Application of Incremental Benefit-Cost Analysis for Optimal Budget Allocation to Maintenance, Rehabilitation, and Replacement of Bridges

FOAD FARID, DAVID W. JOHNSTON, MARTHA A. LAVERDE, AND CHWEN-JINQ CHEN

Bridge improvement funding in the United States has been insufficient for years. Thus, a systematic algorithm for efficient allocation of limited budgets to deficient bridges is needed, as part of a comprehensive bridge management system. Application of one such algorithm, the Incremental Benefit-Cost (INCBEN) program, for optimal allocation of the limited budgets to bridge improvement alternatives at the system level is investigated. INCBEN is applied to a sample of highway bridges to determine a near-optimal set of improvement alternatives. The sample consists of 25 in-service bridges in North Carolina with varying structural or functional deficiencies. Selection of the near-optimal bridge improvement alternatives under several levels of budget granted; sensitivity of budget-allocation results to the discount rate, remaining life, and service life; and comparison of results with those of the sufficiency rating methods are described.

Due to the insufficient funding of bridge improvements over the years, many bridges have become deficient in the United States (*1*). Budgets granted for bridge improvements are expected to be lower than budgets requested by most agencies. Thus, a comprehensive bridge management system (BMS) is needed for consistent and efficient management of bridge improvement activities. BMS is a systematic framework that formalizes the decision-making process for bridge improvement. 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 making optimal use of the bridge improvement budgets (*2*).

A major BMS module is an optimization algorithm that maximizes the performance standards and the net benefits expected from the budgets granted. Application of one such algorithm, the Incremental Benefit-Cost (INCBEN) program (*3*), for optimal allocation of the limited budgets to bridge improvement alternatives at the system level is investigated. The input data to INCBEN are random variables because they are forecasts of future events. Thus, sensitivity of the INCBEN results to major input data is analyzed.

INCBEN PROGRAM

INCBEN can allocate a limited budget to maximize the net benefits expected from improvement alternatives. Farid et al. have provided a detailed description of INCBEN (*4*; another paper in this Record), and a complete description of INCBEN has also been presented by McFarland et al. (*3*).

INCBEN is used to rank a sample of 25 North Carolina bridges under budget constraints. The input data required for applying INCBEN in BMS are

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

Forecasting Input Data

Farid et al. (*4*; another paper in this Record) described the techniques used for developing the improvement alternatives and their life-cycle costs. Agency and user costs were estimated on the basis of approaches developed by Chen and Johnston (*5*). Replacement is adopted as the base alternative for forecasting agency benefits because it usually results in the highest life-cycle cost to the agency (*6*). Thus, the agency net benefit of a bridge improvement alternative is defined as the difference between the agency life-cycle cost of the base alternative and that of this alternative. The agency total benefits of an improvement alternative is equal to its agency net benefit plus its initial cost. Column 3 of Table 1 presents the agency total benefits of the 25 North Carolina bridges.

User costs are due to level-of-service deficiencies in load capacity, clear deck width, alignment, and vertical clearance. User benefits of a bridge improvement alternative is interpreted as the difference between the user life-cycle cost of the base alternative and that of this alternative. The most cost-effective alternative to the agency, representing the last investment increment with an incremental benefit-cost ratio greater than 1, is taken as the base alternative (*4,6*). For example, the agency incremental benefit-cost ratios for Bridge 05125 are estimated in Table 2. Rehabilitation is the most cost-effective alternative because it is the last increment with an incremental benefit-cost ratio greater than 1. Thus, user benefits will be estimated using rehabilitation as the base alternative—that is, user benefits of an improvement alternative are the difference between the user life-cycle cost of the rehabilitation alternative and that of this alternative. Column 4 of Table 1 gives the agency and user benefits for the 25 bridges.

F. Farid, P.O. Box 99, Santa Monica, Calif. 90406. W. Johnston and M. A. Laverde, Department of Civil Engineering, North Carolina State University, Raleigh, N.C. 27695. C. J. Chen, Second District, Taiwan Area National Expressway Engineering Bureau, Taipei, Taiwan, Republic of China.

INCBEN Analysis

INCBEN cannot be applied directly in BMS because it automatically adds "do-nothing" alternatives. Its algorithm should eventually be modified to exclude the do-nothing alternative (*4*, other paper by Farid et al. in this Record). The INCBEN input data are manipulated so that the existing INCBEN could produce correct results.

Data manipulation essentially ensures that the least-cost bridge improvement alternatives are funded first. The modified marginal input data are compiled by subtracting the cost and benefits of the least-cost alternative for every bridge from the corresponding cost

TABLE 1 Costs and Benefits for All Bridge-Improvement Alternatives ($ thousands)

Bridge[a]	Initial Cost	Agency Benefit	Agen. & User Benefits	Bridge[a]	Initial Cost	Agency Benefit	Agen & User Benefits
00210*M*	165	827	827	59100*r*	163	464	464
R	742	819	2641	*R*	462	450	657
N	895	895	2752	*N*	485	485	692
05125*M*	2	92	-212	58102*r*	173	505	505
R	40	210	210	*R*	496	485	694
N	283	283	647	*N*	521	521	730
08052*M*	4	548	548	58128*r*	202	462	462
N	520	520	905	*R*	297	454	585
				N	471	471	602
10381*M*	429	1703	1703				
R	1550	2512	-3884	61010*M*	3	114	114
N	2650	2650	9268	*R*	86	112	278
				N	145	145	312
17001*M*	70	1600	1600				
R	725	699	724	73411*M*	17	994	2173
N	1400	1400	1560	*R*	86	2667	2667
				N	3600	3600	5743
29058*M*	7	363	363				
R	627	479	931	75171*M*	4	150	150
N	548	548	1000	*R*	116	236	2185
				N	444	444	2549
45009*R*	6	1747	1747				
M	28	1207	16564	80173*M*	1	80	80
N	3755	3755	19162	*R*	4	78	79
				N	115	115	119
58016*r*	102	280	280				
R	289	270	395	84007*M*	1	53	53
N	304	304	1863	*r*	40	61	177
				R	50	61	188
58030*r*	121	350	350	*N*	80	80	207
R	349	344	611				
N	366	366	633	84133*C*	0	583	583
				R	53	358	80
58032*r*	168	363	363	*N*	516	516	689
R	247	356	388				
N	392	392	424	89034*M*	9	250	250
				R	72	242	524
58033*r*	209	637	637	*N*	319	319	645
R	712	611	698				
N	682	682	1863	91014*M*	1	275	275
				R	455	273	474
58089*r*	129	386	386	*N*	410	410	611
R	370	373	538				
N	388	388	553	97060*M*	5	365	365
				R	300	424	584
58091*r*	129	371	371	*N*	560	560	1084
R	370	359	526				
N	388	388	555				

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

and benefits of every other alternative for the same bridge. These marginal input data are used to allocate the balance of the budget granted; the balance is determined by subtracting the sum of all the least-cost alternatives' initial costs from the budget granted. This marginal budget allocation ensures that if INCBEN selects no alternative for a bridge, its least-cost alternative is automatically recommended for funding.

INCBEN is used to analyze the data for two types of benefits expected from the improvement alternatives: the first analysis considers both agency and user benefits, and the second analysis considers agency benefits only. Alternatives are ranked for several budget levels.

INCBEN Results Considering Agency and User Benefits

Results of the INCBEN analysis are presented in Tables 3 and 4 and in Figure 1. Up to $8,036,000, the higher the budget granted, the higher the net benefits expected. However, for granted budgets of more than $8,036,000, the budget allocated and benefits expected remain constant. The net benefits are expected to be at their highest level of $39,493,000. Thus, $8,036,000 is the optimum budget justified under no budget constraints for improving the 25 bridges.

Figure 1 and Table 3 demonstrate that as the granted budget is increased from $2,120,000 to $2,142,000, sharp increases in total benefits and net benefits are expected. A $2,120,000 budget is just enough to fund all least-cost alternatives for the 25 bridges. These alternatives include 45009*R* which is not cost-effective at all, as indicated in Table 1. If the granted budget is increased by a small $22,000, Table 4 indicates that the maintenance alternative is selected for Bridge 45009 that is significantly more cost-effective than 45009*R*, as shown in Tables 1 and 3 and in Figure 1.

Table 4 verifies that only replacing Bridges 05125, 10381, 29058, 58016, 58033, 75171, and 97060 is cost-effective even under unlimited funding. The other 17 bridges should not be replaced, even under no budget constraints. For granted budgets of $1,000,000 or less, maintenance is the preferred alternative (52 percent), but 28 percent of the bridges will receive no improvement because of insufficient funding. For budgets of $8,036,000 or more, 32 percent of the bridges would be replaced, 44 percent rehabilitated, and 20 percent maintained; 4 percent would remain closed.

Table 4 also shows that Bridges 08052, 17001, 80173, and 91014 should always be maintained as long as the budget granted is at least $250,000. Bridge 84133 must remain closed regardless of the granted budget; the other 24 bridges receive some improvement and granted budgets of at least $2,120,000.

INCBEN Results Considering Agency Benefits Only

Table 3 and Figure 2 indicate that budgets allocated and benefits expected remain constant for granted budgets over $2,227,000. At such levels, net benefits expected are at their highest level of $13,126,000. Thus, $2,227,000 is the optimum justifiable budget under no budget constraints, if user costs are excluded. Figure 2 shows that up to $2,227,000, the higher the budget granted, the higher the net benefits expected. Table 5 indicates that replacement is never cost-effective for these 25 bridges if user benefits are excluded. Maintenance is the alternative selected most when only agency benefits are considered.

Figure 2 and Table 3 also show that total and net benefits expected gradually increase with increasing budgets up to $2,158,000. As the budget granted is further increased to $2,189,000, sharp increases are expected in net benefits and total benefits because of changes in the alternatives selected, as indicated in Table 5. For a $2,158,000 budget, the alternatives selected for Bridges 05125 and 73411 are *R* and *M*, respectively. For a $2,189,000 budget, these selections change to 05125*M* and 73411*R*. As a result, net benefits expected increase by $1,524,000, as shown in Figure 2 and in Tables 1 and 3.

Table 5 shows that Bridges 08052, 17001, 29058, 61010, 75171, 80173, 84007, 89034, 91014, and 97060 should always receive maintenance as long as the budget granted is $250,000 or more. Again, Bridge 84133 must remain closed regardless of the budget granted. For a $2,120,000 budget or more, all the other bridges receive some improvement: 48 percent of the bridges would be maintained, 48 percent would be rehabilitated, and 4 percent would remain closed. For budgets less than $1,000,000, maintenance is the alternative selected most.

SENSITIVITY ANALYSIS OF BRIDGE IMPROVEMENT DECISIONS

The accuracy of the INCBEN results is, of course, a function of the accuracy of the input data. These data are best described as

TABLE 2 Incremental Benefit-Cost Ratios for Bridge 05125, Agency Costs Only

Alternative (1)	Net Benefit (2)	First Cost (3)	Total Benefit (4)	ΔB (5)	ΔC (6)	ΔB/ΔC (7)
	Thousands of Dollars					
Maintenance	90	2	92	NA[a]	NA[a]	NA[a]
Rehabilitation	170	40	210	118	38	3.11
New Bridge	0	283	283	73	243	<1

[a] Not Applicable

TABLE 3 INCBEN Results at 6 Percent Discount Rate ($ thousands)

Budget Granted (1)	Budget Allocated (2)	Total Benefits (3)	Net Benefits (4)	Excess Budget (5)
250	249	8,651	8,402	1
500	466	9,633	9,167	34
1,000	972	11,567	10,595	28
2,120	2,120	14,437	12,317	0
2,142	2,142	29,254	27,112	0
2,180	2,180	29,676	27,496	0
2,249	2,249	30,170	27,921	0
3,000	2,991	34,787	31,796	9
4,000	3,903	37,524	33,621	97
5,000	4,979	41,926	36,947	21
6,000	5,946	44,802	38,856	54
7,000	6,922	46,244	39,322	78
8,036	8,036	47,529	39,493	0

TABLE 4 Alternatives Selected for Several Budget Levels, Agency and User Benefits

	Budget Granted ($1,000)									
Bridge No. (1)	250 (2)	500 (3)	1000 (4)	2120 (5)	2142 (6)	2180 (7)	2249 (8)	3000 (9)	5000 (10)	≥8036 (11)
00210	-	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*R*
05125	-	-	-	*M*	*M*	*R*	*R*	*N*	*R*	*N*
08052	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
10381	-	-	*M*	*M*	*M*	*M*	*M*	*M*	*N*	*N*
17001	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
29058	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*N*
45009	*R*	*R*	*R*	*R*	*M*	*M*	*M*	*M*	*M*	*M*
58016	-	-	-	*r*	*r*	*r*	*r*	*N*	*N*	*N*
58030	*r*	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*	*N*
58032	-	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*
58033	-	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*N*
58089	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*	*r*
58091	-	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*
58100	-	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*
58102	-	*r*	-	*r*	*r*	*r*	*r*	*r*	*r*	*r*
58128	-	-	-	*r*	*r*	*r*	*r*	*r*	*r*	*R*
61010	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*R*	*R*	*R*
73411	*M*	*M*	*M*	*M*	*M*	*M*	*R*	*R*	*R*	*R*
75171	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*R*	*R*	*N*
80173	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
84007	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*r*	*R*	*R*
84133	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*
89034	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*R*	*R*	*R*
91014	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
97060	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*N*

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

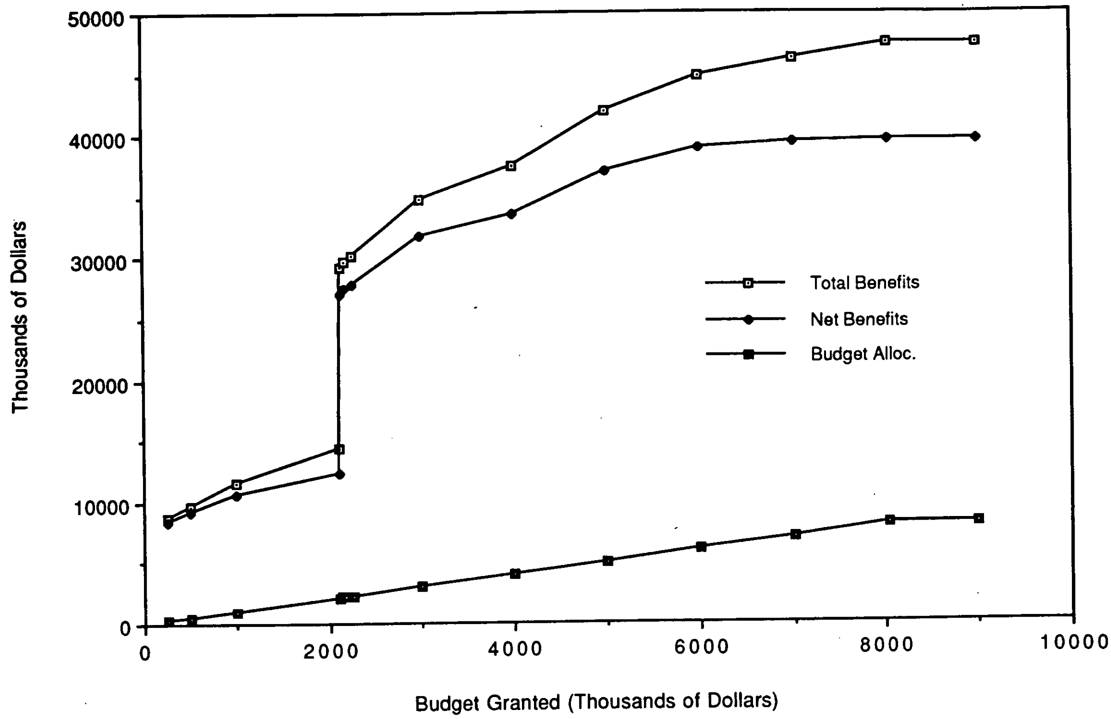

FIGURE 1 **INCBEN results, agency and user benefits at 6 percent discount rate.**

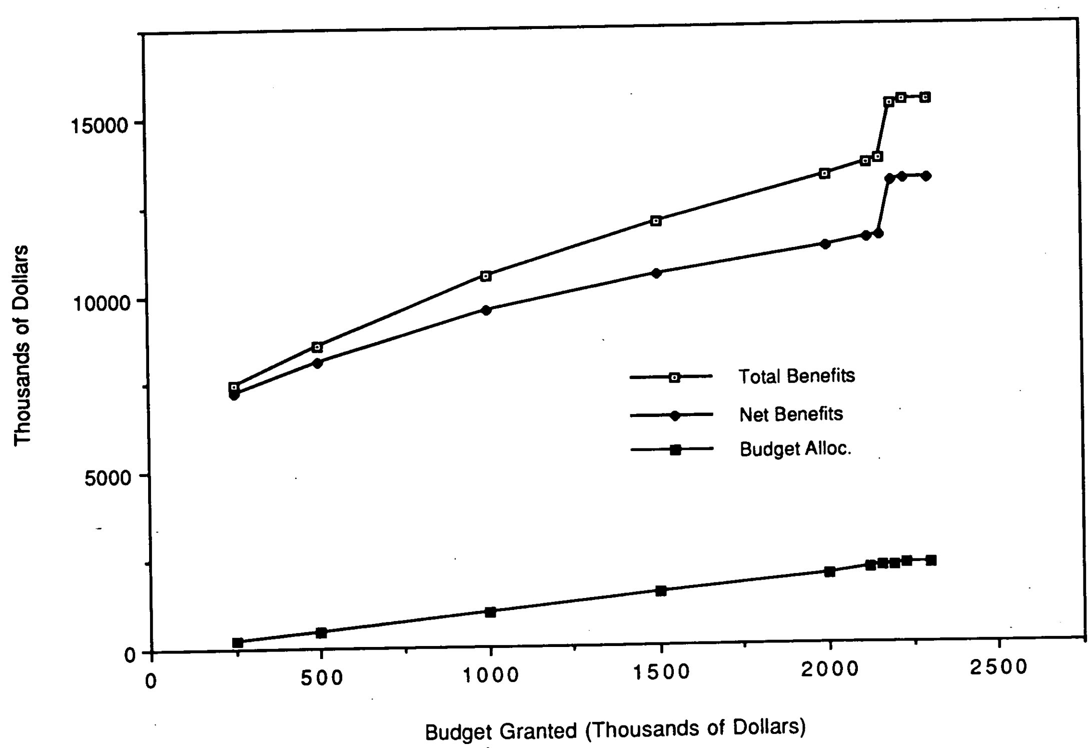

FIGURE 2 **INCBEN results, agency benefits only at 6 percent discount rate.**

random variables because they are only forecasts of future events. Thus, impacts of varying major input data on the INCBEN results should be of interest. Such a "sensitivity analysis" is a "study to see how the economic decision will be altered if certain factors are varied" (*7*). Or, "sensitivity refers to the relative magnitude of the change in one or more elements of an engineering economy problem that will reverse a decision among alternatives" (*8*). To perform a sensitivity analysis, variables that are most likely to affect the results and their probable ranges are determined first. A variable's expected value is often selected as the base. Results obtained by using other values of the variable are compared with those obtained by using the base value. Under a limited budget, sensitivity of the ranking of the bridge improvement alternatives and their expected net benefits to the discount rate, remaining life, and service life are analyzed.

Sensitivity to Discount Rate

The discount rate is used to compute the present value of the future cash-flow stream representing costs and benefits. Selection of an appropriate discount rate is an important step in any discounted cash flow analysis because it can easily affect the results (*9*). A 6 percent discount rate is used as the "base," the recommended are for long-term public projects. Outcomes obtained by using discount rates of 4, 5, 7, and 8 percent are compared with those obtained at the 6 percent base rate.

Figure 3 depicts the sensitivity of net benefits to the discount rate. If both agency and user benefits are considered, the higher the discount rate, the lower the net benefits expected. This is because the present value of user benefits, which usually lag behind costs, decreases more than the present value of costs as the discount rate increases. The results appear consistent with Miller et al.'s position that low discount rates favor projects with high capital costs (*10*). While net benefits vary slightly with the discount rate, the improvement alternatives selected remain essentially unaffected (*4*). Thus, the INCBEN results are not sensitive to discount rate when both agency and user benefits are considered.

Figure 3 also depicts the sensitivity of net benefits to discount rate considering agency benefits only. Net benefits vary slightly: the higher the discount rate, the higher the net benefits expected. Again, the improvement alternatives selected are not sensitive to the discount rate for a $2,200,000 budget. No new-bridge alternative is selected for any of the 25 bridges at any discount rate (*4*). These results signal that replacement is rarely economical if user benefits are excluded.

TABLE 5 Alternatives Selected for Several Budget Levels, Agency Benefits

	Budget Granted ($1,000)							
Bridge No.	250	500	1000	2000	2120	2158	2189	≥2227
00210	-	*M*	*M*	*M*	*M*	*M*	*M*	*M*
05125	*M*	*M*	*M*	*M*	*M*	*R*	*M*	*R*
08052	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
10381	-	-	*M*	*M*	*M*	*M*	*M*	*M*
17001	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
29058	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
45009	*R*	*R*	*R*	*R*	*R*	*R*	*R*	*R*
58016	*r*	-	-	*r*	*r*	*r*	*r*	*r*
58030	-	-	*r*	*r*	*r*	*r*	*r*	*r*
58032	-	-	-	-	*r*	*r*	*r*	*r*
58033	-	-	-	*r*	*r*	*r*	*r*	*r*
58089	-	-	*r*	*r*	*r*	*r*	*r*	*r*
58091	-	-	-	*r*	*r*	*r*	*r*	*r*
58100	-	-	-	*r*	*r*	*r*	*r*	*r*
58102	-	*r*	-	*r*	*r*	*r*	*r*	*r*
58128	-	-	-	*r*	*r*	*r*	*r*	*r*
61010	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
73411	*M*	*M*	*M*	*M*	*M*	*M*	*R*	*R*
75171	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
80173	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
84007	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
84133	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*
89034	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
91014	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
97060	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*

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

Sensitivity to Remaining Life

A bridge's remaining life is a function of the deterioration rate of its structural elements. Some prediction data are available, but the actual remaining lives can be highly variable. Thus, variations in remaining life can affect the INCBEN results.

Sensitivity analyses are preformed covering a ±30 percent range of the expected remaining lives of the bridges. As depicted in Figure 4, the higher the remaining life, the higher the net benefits expected if both agency and user benefits are considered. But results are more sensitive to the shorter remaining lives. Improvement alternatives selected for the 30 percent shorter remaining lives are different from selections for the other two cases (*4*).

Considering agency benefits only, Figure 4 confirms that the expected benefits are slightly sensitive to the remaining life. Improvement alternatives selected are slightly sensitive to the longer remaining life. For a 30 percent longer remaining life, the maintenance alternative for Bridge 73411 and the rehabilitation alternative for Bridge 05125 are the only changes in the alternatives selected for the other two cases (*4*).

Sensitivity to Service Life

A bridge's service life is the number of years that it can serve the traffic before it becomes structurally unsafe (*6*). Therefore, estimating the service life of a bridge is a function of how its structural conditions will deteriorate because of factors such as the weather and traffic conditions. Statistical techniques can be used to estimate deterioration formulas from which the service life can be approximated. However, estimated the extended service life after rehabilitation or maintenance "is not exact and requires engineering judgment" (*6*). Service life may be reduced by significant increases in the level-of-service needs.

Sensitivity analyses of the INCBEN results to service life considers ±30 percent variation in the 50-year expected service life of the bridges. Figure 5 confirms that longer service lives result in slightly higher net benefits, when both agency and user benefits are considered. Bridge improvement decisions are somewhat sensitive to the service life. Improvement alternatives selected for Bridges 58128 and 61010 are the same for ±30 percent service life cases, but they are different from the expected service life case. Bridge 84007 should also receive a different improvement for the shorter service life case compared with the other cases (*4*).

Figure 5 also confirms that the expected net benefits are not very sensitive to the service life if only agency benefits are considered. Improvement alternatives selected are not sensitive to the service life, either. As a result, the total initial costs of the alternatives selected remain constant for the three cases (*4*).

Analysis of Sensitivity Results

Results of the three sensitivity analyses indicate that variances of net benefits from the base cases are generally less than ±10 percent. One exception is for the remaining life when considering both agency and user benefits, where the variance of net benefits ranges from −22.5 to +16.5 percent (*4*). Since estimates of agency and user costs and benefits are generally no more reliable, these variations are not considered significant.

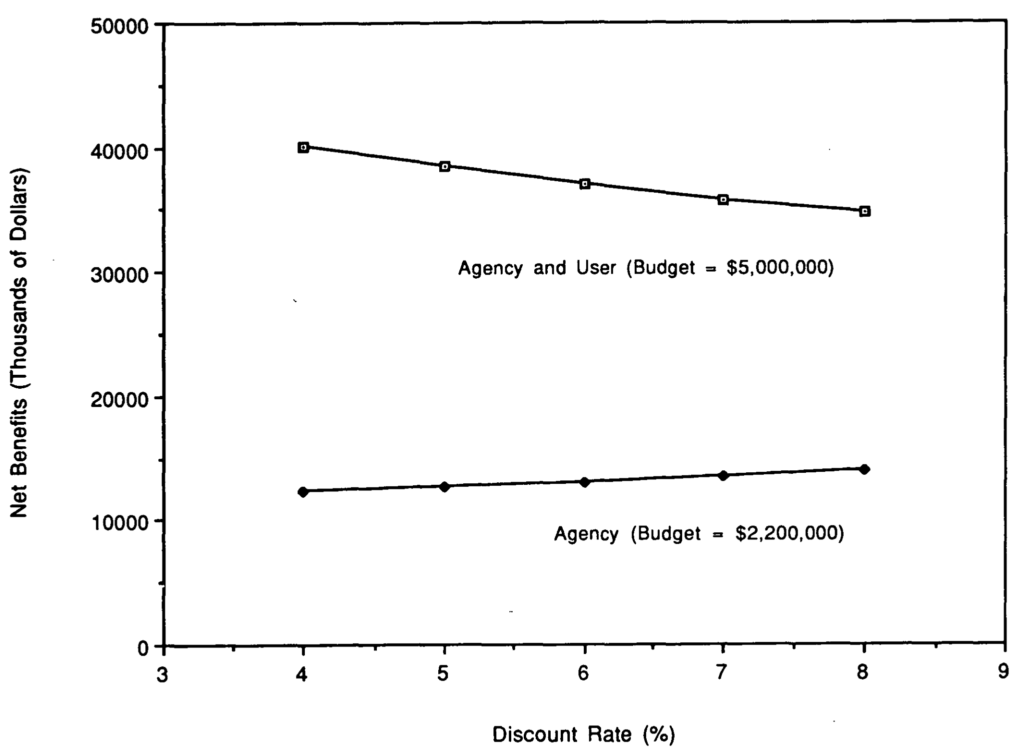

FIGURE 3 Sensitivity of net benefits to discount rate.

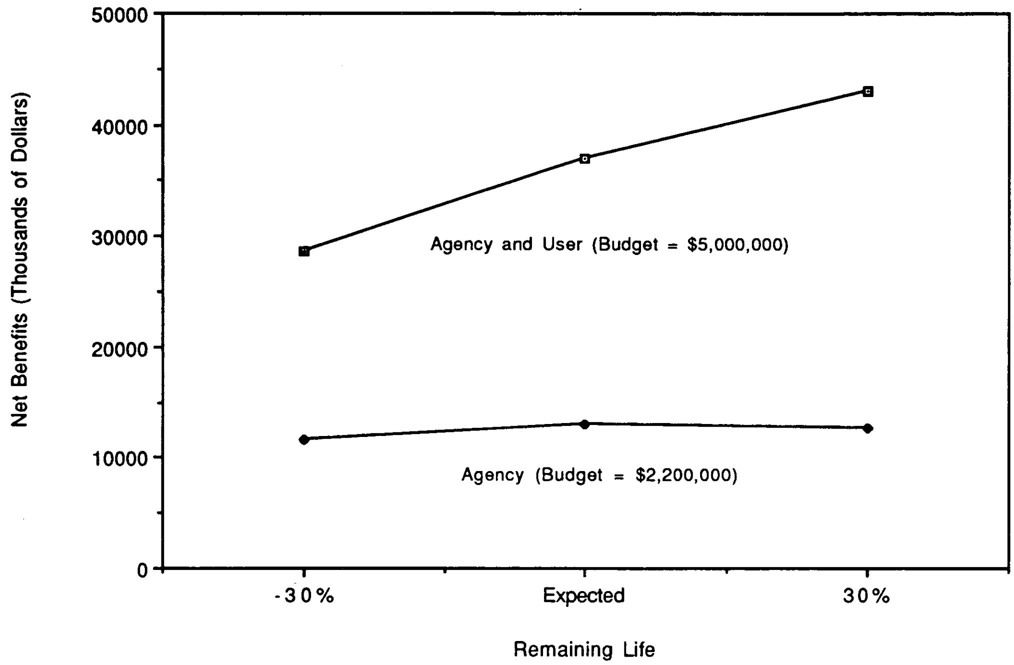

FIGURE 4 Sensitivity of net benefits to remaining life.

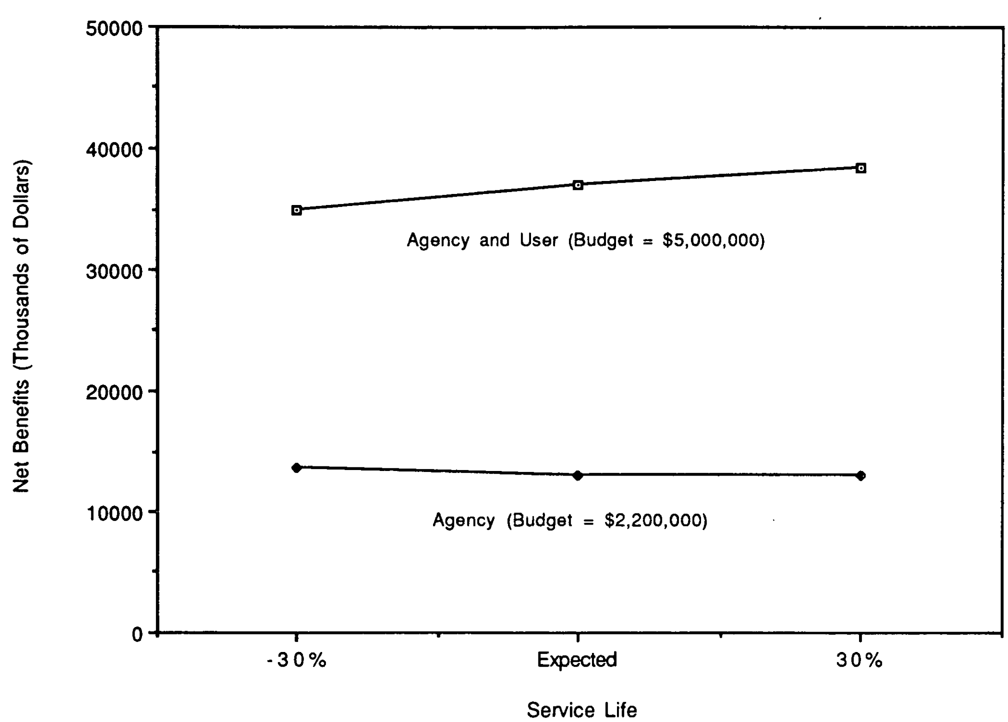

FIGURE 5 Sensitivity of net benefits to service life.

Selections of improvement alternatives change only slightly from one end of the probable ranges of the variable to the other. Improvement alternatives always change for fewer than 20 percent, usually for fewer than 10 percent, of the bridges. Alternative changes usually result in small additional first costs (*M* to *R*, *r* to *R*, or *R* to *N*). Large alternative shifts (*M* to *N*) are not encountered (*4*).

Sensitivity of the INCBEN results is somewhat greater when both agency and user benefits are considered as opposed to when only agency benefits are considered. Overall, while improvement alternatives selected and their expected net benefits vary somewhat, the results are relatively insensitive to the discount rate, remaining life, and service life, within reasonable ranges of these variables.

COMPARISON OF INCBEN AND SUFFICIENCY RATING METHODS

Many states have used the sufficiency rating to priority rank bridges for improvement (*4*). The budget granted is sometimes allocated to bridges in ascending order of their sufficiency ratings—that is, a bridge having a lower sufficiency rating receives a higher priority for improvement. Table 6 gives the priority rankings of the 25 sample bridges by sufficiency rating.

After the priority rankings are formulated, a specific improvement alternative should be selected from all the possible alternatives for every bridge. Methods available for selecting improvement alternatives at the bridge level produce varying results. Table 7 gives the results of budget allocations by five sufficiency rating methods that may be used to select improvement alternatives for bridges in the order of their priority rankings. Budget allocations produced by INCBEN are also listed.

To have a compatible comparison with the INCBEN analysis, sufficiency rating methods also assume that an improvement alternative on every bridge is mandatory. Thus, all sufficiency rating methods first fund the least-cost alternatives in the order of the priority rankings. If all the least-cost alternatives are funded, the budget balance is then allocated in the priority-ranking order according to the specific criteria of various methods:

1. "Economic Analysis," shown in Column 4 of Table 7, funds improvement alternatives on the basis of an economic analysis at the bridge level.
2. "All Replacement," shown in Column 5 of Table 7, funds the replacement alternative for each bridge.
3. "<50 Replacement/<80 Rehabilitation," shown in Column 6 of Table 7, funds replacement if the sufficiency rating is lower than 50 or funds rehabilitation if the sufficiency rating is between 50 and 80.
4. "Rehabilitation if $ <50%," shown in Column 7 of Table 7, funds replacement unless the initial rehabilitation cost is less than 50 percent of the replacement cost.
5. "Worst Case," shown in Column 8 of Table 7, funds the least economic alternatives.

None of these five sufficiency-rating methods is advocated; they are presented for comparison only. Budget allocations based on the economic analysis and worst-case criteria theoretically form the two extremes of the budget allocations using priority rankings based on sufficiency ratings.

Table 7 compares budget allocations by INCBEN and five sufficiency rating methods at various levels of budget granted. Based on these results, the incremental benefit-cost analysis consistently produces selections for all budget levels analyzed that are equal to or better than other methods using priority rankings based on sufficiency ratings. At a $2,120,000 budget level, which is the minimum budget required to fund the least-cost alternatives for all bridges, all five sufficiency rating methods produce results identical to those produced by INCBEN. The percentages shown inside the parenthesis in Table 7 indicate variances from net benefits expected from INCBEN selections. A negative sign indicates lower net benefits than those produced by the incremental benefit-cost analysis.

TABLE 6 Priority Rankings of Sample Bridges in Ascending Order of Sufficiency Ratings

Priority Ranking (1)	Sufficiency Rating (2)	Bridge Number (3)	Priority Ranking (4)	Sufficiency Rating (5)	Bridge Number (6)
1[a]	0.0	05125	14	61.4	80173
1[a]	0.0	84133	15	66.8	58091
3	1.0	17001	16	67.0	58089
4	5.0	73411	17	67.8	58030
5	29.2	45009	18	70.8	89034
6	30.2	00210	19	70.9	91014
7	37.1	10381	20	71.9	58128
8	37.3	08052	21	73.6	84007
9	46.1	58100	22	74.8	61010
10	49.8	75171	23	75.1	58102
11	56.1	29058	24	76.0	58016
12	56.6	97060	25	78.4	58032
13	56.9	58033			

[a] A 2-way tie

TABLE 7 Comparison of Budget Allocations by INCBEN and Sufficiency Rating Methods

Granted Budget	Expected Value of	INCBEN[b]	Sufficiency-Rating Method[a]: Economic Analysis	All Replace.	<50 Rep. <80 Reh.	Reh. If $ < 50%	Worst Case
All Figures in Thousands of Dollars Except Percentages							
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
250	Total Benefits	8,651	7,673	7,673	7,673	7,673	7,673
	Budget Allocated	249	249	249	249	249	249
	Net Benefits	8,402	7,424	7,424	7,424	7,424	7,424
			(-11.6%)[c]	(-11.6%)	(-11.6%)	(-11.6%)	(-11.6%)
2,120	Total Benefits	14,437	14,437	14,437	14,437	14,437	14,437
	Budget Allocated	2,120	2,120	2,120	2,120	2,120	2,120
	Net Benefits	12,317	12,317	12,317	12,317	12,317	12,317
			(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)
2,142	Total Benefits	29,254	29,254	14,437	14,436	29,254	14,437
	Budget Allocated	2,142	2,142	2,120	2,123	2,142	2,120
	Net Benefits	27,112	27,112	12,317	12,313	27,112	12,317
			(0.0%)	(-54.6%)	(-54.6%)	(0.0%)	(-54.6%)
5,000	Total Benefits	41,926	37,413	17,287	17,286	33,943	8,060
	Budget Allocated	4,979	4,959	4,977	4,980	4,993	4,878
	Net Benefits	36,947	32,454	12,310	12,306	28,950	3,182
			(-12.2%)	(-66.7%)	(-66.7%)	(-21.6%)	(-91.4%)
8,036	Total Benefits	47,529	47,529	19,125	19,328	42,962	11,273
	Budget Allocated	8,036	8,036	8,023	7,991	8,009	7,945
	Net Benefits	39,493	39,493	11,102	11,337	34,953	3,328
			(0.0%)	(-71.8%)	(-71.3%)	(-11.5%)	(-91.6%)
11,836	Total Benefits	47,529	47,529	36,540	36,501	47,923	13,504
	Budget Allocated	8,036	8,036	11,772	11,823	11,604	11,836
	Net Benefits	39,493	39,493	24,768	24,678	36,319	1,668
			(0.0%)	(-37.3%)	(-37.5%)	(-8.0%)	(-95.8%)
17,698	Total Benefits	47,529	47,529	51,596	50,084	47,923	13,504
	Budget Allocated	8,036	8,036	17,570	17,698	11,604	11,836
	Net Benefits	39,493	39,493	34,026	32,386	36,319	1,668
			(0.0%)	(-13.8%)	(-18.0%)	(-8.0%)	(-95.8%)
≥20237	Total Benefits	47,529	47,529	55,168	51,460	47,923	13,504
	Budget Allocated	8,036	8,036	20,237	19,272	11,604	11,836
	Net Beneftis	39,493	39,493	34,931	32,188	36,319	1,668
			(0.0%)	(-11.6%)	(-18.5%)	(-8.0%)	(-95.8%)
Cum. Net Benefits at all Budget Levels		242,750	237,279 (-2.3%)[c]	149,195 (-38.5%)	144,949 (-40.3%)	219,713 (-9.5%)	43,572 (-82.1%)
Cum. Net Benefits at Budget Levels ≤ $8,036		124,271	118,800 (-4.4%)[c]	55,470 (-55.4%)	55,697 (-55.2%)	110,756 (-10.9%)	38,568 (-69.0%)
Performance Ranking		1	2	4	5	3	6

[a] All methods first fund the least-cost alternatives in the order of priority rankings. If all least-cost alternatives are funded, the balance of the granted budget is then allocated according to their specific criteria and in priority-ranking order. Specific allocation criteria are defined in the text.

[b] INCBEN first considers only the least-cost alternative for every bridge. After all least-cost alternatives are funded, the granted budget balance is then allocated to other alternatives using their *marginal* benefits and costs over their corresponding least-cost alternatives.

[c] Net-benefits percentage variance from net benefits expected from the INCBEN selections.

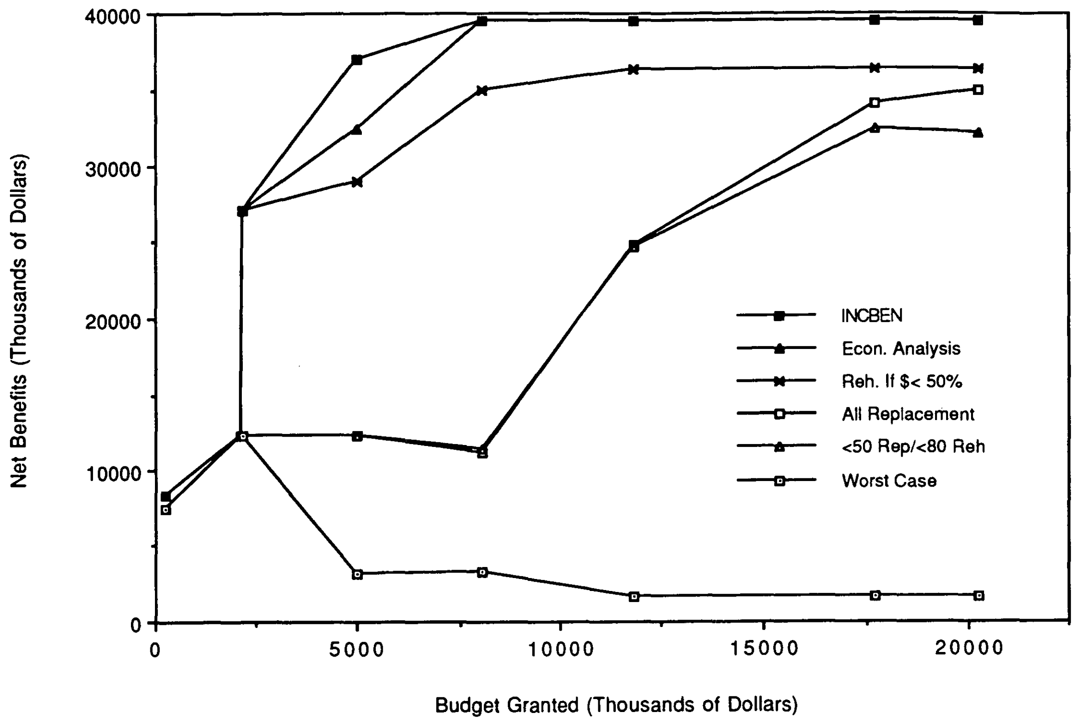

FIGURE 6 Comparison of budget allocations by INCBEN and sufficiency rating methods.

The results in Table 7 are also depicted in Figure 6. The economic analysis method at the bridge level produces the best results among all sufficiency rating methods. This is because it selects the best improvement alternative at the bridge level on the basis of the same economic principles used by the incremental benefit-cost analysis. Of course, the INCBEN analysis at the system level produces superior results under budget constrains. For example, at a $5,000,000 budget granted, net benefits expected from the economic analysis allocation are nearly 12 percent lower than those expected from the INCBEN allocation. For granted budgets of $8,036,000 or more, INCBEN and economic analysis produce the same results because the most cost-effective improvement alternative for every bridge can be funded at these levels. Thus, economic analysis at the bridge level produces results identical to those produced by the INCBEN analysis at the system level under unlimited budgets.

The all-replacement method produces net benefits that are as much as 72 percent lower than those produced by INCBEN. The <50-replacement/<80-rehabilitation method produces results that are up to 70 percent inferior to those produced by the INCBEN analysis. The Rehabilitation-if-$<50% method produces results that are up to 22 percent worse than the INCBEN analysis. The worst-case method, of course, produces the lowest net benefits at every budget level.

The cumulative net benefits expected from each method at all budget levels are also presented in Table 7. These cumulative net benefits provide an approximate measure of the overall performance of various methods. The percentages shown inside the parentheses here indicate the variance of the cumulative net benefits expected from the corresponding method from those expected from the INCBEN analysis. From these cumulative data, the INCBEN analysis produces better results than the five sufficiency rating methods evaluated. The sufficiency rating methods are expected to produce cumulative net benefits that are 2 to 82 percent lower than those expected from the INCBEN analysis, as indicated in Table 7.

The data presented in Table 7 and Figure 6 can also be used for preparing and justifying budget requests. Figure 6 clearly indicates that budget requests of more than $8,036,000 are not economical. The cumulative net benefits expected from every method at budget levels of $8,036,000 or lower are given in Table 7, immediately below the same data at all budget levels. These data confirm that INCBEN selections produce significantly higher cumulative net benefits than any of the sufficiency rating methods under more realistic levels of budget granted.

Figures 6 and 1 confirm that budget requests lower than $2,142,000 are not prudent. At such low budget levels, many of the least-cost improvement alternatives must be selected at the expense of the more cost-effective alternatives.

CONCLUSIONS

The INCBEN program can be used for optimal allocation of limited budgets to maintenance, rehabilitation and replacement of bridges. Major conclusions of the INCBEN application to a sample of 25 bridges in North Carolina include the following:

1. INCBEN generates priority rankings of the improvement alternatives in the decreasing order of their incremental benefit-cost ratios. These rankings are superior to those generated by the sufficiency rating methods. INCBEN rankings are superior not only

because they are based on sound economic principles but also because INCBEN selects specific improvement alternatives for deficient bridges.

2. INCBEN recommends near-optimal sets of bridge improvement alternatives under limited budgets. INCBEN selections under unlimited budgets are optimal and identical to the alternatives selected by the economic analysis at the bridge level.

3. Results of the budget allocations by INCBEN are only slightly sensitive to the discount rate, remaining life, and service life of a bridge. Variations in net benefits expected are small. Changes in improvement alternatives selected, or in their priority rankings, are minimal.

4. The replacement alternative is never cost-effective for any of the 25 bridges if user costs are excluded. Thus, both agency and user costs must be considered in any realistic bridge management system.

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DISCUSSION

WAHEED UDDIN
Department of Civil Engineering, University of Mississippi, University, Miss. 38677.

The paper illustrates a good example of life-cycle cost analysis of user costs and benefits in bridge management. However, the authors provide very little description of the INCBEN software methodology, especially the benefits and user costs. A significant amount of life-cycle user costs are related to the vehicle operating costs, which increase when the bridge deck condition deteriorates. This is a rational and quantified approach because this user cost component is directly a function of vehicular traffic and operating speed (*1*). Therefore, vehicle operating costs also reflect the user costs due to a decrease in the level of service.

Finally, it is recommended that user costs and benefits should be included for objective evaluation of competing maintenance, rehabilitation, and reconstruction/replacement alternative strategies in all areas of management systems identified in the Intermodal Surface Transportation Efficiency Act of 1991.

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AUTHORS' CLOSURE

The discussant's interest in this paper, and in highway management systems in general, is appreciated. INCBEN and the required input data are described in the section of the paper entitled "INCBEN Program." This section further states: "Farid et al. have provided a detailed description of INCBEN (*4*; another paper in this Record), and a complete description of INCBEN has also been presented by McFarland et al. (*3*)." Since this and the companion paper by Farid et al. will appear in the same Record, readers can easily refer to the companion paper for additional information on INCBEN. Both papers were presented in Session 115, and their preprints were available side by side, at the 73rd Annual Meeting of the Transportation Research Board. Thus, it is unclear why the companion paper has been overlooked.

User costs and benefits are covered in the subsection entitled "Forecasting Input Data." Again, this section states: "Farid et al. (*4*; another paper in this Record) describe the techniques used for developing the improvement alternatives and their life-cycle costs." Increases in operating costs of vehicles traveling over long bridges with deteriorated decks may prove significant enough to be included in user costs. But, the USER microcomputer program (*1*) cannot be used for estimating bridge user costs because bridge decks deteriorate differently from highway pavements. Further, this research was conducted and its final report published long before the discussant's paper (*1*) was published. Only references actually used are cited in the references. Many other publications have made significant contributions to infrastructure management systems. Space limitations preclude publication of bibliographies in technical papers such as those published by TRB. Interestingly enough, Uddin and George (*1*) did not reference Farid et al. (*2*) or Chen and Johnston (*3*), even though these reports have been widely distributed by FHWA and frequently cited in publications on bridge management systems.

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