COST-EFFECTIVENESS EVALUATION OF ROADSIDE SAFETY IMPROVEMENTS

King K. Mak

INTRODUCTION

In today's environment of ever increasing demand and decreasing resources, it is crucial to make sure that the best use is made of the limited funds available. Cost-effectiveness analysis is one such tool to assist the engineers to compare alternatives and to select the most cost-beneficial alternative. This presentation provides an overview on cost-effectiveness procedures for use in evaluating roadside safety improvements. The discussions are necessarily general and brief in nature. The intent is to provide some background information to the meeting participants on issues related to cost-effectiveness procedures and their role in the highway safety management system.

Over the last 25 years, roadside safety has seen major advances. A look at any recently constructed freeway would show the high level of roadside safety built into these highways. For new constructions with few constraints, e.g., choice of alignment, available right-of-way, sufficient funding, etc., cost-effectiveness analysis is probably of limited value. The design engineers can follow established guidelines and practices to attain a high level of safety. However, the challenge facing highway agencies today is not new construction, but maintaining and upgrading the existing physical plant. The bulk of the activities in the foreseeable future will be in the area of resurfacing, restoration, and rehabilitation (3R) and/or reconstruction (4R) type of projects. For 3R or 4R projects, the design engineers are faced with many existing constraints, such as poor geometrics and cross-sectional design, limited right-of-way, cluttered roadside, etc. Also, there are many instances in which the best design alternatives are not apparent or the specific situations are not covered under existing warrants or guidelines.

For example, consider a project to upgrade an existing two-lane highway with 22-foot pavement width to two 12-foot lanes with 10-foot shoulders. This would undoubtedly improve the safety of the travelway. On the other hand, this would reduce the width of the roadside available for the clear recovery area unless more right-of-way is purchased. The cost of purchasing the additional right-of-way would greatly increase the cost of the project, resulting in fewer projects to be accomplished under a given budget. Yet, without the additional right-of-way, it may be necessary to reduce the width of the clear recovery area use steeper sideslopes, or use guardrails extensively, which would be a detriment to roadside safety. These are difficult issues facing highway design engineers who are required to make such decisions on a routine basis.

Cost-effectiveness analysis provides the engineers with an objective and rational approach to evaluate design alternatives. The benefits and costs associated with each design alternative are quantified and compared to determine the most cost-effective alternative. This ability to assess the cost-effectiveness of design alternatives is unquestionably an important component of any highway/roadside safety management system. This paper reviews the cost-effectiveness approach and some of the existing procedures available for evaluating roadside design alternatives.

COST-EFFECTIVENESS ANALYSIS

As mentioned previously, the cost-effectiveness approach is an objective and rational means for assessing the relative merits of safety design alternatives. Cost-effectiveness analyses have been used in the following applications:

1. To formulate warrants, guidelines and policies, such as the 1989 American Association of State Highway and Transportation Officials (AASHTO) "Guide Specifications on Bridge Railings"(*1*) and the guidelines for pavement edge dropoffs in construction zones adopted by the Texas State Department of Highways and Public Transportation (SDHPT)(*2*);
2. To evaluate alternative site-specific designs, particularly where exceptions to design standards and guidelines are needed; and
3. To develop performance level selection criteria, such as the 1989 AASHTO "Guide Specifications on Bridge Railings"(*1*).

Most of the existing cost-effectiveness procedures are based on the concept of benefit/cost (B/C) analysis. The principle behind the benefit/cost analysis is that, for an improvement to be considered for implementation, benefits derived from the improvement must be greater than the costs associated with that improvement, i.e., a benefit/cost (B/C) ratio of greater than 1. In the case of

comparing design alternatives, choice among the alternatives can be made on the basis of incremental benefit/cost ratios, expressed as follows:

$$\text{B/C Ratio}_{2\text{-}1} = (B_2 - B_1)/(C_2 - C_1) \qquad (1)$$

where,

- B/C $\text{Ratio}_{2\text{-}1}$ = Incremental benefit/cost ratio between alternatives 1 and 2;
- B_1, B2 = Benefits associated with alternatives 1 and 2; and
- C_1, C_2 = Costs associated with alternatives 1 and 2.

Roadside safety cost-effectiveness procedures currently in use include: the cost-effectiveness procedure contained in the 1977 AASHTO Barrier Guide(*3*); the ROADSIDE program presented in the 1988 AASHTO "Roadside Design Guide"(*4*); the Benefit-Cost Analysis Program (BCAP)(*5*), and the TTI Benefit/Cost Program(*6*). All these cost-effectiveness procedures are based on the encroachment probability model, which is unique to roadside safety cost-effectiveness models.

An encroachment probability model is based on the concept that the ran-off-the-road accident frequency can be directly related to the encroachment frequency, i.e., the number of vehicles inadvertently leaving the traveled portion of the roadway. It is also assumed that the encroachment frequency is a function of roadway and traffic characteristics and the severity of ran-off-the-road accidents is related to encroachment characteristics, such as speed and angle of encroachment. The basic formulation of the encroachment model is expressed by the following equation:

$$E(C) = \sum_{i=1}^{n} P(E)*P(A|E)*P(I_i|A)*C(I_i) \qquad (2)$$

where,

- E(C) = Expected accident cost;
- P(E) = Probability of an encroachment;
- P(A|E) = Probability of an accident given an encroachment;
- $P(I_i|A)$ = Probability of injury, i, given an accident; and
- $C(I_i)$ = Cost associated with injury i.

There are three major components to the encroachment probability model:

1. An algorithm to predict the frequency of accidents;
2. An algorithm to predict the severity of accidents; and
3. A procedure to estimate accident costs and determine benefit/cost ratio.

Brief descriptions of each of these components are presented as follows.

Accident Frequency Prediction

The accident frequency prediction algorithm is based on the probability of an encroachment, P(E), and the probability of an accident given an encroachment, P(A|E). The model starts with a base or average encroachment rate. For example, the BCAP program uses a base encroachment rate of 0.0005 encroachments (to one side of the road) per mile per year per average daily traffic (ADT). Some models, such as the BCAP program, use a single base encroachment rate for all highway types while other models, such as the TTI Benefit/Cost program, use different base encroachment rates for the various highway types.

The base encroachment rate is then adjusted for specific site conditions, such as geometric and roadway cross-sectional characteristics. The rationale for these adjustment factors is that encroachment rates are affected by certain geometric and roadway cross-sectional characteristics and the base encroachment rates should be adjusted to account for these characteristics. For example, previous studies have found that vehicle encroachments are more likely on the outside of horizontal curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature.

The encroachment characteristics, such as speed and angle of encroachment, and the extent of lateral encroachment, are expressed in terms of probability distributions so that the probability for an errant vehicle to have certain combination of encroachment characteristics can be determined from these distributions. The probability and impact conditions of an errant vehicle impacting with a roadside object or feature are determined from the encroachment characteristics, after accounting for the trajectory of the vehicle subsequent to leaving the roadway. The trajectory of the vehicle refers to the path of the vehicle and driver inputs, such as braking and steering. The vehicle trajectory is also affected by roadside conditions, such as presence/absence of shoulder, shoulder width, roadside slope, lateral offset of roadside object or feature, etc.

The probability of an accident given an encroachment is estimated using an impact envelope, which is defined as the region along the roadway within which a vehicle leaving the travelway at a prescribed angle will impact the roadside object or feature. The impact envelope is a function of the encroachment angle and the physical dimensions and lateral offset of the roadside object or feature impacted. Another factor influencing the probability of an impact is the encroachment speed and the vehicle trajectory. Some vehicles may stop or recover and return to the roadway prior to impact with the roadside object or feature.

Accident Severity Prediction

The severity of an accident (i.e., probability of injury given an accident, $P(I|A)$) is a function of many factors, including impact conditions (i.e., impact speed, angle, and vehicle orientation), the size and weight of the impacting vehicle, and the nature of the impacted roadside object or feature. For a given roadside object or feature and impacting vehicle, the conditions under which the vehicle impacts the roadside object or feature, i.e., speed, angle and vehicle orientation, determine the outcome and severity of the accident. In the case of a roadside safety device, e.g., guardrail, crash cushion, etc., the performance limit of the safety device should also be taken into account. When the impact conditions exceed the performance limit of the safety device, some catastrophic outcome could occur and the severity of the impact is usually a function of the catastrophic outcome. For example, if the impact loading on a bridge railing is greater than its structural capacity, the impacting vehicle would penetrate the bridge railing and fall into the river below. The severity of the accident is determined by not only the impact with the bridge railing, but also by the fall of the vehicle into the river.

Accident severity is typically expressed in terms of a severity index, which is a surrogate measure for injury probability and severity. The severity indices are developed from various sources, including accident data, simulation and full-scale test results, and in some instances, subjective judgement.

Cost Estimation and Benefit/Cost Ratio Determination

Benefits derived from a safety improvement are measured in terms of reduced accident frequency and/or severity. Costs associated with a safety improvement include increases in the cost for initial installation, normal maintenance, and repair of damages from accidents. Computation of the incremental benefit/cost ratios is very straightforward once the benefits and costs are determined.

The accident severity, expressed in terms of a severity index, is then converted to societal or accident costs based on some pre-selected cost figures, C(I). Most states currently use cost figures developed by the National Safety Council (NSC). However, the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA) and the NSC have all endorsed the use of the comprehensive cost figures for cost-benefit analyses. The comprehensive cost figures are based on the concept of willingness to pay and are substantially higher than the NSC cost figures.

Existing Cost-Effectiveness Procedures

As mentioned previously, roadside safety cost-effectiveness procedures currently in use include: the cost-effectiveness procedure contained in the 1977 AASHTO Barrier Guide(*3*); the ROADSIDE program presented in the 1988 AASHTO "Roadside Design Guide"(*4*); the Benefit-Cost Analysis Program (BCAP)(*5*), and the TTI Benefit/Cost Program(*6*). Brief descriptions of these procedures are presented as follows.

The cost-effectiveness procedure contained in the 1977 AASHTO Barrier Guide(*3*) is one of the earlier encroachment probability models. This procedure incorporates the fundamental encroachment probability model with many simplifying assumptions, which limit its applicability. For example, the model does not take into account the shielding of hazards from one another. In other words, a hazard placed behind a barrier could still be impacted by an errant vehicle. Also, the model cannot distinguish between impacts with tangent and flared barrier sections so that the effects of a flared barrier section on impact frequency and severity are ignored. Furthermore, the average impact severity used for the hazards are now considered somewhat excessive.

The ROADSIDE program, mentioned in the 1988 AASHTO "Roadside Design Guide",(*4*) is similar to the procedure contained in the 1977 AASHTO Barrier Guide. The biggest improvement of the ROADSIDE program over the previous procedure is the method for specifying accident severity. The program provides improved severity indices and allows users to input different severity indices for the upstream ends of hazards, e.g., an end terminal for a barrier. The program also incorporates different average encroachment angles based upon the design speed. While the ROADSIDE

program has a few enhancements over the procedure contained in the 1977 AASHTO Barrier Guide, it shares many of the same limitations. Also, users have experienced difficulties in using the program due to the lack of a user-friendly interface, and some have found the results to be questionable.

The Benefit-Cost Analysis Program (BCAP),(*5*) used in the development of the performance level selection table in the 1989 AASHTO Guide Specifications for Bridge Railings,(*1*) is a sophisticated encroachment probability model that is capable of analyzing virtually any roadside safety problem. The program incorporates a fine distribution of vehicles, impact speeds, and impact angles in an attempt to accurately calculate the severity of predicted accidents. This procedure is ideally suited for development of warrants and guidelines for safety appurtenance implementation. The program also incorporates a sophisticated hazard imaging procedure which allows the program to analyze barrier runout lengths and flare rates. However, the recently completed validation effort on the program under National Cooperative Highway Research Program (NCHRP) Project 22-8(*7*) has identified significant problems with the recommended barrier performance limits and the algorithm for predicting rollover during barrier impacts. Further, the program's assumed distributions of encroachment speed and angle are also questionable.

The TTI Benefit/Cost program is another sophisticated encroachment probability model (*6*). This program, a forerunner of the BCAP model, has undergone significant improvements and validation. Primary differences between the BCAP and the TTI Benefit/Cost models include: the barrier penetration algorithm, the impact speed and angle distributions, and the lateral extent of encroachment distributions. This program has been used extensively in recent years for a number of different applications, including development of warrants for replacement of outdated small sign supports, barrier flare rates, and safety treatment of utility poles.

NCHRP Project 22-9(*8*), is currently developing improved cost-effectiveness procedures for analyzing roadside safety features. It is anticipated that the new procedures will be based on the encroachment probability model with enhanced features and better validation over the existing cost-effectiveness models. Also, a study(*9*) was recently completed for the FHWA to identify gaps in the state-of-the-knowledge for improving the cost-effectiveness procedure to be developed under NCHRP Project 22-9.

Comparison Between Encroachment Probability Model and Accident Data Based Model

One continuing area of discussion is the use of encroachment probability models versus accident data based models as the means to predict accident frequency. Accident data based models use historical data from reported accidents to develop multiple regression models for predicting roadside accident frequencies as a function of roadway and roadside characteristics. The appeal of an accident data based model is that accident frequencies are predicted directly as opposed to the indirect approach used with the encroachment probability model.

Accident data based models are generally specific in nature and of little use for other safety features and appurtenances. For example, a model developed to predict the frequencies of utility pole accidents would be of no use for predicting guardrail accidents. Findings of most accident data based studies are often questioned because of the poor quality of police level accident data and problems associated with the regression technique. Problems associated with police level accident data include: inaccurate and imprecise location coding of accidents, incorrect use of nomenclature, lack of detailed information, unreported accidents, etc.(*10*)

There are also inherent problems associated with the regression technique and many of the models were developed improperly. The number of variables that can realistically be included in a model is very small, e.g., 5 or less, when compared to the large number of roadside and roadway variables that could influence roadside accidents. The predictability of the models are at best marginal. Even the best multiple regression model can explain only 60 percent of the variation in accident frequencies with traffic volume accounting for most of the variations. The poor predictability of the models is to be expected given that accidents are extremely rare and random events. Further, over 80 percent of accidents are caused by driver errors while roadway and roadside elements account for less than 20 percent of the accident causative factors.

As mentioned previously, most of the existing cost-effectiveness procedures are based on the encroachment probability model. The primary advantage of encroachment probability models over accident data based model is the versatility of the approach. Unlike accident data based models, one encroachment model can be used to predict accident frequencies for a wide variety of roadside objects and features as well as different traffic and roadside conditions. The encroachment model is not based on historical data and is the only method of predicting accident frequency for

newly constructed or reconstructed roadways and for unusual hazards that are not commonly found along roadsides. Another application in which the encroachment probability model is used instead of accident data based model is the evaluation of multiple performance levels for roadside safety devices. Existing accident records are inappropriate since virtually all existing roadside safety appurtenances are designed to a single performance level. Even after the roadside hardware with different performance levels are deployed, police level accident data will not provide the level of detail needed to distinguish among the various performance levels.

Another advantage of the encroachment probability model is the greater level of detail that can be included in the model, such as different traffic and roadside conditions. Also, the encroachment probability model provides information on impact conditions which allows for better prediction of accident severity. In comparison, accident based models use average severity and typically do not account for impact conditions and other factors. The encroachment probability model is not without its problems. One of the major weakness with encroachment probability model is the limitations of the encroachment frequency data. Most encroachment frequency data were collected from observing tire tracks along the roadside left by encroaching vehicles. There is no means to determine whether the sets of tire tracks were left by vehicles encroaching in a controlled or uncontrolled manner. On roadways with paved shoulders, vehicles that encroached within the shoulder area do not leave any tire tracks. Also, there may be built-in biases in the encroachment data due to the weather and surface conditions of the highways during the data collection periods.

Other problems associated with encroachment probability models include difficulties in obtaining information regarding encroachment characteristics, such as encroachment speed and angle distributions, distributions of lateral vehicle movement, distribution of sizes of encroaching vehicles, and the attitude of encroaching vehicles. Numerous assumptions were made in formulating the algorithms built into the encroachment probability model. Due to the complexity of the encroachment probability model, it is very difficult to thoroughly validate the model.

SUMMARY

This paper provides an overview on the use of cost-effectiveness analysis in the evaluation of roadside safety improvements. The major components of a cost-effectiveness procedure are outlined and discussed briefly. An overview of various existing cost-effectiveness procedures is presented. Also, a brief discussion is presented on the pros and cons of encroachment probability models versus accident data based models.

REFERENCES

1. *Guide Specifications for Bridge Railings*, American Association of State Highway and Transportation Officials, Washington, D. C., 1989.
2. Ivey, D. L., and Mak, K. K., *Assuring Appropriate Levels of Safety in Construction Zones where Pavement Edge Dropoffs Exist*, Policy Development Report 0130-1, prepared for the Texas State Department of Highways and Public Transportation, Austin, Texas, November 1986.
3. *Guide for Selecting, Locating, and Designing Traffic Barriers*, American Association of State Highway and Transportation Officials, Washington, D. C., 1977.
4. *Roadside Design Guide*, American Association of State Highway and Transportation Officials, Washington, D. C., October 1988.
5. *Benefit to Cost Analysis Program, Volumes 1-3*, Federal Highway Administration, U. S. Department of Transportation, Washington, D. C., 1988.
6. Sicking, D. L., and Ross, H. E., *Benefit-Cost Analysis of Roadside Safety Alternatives*, Transportation Research Record No. 1065, Transportation Research Board, Washington, D. C., 1986
7. *Evaluation of Performance Level Selection Criteria for Bridge Railings*, NCHRP Project 22-8, recently completed study conducted by Texas Transportation Institute, Texas A&M University System, College Station, Texas.
8. *Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features*, NCHRP Project 22-9, ongoing study conducted by Texas Transportation Institute, Texas A&M University System, College Station, Texas.
9. Mak, K. K., and Sicking, D. L., *Development of Roadside Safety Data Collection Plan*, Final report on FHWA Contract No. DTFH61-90-C-00040, Texas Transportation Institute, Texas A&M University System, College Station, Texas, December 1992.
10. Mak, K. K., *Problems Associated with Police-Level Accident Data in Evaluation of Roadside Appurtenance Performance*, Transportation Research Circular No. 256, Transportation Research Board, Washington, D. C., 1983.