application of maintainability and expected cost decision analysis to highway design

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There are many trade-offs between construction and maintenance of highways. Conventional engineering economy methods such as the benefit-cost ratio are sometimes used to compare these trade-offs. However, conventional methods often cannot incorporate all the factors that should influence a decision. Two techniques that can extend the capabilities of the conventional engineering economy analysis are maintainability and expected cost decision analysis. These techniques are not new. They have been applied to real problems in the fields of aerospace and business administration for several years. This paper urges that these techniques be used to analyze highway design trade-offs and illustrates their use with the aid of example problems. Maintainability and expected cost decision analysis allow the engineer to use a more systematic approach to certain types of design problems. Application of this approach would lead to better decisions in many situations involving trade-offs between construction and maintenance costs.

•In highway design, as in the design of any facility, there are always trade-offs between initial costs and future costs. The major future costs for a highway are maintenance costs and road user costs.

For any component of a highway, or for the overall highway itself, there are usually options available that offer the engineer the choice of either high initial cost and low maintenance costs or lower initial cost and higher maintenance costs. Road user costs are also affected by the design, and, here also, lower future costs usually must be paid for by higher initial costs.

It is sometimes claimed that there is no significant trade-off between construction costs and maintenance costs. Anyone who has maintained a gravel surface under heavy traffic and then compared the maintenance costs to those of maintaining the same traffic over an adequate pavement knows that there are trade-offs to be considered. This is an exaggerated example but there are less obvious examples in every highway design. Various membranes, seals, and treatments on bridge decks usually have no purpose other than to reduce future maintenance and replacement costs. The same can be said of galvanized or other corrosion-resistant materials.

Balancing these trade-offs is a necessary part of any highway design. The trade-offs are always made. They cannot be avoided. They are made whether the designer consciously considers them or not.

Because reductions in future maintenance costs are usually hard to estimate, the "seat of the pants" method is often used to make the trade-off decision. No cost comparison or formal analysis of costs is attempted. "Seat of the pants" decision-making is sometimes coupled with a strong temptation to design highways as maintenance free as possible. Because it is often possible to spend far more in construction than can ever be recovered in reduced maintenance costs, this may, and sometimes does, lead to extravagant waste of public funds.

Low maintenance is not a virtue in itself and should not be sought to the point where further reduction requires a disproportionate increase in construction cost. At the other extreme, various pressures to limit the cost of construction can result in uneconomical trade-offs if construction cost savings are small compared to the additional required maintenance costs.

Proper consideration of trade-offs involves comparing the costs of competing designs. A valid comparison requires that the costs that occur in different years be properly discounted through use of an appropriate interest rate. This is usually done for highway designs by the familiar benefit-cost method. A straightforward benefit-cost analysis (or other similar engineering economy technique) should probably be the basic method of analyzing the trade-off opportunities in highway design. However, conventional engineering economy studies often cannot incorporate all the factors that should influence a decision. Certain types of easily overlooked constraints and the effect of uncertainty are two such factors that are often missing in conventional analyses. Two techniques that can extend the capabilities of the conventional engineering economy analysis are maintainability and expected cost decision analysis. Use of these techniques could improve the analysis of many trade-offs found in highway design.

The objective of this paper is to show how these techniques can be used in highway design, and the paper is written for the practicing highway engineer. Examples of the application of these techniques have been made as simple as possible to better illustrate the methods involved. As a result of this objective and approach, the paper will probably not be of great interest to those already familiar with these and the more sophisticated methods of decision analysis.

APPLICATION OF MAINTAINABILITY

The concept of maintainability and most of the existing techniques based on this concept were developed in the electronics and aerospace fields. The systems developed in these fields, like highway systems, often require high operating and maintenance costs. As the electronics and aerospace systems became more complex, the problem of keeping these systems in operation became increasingly difficult. Problems with equipment failure and high maintenance cost became intolerable (1). This led to gradual change in the design philosophy.

The dominant objective of design had been to achieve high levels of performance when the system was functioning properly. This objective was gradually modified so that, in addition to concern about potential performance level, more emphasis was placed on questions relating to how often the system was going to function properly and how much effort would be required to keep it functioning.

Because the systems in question were complex, it was not usually apparent what effect various design options would have on behavior during service life. To answer these questions a variety of systematic methods were developed to assist the designer. Some of these methods are based on the concept of maintainability.

Definition of Concept

Maintainability is a built-in characteristic of the physical system. It can be defined as a measure of the effort needed to maintain the system. In actual application, maintainability is defined to be most compatible with the analyses being made (2).

The concept of maintainability provides a means of quantifying the expected future maintenance of a system and allows consideration of this maintenance at the design stage along with the more familiar design parameters of performance, reliability, and initial cost.

Maintainability can be used as a design parameter (a) to allow trade-off between future maintenance requirements and other design parameters in order to find the optimum design or (b) to specify a maximum acceptable maintenance effort that the system may require.

The annual maintenance costs for the life of the system can be considered a measure of maintainability. Thus, the use of estimated maintenance costs in a conventional benefit-cost ratio analysis is an example of the use of the maintainability concept. Highway engineers have been using this type of maintainability analysis for many years, under a different name.

The other use of maintainability as a means of specifying the maximum acceptable amount of maintenance may also be useful for highways. This is now done in the electronics and aerospace fields where the required maintainability is routinely specified by the Department of Defense and the National Aeronautics and Space Administration.

If one of the designs being considered for a highway involves a level or type of maintenance that is unrealistic to expect in practice, it should be rejected no matter how low the estimated total cost may be. If a strategy requires heavy maintenance that is not provided, premature failure of the road, high user costs, or both may result. This in turn may cause the actual total cost to be higher than it would be for alternative designs that required only realistic maintenance efforts. This type of situation can be avoided by considering any future limitations on maintenance at the design stage.

Limitations or constraints on the amount or type of maintenance that will be available are real problems in highway design. These constraints may stem from a variety of causes. Future maintenance budgets may be limited for administrative or political reasons; the maintenance organization may not be capable of performing certain types of operations for lack of equipment, materials, or training; or there may be an administrative or political decision to make low maintenance a goal in itself.

Example 1—Use of Maintainability as a Design Constraint

The following example will illustrate how a limitation on the future maintenance available to a system can be specified as a system requirement and how this may lead to improved decision-making.

The example problem involves the selection of a surface for a low-volume highway. Traffic demand, prices for labor, equipment, material, environmental conditions, and other factors needed to define the problem have been estimated. The design is to be selected on the basis of lowest annual cost subject to a minimum maintainability specification.

This maintainability specification is based on knowledge of the local government and its maintenance organization. It is unrealistic to expect that roads in the area will receive more surface maintenance than can be provided by $380 per mile (annual cost) for the analysis period. An arbitrary definition of maintainability, M, for use in this example might be

$$M = \frac{1}{MC} \times 10{,}000$$

where MC is the annual cost of maintenance. This gives an index of maintainability that increases as maintenance costs decrease. A minimum M of 26 is specified to stay within the expected maintenance constraint of $380 per mile (10,000 ÷ 380 = 26). Maintainability could also have been defined to equal the maintenance cost directly; we then would have specified a maximum limit.

A computer-based simulation model (3) was used to estimate the average costs of providing a surface for the road by a variety of designs. As a result of a series of runs the four surfaces given in Table 1 were selected as the most promising. The best of these four designs can be selected on the basis of lowest annual cost subject to our minimum maintainability constraint of 26. Design A (which specifies a well-maintained gravel surface) is eliminated from consideration because its expected M is less than the specified minimum. Of the remaining three designs, C, which specifies a bituminous surface treatment plus two additional seal coats during the analysis period, results in the lowest total annual cost. Although the expected maintainability of this strategy is above the specified minimum, it is very close to the limit. The degree of uncertainty in selecting the minimum required maintainability and in the accuracy of the model should be considered in the decision. If these estimates involve a high degree of uncertainty, as is likely, design D, which has a much higher maintainability, may be the best choice.

If the design for this project had been selected on the basis of minimum total cost, with no consideration given to the limit on future maintenance, design A would have been selected. But the limit on available maintenance would have resulted in a maintenance policy similar to that of design B. Actual user costs would also have been similar to those of design B, and the total costs of providing the system would have been greater than for either designs C or D.

This example illustrates how an anticipated constraint on future maintenance can be analytically specified as a design constraint by using the concept of maintainability, and how this can lead to a better decision. The construction, maintenance, and road user costs used in this example were estimated by the computer simulation model mentioned earlier. However, the principle involved (use of a maintainability constraint) is valid no matter how the costs are estimated. The problem of limited available maintenance is a reality in highway design. The concept of maintainability allows us to formally incorporate it into the design process.

APPLICATION OF EXPECTED COST DECISION ANALYSIS

In the usual economic analysis, estimated future costs are taken at face value and no allowance is made for the often highly uncertain nature of these estimates. The uncertain nature of the predicted costs should be considered in the decision process. Expected cost decision analysis is a method of incorporating this uncertainty into the analysis (4).

The expected cost (EC) of a situation that may have any one of n outcomes can be defined as

$$EC = \sum_{i=1}^{i=n} [p(X_i) \times V_i]$$

where

$p(X_i)$ = probability that the outcome will be X_i, and
V_i = cost of outcome X_i.

Table 1. Annual costs and maintainability index for various surface designs.

		Annual Cost (dollars/mile)				
No.	Design	Construction	Maintenance	User	Total	M
A	Gravel (1 blading per week)	2,580	610	3,460	6,650	16
B	Gravel (1 blading per 3 weeks)	2,580	320	5,320	8,220	32
C	Surface treatment (+2 seal coats)	4,050	340	2,660	7,050	25
D	Bituminous concrete (2 in.)	5,200	210	2,400	7,810	48

Figure 1. Basic decision tree for example 3.

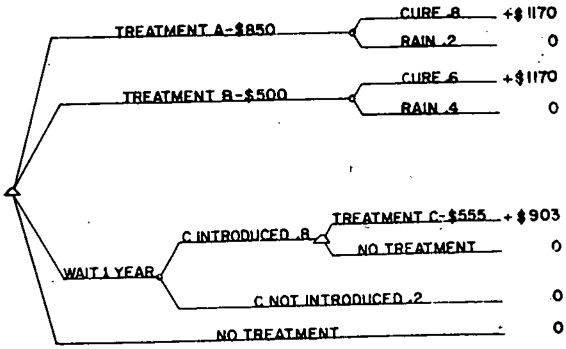
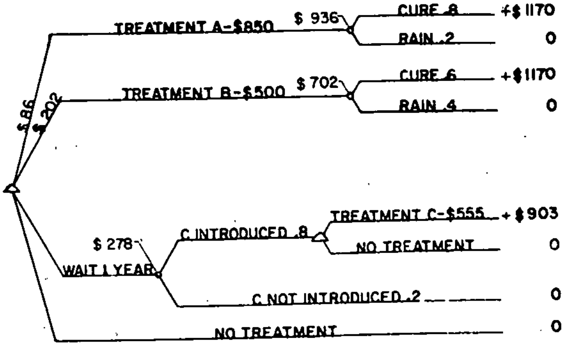
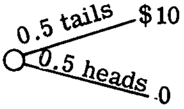


Figure 2. Completed decision tree for example 3.



To illustrate this concept, suppose a benevolent gambler offers to pay someone $10 if he gets tails and nothing if he gets heads on one flip of a coin. How much value has he really given away? Certainly not $10 because winning the $10 is not certain. But the offer is of some value. If we assume that there is a 0.5 probability of getting tails, the expected cost to the gambler is $5. The position the gambler has put himself in can be represented by a chance node with two branches.

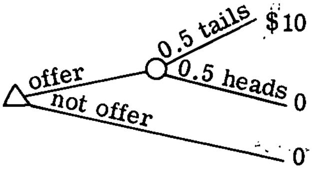


0.5 × $10 = $5

0.5 × 0 = 0

EC = $5

The gambler's choice of whether to offer the gift or not can be diagrammed in decision-tree form in which the decision nodes are marked with a △ and the chance nodes are marked with a ○.



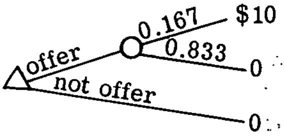
0.5 × $10 = $5

0.5 × 0 = 0

EC = $5

The decision-tree diagram is especially useful for systematically representing more complicated decisions.

Similarly an offer to pay $10 for rolling a six with one roll of a die has an expected cost of $1.67, inasmuch as the probability of success is one out of six or 0.167.



0.167 × $10 = $1.67

0.883 × 0 = 0

EC = $1.67

The following example will attempt to illustrate the use of expected cost in the analysis of a highway design trade-off.

Example 2—Use of Expected Cost in Trade-Off Analysis

Suppose that present efforts to develop a treatment for preventing ice from bonding to pavements are successful. The treatment consists of a chemical treatment of the pavement surface that costs $1,000 per lane-mile. The treatment has the proven ability to prevent bonding for 5 years if allowed to cure for 5 days without being rained on. If it rains within 5 days of application, the treatment will be of no value.

From a pilot test section it has been found that maintenance costs can be reduced by $285 per lane-mile if ice is prevented from bonding.

The benefit-cost ratio of a successful treatment can be computed, based on a 7 percent interest rate, as follows:

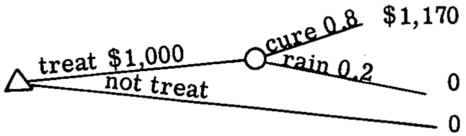
Present worth of cost = $1,000

Present worth of benefits = $285 × 4.10 = $1,170

$$\text{Benefit-cost ratio} = \frac{1,170}{1,000} = 1.2$$

The 4.10 is the present worth factor for 5 years and 7 percent interest. This indicates that the treatment is a good investment because the benefit-cost ratio is larger than one. However, this analysis was made on the basis of a successful treatment, and there is some danger that rain will ruin the treatment before it has a chance to cure.

Assume that the probability of a successful treatment is estimated from weather records to be 0.8. At a probability of success of 0.8, the expected present worth of the benefits is $936. Because this is less than the $1,000 present cost of the treatment, it is now obvious that the treatment is not a good gamble. The decision to treat or not to treat can be represented by the following decision tree.



$$0.8 \times \$1{,}170 = \$936$$

$$0.2 \times 0 = \underline{\quad 0}$$

$$EC = \$936$$

The benefit-cost ratio for this expected benefit is

$$\text{b-c} = \frac{936}{1{,}000} = 0.94$$

Because this ratio is smaller than 1.0, the expected cost analysis indicates that the treatment is not a good investment. Stated another way, the odds do not favor paying $1,000 for a treatment that will save $280 per year for 5 years at a probability of 0.8.

Use of expected cost analysis for more complicated problems requires finding the expected costs for all the available alternative designs and then selecting the design by an engineering economy comparison. This process is used in the following example.

Example 3

Assume that the engineer making the decision in example 2 has more than one available treatment for preventing ice from bonding. Potential treatments are as follows:

1. Treatment A is the same as treatment in example 2 except that the cost per lane-mile is reduced to $850;
2. Treatment B is similar to treatment A but costs $500 per lane-mile and requires a longer curing period without rain (probability of success = 0.6); and
3. Treatment C must be applied yearly at a cost of $175 per lane-mile and requires no curing period (probability of success = 1.0); this treatment is not now available but will be available next year maybe (probability of introduction next year = 0.8).

Treatments A and B are effective for 5 years. All three treatments are equally effective if successfully applied and save $285 per lane-mile per year. The engineer now has four alternatives:

1. Use treatment A,
2. Use treatment B,
3. Wait 1 year, and then use treatment C for the 4 remaining years in the analysis period, and
4. Use no treatment.

Because the probabilities of success and the costs are different for each alternative (as they always are in actual situations), it is not easy to pick the best alternative.

The problem can be represented by the decision tree shown in Figure 1. Although any one of the three treatments may reduce maintenance costs by $285 per year, treatment

C can reduce these costs only in years 2 through 5. Therefore, the present worth of the benefits shown at the end of that branch of the decision tree is smaller than for the other two treatments. Computations of present worths of costs and benefits were done from standard tables and will not be shown.

To select the best alternative by the expected cost method requires that each branch of the tree be evaluated by starting at the right end and working toward the left. Computations are similar to those shown in example 1. The results of these computations are shown on the completed decision tree in Figure 2.

The expected values of the four alternatives (branches) are as follows:

Treatment A
(0.8 × \$1,170 + 0.2 × 0) - \$850 = \$86

Treatment B
(0.6 × \$1,170 + 0.4 × 0) - 500 = \$202

Treatment C (at year 1)
(\$903 - \$555) × 0.8 + 0.2 × 0 = \$278

No Treatment 0

Treatment C can now be selected as the best of the alternatives on the basis of maximum present worth. Analysis by the benefit-cost method would lead to selection of the same alternative.

Estimates of future costs and benefits always involve some uncertainty. The degree of uncertainty should be considered in trade-off analysis. Expected cost decision analysis provides a simple technique for incorporating this uncertainty into the decision-making process in a quantitative way. Stated another way, expected cost decision analysis provides a technique for determining which choice in a trade-off decision has the best odds.

Thus, the decision does not depend entirely on point estimates of future costs and benefits but may also take into account the uncertainty of these estimates. In many trade-off situations, expected cost decision analysis will lead to a more rational decision than an analysis that ignores the inherent uncertainty of the cost estimates.

SUMMARY

Examples have been used to illustrate the application of maintainability and expected cost decision analysis to highway design problems. However, the chief value of these techniques involves their application to more complex problems in which it is not so obvious what effect constraints and uncertainties should have on the decision. Illustration of more complex applications is beyond the scope of this paper, but more complete discussion may be found in the references.

The techniques described allow the engineer to use a more systematic approach to certain types of design problems. Application of these techniques would lead to more rational decisions in many situations involving trade-offs between construction costs and maintenance costs.

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