# Benefit-Cost Analysis of Roadside Safety Alternatives

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ABSTRACT

In recent years, benefit-cost (B-C) analysis procedures have been widely accepted as a rational method for evaluating safety treatment alternatives. Most methods of analysis employed to date have significant limitations, overstate the severity of accidents, and are cumbersome to use. An advanced B-C analysis model that incorporates numerous modifications to enhance versatility and improve determination of accident severity is described. Basic encroachment data on which the model is based are presented, and the applications and limitations of the model are discussed. An example of the use of the model to develop general barrier use guidelines is also included.

Highway engineers have always faced the difficult problem of determining when and where safety features should be used. Until recently, safety feature use guidelines were based primarily on the relative hazard of the possible alternatives. For example, if a high-speed traversal of a roadside slope was thought to be more hazardous than a similar impact with a roadside barrier, a barrier was deemed to be necessary. No consideration was given to the probability that a high-speed accident would occur. This led highway agencies to invest large sums of money to erect guardrail at sites where there was little or no probability of the occurrence of a severe accident.

When safety improvement programs gained higher priority, safety projects began to compete with construction and other projects for highway agency funds. Therefore it became necessary to evaluate the relative merits of all projects. A benefit-cost (B-C) analysis procedure for studying safety improvements was developed to determine the benefits obtained from each dollar spent on safety improvement (1). The 1977 AASHTO barrier guide presented highway engineers with a "simplified" B-C analysis procedure (2). Accident severities were estimated by highway safety professionals including accident investigators, highway engineers, and researchers. Severities derived in this manner have been found to be representative of high-speed accidents. As a result, all predicted accidents were by default assumed to involve high impact speeds, and the procedure overstated the severity of many types of accidents. Therefore the technique frequently led to the use of safety appurtenances at sites where such devices were not warranted. In these cases accidents involving the safety treatment occur more frequently and are more severe than accidents at similar untreated sites.

Efforts to further refine the B-C analysis technique have led researchers to develop relatively sophisticated algorithms (3-5). Although these programs do a better job of properly accounting for all of the costs associated with a safety improvement, the procedures have significant limitations, generally continue to overstate the severity of most accidents that are predicted to occur, and are quite difficult to use.

In an effort to resolve some of the problems associated with existing warranting procedures, an advanced B-C analysis algorithm was developed. Major improvements have been made in the algorithm to improve the versatility of the procedure and the determination of the severity associated with predicted accidents. Further, the algorithm has been coded for use with microcomputers to reduce implementation problems.

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## BENEFIT-COST METHODOLOGY

The B-C methodology compares the benefits derived from a safety improvement to the direct highway agency costs incurred as a result of the improvement. Benefits are measured in terms of reductions in societal costs due to decreases in the number or severity, or both, of accidents. Direct highway agency costs are comprised of initial, maintenance, and accident repair costs of a proposed improvement. A ratio between the benefits and costs of an improvement is used to determine if the improvement is cost beneficial:

$$BC_{2-1} = (SC_1 - SC_2)/(DC_2 - DC_1) \quad (1)$$

where

$BC_{2-1}$ = B-C ratio of Alternative 1 compared with Alternative 2,
$SC_1$ = annualized societal cost of Alternative 1,
$DC_1$ = annualized direct cost of Alternative 1,
$SC_2$ = annualized societal cost of Alternative 2, and
$DC_2$ = annualized direct cost of Alternative 2.

For Equation 1, Alternative 2 is normally considered to be an improvement relative to Alternative 1. When the B-C ratio for a safety improvement is below 1.0, the improvement should not normally be implemented. However, budgetary limitations prevent funding of all projects that have a B-C ratio of 1.0 or more. Ideally, a highway agency can use a B-C approach to analyze all proposed projects, including safety improvements, rehabilitation, and new construction, to determine the optimum use of available funding.

## ACCIDENT PREDICTION MODEL

Most benefits and some costs associated with a safety improvement are directly related to the number and severity of accidents that will occur at the site under consideration. Thus accident prediction is critical to the analysis of the need for safety improvements. Although some authors have attempted to use accident data to predict accident frequency and severity, to date these efforts have met with limited success due to poor quality or small accident data bases, or both. Currently, the best available methods for predicting accident frequency and severity are based on encroachment probability models.

An encroachment probability model is based on the concept that the number of run-off-the-road accidents that occurs at a given site can be related to the number of vehicles that inadvertently leave the roadway at that site. Further, it is assumed that the frequency and nature of uncontrolled encroachments can be related to roadway and traffic characteristics. Thus the goal of an encroachment probability model is to relate roadway and traffic characteristics to the expected accident frequency at a site.

The general approach in calculating accident frequency is to determine the region along the roadway, or hazard envelope, within which a vehicle leaving the travelway at a prescribed angle will strike the hazard. A typical hazard envelope is shown in Figure 1. Note that the hazard envelope is divided into three basic ranges. The first encroachment range corresponds with accidents involving the side of the hazard parallel to the roadway and is the same length as the hazard. The second range corresponds to impacts on the corner of the hazard between the two exposed faces and is a function of the effective width of the vehicle. Accident analysis studies have shown that many vehicles involved in roadside accidents are not tracking (6,7). Therefore the effective vehicle width used in the encroachment algorithm is the average of the vehicle width and length. The third encroachment range corresponds to vehicles striking the side of the hazard and is a function of the width of the hazard.

As shown in Figure 1, uncontrolled vehicles are assumed to encroach along a straight path. The probability that a vehicle of a particular size will leave the traveled way within a specific encroachment range at a prescribed angle and speed is merely the length of the range in miles times the probability of a vehicle encroaching under the given conditions:

$$P(E_{V,\theta}^{W,2}|E) = P(W)P(E_{V,\theta}|E)(W_e/\sin\theta)/5{,}280 \qquad (2)$$

where

$P(E_{V,\theta}^{W,2}|E)$ = probability that a vehicle of size W will encroach at speed V and angle $\theta$ into encroachment range 2, given that an encroachment has occurred;
$P(W)$ = probability that an encroaching vehicle will be of size W;
$P(E_{V,\theta}|E)$ = probability that an encroaching vehicle will be traveling at speed V and encroaching at angle $\theta$; and
$W_e$ = effective vehicle width (1/2 vehicle width + 1/2 vehicle length) in feet.

Note that this probability is based on the assumption that vehicles encroach randomly within the area of interest.

When a vehicle leaves the travelway within the hazard envelope, there is some probability that the vehicle will stop or steer back to the roadway before striking the hazard. Therefore the probability of entering the hazard envelope must be modified by the probability of a vehicle encroaching far enough laterally to reach the obstacle. The probability

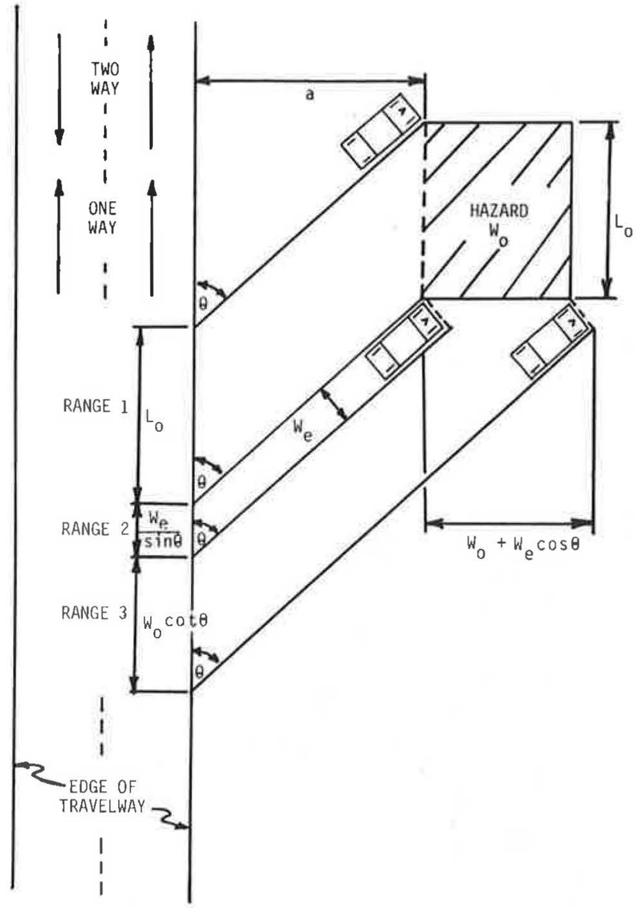


**FIGURE 1 Hazard envelope for single hazard.**

that an encroaching vehicle will strike the corner of the hazard is

$$P(C_{V,\theta}^{W,2}|E) = P(W)P(E_{V,\theta})(1/5{,}280)\{\sec\theta\csc\theta\sum_{j=1}^{N} P[LE>(a+j-1/2)]\} \qquad (3)$$

where

$P(C_{V,\theta}^{W,2}|E)$ = probability that a vehicle of size W encroaching at speed V and angle $\theta$ will strike hazard within range 2, given that an encroachment has occurred;
a = distance from travelway to fixed object (ft);
$P[LE>(a+\ldots)]$ = probability that the lateral extent of encroachment is greater than or equal to a+...; and
$N = W_e \times \cos\theta$ (ft).

The probability that an encroaching vehicle will strike a single hazard is merely the sum of the probabilities of impacts within each encroachment range.

For most circumstances of interest, two or more hazards are present at one location. For these situations the hazard envelopes can overlap and create a complex geometric problem as shown in Figure 2. This figure shows a rectangular hazard shielded by guardrail. Some vehicles encroaching within this region will strike the longitudinal barrier and be redirected, and other accidents will involve vehicles going behind or through the barrier and striking the

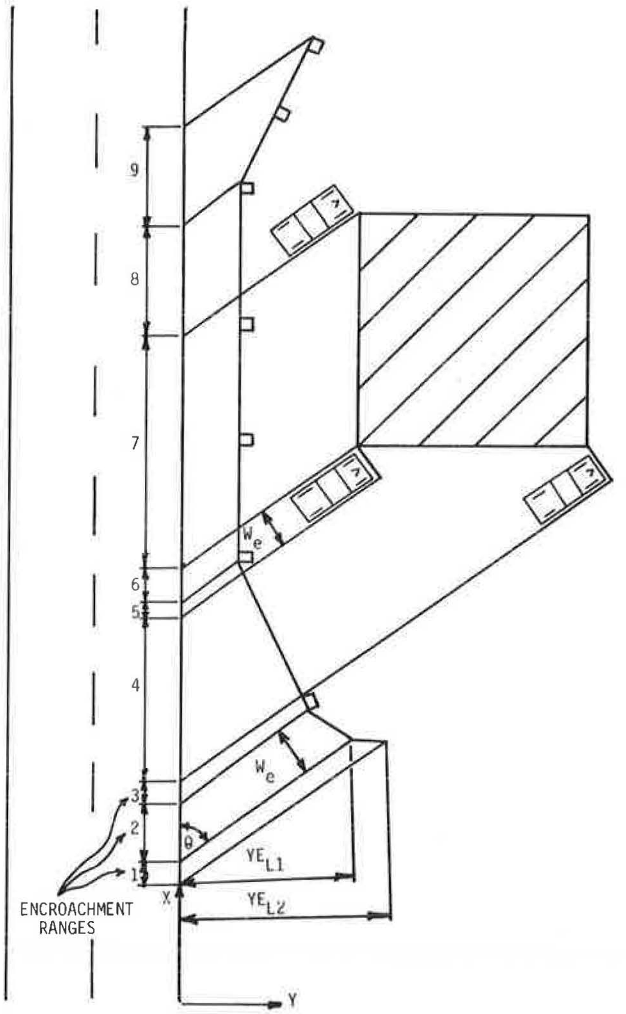


FIGURE 2 Hazard envelope for multiple hazards.

protected hazard. Hazard envelopes for multiple-hazard locations can be described if the relative locations and the geometry of all hazards are known. Figure 2 shows nine encroachment ranges comparing the overlapping hazard envelopes of the two hazards. Each encroachment range describes a unique combination of hazard faces that an encroaching vehicle would contact. For example, a vehicle with sufficient speed to penetrate the barrier, leaving the roadway within encroachment range 7, would first contact the longitudinal face of the barrier and then the longitudinal face of the hazard.

The encroachment probability model developed in this study uses hazard locations and geometry to determine the limits of all encroachment ranges and the lateral distances to each hazard within the range. The model then calculates the probability of a collision within each encroachment range in a manner analogous to that given in Equation 3:

$$P(C^{W,i}_{V,\theta} | E^{W}_{V,\theta}) = L_i/5{,}280 \sum_{j=YB_{L_i}}^{YE_{L_i}} [P(LE \geq j)]/|YE_{L_i} - YB_{L_i}| \quad (4)$$

where

$P(C^{W,i}_{V,\theta} | E^{W}_{V,\theta})$ = probability that a vehicle of size W leaving the roadway at speed V and angle θ will strike the first hazard within encroachment range i given that an encroachment has occurred involving a vehicle of size W, speed V, and angle θ;

$L_i$ = length of encroachment range i;

$YE_{L_i}$ = lateral distance from end of encroachment range i to first hazard within the range; and

$YB_{L_i}$ = lateral distance from beginning of encroachment range i to first hazard within the range.

The total accident costs for any site can then be determined by multiplying the collision probability from Equation 4 by the encroachment frequency and the accident cost of the predicted accident and summing overall possible accident types:

$$AAC = \sum_W \sum_V \sum_\theta \sum_i P(C^{W,i}_{V,\theta}\ E^{W}_{V,\theta})\ AC^{W,i}_{V,\theta}\ E_f \quad (5)$$

where

AAC = annual accident costs arising from run-off-the-road traffic accidents within the region of interest ($/year),

$E_f$ = uncontrolled encroachment frequency (encroachments per mile per year),

$\sum_W$ = summation over all encroachment vehicle sizes,

$\sum_V$ = summation over all encroachment velocities,

$\sum_\theta$ = summation over all encroachment angles,

$\sum_i$ = summation over all encroachment ranges, and

$AC^{W,i}_{V,\theta}$ = accident costs associated with an accident involving a vehicle of size W striking hazard i at speed V and angle θ.

Equation 5 is based on the probability of the encroaching vehicle striking the first hazard within encroachment range i. For some predicted accidents, the errant vehicle will penetrate the first hazard within the encroachment range. For example, longitudinal barriers have a performance level beyond which vehicle restraint cannot be assured. When a vehicle is predicted to penetrate the first hazard within the range, it is assumed that the vehicle will strike the next hazard within the range.

Accident costs shown previously were calculated for traffic moving in only one direction. A similar procedure was developed for use on two-lane, two-way highways. In this application, the accident prediction algorithm is used twice. The procedure is first used to determine the costs of accidents resulting from vehicles leaving the right side of the roadway. Then accident costs are developed in an analogous procedure for accidents involving vehicles leaving the left size of the roadway. Encroachments from the right lane have been shown to comprise approximately 65 percent of all encroachments (6,8). For two-lane roadways, the remaining encroachments must originate from the left side of the travelway.

## Encroachment Characteristics

The accident prediction model described requires a knowledge of certain characteristics of uncontrolled encroachments including frequency, speed, angle, and lateral movement. Few pure encroachment data are currently available. The largest data base containing pure encroachment information was collected on Canadian highways by Cooper (9). Unlike other efforts (10), this study involved highways with operating speeds in the same range as those on most U.S. highways today. Therefore findings from Cooper (9) were used to determine both encroachment frequency and lateral movement information. Cooper collected encroachment frequency data on relatively straight, flat sections of roadways of two different classes, four-lane divided and two-lane, two-way. These data included both controlled and uncontrolled encroachments. Accident data have been used to adjust encroachment frequencies from Cooper to eliminate controlled encroachments (11,12). The adjusted encroachment frequency curves are shown in Figure 3. Accident data have also been used to develop encroachment frequency adjustment factors, given in Table 1, to account for the effects of vertical or horizontal curvature on encroachment frequency (13).

Cooper also collected information on the lateral extent of encroachment. Information on lateral extent of encroachment from other sources is considered unrepresentative of modern accident characteristics because it involves either high-speed traffic (speed limit of 70 mph) (10) or was collected from accident data (8). Distributions of lateral vehicle movement developed from Cooper's data show few vehicles encroaching less than 10 ft before returning to the roadway. Many of the highways studied had paved or graveled shoulders that tend to hide evidence of encroachments with short lateral extent. Data on lateral extent of movement from Cooper have been adjusted by curve fitting the data points beyond 12 ft (the widest shoulder width in the study) to eliminate the effects of paved shoulders. Figure 4 shows both the raw and the adjusted lateral extent of movement distributions from Cooper (9). Note that for very short encroachments, the probability of lateral encroachment is greater than 1. Thus the curve in Figure 4 serves as an adjustment for the encroachments of short lateral extent that were not detected in the encroachment study.

No pure encroachment data published to date have contained any information on encroachment speed. Encroachment velocity and angle are known to be related. Therefore encroachment angle data are be-

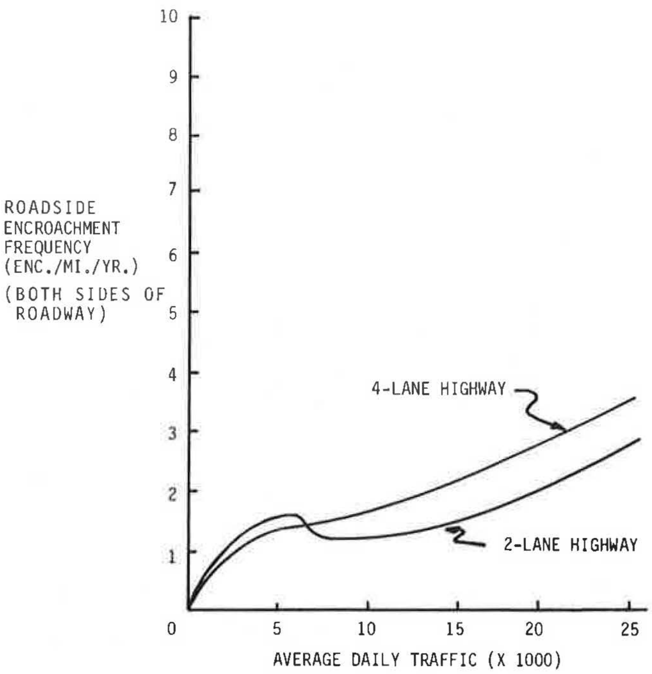


**FIGURE 3 Adjusted encroachment frequencies (7).**

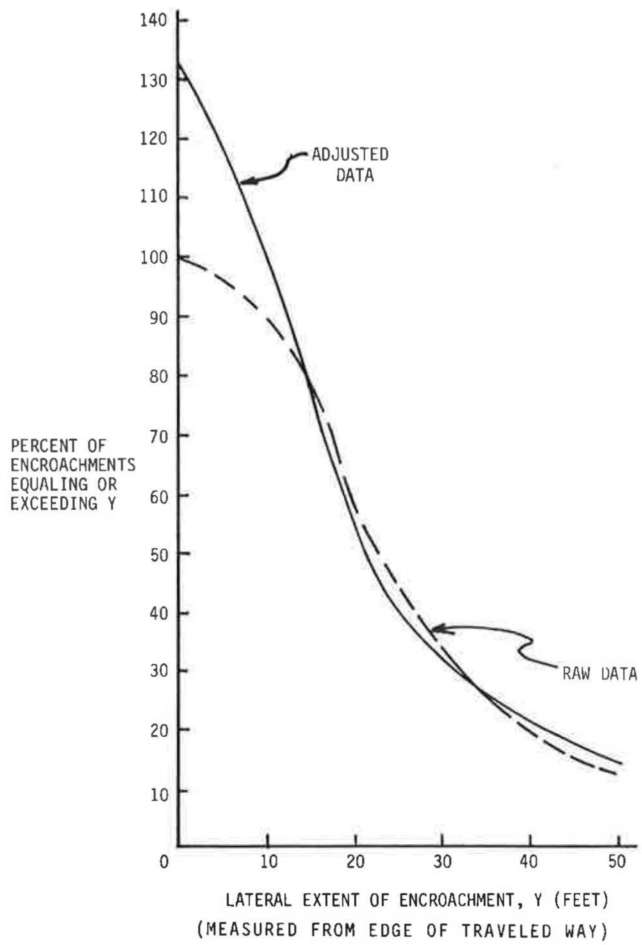


**FIGURE 4 Adjusted lateral encroachment distribution (9).**

**TABLE 1 Encroachment Frequency Adjustment Factors for Horizontal and Vertical Alignment *(13)***

| | Encroachment Location with Respect to Curve | | | |
|---|---|---|---|---|
| | Inside | | Outside | |
| Roadway Curvature (degrees) | Uphill or Moderate Downhill Grade (>-2%) | Steeper Downhill Grade (≤-2%) | Uphill or Moderate Downhill Grade (>-2%) | Steeper Downhill Grade (≤-2%) |
| 0-3 | 1.00 | 0.80 | 1.00 | 0.80 |
| 3.01-6 | 1.24 | 2.06 | 2.76 | 4.60 |
| >6 | 1.98 | 4.00 | 4.42 | 9.00 |

lieved to be of little value without accompanying speed data. The best available method of estimating combined impact speed and angle distributions is through computer reconstruction of traffic accidents (7,14). Table 2 gives the distribution of freeway encroachment speeds and angles developed from Mak et al. (7) and Mak and Calcote (14). Although impact speed distributions developed from accident data are biased toward high impact speeds, accident severities from these distributions are more representative of real-world accidents than are severity estimates based solely on high-speed impacts. Distributions such as the ones given in Table 2 have been developed for a variety of functional classes of highways. The procedure described herein uses the appropriate distribution based on the functional class of highway under consideration.

Although small vehicles have been shown to be overrepresented in reported accident data, it is believed that much of this overrepresentation is the result of reduced crashworthiness of small automobiles rather than an increased encroachment probability. Few data are currently available to relate encroachment probability to vehicle size. Therefore it has been assumed that encroachment rates are independent of vehicle size and that the probability of an encroaching vehicle being of a particular size is equal to the decimal fraction of vehicles of that size in the traffic stream.

## Accident Costs and Performance Levels

Accident costs of primary interest in a B-C analysis are the societal costs that result from occupant injury and vehicle damage and the direct highway agency costs that arise from damage to highway facilities. Societal and direct costs are strongly related to the performance of the highway appurtenance that is struck. For example, if a barrier contains and redirects an impacting vehicle, the expected societal costs will normally be well below those of an accident involving barrier penetration. Thus the performance level of a safety device must be defined before accident costs can be determined.

The impact performance of highway appurtenances is generally believed to be limited by the degree of impact loading the device can safely withstand or attenuate. For barriers, the degree of loading has been shown to be related to the impact severity (IS) (15-17):

$$IS = 1/2\ m(V \sin \theta)^2 \qquad (6)$$

where

IS = impact severity (ft-lb),
m = vehicle mass ($lb\text{-}sec^2$),
V = vehicle impact velocity (ft/sec), and
$\theta$ = vehicle impact angle (angle between resultant velocity vector and face of barrier) (degrees).

For the B-C algorithm described herein, the performance level for barriers is measured in terms of impact severity. For other devices, such as crash cushions, performance level is measured in terms of total kinetic energy of the impacting vehicle.

Societal costs have traditionally been linked to the severity or probability of injury to vehicle occupants through a severity index scale. This scale was first developed in the mid-1970s (2) and has since been updated to reflect current cost figures (12). Table 3 gives the severity index scale from Bronstad and Michie (16).

**TABLE 3 Severity Index Scale**

| Severity Index | PDO Accidents[a] (%) | Injury Accidents (%) | Fatal Accidents (%) | Societal Cost per Accident ($) |
|---|---|---|---|---|
| 0 | 100 | 0 | 0 | 1,600 |
| 1 | 85 | 15 | 0 | 3,450 |
| 2 | 70 | 30 | 0 | 5,500 |
| 3 | 55 | 45 | 0 | 7,500 |
| 4 | 40 | 59 | 1 | 15,800 |
| 5 | 30 | 65 | 5 | 42,400 |
| 6 | 20 | 68 | 12 | 87,900 |
| 7 | 10 | 60 | 30 | 203,000 |
| 8 | 0 | 40 | 60 | 393,000 |
| 9 | 0 | 21 | 79 | 513,000 |
| 10 | 0 | 5 | 95 | 614,000 |

[a]PDO refers to those accidents in which property damage only is involved.

Crash testing and simulations have been used to estimate impact severities of many common highway hazards in terms of vehicle accelerations and damage. Vehicle accelerations have been linked to occupant injury by comparing damage to crash test vehicles and damage to vehicles involved in traffic accidents (18). Procedures from Olson et al. (18) can be used to estimate crash test injury probabilities from measured vehicle accelerations. However, crash testing is normally conducted at speeds near 60 mph. A large gap therefore exists in severity indices data for roadside features at speeds of less than 60 mph. In the absence of test data, the researchers have assumed a linear relationship between the severity index, given in Table 3, and impact speed. It should be noted that linearity is assumed between severity index and impact speed, not severity per se. As can be seen from Table 3, accident costs increase exponentially as the severity index increases. Figure 5 shows severity indices of W-beam guardrail accidents derived from measured crash test accelerations. Crash test data used in the development of Figure 5 were collected from tests involving full-sized, subcompact, and mini-sized vehicles. Note that most crash tests involve impact angles of 15 and 25 degrees. Therefore severity indices for other impact angles must be interpolated and extrapolated from the curves shown in Figure 4.

Costs that arise from damage to a highway ap-

**TABLE 2 Combined Impact Velocity and Angle Distributions from Accident Studies *(9,10)***

| Speed (mph) | Combined Gamma Function Probabilities for Angle (degrees) | | | | | | |
|---|---|---|---|---|---|---|---|
| | <5 | 5-15 | 15-25 | 25-35 | 35-45 | >45 | Total |
| <20 | .0429 | .1862 | .1163 | .0466 | .0157 | .0067 | .414 |
| 20-30 | .0268 | .1163 | .0726 | .0291 | .0098 | .0042 | .259 |
| 30-40 | .0168 | .0732 | .0458 | .0183 | .0062 | .0026 | .163 |
| 40-50 | .0093 | .0392 | .0245 | .0098 | .0033 | .0014 | .088 |
| 50-60 | .0044 | .0191 | .0119 | .0048 | .0016 | .0007 | .043 |
| >60 | .0035 | .0152 | .0095 | .0038 | .0013 | .0005 | .034 |
| Total | .104 | .4490 | .2810 | .1120 | .1790 | .016 | |

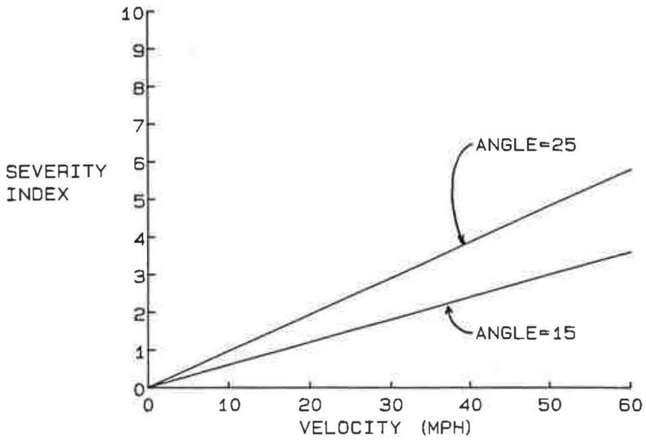


**FIGURE 5** W-beam guardrail crash test severity indices.

purtenance are generally believed to be proportional to the degree of impact loading on the appurtenance. Bronstad and Michie (16) and Ivey et al. (17) have shown that IS is approximately proportional to the degree of barrier loading and that it follows that barrier repair costs should be roughly proportional to IS. Figure 6 shows repair costs for W-beam guardrail estimated from crash test results. Repair costs of other safety appurtenances are assumed to be roughly proportional to the total kinetic energy of the impacting vehicle. More detailed descriptions of performance level and accident cost determination can be found elsewhere (5).

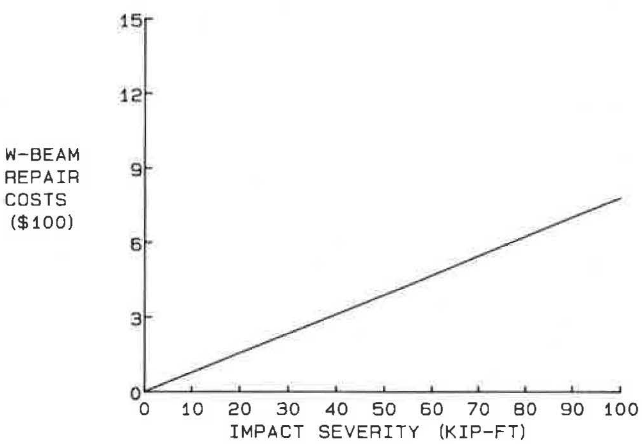


**FIGURE 6** W-beam guardrail repair costs.

## Improvements to the B-C Model

The B-C model described herein has incorporated most of the improvements found in all previous models. Additional modifications have been added to improve accuracy and enhance the capability of the algorithm, including shielding of one obstacle by another, accident cost and appurtenance repair as a function of accident impact conditions, use of reconstructed accidents to predict impact conditions, and relating appurtenance performance to impact conditions.

## Applications

The encroachment probability model on which the B-C model is based is general in nature and can therefore be used to study a wide variety of highway conditions. These models are well suited for use in developing general safety treatment guidelines or policies (5).

For example, a common problem faced by many highway engineers is how to safely treat the slope hazard at deep fill sections. In such cases an engineer must determine whether to place the slope breakpoint away from the shoulder by increasing the amount of fill material and to use a barrier to shield the slope. Safety treatment alternatives for deep fill sections, shown in Figures 7 and 8, include increas-

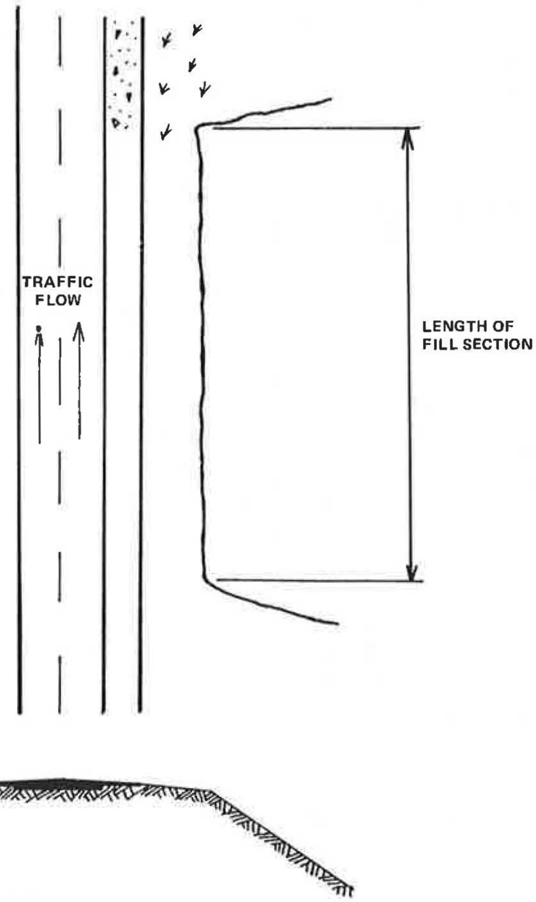


**FIGURE 7** Typical barn roof fill section.

ing the available recovery area by moving the slope breakpoint away from the travelway and using W-beam guardrail to shield the slope. Typical cost and severity data for safety treatments of a 20-ft-deep fill section are presented next. (Note that for this example the severity of a 60-mph encroachment onto a deep 1 1/2:1 slope is estimated to correspond to a severity index of 8.0. Impact severities for other speeds are estimated on the basis of the assumed linear relationship between impact speed and severity index discussed previously. Further, the severity of impact with steep roadside slopes is assumed to be relatively independent of impact angle.)

1. Safety alternative costs
   - W-beam barrier, $15/ft;
   - Repair costs, $7.8/ft-kip (IS) (see Figure 6);
   - Performance level, 97 kip-ft; and
   - Cost of additional fill, $5/yd (in place).
2. Accident severity indices
   - W-beam barrier

Impacts below PL (Figure 5)
Impacts above PL SI = 7.0

- 1.5:1 slope SI = 0.133 x impact velocity (mph)

Additional input data sources and highway descriptors were assumed to be as follows:

| Variable | Assumed Value or Source |
|---|---|
| Accident costs | Table 3 |
| Discount rate | 4 percent |
| Project duration | 20 years |
| Roadway alignment | Straight, flat |
| Functional highway class | Freeway |
| Type of highway | Four-lane, divided |
| Encroachment speeds and angles | Table 2 |
| Lateral vehicle movement | Figure 4 |

The B-C model was then used to determine the relative benefits and costs for barrier-protected and unprotected slopes with the slope breakpoint offset 3, 15, 30, and 45 ft from the traveled way. The most cost beneficial alternative was determined for a wide variety of fill section lengths and traffic volumes. General guidelines for safety treatment of deep fill sections were then developed as shown in Figure 9.

Another application of the B-C analysis algorithm described herein is in the study of special or new safety appurtenances and unusual sites. General guidelines, such as those shown in Figure 9, cannot be applied to all situations. Further, some safety appurtenances are designed for special sites that cannot be generalized. Highway engineers have expressed a need for a method of studying these special situations whenever they arise. Finally, this algorithm provides for the first time an objective method for determining optimum barrier flare rates and optimum barrier runout lengths in front of fixed hazards.

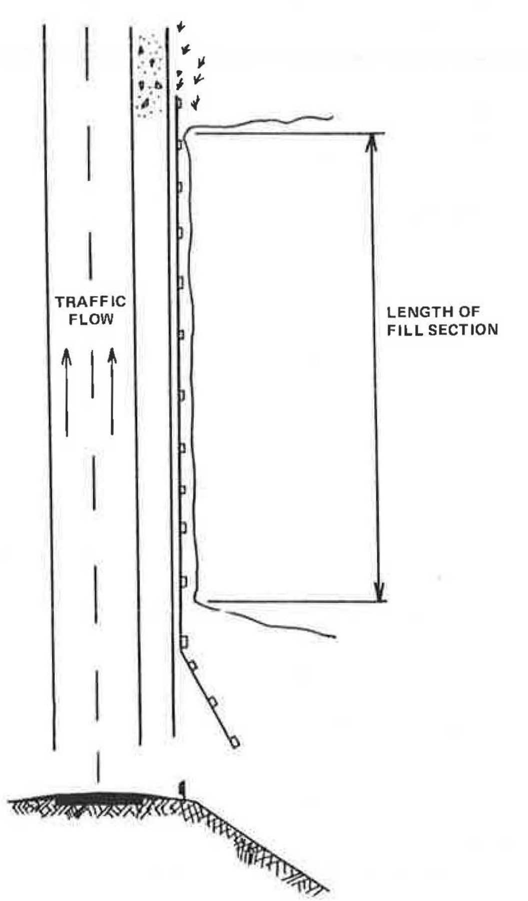


FIGURE 8 Typical guardrail placement on fill section.

## Limitations

As shown in the foregoing discussion, encroachment models have been developed to study accident frequencies of roadside hazards. These models are not designed to examine other types of accidents such as multiple-vehicle accidents. Therefore this technique cannot be used to study most safety treatments at intersections or to determine warrants for median barrier applications.

Another limitation of encroachment probability models is found in the determination of accident severity based on predicted impact conditions. Accident severity is an important factor in determining the total accident costs of a safety alternative. There is still only a tenuous link between impact conditions and accident severity. Further, accident severities of some hazards, such as dropoffs and roadside slopes, are quite difficult to quantify. Thus the model has a limited value in the analysis of problems in which the severity of potential accidents cannot be estimated.

## CONCLUSIONS

The B-C procedures described herein represent a significant improvement over existing procedures in the accuracy and versatility of analysis of the need for safety improvements. The technique is based on the best accident, encroachment, and impact severity information currently available. When better data become available, they should be incorporated into the procedures. The computer model can be used to develop general roadside safety appurtenance use guidelines. The FHWA has adopted the model for developing barrier use guidelines for the update to the 1977 barrier guide.

Microcomputer versions of this program should allow practicing highway engineers to apply these procedures without the difficulty associated with most other methods. Therefore this B-C model should allow more potential safety improvement projects to be analyzed in terms of the expected benefits and costs, thereby resulting in a more efficient application of available highway improvement dollars.

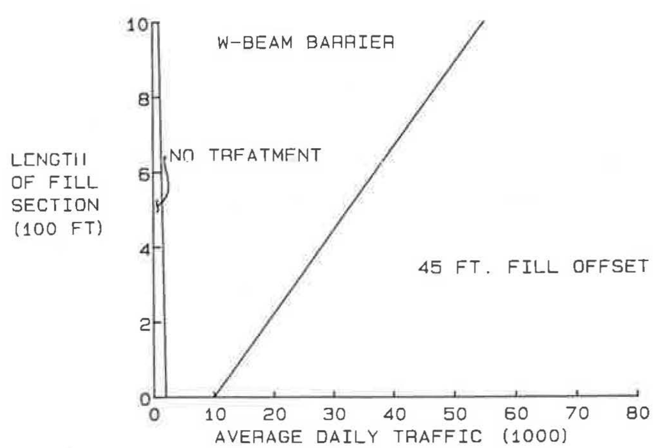


FIGURE 9 Guidelines for safety treatment of fill section 20 ft deep.

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