each bridge BRIDGIT considers four LCAP alternatives (Level 1 repairs, Level 2 repairs, rehabilitation, and replacement) in each period of the 20-year planning horizon, as well as a do-nothing LCAP. The costs calculated for different repair or improvement actions in any year of an LCAP include agency costs as well as user costs associated with vertical clearance, deck width, and load capacity deficiencies. As part of its optimization analysis, BRIDGIT compares the benefits and costs for each LCAP alternative with those for the do-nothing LCAP.

**Acknowledgments**

This work formed part of an NCHRP project and was sponsored by AASHTO in cooperation with FHWA and was conducted in NCHRP, which is administered by TRB of the National Research Council.

**References**


The opinions and conclusions expressed or implied in this paper are those of the research agency. They are not necessarily those of TRB, the National Research Council, FHWA, AASHTO, or the individual states participating in NCHRP.