Cost-Effectiveness Analysis for Strengthening Existing Bridges

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An economic analysis procedure has been developed to assist in the decision-making process for replacing or strengthening a bridge having a deficient load-carrying capacity. Often, decisions are made either to strengthen or replace the structure by considering only the initial costs of each alternative without regard to life-cycle costs. The analysis procedure developed in this study determines an equivalent uniform annual cost for each alternative from which the most cost-effective alternative can be chosen. In addition, this procedure also allows cost comparisons to be made among various applicable strengthening methods. The equivalent uniform annual-cost procedures are based on mathematical models, commonly used in engineering economy studies, that involve cost comparisons between alternatives of different economic lives. A brief discussion of the life-cycle costs used in the mathematical models, and examples using the models developed, are included.

As existing bridges deteriorate in the United States, the most cost-effective methods of maintaining the nation's bridge infrastructure need to be determined. Approximately 40 percent of the nation's bridges are classified as deficient and are therefore in need of replacement or rehabilitation. With limited funding available to address this problem, strengthening of these deficient bridges is becoming a commonly used method to keep them in service.

Faced with a bridge having a deficient load rating, the bridge engineer has three alternatives: (a) to replace the existing bridge, (b) to strengthen the existing bridge (which also includes selecting the best strengthening method from those available), or (c) to leave the existing bridge in its present state. Making a decision among the three alternatives involves a number of factors, all of which must be carefully evaluated.

Evaluating the economic advantages associated with each alternative is the most effective method of selection. By attempting to quantify each alternative in terms of its economic value, the engineer can achieve a rational method of making comparisons among alternatives. A systematic economic analysis of each strengthening or replacement alternative will ensure that the most efficient use is made of limited bridge funds. The analysis should consider all pertinent costs over the life of the bridge, determine whether replacement or strengthening is the desired alternative, and provide insight into which strengthening method is the best alternative. The purpose of this paper is to present an analysis tool for making cost-effective decisions on strengthening of deficient bridges. The work was performed as one of the tasks of the National Cooperative Highway Research Program Study 12-28(4) *(1)*.

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BACKGROUND

It is only within the past 10 to 15 years that engineers have begun to implement systems capable of better managing the nation's bridges. These management systems have come at a time when fewer bridges are being replaced *(2)*; thus, better maintenance of our present inventory of bridges is required. As usual, maintenance funds are limited, and effective management systems are required to ensure that the most effective use is made of these limited resources. Obsolete and deficient bridges on our road systems also pose potentially high liability costs. These factors, combined with the rapidly deteriorating condition of the nation's bridges, have prompted the need for better bridge management programs.

Among the first steps taken in improving the management of our current inventory of bridges was the implementation of the National Bridge Inspection Program in 1968. This program established a numerical sufficiency rating for each bridge, on which eligibility for federal funding for rehabilitation or replacement was determined. As a result, nearly all of the nation's bridges have now undergone inspection, and the results are available on computer files both at the federal and state levels *(2)*.

With information available for such a large number of bridges, it has become necessary to develop a system capable of sorting the inspection data and establishing priorities for bridge replacement and rehabilitation projects. One such program is the Level-of-Service System for Bridge Evaluation developed by the North Carolina Department of Transportation (DOT). The North Carolina DOT system ranks bridge replacement and rehabilitation projects based on deficiency points accumulated in a level of service evaluation of each bridge *(3)*. Bridges are then ranked based on deficiency points. By using these data, decisions as to what action should be undertaken (e.g., rehabilitation, strengthening, or replacement) are made.

In determining a corrective course of action, each bridge must be carefully evaluated to determine the alternatives that will provide the most cost-efficient means of correcting deficiencies and providing the road user with the level of service required. After the various alternatives are proposed, the one having the least initial cost is usually selected as being the most cost effective. The problem with comparing initial costs rather than life-cycle costs, however, is that the initial cost of most projects represents less than half of the total life-cycle costs. The difficulty in using a life-cycle cost analysis lies in accu-

rately predicting future costs. However, progress is being made in determining life-cycle costs through the use of better accounting procedures for bridge maintenance and operating costs.

Several states are now managing their long-term bridge maintenance needs with specialized computer programs that can carefully account for dollars spent on bridge maintenance and operation costs and forecast future long-term bridge expenditures. The Pennsylvania DOT recently completed a study of a new computerized system that will enable them to manage their large bridge inventory more effectively *(4)*. When this system is fully implemented, the Pennsylvania DOT will have a large cost data base to use in determining and forecasting life-cycle bridge costs.

The progress made in the inspection of the nation's bridges, the recording of those results, the systems capable of sorting the inspection results and ranking bridge rehabilitation projects, and the programs capable of accounting for and forecasting long-term bridge expenditures have all made significant contributions to the overall management of our nation's bridges. In an efficient bridge management system, each bridge must be evaluated for the most cost-effective method of keeping it in service. Factors such as initial rehabilitation and replacement costs, long-term bridge maintenance and operating costs, and potential savings and benefits to the road user should be included.

METHODOLOGY

Generally, decisions based on first costs for various alternatives will not yield the most economical solution. The most practical approach is an analysis procedure that takes into account the costs over the life of a structure. The cost-effectiveness procedure used in this paper involves the determination of an equivalent uniform annual cost (EUAC) for a replacement bridge and for various strengthening methods. In the analysis procedure, significant costs incurred during the bridge service life are considered. Once EUACs have been determined, a cost comparison may be made among the various alternatives.

The analysis procedure presented in this paper considers only two alternatives: (a) replacement of an existing bridge, or (b) strengthening of the existing bridge. No consideration is given to the "do nothing" alternative. A cost study is presented at the end of this paper to illustrate the application of the proposed cost analysis procedure to strengthening a given bridge.

Models

The generalized models that have been developed for use in calculating EUACs are shown in Figures 1 and 2. The cash-flow diagrams in the figures depict typical life-cycle costs associated with each model. Mathematical expressions based on the time value of money are developed for each model. For the replacement model,

$$\text{EUAC replacement} = R(A/P, i, N) - B(A/P, i, N) - S(A/F, i, N) + C_{AR} + (A/P, i, N)\left[\sum_{j=1}^{m} F_j\,(P/F, i, n_j)\right] \quad (1)$$

where

R = replacement structure first cost
B = net salvage value of present structure

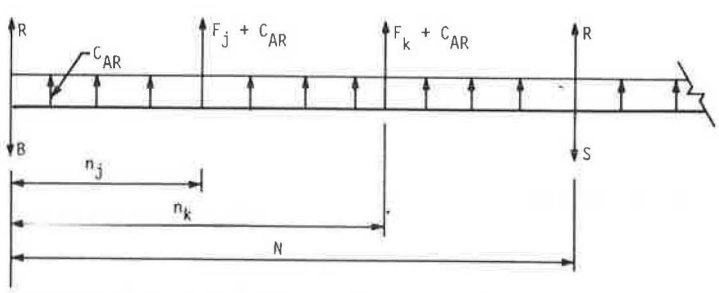

FIGURE 1 Cash-flow diagram for replacement model.

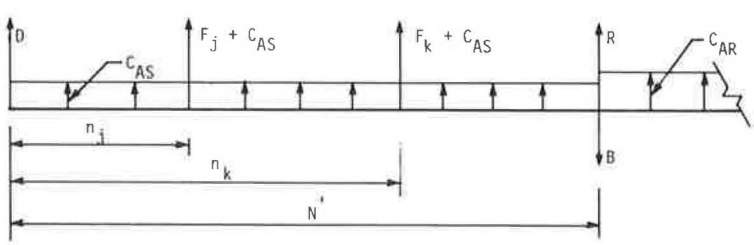

FIGURE 2 Cash-flow diagram for strengthening model.

C_{AR} = annual maintenance costs associated with a new structure
S = net salvage value of replacement structure
N = service life of new structure
i = interest rate

$(A/P, i, N)$ = capital recovery factor = $\dfrac{i(1+i)^N}{(1+i)^{N-1}}$

$F_{j,k}$ = single future expenditure (i.e., deck replacement or deck overlay)

$(P/F, i, n_j)$ = present worth of a future sum = $\dfrac{1}{(1+i)^{n_j}}$

It should be noted that salvage values can be either positive or negative. In most situations there is little salvage value to be gained from an existing bridge, and the bridge owner normally pays for its removal (usually as part of the bid price of a replacement structure). The removal cost would be represented by a negative salvage value in the EUAC equations.

By assuming N to be very large and B to be relatively small in comparison to R, Equation (1) can be simplified to

$$\text{EUAC replacement} = (A/P, i, N)(R-S) + C_{AR} + (A/P, i, N)\left[\sum_{j=1}^{m} F_j\,(P/F, i, n_j)\right] + (S-B)i \qquad (2)$$

There are two distinct advantages to using Equation (2) rather than Equation (1). In general, the removal cost of the existing structure, B, will be approximately that of the replacement structure, S. Therefore, the last term of Equation (2), $(S-B)i$, becomes insignificant and may be ignored. In addition, the bid price of the replacement structure normally includes the removal cost of the existing structure. The $(R-S)$ term in Equation (2) then will be the total bid price of the replacement structure (see Table 1).

The strengthening model is more difficult to represent mathematically than the replacement model. Two key factors in developing the strengthening EUAC equation are presented below. The first is that after eventual replacement all costs are assumed to be common to both the replacement and strengthening model. As a result, these costs will offset one another in a comparison of differences. The second and more crucial factor is that the strengthening improvement benefits only the existing structure. Therefore, investment costs of bridge strengthening should be recovered only over the remaining life of the strengthened bridge. The mathematical equation for the strengthening model can now be written as

$$\text{EUAC strengthening} = (A/P, i, N')(D) + C_{AS} + (A/P, i, N')\left[\sum_{j=1}^{m} F_j \cdot (P/F, i, n_j)\right] + LS \qquad (3)$$

where

D = initial strengthening cost
C_{AS} = annual maintenance costs of the existing structure after strengthening
LS = level of service factor
N' = remaining service life of the existing bridge

TABLE 1 BRIDGE REPLACEMENT COSTS FOR 1985 FROM SELECTED STATES

State	Bridge Type	Cost/ft^2 ($)[a] Range	Average	Remarks
Illinois	WF steel beam	35–55	47	
	Plate girder	50–65	54	
	Deck beams, prestressed concrete	30–45	40	
	Reinforced concrete beam, deck girder	50–70	60	
	Prestressed precast concrete I girder, cast-in-place deck	35–50	44	
Iowa	Steel beam, continuous		45	
	Prestressed precast concrete I girder, cast-in-place deck		40	
	Concrete slab		35	
Minnesota	Prestressed beam	36–54	40.84	Data from state cost study (13 bridges)
		33–129	44.74	Data from county cost study (13 bridges)
	Welded steel, continuous beam	45–81	50.94	Data from state cost study (8 bridges)
		30–70	55.71	Data from county cost study (8 bridges)
	Timber slab	0–46	36.66	Data from county cost study (15 bridges)
	Rolled steel, continuous beam	40–88	60.25	Data from county cost study (6 bridges)
	Quad tee	0–45	37.55	Data from county cost study (11 bridges)
Missouri	Steel beam		42	
	Steel beam, continuous		45	
	Prestressed concrete		37	
Wisconsin	Steel beam, continuous	31–50	45	(10–20 bridges constructed per yr)
	Prestressed concrete	27–42	35	(20–40 bridges constructed per yr)
	Concrete slab	30–45	35	(50–60 bridges constructed per yr)

[a]All costs listed are bid prices for replacement structures and include removal of the existing bridge, construction of a new bridge (labor and materials), and traffic control costs (if applicable).

$$(A/P, i, N') = \text{capital recovery factor} = \frac{i\,(1+i)^{N'}}{(1+i)^{N'-1}}$$

$F_{j,k}$ = single future expenditure (i.e., deck replacement or deck overlay)

$$(P/F, i, n_j) = \text{present worth of a future sum} = \frac{1}{(1+i)^{n_j}}$$

A brief discussion of the different variables used in the economic analysis models and the factors that may affect them are presented in the following sections. Included in the discussion of each variable are cost figures obtained from different sources and pertinent comments as to the variables' effect on the total EUAC. Additional factors that may be considered in the economic analysis models are also presented.

Replacement Structure First Cost *(R)*

The factor that has the greatest effect on the EUAC for the replacement model is the initial replacement cost. Several key factors may significantly influence initial bridge replacement costs, these are

- Span length. As a general observation, costs per square foot for the construction of new bridges tend to increase with longer span lengths.
- Roadway realignment.
- Environmental studies and their effects need to be considered in the initial replacement costs.
- Construction of temporary detours or bridges.

A survey of initial bridge replacement costs obtained from various states is shown in Table 1. As can be seen from the table, longer spans, which are most economically built from rolled steel sections or plate girders, tend to have higher costs per square foot compared with shorter spans of concrete slab and precast, prestressed, concrete I-beam bridges.

Structure Service Life *(N, N')*

Information obtained from various state DOTs indicated that a minimum service life of 50 years is commonly assigned to new structures for use in a life-cycle cost analysis. This is also consistent with information obtained from literature reviews. One exception to this 50-yr service life is found in the southwest portion of the United States, where a 70-yr service life is often assumed. Factors that affect the service life of a new structure are (a) the initial design and its quality, (b) the quality of the construction materials used, (c) the degree of workmanship used in construction, (d) the level of maintenance performed over the life of the structure, and (e) the severity of the climate and the effects of factors such as water and deicing agents on the bridge. The use of a structure service life of 50 yr or more in determining the EUAC of the replacement alternative has little effect on the sensitivity of the results obtained from the models. In addition, because of the many uncertainties in predicting the long-term plans for the use of a particular bridge, it is probably better to err on the conservative side by using 50 yr as the service life.

The remaining service life of existing bridges is a variable that is difficult to quantify accurately. The most common method for determining remaining service life is based on the engineer's estimate from field inspections. Several problems exist with this approach: (a) There are few if any quantitative guidelines for evaluating remaining service life, and the engineer's estimate of remaining service life is usually a subjective one; and (b) it is difficult to eliminate the possibility of bias being involved in the estimate depending on preferred plans for the bridge (e.g., assigning a bridge a short service life if replacement is preferred). Research methods are currently under way that will allow accurate assessments of remaining service to be determined *(5)*. These methods, however, involve experimental techniques and will be useful only for steel stringer and steel girder bridges.

An additional factor to consider in determining the remaining service life of an existing bridge is the effect of strengthening or rehabilitating the bridge. Unless an extensive rehabilitation program is undertaken at the time of strengthening, most strengthening methods are unlikely to significantly increase the bridge's remaining service life. Only an extensive rehabilitation project undertaken at the same time the bridge is strengthened can be considered capable of extending the remaining service life of an existing bridge.

Interest Rate *(i)*

The interest rate used in the analyses in this paper is assumed to be 6 percent and represents the real or effective interest rate on borrowed capital. In general, a higher interest rate favors future expenditures (i.e., strengthening) while a lower interest rate favors the immediate expenditure of capital (i.e., replacement).

The effects of inflation are accounted for in the effective interest rate of 6 percent. The relationship between interest rates and inflation is given in Equation (4):

$$i_o = \frac{1 + i_p}{1 + y} - 1 \tag{4}$$

where

i_o = real or effective interest rate
i_p = nominal interest rate (usually based on highgrade municipal bonds)
y = rate of inflation (usually based on changes in the consumer price index)

More detailed information of the effects of inflation and interest rates on highway construction and financing can be found in published work by Smith *(6)*, Winfrey *(7)*, and Cady *(8)*.

Bridge Maintenance Costs

Annual bridge maintenance costs *(C_{AR}, C_{AS})* may be the most difficult life cycle costs to predict. Improvements in bridge

TABLE 2 ANNUAL MAINTENANCE COSTS BASED ON DATA PROVIDED BY SELECTED STATES

State	Bridge Type	Annual Maintenance Costs ($)
Illinois	All	1,227 per bridge[a]
Iowa	Steel beam	0.091/ft^2
	Steel beam, continuous	0.043/ft^2
	Prestressed concrete	0.052/ft^2
	Reinforced concrete beam, deck girder	0.082ft^2
	Slab	0.062/ft^2
	Steel high truss	0.114/ft^2
	Pony truss	0.227/ft^2
Minnesota	Steel beam	1,925 per bridge
	Steel beam, continuous	1,880 per bridge
	Prestressed concrete	1,245 per bridge
	Reinforced concrete beam, deck girder	2,000 per bridge
	Other (the majority being steel trusses)	2,830 per bridge
Missouri	All	0.093/ft^2
Wisconsin	All	300 per bridge[b]

[a]1985 average cost based on approximately 7,500 bridges.
[b]Wisconsin also reported an average cost of 5/ft^2 for a deck overlay and $23/ft^2 for a deck replacement.

maintenance accounting procedures should soon provide data in a form that allows accurate forecasts of required future bridge maintenance expenditures. Table 2 lists annual bridge maintenance costs obtained from various state DOTs that were surveyed. Factors that may affect maintenance costs include accounting procedures used to classify bridge maintenance, rehabilitation, and repair; location and environmental factors; and the use of deicing agents applied by each state.

Some strengthening methods may require maintenance beyond that normally performed on the bridge. These costs should be estimated on a perennial basis and added to the annual bridge maintenance costs, C_{AR} and C_{AS}.

Large bridge maintenance expenditures (e.g., a deck replacement or a deck overlay) that occur as single future disbursements should not be included in the terms C_{AR} and C_{AS}. These disbursements, represented by the symbol F in Figures 1 and 2, are future capital expenditures and are converted to EUACs based on the time value of money. The terms

$$(A/P, i, N) \cdot \left[\sum_{j=1}^{m} F_j \cdot (P/F, i, n_j)\right]$$

and

$$(A/P, i, N') \cdot \left[\sum_{j=1}^{m} F_j \cdot (P/F, i, n_j)\right]$$

in Equations (2) and (3) account for this.

Bridge Removal Costs *(B, S)*

Key factors that may significantly affect bridge removal costs are superstructure type, bridge length, number and type of abutments, depth of removal below the existing ground line, and environmental precautions required during removal. Disposal costs of bridge debris may vary widely depending on haul distances and landfill costs if the debris cannot be buried at the site. In addition, specifying some items for salvage, such as guardrails and beams for future use, may partially affect some of the cost of removal.

Figure 3 summarizes bridge removal costs obtained from local Iowa contractors. When the data were analyzed from the surveys, it was found that costs per square foot versus length were much more varied than total cost versus length. This would indicate that bridge width is not a significant factor in estimating bridge removal costs. In addition, comments and results from the surveys indicated that removal costs of bridges having timber abutments and piers could be as much as 30 percent less than similar bridges having concrete abutments and piers.

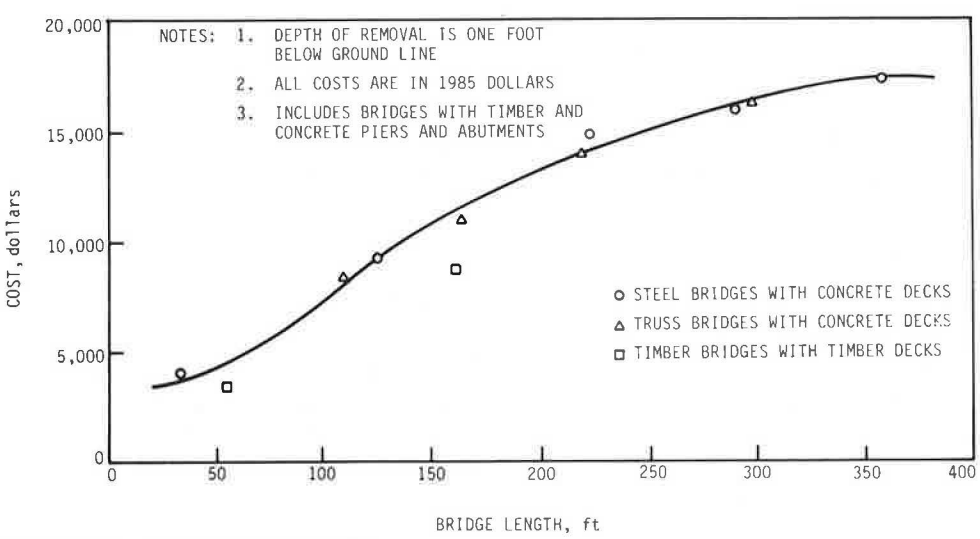

FIGURE 3 Bridge removal costs.

Level of Service Factor *(LS)*

The concept of a level of service factor is introduced as a means of quantifying the economic benefits a road user would realize with the construction of a new bridge. An existing bridge, particularly one with an obsolete geometry or poor load rating, cannot be expected to provide the same level of service to the road user as a new bridge would. A new bridge can be expected to offer reduced accident rates, reduced traffic delays, a reduction in extra mileage due to detours of overweight vehicles, and other intangible savings to the user. These reductions and savings are an additional annual cost of keeping an existing bridge in service and are represented as an additional cost in the strengthening alternative. Therefore, the level of service factor is a measure of the cost difference in the level of service provided to the road user between a new and existing bridge.

Assuming the existing bridge can be strengthened to a legal load rating, the level of service factors are reduced principally to functions of bridge geometry. A bridge with a poor geometry can be expected to cause traffic congestion, delays, and higher accident rates. Traffic congestion and delays are normally difficult to quantify in terms of cost without the governing agency conducting an on-site study of their effects. Accident costs are more easily predicted, however, either through the use of historical data or accident rate tables for narrow bridges. Thus, only accident costs are used in this paper as an aid in determining the increased costs to the road user associated with an existing narrow bridge that is to be strengthened or replaced.

To demonstrate the approach of quantifying level of service for the analytical model in this paper, reference is made to previous work by McFarland et al. *(9)*. As most studies dealing with accident rates associated with bridges have done, this study relates accident rates to roadway approach width and bridge width. Figure 4, taken from the study by McFarland et al., shows the percent reduction in the accident rate that could be expected with an increase in relative bridge width.

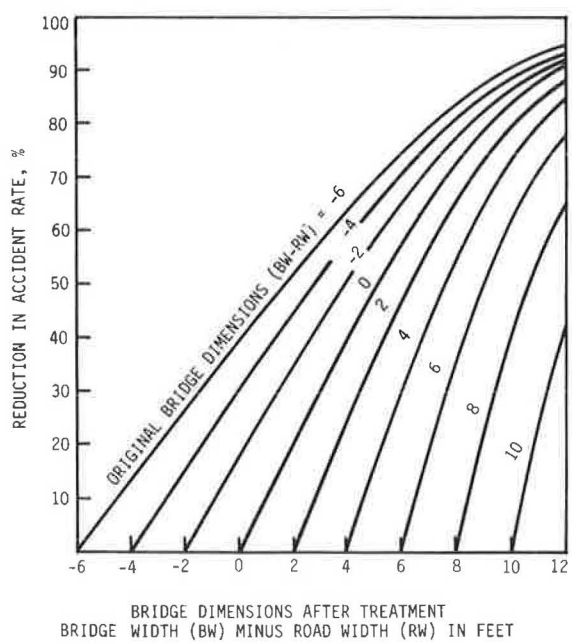

FIGURE 4 Percent reduction in accident rate associated with increases in relative bridge width.

TABLE 3 HIGHWAY ACCIDENT COSTS[a]

Type of Accident	Cost ($)
Fatal accidents	268,700 per fatality
Personal injury[b]	2,280 per injury
Property damage	530 per accident
All accidents	1,636 per accident

[a]The cost of an average accident includes medical costs, productivity losses, property damage, and other costs to society as estimated by the NHTSA *(10)*. The average cost was determined by taking the total estimated 1980 economic-loss-to-society costs owing to motor vehicle accidents divided by the total number of accidents and adjusted for inflation.

[b]Based on the average cost of Abbreviated Injury Scale 1 (AIS1) accidents.

Table 3 lists accident costs based on accident severity *(10)*. These costs, multiplied by predicted accident rates at the existing bridge, are the total costs incurred by the road user in keeping the existing bridge in service. The level of service cost, therefore, is the percent reduction in the accident rate multiplied by the total accident cost incurred by the existing bridge.

Maintenance of Essential Traffic Flow

One other factor to be considered in the economic analysis of bridge strengthening versus replacement is the maintenance of essential traffic flow during construction. This construction aspect is very situation dependent *(11)* and is difficult to quantify accurately. Several methods, such as the Queue and User Cost. Evaluation of Work Zones QUEWZ, developed by the Texas Transportation Institute, have been developed for determining the many costs associated with traffic flow at construction sites. Only some of the key factors in maintaining essential traffic flow are listed below.

Costly temporary bridges or bypasses may need to be constructed if a bridge is to be closed for strengthening or replacement. A detour, however, involves additional costs to the road user as well as possible usage payments to other counties or municipalities for rerouting traffic onto their highway systems. Partial lane closures on high-volume roadways may cause traffic congestion and unacceptably long delays for motorists as well as a possible safety hazard to construction site workers. In addition, liability costs will need to be considered for each method of maintaining essential traffic flow during construction.

NUMERICAL EXAMPLE

An example is presented to illustrate the analysis procedure developed in this paper. A typical bridge is considered to be in need of either strengthening or replacement, and EUACs are computed for various alternatives given the information below for an existing bridge:

- Superstructure type: simply supported, steel stringer, concrete deck bridge

- Span length: 60 ft
- Roadway width: 24 ft
- Present load capacity: AASHTO HS-15 Design Vehicle
- Estimated remaining service life: 20 yr
- Desired load capacity: AASHTO HS-20 Design Vehicle

Replacement Alternative

It can be expected that the replacement structure will have a greater span length than the original bridge because of slight changes in highway alignment and a planned increase in the vertical clearance under the bridge.

Replacement Bridge

- Superstructure type: simply supported, precast, prestressed concrete (PPC) I-beams with a cast-in-place (CIP) deck
- Span length: 70 ft
- Roadway width: 30 ft
- Expected service life: 50 yr

Replacement Structure First Cost

The replacement cost for a PPC I-beam bridge with a CIP deck is estimated at \$33/ft^2 (excluding removal costs of the existing structure). Total replacement cost:

$$R = (70 \text{ ft})\ (30 \text{ ft})\ (\$33/\text{ft}^2) = \$69{,}300$$

Projected Annual Maintenance Costs

Basic annual maintenance and operating costs, C_{AR} = \$450/year. Projected deck overlay in 15th year at \$5/ft^2:

- F_1 = (30 ft) (70 ft) (\$5/ft^2) = \$10,500
- Projected deck replacement in 30th year at \$23/ft^2
- F_2 = (30 ft) (70 ft) (\$23/ft^2) = \$48,300

Changing these single disbursements into an equivalent uniform annual cost, we obtain

$$(A/P, 6, 50)\left[\sum_{j=1}^{2} F_j\ (P/F, 6, n_j)\right] = (0.06344)\ [(\$10{,}500) \times (0.4173) + (\$48{,}300) \times (0.1741)] = \$811$$

Net Salvage Value of Present Structure

The estimated cost of removal for a 60-ft bridge from Figure 3, B = –\$4,700.

Net Salvage Value of Replacement Structure

The estimated cost of removal for a 70-ft bridge from Figure 3, S = –\$5,500.

EUAC for Replacement Alternative

$$\text{EUAC}_R = (A/P, 6, 50)\ (R - S) + C_{AR} + (S - B)\ 0.06 + (A/P, 6, 50)\left[\sum_{j=1}^{2} F_j\ (P/F, 6, n_j)\right]$$

$$\text{EUAC}_R = (0.06344)\ [\$69{,}300 - (-\$5{,}500)] + \$450 + [-\$5{,}500 - (-\$4{,}700)]\ (0.06) + \$811$$

$$\text{EUAC}_R = \$5{,}958/\text{yr}$$

Strengthening Method 1

Strengthening Method 1 involves making the deck composite with the steel stringers. This method requires coring out the concrete above the stringers, adding shear connectors, and replacing the concrete. The initial strengthening cost, to include traffic control measures, is estimated at D = \$12,190. No additional maintenance costs per year for this strengthening method are expected.

Projected Annual Maintenance Costs

Projected costs of maintaining and operating the existing bridge on a yearly basis, C_{AS} = \$950. Projected deck overlay required in 5 yr at \$5/ft^2:

$$F_1 = (24 \text{ ft})\ (60 \text{ ft})\ (\$5/\text{ft}^2) = \$7{,}200$$

Putting this single disbursement into an equivalent uniform annual cost, we obtain

$$(A/P,6,20)[(F_1)(P/F,6,5)] = (0.08718)[(\$7{,}200)(0.7473)] = \$470/\text{yr}$$

Level of Service Factor

A 3-yr study was conducted of accidents reported at the existing bridge site. The study determined that the number of accidents that could be expected per year if the existing bridge remained in service was 1.84. A new bridge, with a 30-ft roadway, can be expected to provide a 60 percent reduction in the accident rate (Figure 4).

LS = (annual accident rate) (average accident cost) (percent reduction)
LS = (1.84) (\$1,636) (0.60)
LS = \$1,806/yr

EUAC for Strengthening Method 1

$$\text{EUAC}_{S1} = (A/P, 6, 20)\ (D) + C_{AS} + LS + (A/P, 6, 20)\left[\sum_{j=1}^{1} F_j\ (P/F, 6, n_j)\right]$$

$$\text{EUAC}_{S1} = (0.08718)\ (\$12{,}190) + \$950 + \$1{,}806 + \$470$$

$$\text{EUAC}_{S1} = \$4{,}289/\text{yr}$$

Strengthening Method 2

Strengthening method 2 involves adding a pier at the midpoint of the span. The initial strengthening cost, to include traffic control measures, is estimated at D = \$26,767.

Projected Annual Maintenance Costs

An additional maintenance cost per year, because of increased waterway maintenance, is projected to be \$300/yr.

$$C_{AS} = \$950 + \$300 = \$1,250$$

Projected deck overlay required in 5 yr at \$5/ft^2:

$$F1 = \$7,200$$

The equivalent uniform annual cost of this disbursement is equivalent to \$470/yr, as shown in the calculation for Strengthening Method 1.

Level of Service Factor

Same as strengthening method 1: LS = \$1,806/yr.

EUAC for Strengthening Method 2

$$\text{EUAC}_{S2} = (A/P, 6, 20)\,(D) + C_{AS} + LS + (A/P, 6, 20)\left[\sum_{j=1}^{1} F_j\,(P/F, 6, n_j)\right]$$

$$\text{EUAC}_{S2} = (0.08718)\,(\$26,767) + \$1,250 + \$1,806 + \$470$$
$$\text{EUAC}_{S2} = \$5,860/\text{yr}$$

Comparison of Alternatives

$$\text{EUAC}_{S1} = \$4,289/\text{yr}$$
$$\text{EUAC}_{S2} = \$5,860/\text{yr}$$
$$\text{EUAC}_{R} = \$5,958/\text{yr}$$

Strengthening Method 1, providing the composite action, is the most cost-effective alternative.

SENSITIVITY ANALYSIS OF ECONOMIC MODEL

The results of a sensitivity analysis are presented to illustrate the effect of changing certain input variables used in determining EUACs. Replacement and strengthening EUACs were computed for a potential strengthening situation by using the variables previously introduced. The magnitudes of each input variable were varied, whereas all other variables were kept constant, and EUACs were then calculated.

The costs associated with the replacement structure are summarized as follows:

$$R = \$50,000$$
$$N = 50 \text{ yr}$$
$$i = 6 \text{ percent}$$
$$B = -\$4,000$$
$$S = -\$4,000$$
$$C_{AR} = \$300$$
$$(A/P, i, N)\left[\sum_{j=1}^{m} F_j\,(P/F, i, n_j)\right] = \$487$$
$$\text{EUAC}_R = \$3,960$$

The costs associated with strengthening the existing bridge are summarized below. It should be noted that the initial strengthening cost is one-half of the initial replacement cost.

$$D = \$25,000$$
$$C_{AS} = \$400$$
$$LS = \$1,073$$
$$N' = 20 \text{ yr}$$
$$(A/P, i, N')\left[\sum_{j=1}^{m} F_j\,(P/F, i, n_j)\right] = \$307$$
$$\text{EUAC}_S = \$3,960$$

Figure 5 illustrates the changes that occurred as each input variable was changed. For the replacement alternative, the magnitude of the effective interest rate chosen is clearly the most significant factor. A service life of 50 yr or more has little effect on the EUAC$_R$. For the strengthening alternative, the effective interest rate, remaining service life, and level of service factor can significantly affect the EUAC of strengthening.

SUMMARY AND CONCLUSIONS

Described in this paper is a useful analytical approach that has been developed for determining the cost effectiveness of various alternatives for strengthening or replacing an existing deficient bridge. The mathematical models developed for the analysis are based on engineering economy procedures and involve the determination of an equivalent uniform annual cost for each alternative.

The models can also be adapted to fit any bridge-strengthening situation, thereby allowing bridge owners the flexibility of including their own cost data in the analysis. The models form a necessary addition to bridge management systems, as an important final step in the decision-making process relating the cost effectiveness of bridge strengthening versus replacement.

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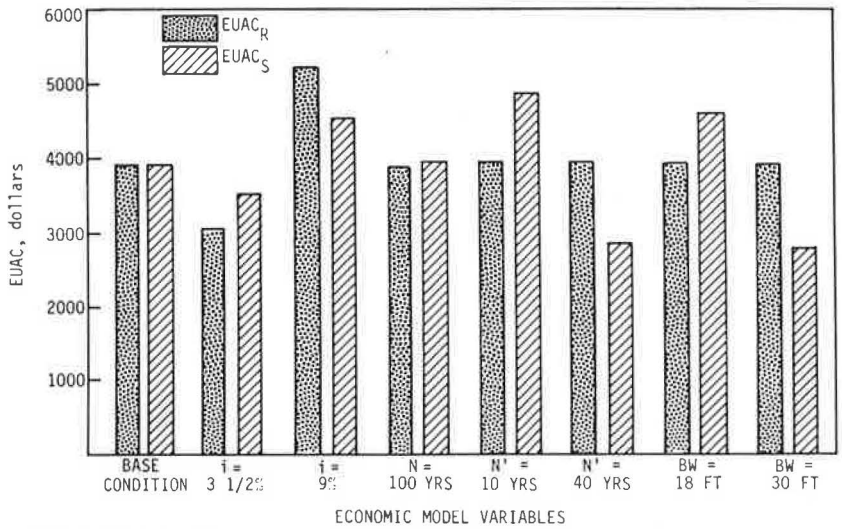

FIGURE 5 Results of sensitivity study indicating effects on EUAC by changing selected model variables.

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