Feasibility of Incremental Benefit-Cost Analysis for Optimal Budget Allocation in Bridge Management Systems

FOAD FARID, DAVID W. JOHNSTON, BASHAR S. RIHANI, AND CHWEN-JINQ CHEN

A bridge management system (BMS) is a systematic framework that formalizes the decision-making process for bridge improvements. BMS decisions are analyzed at two levels: (a) at the bridge level, BMS determines the optimal improvement alternative for a bridge, and (b) at the system level, BMS supports decision makers in developing systemwide strategies for optimal use of the limited bridge improvement budgets. A major BMS module is an optimization algorithm for selecting the optimal combination of alternatives to maximize net benefits expected from the budget granted. The feasibility of implementing the Incremental Benefit-Cost (INCBEN) program for optimal allocation of the limited budgets to bridge improvement alternatives at the system level is investigated. Techniques and data exist for forecasting bridge agency costs and user costs, needed as input to INCBEN. Incremental benefits and costs are estimated from a base alternative. INCBEN ranks improvement alternatives in the decreasing order of their incremental benefit-cost ratios. These rankings are superior to those based on sufficiency ratings or level-of-service goals. INCBEN recommends near-optimal sets of bridge improvement alternatives under limited budgets. INCBEN selections under unlimited budgets are optimal and identical to the best alternatives selected by the economic analysis at the bridge level. INCBEN internally adds "do-nothing" alternatives to bridges without considering their consequences. This problem can be circumvented by manipulating the input data to ensure that the least-cost alternatives are funded first.

Because of the insufficient funding of bridge improvements, many bridges have become deficient in the United States (*1*). Budgets granted for bridge improvements are expected to be lower than budgets requested. Thus, a comprehensive bridge management system (BMS) is needed for consistent and efficient management of bridge improvements. BMS is a systematic framework that formalizes the decision-making process for bridge improvements. BMS decisions are analyzed at two levels: (a) at the bridge level, BMS determines the optimal improvement alternative for a bridge, and (b) at the system level, BMS supports decision makers in developing systemwide strategies for optimal use of the limited bridge improvement budgets (*2*).

Many states allocate their limited bridge improvement budgets by using sufficiency ratings or empirical formulas used to priority rank deficient bridges. Usually, a priority ranking formula translates physical conditions and level-of-service deficiencies into a priority index for every bridge. Bridges are then ranked according to their priority indexes for receiving improvement funding. Priority ranking formulas cannot select the optimal improvement alternative for a bridge, nor can they optimize net benefits expected from the bridge improvement budget granted. Thus, a systematic algorithm is needed for efficient allocation of the limited budget to deficient bridges.

Such an optimization algorithm is a major BMS module for selecting the optimal combination of alternatives that maximizes the performance standards and net benefits expected from the budgets granted. The primary objective is to investigate the feasibility of implementing the Incremental Benefit-Cost (INCBEN) program (*3*) for optimal allocation of the limited budgets to bridge improvement alternatives at the system level. More specifically, the objectives are to

1. Evaluate the theoretical framework, limitations, and implications using INCBEN as the optimization algorithm in BMS; and
2. Review techniques available for estimating bridge agency costs and benefits, and user costs and benefits.

ECONOMIC EVALUATION OF BRIDGE IMPROVEMENTS AT BRIDGE LEVEL

Economic analysis has been successfully applied to evaluating highway improvements. Application areas include highway and bus transit improvements (*4*), pavement management systems (*5*), and highway accident countermeasures (*6*). It can be used to evaluate bridge improvements as well. Economic analysis of highway improvements requires identifying all feasible alternatives and evaluating their consequences (*7*). Since any economic analysis deals with estimated future cash flows, it involves uncertainty. Economic analysis reduces the uncertainty surrounding the consequences of decisions. However, it does not dictate a decision; it is merely a management tool. Economic analysis at the bridge level evaluates the agency and user costs of the improvement alternatives to identify the alternative that maximizes net benefits expected, without violating budget constraints.

Improvement Alternatives

Three improvement alternatives are considered for deficient bridges: maintenance, rehabilitation, and replacement. The expected future costs of the "with and without" improvement are

F. Farid, P.O. Box 99, Santa Monica, Calif. 90406. D. W. Johnston, Department of Civil Engineering, North Carolina State University, Raleigh, N.C. 27695. B. S. Rihani, Dar Al-Handasah Consultants, P.O. Box 895, Cairo 11511, Egypt. C.-J. Chen, Second District, Taiwan Area National Expressway Engineering Bureau, Taipei, Taiwan, Republic of China.

compared to determine "benefits." However, these benefits cannot justify a bridge at the system level. The need for a bridge is established at the bridge level instead.

The "with and without" concept requires adding the so-called do-nothing alternative to improvement proposals. If deficient bridges are left without improvement, however, they will deteriorate faster than if they were improved. Thus, the do-nothing alternative results in increased future agency and user costs. In short, consequences of the do-nothing alternative should be evaluated if it is considered. In general, only deficient bridges needing immediate improvements are considered at the system level. Thus, the do-nothing alternative is considered unfeasible. As a result, improvement benefits are determined by comparing the expected future costs of improvement alternatives with those of a base alternative.

Forecasting Input Data

Agency costs and benefits as well as user costs and benefits are the required input data to INCBEN. Agency benefits are defined as the present value of future agency cost savings due to the proposed improvements. Agency costs generally include periodic maintenance and rehabilitation costs over, and the replacement cost at the end of, the useful life of the bridge. User benefits are defined as user costs before improvement minus user costs after improvement (*8*).

Agency Costs

Three improvement alternatives are usually available for a bridge that is deficient but needed:

1. *New-bridge alternative* replaces the existing bridge with a new one having desirable levels of service. Regular maintenance needs increase with age to prevent future accelerated deterioration of the bridge. Eventually, a major rehabilitation is probably considered to reduce its level-of-service deficiencies. The cost profile for one replacement cycle of a new bridge is depicted in Figure 1 (*top*). The replacement-cycle cost of a new bridge is

$$\text{RCC(NB)} = \text{ICNB} + \sum_{t=1}^{\text{SL}} \text{ARMC}(t) * (P/F, r, t) + \text{TRHC} * (P/F, r, n) \quad (1)$$

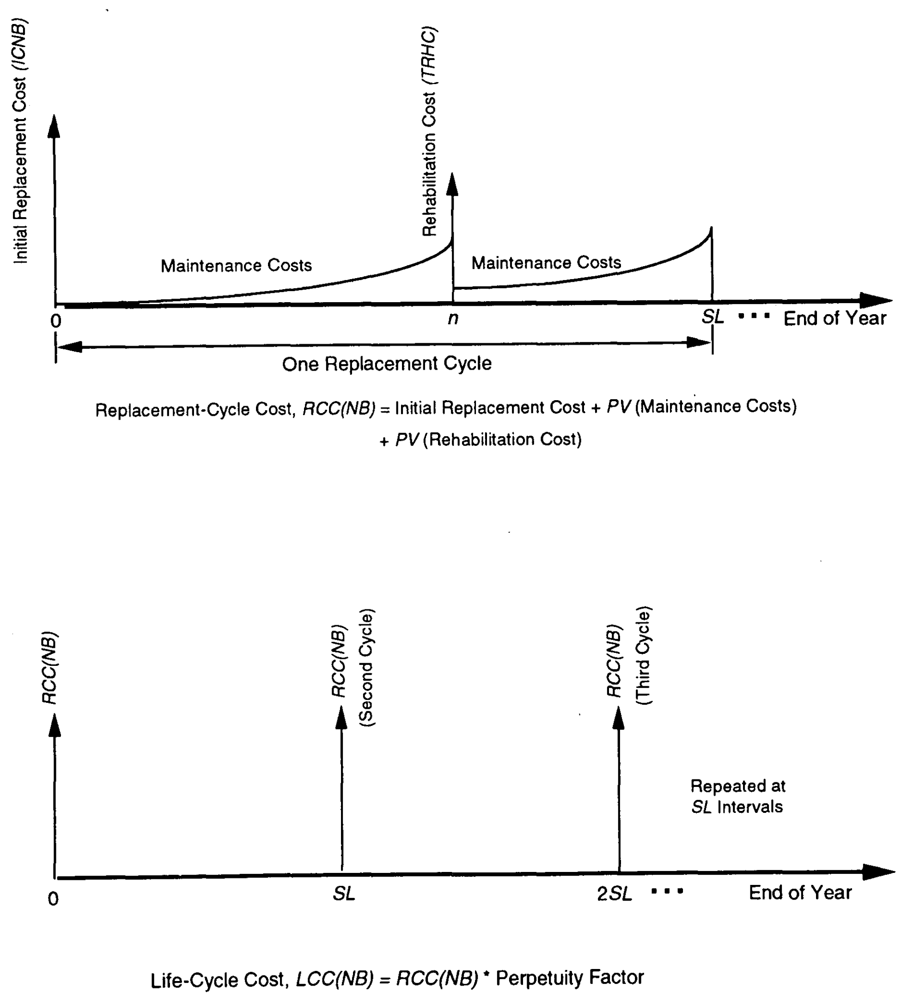

FIGURE 1 Life-cycle cost of replacement (new-bridge) alternative: *top*, cost profile for one replacement cycle; *bottom*, cost profile in perpetuity.

where

RCC(NB) = present value of one replacement-cycle cost of a new bridge;
ICNB = initial cost of a new bridge;
ARMC(t) = annual regular maintenance cost by end of year t;
TRHC = total rehabilitation cost at end of year n;
$(P/F, r, t)$ = single-payment present-value factor;
r = discount rate or required rate of return; and
SL = expected service life of bridge (*9*).

If the first replacement cycle is followed by another cycle, RCC(NB) would be repeated at SL intervals. The cost profile for repeated replacement cycles in perpetuity (i.e., forever) is shown in Figure 1 (*bottom*). Thus, the life-cycle cost of the new-bridge alternative in perpetuity, LCC(NB), is

$$\text{LCC(NB)} = \frac{\text{RCC(NB)}}{1 - (1 + r)^{-\text{SL}}} \tag{2}$$

2. *Rehabilitation alternative* extends the bridge service life by several years before it is replaced, as shown in Figure 2 (*top*). Thus, the perpetual life-cycle cost of the rehabilitation alternative, LCC(RH), is

$$\text{LCC(RH)} = \text{ICRH} + \sum_{t=1}^{e} \text{ARMC}(t) * (P/F, r, t) + \text{LCC(NB)} * (P/F, r, e) \tag{3}$$

where ICRH is the initial cost of the rehabilitation alternative, and e is the extended service life of the bridge after rehabilitation (*9*).

3. *Maintenance alternative* maintains the deficient bridge until the end of its remaining life and then replaces it with a new bridge, as depicted in Figure 2 (*bottom*). The perpetual life-cycle cost of the maintenance alternative, LCC(MT), is

$$\text{LCC(MT)} = \sum_{t=1}^{\text{RL}} \text{ARMC}(t) * (P/F, r, t) + \text{LCC(NB)} * (P/F, r, \text{RL}) \tag{4}$$

where RL is the remaining life of the existing bridge (*9*).

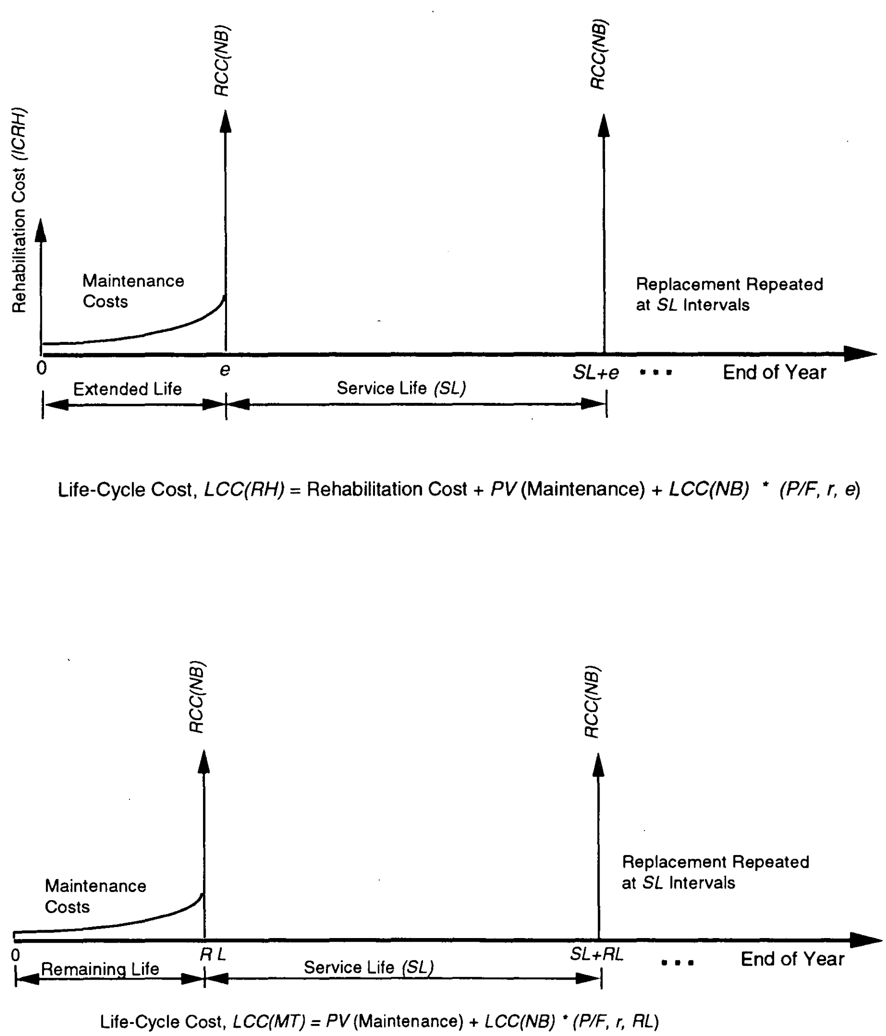

FIGURE 2 Life-cycle costs of rehabilitation (*top*) and maintenance (*bottom*) alternatives.

Agency Benefits

The agency net benefit of a bridge improvement alternative is the difference between the agency life-cycle cost of the base alternative and the agency life-cycle cost of the alternative in question. FHWA selected the new bridge alternative as the base alternative because it usually results in the highest life-cycle cost to the agency (*8*,pp.VI-11–VI-12).

The agency total benefit is "the present worth of future cost savings to the agency because of a bridge expenditure" (*8*,p.VI-11). Thus, for incremental benefit-cost analysis, the agency total benefit is the agency net benefit plus the initial cost of the bridge improvement alternative.

User Costs

User costs of deficient bridges are often due to narrow clear-deck width, low vertical clearance, poor alignment, and low load capacity. Bridges with narrow widths, low vertical clearances, or poor alignments have high accident probabilities. Bridges with low vertical clearances and low load capacities cause additional user costs to detoured vehicles. Chen and Johnston (*10*,p.122) estimated the annual user cost of a deficient bridge as

$$\mathrm{AURC}(t) = 365 * \mathrm{ADT}(t) * [(C_{\mathrm{ADW}} + C_{\mathrm{AAL}} + C_{\mathrm{ACL}}) * U_{\mathrm{AC}} + (C_{\mathrm{DCL}} * U_{\mathrm{DCL}} + C_{\mathrm{DLC}} * U_{\mathrm{DLC}}) * \mathrm{DL}] \quad (5)$$

where

$\mathrm{AURC}(t)$ = annual user cost of existing bridge during year t;
$\mathrm{ADT}(t)$ = average daily traffic over bridge during year t;
C_{ADW} = proportion of vehicles incurring accident costs due to a deck-width deficiency;
C_{AAL} = proportion of vehicles incurring accident costs due to an alignment deficiency;
C_{ACL} = proportion of vehicles incurring accident costs due to a vertical clearance deficiency;
U_{AC} = average unit cost of vehicle accidents on bridges ($/accident);
C_{DCL} = proportion of vehicles detoured due to a vertical clearance deficiency;
U_{DCL} = average unit cost for vehicles detoured due to a vertical clearance deficiency ($/mi);
C_{DLC} = proportion of vehicles detoured due to a load capacity deficiency;
U_{DLC} = average unit cost for vehicles detoured due to a load capacity deficiency ($/mi); and
DL = detour length (mi).

C_{ADW}, C_{AAL}, C_{ACL}, and C_{DCL} generally remain constant during the service life unless bridge deficiencies are corrected. If the load capacity deteriorates, however, the proportion of vehicles detoured (C_{DLC}) will increase with time. For a given level-of-service deficiency, bridges with higher ADTs cause proportionally higher user costs because of higher numbers of detours and accidents. Chen and Johnston (*10*) estimated these proportions as functions of the bridge functional classification and level-of-service deficiencies. Average unit costs of vehicles detoured and those of accidents were also estimated.

User Benefits

User benefits are interpreted as the reduced user costs due to the initial cost of a bridge improvement alternative. More generally, user benefits are the difference between the user life-cycle cost of the base alternative and that of the alternative under consideration.

Economic Decision Criteria

Four decision criteria are used for evaluating highway improvements (*8*,pp.VI-3–VI-30). These criteria can also be used to evaluate bridge improvement alternatives: (a) first-cost analysis, (b) life-cycle cost analysis, (c) simple benefit-cost analysis, and (d) incremental benefit-cost analysis. The selected criteria should provide analysts with correct and consistent results to

1. Determine the economic desirability of proposed improvement alternatives, and
2. Compare merits of these mutually exclusive options to select the most desirable alternative.

Farid et al. (*9*,pp.11–18) stated that incremental benefit-cost analysis satisfied both requirements.

Incremental Benefit-Cost Analysis

The incremental (marginal) benefit-cost ratio is "the extra benefits of advancing from one improvement level to the next divided by the corresponding extra costs" (*8*,p.VI-16). Thus, to have a justifiable investment increment, its incremental benefit-cost ratio must be at least 1. To apply the incremental benefit-cost analysis for selecting an alternative for an independent project under no budget constraints:

1. Sort all mutually exclusive alternatives in increasing order of their initial costs.
2. Tentatively accept the first economical least-cost alternative.
3. Calculate the incremental benefit-cost ratio for the second least-cost alternative. If the ratio equals or exceeds 1, replace the alternative accepted previously with the current alternative. This now becomes the base alternative for comparison with the least-cost alternative.
4. Repeat Step 3 for all alternatives.
5. Select the highest-cost alternative with an incremental benefit-cost ratio of at least 1. The incremental benefit-cost analysis seeks the maximum net benefit by justifying each cost increment.

For independent projects under budget limits, the last step is changed to

5. Select the highest-cost alternative that satisfies budgetary constraints and has an incremental benefit-cost ratio of at least 1 (*4*,p.140;*11*).

Incremental Benefit-Cost Analysis Applied to Hypothetical Bridge

The incremental benefit-cost analysis can select the most desirable improvement alternative for a bridge in tabular form. Table 1

TABLE 1 Incremental Benefit-Cost Ratios for Improvement Alternatives of a Hypothetical Bridge

Alternative[a]	First Cost $1,000	Total Benefit $1,000	ΔC $1,000	ΔB $1,000	$\Delta B/\Delta C$	Net Benefit $1,000
(1)	(2)	(3)	(4)	(5)	(6)=(5)/(4)	(7)=(3)-(2)
M	1	62	-	-	-	61
r	40	206	39	144	3.69	166
R[b]	50	217	10	11	1.10	167
N	80	238	30	21	0.70	158

[a] *M* stands for Maintenance, *r* or *R* for Rehabilitation, *N* for New bridge (replacement), and *C* for Closure

[b] Best Alternative

gives benefits and first costs of four improvement alternatives for a hypothetical bridge. The alternatives are listed in ascending order of their first costs. The incremental benefit-cost ratios are calculated. Step 5 selects Alternative *R* under no budget constraints. *R* is the highest-cost alternative with an incremental benefit-cost ratio of at least 1.

ECONOMIC EVALUATION OF BRIDGE IMPROVEMENTS AT SYSTEM LEVEL

The bridge-level analysis outcome is important as input to economic analysis at the system level. The objective is to select improvement alternatives that yield the highest net benefits expected under the budget granted. Economic analysis at the system level can generate a priority ranking of improvement alternatives. It can also analyze the sensitivity of the results to bridge improvement policies.

Priority Ranking and Budget Allocation

Only bridges needing improvement should be considered for budget allocation. Such screening should considerably reduce the size of the analysis. To set improvement priorities and to optimize the budget allocation, do the following:

1. Establish level-of-service goals or standards for a safe and functional operation.
2. Determine the deficient bridges, with attributes below the level-of-service goals, needing improvement in this period.
3. Determine the improvement alternatives for deficient bridges and their costs, benefits, and the remaining or extended service lives.
4. Allocate part of the budget granted to the least-cost improvement alternatives for all bridges deemed deficient in Step 2 in descending order of their benefit-cost ratios (this approximate ranking formula should be adequate for those rare periods in which not all the least-cost alternatives can be funded).
5. Obtain a priority ranking of the remaining alternatives (those not funded in Step 4) in descending order of their incremental benefit-cost ratios.
6. Allocate the remaining budget, if any, to increase the improvement levels of these bridges on the basis of the priority ranking determined in Step 5.

First costs are used to calculate the incremental benefit-cost ratios necessary for ranking the alternatives. This procedure is appropriate for allocating a one-period budget, usually no longer than 5 years. First costs, however, are not suitable for multiperiod budget allocation (*9*).

INCBEN Algorithm

INCBEN is designed to allocate a granted budget such that net benefits expected from improvement alternatives are maximized (*3*). It generates a decreasing order of incremental benefit-cost ratios as a priority ranking. An initial set of locations, along with the best possible alternative at each location, is then selected. A switching rule is used to induce ''marginal'' improvements to the initial solution (*3*,p.2). The input data required for applying INCBEN in BMS are as follows:

1. Identification of every improvement alternative and its bridge number;
2. Initial cost of every improvement alternative;
3. Total benefits expected from every improvement alternative; and
4. Granted budget.

INCBEN processes the input data by performing these steps:

1. Alternatives for every bridge are sorted in the increasing order of their first costs.
2. If two or more alternatives for a deficient bridge have the same initial cost, only the alternative with the highest total benefit is retained.

3. The incremental benefit-cost ratios for all bridges are calculated.
4. All alternatives with incremental benefit-cost ratios of 1 or less are discarded.
5. The incremental benefit-cost ratios must be in descending order. If an alternative's ratio exceeds that of the previous, less-expensive alternative for the same bridge, the incremental benefits and costs for the two alternatives are combined. The overall ratio for the more expensive alternative will be in decreasing order.
6. All deficient bridges in the data base are ranked in the descending order of their adjusted incremental benefit-cost ratios.
7. INCBEN selects the highest-ranking alternative and proceeds downward until the granted budget is exhausted. When a bridge alternative is selected, it replaces the less-expensive alternative previously selected for the same bridge. The algorithm may skip an alternative, and consider the next less-costly alternatives, *if* it cannot be funded with the remaining budget.
8. When the selection of an alternative causes the cumulative cost to exceed the budget, INCBEN replaces the last selected alternative with additional increments until the budget is exhausted. The algorithm compares the initial and revised improvement-alternative sets and selects the one with higher "total benefits," although it should select the solution with higher *net benefits*.

INCBEN internally adds do-nothing alternatives to all bridges. It considers this alternative's benefits to be zero, which is not necessarily true for bridges. Hence, INCBEN should be modified to exclude the do-nothing alternative before applying it in BMS.

INCBEN Applied to Four Hypothetical Bridges

Table 2 gives four hypothetical bridges along with their alternatives, first costs, and total benefits. These data are processed in the same order as INCBEN to illustrate its algorithm:

1. Alternatives for each bridge are sorted in the increasing order of their first costs.
2. For Bridge 2, Alternatives *R* and *N* have the same initial cost. Thus, Alternative *R*, with the lower benefit, is eliminated.
3. The incremental benefit-cost ratios for remaining alternatives are calculated. INCBEN considers the simple benefit-cost ratio for every least-cost alternative to be an incremental ratio. This adds a do-nothing alternative with zero first-cost and benefits to every bridge. But such an alternative may have some benefits or be unacceptable.
4. Alternative *N* for Bridge 4 is deleted because its incremental benefit-cost ratio is less than 1.
5. Alternative *N* for Bridge 1 has a 3.44 incremental benefit-cost ratio (R_{1N}), higher than that of Alternative *R* (R_{1R} = 3.41). A combined incremental benefit-cost ratio (R'_{1N}) is calculated to ensure its decreasing order:

$$R'_{1N} = \frac{\Delta B_{1R} + \Delta B_{1N}}{\Delta C_{1R} + \Delta C_{1N}} = \frac{23{,}900 + 8{,}600}{7{,}000 + 2{,}500} = 3.42 \quad (6)$$

The same applies to Alternatives *M* and *R* for Bridge 3.

6. Alternatives are ranked in decreasing order of their adjusted incremental benefit-cost ratios, as shown in Table 3. 3-*R* now combines the cost and benefit increments for 3-*R* and 3-*M*. Similarly, 1-*N* represents 1-*N* and 1-*R* combined. 3-*M* and 1-*R* are still included, but their incremental costs and benefits are not added again to the cumulative cost or benefit. This is because their costs and benefits are included in the combined entries 3-*R* and 1-*N*. 3-*M* will be considered only if 3-*R* cannot be funded without exceeding the budget. The same applies to 1-*R* and 1-*N*. For example, if the budget is between $13,600 and $23,100, 1-*N* cannot be funded. Instead, 1-*R* should be funded if the budget granted is $20,600 to $23,100.
7. Alternatives are selected by adding the incremental costs until the granted budget is exhausted. For example, 2-*N*, 4-*R*, and 3-*R* are tentatively selected for a $12,000 budget. These replace other alternatives previously selected for the same bridges. The allocated budget is $11,100, with a $900 balance. The total benefits expected are $64,500. No alternative for Bridge 1 is selected. Direct INCBEN application may leave out several bridges.
8. The "switching rule" now becomes active. The last added alternative, 2-*N*, is tentatively replaced by the next alternatives until the budget is exhausted. Only 1-*M* can be added. The total benefit expected from 1-*M*, 4-*R* and 3-*R* is reduced to $52,500, for a cumulative cost of $9,000. Thus, the initial set of 2-*N*, 4-*R*, and 3-*R* with higher total benefits is adopted. If 3-*R*, 4-*R*, and 1-*M* were adopted, Bridge 2 would have received no improvement because the switching rule drops 2-*N* without readopting 2-*M*.

Unlimited Budget Forecasts

Budget requests initially assume an unlimited budget and reflect the actual conditions of bridges. When the granted budget falls below these requests, the bridge program is "underfunded." The budget granted must then be allocated among improvement alternatives. INCBEN can forecast the optimal unlimited budget by assuming a huge budget to ensure all alternatives with incremental benefit-cost ratios of at least 1 are selected. Alternatively, the incremental benefit-cost analysis at the bridge level is applied to every bridge independently, as demonstrated in Table 1. The sum of the initial costs of all "best" alternatives represents the optimal unlimited budget forecast.

EVALUATION OF INCBEN PROGRAM

INCBEN systematically ranks all improvement alternatives in descending order of their incremental benefit-cost ratios. The program then selects a set of bridge improvement alternatives that will nearly maximize the expected net benefits. McFarland and Rollins (*12*) indicated that INCBEN performed satisfactorily.

Theoretical Framework

The incremental benefit-cost analysis at the bridge level produces optimal results, given a discount rate. Difficulties arise when several bridges with multiple improvement alternatives are evaluated under budget constraints. To find an optimal combination of improvement alternatives, all possible alternative combinations for various bridges must be compared. A statewide BMS covering hundreds of bridges, each with several improvement alternatives, requires comparing a large number of combinations. The total number of combinations is $(X_1)(X_2)(X_3) \ldots (X_i) \ldots (X_n)$, where X_i is the number of proposed alternatives for Bridge *i* and *n* is the

TABLE 2 Incremental Benefit-Cost Ratios for Sample Bridges

Bridge i (1)	Alternative[a] j (2)	First Cost \$1,000 (3)	Total Benefit \$1,000 (4)	ΔC \$1,000 (5)	ΔB \$1,000 (6)	$R_{ij}=\Delta B/\Delta C$ (7)=(6)/(5)	R'_{ij} (8)
(a) Four Hypothetical Bridges							
1	*M*	2.5	10.0	2.5	10.0	4.00[c]	
	R	9.5	33.9	7.0	23.9	3.41	
	N	12.0	42.5	2.5	8.6	3.44	3.42
2	*M*	2.0	11.0	2.0	11.0	5.50[c]	
	R[b]	4.6	20.0	---	----	----	
	N	4.6	22.0	2.6	11.0	4.23	
3	*M*	1.5	9.0	1.5	9.0	6.00[c]	
	R	5.0	33.0	3.5	24.0	6.86	6.60[c]
4	*M*	0.5	4.5	0.5	4.5	9.00[c]	
	R	1.5	9.5	1.0	5.0	5.00	
	N[b]	2.5	10.4	1.0	0.9	0.90	
(b) Five North Carolina Bridges							
05125	*M*[b]	2	-212	2	-212	-106.00[c]	
	R	40	210	40	210	5.25[c]	
	N	283	647	243	437	1.80	
61010	*M*	3	114	3	114	38.00[c]	
	R	86	278	83	164	1.98	
	N[b]	145	312	59	34	0.58	
73411	M	17	2,304	17	2,304	135.53[c]	
	R	86	2,667	69	363	5.26	
	N[b]	3,600	5,743	3,514	3,076	0.88	
89034	*M*	9	250	9	250	27.78[c]	
	R	72	524	63	274	4.35	
	N[b]	319	645	247	121	0.49	
97060	M	5	365	5	365	73.00[c]	
	R[b]	300	584	295	219	0.74	
	N	560	1,084	555	719	1.30	

[a] *M* stands for Maintenance, *R* or *r* for Rehabilitation, *N* for New bridge (replacement), and *C* for Closure

[b] Alternative Deleted

[c] Simple benefit-cost ratio for this alternative

number of bridges. Apart from using mathematical programming to solve the combinatorial problem, INCBEN can provide near-optimal solutions. INCBEN deletes all bridge improvement alternatives with incremental benefit-cost ratios of 1 or less. All alternatives with incremental ratios of at least 1 are economical. Thus, INCBEN should be modified to delete only alternatives with incremental benefit-cost ratios of less than 1.

INCBEN was developed for allocating safety improvement budgets. It initially assumes no improvement at all "locations." Funds are then allocated to successively higher improvement increments in the decreasing order of their incremental benefit-cost ratios. If the budget is exhausted before any improvement level is funded for a location, the do-nothing alternative is selected. Its benefits and first cost are assumed to be 0. The do-nothing alternative is generally unacceptable in BMS. Even if it were acceptable, its consequences would not necessarily be 0.

Submarginal alternatives can often replace one or more previously selected alternatives to obtain greater "benefits" without exceeding the budget (*6*,pp.301–302). Thus, INCBEN is expected to select near-optimal sets of improvement alternatives. This may occur because the optimal set may contain one or more alternatives with incremental benefit-cost ratios lower than those of the last alternative selected by INCBEN. McFarland et al. (*3*,p.4) subsequently added a switching rule to the INCBEN algorithm. This rule replaces the last accepted cost increment with other increments until the budget is exhausted. The total benefits of the initial and revised solutions are compared, and the solution with the greatest total benefits is selected. Although this rule may improve

TABLE 3 Alternatives Ranked in Decreasing Order of Incremental Benefit-Cost Ratios

Bridge i	Alternative[a] j	First Cost \$1,000	Total Benefit \$1,000	ΔC \$1,000	$\Delta B/\Delta C$	Budget Allocated \$1,000
(1)	(2)	(3)	(4)	(5)	(6)	(7)
			(a) Four Hypothetical Bridges			
4	*M*	0.5	4.5	0.5	9.00[c]	0.5
3	*R*	5.0	33.0	5.0	6.60[c]	5.5
3	*M*[b]	1.5	9.0	1.5[b]	6.00[c]	---
2	*M*	2.0	11.0	2.0	5.50[c]	7.5
4	*R*	1.5	9.5	1.0	5.00	8.5
2	*N*	4.6	22.0	2.6	4.23	11.1
1	*M*	2.5	10.0	2.5	4.00[c]	13.6
1	*N*	12.0	42.5	9.5	3.42	23.1
1	*R*[b]	9.5	33.9	7.0[b]	3.41	---
			(b) Five North Carolina Bridges			
73411	*M*	17	2,304	17	135.53[c]	17
97060	*M*	5	365	5	73.00[c]	22
61010	*M*	3	114	3	38.00[c]	25
89034	*M*	9	250	9	27.78[c]	34
73411	*R*	86	2,667	69	5.26	103
05125	*R*	40	210	40	5.25[c]	143
89034	*R*	72	524	63	4.35	206
61010	*R*	86	278	83	1.98	289
05125	*N*	283	647	243	1.80	532
97060	*N*	560	1,084	555	1.30	1,087

[a] *M* stands for Maintenance, *r* or *R* for Rehabilitation, *N* for New bridge (replacement), and *C* for Closure

[b] Included in entry immediately preceding; not added separately to cumulative costs and benefits

[c] Simple benefit-cost ratio for this alternative

the initial solution, it does not guarantee that the optimal solution under the budget constraint is selected. Further, the switching rule should compare net benefits, not total benefits, as illustrated later.

Limitations of Incremental Benefit-Cost Analysis

Although the algorithm is straightforward, many calculations and checks are required for large bridge systems. INCBEN can process up to 85 bridges, each with up to eight improvement alternatives (*3*). These limits can be increased to fit the available computer hardware. Results should be examined carefully because of theoretical and other limitations of the incremental benefit-cost analysis.

General Limitations

Economic analysis and resource allocation organize information that is useful to decision makers (*13*,p.41), but they cannot account for all available information. Winfrey (*13*,p.42) classified other factors that need be considered as (a) road-user nonpriceable, personal preferences; and (b) nonuser socioeconomic consequences. Thus, any incremental benefit-cost analysis is merely a management tool. Applied in BMS, its underlying assumptions and limitations are as follows:

1. Bridge improvement needs remain constant. Only bridges deemed deficient at the time compete for funds, but deficient bridges and their deficiency types and levels change with time.
2. Statistical techniques are used to forecast the bridge remaining life, extended life, and service life due to improvement alternatives. Future cost profiles and trends are also forecast to model the costs of improvement alternatives under uncertainty.
3. A single risk-adjusted discount rate is used for calculating the agency and user costs (*14*). This fixed rate is assumed to be known and is not expected to change significantly in the future.

These assumptions make the incremental benefit-cost analysis suitable for allocating budgets over a short horizon, perhaps 1 to 5 years (*8*,p.VI-39). The quality of the results can be improved by conducting sensitivity analysis, as an intermediate step between economic analysis based on best estimates and the final decision (*15*,p.236). In another paper in this Record, Farid et al. analyze sensitivity of INCBEN results to the discount rate, remaining life, and service life of bridges.

Limitations of INCBEN Application in BMS

INCBEN has several features that may produce improper results. These features were discovered through experimentation and by examining the algorithm.

First, INCBEN does not necessarily select the "optimal" set of improvement alternatives. The optimal set should maximize net benefits expected from alternatives selected under the limited budget. To illustrate, Table 2 presents initial costs and total benefits expected from improvement alternatives for five North Carolina bridges. The incremental benefit-cost ratios are estimated by INCBEN. Alternatives 05125-*M*, 61010-*N*, 73411-*N*, 89034-*N*, and 97060-*R* with incremental benefit-cost ratios of 1 or less are dropped. Table 3 ranks the remaining alternatives in decreasing order of their incremental benefit-cost ratios.

Under a $205,000 budget, INCBEN selects 61010-*M*, 73411-*R*, 89034-*R*, and 97060-*M*, as listed in Table 4. These are the final INCBEN selections after the switching rule replaces alternatives 05125-*R* and 89034-*M* by 89034-*R*. The budget allocated (cumulative first cost) is $166,000, total benefits expected are $3,670,000, and net benefits expected are $3,504,000.

TABLE 4 Alternatives Selected for Several Levels of Budget Granted

	Budget Granted ($1,000)		
Bridge No. (1)	205 (2)	750 (3)	1,000 (4)
05125	-	*N*	-
61010	*M*	*R*	*R*
73411	*R*	*R*	*R*
89034	*R*	*R*	*R*
97060	*M*	*M*	*N*
Expected Total Benefits	3,670	4,481	4,553
Budget Allocated	166	532	804
Expected Net Benefits	3,504	3,949	3,749
Excess Budget	39	218	196

M stands for Maintenance, *R* or *r* for Rehabilitation, *N* for New bridge (replacement), and *C* for Closure

By inspection, Alternative 05125-*R* can replace 61010-*M*. This set comprises 05125-*R*, 73411-*R*, 89034-*R*, and 97060-*M*, with $3,766,000 in total benefits and $203,000 in cumulative first costs. The $3,563,000 net benefits expected from this set are greater than the $3,504,000 expected from the INCBEN selections. The revised set leaves out Bridge 61010, which is usually unacceptable. But INCBEN left Bridge 05125 without improvement.

Such complications become particularly troublesome where alternatives, especially those near the budget limit, vary considerably in cost, are quite costly in relation to the budget, and have widely varying incremental benefit-cost ratios. Selecting proper submarginal alternatives in highway safety programs is not critical because most safety-program budgets are large relative to the first cost of any alternative. Thus, INCBEN is expected to provide near-optimal solutions (*6*,p.302).

The bridge improvement budgets are also large in relation to the first costs of improvement alternatives. However, wide variations in costs and incremental benefit-cost ratios of alternatives are expected. Thus, their effects on INCBEN application in BMS may be significant. For example, the $40,000 first cost of 05125-*R* is large in relation to the $205,000 budget because only five bridges are analyzed. This results in $39,000 of excess budget and clearly suboptimal INCBEN selections. Later in this Record, Farid et al. demonstrate that INCBEN produces near-optimal results even for as few as 25 bridges.

Second, the switching rule compares total benefits of the initial and revised solutions (*3*,p.26). But the algorithm's objective is to maximize net benefits under budget constraint (*3*,p.1; *12*,p.9). Moreover, INCBEN's Step 8 (*3*,pp.4–5) contains conflicting statements on the comparison basis of the switching rule.

This problem is best illustrated by reanalyzing bridges listed in Tables 2, 3, and 4 at two more budget levels. At $750,000, INCBEN selects the optimal set 05125-*N*, 61010-*R*, 73411-*R*, 89034-*R*, and 97060-*M* with a $532,000 cumulative first cost. Total benefits of $4,481,000 and net benefits of $3,949,000 are expected. Under $1,000,000, INCBEN selects 61010-*R*, 73411-*R*, 89034-*R*, and 97060-*N*. An $804,000 cumulative first cost and $4,553,000 total benefits are expected. The $3,749,000 net benefits expected under $1,000,000 budget are lower than $3,949,000 under $750,000 budget because of the switching rule. The initial solution under the $1,000,000 budget is the same optimal set as the solution under the $750,000 budget. Since the initial $4,481,000 total benefits are less than the revised $4,553,000, the switching rule selects the revised solution. This decision is not cost-effective, however, because the correct criterion for comparing alternatives is net benefits. This criterion would have properly selected the initial solution. Thus, the switching rule should be modified to compare net benefits.

Finally, INCBEN internally adds a do-nothing alternative, with a zero first cost and zero total benefits, to all "locations" because the simple benefit-cost ratios of the least-cost alternatives are taken as incremental ratios (*3*,p.26). The do-nothing alternative may be acceptable in evaluating highway accident countermeasures, but it is unacceptable in BMS for two reasons. First, INCBEN may leave a deficient, unsafe bridge without improvement. Second, INCBEN assumes that benefits of the do-nothing alternative are 0. This is inconsistent with the economic analysis principles requiring that consequences of alternatives be incorporated (*15*,pp.9–10).

If the do-nothing alternative is acceptable, the remaining lives of the deficient bridges left without improvement should be estimated to forecast the associated benefits. No data exist for estimating the remaining life of a bridge receiving no improvement. Thus, INCBEN should be modified to consider alternatives entered by bridge managers only. The do-nothing problem can be avoided by ensuring that all least-cost alternatives are funded first. The budget balance can then be allocated to further improve these deficient bridges.

Implementation and Advantages of Incremental Benefit-Cost Program

INCBEN application in allocating limited budgets to bridge improvement alternatives may result in considerable savings over priority ranking formulas and simple benefit-cost ratios. INCBEN generates near-optimal solutions and offers these improvements over existing practices:

1. Explicit consideration of the time value of money,
2. Systematic allocation of limited budgets among improvement alternatives,
3. Computerized algorithm capable of evaluating many alternatives,
4. Maximized net benefits expected from alternatives under limited budget, and
5. Incremental benefit-cost ratio as criterion for selecting improvement alternatives under budget constraint.

INCBEN produces a superior priority ranking of the improvement alternatives in the decreasing order of their incremental benefit-cost ratios. The INCBEN ranking is based on economic principles and prescribes specific improvement alternatives for deficient bridges.

Difficulties in implementing INCBEN are in estimating the user costs and the extended lives of bridges due to improvement alternatives. Procedures exist for estimating the remaining, and the extended, lives (*8*,pp.IV-1–VI-7). Improved estimates are expected as bridge data bases are upgraded and states' resources are pooled (*8*,p.VI-41). States may link their data bases to allow automated estimates of the detoured traffic, accident costs, travel time, and vehicle operating costs that account for user costs. Automation may facilitate the preparation of INCBEN input data. Estimating costs and benefits of improvement alternatives requires numerous calculations and checks. This is particularly cumbersome in sensitivity analysis, requiring repeated calculations and checks for ranges of input variables.

Once costs and benefits expected from all improvement alternatives are estimated, running INCBEN, designed for batch input, is straightforward. The INCBEN documentation describes data requirements and program testing procedures (*3*) and the program documents solutions in clear tables. The output includes the input echoprints, incremental benefit-cost ratios, deleted alternatives, alternatives ranked in decreasing order of their incremental benefit-cost ratios, and the improvement alternatives selected under the granted budget. Users may become familiar with the INCBEN algorithm by comparing their manual solutions to small examples with the INCBEN results.

CONCLUSIONS

Implementing a revised INCBEN program for optimal budget allocation in BMS appears feasible. Major conclusions include the following:

1. Techniques and data exist for forecasting bridge agency costs and user costs, which are the required INCBEN input data. Incremental benefits and costs are estimated from a base alternative. Thus, the input data are meaningful only for comparing improvement alternatives.

2. INCBEN ranks improvement alternatives in the decreasing order of their incremental benefit-cost ratios. INCBEN rankings are superior to those based on sufficiency ratings or level-of-service goals. INCBEN generates rankings based on economic principles and recommends specific alternatives for deficient bridges.

3. INCBEN recommends near-optimal sets of bridge improvement alternatives, which nearly maximize net benefits, under limited budgets. INCBEN selections under unlimited budgets are optimal and identical to alternatives selected by bridge-level economic analysis.

4. INCBEN internally adds do-nothing alternatives without considering their consequences. This is inappropriate for BMS applications. The problem can be overcome by manipulating the input data to ensure that the least-cost alternatives are funded first. The budget balance can then be allocated to further improve deficient bridges in the decreasing order of their incremental benefit-cost ratios.

ACKNOWLEDGMENTS

The research documented was sponsored by the Demonstration Projects Division of FHWA, U.S. Department of Transportation, under a work order to the North Carolina State University Center for Transportation Engineering Studies through the North Carolina Department of Transportation (NCDOT).

The authors gratefully acknowledge the comments provided by Daniel O'Connor of FHWA. Thanks are also due Jimmy Lee and Don Idol of the NCDOT Bridge Maintenance Unit for assistance in identifying sample bridges and alternatives, and to M. P. Strong of the NCDOT Planning and Research Branch for assistance with project coordination.

REFERENCES

1. *Highway Bridge Replacement and Rehabilitation Program.* 10th Annual Report of the Secretary of Transportation to the Congress of the United States. Bridge Division, Office of Engineering, FHWA, U.S. Department of Transportation, 1991.
2. De Velasco, M. G., and B. F. McCullough. Rigid Pavement Network Rehabilitation Scheduling. In *Transportation Research Record 938,* TRB, National Research Council, Washington, D.C., 1983, pp. 53–60.
3. McFarland, W., J. Rollings, and R. Dheri. *Documentation for Incremental Benefit-Cost Technique.* Technical Report prepared for FHWA, U.S. Department of Transportation; Texas Transportation Institute, Texas A&M University System, College Station, 1983.
4. *A Manual on User Benefit Analysis of Highway and Bus Improvements.* AASHTO, Washington, D.C., 1978.
5. Haas, R., and W. R. Hudson. *Pavement Management Systems.* McGraw-Hill, Inc., New York, 1978.
6. McFarland, W. F., L. I. Griffin, J. B. Rollins, W. R. Stockton, D. T. Phillips, and C. L. Dudek. *Assessment of Techniques for Cost-Effectiveness of Highway Accident Countermeasures.* Report FHWA-RD-79-53. FHWA, U.S. Department of Transportation, 1979.
7. Winfrey, R. *Economic Analysis for Highways.* International Textbook Co., Scranton, Pa., 1969, pp. 21–30.
8. *Bridge Management Systems.* Report FHWA-DP-71-01R. FHWA, U.S. Department of Transportation, 1989.
9. Farid, F., D. W. Johnston, C.-J. Chen, M. A. Laverde, and B. S. Rihani. *Feasibility of Incremental Benefit-Cost Analysis for Optimal Allocation of Limited Budgets to Maintenance, Rehabilitation and Replacement of Bridges.* Research Project DTFH71-87-NC-07. Center of Transportation Engineering Studies, Department of Civil Engineering, North Carolina State University, Raleigh, 1988.
10. Chen, C.-J., and D. W. Johnston. Bridge Management Under a Level of Service Concept Providing Optimum Improvement Action, Time, and Budget Prediction. Report FHWA/NC/88-004, Research Project 86-2. Center for Transportation Engineering Studies, Department of Civil Engineering, North Carolina State University, Raleigh, 1987.
11. Bernhard, R. H. A Comprehensive Comparison and Critique of Discounting Indices Proposed for Capital Investment Evaluation. *The Engineering Economist,* Vol. 16, No. 3, Spring 1971, pp. 157–186.
12. McFarland, W., and J. B. Rollins. *Cost-Effectiveness Techniques for Highway Safety: Resource Allocation.* Report FHWA/RD-84/011. U.S. Department of Transportation; Texas Transportation Institute, Texas A&M University System, College Station, 1985, pp. 20–25.
13. Winfrey, R. *Handbook of Highway Engineering.* Van Nostrand Reinhold Co., New York, 1975.
14. Farid, F., L. T. Boyer, and R. Kangari. Required Return on Investments in Construction. *Journal of Construction Engineering and Management,* ASCE, Vol. 115, No. 1, March 1989, pp. 109–125.
15. Grant, E. L., W. G. Ireson, and R. S. Leavenworth. *Principles of Engineering Economy,* 7th ed. Ronald Press Company, New York, 1982.

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FHWA or NCDOT. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Structures Maintenance and Management.