METHODS FOR ANALYZING THE COST-EFFECTIVENESS OF ROADSIDE SAFETY FEATURES

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Highway agencies are continually faced with decisions relating to roadside safety, from the use and selection of specific roadside safety features and appurtenances at specific locations to the development of warrants, policies, and guidelines on a system-wide basis. 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 provides a logical and systematic approach to these decisions, from comparing alternatives and selecting the most cost-beneficial alternative to the development of warrants, policies, and guidelines.

This presentation provides brief descriptions of various existing cost-effectiveness analysis procedures and how the procedures are used in actual applications, followed by an overview of the cost-effectiveness analysis methodology. Some future research needs to improve on existing cost-effectiveness analysis procedures are then suggested as a starting point for discussions in the breakout group sessions.

OVERVIEW OF COST-EFFECTIVENESS ANALYSIS

Most existing cost-effectiveness (C/E) analysis procedures are based on the benefit/cost (B/C) methodology and the two terms, cost-effectiveness and benefit/cost analysis, are often used interchangeably. The basic concept behind the benefit/cost analysis is that public funds should be invested only in projects where the expected benefits would exceed the expected direct costs of the project. Benefits are measured in terms of reductions in accident or societal costs from decreases in the frequency or severity of accidents. Direct highway agency costs are comprised of initial installation, maintenance, and accident repair costs. An incremental benefit/cost ratio between the additional benefits and costs associated with an improvement option over the existing conditions or another improvement option is normally used as the primary measure of whether or not a safety improvement investment is appropriate. The formulation of the incremental benefit/cost ratio is expressed as follows:

$$B/CRatio_{2-1} = \frac{B_2 - B_1}{C_2 - C_1} \qquad (1)$$

where

BC_{2-1} = Incremental B/C ratio of alternative 2 compared with alternative 1
B_1, B_2 = Annualized accident or societal cost of alternatives 1 and 2
C_1, C_2 = Annualized direct cost of alternative 1 and 2

When the incremental benefit/cost ratio is greater than 1, the analysis indicates that, comparing safety improvement alternative 2 to alternative 1, the benefits of alternative 2 are greater than the increased costs associated with that improvement.

A variety of cost-effectiveness analysis procedures have been developed over the years. These procedures can be classified as either encroachment probability based or accident data based models. Brief discussions on these two types of cost-effectiveness analysis procedures are outlined below.

ENCROACHMENT PROBABILITY BASED PROCEDURES

All encroachment probability based cost-effectiveness procedures are predicated on the concept that run-off-road accident frequency can be linked to roadside encroachment frequency through a probability model. McFarland and Ross(1) developed the first encroachment probability model to estimate the frequency of luminaire impacts. The authors proposed most of the major components of modern encroachment probability models. However, due to data limitations, this early model was somewhat simplistic in that all vehicles were assumed to encroach onto the roadside at the same speed and angle. Further, the model was developed for the specific purpose of predicting impacts with point hazards and therefore was not general in nature. Glennon(2)generalized and refined this procedure for application to any run-off-road situation.

The first cost-effectiveness procedure to be widely used by practicing engineers was published in the 1977

AASHTO *Guide for Designing, Selecting, and Locating Traffic Barriers*.(3) This model was very similar to previous procedures in that it assumed constant encroachment angles and speeds. Accident severity estimations were based on the collective judgement of a panel of highway safety experts. Although the survey requested information regarding average severity, most respondents envisioned high speed impacts when assigning the severity. Thus, resultant severity for most hazards was very high. The 1977 AASHTO Barrier Guide procedure was originally presented in a graphical format, but many highway agencies developed computer programs to simplify its use.(4) Major limitations associated with this procedure include overestimated impact severity, high encroachment frequencies, and a cumbersome analysis procedure.

Many of these problems were addressed in a comprehensive benefit/cost model, called ABC, developed by the Texas Transportation Institute.(5) Specific improvements included a hazard imaging system, velocity-dependent accident severity, real-world impact conditions, and a distribution of vehicle sizes. The hazard imaging system was designed to consider the effect of one hazard shielding another so that the program could properly evaluate the effectiveness of shielding hazards with barriers. Before this technique was implemented, every guardrail, regardless of length, was assumed to eliminate all accidents involving the shielded hazard.

The TTI ABC program also linked accident severity to impact speed and angle. Accident severity for specific impact conditions was estimated using data from full-scale crash tests and computer simulation. Distributions of impact speed and angle were identified from computerized reconstructions of real-world accidents. A distribution of vehicle sizes was also incorporated into the TTI ABC program in an effort to further refine severity estimates. This approach linked safety hardware performance to both vehicle size and accident severity. In this manner, performance limits of barriers or crash cushions were predicted based on vehicle size, impact speed, and impact angle and accident severity estimates were then revised when the performance limit was exceeded.

The TTI ABC program resolved many of the problems associated with previous benefit/cost analysis procedures, including the ability to study the effects of different barrier configurations and parameters, such as runout length and flare rate. However, due to the lack of a user friendly interface and proper distribution, the program never gained wide acceptance. Another problem associated with this program is the relatively coarse speed, angle, and vehicle size distributions used in the model. This limitation prevented the program from identifying small geometric differences between two guardrail treatment alternatives.

The Federal Highway Administration (FHWA) revised the TTI ABC program to develop the Benefit Cost Analysis Program (BCAP).(6) The BCAP program incorporated several unique features, including an algorithm to allow encroaching vehicles to decelerate after leaving the road, acceleration-based accident severity estimates, and refined vehicle type and encroachment speed and angle distributions. The BCAP program's encroachment model assumed that all vehicles would decelerate at a constant rate after encroaching into the roadside. The program also incorporated procedures for predicting the average lateral accelerations during longitudinal barrier impacts and using them to predict accident severity. One area of the program that was significantly improved over previous procedures was the refinement of the encroachment speed and angle and vehicle size distributions. This refinement eliminated some of the inconsistencies observed with the TTI ABC program.

Although the BCAP program was distributed with an ostensibly user friendly preprocessor, the user interface was so cumbersome and difficult to use that most users found it worse than conventional batch processing. A comprehensive review of the BCAP program recently identified several problems with the code that caused the program to overpredict the numbers of barrier penetrations and underestimate vehicle rollovers.(7) Also, the distributions of encroachment speed, angle, and lateral extent of encroachment were found to be somewhat different than those found in encroachment and accident studies.

The FHWA developed the ROADSIDE program, which is included as an Appendix to the 1988 AASHTO *Roadside Design Guide*(8), in an effort to provide highway agencies with a simplified cost-effectiveness analysis procedure that did not require as much input data as the more sophisticated BCAP program. The ROADSIDE program is a simplified version of the BCAP program and retained many of the basic features. Unfortunately, the ROADSIDE program did not retain the encroachment speed and angle distributions nor the algorithm for predicting impact conditions contained in the BCAP program. Instead, average impact severity was used in the same manner as the procedures contained in the 1977 AASHTO Barrier Guide. These simplifications severely limited the usefulness of the program since it could no longer predict when the performance limits of safety hardware were exceeded. Also, the impact severity had to be estimated from police level accident data or engineering judgement. Sensitivity analyses on the TTI ABC and BCAP programs demonstrated that benefit/cost analysis procedures are most sensitive to impact severity estimates. Thus, the accuracy of the ROADSIDE program is greatly diminished due to the relatively crude impact severity estimation algorithms.

An effort to develop improved cost-effectiveness analysis procedures is currently underway in NCHRP Project 22-9 conducted by TTI.(9) The procedures will be based on the encroachment probability model and will include the best features from the existing procedures plus new additions and improvements.

ACCIDENT DATA BASED PROCEDURES

Benefit/cost analysis procedures based on accident data utilize statistical models developed from analysis of police level accident data to predict accident frequencies and severity. These procedures fall into two general categories: site specific and feature specific models. Site specific techniques utilize the accident history at a specific site to predict future accident occurrences.(10) The basic approach is to use statewide accident data bases to determine average severity of various types of roadside accidents and accident reduction factors for different safety treatment options. The benefits of an accident countermeasure are merely differences in the historical accident costs and the expected future accident costs associated with a proposed safety improvement. These procedures are widely used to evaluate safety improvements on existing highways, especially in hazard elimination programs. The primary advantage of this technique is that the accident experience pertains to the specific site and includes the effects of the specific roadway and roadside features. Unfortunately, these techniques often rely on a very limited number of accidents and therefore their accuracy is sometimes questioned. However, these procedures continue to be the most appropriate means of identifying accident loss reductions that can be expected from roadside safety improvements at sites where significant accident history is available.

Benefit/cost analysis procedures based on feature-specific accident data are generated through statistical models developed from analysis of large accident data bases. These data bases must contain a great deal of roadway and roadside information so that the resulting accident prediction models can include such important variables as traffic volume, highway alignment, and hazard size and location. Police level accident records do not contain all of this information and therefore must be supplemented with roadway inventory data and/or information collected from field investigations. Unfortunately, roadway inventory files maintained by highway agencies seldom contain information concerning the roadside such as sideslope, or type, quantity and characteristics of roadside hazards and features. Thus, field investigations are often necessary to obtain the data required for analysis.

Accident data based accident prediction algorithms involve correlating roadway and roadside conditions with the observed accident frequencies using some form of regression analysis techniques. One of the major problems with police level accident data is the extent of unreported accidents, i.e., accidents that are not reported to law enforcement agencies for whatever reasons. Some roadside features, such as breakaway sign and luminaire supports, have a very high incidence of unreported accidents while other hazards, such as utility poles, have a relatively low rate of unreported accidents. As a result, accident prediction algorithms must be developed separately for each roadside hazard or feature type. This greatly complicates the process of developing general accident prediction routines necessary for a benefit/cost analysis model used to evaluate roadside safety improvements.

Other problems associated with police level accident data include inaccurate and improper coding by the reporting officers, incorrect use of nomenclature, lack of detail on the reported variables, and inaccurate location coding of accidents.(11) The poor quality of police level accident data oftentimes raises questions about the accuracy and validity of the results from accident data based studies.

The extreme variability in accident rates and the large numbers of highway variables that could potentially affect run-off-road accident frequencies also presents major problems when developing accident prediction algorithms. Run-off-road accident rates are affected by a large number of factors, many of which are unrelated to roadway, roadside, and traffic conditions and cannot be properly considered in an accident data regression analysis, such as driver demographics, drinking establishment locations, and economic vitality of the local economy. As a result, even the best accident data based prediction models could seldom explain more than 50 percent of the variations in accident frequencies or rates based on roadway, roadside and traffic variables. Exposure, or the opportunities for an accident to occur, accounts for most of this correlation obtained in the regressions equations. When the effect of exposure is taken into account, such as using accident rate (i.e., accidents per million vehicle miles of travel) as the dependent variable, the resulting prediction models generally explain less than 25 percent of the observed variations.

Further, the number of roadway, roadside, or traffic variables that are found in regression models to have a significant effect on accident frequency or rate is typically very small, e.g., 5 or less, and most of these variables are exposure related. Beyond this handful of significant variables, the other variables would have very little effect on accident frequency or rate and are statistically insignificant. Variables of interest are oftentimes forced into the regression equations even though they are not significant in order to be included in the model. For example, in a major study to develop procedures for predicting utility pole accident frequency, the researchers found that only traffic volume, pole density, and pole offset had any significant effect on utility pole accident frequency.(12) Note that all of these variables are closely related to exposure. Traffic volume and pole density are the two variables that control the number of times that a vehicle passes by a utility pole and has the opportunity for an accident. Pole offset can also be considered an exposure factor since it strongly effects the chances that an errant vehicle will encroach far enough onto the roadside to cause an accident.

A computer program, called UPACE, was developed based on this accident prediction model to help engineers determine when utility pole countermeasures should be taken. The program has gained some distribution, but has not been widely implemented. The specificity of the program has tended to limit its usefulness. Most highway engineers do not encounter a utility pole safety analysis with enough regularity to develop a widespread interest in this code.

Another effort to develop accident data based prediction procedures involved an investigation of the effects of cross-sectional design parameters on accident rates.(13) Regression equations were developed relating accident frequencies and rate to various roadway and roadside parameters, such as lane width, shoulder width, traffic volume, roadside recovery distance, type of terrain, and roadside sideslopes. Note that roadside hazards and features were classified only in terms of a general hazard rating, with no specificity regarding the type or density of hazards or features. Accident reduction factors were derived from the regression models which may be used as inputs to benefit/cost analysis. The predictive power of the regression models is generally limited and some of the included parameters were apparently forced into the models with little statistical significance. Findings from this study would not be directly applicable to most roadside countermeasure evaluations.

APPLICATIONS OF COST-EFFECTIVENESS PROCEDURES

Cost-effectiveness analysis procedures are used for three general purposes, evaluation of safety improvements at a specific site, development of warrants, policies and guidelines, and establishment of multiple performance level selection guidelines. Both accident data based and encroachment probability based procedures are used to evaluate countermeasure effectiveness at specific sites. Many state highway agencies require a benefit/cost analysis of all projects to be funded using safety funds. Thus, these procedures are widely used. Accident data based procedures are believed to be the better approach for predicting future accident frequency provided sufficient accident data are available during which the roadway geometrics and traffic patterns were not changed significantly. As discussed previously, these procedures are based on the assumption that the accident experience will remain unchanged in the future.

It is sometimes appropriate to utilize encroachment probability based accident procedures even when the historical accident record indicates no accidents at that site. When very severe hazards are located close to the roadway, safety treatments can be justified even though a reported accident may only occur infrequently. Thus, some states use encroachment probability based analyses even when historical accident data is available.

Historical accident data are no longer meaningful when major changes occurred to highway geometrics or traffic patterns. For example, run-off-road accident frequencies would be expected to change significantly when a highway is realigned to straighten sharp curves. In this case, highway engineers can no longer evaluate roadside safety treatment options with an accident data based procedure since the conditions have changed significantly to render the historical accident pattern inappropriate. An encroachment probability based procedure would be the choice even though the procedure cannot accurately evaluate all of the local conditions at a specific site. The encroachment probability based procedure should be capable of predicting average accident frequencies for all sites similar to the one under consideration. Although the model would be expected to be in error for specific sites, it should select the appropriate safety treatment for the average site. Prior analysis of encroachment probability based models indicates that they are most sensitive to accident severity estimates and only moderately sensitive to accident frequency estimates.(7,14) Therefore, inaccuracies in the prediction of accident frequencies would have much less effect on the validity of the analysis results provided the severity estimates are appropriate.

As mentioned previously, accident data based prediction models are very specific in nature and cannot be readily extended for use with other roadside features. Thus, encroachment probability based models are currently the only available alternative for development of general use guidelines for roadside safety hardware. Development of safety improvement implementation guidelines involves conducting cost-effectiveness analysis of a limited number of typical roadside sites. The study sites are selected to be representative of common highway situations on various highway classes. A large number of runs are then conducted while varying pertinent highway and roadside parameters. The conditions under which a safety improvement is warranted can then be tabulated or graphed for all traffic and roadway conditions investigated.

Encroachment probability based cost-effectiveness procedures have been used to develop guidelines for the implementation of a number of roadside safety features. The 1989 AASHTO *Guide Specifications for Bridge Railings* is probably the most widely distributed of these efforts.(15) This research involved conducting a cost-effectiveness analysis of three different bridge rail performance levels for three different types of highways (four or more lane divided, two-lane undivided, and one-way). The analysis was used to determine the most cost-beneficial bridge railings on each highway type for a variety of highway design speeds, vehicle mix (percent truck), and bridge rail offsets. This information was then tabulated to form the bridge rail selection tables contained in the Guide Specifications. This process can again be expected to be most sensitive to accident severity assigned to various safety treatment alternatives.

In a survey of users of cost-effectiveness analysis procedures(9), including personnel from FHWA, state highway agencies, and research organizations, the most commonly used cost-effectiveness procedures are the 1977 AASHTO Barrier Guide and the ROADSIDE program. There was no specific mention of any of the accident data based procedures. Very few people are familiar with the BCAP program and it appears that the only major application of the program is in the development of the selection guidelines contained in the 1989 AASHTO *Guide Specifications for Bridge Railings*. The ABC program was used in a number of studies, but its use was limited to only work conducted by the Texas Transportation Institute.

COST-EFFECTIVENESS ANALYSIS METHODOLOGY

This section provides an overview on the encroachment probability based cost-effectiveness analysis methodology. The encroachment probability model is unique to roadside safety cost-effectiveness procedures. It 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, which is a function of roadway and traffic characteristics and that the severity of ran-off-the-road accidents is related to encroachment characteristics, such as the 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 severity i, given an accident

$C(I_i)$ = Cost associated with injury severity i

n = Number of injury severity levels

Figure 1 shows a schematic of the key modules and data parameters of the encroachment probability model based cost-effectiveness analysis procedure. As shown in Figure 1 (Overview of Encroachment Probability-Based Cost-Effectiveness Analysis Procedure), there are four major modules to the procedure:

1. Encroachment module,
2. Accident prediction module,

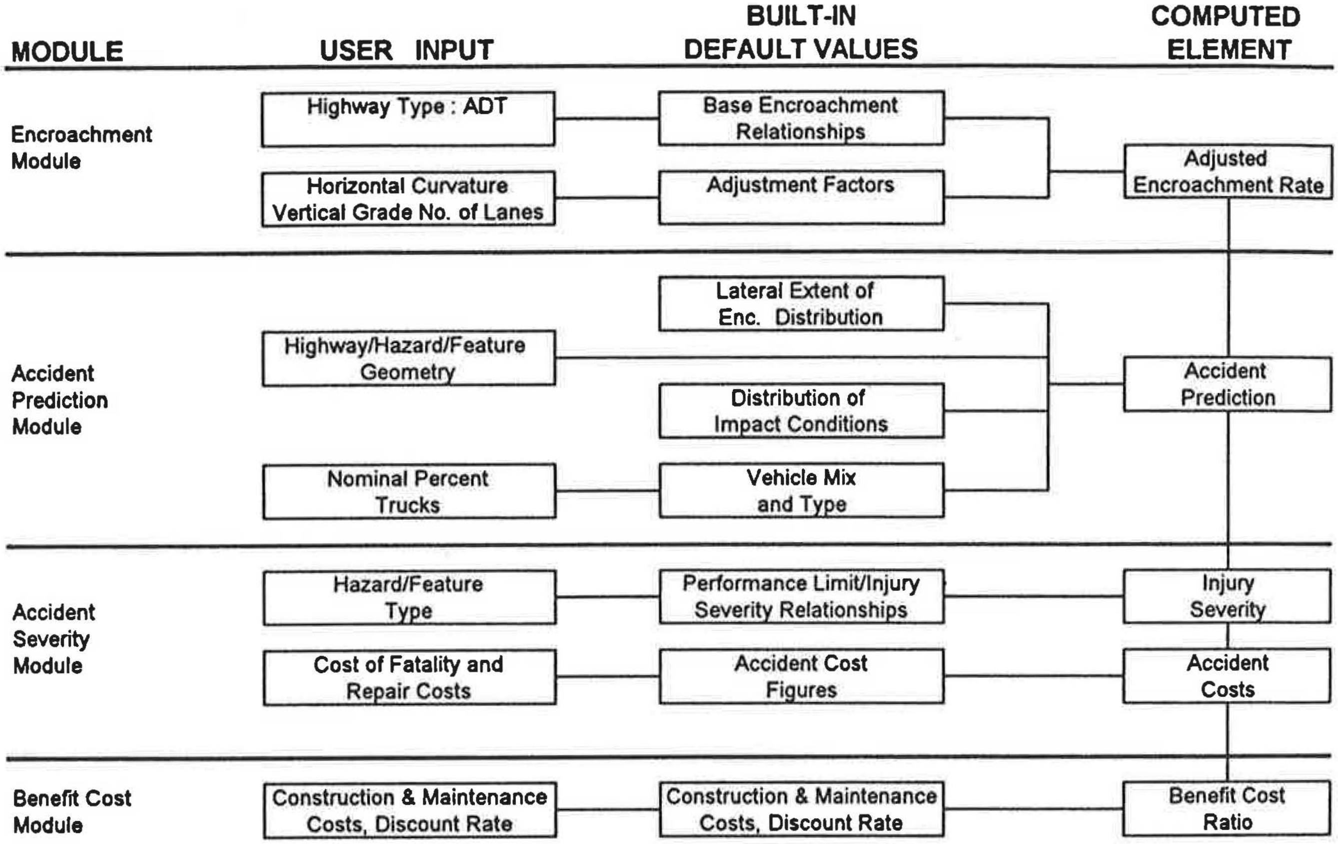

FIGURE 1 Overview of encroachment probability-based cost-effectiveness analysis procedure.

3. Accident severity module, and
4. Benefit cost module.

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

Encroachment Module

The encroachment module, a flowchart of which is shown in Figure 2 (Flowchart of Encroachment Module), utilizes roadway and traffic information to estimate the expected encroachment frequency along any highway segment, P(E). A two-step process is used to estimate encroachment frequencies. The first step involves using basic highway type and traffic volumes inputs by the user to estimate a base encroachment frequency. The encroachment frequency-traffic volume relationships are established from available encroachment data.

There have been three previous efforts in collecting encroachment data: Hutchinson and Kennedy, Cooper, and Calcote(16-18). The first study of roadside encroachments was conducted by Hutchinson and Kennedy in the mid-1960's.(16) This research involved periodic observations of wheel tracks on snow covered medians on rural interstate highways. One major drawback of this study is that the researchers could not distinguish between controlled and uncontrolled, i.e., intentional and unintentional, encroachments. Although snow in the median is believed to be a significant deterrent to drivers intentionally leaving the roadway, some of the wheel tracks were undoubtedly from controlled excursions onto the roadside that would never have resulted in accidents. Overrepresentation of adverse weather conditions and the 70 mph (112.7 km/h) speed limit on rural interstate highways at that time would also have increased the observed encroachment frequencies. Thus, the encroachment frequency data from this study, as shown in Figure 3 (Encroachment Frequency Data), should only be considered as an upper bound. Also, the data were collected on sections of highways that are relatively straight and flat. Insufficient data were collected in this study on horizontal and vertical curves or grades to determine the potential effects of these elements on encroachment frequency.

A more comprehensive study of roadside encroachments was undertaken in Canada by Cooper

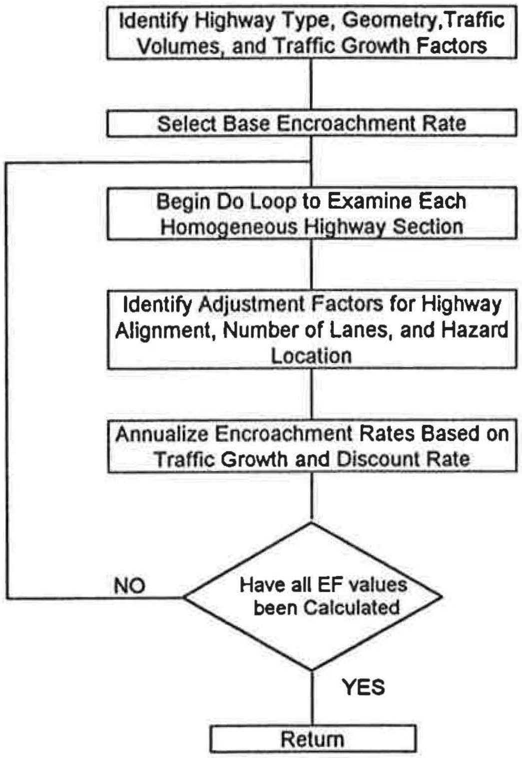

FIGURE 2 Flow chart of encroachment module.

during the late 1970's.(17) This study involved weekly observations of wheel tracks on grass-covered roadsides of rural highways. All of the encroachment data were collected during the summer months on highways with speed limits in the 50 to 60 mph (80.5 to 96.6 km/h) range. Thus, adverse weather conditions were underrepresented in this study and the speed limits were slightly lower than the 55 to 65 mph (88.6 to 104.7 km/h) range currently used in this country. This study also suffers from the inability to distinguish controlled from uncontrolled encroachments. Further, the grassy areas in the roadsides were occasionally used by farm equipment and other slow-moving vehicles. The effects of favorable weather conditions and lower speed limits on the encroachment rates are believed to be more than offset by the inclusion of controlled encroachments in the data. As expected, encroachment frequencies on straight and flat sections of highways observed by Cooper, shown in Figure 3, were somewhat lower than those measured by Hutchinson and Kennedy.

In another study of roadside encroachments, Calcote used time-lapse video photography and electronic monitoring to identify encroachments along urban freeways and rural highways, respectively.(18) The electronic monitoring approach failed to produce any useful results due to the use of the shoulder area by slow-moving vehicles to allow faster vehicles to pass and the propensity for false signals. The time-lapse video photography approach did record a large number of encroachments. However, despite the visual records of the encroachments, the researchers were still unable to determine whether or not encroaching vehicles were under control. Most encroachments involved vehicles moving slowly off of the roadway for some distance and then moving back into the traffic stream without any abrupt changes in vehicle trajectory. Researchers assumed that all encroachments were controlled unless the vehicle exhibited a rapid change in trajectory or hard braking. Using this relatively restrictive definition of uncontrolled encroachment, only 14 of the approximately 7,000 encroachments were judged to be uncontrolled, or a ratio of 500 to 1 between controlled and uncontrolled encroachments. The limited nature of the study and the high ratio between controlled and uncontrolled encroachments rendered the research results statistically insignificant and not too meaningful.

The various existing procedures use different base encroachment rates. For example, the 1977 AASHTO Barrier Guide uses the encroachment data collected by Hutchinson and Kennedy while the TTI ABC model uses the Cooper encroachment data. The BCAP and ROADSIDE programs use a constant encroachment rate of 0.0005 encroachments (to one side of the road) per mile per year per average daily traffic (ADT). which is not based on either the Hutchinson and Kennedy or Cooper encroachment data. The new cost-effectiveness

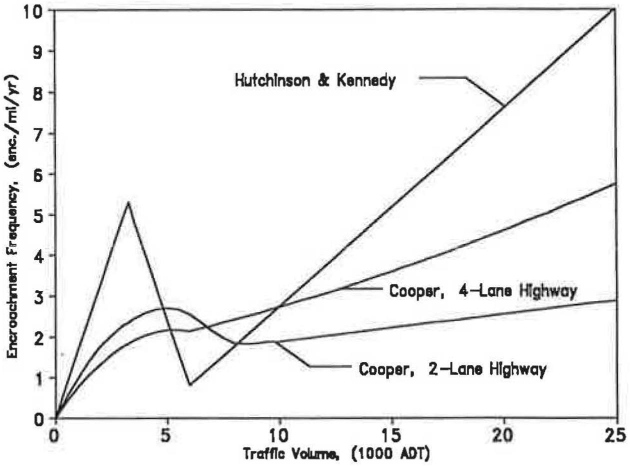

FIGURE 3 Encroachment frequency data.

procedure being developed under NCHRP Project 22-9 uses encroachment data from the Cooper study with breakdowns by highway type: two-lane undivided, four-lane undivided, and four lane-divided highways.

Base encroachment rates are then modified to account for specific highway characteristics, such as horizontal and vertical alignment, and number of lanes. The rationale for these adjustment factors is that encroachments 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 curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature of the horizontal curve.(19, 20)

The BCAP program provides adjustments for horizontal curvature and vertical grade, based on results from the study on fatal single vehicle accidents by Wright and Robertson.(19) It is believed that these adjustment factors are too high because only fatal accidents were included in the sample. There are also other concerns with the study, such as the small sample size, the lack of control for other potential covariates, e.g., area type, highway type, number of lanes, etc. Also, the effect of vertical grade on encroachment rate is questionable and not supported by data from other more recent studies, which found no significant relationships between vertical grade and accident rates.(12,20)

The 1989 AASHTO *Guide Specifications on Bridge Railings* also incorporates encroachment frequency adjustment factors to account for the effect of bridge deck height and water depth below bridge. These factors are designed as a surrogate to account for the increase in severity of bridge rail penetration accidents. Increasing the encroachment frequency would increase the number of accidents involving bridge rail penetration and rolling over the bridge rail, which in turn would increase total accident costs. Unfortunately, this approach also increases the frequency and costs associated with all other accident types, such as those involving redirection and rollover on the traffic side of the bridge railings. There is no supporting data or theoretical basis for these adjustment factors and they are not considered appropriate.

The new cost-effectiveness procedure being developed under NCHRP Project 22-9 will consider adjustment factors for horizontal curvature, vertical grade, number of lanes, and left versus right encroachments. The adjustment factors for horizontal curvature and vertical grade will be established from the more recent studies by Zegeer, et al. on two-lane rural highways(13) and horizontal curves(20). Adjustment factors for number of lanes and left versus encroachments are new additions. It is intuitively obvious that the encroachment rates are different from different lanes on multi-lane facilities. For example, a vehicle in the center lane is less likely to encroach into the roadside than a vehicle in the right lane since the vehicle will first have to cross the right lane before encroaching into the roadside, thus allowing more time for the driver to take corrective actions. Another consideration is that the traffic volume is not distributed equally among the lanes, e.g., the right lane tends to carry more traffic than the center lane. Also, in a study on single vehicle, ran-off-road accidents by Perchonok, et al.(21), it was found that the ratio between right and left encroachments was approximately 2 to 1.

The encroachment frequency algorithm will then consider the effect of traffic growth on encroachment frequencies. Since the cost-effectiveness analysis procedure will incorporate an annualized cost basis for comparing various safety treatment alternatives, estimated encroachment frequencies will be further adjusted to annualize the traffic growth effects. This process involves estimating encroachment frequencies in future years and annualizing those encroachments over the life of the treatment alternative using economic discounting procedures. This analysis is appropriate since all accident related costs are assumed to be directly proportional to the encroachment frequency. Thus, using economic discount factors to adjust encroachment frequency would yield the same result as converting encroachment frequency to accident costs and then annualizing the result.

Accident Prediction Module

The accident prediction module estimates the conditional probability than an accident will occur given an encroachment, $P(A|E)$. The basic process involves considerations for the lateral extent of vehicle encroachment, and the probability of the vehicle impacting with a roadside feature (which in turn are based on the encroachment characteristics, i.e., speed and angle, vehicle trajectory, i.e., steering and braking, and vehicle and hazard size, i.e., length and width). The impact conditions, i.e., speed and angle, are also determined as part of the accident prediction module.

The model first determines the probability that the vehicle would encroach far enough laterally to impact the roadside feature under consideration based on the

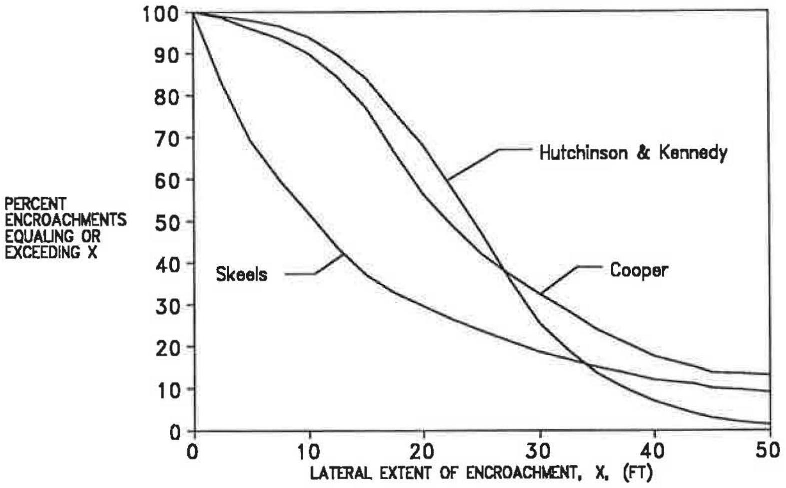

FIGURE 4 Lateral extent of encroachment data.

lateral extent of vehicle encroachment. In other words, the vehicle may stop or steer back to the roadway before encroaching far enough to impact the feature. Figure 4 (Lateral Extent of Encroachment Data) shows the distributions of lateral extent of vehicle encroachment from studies by Hutchinson and Kennedy(16), Cooper(17) and Skeels(22).

As may be expected, the percentage of vehicles encroaching beyond a given lateral distance decreases with increase in the lateral distance. In other words, a roadside feature located further away from the edge of the travelway is less likely to be impacted than one that is closer to the travelway. Note that the shape of the curve from the Skeels data is significantly different from that of the curves from encroachment studies by Hutchinson and Kennedy and Cooper. The difference is attributed to the presence of paved shoulders where tire tracks are not evident. Thus, only encroachments beyond the paved shoulders are included in the data.

The model then estimates the probability that the vehicle will impact the roadside feature if the vehicle encroaches far enough laterally. Existing encroachment probability models use an approach known as hazard imaging. 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, as shown in Figure 5 (Hazard Imaging). Given an encroachment by a vehicle of a particular type and size, the probability that the vehicle will leave the highway within the hazard envelope of a particular roadside obstacle is given by the equation shown below:

$$P(H^{w,i}_{v,\theta} \mid E^{w}_{v,\theta}) = \frac{1}{5280}\left(L_i + \frac{W_e}{\sin\theta} + W_i\cos\theta\right) \tag{3}$$

where

$P(H^{w,i}_{v,\theta} \mid E^{w}_{v,\theta})$ = Probability that an errant vehicle of size, W, encroaching at speed, V, and angle, θ, will be within the impact envelope of hazard, i, given that a vehicle of size, W, has encroached at speed, V, and angle, θ.

L_i = Length of hazard i

W_e = Effective width of vehicle size W

θ = Encroachment angle (deg.).

W_i = Width of hazard i

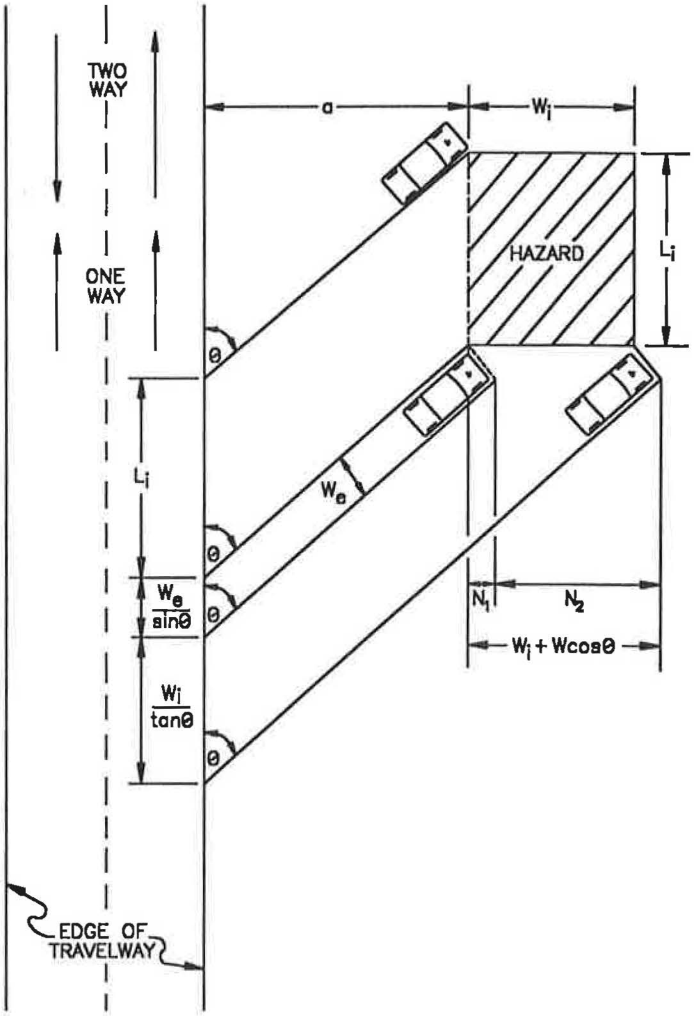

FIGURE 5 Hazard imaging.

The hazard imaging algorithm assumes that uncontrolled vehicles encroach along a straight path, i.e., no steering input. It takes into account the encroachment angle, the length and width of the hazard, and the vehicle size. The 1977 AASHTO Barrier Guide and the ROADSIDE programs use average encroachment angles and vehicle size. The BCAP and TTI ABC programs allow for a distribution of encroachment angles and different vehicle sizes.

The new procedure being developed under NCHRP Project 22-9 does not use the hazard imagining approach. Instead, a Monte Carlo simulation technique is planned for use with the new procedure. The Monte Carlo simulation technique involves using random selection processes to simulate vehicles running off of the road within the highway section of interest. As shown in Figure 6 (Flowchart of Accident Prediction Module), the first step in the accident prediction process is to define the geometry of roadside hazards and features. Random numbers are then generated to define the location and nature of an encroachment, i.e., vehicle type and size, impact speed and angle, vehicle orientation at impact, and lateral extent of encroachment. (Note that the inclusion of vehicle orientation at impact is another improvement incorporated into the new procedure.) The roadside region that the vehicle will traverse, vehicle traversal region (VTR), is then defined based on the encroachment point, the impact angle, vehicle size, and vehicle orientation, as shown in Figure 7 (Vehicle Traversal Region). Objects within this region are then identified according to proximity to the roadway and

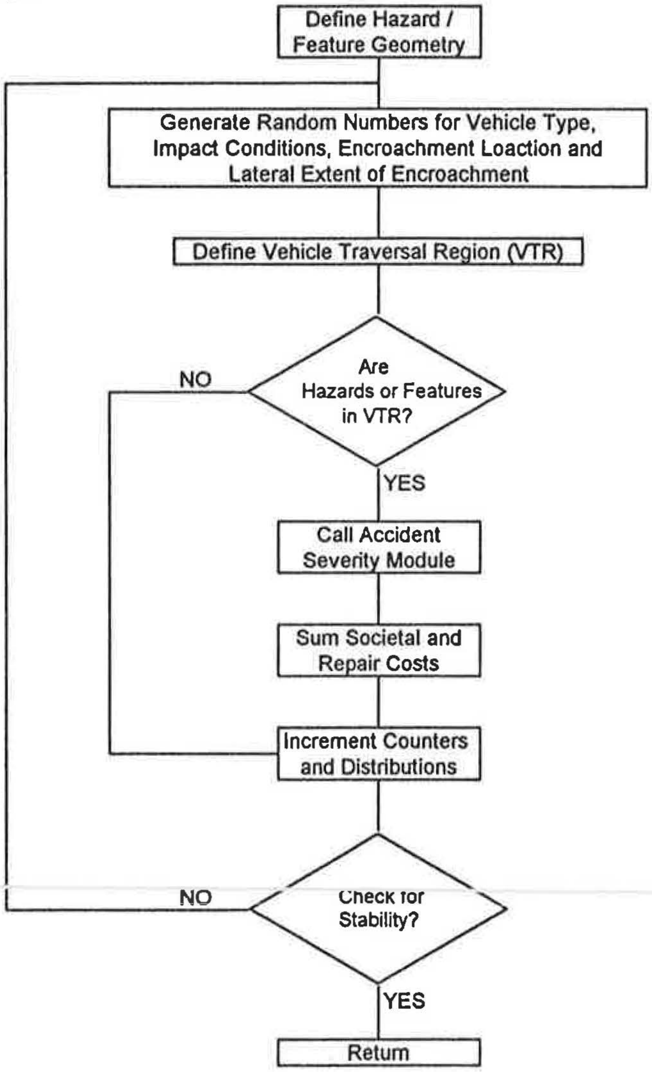

FIGURE 6 Flow chart of accident prediction module.

compared to the lateral extent of encroachment to determine if an accident will occur. If an accident is predicted to occur, the program will then continue on to estimate the impact severity and the associated accident costs. A new set of random numbers is then generated and the process is repeated.

The stability and convergence of the solution will be checked every 10,000 simulated runs. The checks will include comparing the distributions of the simulated samples to the target distributions built into the model, such as impact speed, angle and orientation, lateral extent of encroachment, vehicle type and size, etc. If all of these checks are within acceptable levels of accuracy, the simulation effort will then terminate. Otherwise, another 10,000 iterations will be undertaken and the convergence checks outlined above are repeated.

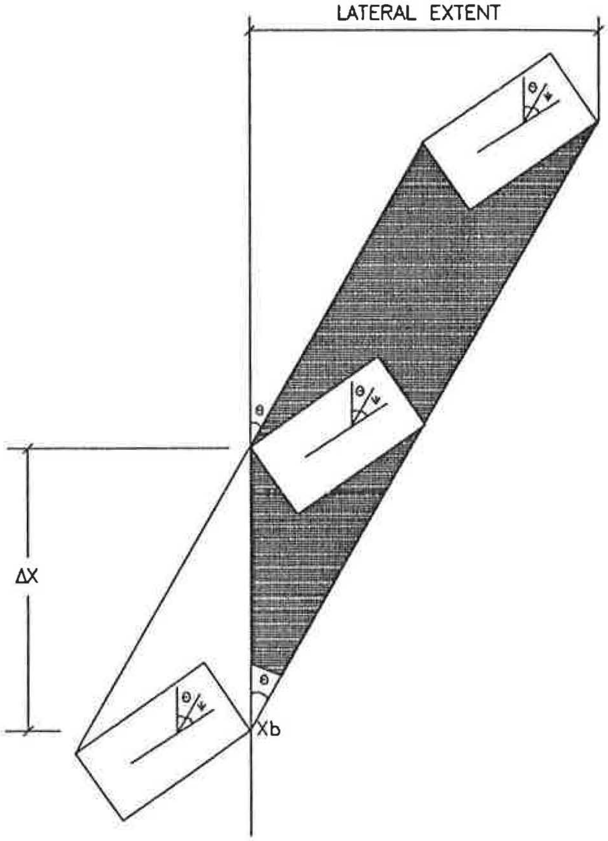

FIGURE 7 Vehicle traversal region.

The accident prediction module will also determine the impact conditions, i.e., impact speed and angle, for estimation of the accident severity. The 1977 AASHTO Barrier Guide and the ROADSIDE programs use average severity indices for accident severity and do not require the use of impact conditions. The BCAP program assumes certain encroachment speed and angle distributions, based on which the impact speed and angle distributions are estimated. It should be noted that the encroachment speed and angle distributions used in the BCAP program are based strictly on engineering judgement, with no theoretical basis of supporting data. With the assumption of straight path for the encroaching vehicles, i.e., no steering input, the impact angle would be the same as the encroachment angle. As for estimation of the impact speed, the BCAP program assumes braking with a constant deceleration rate and the impact speed is calculated by subtracting the speed loss due to braking from the encroachment speed.

The TTI ABC program and the new procedure being developed under NCHRP Project 22-9 do not use encroachment conditions to estimate impact conditions. Instead, the impact conditions are established from real-world accident data.(23-25) The advantage of this approach is that the impact conditions are from real-world accident data and not derived from some arbitrarily chosen theoretical distributions. The drawback is that the impact speed is independent of the lateral location of the hazard. Although intuition suggests that impact speeds should decrease as the distance from the roadway increases, both accident data and deterministic encroachment models indicate that the degree of speed reduction is relatively minor for hazards located within 30 ft (9.1 m) of the travelway. Since most roadside hazards of interest are located within a 30-ft (9.1-m) clear zone, this limitation is not believed to be a major source of error. However, the Monte Carlo technique proposed for use in the new cost-effectiveness procedure could be easily modified to link extent of lateral encroachment distributions to impact conditions, should the data become available in the future.

Accident Severity Prediction Module

The accident severity prediction module estimates the severity of the accident and associated costs given that an accident has occurred, $P(I_i|A)$. The severity of an accident 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.

Most existing encroachment probability models have used a severity index (SI) as a surrogate measure for accident severity. The severity index was developed as a tool when estimating severity of roadside hazards through surveys of transportation and law enforcement experts.(3) A probability of injury and fatality was arbitrarily assigned to each index as shown in Table 1. Survey respondents were then asked to consider the table when assigning a subjective SI value to each roadside hazard. This SI concept has continued to be used by most encroachment probability based procedures even though severity is no longer assigned through subjective evaluation.

Accident severity from police reports is normally recorded in terms of five severity levels: fatal (K), incapacitating injury (A), non-incapacitating injury (B), possible injury (C), and property-damage-only (PDO). A more accurate and detailed injury severity rating scheme, based on the Accident Injury Scale (AIS), is sometimes used. This scale has six levels (1 through 6) that are based on the medical evaluations of the injured parties. Unfortunately, the AIS scale is too sophisticated for use by police and therefore is available only from in-depth accident investigation studies where medical records of injured occupants are collected..

Neither of the accident severity reporting schemes fits conveniently into the Severity Index concept described previously. Further, accident data analysis indicates that the relationships between PDO, injury, and fatal accidents used in the severity index scale are seldom appropriate.(10) In other words, when the percentage of injury accidents reaches the level for any given severity index shown in Table 1, the percentage of fatal accidents seldom correlates with the appropriate SI value. Thus, there are no apparent advantages of continuing to incorporate severity indices as a means of expressing accident severity. Therefore, for the new cost-effectiveness procedures being developed under NCHRP Project 22-9, accident severity will be defined in terms of probability of injury or fatality. These probabilities will then be used to calculate accident costs directly, without the intermediate step of determining a severity index.

As mentioned previously, the 1977 AASHTO Barrier Guide and the ROADSIDE programs use average severity indices for accident severity and do not require the use of impact conditions. The BCAP and TTI ABC programs and the new cost-effectiveness procedures being developed under NCHRP Project 22-9 use a variety of severity estimation procedures tailored to the specific hazard or feature being struck. For example,

TABLE 1 SEVERITY INDEX AND PROBABILITY OF INJURY

Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents
0	100	0	0
1	85	15	0
2	70	30	0
3	55	45	0
4	40	59	1
5	30	65	5
6	20	68	12
7	10	60	30
8	0	40	60
9	0	21	79
10	0	5	95

procedures for predicting the severity of impacts with rigid objects would be very different from those used to predict crash cushion impact severity. Typically, severity for a few impact conditions are estimated from a combination of crash test results, computer simulation, and accident data. Severity indices or probabilities of injury are then assigned to these impact conditions and engineering judgement is used to extrapolate these severity indices to all other possible impact conditions.

Some of the severity estimation analyses are velocity-dependent.(5,26,27) Typically, these procedures used crash testing results or impact analysis techniques to estimate the severity of impact for one or two impact speeds and then extrapolated the data for all other impact speeds using a linear approximation. Other severity estimation procedures are based on vehicle accelerations or impact energy. For example, the BCAP model uses a simple analytical equation to estimate the average lateral acceleration during vehicle redirection in a longitudinal barrier impact. The severity was estimated for two levels of average lateral acceleration and then linearly extrapolated to all other acceleration levels. Crash cushions are a good candidate for energy dependent impact severity models. Such a procedure would involve estimating accident severity for two levels of impact energy and extrapolating the findings to other impact conditions.

The accident severity analysis procedures incorporated into the new cost-effectiveness procedure being developed under NCHRP Project 22-9 will also allow for separate consideration of the location of impact on the obstacle being impacted. The severity of impact with roadside hazards and safety devices are often a function of the point of impact with the obstacle. For example, the severity of an impact with the side of a redirective crash cushion is considerably different than the severity of impact with the front of the cushion. This is another of the improvements incorporated into the new procedure.

Vehicle behavior during and after impact is also included in the severity estimates for roadside obstacles and safety devices. For example, severity for guardrail or roadside slope impacts generally increase dramatically when the impacting vehicle rolls over. Therefore, the first step in estimating impact severity is to identify the expected vehicle behavior during impact. For roadside appurtenances, such as barriers and crash cushions, a performance limit check is first conducted to determine if the vehicle is properly contained. This check can take the form of a simplified theoretical analysis or empirically derived relationships between impact conditions and the structural capacity of the barrier or crash cushion. Impacts wherein the vehicle is predicted to penetrate through the barrier or to exceed the capacity of a crash cushion would then be assigned a much higher severity than impacts within the performance limit of the device.

A stability check is then conducted using simple impulse and momentum or energy based analyses to identify the propensity for vehicles to roll over during impact. For barriers or impacts on the side of redirective crash cushions, this check can be segregated into two categories: vehicles that roll over the barrier and those that roll over in front of the barrier. Impacts involving a vehicle that is predicted to roll over a barrier would then be assigned a severity similar to barrier penetration accidents. Impacts involving a vehicle rolling over in front of the barrier would be assigned a lower severity that is related to the original impact speed. Although not widely used in the past, a similar approach can be used for evaluation of vehicle stability during impacts with many other types of roadside obstacles, such as ditches and slopes. This approach may improve severity predictions for impacts with a number of roadside obstacles and features.

The accident severity is then converted to accident or societal costs, $C(I_i)$, based on some pre-selected accident cost figures. There are two sets of accident cost figures that are commonly used: the accident cost figures developed by the National Safety Council (NSC)(27) and the FHWA Comprehensive cost figures based on the "willingness to pay" principal(28), as shown in Table 2. Note that the current (1994) comprehensive cost figures are even higher than those shown in Table 2, e.g., the estimated cost for a fatality has increased from 1.7 to 2.6 million dollars.

Most States currently use the NSC accident cost figures, which include estimates of direct costs, such as wage loss, medical expense, insurance administration, legal/litigation cost, and property damage, but do not account for indirect costs, such as the consideration of a person's natural desire to live longer or protect the quality of one's life. The NSC cost figures were used as default values in the BCAP program and also adopted in the 1988 AASHTO *Roadside Design Guide*.

The FHWA has adopted the comprehensive cost figures, which are based on the concept of willingness to pay and include the indirect costs mentioned above. It should be noted that the NSC and the National Highway Traffic Safety Administration (NHTSA) has endorsed the use of the comprehensive cost figures for benefit-cost analyses.(27,29) It is evident from Table 2 that the FHWA comprehensive cost figures are substantially higher than those of the NSC, which could have a significant effect on the outcomes of specific cost-effectiveness analysis depending on which set of accident cost figures are used.

TABLE 2 ACCIDENT COST BY SEVERITY

Roadside Design Guide

Accident Severity	Accident Cost ($)
Fatality	500,000
Severe Personal Injury	110,000
Moderate Personal Injury	10,000
Slight Personal Injury	3,000
Property Damage Only (Level 2)	2,500
Property Damage Only (Level 1)	500
No Damage	0

Comprehensive (Willigness to Pay)

Accident Severity	Accident Cost ($)
Fatal	1,700,000
Injury (Overall)	14,000
ABC Injury Scale:	
A Injury - Incapacitating Injury	47,000
B Injury - Nonincapacitating Injury	10,000
C Injury - Possible Injury	3,000
Property Damage Only (PDO)	2,500

The cost of repairing roadside safety hardware will also be estimated by the accident severity module. This process will usually involve estimating extent of damage based on impact energy terms. The repair cost for any given accident is then estimated from the extent of damage and unit repair costs. For example, results from full-scale crash testing and computer simulations can be used to determine the relationship between impact energy terms and length of guardrail damage. The repair cost is then the product of the length of damaged rail and the unit cost for repair.

Benefit Cost Module

Benefits derived from a safety improvement are measured in terms of reduced accident or societal costs resulting from 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. As summarized in Figure 9 (Flow chart

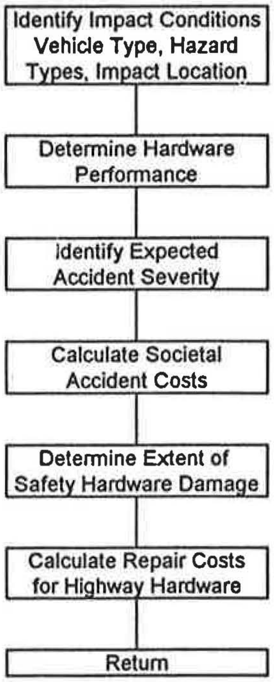

FIGURE 8 Flow chart of accident severity module.

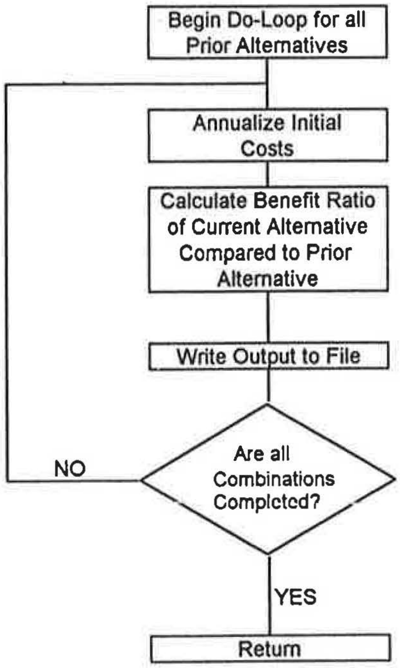

FIGURE 9 Flow chart of benefit cost module.

of benefit cost module), the benefit cost module will first annualize the accident or societal costs and the construction and maintenance costs and then ratio the benefits and costs of each pair of alternatives under consideration. The formulation for determining the incremental benefit/cost ratio between two alternatives is shown previously in Equation 1.

FUTURE RESEARCH NEEDS

The encroachment probability based cost-effectiveness analysis procedures, as briefly described above, is a sophisticated and complex program involving numerous algorithms, data sources, and assumptions. As such, there are numerous areas within the procedure where improvements are needed, ranging from updated or new data to revised algorithms and assumptions that better define the process. The new cost-effectiveness analysis procedure being developed under NCHRP Project 22-9 recognizes this need for continuing improvement of the procedure and is designed to be modular in nature so that future improvements can be incorporated with a minimum level of effort as new data and methodologies become available.

The most important area requiring improvement is perhaps the accident severity estimation procedures, which are shown to have the most effect on the outcomes of the cost-effectiveness analyses. Available data in this area are mostly comprised of full-scale crash test data which are limited to selected vehicle types and impact conditions. The crash test data can be supplemented with computer simulation studies, but there are severe limitations to the capability of existing computer simulation models. Available accident data are mostly limited to police reports which lack the level of detail and accuracy required to evaluate the safety and performance of roadside safety features. More detailed accident data and in-service evaluation are sorely needed.

Another major weakness with encroachment probability models 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, the attitude of encroaching vehicles, and the trajectories of the 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 and the existing procedures are basically unvalidated..

Gaps in the state-of-the-knowledge regarding the encroachment probability based cost-effectiveness procedures and potential research studies to fill in these gaps were identified in a recently completed study sponsored by FHWA(30) and the ongoing NCHRP Project 22-9(9). The following is a list of major data gaps identified from these two studies and are listed in order of relative importance to the procedure. These data gaps are by no means all inclusive, but serve to illustrate the major data gaps for the purpose of further discussions in the breakout group sessions.

- Performance limits of roadside safety features and - associated severity.
- Relationships of injury probability and severity to impact conditions.
- Distributions of impact conditions.
- Effects of sideslopes on extent of lateral encroachment.
- Severity associated with sideslopes.
- Validation of encroachment frequency/rate.
- Encroachment frequency/rate adjustment factors.
- Extent of unreported accidents.
- Vehicle trajectory after encroaching into roadside.
- Relationships of surrogate severity measures to Injury probability and severity.

For each data gap, brief background information and discussions of its importance to the new cost-effectiveness analysis procedure are presented as follows:

Performance Limits of Roadside Safety Features and Associated Severity

The results of cost-effectiveness analysis regarding roadside safety features are controlled to a large extent by catastrophic events, such as penetration of the barrier or rolling over the barrier by the impacting vehicle, particularly when comparing among multiple performance levels. The occurrence of catastrophic events is a function of the performance limit of the impacted roadside object or feature. In other words, when the performance limit of a given roadside object or feature is exceeded, e.g., loading is greater than barrier capacity, some catastrophic outcome would occur. Thus, the performance limit of the impacted roadside object or feature is an important factor to the determination of the severity of an impact. Currently, the performance limits of roadside objects and features and the potential outcomes of exceeding the performance limits are not well defined.

Although numerous crash tests are conducted with many types of roadside safety features each year, virtually all of these tests are limited to two or three vehicle sizes impacting in a tracking mode at speeds of 45 and 60 mph (72.4 and 96.6 km/h). These impact conditions were selected to be representative of relatively severe accidents or worst case conditions. Even so, the performance limits of various roadside safety features are often not defined by crash tests under these test conditions. There remains a need to more accurately define impact conditions that can cause safety hardware performance to become unacceptable.

The required data may be obtained from crash testing or computer simulation studies to include a wider spectrum of vehicle sizes and impact conditions. Full-scale crash testing is a very expensive endeavor and its use will necessarily be very limited in scope. Computer simulation study is a good and relatively inexpensive approach, provided accurate and validated computer simulation models are available. Unfortunately, existing computer simulation models have severe limitations and their use is confined to only selected roadside safety features and vehicle types. Another means of collecting the required data is through in-depth investigation of real-world accidents and the conduct of in-service evaluation. Efforts in this area have been very limited so far, but it is potentially a very promising approach worthy of further consideration.

Relationships of Injury Probability and Severity to Impact Conditions

For impacts where the performance limit of the impacted roadside object or feature is not exceeded, e.g., redirection for a barrier, severity is a function of the impact conditions, i.e., impact speed and angle and vehicle orientation at impact. These relationships between impact conditions and impact severity are particularly important when evaluating several safety treatment alternatives, such as different levels of performance. These relationships are currently not well defined, thus requiring some form of approximation or hypotheses in what the relationships are. For example, in a redirectional impact by a barrier, the severity is often defined as a linear function of the lateral acceleration experienced by the impacting vehicle. There is a definite need to better define these relationships between injury probability and severity to impact conditions for the various roadside safety features.

The study approaches would be similar to that for defining the performance limits of roadside safety features, i.e., crash testing, computer simulation, in-depth accident study, and in-service evaluation. Actually, the efforts for these two studies can probably be combined into a single study with the proper experimental design.

Distributions of Impact Conditions

An important factor to the outcome and severity of an accident involving a roadside object or feature is the impact conditions, i.e., speed, angle, and vehicle orientation at impact. The impact speed and angle determine whether the performance limit of the roadside safety features is exceeded and the associated injury probability and severity. Vehicle orientation at impact is also important since non-tracking impacts are believed to be of significance with regard to the severity of impacts with breakaway structures, narrow fixed objects, end terminals and crash cushions. Thus, the distributions of impact conditions are crucial to the accuracy and validity of the cost-effectiveness model. However, there is only limited information available on the distribution of impact conditions from studies such as Perchonok, et al.(21), Lampela and Yang(31), and Mak, et al.(23-25), and the data are somewhat dated. There is a need to obtain better more updated information on the distribution of impact conditions.

In order to determine the impact conditions, the data collected on the accidents has to provide sufficiently detailed information for the accidents to be reconstructed. This requires, as a minimum, information on the vehicle trajectory, impact sequence, nature of object(s) struck or harmful event(s), and damage to the vehicle and object(s) struck for each accident investigated. This detailed level of accident data is typically not available from police level accident data, but requires in-depth data collection by trained investigators. Also, the accidents will have to be reconstructed to determine the impact conditions. There have been very few in-depth accident studies conducted in recent years since they are relatively expensive to conduct. The most recent effort is the National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS), which resulted in a data file with in-depth data on over 1,000 longitudinal barrier accidents. However, these accidents were non-representative samples with bias toward the more severe accidents. The NASS Continuous Sampling System (CSS) data file may also provide some useful information, but the sample of fixed-object impacts is expected to be rather small.

Effect of Sideslopes on Extent of Lateral Encroachment

All previous encroachment probability models have not incorporated the effect of roadside conditions, e.g., sideslope, ditch configuration, etc., into the determination of impact probability and severity. Yet it is intuitively apparent that the steepness of the sideslope should have significant effect on the extent of lateral encroachment of an errant vehicle after it leaves the roadway and on the ability of a driver to maintain control of the vehicle and to recover from the errant path. The extent of lateral encroachment would in turn affect the probability of an errant vehicle impacting roadside hazards. In a study to assess the effect of sideslopes on the clear zone distance requirement, the responses of selected passenger cars on a range of sideslopes were studied for selected encroachment conditions and driver inputs.(32) The study results clearly indicate that the extent of lateral encroachment is significantly affected by the sideslopes. A study to evaluate the effect of sideslope on the lateral extent of encroachment is therefore recommended. Currently, a new study under NCHRP (Project 17-11) is planned to re-examine the clear recovery distance concept, part of which will involve studying the relationships between sideslopes and the extent of lateral encroachment.

Severity Associated with Sideslopes

In the cost-effectiveness analysis procedures, sideslope is typically considered as a traversable roadside feature with an associated severity rating. It can be argued that the severity associated with a sideslope is totally the result of rollover accidents, assuming that the errant vehicle does not impact with another roadside object or feature. In other words, assuming that the sideslope is of infinite width and totally free of other roadside objects or features, the only harm that could happen to an errant vehicle on the sideslope is for the vehicle to roll over. Studies by Zegeer, et al.(13,20) attempted to ascertain the severity associated with sideslopes, but the data are considered too gross for useful results. A study to determine the probability and severity of rollover accidents for various sideslopes is therefore proposed.

Validate Encroachment Frequency/Rate

The basic underlying assumption of an encroachment probability based cost-effectiveness analysis model is that the rate of roadside accidents is directly related to the encroachment rate. The model starts with an average or base encroachment rate and proceeds from there. Needless to say, the encroachment rate is important to the validity and accuracy of the cost-effectiveness model. Available data on encroachment rates are limited to three previous studies by Hutchinson and Kennedy(16), Cooper(17), and Calcote(18).

The approach employed by Hutchinson and Kennedy(16) and Cooper(17) involved periodic observations of tire tracks along the roadside and/or median areas of highways. A major limitation of this approach is that controlled encroachments, wherein the drivers intentionally leave the travelled portion of the roadway for whatever reason, cannot be distinguished from uncontrolled encroachments. Another problem is that most of the studied highways have paved or gravel shoulders. Vehicles encroaching only a short distance from the travelway, i.e, within the shoulder area, would not leave any evidence of an encroachment and thus could not be identified. On the other hand, the presence of paved shoulders reduces the likelihood that tire tracks observed beyond the shoulder areas are from controlled encroachments since controlled encroachments are more likely to occur on the shoulder areas. Existing encroachment data from observation of tire tracks are also biased by the effects of seasonal and weather changes on the encroachment rates. Much of the data studied by Hutchinson and Kennedy(16) were collected during winter months in Illinois where snowy and icy weather and surface conditions could significantly increase encroachment rates. Conversely, the data by Cooper(17) were collected only during the summer months when favorable weather conditions may produce encroachment rates that are lower than the annualized averages.

Calcote, et al.(18) used video monitoring or electronic surveillance of highway sections to collect encroachment data. The video monitoring did provide visual records of all encroachments along the highway sections under observation and the characteristics of the encroachments, but the researchers still had tremendous difficulty distinguishing between controlled and uncontrolled encroachments. Electronic monitoring was found to be highly unreliable. Also, the high costs of these approaches limited the study to only a few short sections of highways, resulting in a sample size considered too small to be reliable or statistically significant. Until better and less expensive data collection techniques and equipment become available, these approaches are considered impractical and not recommended for further consideration.

As described above, there are many unanswered questions regarding the validity of existing encroachment data. The most important of these questions centers around the effect of controlled encroachments on the estimated encroachment frequencies. However, these questions cannot be answered by collecting additional encroachment data using available techniques, such as observation of tire tracks. Video monitoring and electronic surveillance are too expensive to be a feasible alternative. Thus, some other means to check on the validity of the existing encroachment data is needed, such as approaches used in of NCHRP Report 77(1)and TRB Special Report 214(33), and approaches proposed in the report by Mak and Sicking.(30). Regardless of the approach used, a study to validate/ calibrate encroachment frequency/rate is needed and recommended for consideration.

Encroachment Frequency/Rate Adjustment Factors

Encroachment rate is believed to be affected by various geometric and roadway characteristics, such as horizontal and vertical alignments, number of lanes, etc. The base encroachment rates used as initial inputs to the cost-effectiveness analysis models are average values and do not account for variations of these characteristics at individual sites. Thus, it is necessary to adjust the base encroachment rates to reflect specific site conditions. One approach is the use of empirical adjustment factors. For example, the Benefit Cost Analysis Program (BCAP) uses empirical adjustment factors to account for horizontal curvature and vertical grade. The adjustment factor for horizontal curvature is a function of the location relative to the curve and the degree of curvature. The adjustment factor for vertical grade is a function of the type and degree of grade.

These adjustment factors are based on a study by Wright and Robertson(19) in which 300 fatal single-vehicle, ran-off-the-road, fixed-object accidents were studied. While the study was well designed, it has a very small sample size and the effects of horizontal and vertical alignment are likely over-estimated since the study included only fatal accidents. More recent studies by Zegeer, et al.(13,20) found the effect of horizontal curvature to be less than that indicated by the Wright and Robertson study(19) and vertical grade was found to have no significant effect on accident rates. Also, there may be additional roadway characteristics that could potentially affect encroachment rates that were not included in the adjustment factors. In order to account for roadway characteristics that may have significant effect on encroachment frequency and rate, there is a need to identify these roadway characteristics and to develop the appropriate empirical adjustment factors.

Extent of Unreported Accidents

Accident data is generally not a good means of adjusting encroachment data since only a fraction of the accidents involving roadside objects and features are actually reported to police. While the severity of these unreported accidents is likely to be minor in nature when compared to reported accidents, it is important to know the extent of these unreported accidents, especially for evaluation of the performance of safety devices. A number of studies have examined the extent of unreported accidents with widely varying results. For example, a study by Make and Mason on utility pole accidents(24) found that the approximately 60 percent of all utility pole accidents are reported while another study by Lampela and Yang on concrete barrier used in work zones reported that only 2 percent of accidents are reported(31). Such variations indicate that the extent of unreported accidents is affected by a number of factors, including type of roadside object or feature and location. A better understanding of the extent of unreported accidents could lead to improved accident data based benefit-cost procedures and allow accident data to be used for validation of encroachment probability models.

Trajectory of Vehicle after Encroaching into Roadside

There is currently very little information regarding the trajectory of an errant vehicle prior to leaving the roadway or after encroaching onto the roadside. For example, did the vehicle leave the roadway on the right, on the left, first right and then left, or first left and then right? Is the vehicle path straight or curved? How do the roadside conditions interact with the vehicle trajectory and the distance travelled by the vehicle prior to impact? Are drivers braking, steering, or both? How do driver actions affect the impact probability and impact conditions? All these vehicle trajectory parameters could potentially affect the impact probability and severity, but there are simply insufficient data to even speculate on the answers to these questions, not to mention incorporating them into a cost-effectiveness model. Better understanding and more information on the vehicle trajectory is needed and therefore proposed.

Relationships of Surrogate Severity Measures to Injury Probability and Severity

The severity of a given roadside object or feature is oftentimes determined from full-scale crash testing or simulation and is expressed in terms of surrogate severity measures, such as highest 50-msec average acceleration, occupant impact velocity, and highest average 10-msec ridedown acceleration. On the other hand, accident severity is defined by injury probability and injury severity for the cost-effectiveness analysis procedure. Existing relationships between these crash test severity measures and actual injury probability and severity are limited to longitudinal barrier impacts and are based on extremely limited data and are therefore suspect. However, such relationships are important to cost-effectiveness analysis in order to develop more accurate relationships between impact conditions and injury probability and severity. These relationships also provide an important method for evaluating the performance of safety hardware during the development process. Previous attempts to develop such relationships, such as the study by Calcote and Mason(34), have not been successful. There remains the need to establish the relationships between these surrogate severity measures used in full-scale crash testing or computer simulation to actual injury probability and severity.

SUMMARY

This paper provides an overview on the use of cost-effectiveness analysis and existing cost-effectiveness analysis procedures in the evaluation of roadside safety improvements. The major components of a cost-effectiveness procedure are outlined and discussed briefly. Various gaps in the state-of-the-knowledge regarding cost-effectiveness analysis procedures and suggested future research needs are identified to serve as a starting point for discussions in the breakout group sessions.

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