NCHRP

REPORT 492

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Roadside Safety Analysis Program (RSAP)— Engineer's Manual

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Roadside Safety Analysis Program (RSAP)—Engineer's Manual

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SUBJECT AREAS

Highway and Facility Design • Safety and Human Performance

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in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The research reported herein was performed initially under NCHRP Project 22-9 and later completed under NCHRP Project 22-9(2). The initial project was performed by the Texas Transportation Institute (TTI), with the University of Nebraska–Lincoln (UNL) as a subcontractor on the project. King K. Mak, Research Engineer, TTI, was the principal investigator and Dean L. Sicking, Director, Midwest Roadside Safety Facility, UNL, was the co-principal investigator. The other primary research staff for the project consisted of Karl Zimmerman, graduate research assistant, UNL, who programmed the main analysis program. The follow-on project under NCHRP Project 22-9(2) was performed by King K. Mak, consultant, and assisted by Dean L. Sicking and Karl Zimmerman. Programming of the user interface program was performed by Capsher Technology, with Kevin Sherry as the lead programmer.

The research staff would like to recognize the support and guidance provided by the two NCHRP project panels. The panel members for these projects include Mr. Thomas E. Bryer (chair), Pennsylvania DOT; Mr. Eugene D. Arnold, Jr., Virginia Transportation Research Council: Mr. James H. Hatton, Jr., Mr. Harry W. Taylor, Mr. John G. Viner, and Mr. Joe Bared, FHWA; Dr. Thomas L. Maleck, Michigan State University; Mr. Daniel Paddick, New York DOT; Mr. Thomas H. Scheck, Arizona DOT; and Mr. Charles Sanders, Illinois DOT.

The alpha and beta versions of the RSAP program were reviewed and tested by various members of the project panel and other interested organizations and individuals, including members of the AASHTO Task Force on Roadside Safety. There was also an independent review conducted by Dr. Snehamay Khasnabis of Wayne State University. Comments from the reviewers and testers were instrumental in improving and enhancing the program and are gratefully acknowledged.

FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report presents the findings of a research project to develop an improved cost-effective analysis procedure for assessing roadside safety improvements. The project objective has been accomplished with the development of the Roadside Safety Analysis Program (RSAP). The report will be of particular interest to roadside safety engineers with responsibility for evaluating the impacts of roadside safety improvements.

Highways are designed to provide motorists with reasonable levels of protection against serious ran-off-road crashes. The clear zone concept has been the cornerstone of this protection philosophy for many years. Under this philosophy, roadside hazards within the clear zone are either eliminated or moved. When hazards cannot be removed or relocated, a determination needs to be made if a safety device (e.g., guardrail or crash cushion) is warranted to protect motorists from the roadside obstacle.

When determining locations and the types of roadside safety devices to be used, it is necessary to weigh the risk of death or injury to the motoring public against the initial cost of installing and maintaining the safety improvement. Many decisions are relatively straightforward and covered under established guidelines and warrants. However, there are instances where the choice of safety treatment is not readily apparent.

Incremental benefit/cost analysis has been widely accepted as the most appropriate method for evaluating safety alternatives. Benefits are measured in terms of the reduction in crash or societal costs associated with a safety improvement while costs are defined as the increase in direct highway agency expenditures associated with the improvement. Benefit/cost analysis compares a safety treatment with the existing or baseline condition or alternative safety treatments. The basic concept is that public funds should be invested only in projects where the expected benefits exceed the expected direct costs of the project. Benefit/cost analysis procedures can be used to study individual sites or to develop general guidelines.

Under NCHRP Projects 22-9 and 22-9(2), "Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features" and "Roadside Safety Analysis Program (RSAP) Enhancement, Update, and Testing," respectively, the Texas Transportation Institute and Mr. King Mak undertook research to develop an improved cost-effectiveness analysis procedure for assessing roadside safety improvements. The product of these research efforts is the Roadside Safety Analysis Program (RSAP).

RSAP is based on the encroachment probability approach and incorporates two integrated programs: the Main Analysis Program, which contains the cost-effectiveness procedure and algorithms; and the User Interface Program, which provides a user-friendly environment for data input and review of program results. The cost-effectiveness procedure incorporated into RSAP is based on the concept of incremental benefit/cost analysis. The encroachment model uses roadway and traffic information to estimate the expected encroachment frequency along a highway segment.

This report describes the inner workings of the cost-effective analysis procedure and the various algorithms and data sources built into the procedure. A separate User's Manual describing the User Interface Program (including the data input process and the program reports) and the RSAP software are on *CRP-CD-33*, which is included with this report.

CONTENTS

CHAPTER **1**

INTRODUCTION

1.1 BACKGROUND

Modern highways are designed to provide motorists with reasonable levels of protection against serious ran-off-road crashes. The clear zone concept has been a cornerstone of this protection philosophy for many years. Under this philosophy, roadside hazards within the clear zone are either eliminated or moved away from the travelway whenever possible. When hazards cannot be removed or relocated, designers need to determine if a safety device, such as a guardrail or a crash cushion, is warranted to protect motorists from the roadside obstacle. The recent introduction of multiple performance or test levels for roadside safety devices has further complicated the safety decision process.

When determining locations and types of roadside safety devices to be used, an engineer needs to weigh the risk of death or injury to the motoring public against the initial cost of installing and maintaining safety improvements. Many decisions are relatively straightforward and are covered under established guidelines and warrants. For example, the need for breakaway sign and luminaire supports along high-speed facilities is well known, as is the importance of appropriate approach guardrails and transition sections for bridge railings. General guidance for use of breakaway devices, longitudinal barriers, and other safety features, are presented in various places, most recently in the 2002 edition of the AASHTO *Roadside Design Guide*[1].

However, sometimes the choice of safety treatment is not as readily apparent, such as for low-volume and/or low-speed roadways. Further, with the advent of multiple performance levels, the decision has become more complicated. Highway engineers have to determine whether or not to use a safety treatment, and they also have to select the appropriate performance level for each situation. Rehabilitation projects present unique problems in that the existing safety hardware may be outdated and not meeting current performance standards, but still offer some level of protection. In these situations, engineers need an analytical technique to determine what specific safety treatment is the most appropriate for the given site conditions.

Incremental benefit/cost analysis has been widely accepted as the most appropriate method for evaluating safety alternatives. Benefits are measured in terms of the reduction in crash or societal costs associated with a safety improvement while the cost is defined as the increase in direct highway agency expenditures associated with the improvement. Benefit/cost analysis compares a safety treatment with the existing or baseline conditions (i.e., the do-nothing option) and/or alternative safety treatments. The basic concept is that public funds should be invested only in projects where the expected benefits would exceed the expected direct costs of the project. Benefit/cost analysis procedures can be used to study individual sites or they can be used to develop general guidelines. For example, the ROADSIDE program, presented in Appendix A of the 1988 and 1996 versions of the *Roadside Design Guide*, is a benefit/cost analysis program intended for use with site-specific decision-making processes. Another benefit/cost analysis program, called the Benefit/Cost Analysis Program (BCAP), was used to develop the bridge rail selection guidelines contained in the 1989 AASHTO *Guide Specifications for Bridge Railings*.[2]

Another consideration is the current trend toward tailoring the use of roadside safety appurtenances to the specific highway and site conditions by providing various performance or test levels. The 1989 AASHTO *Guide Specifications for Bridge Railings* established three performance levels for bridge railings. *NCHRP Report 350*: *Recommended Procedures for the Safety Performance Evaluation of Highway Features*[3], outlines six test (performance) levels for roadside safety features, including work zone traffic control devices. Currently, no guidelines have been established for field application of these test levels. A research study, NCHRP Project 22-12, “Guidelines for the Selection, Installation, and Maintenance of Highway-Safety Features,” is underway to develop guidelines for the various test levels using the benefit/cost analysis technique.

Existing procedures for benefit/cost analysis of roadside conditions have varying degrees of usefulness.[4–26] Several of these procedures are for specific roadside objects or features, such as utility poles or luminaire supports, and are of little general use. Other procedures are either obsolete or have outdated supporting data. A notable example is the procedure in the 1977 AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers*[17], which was state-of-the-art in the mid-1970s. Also, some of the procedures are not computerized and require extensive manual computations. The result is a time-consuming and sometimes inaccurate mix of tools for making decisions about roadside safety.

1.2 STUDY OBJECTIVES AND SCOPE

The objective of this study is to develop an improved cost-effectiveness analysis procedure for use in assessing roadside safety improvements. The new procedure will do the following:

- Incorporate new or improved data and algorithms wherever available;
- Be capable of evaluating alternative roadside safety treatments at spot locations and over sections of roadway;
- Be applicable for development of warrants and guidelines of safety features with different performance levels;
- Provide a framework that will allow rapid incorporation of new data, such as the driver responses to ran-off-road situations to be developed under NCHRP Project 17-11; and
- Be computerized and easy to use (i.e., be user-friendly).

The result of this research effort is the development of a new improved cost-effectiveness procedure, known as the Roadside Safety Analysis Program (RSAP). RSAP is based on the encroachment probability approach and incorporates two integrated programs: the Main Analysis Program, which contains the cost-effectiveness procedure and algorithms, and the User Interface Program, which provides a user-friendly environment for data input and review of the program results. This report, the Engineer's Manual, describes the inner workings of the cost-effectiveness analysis procedure and the various algorithms and data sources built into the procedure. A separate User's Manual describes the User Interface Program, including the data input process and the program reports. This User's Manual and the RSAP software are provided on the accompanying CD-ROM.

Chapter 2 summarizes the various existing cost-effectiveness analysis procedures. An overview of RSAP is presented in Chapter 3. The major components of RSAP are described in Chapters 4 through 8: Chapter 4—Monte Carlo Simulation Technique; Chapter 5—Encroachment Module; Chapter 6—Crash Prediction Module; Chapter 7—Crash Severity Prediction Module; and Chapter 8—Benefit/Cost Analysis Module. The validation effort for RSAP is presented in Chapter 9, and the summary of findings and conclusions are presented in Chapter 10.

CHAPTER **2**

LITERATURE REVIEW

Several benefit/cost (and/or cost-effectiveness) analysis procedures have been developed over the past 30 years. These procedures can be grouped into two general categories: encroachment probability based or crash data based. These two categories of procedures vary in the analysis methodology, the source of data used, and in their predictive power and general usefulness. Brief descriptions of existing cost-effectiveness analysis procedures and their limitations are presented in this chapter.

2.1 ENCROACHMENT PROBABILITY BASED PROCEDURES

The underlying assumption of an encroachment probability based model is that crash frequency is proportional to encroachment frequency, which is a function of the highway type or functional class and average daily traffic. Encroachments are assumed to occur randomly and uniformly along any length of straight and level roadway. In other words, a vehicle has an equal probability of encroaching at any point along a straight and level roadway. However, crash data have shown that crash frequencies are higher at certain locations, such as at horizontal curves and on vertical grades. Thus, it can be expected that encroachment frequencies would also be higher at such locations. The first major element of an encroachment probability based model is, therefore, the determination of a base or average encroachment frequency for the highway type and average daily traffic under evaluation. The base encroachment frequency is then adjusted for parameters that may affect the encroachment rate.

The second major element of an encroachment probability model involves linking encroachment frequency to crash frequency. This link is established by determining the region, known as the hazard envelope, along the travelway wherein an encroaching vehicle would impact the roadside feature under consideration. As shown in Figure 1, the hazard envelope is constructed assuming that the vehicle encroaches along a straight path. This straight vehicle path assumption is necessitated by the lack of quantitative information on vehicle and driver behavior after encroaching into the roadside and the complexity of modeling a curvilinear vehicle path.

The hazard envelope is a function of the size and orientation of the vehicle, the size and lateral offset of the hazard, and the encroachment angle. For a given vehicle of size w, encroachment speed v, encroachment angle θ, and orientation ψ, the vehicle will strike the hazard if it leaves the road within the envelope and does not stop before it reaches the hazard. The probability, $P(H^{w\theta}_{v\psi} \mid E^{w\theta}_{v\psi})$, that an encroaching vehicle is within the hazard envelope ($H^{w\theta}_{v\psi}$), given that the vehicle is of size w and encroaches with speed v, angle θ, and orientation ψ ($E^{w\theta}_{v\psi}$), is shown in the following equation:

$$P(H^{w\theta}_{v\psi} \mid E^{w\theta}_{v\psi}) = (1/5280) * [L_h + (W_e/\sin\theta) + W_h \cot\theta] \qquad (1)$$

where

L_h = Length of hazard (m)
W_e = Effective width of vehicle (m) = $L_v \sin\psi + W_v \cos\psi$
L_v = Length of vehicle (m)
W_v = Width of vehicle (m)
W_h = Width of hazard (m)

The probability of collision is then calculated by incorporating the probability that the vehicle will encroach far enough laterally to reach the hazard in question. As shown in Figure 1, given that the face of the hazard (Zone 3), the upstream corner of the hazard (Zone 2), and the end or width of the hazard (Zone 1) all have different lateral offsets from the edge of the travelway, the equation has to incorporate the differing probabilities of reaching different lateral offsets. Thus, the probability, $P(C^{w\theta}_{v\psi} \mid E^{w\theta}_{v\psi})$, that a vehicle—of size w, encroaching with a given speed v, angle θ, and orientation ψ—is within the hazard envelope and encroaching far enough to impact the hazard is given by Equation 2:

$$P\left(C^{w\theta}_{v\psi} \middle| E^{w\theta}_{v\psi}\right) = (1/5280) * \Bigg[L_h * P(L_e \geq A) + \sec\theta * \csc\theta * \sum_{j=1}^{W_e \cos\theta} * W_e P(L_e \geq B) + \cot\theta * \sum_{j=1}^{W_h} P(L_e \geq C) \Bigg] \qquad (2)$$

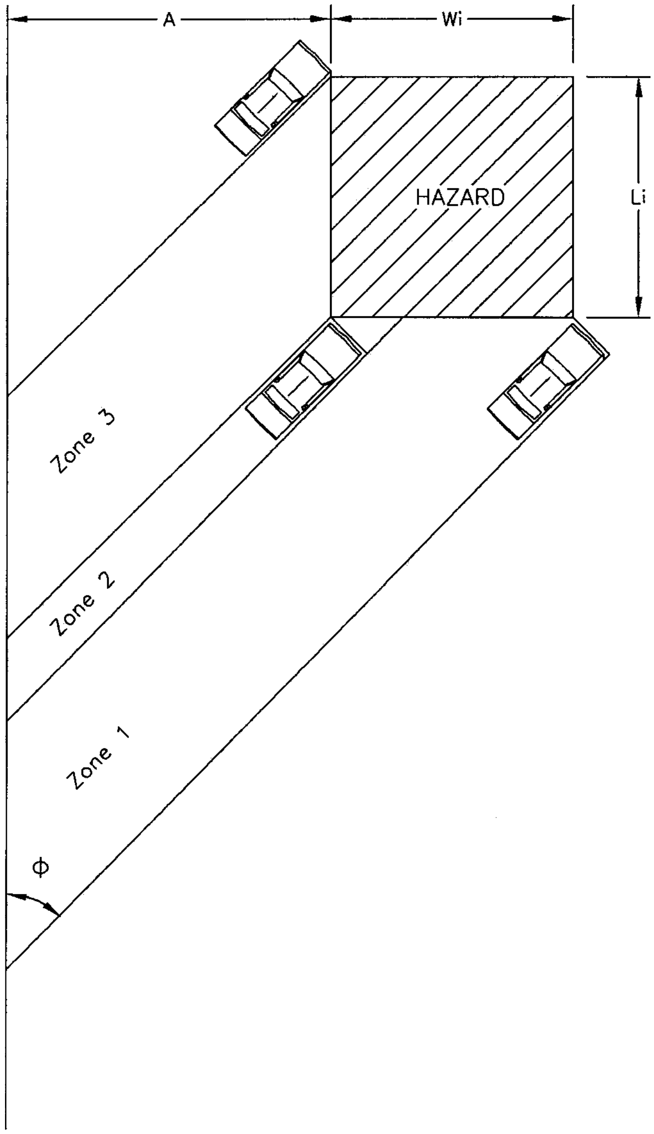


Figure 1. Hazard envelope.[15]

where

B = Lateral offset to upstream corner of hazard (Zone 2) $= (A + j - 2)$, where j is a variable from 1 to $W_e \cos\theta$
C = Lateral offset to end or width of hazard (Zone 1) $= (A + W_e \cos\theta + j - 2)$ where j is a variable from 1 to W_h.

The probability of an impact on a hazard, $P(C|E)$, given an encroachment per kilometer of roadway is, therefore, the probability of the encroachment with a given vehicle size w, encroachment speed v, encroachment angle θ, and vehicle orientation ψ, $P(E^{w\theta}_{v\psi}|E)$, multiplied by the probability of collision, $P(C^{w\theta}_{v\psi}|E^{w\theta}_{v\psi})$, and summed over all vehicle size, encroachment speed, encroachment angle, and vehicle orientation, as shown in Equation 3:

$$P(C|E) = \sum_{w}\sum_{v}\sum_{\theta}\sum_{\psi} P\left(E^{w\theta}_{v\psi}|E\right) * P\left(C^{w\theta}_{v\psi}|E^{w\theta}_{v\psi}\right) \qquad (3)$$

where

$P(C|E)$ = Probability of a crash given an encroachment
$P(E^{w\theta}_{v\psi}|E)$ = Probability of an encroachment with a given vehicle type w, speed v, angle θ, and vehicle orientation ψ.
$P(C^{w\theta}_{v\psi}|E^{w\theta}_{v\psi})$ = Probability of a collision for an encroachment with given vehicle type w, speed v, angle θ, and vehicle orientation ψ.

The third major component of the encroachment probability model is the estimation of crash severity. This is done by determining the probability of each injury level (i.e., property-damage-only [PDO], possible injury, moderate injury, severe injury, and fatal injury) for each impact with the given conditions, (i.e., vehicle type, speed, angle, and so forth). The method of estimating the crash severity varies from model to model.

The fourth major element of the encroachment probability model involves calculations of the crash costs and the resulting benefit/cost ratios. Crash costs are estimated by multiplying the probability of each injury level by the cost associated with each injury level. The expected cost of a crash, multiplied by the probability of that crash, yields the expected cost of the encroachment. Multiplying the cost per encroachment by the encroachment frequency gives an estimate of the annual crash cost. Finally, the benefit/cost ratios are determined. Benefits are expressed in terms of reduction in crash costs while costs are expressed in terms of the difference in direct costs to the agency.

The following sections describe the historical development of the relevant encroachment probability models and real-world crash data models, respectively.

2.1.1 Encroachment Data

There are only three previous studies on encroachment data: Hutchinson and Kennedy[29], Cooper[30], and Calcote et al.[31] The Hutchinson and Kennedy study involved observation of wheel tracks on medians of rural interstate highways in Illinois in the mid 1960s.[29] The encroachment frequency as a function of traffic volume is shown in Figure 2.

In general, the encroachment frequency increases proportionally to the traffic volume. However, between traffic volumes of 3,000 to 6,000 vehicles per day, the encroachment frequency exhibits a decrease with increase in traffic volume. This unusual shape of the curve can be explained when driver behavior is taken into consideration. At low traffic volumes, drivers have little contact with other vehicles and tend to drive

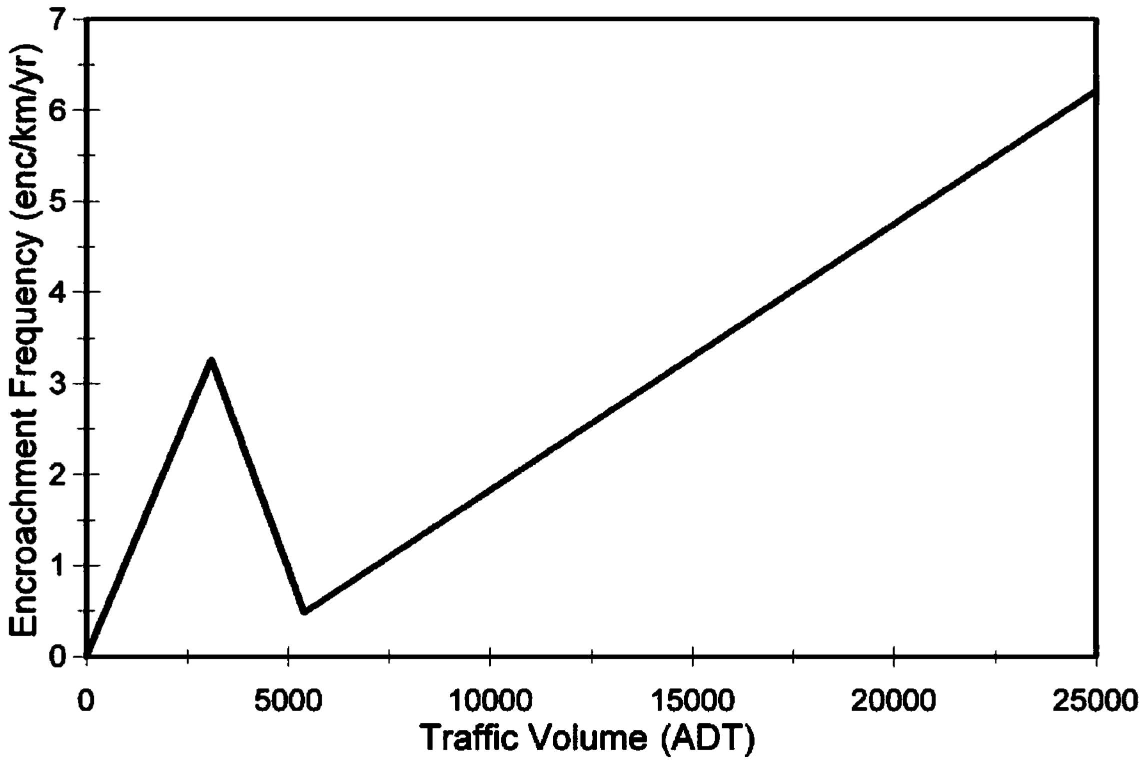


Figure 2. Hutchinson and Kennedy encroachment frequency.[29]

faster and be less attentive to the driving task. This combination of factors could lead to a higher incidence of driver error, such as drowsiness or excessive speed, thus resulting in a higher encroachment rate. As traffic volumes increase, drivers begin to have more interaction with other traffic, which tends to better define the roadway and reduce the monotony, resulting in the driver paying more attention to the driving task and less driver error. Above traffic volumes of 6,000 vehicles per day, the encroachment rate begins to rise again because of increased vehicle-to-vehicle interactions.

The Hutchinson and Kennedy study has some limitations, however. First, determining whether a vehicle was under control or not by observing wheel tracks is an unreliable method. Although snow in the median is believed to be a significant deterrent to vehicles intentionally leaving the roadway (i.e., a controlled encroachment), some of the tracks observed reportedly involved vehicles making U-turns in snow-covered, paved medians. Another problem with the wintertime observation period is increased adverse weather conditions, which could cause an increase in uncontrolled encroachments. Another problem is that the encroachment data were collected only on interstate highways, and it may be argued that the data could not and should not be extrapolated to other functional classes. Finally, the encroachment data were collected on relatively straight and flat sections of highways with little information on horizontal curves and vertical grades to determine what effects these parameters had on encroachment rates. The combination of higher operating speeds on interstate highways and adverse weather conditions would suggest that the probability of encroachment is likely to be overestimated by the Hutchinson and Kennedy encroachment data.

Cooper conducted a similar encroachment study in Canada in the late 1970s.[30] This research involved weekly observations of wheel tracks on grass-covered roadsides of rural highways of various functional classes. The data collection periods were during summer months on highways with speed limits between 80 to 100 km/h. As a result, adverse weather conditions were under-represented, and the speeds were considerably lower than those found on interstate highways. The encroachment frequencies observed by Cooper are shown in Figure 3.

The Cooper study suffers from the same problem of not being able to distinguish between controlled and uncontrolled encroachments. Summertime is also a period of increased roadway maintenance and farm activity with slow-moving equipment and vehicles occasionally using the grassy areas on the roadsides. The inclusion of controlled encroachments is believed to have more than offset any reduction in encroachment rates caused by better weather and lower speeds. Also, the encroachment rates observed by Cooper are somewhat lower than those observed by Hutchinson and Kennedy, which is not surprising given the better weather conditions and lower traffic speeds. A similar hump in the curve at traffic volumes of 3,000 to 6,000 vehicles per day is also present for the

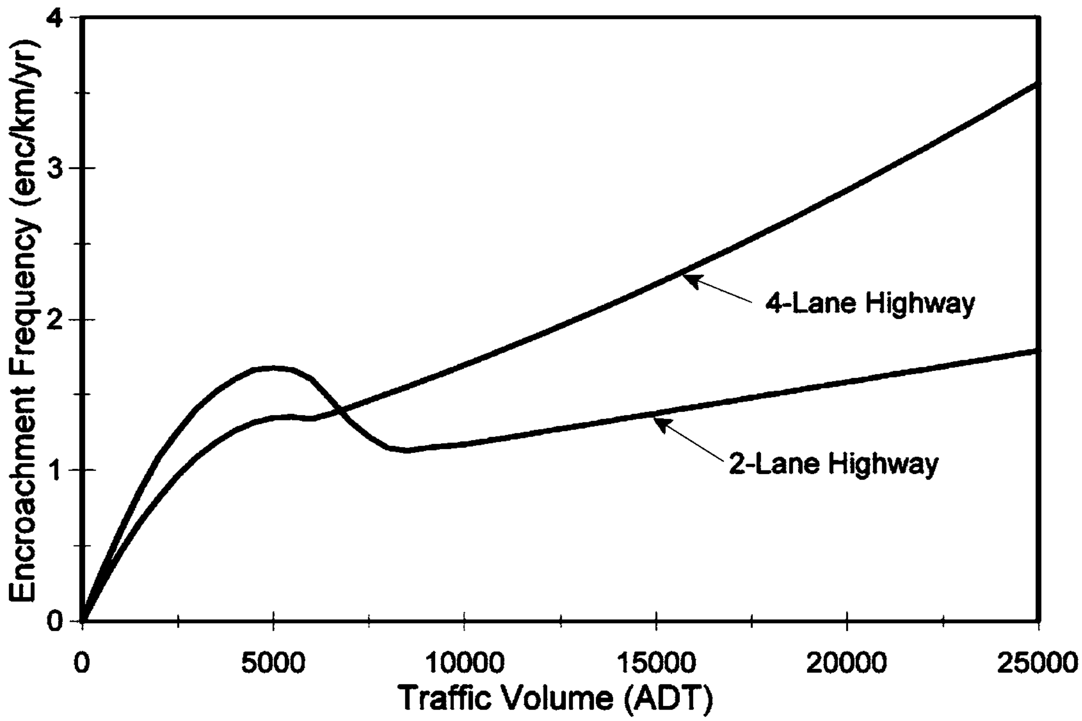


Figure 3. Cooper encroachment frequency.[30]

Cooper data. Furthermore, because of the presence of paved shoulders, encroachments within or just beyond the shoulder area would be difficult to detect. Thus, it is believed that the Cooper encroachment data are under-reported for encroachments with small lateral extent, perhaps in the 0 to 4 m region.

Calcote et al.[31] attempted to overcome the major problems with both the Cooper and Hutchinson and Kennedy studies (i.e., some encroachments are not detected because of paved shoulders and controlled and uncontrolled encroachments are indistinguishable by observing wheel tracks). This research effort used electronic monitoring along rural highways and time-lapse video photography along urban freeways. The electronic monitoring approach was unsuccessful because of technical problems.

The time-lapse video approach recorded numerous encroachments, but still did not offer an effective method to distinguish between controlled and uncontrolled encroachments. An overwhelming majority of the encroachments recorded involved vehicles moving slowly off the roadway for some distance and then returning into the traffic stream without any sudden changes in trajectory. A fatigued or distracted driver drifting off the roadway, or a controlled driver responding to roadway or traffic conditions, could both cause this type of encroachment. By restricting the definition of uncontrolled encroachments to sudden changes in vehicle trajectory or hard braking, only 14 of the approximately 7,000 recorded encroachments were considered to be uncontrolled, which gives a ratio of about 500 controlled encroachments for every uncontrolled encroachment. Also, video monitoring could only be used on relatively short sections of roadway, thus limiting the amount of data that could be obtained. As a result, the findings of this study are not very useful.

The encroachment frequency distributions described above are mostly from straight and level roadway sections. Findings from several crash data analysis studies have shown that highway alignment and profile have significant effects on crash rates. It is reasonable to assume that highway alignment and profile would also have similar effects on encroachments. Thus, the encroachment frequencies should be adjusted accordingly.

The most widely used source of information for adjusting encroachment rates at horizontal curves and vertical grades is the study by Wright and Robertson.[32] This study analyzed 300 single-vehicle, fixed-object fatal crashes in Georgia in an effort to identify roadway and roadside characteristics that could have contributed to the crashes. The researchers compared the characteristics of the fatal crash sites with control sites, 1.6 km upstream of the crash sites. Horizontal curves were significantly over-represented at the fatal crash sites, with the outside of the curve accounting for 70% of the fatal crashes on curves. Downgrades of 2% or more were also found to have some effect, but upgrades were not over-represented.

There are several drawbacks to this study, however. First, the sample size of 300 is relatively small. Second, the study included only fatal crashes, which are extremely rare events and not necessarily representative of crashes of lower severity. Thus, the effects of horizontal curves and vertical grades at crash rates are probably overstated. Third, there was no control for other influential factors, such as highway type and traffic volume. For example, the highway types varied from urban freeways to unpaved rural local roads with wide variations in traffic volumes. Furthermore, the effect of these factors on fatal crashes may or may not be directly applicable to changes in the encroachment rates.

Perchonok et al.[33] also investigated the effects of roadway curvature and grade on vehicle crashes as part of a more extensive study of single-vehicle ran-off-road crashes. Crashes from six states were investigated with a sample size of 7,972 crashes. This study also found that crashes occur more frequently on horizontal curves and downgrades. However, the authors were not able to quantify this effect. Although the data do not provide complete verification, the study results tend to confirm the Wright and Robertson[32] findings.

Perchonok et al.[33] also compared crashes that ran off the left side versus the right side of the roadways. The study concluded that the ratio of right-side crashes to left-side crashes on two-lane, two-way highways was approximately 2 : 1. The median lateral offset of the struck object at crash locations investigated was about 3.7 m from the edge of the travelway, which is the same as the width of a typical lane. For a left-hand encroachment, the vehicle would have to cross the opposing lane of traffic prior to departing the travelway. Because the probability of encroaching a lateral distance of 3.7 m is about 50%, this indicates that the actual ratio of left-side encroachments to right-side encroachments is approximately the same, which is consistent with the assumptions made in most encroachment probability models.

The Perchonok et al. study[33] also investigated the effect of multiple lanes on crash rates. In this case, many more left-hand crashes were observed from the inside (left) lane of a four-lane facility than from the outside (right or shoulder) lane. Again, this is to be expected because a vehicle encroaching from the outside lane would have to first cross the inside lane before encroaching to the left. However, the number of left-hand crashes from the inside lane does not equal the number of right-hand crashes from the outside lane. This can be explained by the fact that, on a four-lane divided highway, the traffic volume on the outside lane is typically much higher than the traffic volume on the inside lane.

One interesting result is that impact speeds vary only moderately, a difference of 11 to 16 km/h over the first 30 m of lateral encroachment distance. The study also investigated the effects of various geometric conditions on vehicle tracking (i.e., whether the rear wheels follow the front wheels during an encroachment), lateral offset of vehicles, vehicle behavior by object contacted, severity of crashes, and a variety of covariates on these and other conditions. Unfortunately, the results are generally not useful in quantitative terms, and the severity estimates are probably not representative. The use of specially trained police officers for data collection possibly biased the study toward more severe crashes, although the researchers made efforts to include lower severity crashes.

Mak performed an analysis to estimate real-world impact conditions using reconstructed crashes in the mid-1980s.[24,34–36] Impact speed and angle distributions for five different functional classes, including freeways, rural arterials, rural collectors/local roads, urban arterials, and urban collectors/local roads, were developed by fitting gamma functions to the crash data. These distributions are used in some of the procedures to describe the probability of impact conditions.

2.1.2 *NCHRP Report 77*

The first encroachment probability based model was developed by McFarland et al. and presented in *NCHRP Report 77*.[4] This model was designed to analyze impacts with luminaire supports and contained all of the essential elements of an encroachment probability based model. The Hutchinson and Kennedy encroachment data[29], which was the only data source available at that time, were used for the encroachment frequency and the probability of lateral extent of vehicle encroachment. McFarland et al. redistributed the lateral extent of encroachment data using normal distributions for use in the model.

The encroachment model assumed an average encroachment angle of 11 deg. The width of the vehicle for the purposes of the model was assumed to be the average of its length and width. Presumably, this approximation was incorporated to account for non-tracking crashes. This creates a vehicle path as shown in Figure 4. The ratio between L_D, the width of the vehicle's path parallel to the roadway, and L_s, the pole spacing, is the probability that an encroaching vehicle's path will impact a pole. This probability, when multiplied by the probability of reaching the line of poles and encroachment frequency, yields the predicted impact frequency. The purpose of the model was to provide estimates of average crash frequencies without accounting for specific site conditions. Results of the model's predictions for three case studies are shown in Table 1.

Although the predicted impact frequencies do not match the frequencies observed for the individual sites, the averages of the predicted and actual impact frequencies are similar. Variations for the individual sites may be the result of specific site conditions not accounted for in the model, such as horizontal curvature, vertical grade, presence and density of weaving sections and entrance and exit ramps, pavement conditions, vehicle-to-vehicle interactions, and driver demographics. The actual impact frequencies included both crashes reported by law enforcement agencies and unreported impacts based on maintenance records.

For the crash severity component, costs from crash data were used to determine the direct (i.e., repair) costs and the indirect (i.e., occupant injury and vehicle damage) costs for each type of luminaire support. These costs were then multiplied by the estimated impact frequency to get an average

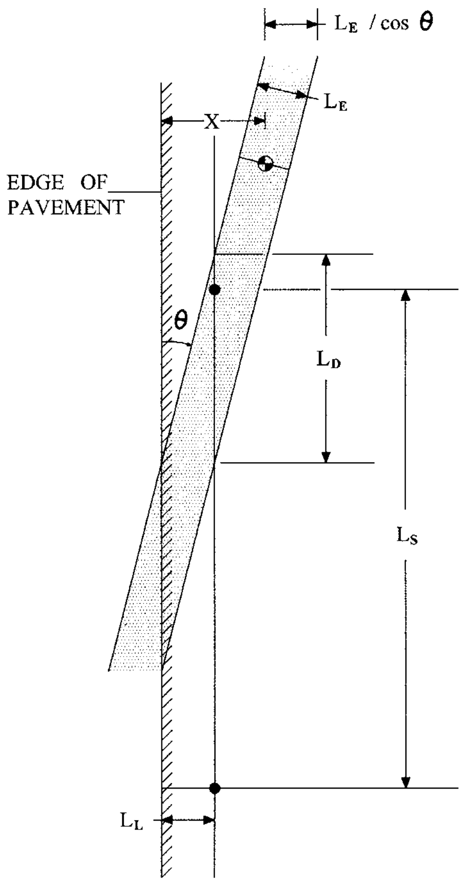


Figure 4. NCHRP Report 77 encroachment path.[4]

cost per year. Safety alternatives were evaluated by comparing the predicted costs for each option.

The model requires a limited amount of user input (i.e., traffic volume, spacing between supports, lateral offset, average vehicle width, and average angle of encroachment), and incorporated many simplifying assumptions, such as a straight-line encroachment path, a single vehicle type, and an average encroachment angle. As such, the versatility of the model is limited and it does not account for some of the important parameters, such as highway type, horizontal curvature, vertical grade, and roadside slope. Also, the model is specific to point objects, such as poles and luminaire supports, and cannot be applied to other types of objects, such as longitudinal barriers.

2.1.3 *NCHRP Report 148*

Glennon expanded the model from *NCHRP Report 77* so that it can be used with any type of object.[15] This was done by using the hazard envelope concept, as shown in Figure 1, which allowed the length and width of the hazard to be included in the determination of impact probability. However, all of the other limiting assumptions associated with the *NCHRP Report 77* model still apply, particularly the use of a single vehicle type, an average encroachment angle, and the straight-line encroachment path assumption.

2.1.4 1977 *AASHTO Guide for Selecting, Locating, and Designing Traffic Barriers*

The first generalized encroachment probability based procedure to be widely used appeared in the 1977 AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers*, also known as the 1977 Barrier Guide or the Yellow Book.[17] The model was intended for use in determining whether a particular type of barrier protection is cost-effective or not. It used a graphical solution technique to avoid the extensive calculations, but is otherwise similar to Glennon's model, with all of the attendant shortcomings. However, the graphical solution was too cumbersome and the model was not widely used until computerized versions of the procedure became available some years later.

The severity index (SI) concept was introduced as a means to estimate crash severity, which was a major change from previous models. The SI defines the severity of a crash using an ordinal scale of 0 to 10, which in turn is linked to the probability or percentages of injury for different injury levels—PDO, injury, and fatality—as shown in Table 2.

The injury levels have been expanded in the 1996 AASHTO *Roadside Design Guide* to include six severity levels: PDO Level 1, PDO Level 2, Slight Injury, Moderate Injury, Severe Injury, and Fatality. Crash costs associated with a given SI can be determined by multiplying the cost of each injury severity level by the associated probability or percentages for that severity level and summing over all severity levels. This approach provides a general, easy-to-use method for determining crash costs.

TABLE 1 Results of *NCHRP Report 77* case studies

Case No.	ADT	Section Length (mi)	No. Of Crashes	Years of Record	Crash Frequency	
					Actual	Predicted
1	6000	11.6	35	2.17	1.39	0.83
2	9300	4.7	8	6	0.28	1.89
3	8500	5.1	22	6	0.72	1.15
Average	N/A	N/A	N/A	N/A	0.80	0.96

TABLE 2 Yellow Book SI table

Severity Index (SI)	% PDO	% Injury	% Fatal
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

The 1977 Barrier Guide included a suggested list of severity indices for various roadside features, based on results from a survey of highway safety and law enforcement experts. Because of the way the survey was conducted, respondents tended to consider only high-speed crashes and, consequently, it is believed that the relative severity of impacts and the resulting SI values were overestimated. Take crashes involving bridge piers and abutments as an example. Table 3 compares the injury probabilities as indicated by the assigned SI values of 9.3 for bridge piers and abutments to the severity distribution from crash data in Michigan for the years 1985 to 1991. It is evident that the severity as estimated by the assigned SI values is greatly overestimated, particularly for severe injury and fatal crashes. This overestimation of severity would, in turn, overestimate the benefits and cost-effectiveness associated with most safety improvements.

The SI table has some other problems as well, most notably a fixed distribution of injury levels. This fixed distribution means that hazards with unusual severity distributions cannot be modeled well by the SI approach. For example, bridge rails over deep bodies of water would be expected to have a low proportion of severe injury and fatal crashes when vehicles are successfully redirected, but a nearly 100% fatality rate when vehicles go through or over the bridge railing.

The model also overestimates the effectiveness of longitudinal barriers and crash cushions because it does not account for penetration or the probability for the vehicles to run behind or around the safety treatments and impact with the shielded hazards.

2.1.5 Studies for Nebraska Department of Roads

A series of studies conducted by Post et al., at the University of Nebraska for the Nebraska Department of Roads[9–12] are noteworthy because the studies attempted to overcome some of the shortcomings of previous procedures by using computer simulation of vehicle behavior. Rather than relying on the traditional assumptions about off-road vehicle behavior, the research approach was to directly model a vehicle during impacts with different roadside features, including guardrails, guardrail to rigid barrier transitions, bridge pier protection, and driveway slopes. The general procedure is illustrated by the study on driveway slopes, as described below.

Encroachment frequency and lateral extent of encroachment distributions were estimated from the Hutchinson and Kennedy[29] data. However, instead of assuming a hazard geometry and location, the researchers defined the various roadside slopes and dimensions of an actual driveway, varying only the slopes on the sides of the driveway, as shown in Figure 5. The Highway-Vehicle-Object Simulation Model (HVOSM)[37, 38, 39] was used for the simulation effort. The HVOSM program idealizes a vehicle as four isolated masses (i.e., vehicle sprung mass, left and right front wheels, and a solid rear axle) with 11 deg of freedom.

A mid-size (1724-kg) passenger car was selected for this study, and it was assumed that there was no steering or braking during any of simulated encroachments to represent an inattentive driver. Simulations were run for two-lane, two-way highways with different driveway slopes: 1:3, 1:4, 1:6, 1:8, and 1:10. Several runs were made for each slope to determine the effects of traversing different parts of the driveway slope. All the runs were made at 88.5 km/h with an encroachment angle of 10 deg.

Crash severity was estimated based on the lateral acceleration of the vehicle during impact. The lateral acceleration was related to a severity index (different from the SI defined in the 1997 AASHTO Barrier Guide) based on tolerable lateral and longitudinal acceleration of the vehicle.[40] The "severity index" was related to a probability of injury based on results from the Olsen study in which damages to vehicles in

TABLE 3 1977 Barrier Guide SI versus Michigan HSIS data

Source	Severity Index (SI)	Injury Levels*			
		%(K)	%(K+A)	%(K+A+B)	%(K+A+B+C)
1977 AASHTO Barrier Guide	9.3	82.5	95.6	100.0	100.0
Michigan Data**	N/A	2.1	15.3	17.6	35.6

* K = fatal injury, A = incapacitating injury, B = moderate injury, and C = possible injury.
** Data presented are average for all functional classes.

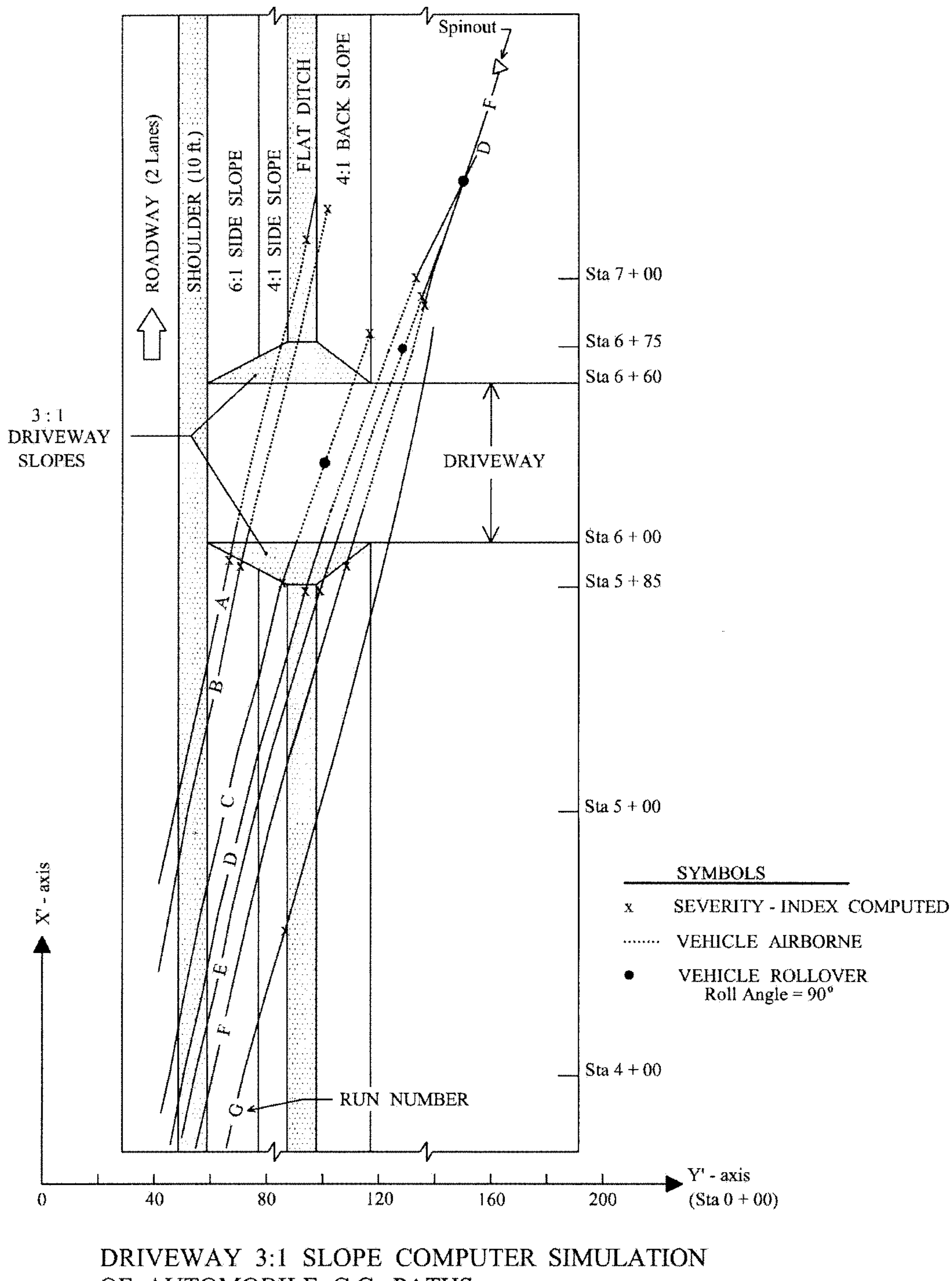


Figure 5. NDOR study roadside geometry.[9]

crash tests were compared with those of real-world crashes involving longitudinal barriers.[41] The severity index, SI, for a given crash was calculated as follows:

$$SI = \sqrt{\left[\frac{G_{long}}{G_{x1}}\right]^2 + \left[\frac{G_{lat}}{G_{y1}}\right]^2} \tag{4}$$

where

G_{lat} = Average lateral acceleration

G_{long} = Average longitudinal accelerations = μG_{lat}

G_{x1} = Tolerable longitudinal acceleration (assumed to be $7g$)

G_{y1} = Tolerable lateral acceleration (assumed to be $5g$)

Six severity levels were defined as a function of the severity index with corresponding probabilities of injury as shown in Table 4.

Finally, the crash frequency for each vehicle trajectory was calculated as the product of the encroachment frequency and the length of the paths projected along the travelway measured in miles. Each slope in question would be hit at a different lateral offset for each path, and the probability of reaching that lateral offset affected the likelihood of encountering each slope. The number of injury crashes per year was then obtained by multiplying the crash frequency by the probability of reaching the appropriate lateral offset. The crash costs were then compared with the costs of installing different driveway configurations to determine the cost-effectiveness of flattening driveway slopes.

The later studies improved on this technique by using three encroachment angles and three speeds instead of one of each, which produced a range of results for each study. Also, the later studies used both cost-effectiveness and benefit/cost analysis. The guardrail studies used the BARRIER VII computer program[42] to determine the dynamic effect of a car striking a longitudinal barrier.

Despite these improvements, some problems remained. Only one vehicle type was selected for analysis, probably because of the relatively extensive input and computational requirements. The encroachment speeds and angles were selected arbitrarily and may or may not represent average real-world encroachment or crash conditions. Collisions with multiple hazards were not considered. Also, these studies were conducted for specific applications and have little general applicability.

2.1.6 TTI ABC Model

The ABC computer program was developed by the Texas Transportation Institute (TTI), Texas A&M University, in the mid-1980s, and represented a significant advance in the complexity and accuracy of encroachment probability based models. Several drawbacks to previous methods were addressed and, to some extent, rectified. However, the complexity of the program and the lack of a user-friendly interface and documentation prevented the program from gaining wide acceptance.

TABLE 4 Severity levels

Severity Index (SI)	Probability of Injury
SI < 0.5	0.1
0.5 < SI < 1.0	0.3
1.0 < SI < 1.5	0.5
1.5 < SI < 2.0	0.7
2.5 < SI	1.0

Tolerable Accelerations: Longitudinal = 7 *g*'s
Lateral = 5 *g*'s
Vertical = 6 *g*'s.

All previous models used encroachment frequency and lateral extent of encroachment distributions based on data from the Hutchinson and Kennedy study.[29] The TTI ABC model incorporated data from the Cooper encroachment study, as shown in Figure 3.[30] It was thought that the Cooper encroachment data were better and more representative of highways in the United States at that time than the Hutchinson and Kennedy data, particularly in light of the national speed limit of 88.5 km/h (55 mph).

The TTI ABC model adjusted the Cooper encroachment data by assuming that approximately 60% of all observed encroachments were uncontrolled. This adjustment is based on the 1 : 1.7 controlled-to-uncontrolled ratio found in a study of barrier impacts.[43] This ratio of 1 : 1.7 between controlled and uncontrolled encroachments is the lowest estimate found among several studies. For example, recall the results of the encroachment study by Calcote et al.[31], which suggested a ratio of 1 : 500. The lowest reasonable value was chosen for use in the TTI ABC model so that the analysis would be on the conservative side. Lower ratios between controlled and uncontrolled encroachments lead to higher predicted crash rates and hence a more conservative analysis.

The ABC model modifies the base encroachment rate for horizontal curvature and vertical grade using adjustment factors developed from the Wright and Robertson study of 300 fatal, single-vehicle crashes in Georgia.[32] The adjustment factors were incorporated as step functions as shown in Table 5.

The distributions of lateral extent of encroachment are also based on the Cooper encroachment data, which suffers from the same problems as the Hutchinson and Kennedy data (in terms of under-reporting of encroachments that remained within or just went beyond the paved shoulder areas because tire tracks would be difficult to detect on paved surfaces). The TTI ABC model adjusts for the effects of paved shoulders on encroachment frequency and lateral extent of encroachment distributions by fitting the Cooper lateral extent of encroachment data to the curve form developed in the Skeels study.[44]

Another important feature of the TTI ABC model is the incorporation of a hazard imaging system that analyzes multiple hazards simultaneously. As shown in Figure 6, the roadside is divided into several impact regions that define the order of impact with multiple hazards. In this way, the probability that a vehicle going around the end of a barrier or going through or over a barrier to impact the hazard shielded by the barrier is accounted for. It is assumed that, if a vehicle penetrates a barrier or a breakaway object, the vehicle will continue on its straight line path without any change to its course or heading. Again, the assumption was necessitated by limitations of the hazard imaging technique and the lack of available data.

The TTI ABC model was designed to consider four vehicle types and an array of speed and angle distributions created from reconstructed crash data.[24] The hazard images

TABLE 5 ABC encroachment frequency modifiers

Horizontal Curvature (Degrees)	Encroachment Location with Respect to Curve			
	Inside		Outside	
	Upgrade or Downgrade <2%	Downgrade >2%	Upgrade or Downgrade <2%	Downgrade >2%
0.0-3.0	1.000	0.800	1.000	0.800
3.1-6.0	1.240	0.960	2.760	1.656
>6.0	1.984	5.200	4.416	7.800

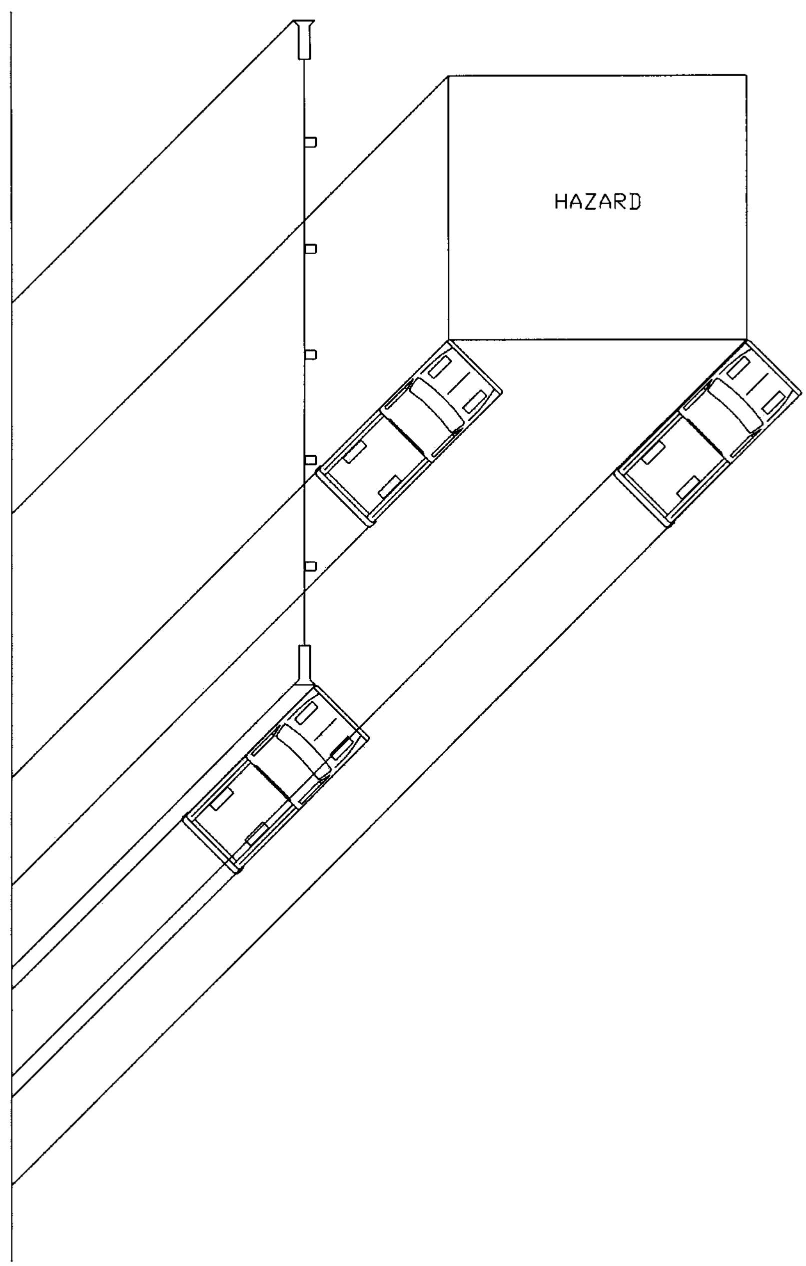


Figure 6. Multiple hazard envelopes.[24]

shown in Figure 6 are a function of both vehicle size and encroachment or impact angle. Incorporating multiple vehicle types and speed and angle combinations also allowed the TTI ABC model to estimate the distribution of crash outcomes. For example, the performance of a longitudinal barrier is greatly affected by the vehicle size, impact speed, and impact angle.

The performance of safety hardware and impact severities are then linked to impact conditions in a two-step process. First, the impact conditions are compared with measures of the hardware's performance limit to determine if the system would perform as intended. For longitudinal barriers, performance limits were generally defined in terms of redirection or penetration. The TTI ABC model used Impact Severity (IS) as the primary measure of a barrier's performance or containment limit. The IS is a measure of the vehicle's kinetic energy associated with the lateral component of velocity as shown in Equation 5:

$$IS = \frac{1}{2} * m(V * \sin\theta)^2 \qquad (5)$$

where

IS = Impact Severity (*N*-m)
m = Vehicle mass (kg)
V = Impact speed (m/s)
θ = Impact angle

When the IS value for a given set of impact conditions is at or below the capacity or performance limit of the barrier, the impacting vehicle is considered to be successfully redirected. The program would then proceed to estimate the severity associated with the redirective impact. The impact severity is expressed in terms of the severity index (SI) as a function of vehicle size, impact speed, and impact angle. Figure 7 shows the relationships between SI and impact speed for five different impact angles for a full-size automobile impacting a longitudinal barrier. A linear relationship is assumed between SI and impact speed.

When the IS values for a given set of impact conditions exceed the capacity or performance limit of the barrier, the impacting vehicle is considered to have penetrated the barrier and a minimum severity, termed the penetration severity, is assigned to the penetration event. The penetration severity reflects the average severity for vehicles penetrating through barriers without impacting the hazards beyond. The model then checks for subsequent impact(s) with another hazard. The severity of the subsequent impact(s) is compared with the penetration severity and the higher (or highest) severity is assigned as the impact severity for that crash.

As described above, the distributions of impact speeds and angles were an important component of the crash severity prediction process for the TTI ABC program. The program incorporated impact speeds and angle distributions developed by Mak using data from reconstructed ran-off-road

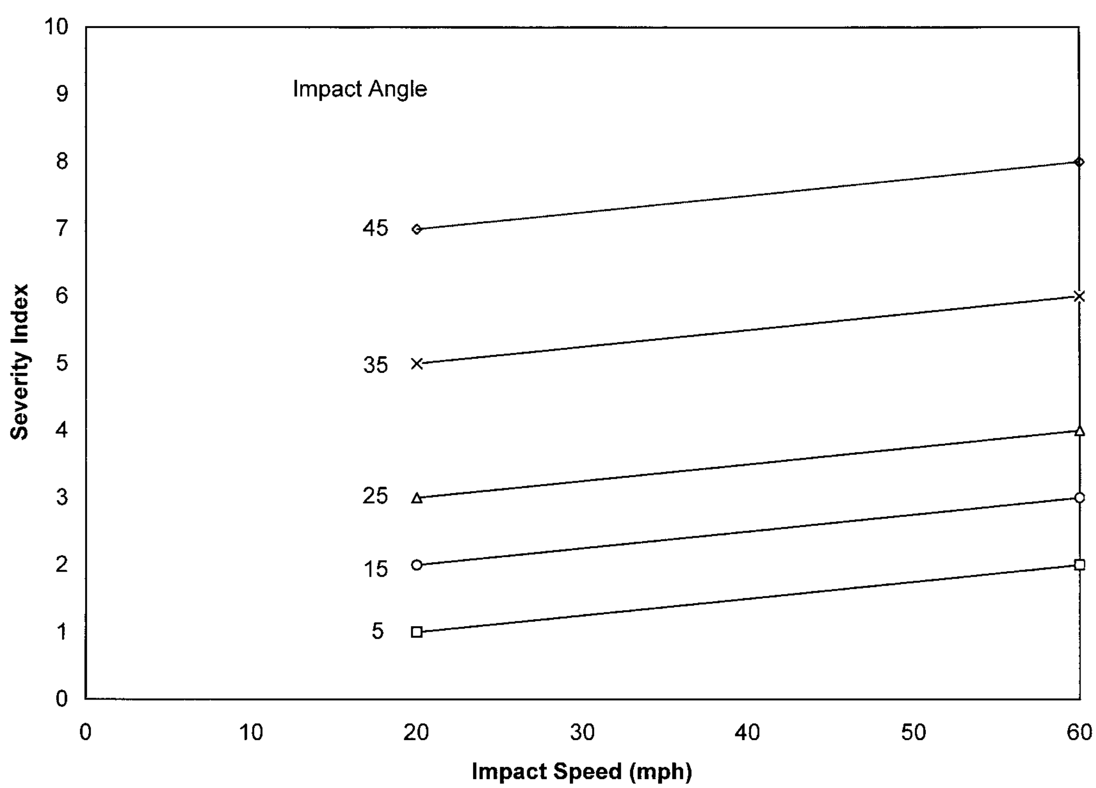


Figure 7. TTI ABC impact severity model for longitudinal barriers.[24]

crashes.[24] By using real-world crash conditions, the TTI ABC model obtained the best possible estimate of impact conditions, provided the data are representative of all crashes and incorporate a wide range of crash types and location.

Unfortunately, there are some limitations to the crash data used for estimating impact conditions. The data were collected from studies of utility pole and bridge rail crashes. Given that the crashes were sampled from crashes reported by police, unreported crashes were not accounted for (however, it is reasonable to assume that the severities of unreported crashes are typically low). Further, because both bridge rails and utility poles tend to be located close to the edge of the travelway, the crash data may not be representative of crashes with lateral offsets of more than 7.5 m. These factors should have the effect of overestimating the impact severities (however, given that the unreported crash rate for utility poles is believed to be low and there did not appear to be significant variations in impact speeds for differing lateral offsets, the magnitude of this overestimation may not be too great).

Although a significant improvement, the TTI ABC model has a few drawbacks that limit its acceptance. The single biggest problem is the lack of a user-friendly interface. The input files contain large amounts of data that must be entered in the correct fields with the proper format. Creating the input files can be a difficult and time-consuming process, and few users were willing to invest the large amount of time necessary to learn and use the required input procedures. The program was not well documented, which further increased the effort required to learn the program's operation.

2.1.7 Benefit/Cost Analysis Program (BCAP)

The FHWA modified the TTI ABC model in 1988 to create the Benefit/Cost Analysis Program (BCAP).[25] BCAP attempted to add features to the crash prediction and severity estimation procedure and incorporate a user interface that would the make the program easier to use. Unfortunately, some of the added features to the crash and severity prediction routines relied heavily on engineering judgment and were not well received. Nevertheless, BCAP was used to generate the performance level selection guidelines contained in the 1989 AASHTO *Guide Specifications for Bridge Railings*.[2]

The BCAP model used a completely different encroachment probability distribution than previous methods. The BCAP model incorporated a base encroachment rate of 0.0003 encroachments per km per year per average daily traffic (ADT), which in turn assumes that encroachment frequency is directly proportional to traffic volume. As shown in Figure 8, the encroachment frequencies used by the BCAP model were considerably higher than those found by Hutchinson and Kennedy[29] or Cooper[30]. Furthermore, the linear relationship between encroachment rate and traffic volume assumed by the BCAP model contradicted the findings from these two encroachment studies. Although not well documented in the BCAP report, this higher encroachment rate appears to be based on reported crash rates for longitudinal barriers that have been adjusted upward to account for unreported crashes. It is believed that the encroachment rates used by the BCAP model are too high.

Like the TTI ABC model, the BCAP model also adjusts the base encroachment rates to account for the effects of horizontal curves and vertical grades, using the results from the Wright and Robertson study.[32] However, as shown in Figure 9, instead of using step functions, linear functions are used in between the data points.

Also, in developing the 1989 AASHTO *Guide Specifications for Bridge Railings*,[2] the encroachment frequency was adjusted for increasing water depth below a bridge. The intent

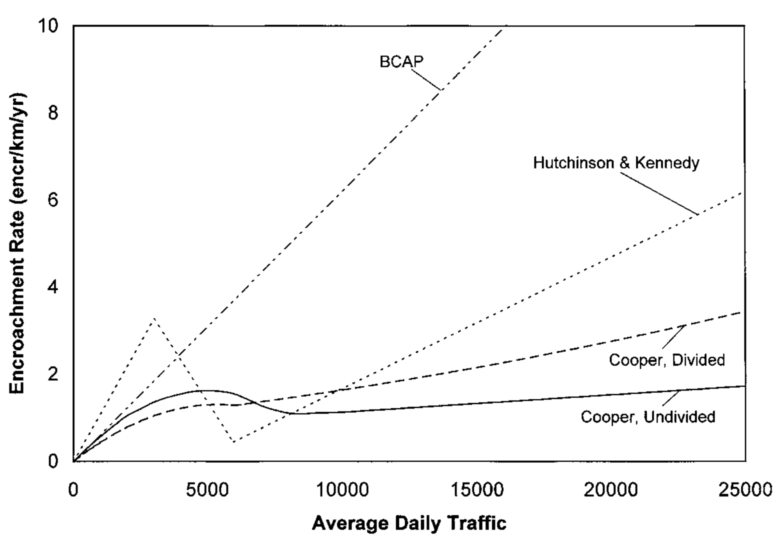


Figure 8. BCAP encroachment frequency compared with Cooper[30] and Hutchinson and Kennedy.[29]

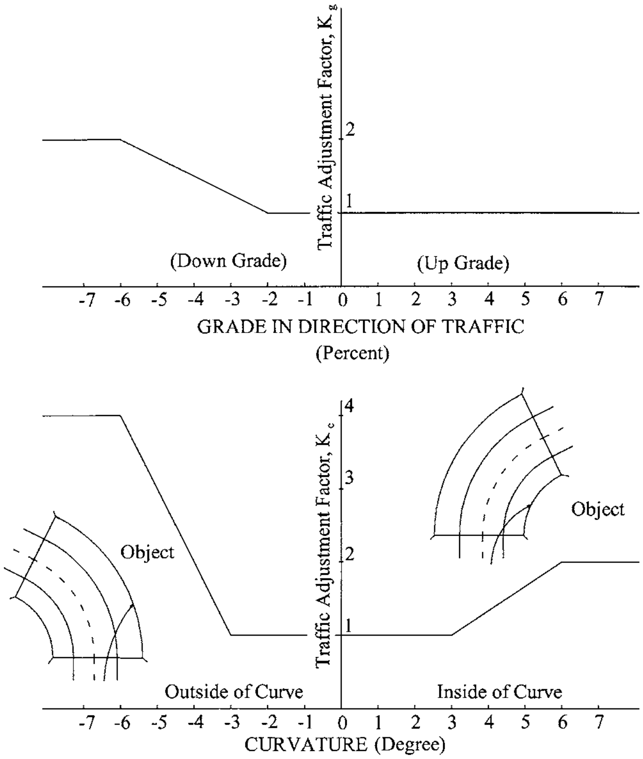


Figure 9. BCAP encroachment frequency adjustment factors.[32]

of this adjustment factor was to increase the frequency of bridge rail penetrations and rollovers, thereby increasing the total crash costs. Unfortunately, increasing encroachment rates also increases the frequency of all types of crashes, not just barrier penetration crashes, and was shown to have distorted the results of the overall cost-effectiveness analysis.

BCAP made several significant changes to how the distributions of encroachment conditions were estimated. Instead of using real-world crash data as does the TTI ABC model, BCAP uses a hypothetical speed distribution, as shown in Figure 10. This encroachment speed distribution, based largely on engineering judgment, is related to the design speed of the highway and then segmented into 10 cells. The area of each cell, divided by the total area of all cells, is the probability of occurrence of the mid-point speed of that cell. The average and maximum encroachment velocities using this speed distribution for the five different design speeds are shown in Table 6.

To estimate impact speed, BCAP assumes a constant deceleration rate of 0.4 *g*'s to account for the reduction in vehicle velocity as it traveled farther from the roadway.

Distributions of encroachment angles, shown in Figure 11, were also estimated based mainly on engineering judgment. BCAP uses a point-mass model to generate a link between impact speed and angle distributions. As shown in Figure 12, the point-mass model is used to determine the maximum encroachment angle that can be attained for a given roadside offset for any combination of vehicle size and speed. The impact angle distribution is then adjusted for that vehicle and speed combination by uniformly redistributing all of the area above the limiting angle as shown in Figure 11.

BCAP has some serious limitations. Encroachment angle distributions from crash data have been found to have a much more different shape than the assumed distribution shown in this Figure 11.[24] Furthermore, maximum encroachment angles are based on the assumption that vehicles are initially traveling in their lanes and then steered rapidly toward the roadside. This does not account for situations in which the vehicles are steered first in one direction and then overcorrected in the opposite direction. Consequently, impact

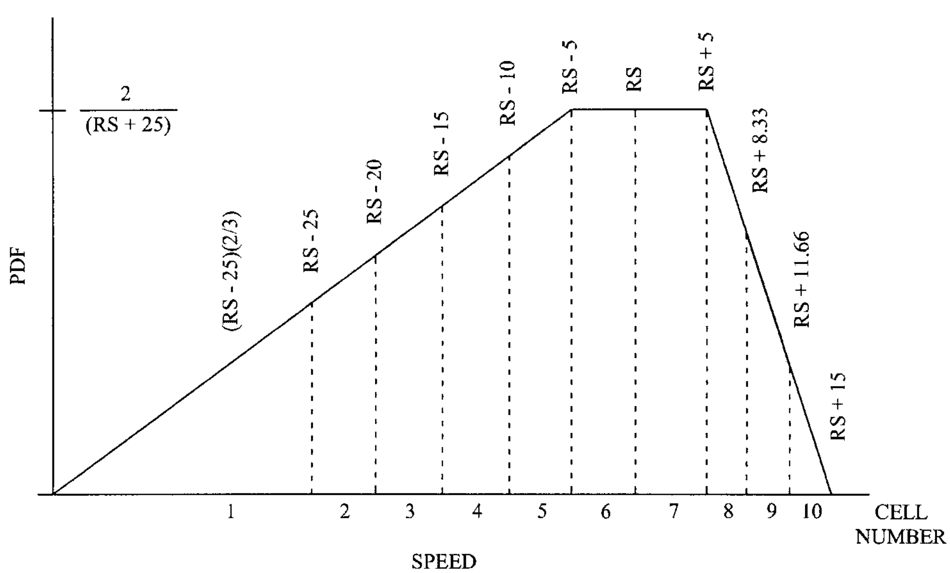


Figure 10. BCAP encroachment speed distribution.

TABLE 6 BCAP encroachment speed distribution

Design Speed (km/h)	Average Encroachment Speed (km/h)	Maximum Encroachment Speed (km/h)
48	37.4	64.5
64	47.4	78.9
80	57.1	93.3
96	66.9	107.7
112	76.6	122.1

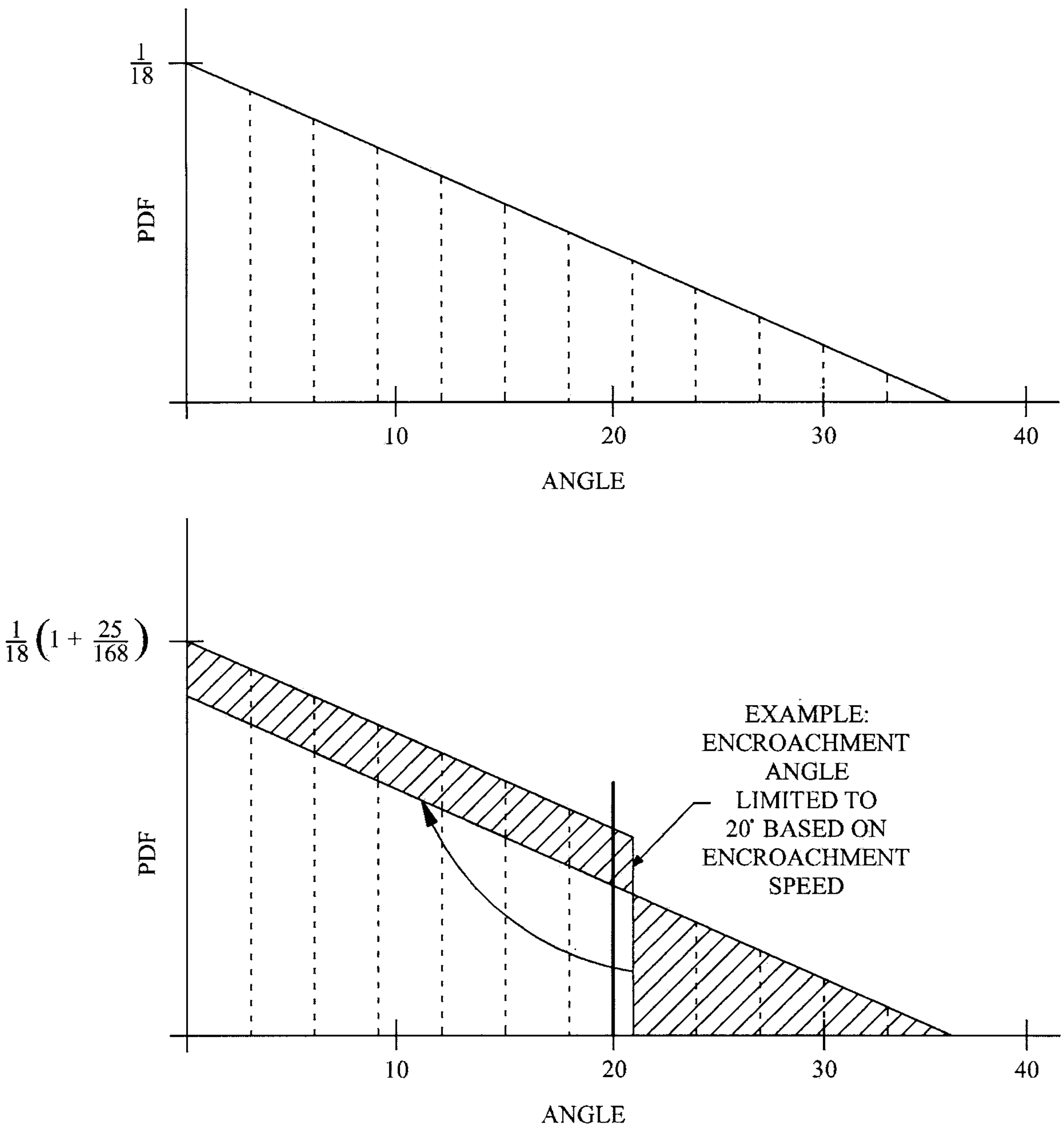
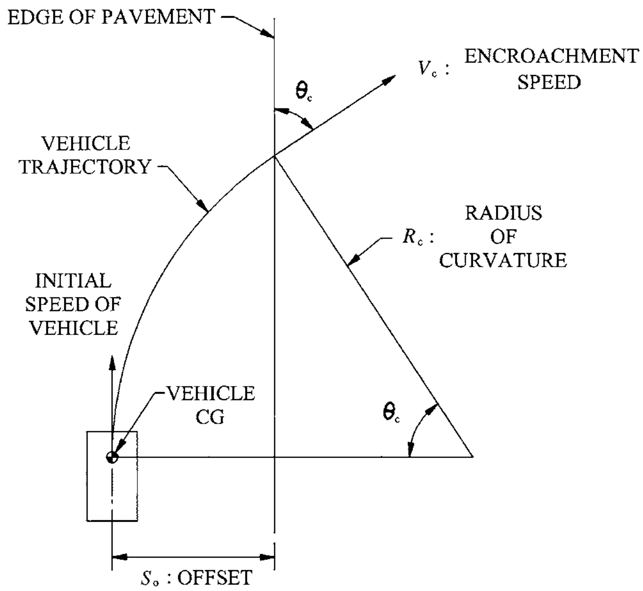


Figure 11. BCAP encroachment angle distribution.



$R_c = V_c^2/gf_m = S_o/(1-\cos\theta_c)$

$\theta_c = \cos^{-1}(1 - S_o\, gf_m/V_c^2)$

= Maximum encroachment angle

V_c = Encroachment Speed = Initial speed of vehicle

S_o = Vehicle offset from edge of pavement

f_m = Maximum available friction coefficient

R_c = Minimum radius of curvature

g = Acceleration of gravity

Figure 12. Point-mass cornering model.

angle distributions from real-world crash data are much higher than those estimated using the point-mass model. These factors are believed to be the primary reasons that impact speed and angle distributions generated by BCAP do not correlate well with real-world crash data. Because impact conditions have an important effect on both the predicted performance of safety hardware and impact severities, these problems are viewed as major limitations of BCAP.

BCAP greatly improved procedures for predicting the outcome of crashes involving impacts with roadside safety hardware. The program incorporates algorithms that predict vehicles rolling over the barrier and rolling over in front of the barrier. Also, the number of options for estimating hardware capacity was significantly increased. Another important improvement involved expanding the vehicle mix to 13 vehicle types: 4 sizes of automobiles, 3 sizes of light trucks, 3 single-unit trucks, and 3 combination trucks.

Crash severity estimation procedures were also revised in BCAP. The program retains the speed and angle relationship to SI used in the TTI ABC model and adds several others, including speed loss (for breakaway objects) and kinetic energy. These added features allow users to select the type of model they want to use, but increases the input data requirements.

BCAP has a user-friendly interface, known as BCAP's Data Input Manager (BDIM), but this interface turned out to be problematic. Data has to be entered correctly the first time—There is no allowance to edit any previously entered input without starting the process all over again. Also, the interface has a tendency to "hang" unexpectedly if incorrect data are entered, resulting in loss of all input data. BCAP has not been widely accepted because of the problems with the BDIM and the massive amount of input data required.

2.1.8 ROADSIDE Program

In an effort to provide a simplified benefit/cost analysis program that could gain wider acceptance by practicing engineers, FHWA developed a greatly simplified version of BCAP with far fewer data input requirements, known as the ROADSIDE program.[26] Documentation for the ROADSIDE program is included as Appendix A of the AASHTO *Roadside Design Guide*.[1] The ROADSIDE program essentially uses the same procedures as BCAP, but with some important and limiting differences; these differences are described below.

In order to reduce the program running time, the arrays of vehicle sizes, impact speeds, and impact angle distributions used by BCAP were reduced to a single vehicle, speed, and angle combination. The encroachment angle used in the ROADSIDE program is the average angle calculated using the point-mass model for a given speed. Also dropped were the provisions for multiple impacts and multiple hazards. These changes eliminate the computationally intensive hazard imaging system and force the program to analyze only one hazard at a time. As a result, the ROADSIDE program cannot consider the effect of one hazard, such as a longitudinal barrier, shielding traffic from another hazard. Instead, the ROADSIDE program assumes that vehicles cannot penetrate or travel behind a barrier to impact another hazard and, therefore, all longitudinal barrier configurations are 100% effective. Further, when several hazards are located on the roadside, the program must be run multiple times for each safety treatment alternative.

Because of the single speed and angle combination incorporated into the ROADSIDE program, it is no longer possible to use the crash severity estimation algorithms from the TTI ABC or the BCAP models, where severity is estimated as a function of impact speed and angle. The ROADSIDE program, therefore, reverts to an average severity for all impacts on a hazard. The original version of the ROADSIDE program provided a very incomplete list of roadside objects.[45] The list of roadside objects has since been expanded exhaustively in the latest edition of the *Roadside Design Guide*[1] with estimates of SIs for various object types, impact points on the object, and design speeds. Although most of these severities appear to be reasonable, they were based largely on engineering judgment, with only modest objective basis. As a result, a high degree of uncertainty still exists regarding the appropriate severity indices used in the model. When compared with severities of real-world crash data, many of these SIs still appear to be too high. Furthermore, the new SI list has some inconsistencies and eccentricities, such as listing severities for corner impacts on round objects.

The documentation for the ROADSIDE program also includes several other features, such as adjustment to the lateral extent of encroachment to account for the effects of sideslopes and slope rounding. These provisions are based on an assumed point-mass trajectory for vehicles traversing a slope break point and a linear approximation to the effects of slopes on a driver's ability to steer back toward the travelway. These procedures have not been adequately validated and are not included in the program itself. The users are required to perform manual calculations for these adjustments. Because the ROADSIDE program often requires many runs to fully analyze a single safety treatment alternative, the additional hand calculations for each run make the use of these adjustments a great burden for most practicing engineers. As a result, most users do not incorporate these additional features when using the program.

2.2 CRASH DATA BASED MODELS

Crash data based procedures use statistical models, typically regression models, developed from analysis of police-level crash data to predict crash frequencies and severity. The crash data based approach has one important advantage over the encroachment probability based approach in that actual crash data are used. The crash data based procedures fall into one of two general categories: site specific and feature specific. Site-specific analysis involves using the crash history for a specific site to estimate the expected number and severity of crashes at that site in the future. Feature-specific crash data studies involve analyzing large databases of crashes involving the feature under consideration. Both of these techniques have some advantages and disadvantages as described below.

As mentioned above, site-specific techniques use the crash history at a specific site to predict future crash occurrences. This is the most common method for evaluating the benefits and costs of implementing safety improvements at high crash locations. Use of such site-specific techniques involves identifying all crashes that occur at a given site and then devising a plan to mitigate the situation. The benefits of the proposed safety improvement are estimated by multiplying the number of historical crashes by an accident reduction factor to account for the reduction in crash frequency or severity associated with that particular improvement. For example, installing a guardrail to shield bridge piers would be expected to increase the crash frequency, but decrease the crash severity. The accident reduction factor for installing a guardrail to shield the bridge piers would be calculated as the proportional change in crash costs for crashes involving the bridge pier in the before period and crashes involving the guardrail and the bridge pier in the after period. Accident reduction factors are typically developed for a wide variety of safety improvements and are calculated on a statewide basis from before-and-after studies of roadside improvement projects.

One problem with this accident reduction factor approach is that before-and-after studies are subject to the regression-to-the-mean phenomenon. Regression to the mean describes a situation wherein crash rates are artificially high during the before period of the study due, in large part, to random variations. The crash rates would have been reduced to a lower level (i.e., the mean or average) even if nothing was done to the site. Thus, if a safety improvement is implemented and a lower crash rate is found during the after period of the study, the reduction in crash rates may or may not result from the safety improvement. Thus, accident reduction factors developed from before-and-after studies may overestimate the actual effect of the safety improvement. This regression-to-the-mean phenomenon can be properly evaluated by using control sites to determine what portion of the crash reduction results from the safety improvement.

Site-specific crash data analysis, when properly conducted, is a good approach for evaluating safety improvements at sites where crash records are available in significant quantities; however, there is generally little or no crash history at a site with which to evaluate the potential merits of implementing a safety improvement. For example, the average crash rate for a rural two-lane highway is less than one crash per km per year. With such a small number of crashes at a given site, it would be most difficult to assess the benefits of implementing a safety improvement properly. Thus, site-specific crash data analysis procedures are recommended only when significant crash data are available.

Feature-specific crash analysis involves using large crash databases to predict crash frequency and severity for a specific roadside feature under consideration. The best example of this type of analysis is a study of utility pole crashes by Zegeer and Parker.[7] This study involved collecting police-reported crash data and exposure data on utility poles, as well as some roadway geometric and traffic data along many sections of highway. A regression model was then developed relating utility pole crash frequencies to various traffic and roadside parameters, including traffic volume, pole offset, and pole spacing.

The primary advantage of this approach is that it relies on historical crash data to predict crashes. The approach is relatively simple and intuitively appealing; however, this approach has major limitations. First, police-level crash data are somewhat unreliable because of the extent of unreported crashes (i.e., crashes that are not reported to law enforcement agencies for whatever reasons). In terms of severity, it is reasonable to assume that the severity of unreported crashes is generally very low and of minor consequences to the severity estimation. On the other hand, unreported crashes also mean that it is virtually impossible to use crash prediction algorithms from one roadside feature to predict crash frequency for another feature. Some roadside features, such as breakaway sign and luminaire supports, have a very high incidence of unreported crashes while other hazards, such as utility poles, have a relatively low rate of unreported crashes. As a result, crash prediction algorithms must be developed separately for each roadside hazard or feature type, which is cost prohibitive and greatly complicates the process of developing the general crash prediction routines necessary for a benefit/cost analysis model for use in evaluating roadside safety improvements.

Other problems associated with police-level crash 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 crashes.

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

Further, the number of roadway, roadside, and traffic variables found in regression models to have a significant effect on crash frequency or rate are 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 crash frequency or rate and are statistically insignificant. Variables of interest are often forced into the regression equations, even though they are not significant, in order to be included in the model. For example, in the Zegeer and Parker study to develop procedures for predicting utility pole crash frequency, the researchers found that only traffic volume, pole density, and pole offset had any significant effect on utility pole crash frequency.[7] 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 a crash. Pole offset can also be considered an exposure factor because it strongly affects the chances that an errant vehicle will encroach far enough onto the roadside to cause a crash.

The computer program UPACE was developed on the basis of this crash 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.

CHAPTER 3

PROGRAM OVERVIEW

An overview of the cost-effectiveness analysis procedure incorporated into RSAP is presented in this chapter. More detailed descriptions of the major components of the procedure are presented in Chapters 4 through 8.

3.1 GENERAL FORMULATION

The cost-effectiveness procedure incorporated into RSAP is based on the concept of incremental benefit/cost (B/C) ratio, similar to that used in the cost-effectiveness procedures described in Chapter 2. The general formulation for the incremental B/C ratio is as follows:

$$B/C \text{ Ratio}_{2-1} = \frac{CC_1 - CC_2}{DC_2 - DC_1} \quad (6)$$

where

B/C Ratio$_{2-1}$ = Incremental B/C ratio of Alternative 2 to Alternative 1
CC_1, CC_2 = Annualized crash cost for Alternatives 1 and 2
DC_1, DC_2 = Annualized direct cost for Alternatives 1 and 2

The basic concept 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 crash or societal costs as a result of decreases in the number or severity of crashes. Direct highway agency costs comprise of initial installation, maintenance, and repair costs for the safety treatment.

The incremental B/C ratio, as shown in the equation above, is the ratio of the benefit (i.e., reduction in crash costs) to the increase in direct costs between the alternatives. The direct cost for Alternative 2 is assumed to be higher than that for Alternative 1, thus the difference is calculated as ($DC_2 - DC_1$) to ensure that the denominator is always positive.

The cost-effectiveness procedure incorporated in RSAP is based on the encroachment probability model, which is built on a series of conditional probabilities. The general formulation for the encroachment probability model is as follows:

$$E(C) = V * P(E) * P(C|E) * P(I|C) * C(I) \quad (7)$$

where

$E(C)$ = Estimated crash cost
V = Traffic volume
$P(E)$ = Probability of encroachment (encroachment rate)
$P(C|E)$ = Probability of crash given encroachment
$P(I|C)$ = Probability of injury given crash
$C(I)$ = Cost of injury

There are four basic modules associated with the cost-effectiveness procedure:

- The Encroachment Module,
- The Crash Prediction Module,
- The Severity Prediction Module, and
- The Benefit/Cost Analysis Module.

Brief overviews of these four modules are presented in the following sections.

3.1.1 Encroachment Module

The encroachment module uses roadway and traffic information to estimate the expected encroachment frequency, $V * P(E)$, along a highway segment. A two-step process is used to estimate encroachment frequencies. The first step involves estimating a base or average encroachment rate (based on highway type), and then multiplying the encroachment rate with the traffic volume to estimate encroachment frequency.

The two available sources of encroachment data result from studies by Hutchinson and Kennedy[29] in the mid 1960s and Cooper[30] in the late 1970s. Both studies involved observation of tire tracks in the medians or on roadsides. The Cooper encroachment data were selected for use in RSAP for the encroachment rate-traffic volume relationships. The Cooper data are more recent, constitute a larger sample size, and are believed to be of better quality than the Hutchinson and Kennedy data.

The next step is to adjust the base encroachment frequencies to account for specific highway characteristics that affect the encroachment rates. For example, previous studies found that vehicle encroachments are more likely on the outside of horizontal curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature. The encroachment module then combines the base encroachment frequencies and adjustment factors to determine encroachment frequencies for the highway segments under study. The adjustment factors used in RSAP include horizontal curvature and vertical grade, traffic growth factor, and a user-defined adjustment factor.

Detailed descriptions of the encroachment module are presented in Chapter 5.

3.1.2 Crash Prediction Module

Given an encroachment, the crash prediction module then assesses if the encroachment would result in a crash, $P(C|E)$. The first step is to determine the path of the encroaching vehicle. The vehicle path, sometimes called the impact envelope or hazard image, is a function of the encroachment angle, vehicle size, and the vehicle orientation (i.e., yaw angle). A straight path with no steering or braking is assumed in the current version of RSAP because (1) there is no information available on driver inputs subsequent to encroachment, and (2) this assumption simplifies the formulation and calculations. However, RSAP can be easily modified to take into account steering and braking when data become available in the future.

The vehicle path is then checked against the locations or coordinates of the roadside features to determine if one or more roadside features are in the path of the vehicle. If no features are in the path of the vehicle, the encroachment would not result in a crash. If one or more roadside features are in the path of the vehicle, a crash is predicted to occur. To account for the possibility that the vehicle may return to the travelway or come to a stop before reaching the roadside feature, the resulting crash cost is multiplied by the probability that the vehicle would encroach far enough laterally to impact the roadside feature.

If the encroachment is predicted to result in a crash, the impact conditions (i.e., speed, angle, and vehicle orientation) will then be estimated. Impact speed is included in the crash prediction module primarily as input for severity estimation in the severity prediction module. Also, under the straight-line vehicle path assumption, the angle and vehicle orientation at encroachment are assumed to be the same as the angle and vehicle orientation at impact.

For each predicted impact with a roadside safety device (e.g., guardrail or crash cushion), the program will check for penetration of the feature and subsequent impacts. If the impact conditions are beyond the performance limit of the safety device, penetration of the device is assumed to result. For example, penetration of a longitudinal barrier is predicted if the impact severity is greater than the structural capacity of the barrier. For breakaway support structures, the performance limit would be the force or energy level required to activate the breakaway mechanism. Once the force or energy level is reached, the support structure would be considered to have broken away and the vehicle would be allowed to proceed behind the support.

If penetration of the feature is predicted, the program will adjust the speed of the vehicle and then check the vehicle path against other roadside features for subsequent impacts. This process will be repeated until no penetration is predicted (i.e., the vehicle comes to a stop or there are no more roadside features in the path of the vehicle). In the case of multiple impacts, the severity for the most severe impact will be used.

For impacts with longitudinal barriers, the program also checks for vehicle stability in terms of the impacting vehicle rolling over the barrier or in front of the barrier on the traffic side. As may be expected, the severity of an impact involving a longitudinal barrier is much higher if the vehicle rolls over.

Detailed descriptions of the crash prediction module are presented in Chapter 6.

3.1.3 Severity Prediction Module

For each crash predicted, the severity of the crash, $P(I|C)$, is estimated in the severity prediction module. A traditional severity index (SI) approach is incorporated into RSAP for severity estimation, similar to that used in the ROADSIDE program. Severity index/impact speed relationships are developed for each roadside feature or hazard, (i.e., severity estimation is a function of the impact speed).

A more sophisticated methodology for estimating severity of impacts, termed the probability of injury (POI) approach, was developed as part of the NCHRP 22-9(2) study. The POI approach establishes crash severity based on police-reported crash data. In comparison, the SI approach is based on subjective judgment using an ordinal scale of 0 to 10, which in turn represents a fixed scale of percentages of fatal, injury, and PDO crashes. The POI approach also takes into account the type of roadside object or feature, vehicle type, and impact conditions (i.e., speed, angle, and vehicle orientation) in the estimation of impact severity. Unfortunately, the effort required to establish the severity estimates using the POI approach was much greater than allowed by the available funding; therefore, the SI approach was eventually adopted for use with the current version of RSAP; however, development of the POI approach is continuing under NCHRP Project 22-12, "Guidelines for the Selection, Installation, and Maintenance of Highway Safety Features."[57]

Detailed descriptions of the severity prediction module are presented in Chapter 7.

3.1.4 Benefit/Cost Analysis Module

The severity estimate of the crash is converted to crash cost using accident cost figures. The two most commonly used accident cost figures are (1) those contained in the AASHTO *Roadside Design Guide* and (2) the FHWA comprehensive cost figures based on the willingness-to-pay concept. RSAP offers users the choice of which set of accident cost figures to use. In addition, users may input customized accident cost values to suit their particular needs.

For each alternative, the average annual crash cost is calculated by summing the crash costs for all the predicted crashes and then normalized to an annual basis. The direct costs, which include the costs for initial installation, normal maintenance, and repair of damages from crashes, are also normalized to an annual basis using the project life and the discount rate. A zero (0) salvage value is assumed for all projects because the salvage value typically is insignificant when compared with the other direct cost items and has little or no effect on the analysis results.

The installation and maintenance costs are user-defined inputs. The cost of repairing roadside safety hardware is estimated by correlating repair costs with impact energy terms. 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 unit repair cost for a standard guardrail is first estimated. The total repair cost is then the product of the length of damaged rail and the unit cost for repair. Procedures for estimating the extent of hardware damage are developed for each longitudinal barrier design, as well as most common crash cushions, barrier terminals, and other roadside safety devices.

After the total crash and direct costs are determined for each alternative, the incremental B/C ratios between each pair of safety alternatives are then calculated using Equation 6 shown previously. Computation of the incremental B/C ratios is very straightforward once the benefits and costs are determined.

Detailed descriptions of the benefit/cost analysis module are presented in Chapter 8.

3.2 STOCHASTIC SOLUTION METHOD

One of the most significant improvements made to the cost-effectiveness analysis procedure in RSAP is perhaps the incorporation of a stochastic solution method using the Monte Carlo simulation technique. Vehicle encroachments are simulated one at a time to (1) determine if a crash would occur and the resulting severity and (2) calculate the associated crash costs. A stochastic solution method provides a relatively easy means of updating or modifying the procedure to incorporate important new or improved data or algorithms (e.g., curved vehicle trajectories) whenever they become available, which is one of the objectives of NCHRP Project 22-9(2).

All previous cost-effectiveness analysis procedures are deterministic models (i.e., the procedure uses a fixed set of algorithms to calculate the solution). A deterministic model renders the procedure difficult to update when new and improved data or algorithms become available. In most instances, the entire procedure and program will have to be rewritten to incorporate the updated or new features.

To illustrate the differences between stochastic and deterministic procedures, and where these differences are important, consider a simple example of coin tosses. Tossing a coin has two possible outcomes: “heads” or “tails.” Assume that the result of heads has a value of 1 and tails a value of zero. The ultimate goal is to determine the average value of a coin toss.

There are two ways to determine the average value of an individual coin toss. The first and the easiest solution is a deterministic approach. This procedure involves first identifying the probability of each possible occurrence. For an unbiased coin, the probability of coming up either heads or tails is 0.5. The average value of a coin toss is then calculated by summing the product of the probability of occurrence and the associated value for all possible outcomes. In this example of an unbiased coin, the average value is $[(0.5 \times 1) + (0.5 \times 0)]$, or 0.5.

The second approach is to use a stochastic solution, which involves taking a number of samples (say, 1,000 coin tosses) and counting the actual results. For example, assume the results of 1,000 coin tosses (of an unbiased coin) were 583 heads and 417 tails. Also, assume that the value of heads is 1 and the value of tails is 0, the total value of all 1,000 tosses would be $[(583 \times 1) + (417 \times 0)]$, or 583. Dividing this value by the number of tosses yields an average value of 0.583. Obviously, this is not the correct solution. However, if enough tosses were made, the average value would approach (or converge to) 0.5. In other words, if the sample size were large enough, the stochastic solution would approach the value of the deterministic solution.

The stochastic solution will not necessarily arrive at exactly the same answer every time. In other words, if 1,000 coin tosses are made twice, the answers may or may not be exactly the same. Also, the solution may not provide the exact answer (i.e., an average value of 0.5), unless the number of heads and tails happened to have occurred the same number of times when a convergence check was made. However, increasing the number of samples and tightening the convergence criteria can increase the accuracy of the solution to the desired level.

It may appear from this simple example that the stochastic solution creates more work while arriving at a somewhat less accurate answer. This assessment may even hold true to some extent for the current version of RSAP. However, the stochastic solution is a better choice in the long run because it provides the needed flexibility for future update and refinement of the procedure. (A discussion of the advantages and limitations of the stochastic approach is presented in Section 3.2.1.) Furthermore, the deterministic approach of summing all the probabilities is not as simple as might be expected initially. The summation procedure requires that crash probabilities be summed over all impact speeds, impact angles, vehicle orientation, vehicle types, and all hazard image surfaces, or fragments thereof. When reasonable array sizes are used, more than 5 million crash probabilities must be summed.

As a result of the stochastic solution method, the logic incorporated into RSAP is somewhat different than the other encroachment probability based models. The Monte Carlo technique simulates one encroachment at a time. The conditions associated with each encroachment, including speed, angle, vehicle type, vehicle orientation, and encroachment location, are randomly generated from built-in distributions of encroachment scenarios for these parameters. The program then determines if an encroaching vehicle's path will lead to an impact with a roadside feature. If an impact is predicted, the type and severity of impact is identified, and crash costs, including societal and highway agency costs, are estimated. The probability that the vehicle will stop or be steered back toward the roadway before reaching a hazard is also estimated, and the estimated crash costs are reduced accordingly. Another encroachment event will then be randomly generated, and the process will be repeated.

This process continues until a stable "average" encroachment cost or convergence is reached. The average encroachment cost is multiplied by the encroachment frequency for each segment of highway to determine the average annual crash costs for each segment and then summed over all the segments. The entire process is repeated for each of the safety improvement alternatives under consideration. The resulting annual crash costs and direct costs for the alternatives are then used to calculate the incremental B/C ratios among the alternatives.

3.2.1 Advantages of Stochastic Solution Method

The stochastic solution method has several advantages over the deterministic models, including the following:

- **Modular design**. The Monte Carlo technique allows for a modular design so that additions and revisions to the model can be made without major structural changes to the program. Previous procedures required major programming changes when any substantial changes were made to incorporate additional encroachment parameters. This use of a modular design greatly enhances the capability and flexibility of the program.
- **Updates and revisions**. In addition to the flexibility offered by the modular design, the stochastic approach of simulating one encroachment at a time allows the procedure to handle many of the needed updates and revisions to the program in the future when data become available (e.g., curvilinear vehicle path and incorporation of vehicle orientation into the severity estimate). For example, one of the major weaknesses with the current procedure is the assumption of a straight vehicle path. The Monte Carlo simulation technique works with encroaching vehicles in a repetitive series of events that are relatively simple to code and can be easily adapted to include curvilinear vehicle paths. Previous techniques rely on the calculation of an "impact envelope" for each possible combination of vehicle size and angle of encroachment, based on the assumption that all vehicles follow a straight path after leaving the travelway. Development of a similar "impact envelope" for most scenarios involving curvilinear vehicle paths is extremely difficult.
- **Vehicle orientation**. Non-tracking encroachments (i.e., where the rear wheels of the encroaching vehicle do not follow the front wheels) constitute approximately one-half of all real-world crashes, and vehicle orientation has been shown to have an important effect on crash severity for some safety devices such as terminals, crash cushions, and breakaway structures. The Monte Carlo simulation technique allows for addition of non-tracking impacts to the analysis; such additions would be difficult to incorporate with the deterministic approach. The vehicle orientation is currently used only in the determination of the vehicle path and not in the estimation of impact severity because the severity index approach is used with the current version of RSAP. Nevertheless, the vehicle orientation will be needed when a more sophisticated severity prediction model (e.g., the POI approach) is for estimating impact severity.
- **Versatility**. The stochastic approach allows for analysis of both sides of a roadway, and both directions of travel, simultaneously. This feature eliminates the need for multiple runs in complex situations on a two-way roadway, thereby eliminating the difference in computational costs between the two procedures for these situations.

3.2.2 Limitations of Stochastic Solution Method

Although the stochastic solution has many advantages, it also has some limitations as follows:

- **Computational time**. Although coding requirements for the Monte Carlo simulation technique are less than those for a deterministic model, the computational requirements for this technique were found to be higher because of its highly repetitive nature. Given the rapid advances in the computing capability and speed of computers, this limitation will be of less concern with the newer generations of computers.
- **Multiple solutions**. Because of the nature of the stochastic process, the answers may vary from run to run within a range as determined by the convergence criteria. In other words, when the same applications is run multiple times, some variations in crash costs and B/C ratios can be expected. For the purpose of most evaluations, slight variations in the answers should not pose any significant problem. The variations are the result of random seed numbers, which determine how the encroachments are sampled as well as the associated encroachment characteristics. Thus, using the same seed number could eliminate variations between runs of the same application.

More discussions on the seed number and its effect on the simulation results are presented in Chapter 4.

- **Convergence**. A stochastic solution must have a convergence level tight enough to achieve an accurate solution, but not so tight as to increase the processing time for the program significantly. The tightness of the convergence level is of particular importance to RSAP because of the high crash costs associated with some extremely rare crash scenarios (e.g., fatalities). The accuracy of the Monte Carlo procedure is directly related to the sample size or the number of simulation runs. RSAP currently provides three levels of convergence: low, medium, and high, which correspond to variations of 10%, 5%, and 1%, respectively, between the simulated and actual distributions. The convergence criteria can be further tightened to improve the accuracy of the results if deemed necessary. Unfortunately, tightening the acceptable range for the convergence criteria would increase the computational time significantly.

3.3 PROGRAM CAPABILITIES, ADVANTAGES, AND LIMITATIONS

3.3.1 Program Capabilities

RSAP can handle evaluations of projects with a maximum of 20 different safety improvement alternatives; 20 consecutive roadway segments for roadways of up to 16 lanes; and 1,000 roadside features. The program is capable of analyzing hazards on either or both sides of the roadway as well as in the median for a divided roadway simultaneously.

Despite the considerable capabilities built into RSAP, it is recommended that the formulation of the project for analysis be kept as simple as possible. An overly complex formulation with a large number of improvement alternatives, roadway segments, and roadside features makes it very difficult to check for errors in the input data or to review the results to make sure that the answers are reasonable. The processing time will also be excessively long.

3.3.2 Comparison with ROADSIDE Program

The ROADSIDE program, presented in the 1989 and 1996 versions of the AASHTO *Roadside Design Guide*, is perhaps the most commonly used cost-effectiveness analysis procedure. RSAP is intended as a replacement for the ROADSIDE program and provides some significant improvements. First, RSAP provides a more user-friendly interface, rendering it much easier to use than the ROADSIDE program. In addition, there are many technical improvements, as summarized in Table 7 and discussed below.

The ROADSIDE program uses a constant encroachment rate of 0.0003 encroachments per km per year per ADT. The lateral extent of encroachment distribution is based on a constant deceleration rate of 3.7 m/sec/sec (0.4 *g*) and a sine curve density function for steer back. In comparison, RSAP uses the Cooper encroachment data, which is considered to be the best encroachment data currently available. Adjustments were made to account for encroachments with 4 m or less of lateral extent that might not have been detected due to presence of paved shoulders

The ROADSIDE program uses a hypothetical distribution for encroachment speed based on design speed and an average encroachment angle based on the point-mass model. A constant deceleration rate of 3.7 m/sec/sec (0.4 *g*) is assumed for calculating the impact speed from the encroachment speed. A straight path is assumed so that the impact angle is the same as the encroachment angle. In comparison, RSAP uses impact speed and angle distributions derived from real-world crash data. A straight path with no braking is assumed so that the encroachment speed and angle are the same as the impact speed and angle.

The ROADSIDE program uses only a single vehicle type and an average encroachment angle for the hazard imaging and vehicle orientation is not taken into account. The program can handle only one hazard at a time and shielding of one hazard by another is not taken into account. For multiple hazards, each hazard has to be analyzed individually and the crash costs summed manually. In comparison, RSAP allows for 12 vehicle types. Vehicle orientation is incorporated into the program based on real-world crash data. Hazard imaging is based on size of the vehicle, encroachment angle, and vehicle orientation. The program can handle multiple hazards with algorithms to account for shielding of one hazard by another and multiple impacts.

The ROADSIDE program uses an average SI with no account for speed. RSAP estimates severity as a function of impact speed instead of an average value. These improvements incorporated into RSAP provide better severity estimates, which is perhaps the most critical element for estimating crash costs. Further, the ROADSIDE program assumes that all impacts with a hazard shielded by a barrier are eliminated regardless of barrier length while RSAP allows for impact with hazard shielded by barrier if the vehicle encroaches upstream of the barrier.

For analysis with multiple alternatives, the ROADSIDE program requires manual calculations for the incremental benefit/cost ratios while RSAP calculates the ratios internally. Finally, the ROADSIDE program is a deterministic model while RSAP is a stochastic model using the Monte Carlo simulation technique. The stochastic approach allows for future updates to the program, such as incorporation of curvilinear vehicle path and severity estimates for side impacts, without major rewrite of the program.

3.3.3 Limitations of RSAP

Although RSAP is an improvement over existing procedures, it also has drawbacks and limitations, most of which

TABLE 7 Comparisons of RSAP and the ROADSIDE program

Parameter	ROADSIDE	RSAP
Encroachment Rate	A constant of 0.0003 encroachments per km per year per vehicle per day.	Cooper encroachment data, adjusted for encroachments with lateral extent <= 4 m.
Encroachment Speed	Function of design speed.	Same as impact speed.
Encroachment Angle	Average angle based on point-mass model.	Same as impact angle.
Impact Speed	= Encroachment speed - speed loss with 3.7 m/sec/sec (0.4 *g*) deceleration rate.	Based on real-world crash data.
Impact Angle	Same as encroachment angle.	Based on real-world crash data.
Lateral Extent of Encroachment	Assumes 3.7 m/sec/sec (0.4 *g*) deceleration rate and sine curve density function for steer back.	Cooper encroachment data, adjusted for encroachments with lateral extent <= 4 m.
Vehicle Type	Single vehicle type.	12 vehicle types, based on nominal percent truck.
Vehicle Orientation	None.	Based on real-world crash data.
Shielding of One Hazard by Another	No.	Yes.
Multiple Hazards	Each hazard has to be analyzed individually and the crash costs summed manually.	Yes.
Effect of Barrier Protection	All impacts with hazard shielded by barrier eliminated, regardless of barrier length.	Vehicles encroaching upstream of barrier could impact hazard shielded by barrier.
Severity (SI)	Average values only.	Function of impact speed.
Incremental *B/C* Ratios for Multiple Alternatives	Have to be calculated manually.	Yes.
Solution Method	Deterministic.	Stochastic, using the Monte Carlo simulation technique.

are the result of lack of available data or requiring level of effort beyond that available for this study. Brief discussions on these limitations and future modifications and refinements are presented in the following:

- **Encroachment data**. The Cooper encroachment data, collected in the late 1970s, are more than 20 years old. Many changes have occurred in the interim (e.g., improved highway and roadside designs, higher speed limits, higher traffic volumes, and better vehicle safety equipment). Unfortunately, no newer or better encroachment data are available. Efforts to collect encroachment data with videotape surveillance and electronic monitoring system in the 1980s were not successful.[31] There have also been exploratory efforts to estimate encroachment rates from police-level crash data and statistical modeling, some of which are still ongoing.[58] The encroachment probability model can greatly benefit from better encroachment data.
- **Vehicle path**. RSAP does not take into account vehicle and driver behavior during encroachments because little data on these factors are available. These factors could have affect crash prediction and impact severity significantly. Vehicle and driver behavior would modify the hazard swath calculations by allowing curvilinear trajectories and changing vehicle orientation along the path of the encroachment and could affect the probability of an encroaching vehicle impacting a hazard with its side. Accounting for vehicle behavior resulting from the environment (e.g., slope effects) would require additional information about slope and soil friction conditions, as well as vehicle tire wear, pavement conditions, and shoulder type and condition.

Under the ongoing NCHRP Project 17-11, single-vehicle, ran-off-road crashes investigated in depth under the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) were manually reviewed and reconstructed. The resulting data may provide more insights into driver avoidance maneuvers and the off-road trajectories of vehicles during encroachments and thus allow the vehicle path to be better modeled.

- **Extent of lateral encroachment**. Under the ongoing NCHRP Project 17-11 mentioned above, more information may also become available on the distributions for the extent of lateral encroachment and their relationships to roadside slopes and geometrics. RSAP has algorithms similar to those in the ROADSIDE program to adjust the extent of lateral encroachment for roadside slopes and horizontal curvature. The new information will be most helpful to update and refine the distributions for the extent of lateral encroachment and the adjustment algorithms for roadside slopes and geometrics.
- **Crash severity estimates**. One of the original goals of this study was to replace the SI with another measure to better estimate crash severity. As may be expected, severity estimation is one of the most critical components of the cost-effectiveness analysis procedure because it directly affects the crash cost calculations. The SI scale has a fixed relationship to injury severity (i.e., a given SI value is associated with specific percentages of fatal, injury, and PDO, and is not flexible or sensitive enough to account for different hazard types. The SI estimates were based on engineering judgment and are believed to be higher than the actual severity.

  A POI approach was developed to replace the SI approach. Under the POI approach, the probability of injury by severity level would be estimated as a function of hazard type and impact conditions and calibrated against real-world crash data. Unfortunately, the level of effort required under the POI approach was much greater than the available funding and it was decided that the SI approach would be adopted for the current version of RSAP. However, there remains the need for a better procedure to estimate the crash severity. The POI approach is used to develop severity estimates for selected roadside features under the ongoing NCHRP Project 22-12 in its efforts to develop selection guidelines for roadside features.
- **Detailed impact models**. The impact models incorporated into RSAP are merits of each individual impact model. Those models found to be relatively effective in identifying impact results can then be incorporated into the cost-effectiveness evaluation procedure.
- **Median barrier warrants**. RSAP is intended for single-vehicle ran-off-road relatively simplistic. Although more sophisticated models can be developed and incorporated, there is some question regarding the validity of these models. Additional research is needed, which was beyond the scope of this project, to evaluate the type crashes and cannot handle cross-median, vehicle-to-vehicle type crashes. Thus, RSAP is not suitable for use in assessing the need for a median barrier directly. As discussed in Appendix D of the User's Manual, the situation may be modeled indirectly to approximate cross-median crashes for the evaluation. Also, a theoretical model was developed under NCHRP Project 22-12 to evaluate cross-median type crashes, but the model was not tested or validated. The addition of such a model to RSAP would allow for evaluation of median barrier warrants and should be considered in enhancements to RSAP.

CHAPTER 4

MONTE CARLO SIMULATION TECHNIQUE

As discussed previously under Chapter 3, "Program Overview," a stochastic approach using the Monte Carlo simulation technique was incorporated into RSAP. The Monte Carlo technique simulates one encroachment at a time. The conditions associated with each encroachment are randomly generated from built-in distributions of encroachment scenarios for these parameters, including the following:

- Encroachment location, including segment, location within segment, travel direction, departure lane, and encroachment direction (right or left);
- Encroachment speed and angle combination;
- Vehicle type; and
- Vehicle orientation.

This chapter describes the process of generating the samples of encroachments and the associated encroachment conditions as defined by these parameters.

4.1 GENERAL

Some of the encroachment parameters are generated individually and others are generated in combination. When two or more encroachment parameters are correlated, the sample generation procedure must take this dependency into account. Independent parameters can be selected using separate random processes while dependent parameters must be lumped into a common random process. Parameters that are selected in combination include (1) encroachment location and (2) encroachment speed and angle. Encroachment speed and angle are clearly correlated through physical limitations on the cornering ability and should, therefore, be selected in combination.

Encroachment location consists of five parameters:

- Segment in which the encroachment occurs,
- Location within the segment,
- Direction of travel,
- Lane in which the encroachment originates, and
- Direction of encroachment (i.e., right or left).

Some segments have higher encroachment rates than others because of adjustments for factors such as horizontal curvature, vertical grade, and user-defined adjustment factors. The sampling of encroachments should, therefore, take the varying encroachment rates among the segments into account. For a given segment, the encroachment location within the segment is independent of other parameters. The encroachment rate by direction of travel has to be adjusted for horizontal curvature and vertical grade. The lane of origination is a function of the number of lanes and traffic distribution among the lanes. As mentioned in Chapter 2, crash data studies suggest that the direction of departure from a lane appears to be uniform and relatively insensitive to the lane of origination.[33] Thus, the encroachment direction needs to account for only the horizontal curvature. Nevertheless, the selection of departure lane and encroachment direction was combined for convenience.

As for vehicle type, although there is clear evidence that some subclasses of vehicles are more likely to be involved in ran-off-road crashes than others, there is insufficient data to develop general relationships between vehicle type and likelihood of an encroachment. Thus, vehicle type is sampled independently. Lack of data is also the primary reason that vehicle orientation is not linked to vehicle type, even though research on vehicle handling clearly indicates a link between wheelbase and spinout crashes.

Probability distributions were developed for these parameters, either individually or in combination. These probability distributions were stored in the program as look-up tables that can be used in conjunction with a random number to specify the appropriate cell for each encroachment. For example, the encroachment speed and angle distribution has 49 cells or possible combinations and each cell has an associated probability. Each cell will then be assigned a unique probability range that correlates with its probability of occurrence. For instance, if a cell has a probability of 0.04, it might be assigned the range from 0.91 to 0.95. Whenever the generated random number (between 0 and 1) is within the range of 0.91 to 0.95, that cell or that combination of encroachment speed and angle will be selected.

4.1.1 Random Number Generation

A random number generator is used to generate the encroachment samples. The random number generator actually produces a sequence of pseudo-random numbers using a linear congruent generator. That is, a specific sequence of "random" numbers (random uniform deviates) is generated from a certain starting point or "seed number." If the same seed number is used, the same sequence of "random numbers" will be generated. These random numbers have a specified range, typically from 0 to 1. More information on linear congruent generators is provided in Park and Miller[46] and Schage.[47]

Given that the linear congruent generator produces a sequence of numbers, it has a period after which the numbers are no longer acceptably random. Therefore, L'Ecuyer[48] suggested combining two random number generators into one, thereby increasing the period tremendously. Because of the large number of encroachments generated by RSAP in a typical analysis before arriving at a solution, this method of dual random number generator was used. Additionally, to break up any serial correlations, a shuffling procedure by Bays-Durham is used.[49] With this shuffling procedure, the (i)th random number generated in the sequence is not used as the (i)th number output. Instead, it is used later as the (i+32)th call on the average. The statistical tests for randomness of this generator are presented in L'Ecuyer and will not be repeated here.

As mentioned previously, one drawback with this stochastic approach using random number generation is that the answers will vary from run to run within a range as determined by the convergence criteria. In other words, when the same application is run multiple times, some variations in crash costs and benefit/cost ratios can be expected. For the purpose of most evaluations, slight variations in the answers should not pose any significant problem. However, variations in the results may cause concern for some users who are used to a deterministic approach with a single answer. Thus, there is a need for ensuring randomness in the simulations and minimizing variations between runs of a given application.

The variations are the result of random seed numbers, which determine how the encroachments are sampled as well as the associated encroachment characteristics. To ensure randomness, it is recommended that the seed number be randomly selected for each new application; it is recommended that the same seed number be used for a given application to eliminate variations between runs.

4.1.2 PROBABILITY DISTRIBUTIONS AND SCALING

The simplest procedure for developing a representative sample of encroachments is to randomly select the parameters. However, most probability density functions have some regions where the probability of occurrence is very low. If these rare events have a significant effect on the overall outcome, it is critical that they are sampled with sufficient frequency in order not to bias the results. For example, the combination of high speed and high angle for any given crash has a very low probability of occurrence, but it is most likely to result in fatal or severe injuries. Given that fatal or severe injuries have high associated crash costs, the frequency in which the combination of high speed and high angle is selected will have a significant effect on the overall average crash cost.

To further illustrate this point, consider Table 8 which offers a hypothetical example with four possible events, each associated with a certain probability of occurrence and resultant crash costs.

For the purpose of illustration, assume that a total of 1,000 samples are selected with the Monte Carlo simulation. The expected frequencies of occurrence for each of the four events are calculated by multiplying the probability of occurrence with the number of samples, such as $1{,}000 \times 0.8 = 800$ for Event A, $1{,}000 \times 0.1 = 1000$ for Event B, and so forth, as shown in Table 9.

Event D is expected to occur only once per 1,000 samples. However, because of the randomness of the selections, the actual number of event D sampled may range from 0 to 1, or 2, or possibly more times. Table 10 shows the average costs for three possible selection scenarios in which event D is sampled 0, 1, or 2 times. The average cost is calculated by summing the product of the expected frequency of occurrence and the resultant crash cost for the four events and then dividing the total cost by the sample size of 1,000.

It is evident from the hypothetical example that the presence or absence of one or two rare events with high associated costs could dramatically alter the results of the simulation. The effect of such rare events would lessen as the sample size increases and eventually approach or converge to the average cost based on probability. Depending on the probability of the rare event, selection of a sufficient number of samples could be computationally prohibitive. To overcome this problem, a scaling procedure is incorporated into RSAP to over-sample rare events and thereby ensure that these accidents are adequately represented in the sample of predicted crashes.

The scaling procedure involves converting the cell probabilities for each look-up table so that all the cells have the same probability of occurrence (i.e., a uniform distribution). The sample generation process now becomes an unbiased selection procedure because each cell has an equal probability of occurrence. The scaling factor to convert the probability of any given cell to a value reflecting a uniform distribution is determined by Equation 8:

$$SF_i = 1/(N_c * P(I)) \qquad (8)$$

TABLE 8 Hypothetical example

Event	A	B	C	D
Probability	0.8	0.1	0.099	0.001
Cost ($)	10	25	500	100000

TABLE 9 Expected frequencies of occurrence

Event	A	B	C	D
Expected Frequency of Occurrence	800	100	99	1

TABLE 10 Average costs for different selection scenarios

Event	A	B	C	D	Average Cost
Event D Not Selected	800	100	100	0	$ 60.50
Event D Selected Once	800	100	99	1	$160.00
Event D Selected Twice	800	100	98	2	$260.00

where

SF_i = Scaling factor for cell i,
N_c = Total number of cells,
$P(I)$ = Probability associated with cell i.

The cell probability is then multiplied by the scaling factor to produce a uniform distribution. As shown in Table 11, the scaling factors are less than 1.0 for cells with higher-than-average probability (i.e., cell probability for a uniform distribution) and greater than 1.0 for cells with lower-than-average probability. The scaling factor can become very large for cells with low probability or "rare events."

With this scaling of cell probabilities to a uniform distribution, the sample encroachments are no longer representative of the population. Thus, the resulting crash costs are also not representative of average encroachment conditions. It is, therefore, necessary to "weight" the estimated crash costs to reflect the actual likelihood of a crash occurring. This is accomplished by dividing the estimated crash cost for each cell by the weighting factor for that cell as shown in Equation 9:

$$ACC_i = CC_i / SF_i \qquad (9)$$

where

ACC_i = Weighted crash cost for cell i,
CC_i = Crash cost for cell i, and
SF_i = Scaling factor for cell i.

The weighted crash costs are summed over all the cells to determine the total crash cost, which is then divided by the number of sampled encroachments to determine the average encroachment cost.

To illustrate this scaling and weighting process, consider the previous hypothetical example with four events in which event D has a very low probability of occurrence, but a very high associated cost. Again assume a total sample size of 1,000 selections. Because the probability distribution is now uniform, each event would have the same probability of 0.25 and the same expected frequency of occurrence of 250, as shown in Table 12.

Although the number of occurrences of event D would still vary, the average cost would not be affected dramatically, as illustrated in Table 13.

As can be seen from Table 13, the effect on average cost when event D is undersampled or over sampled is greatly reduced. Further, the average cost is not affected by the scaling procedure as illustrated by the average sample situation. It is much easier to get a representative sample of a uniform distribution than a non-uniform distribution where some cells have very low probability of occurrence. Note that one of the five sampling parameters, encroachment location, is not

TABLE 11 Scaling factors

Event	A	B	C	D
Original Probability	0.8	0.1	0.099	0.001
Scaling Factor	0.3125	2.5	2.525	250
Adjusted Probability	0.25	0.25	0.25	0.25

TABLE 12 Expected frequencies of occurrence after weighting

Event	A	B	C	D
Adjusted Probability	0.25	0.25	0.25	0.25
Expected Frequency of Occurrence	250	250	250	250

TABLE 13 Average costs for different selection scenarios after weighting

Event	A	B	C	D	Average Cost
Event D Under-Sampled	250	275	275	200	$145.21
Event D with Average Sample	250	250	250	250	$160.00
Event D Over-Sampled	250	225	225	300	$174.75

scaled because the location is continuous along each roadway segment. Only discrete parameters can be scaled because the probability of each event in a continuous distribution is zero and the scaling factor would be infinity. Also note that, in addition to the determination of average crash cost, the weighting factors are also used in the determination of expected impact frequency and average severity for each alternative and each roadside feature.

4.2 SAMPLE GENERATION

This section describes the processes for randomly generating the values for the following parameters associated with an encroachment:

- Encroachment location,
- Encroachment speed and angle combination,
- Vehicle type, and
- Vehicle orientation.

4.2.1 Encroachment Location

As mentioned previously, encroachment location consists of the following five parameters:

- Segment in which the encroachment occurs,
- Location within the segment,
- Travel direction,
- Lane in which the encroachment originates, and
- Direction of encroachment (i.e., right or left).

How each of these parameters is selected are described in the following sections.

4.2.1.1 Encroachment Segment

The probability of encroaching from a given roadway segment depends on the length of the segment and the encroachment rate for the segment after adjusting for horizontal curvature, vertical grade, traffic growth factor, and user-defined encroachment rate adjustment factor. The expected annual number of encroaching vehicles for a given segment is determined by multiplying the adjusted encroachment rate for the segment by the length of the segment. The relative likelihood that an encroachment will occur in any given segment is then the encroachment frequency for that segment divided by the total encroachment frequency for all segments. Note that the segments are defined so that each segment would have a relatively uniform encroachment rate.

4.2.1.2 Encroachment Location Within a Segment

Encroachment location within a segment is determined by generating a random number (between 0 and 1) and then multiplying the random number by the length of the segment in which the encroachment occurs. If the vehicle is traveling in the primary travel direction, the location is appropriate because the reference point is the beginning of the segment. However, if the vehicle is traveling in the opposing direction, the location of encroachment is subtracted from the length of the segment because the reference point is now the end of the segment.

For example, an encroachment occurs in a 1,000-m long segment and the random number generated is 0.397. If the encroaching vehicle is traveling in the primary travel direction, the encroachment occurs at 1,000 x 0.397 or 397 m from the beginning of the segment. If the vehicle is traveling in the opposing direction, the encroachment occurs at 1,000 – 397 or 603 m from the end of the segment. This change in the reference system is needed for the opposing travel direction so that the hazards and features are located properly in relation to the direction of travel of the encroaching vehicle.

4.2.1.3 Travel Direction

The travel direction is determined by comparing a random number between 0 and 1 with the probability of a vehicle traveling in a given direction, assumed to be 0.5. If the random number is less than 0.5, the vehicle is traveling in the primary travel direction; if greater than or equal to 0.5, the vehicle is traveling in the opposing direction. Note that there is no opposing direction for one-way roads.

4.2.1.4 Lane of Origination

The encroachment rate is assumed to be the same for all lanes. This assumption is not necessarily true because the operating speed on the inner lanes is usually higher than that of the outer lanes. The increased operating speed may result in higher encroachment rates. On the other hand, higher traffic volumes on the outer lanes could result in more traffic conflicts and possibly higher encroachment rates. There is simply insufficient data available at this time to determine the differences in encroachment rates from lane to lane. Thus, encroachment rate is assumed to be the same for all lanes. However, RSAP is designed to incorporate this information when it becomes available.

Note that, although the encroachment rate is assumed to be the same for all lanes, the lane of origination affects the lateral distance that a vehicle would travel after leaving the travelway. Therefore, the lane of origination is an important parameter.

Assignment of traffic to each lane is done by simple proportion. It is assumed that the rightmost travel lane in each direction carries twice as many vehicles as any other lane until it reaches capacity. Then, any traffic above this capacity is apportioned to the other lanes until all lanes reach capacity. Note that, because RSAP calculates annual crash costs, the normal hourly, daily, weekly, and seasonal fluctuations in traffic volumes and the actual capacity of the roadway are not important to the evaluation.

For simplicity, the capacity of a single lane of a multilane roadway is assumed to be 2,000 vehicles per hour, which is the capacity of a freeway lane under ideal conditions.[50] Given that roadways generally reach capacity only once or twice a day, RSAP would tend to allow more encroachments from the outermost lanes than would be expected. Because these encroachments are closer to hazards on the right-hand (or left-hand, for the opposing direction) side of the road, RSAP will produce more predicted impacts and, therefore, provide a more conservative solution.

The probability for an encroachment to originate from a particular lane is the assigned traffic volume to that lane divided by the total traffic volume for all lanes. Each lane is then assigned a unique probability range that correlates with its probability of occurrence. Whenever the generated random number (between 0 and 1) is within the unique range for a particular lane, that lane is then selected as the lane of origination for that encroachment.

4.2.1.5 Encroachment Direction

There are two possible encroachment directions, right and left. For a tangent roadway section, the probability for encroachment in either direction is assumed to be the same, that is 0.5. For a curved roadway section, the probability of encroaching to the outside of the curve is higher than that to the inside of the curve. Each encroachment direction is then assigned a unique probability range that correlates with its probability of occurrence. Whenever the generated random number (between 0 and 1) is within the unique range for a particular direction, that encroachment direction is then selected.

4.2.2 Encroachment Speed and Angle Selection

RSAP uses a 7 by 7 matrix for a total of 49 cells or speed and angle combinations to describe possible encroachment conditions for each of five functional classes. Each cell or speed and angle combination is assigned a unique probability range that correlates with its probability of occurrence. Whenever the generated random number (between 0 and 1) is within the unique range for a particular speed and angle combination, that speed and angle combination is selected.

4.2.3 Vehicle Type Selection

RSAP uses 12 different vehicle types in the evaluation. The vehicle type distribution is calculated from the input data item, "nominal truck percent," which was based on published vehicle sales information.[51] Note that this distribution does not currently account for differences in the actual usage or mileage for the various vehicle types or the variations in vehicle mix by functional class or highway type. However, RSAP does allow users to change the built-in vehicle type distribution.

RSAP selects a vehicle type and size for each encroachment by generating a random number, multiplying it by 12, truncating it to an integer, and then adding 1. This provides a range of 1 to 12, each corresponding with one of the 12 vehicle types. Recall that the cell probabilities have been scaled to a uniform distribution. A particular vehicle type is selected when the adjusted random number falls in the range corresponding with that vehicle type. For example, the smallest passenger car is selected when the adjusted random number equals 1.

4.2.4 Vehicle Orientation Selection

As discussed previously, vehicle orientation at impact could have an important effect on the severity of many types of ran-off-road crashes, including those involving breakaway supports, guardrail terminals, and crash cushions. Although vehicle orientation is not yet included in the severity estimation in the current version of RSAP, vehicle orientation is incorporated into the procedure to accommodate future update and improvements. A total of 12 possible vehicle orientations are based on clock directions. RSAP uses the same process as it does for vehicle types to select one of the 12 possible vehicle orientations.

4.3 CONVERGENCE CRITERIA

A basic premise behind the Monte Carlo simulation procedure is that, when a sufficiently large sample of random encroachments is generated, the average costs of those samples will become representative of the actual average encroachment costs. The question then becomes when the sample size is "sufficiently large." Given that there is no method for identifying the correct solution, this process generally involves testing the solution for stability or convergence. A stochastic solution becomes stable or converges to an answer when additional samples do not significantly change the average encroachment costs.

The procedure incorporated into RSAP for determining convergence involves generating a block of samples (e.g., 20,000 simulated encroachments) and comparing the change in average encroachment costs before and after the block is added with the total sample. In addition, the distributions of the encroachment characteristics generated by the sampling process (i.e., encroachment location, speed and angle combination, vehicle type, and vehicle orientation) are checked for uniformity. Recall that the probability distributions for these parameters are scaled to a uniform distribution. These distribution checks are made to ensure that the convergence in average crash costs is not premature or false.

4.3.1 Speed and Angle Distribution

The encroachment speed and angle distributions are very important to cost convergence because of the direct relationships between these parameters and crash costs. Therefore, it is important that the distribution of the predicted encroachments have a uniform distribution of impact conditions. Note that the speed and angle tables do not necessarily converge to a uniform distribution for each hazard or feature, even though the overall encroachment speeds and angles are selected uniformly. This is primarily because of hazard geometry, hazards shielding other hazards, and the penetration resistance and rollover tendencies of particular vehicle types and particular hazards. RSAP keeps track of the converged tables of impact speed and angle combinations associated with each hazard, but no attempt is made to force these distributions to uniformity.

In general, the speed and angle distribution takes the longest to converge. When it does converge, the other three distributions and the average crash costs are almost always within the convergence ranges. Therefore, the speed and angle distribution is the most sensitive to solution accuracy and program running time, and the proper setting of the distribution convergence range is crucial to program performance, particularly on computers with older generation processors.

4.3.2 Vehicle Orientation Distribution

The convergence of the vehicle orientation distribution has only a very small effect on the average crash costs because vehicle orientation currently is not linked to crash severity. The only link between vehicle orientation and average crash cost is through varying vehicle swath dimensions because of vehicle heading. Therefore, the convergence range on vehicle orientation is included largely for use in the future when the link to severity is developed. Also, setting the convergence range too tight for the vehicle orientation distribution will adversely affect the processing time without improving the accuracy. However, when vehicle orientation is linked to severity in the future, this convergence check could become more important.

4.3.3 Vehicle Type Distribution

Unlike vehicle orientation, the convergence of the vehicle type distribution has a noticeable effect on the average crash costs. The vehicle type does not affect crash severity greatly, which is linked primarily to speed and angle. However, the penetration and rollover models use vehicle properties with the impact speed and angle. Thus, the vehicle type distribution has an indirect effect on the determination of hazard penetration and rollover. Given that penetrations, rollovers, and subsequent impacts generally have higher severity than redirection crashes, the increased severity of these crashes will affect the average crash costs.

Similar to the speed and angle distribution, a uniform distribution of the vehicle type distribution is required for all encroachments, but not for individual hazards or features. Also, setting too tight a convergence range will adversely affect the processing time without improving the accuracy of the solution.

4.3.4 Encroachment Location

The distributions of lane of origination and encroachment direction (i.e., right or left) are the only parameters checked under encroachment location. The effects of the lane of origination and encroachment direction relate directly to the lateral offset of the hazard and, therefore, to the probability of impact on that hazard. This effect is fairly important because it can change greatly the average crash costs for certain situations. Like the other distributions, the departure lane and encroachment direction distribution do not necessarily have a uniform distribution across all lanes because of the distance a vehicle must travel to cross multiple traffic lanes. The maximum extent of lateral encroachment is set at 25 m. Thus, any hazard beyond 25 m from the encroaching vehicle's travel lane would not be impacted (i.e., the probability of impact is 0). It is possible that, for some multi-lane facilities (divided or undivided), vehicles departing from the most distant lanes would not impact any hazards on the far side of the roadway.

4.3.5 Crash Costs

Crash costs are, ironically, not the most sensitive of the five convergence parameters. Crash costs are sensitive to the type of hazard struck, the vehicle type, and the speed and angle of impact. Distributions of vehicle type and the speed and angle of impact are already accounted for in separate convergence checks. Nevertheless, in order to ensure a stable solution (i.e., no premature or false convergence), the crash costs convergence test must be met for two consecutive blocks of samples. Tightening the convergence range for crash cost will increase the solution accuracy, but it will also increase the processing time of the program disproportionately. In other words, the increase in accuracy is more than off set by the increase in processing time.

4.3.6 Number of Samples per Convergence Check

The numbers of samples per convergence check cycle, previously referred to as the block of simulated encroachments, affects both the accuracy of the solution and the processing time. Decreasing the number of samples per convergence check cycle produces shorter running times because fewer unnecessary samples are generated prior to convergence and more convergence checks are made. However, the reduction in sample size would decrease the accuracy of the solution. Increasing the number of samples has the opposite effect (i.e., increasing the running time and using fewer convergence checks). The larger sample size would render the solution more stable and well worth the increase in processing time. The default number of samples per convergence check is 20,000 encroachments. It is possible for the user to alter the default number of samples per convergence check by editing the input file BASEDATA; however, this option is intended only for experienced users and thus is not available from the User Interface Program.

CHAPTER 5

ENCROACHMENT MODULE

As mentioned previously, the encroachment module uses a two-step process to estimate encroachment frequency. The first step involves estimating a base or average encroachment rate based on highway type and then multiplying the encroachment rate with the traffic volume to estimate encroachment frequency. The next step is to adjust the base encroachment frequency to account for specific highway characteristics that affect encroachment rates. More detailed descriptions of the encroachment module are presented in this chapter.

5.1 BASE ENCROACHMENT RATE

There are two available sources of encroachment data: the study by Hutchinson and Kennedy[29] in the mid-1960s and the Cooper study[30] in the late 1970s. Both studies involved observation of wheel tracks in the medians or on roadsides. The Cooper encroachment data were selected for use in RSAP for the encroachment rate-traffic volume relationships. The Cooper data were chosen because they are more recent, constitute larger sample size, and are thought to be of better quality than the Hutchinson and Kennedy data. Figure 13 shows the encroachment frequency curves used by RSAP. Encroachment rates are expressed as the number of encroachments per km per year per ADT.

Two adjustments were made to these encroachment frequency curves:

- The Cooper encroachment data were based on observation of tire tracks. However, with the presence of paved shoulders, encroachments that did not travel past the edge of the paved shoulders would not have been detected. Thus, it is believed that the encroachment data are under-reported for encroachments with lateral extent of 4 m or less. The Cooper encroachment data were, therefore, reanalyzed by excluding encroachments of 4 m or less in lateral extent. More detailed descriptions of the reanalysis are presented in Chapter 6, Section 6.4, "Extent of Lateral Encroachment Distribution." Based on results of the reanalysis, it was estimated that encroachments were under-reported by a ratio of 2.466 for two-lane undivided highways and 1.878 for multi-lane divided highways. Thus, the encroachment frequency was adjusted upward by these ratios to account for under-reporting of encroachments because of paved shoulders.
- Another limitation of the Cooper encroachment data was the lack of ability to detect the difference between controlled and uncontrolled encroachments. It is likely that farm and highway maintenance vehicles left some of the observed wheel tracks given that data were collected during the summer. Also, some vehicles might have pulled off the roadway intentionally for various reasons, such as to allow faster traffic to pass, to check on the vehicle, or to switch drivers. Although the number of these controlled encroachments is probably relatively small because of the presence of paved shoulders, they are included in the encroachment data nonetheless. The percentage of uncontrolled encroachments is assumed to be 60% based on a study of reported versus unreported crashes involving barriers.[43] Thus, the encroachment frequency is multiplied by a factor of 0.6 to account for these controlled encroachments.

5.2 ADJUSTMENT FACTORS

The next step is to adjust the base encroachment frequencies to account for specific highway characteristics that affect encroachment rates. For example, previous studies have found that vehicle encroachments are more likely on the outside of horizontal curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature. The adjustment factors incorporated in RSAP include horizontal curvature and vertical grade, traffic growth factor, and a user-defined adjustment factor. These adjustment factors are described in greater detail in the following subsections. The adjusted encroachment rates are determined by simply multiplying the base encroachment rates with the adjustment factors.

5.2.1 Horizontal Curve and Vertical Grade Adjustment Factors

Crash data studies have indicated that crash rates on horizontal curves and vertical grades are significantly higher than those on tangent sections.[32,33] It is logical to assume that encroachment rates would also be similarly affected by horizontal curves and vertical grades. Thus, RSAP incorporates adjustment factors to increase encroachment rates on horizontal curves and vertical grades, as shown in Figure 14. These adjustment factors are based on research conducted by

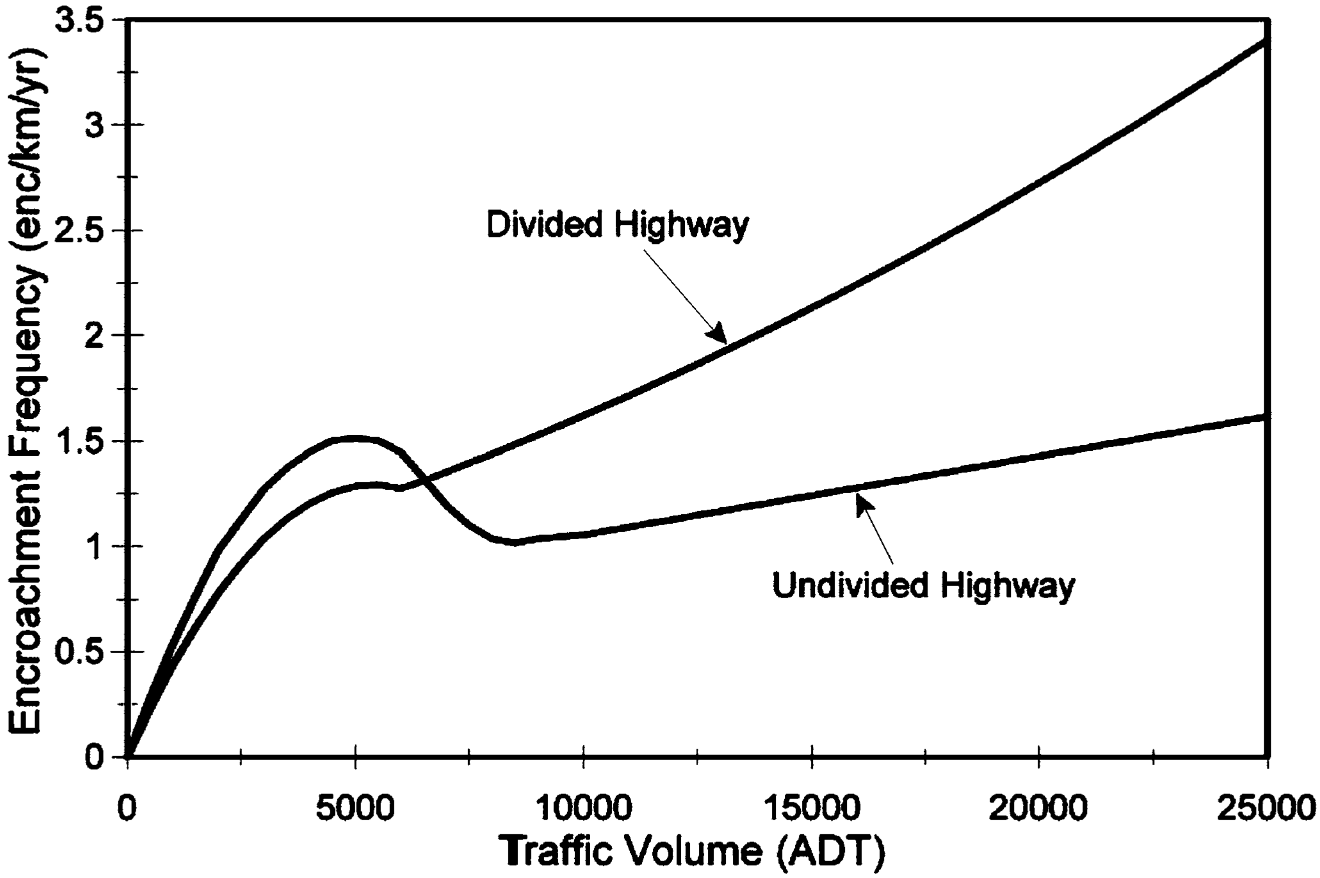


Figure 13. RSAP encroachment rate.[30]

Wright and Robertson[32] and are similar to those in BCAP[25]. The Wright and Robertson study compared the roadway characteristics (e.g., cross-sectional data elements, geometrics, and roadside conditions) at fatal single-vehicle, ran-off-road crash sites with those at sites 1.6 km upstream of the fatal crash sites. The underlying assumption is that differences in roadway characteristics between the fatal crash sites and the comparison sites are correlated with the occurrence of these fatal crashes.

Although the study methodology is generally considered valid and appropriate, drawbacks are as follows:

- The sample size is relatively small, with only 300 fatal crashes investigated.
- There was no control for some variables that are believed to be significant (e.g., highway type, terrain, and traffic volume). For example, some of the crashes occurred on unsurfaced rural roads.
- Only fatal crashes were included in the sample and the results might not be applicable to crashes with lesser severity.

In light of these drawbacks, it is believed that these adjustment factors overstate the effects of horizontal curvature and vertical grade on encroachment rates. However, currently there is no better source of information on the effects of horizontal curvature and vertical grade on encroachment rates. A larger-scale study with greater sample size, more representative crashes, and better control on some of the other influential parameters would be desirable.

Note that the adjustment factors for horizontal curvature and vertical grade are determined in relation to the roadway segment and the direction of travel. The roadway segments are purposely selected to provide homogeneous geometrics within a segment for this reason. In terms of direction of travel, the outside of a curve for one direction of travel would become the inside of a curve for the opposing direction of travel. Similarly, a downgrade for one direction of travel would become an upgrade for the opposing direction of travel.

5.2.2 Traffic Growth Adjustment Factor

The traffic volume or ADT entered into RSAP applies to the current year or construction year. To allow for future increase in traffic volume, RSAP provides for another input on annual traffic growth in percent. For a given year, *n*, in the future, the traffic volume is calculated as follows:

$$ADT_n = ADT_1 * (1 + i/100)^n \quad (10)$$

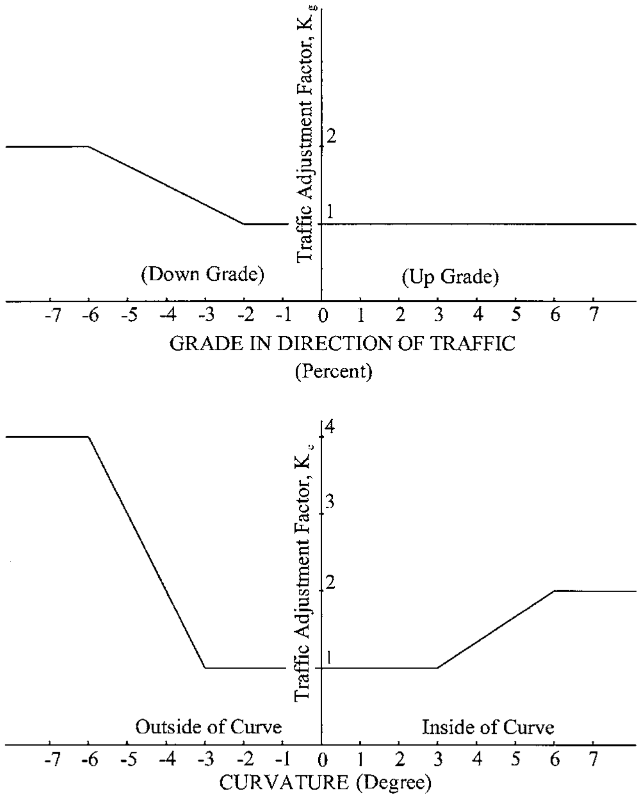


Figure 14. Encroachment frequency adjustment factors.[32]

where

ADT_n = Traffic volume in year n
ADT_1 = Current or base year traffic volume
i = Annual percent traffic growth

The traffic growth adjustment factor averages the traffic volume over the life of the project and is calculated as follows:

$$\text{Traffic growth adjustment factor} = \sum_{n=1}^{N} (1 + i)^n / N \qquad (11)$$

where N = Project life in years.

5.2.3 User-Defined Adjustment Factor

RSAP allows the input of a user-defined adjustment factor to account for special or unusual situations that could affect encroachment frequencies beyond the parameters incorporated into the program. For example, an adjustment factor of greater than 1.0 may be appropriate if the highway section under consideration has a higher-than-average crash history or there is a favorite bar or club nearby that could increase the incidence of drunk driving and encroachment frequencies at night. An adjustment factor of less than 1.0 may be appropriate for a highway section with special safety countermeasures, such as rumble strips on the shoulder or increased law enforcement activities.

CHAPTER **6**

CRASH PREDICTION MODULE

Given that an encroachment has occurred, RSAP then determines which, if any, of the roadside features the encroaching vehicle would encounter. The first step is to sort or arrange the roadside features for each alternative by longitudinal and lateral placement. The next step is to determine the vehicle swath or path associated with each simulated encroachment. The locations of the roadside features are then compared with the vehicle swath to determine which, if any, hazard(s) would fall within the vehicle swath. Brief descriptions of these steps are presented in the following sections.

6.1 HAZARD SORTING ROUTINE

The sorting of the roadside features or hazards is done in three steps. First, the features for each alternative are arranged by their longitudinal locations relative to the beginning of the first segment. The features are next sorted by their placement relative to the travelway (i.e., right side, median, or left side) in accordance with the principal direction of travel. Finally, lateral offsets of the features are then determined relative to the edge of each lane. Note that this sorting routine yields two sets of lateral placement arrays for each lane describing feature locations on the right and the left sides. For a divided highway, the array of features on the left side would include both features in the median and on the far left side. The arrays are arranged in the direction of travel so that, for lanes in the opposing travel direction, the upstream ends of hazards are redefined to provide the correct longitudinal coordinates and the lateral locations and offsets of features are in the direction of travel.

6.2 VEHICLE SWATH

In order to determine if an encroachment vehicle would encounter any of the roadside features, the program identifies a swath or a path for the vehicle. The vehicle swath is determined as a function of the encroachment angle, the vehicle size, and the vehicle orientation. The encroaching vehicle will impact any roadside feature within the swath. If there is no roadside feature within the vehicle swath, no crash would occur and the program will then proceed with another simulated encroaching vehicle. If there is only one roadside feature within the vehicle swath, a crash is predicted to occur and the program will proceed with estimating the severity of the impact, including checks on penetration and rollover.

If more than one roadside features are within the vehicle swath, the first feature struck is determined based on the geometry of the vehicle relative to each feature. The first impacted feature will then be checked for penetration and rollover. If no penetration is predicted or the vehicle rolls over, the impact sequence is assumed to be over and the program will then proceed with estimating the severity of the impact. If penetration of the first impacted feature is predicted, the speed of the vehicle will then be adjusted and the program will check for the next roadside feature to be impacted. This process will continue until the encroaching vehicle either impacts an object it cannot penetrate, the vehicle rolls over, or there are no more roadside features within the vehicle swath. The program will then proceed to estimate the severity of the impacts and the impact with the highest severity will be selected.

The following simple assumptions were made regarding the encroaching vehicle and its behavior during encroachment:

- The vehicle maintains a constant encroachment angle throughout the event.
- The vehicle maintains a constant orientation (slip angle) throughout the event.
- The vehicle's speed does not change appreciably as a result of braking.

Of course, none of these three assumptions holds true in the real world. The initial encroachment speed and angle and vehicle orientation may be altered during an off-road excursion because of steering, braking, slope effects, available roadway and roadside friction, and/or striking or traversing roadside features. However, the off-road behaviors of vehicles and drivers are not clearly understood primarily because of limitations in data collection procedures for encroachment studies[29,30] and crash data studies. There is no available data to allow the incorporation of these effects into the procedure at this time. The recently completed NCHRP Project 22-11 may provide some insight into these areas.[52] Note that RSAP was modular in design so that these effects can be incorporated into the procedure with relative ease when the data do become available.

Although the exact effects of these assumptions are unknown given the lack of data, some inferences could be made. The first assumption of no braking (i.e., vehicle speed remains approximately constant throughout an encroachment) is perhaps the least important of the three assumptions. Through crash reconstructions, impact speed distributions have been found not to change much for the first 6 m (20 ft) from the edge of the travelway.[24,33] Even if impact speeds begin to decrease substantially as the distance from the travelway increases, the effect of assuming no reduction in speed would tend to increase the estimated severity of ran-off-road crashes, making the prediction by RSAP more "conservative," (i.e., the program would tend to predict that a given safety improvement is cost-beneficial at lower traffic volumes than it should).

This assumption only applies to changes to the initial vehicle speed while traversing the roadside. Impact with a roadside feature object obviously would produce speed changes, and RSAP has a built-in algorithm to account for this speed change. When a roadside feature is struck, the impacting vehicle's energy is reduced by an amount equal to the containment level of the impacted feature (in the case of downslopes, the vehicle's energy is actually increased because of the conversion of potential energy to kinetic energy).

The second assumption of a constant encroachment angle and a straight vehicle path (i.e., no steering) is probably the most significant because it affects the vehicle swath and the probability of impacting with the roadside features. However, this assumption does not affect the severity estimates because the impact angle distribution was derived from real-world crash data.

The effect of the third assumption of constant vehicle orientation or slip angle is not believed to be as important as the second assumption on constant encroachment angle. The change in the orientation of the vehicle has only a modest effect on the vehicle swath and the resulting probability of an impact. Again, this assumption does not affect the severity estimates because the vehicle orientation distribution was also derived from real-world crash data.

6.2.1 Basic Swath Calculation

When a vehicle leaves the travelway, eight orientations are possible for the encroaching vehicle:

1. The vehicle's right side is parallel to the edge of the roadway.
2. The vehicle's right front corner leaves the roadway first.
3. The vehicle's front is parallel to the edge of the roadway.
4. The vehicle's left front corner leaves the roadway first.
5. The vehicle's left side is parallel to the edge of the roadway.
6. The vehicle's left rear corner leaves the roadway first.
7. The vehicle's rear is parallel to the edge of the roadway.
8. The vehicle's right rear corner leaves the roadway first.

Geometrically, the front and rear of a rectangular vehicle are identical, as are the left and right sides. Thus, the number of orientations is reduced to four. Also, the orientations where a side of the vehicle (i.e., left, right, front, or rear) is parallel to the roadway can be considered a limiting case for one of the vehicle corners, further reducing the number of orientations to only two (i.e., right front [or left rear] corner or left front [right rear] corner leaving the roadway first).

Next the vehicle orientation is combined with the encroachment angle. This increases the number of possible configurations to four, as illustrated in Figure 15:

A. Right front (or left rear) corner leaves the roadway first and the angle $(\theta + \alpha)$ is between 0 and θ deg.
B. Right front (or left rear) corner leaves the roadway first and the angle $(\theta + \alpha$ is between θ and 90 deg.
C. Left front (or right rear) corner leaves the roadway first and the angle $(\theta + \alpha)$ is between 90 and $(\theta + 90)$ deg.
D. Left front (or right rear) corner leaves the roadway first and the angle $(\theta + \alpha)$ is between $(\theta + 90)$ and 180 deg.

where θ = encroachment angle, and α = vehicle yaw angle.

The vehicle yaw angle, α, is defined as the angle between the vehicle heading (or orientation) and the velocity vector (i.e., direction of travel for the center of gravity of the vehicle). This definition of vehicle yaw angle was chosen to be compatible with crash data studies, which is different from the usual definition used in vehicle dynamics (which defines this angle as a slip angle).

For each of these configurations, six points along the vehicle path are determined. These six points are illustrated in Figure 16 for Case A. For each encroaching vehicle, one corner will leave the roadway first. Because the vehicle orientation is fixed throughout the encroachment, this "first corner" will also be the first to reach the maximum possible lateral extent of encroachment. The next two corners to leave the roadway define the remainder of the encroachment swath. The fourth corner of the vehicle is not important to the calculations. These six points of the encroachment swath are defined as follows:

1. Where the first corner of the vehicle leaves the roadway (given),
2. Where the first corner of the vehicle reaches the maximum lateral extent of encroachment,
3. Where the second corner of the vehicle leaves the roadway,
4. Where the second corner of the vehicle is when the first corner of the vehicle reaches the maximum lateral extent of encroachment,
5. Where the third corner of the vehicle leaves the roadway, and

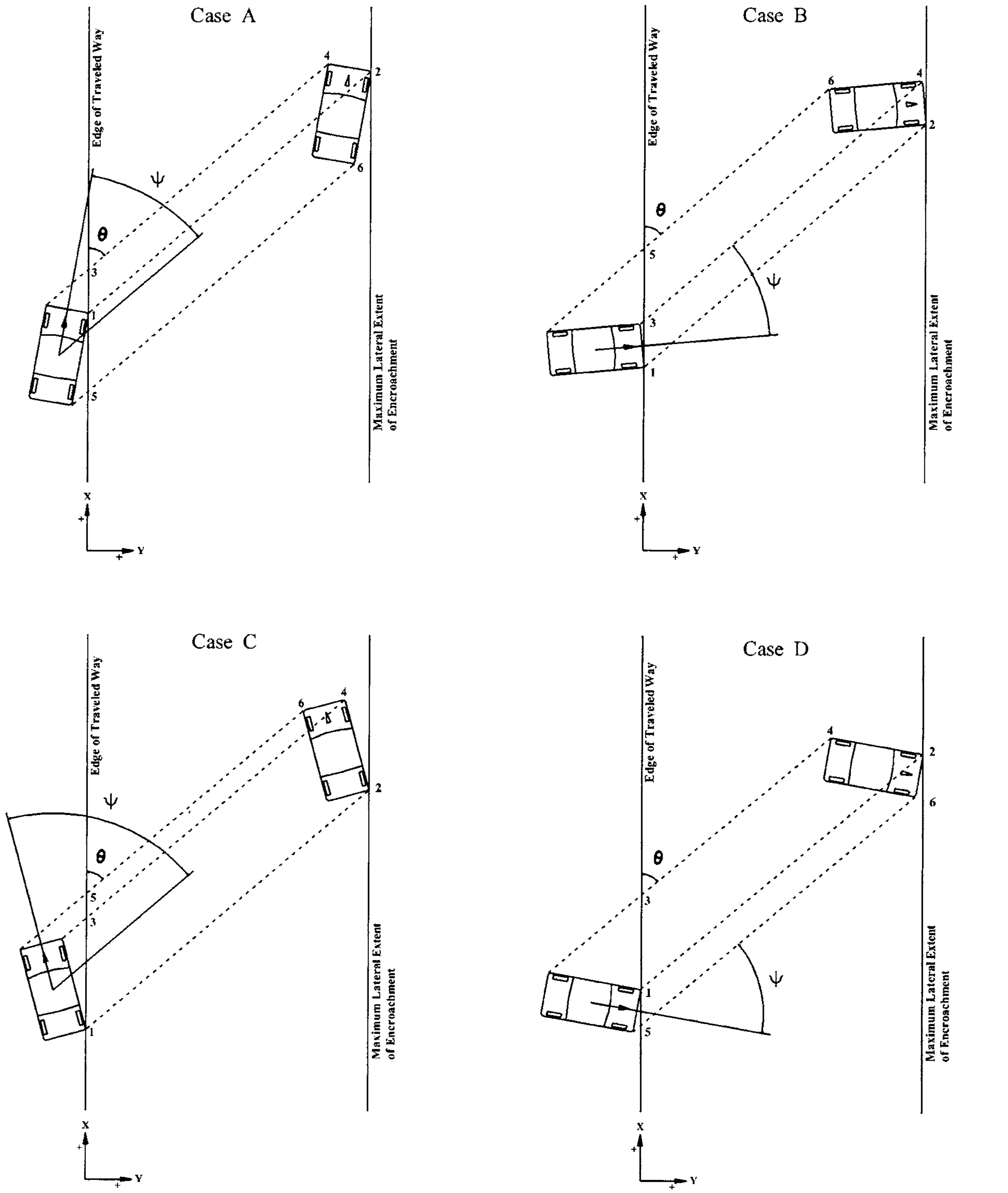


Figure 15. Swath points.

6. Where the third corner of the vehicle is when the first corner of the vehicle reaches the maximum lateral extent of encroachment.

Note that cases A and D, as shown in Figure 15, are similar in that the first corner of the vehicle exits between the second and third corners. Cases B and C are likewise similar because the first corner is the most upstream point. For all encroachment cases, the equations defining the points are shown in Figure 17. Note that, for combination trucks, it is assumed that the trailer will follow the path of the tractor and will not contribute to a larger swath. This obviously does not account

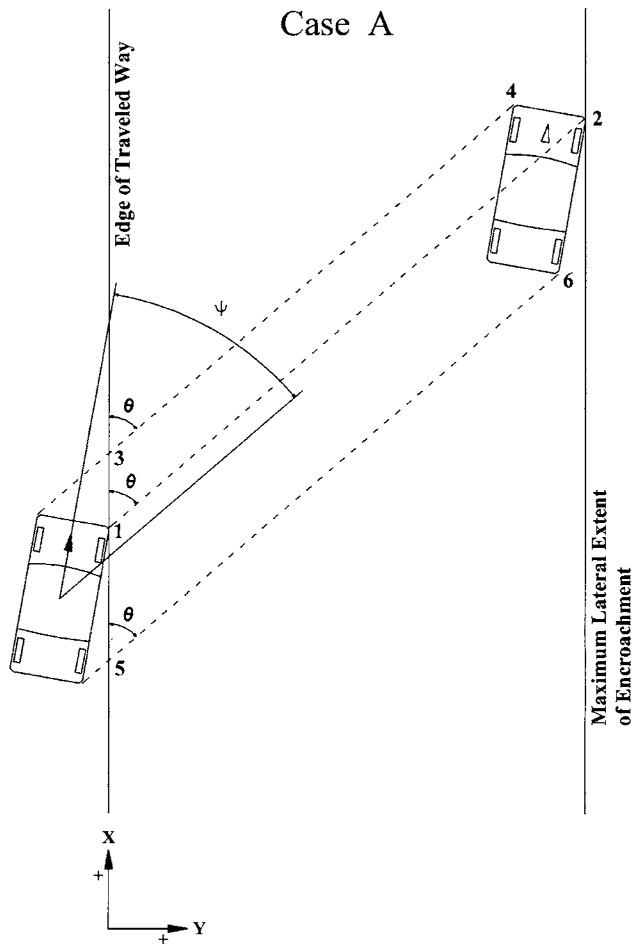


Figure 16. Encroachment cases.

for trucks "jackknifing." Also, the risk of occupant injury for combination trucks is primarily associated with the path of the tractor.

6.2.2 Adjustment of Vehicle Swath for Roadway Curvature

The calculations for the vehicle swath assume a straight-line encroachment from a straight roadway section. When a horizontal curve is present, it is necessary to make an adjustment to the vehicle swath to account for the curvature. Note that this adjustment is only an approximation because of the combination of a curved roadway and a straight path.

An encroachment on a horizontal curve would be expected to follow the path shown in Figure 18. This path, translated to a straight roadway section, would appear as in Figure 19. This in effect creates a curved vehicle trajectory, which RSAP currently is not designed to handle. Instead, RSAP maintains a straight-line path and adjusts the encroachment angle, as shown in Figure 20. For encroachments on the outside of a curve, the encroachment angle becomes

$$\theta_{\text{Adjusted}} = \theta + 1/2\,(\text{degree of curvature per 100 m}) \qquad (12)$$

Similarly, for encroachments on the inside of a curve, the encroachment angle becomes

$$\theta_{\text{Adjusted}} = \theta - 1/2\,(\text{degree of curvature per 100 m}) \qquad (13)$$

This modified encroachment angle is used in the determination of points 2, 3, 4, 5, and 6 on the swath's envelope.

Note that, for long curves with a small radius (i.e., large degree of curvature), the above adjustment to the encroachment angle can be substantial, which in turn could affect the probability of impacting with a feature located on the curve.

6.3 DETERMINATION OF IMPACT

An encroaching vehicle will impact a roadside feature located within its swath. This section describes the process of determining the following:

- If a roadside feature is within the vehicle swath,
- The first roadside feature impacted,
- Penetration of the roadside feature,
- Subsequent impacts,
- Speed change as a result of impact, and
- Vehicle rollover.

6.3.1 Determination of Impact Points

The process of determining the impact points is relatively straightforward because of the straight-line assumption. The presence of a roadside feature within the swath is determined by finding the intersections of the three vehicle corner paths with the front or traffic-facing plane of each roadside feature, as shown in Figure 21. The following three collision points are determined for each roadside feature:

1. The intersection of the line through Swath Points 1 and 2 and the front plane of the roadside feature (INT_{12}),
2. The intersection of the line through Swath Points 3 and 4 and the front plane of the roadside feature (INT_{34}), and
3. The intersection of the line through Swath Points 5 and 6 and the front plane of the roadside feature (INT_{56}).

The longitudinal coordinates of these three intersecting points (i.e., $XINT_{12}$, $XINT_{34}$, and $XINT_{56}$) are then determined. These three collision points represent the boundaries of the vehicle swath at the lateral offset of the roadside feature. These longitudinal end points of the roadside feature are then compared with these three collisions points to determine if that feature would be impacted. If either or both of the feature's end points are within the boundary of the vehicle swath as defined by the three collision points, the encroaching vehicle would impact the feature. An additional check would then be

Case A			Case C		
Point	X	Y	Point	X	Y
1	y_0	x_0	1	y_0	x_0
2	y_e	$\frac{y_e - y_0}{m} + x_0$	2	y_e	$\frac{y_e - y_0}{m} + x_0$
3	y_0	$\frac{VWID \cos\alpha}{\sin\theta} + x_0$	3	y_0	$\frac{-VLENG \cos\alpha}{\sin\theta} + x_0$
4	$y_e - VWID \cos(\theta+\alpha)$	$\frac{y_4 - y_0}{m} + x_3$	4	$y_e - VLENG \sin(\theta+\alpha)$	$\frac{y_4 - y_0}{m} + x_3$
5	y_0	$\frac{VLENG \sin\alpha}{\sin\theta} + x_0$	5	y_0	$\frac{VWID \cos\alpha}{\sin\theta} + x_0$
6	$y_e - VLENG \cos(90 - (\theta+\alpha))$	$\frac{y_6 - y_0}{m} + x_5$	6	$y_e - VENG \cos(\theta+\alpha) - VENG \sin(\theta+\alpha)$	$\frac{y_6 - y_0}{m} + x_5$

Case B			Case D		
Point	X	Y	Point	X	Y
1	y_0	x_0	1	y_0	x_0
2	y_e	$\frac{y_e - y_0}{m} + x_0$	2	y_e	$\frac{y_e - y_0}{m} + x_0$
3	y_0	$\frac{VWID \cos\alpha}{\sin\theta} + x_0$	3	y_0	$\frac{VWID \sin\alpha}{\sin\theta} + x_0$
4	$y_e - VWID \cos(\theta+\alpha)$	$\frac{y_4 - y_0}{m} + x_3$	4	$y_e - VLENG \sin(\theta+\alpha)$	$\frac{y_4 - y_0}{m} + x_3$
5	y_0	$\frac{VLENG \sin\alpha}{\sin\theta} + x_3$	5	y_0	$\frac{-VWID \sin\alpha}{\sin\theta} + x_0$
6	$y_e - VWID \cos(\theta+\alpha) - VLENG \sin(\theta+\alpha)$	$\frac{y_6 - y_0}{m} + x_5$	6	$y_e - VWID \sin(90 - (\theta+\alpha))$	$\frac{y_6 - y_0}{m} + x_5$

Figure 17. Swath equations.

made to determine if the impact is with the side or the end of the feature.

6.3.2 Determination of First Roadside Feature Struck

When two or more roadside features are close to one another, it is necessary to determine which feature will be impacted first. RSAP assumes that the hazard with the smallest lateral offset will be impacted first. However, this assumption is not always true because the lateral offset of the feature may not represent the farthest lateral extension of the vehicle at that point, an example of which is shown in Figure 22. Note that the downstream end of the feature with the smaller lateral offset is not the first feature struck and that the vehicle's lateral extent is greater than that of the feature with the smaller lateral offset.

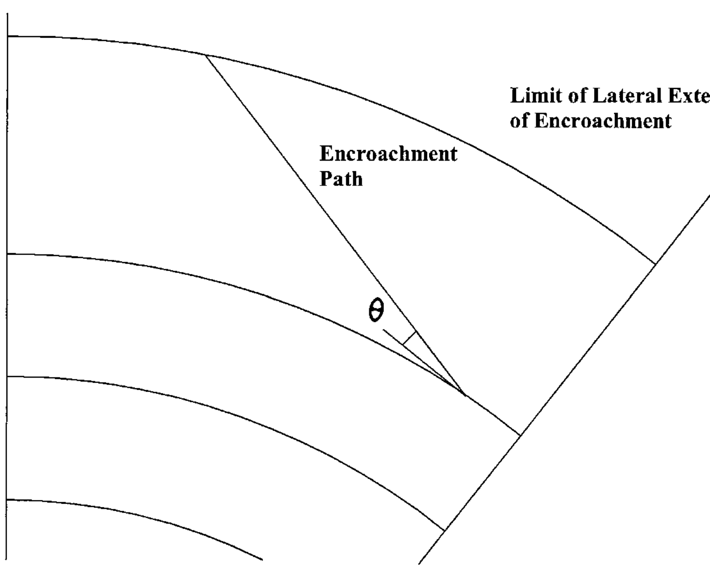


Figure 18. Encroachment on curved roadway section.

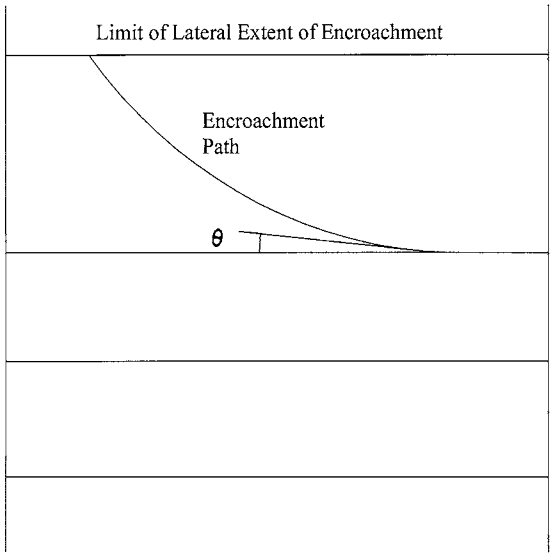


Figure 19. Encroachment on curve translated to straight section.

There are basically two situations where the feature with the smaller lateral offset may not be the first feature struck. The first situation is shown in Figure 22, which demonstrates that the projection of the impact points onto the lead corner's path shows which feature would be impacted first. The second situation is when two hazards have the same lateral offset. Both of these situations are handled by recognizing that the relative distance to the leading corner of the vehicle (not necessarily the first corner) will determine the order of impact.

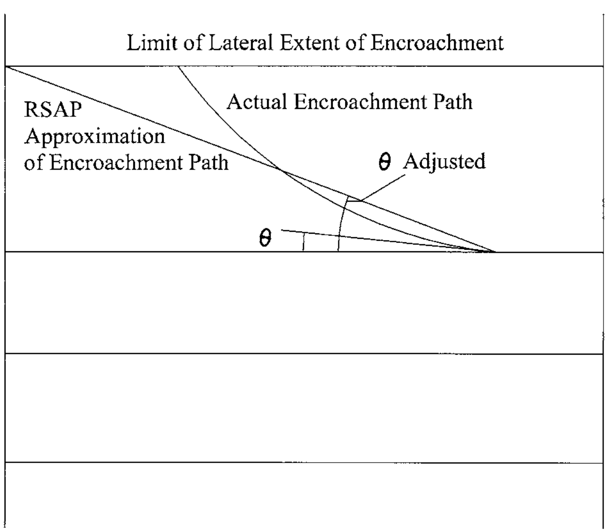


Figure 20. RSAP approximation of encroachment on curved section.

6.3.3 Penetration of Features

After deciding which roadside feature is struck first, the program then examines the impact conditions to determine if the struck feature would be penetrated. Penetration of a longitudinal barrier is controlled by the capacity of the barrier, which is defined in terms of limiting Impact Severity (IS). If the limiting IS is exceeded, the impacting vehicle would be expected to go through or over the barrier. The IS value, as defined below, has been shown to be a good indicator of the lateral deflection associated with crashes involving flexible and semi-rigid barriers.

$$IS = \frac{1}{2} * m(V * \sin\theta)^2 \tag{14}$$

where

IS = Impact severity
m = Mass of impacting vehicle (kg)
V = Velocity of impacting vehicle (m/s)
θ = Angle of encroachment (deg.)

Each type of longitudinal barrier has an assigned maximum capacity, termed the containment limit, which is preset in RSAP's default files. When an impact is predicted to have an IS value in excess of a longitudinal barrier's containment limit, the vehicle is predicted to penetrate through or over the barrier.

The limiting capacity for other objects, such as point hazards and breakaway devices, is measured in terms of the total kinetic energy as calculated in the following equation.

$$KE = \frac{1}{2} * m(V)^2 \tag{15}$$

where

KE = Kinetic energy of impacting vehicle (Joules)
m = Mass of impacting vehicle (kg)
V = Velocity of impacting vehicle (m/s)

When the kinetic energy of an impacting vehicle is predicted to exceed the capacity of a feature, the vehicle is again predicted to penetrate through or over the feature.

6.3.4 Determination of Subsequent Impacts

Whenever penetration is predicted, RSAP then examines the path of the vehicle for subsequent impacts. Also, the speed of the vehicle will be reduced in proportion to the energy required to penetrate the feature. The procedure for determining subsequent impacts is the same as for the first impact in terms of checking for the feature coordinates against the boundaries of the vehicle swath. This process will continue

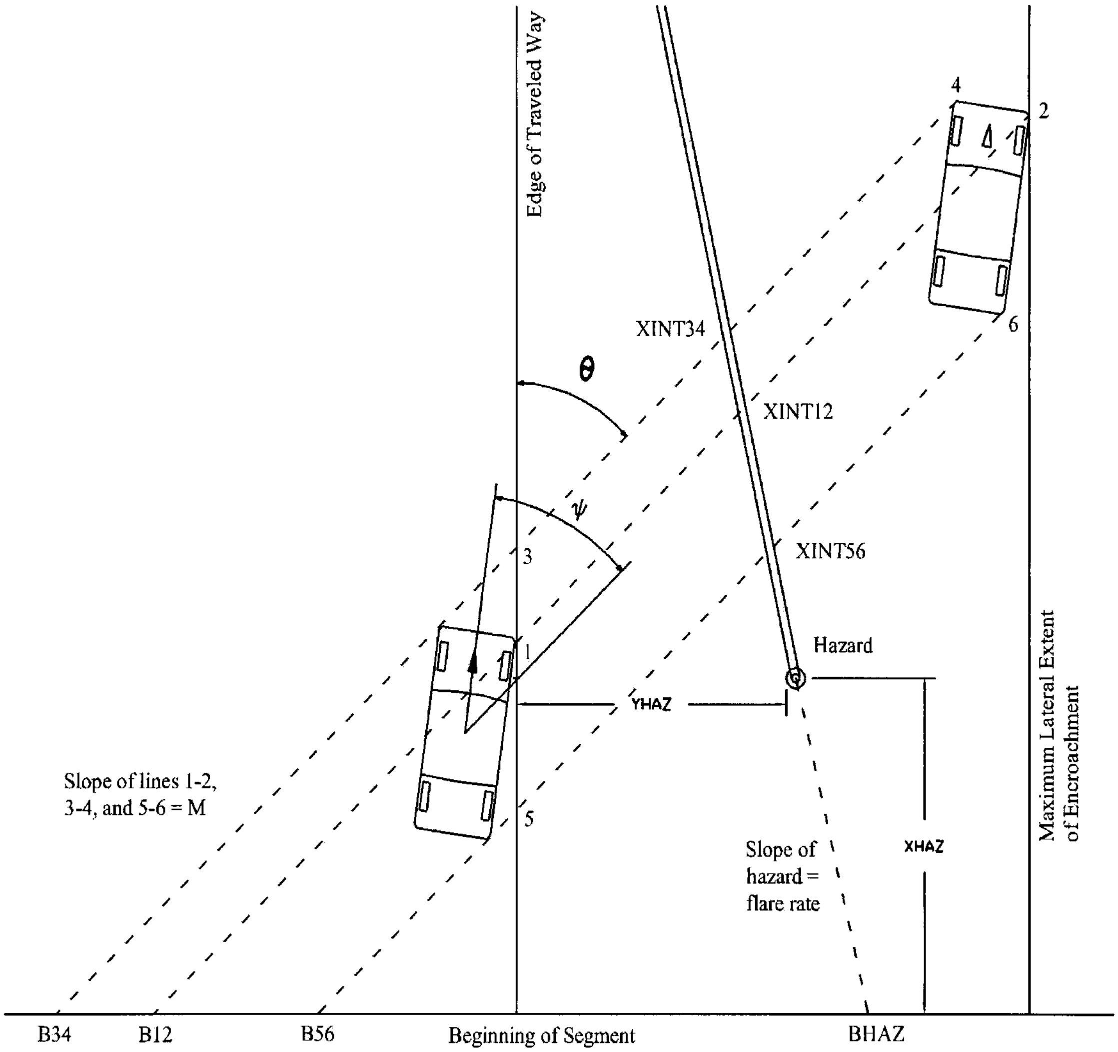


Figure 21. Impact point determination.

until (1) there is no roadside feature in the path of the vehicle, (2) the vehicle strikes a feature and does not penetrate the feature, or (3) the vehicle rolls over.

When tabulating the crash costs of an encroachment with multiple impacts, the repair costs of all roadside features impacted are summed and the crash costs associated with the most severe impact are used. For example, when the program predicts that a vehicle will penetrate a barrier and impact the hazard beyond, the crash cost assigned to the impact is that associated with either penetrating the barrier or impacting the hazard, whichever is higher.

6.3.5 Speed Change as a Result of Impact

As mentioned above, RSAP calculates the energy gained or lost in impacts with roadside features that are penetrated. For roadside features other than sideslopes, the energy associated with the capacity (or containment index) of the feature is subtracted from the vehicle's initial kinetic energy (or its lateral component). A new speed for the vehicle is then calculated on the basis of the remaining energy and this new speed is used for the next impact. A roadside slope, provided it is not very steep, would not be expected to affect the vehicle's kinetic energy appreciably; however, the resultant rise or drop in the vehicle's center of gravity during slope traversal would affect the vehicle's potential energy. Thus, the potential energy associated with traversing a roadside slope is added (or subtracted) from the initial kinetic energy of the vehicle to determine a new speed for the next impact.

6.3.6 Vehicle Rollover

Some types of roadside features, such as longitudinal barriers, could cause impacting vehicles to roll over, which has a higher severity than a redirective impact. Some of the actual mechanisms involved in rollover are not well understood and the model incorporated into RSAP to predict rollover is very crude.

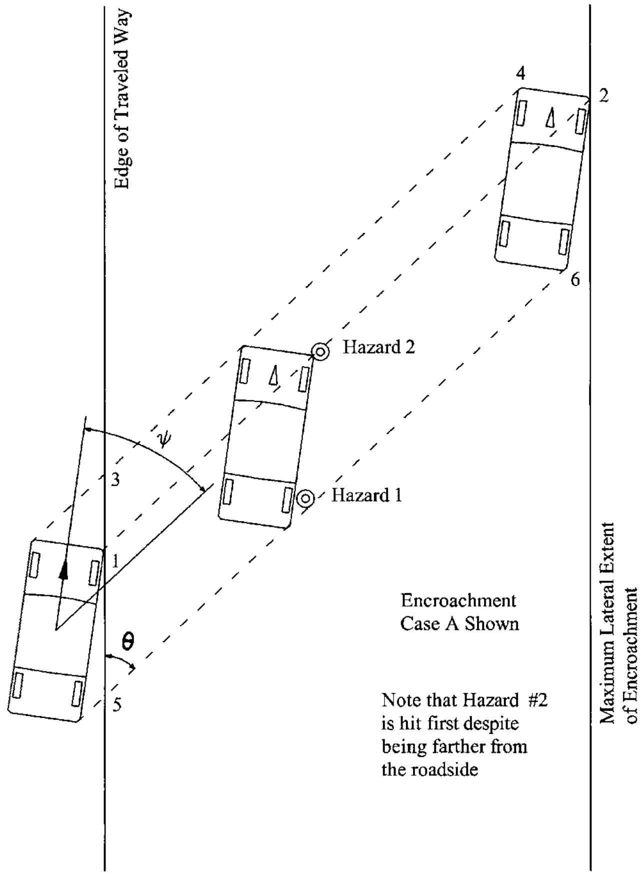


Figure 22. Case where first impact not closest to roadway.

RSAP incorporates a rollover algorithm developed under NCHRP Project 22-8.[27] The rollover routines incorporate simplified impulse and momentum calculations. When a truck strikes a barrier, the redirective forces are applied well below the vehicle's center of gravity. It is assumed that, upon impact, the truck's linear momentum perpendicular to the barrier is transferred into angular momentum. The truck bed is assumed to rotate downward on the impact side until it strikes the top of the barrier. Thereafter, the truck rotates about the bottom of the truck bed until (1) the available angular momentum is exhausted, (2) the truck rolls over in front of the barrier, or (3) the truck rolls over the top of the barrier. Actual equations used in RSAP are presented in reference 27 and are not provided herein. Note that this analysis will only predict rollover for vehicles with a chassis that extends above the top of the barrier. Other vehicles are assumed to remain upright. Obviously, automobiles and light trucks sometimes roll over when impacting longitudinal barriers. Until factors that cause vehicle rollover are better understood, average severities for these vehicles must include the probability that impacting vehicles will roll over in front of the barrier.

Two other sources of rollover are soil tripping and slope or pavement edge breaks. RSAP currently cannot account for these two types of rollover. However, assignment of severity indexes to sideslopes and even small drops can help to account for vehicle rollover under such conditions without determining an actual probability.

6.4 EXTENT OF LATERAL ENCROACHMENT DISTRIBUTION

The lateral extent of encroachment distributions incorporated into RSAP was developed from re-analysis of the Cooper encroachment data[30] by excluding data from the 0 to 4 m region. The rationale for this re-analysis effort briefly is as follows. The Cooper encroachment data were based on observation of tire tracks on the roadside. In situations where there are paved shoulders for the highways, it is believed that many encroachments that remained on the shoulder or did not extend far enough beyond it would not be detected. In other words, encroachments with lateral extent of 4 m or less were under-reported or under-observed because of the presence of paved shoulders. These undetected encroachments explain the almost flat region of the lateral extent of encroachment curves over the first 4 m. Thus, the Cooper encroachment data were re-analyzed, and encroachments with lateral extent of less than 4 m were excluded. Note that encroachments with lateral extent of greater than 4 m represent 77.1% and 91.9% of all observed encroachments for two-lane undivided and multi-lane divided highways, respectively.

The re-analysis of the Cooper encroachment data on the extent of lateral encroachment was based on several premises. First, the distribution of the extent of lateral encroachment can be represented by a regression model of the following form:

$$\ln(Y) = a + bX \tag{16}$$

where

Y = Percent exceeding lateral distance X
X = Lateral distance
a, b = Regression coefficients.

Second, the regression model can be extrapolated back to the 0 to 4 m region. Finally, encroachments with a lateral extent of 0 m must equal to 100%.

The regression coefficients and the R^2 values for the equations for both two-lane undivided highways and four-lane divided highways are shown in Table 14.

The y-intercepts (i.e., the percent exceeding 0 m for the regression models) are 319.9 ($e^{5.768}$) for two-lane undivided highways and 204.4 ($e^{5.320}$) for multi-lane divided highways. Recall that encroachments with a lateral extent of greater than 4 m represent 77.1% and 91.9% of all observed encroachments for two-lane undivided and multi-lane divided highways, respectively. The revised y-intercepts are, therefore, 246.6 (319.9 $*$ 0.771) and 187.8 (204.4 * 0.919) for two-lane undivided and multi-lane divided highways, respectively.

By definition, the y-intercepts for the lateral extent of encroachment distributions (i.e., percent exceeding lateral

TABLE 14 Regression model parameters

Highway Type	a (Intercept)	b (Slope)	R^2
Two-Lane Undivided	5.768	- 0.262	98.68
Multi-Lane Divided	5.320	- 0.161	95.92

extent of 0 m) must equal to 100%. These differences in the y-intercepts can, therefore, be interpreted to represents the extent of under-reporting of encroachments in the 0 to 4 m region. In order to have 100% at the y-intercept, all points on the curves are normalized or scaled down by the ratio of 2.466 (246.6/100) for two-lane undivided highway and 1.878 (187.8/100) for multi-lane divided highways. The normalized curves as used in RSAP are shown in Figure 23.

The probability of reaching a given lateral extent is used to determine impact frequency and crash costs. The probability of any encroaching vehicle reaching a given distance from the roadside is determined from the lateral extent of encroachment distribution curves. This probability is then multiplied by the crash cost of the impact to estimate the crash cost of the encroachment. A more detailed discussion on how to use the probability for lateral extent of encroachment to estimate the crash cost for an encroachment is presented in Chapter 8.

6.4.1 Adjustment for Sideslope

A simple adjustment for the effect of sideslopes on the lateral extent of encroachment, similar to that used with the ROADSIDE program, was incorporated into RSAP. Two basic adjustments are associated with a sideslope. One adjustment is used to account for the increase in speed as a vehicle rolls down a sideslope while the second factor increases the lateral extent of movement. Estimated impact speeds are increased by the change in potential energy from the top of the slope to the point of impact with the roadside hazard. The lateral distance that a vehicle travels is increased by an adjustment factor, E_s.

$$E_s = 1 + s/0.4 \qquad (17)$$

where

E_s = Adjustment factor for lateral offset.
s = Sideslope in fractional form.

This adjustment factor was taken from AASHTO's *Roadside Design Guide* and is based largely on engineering judgment rather than empirical or field data. NCHRP Project 17-11 should provide some additional insight into the effects of roadside slope on the distance that a vehicle travels off of the roadway.

6.5 IMPACT CONDITIONS

Upon determining that the encroaching vehicle would impact one or more of the roadside features, the impact conditions (i.e., impact speed and angle and vehicle orientation at impact) are then randomly selected from their distributions. More detailed descriptions of these parameters and their

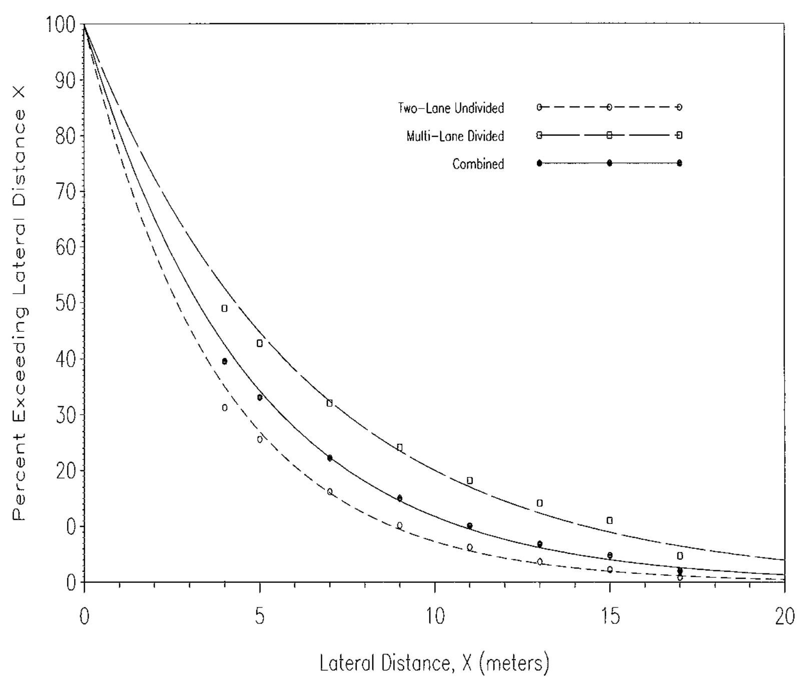


Figure 23. RSAP lateral extent of encroachment distributions by highway type.

distributions as incorporated into RSAP are presented in the following sections.

6.5.1 IMPACT SPEED AND ANGLE DISTRIBUTIONS

Several previous cost-effectiveness models, including BCAP[25], have incorporated vehicle travel speed distributions and a point mass model to establish encroachment speed and angle distributions. This model, as illustrated in Figure 12, gives a limiting encroachment angle for a given speed. Naturally, as the vehicle's encroachment speed increases, the maximum encroachment angle decreases. Crash reconstructions have shown that real-world impact angles can exceed this value by a large margin. These theoretical cornering limitations are easily exceeded when the crash scenario involves a driver steering back and forth across the travelway as the driver attempts to regain control of the vehicle.

In order to use the best available impact speed and angle data, RSAP incorporates distributions of impact speed and angles generated from reconstruction of real-world crashes.[24] Most of the data used to generate the impact speed distributions were from utility pole crashes. Because these crashes have relatively high reporting rates, the effect of unreported crashes on the speed and angle distributions should be relatively low. Only freeways, where utility poles are seldom found, pose a significant problem with unreported crashes. Much of the data used to establish impact conditions on freeways was collected from impacts with luminaire supports and bridge railings. However, unreported crashes would be expected to have generally lower impact speeds and angles when compared with reported crashes. Therefore, although impact conditions for freeways may be more affected by unreported crashes, the resulting speed and angle distributions should be on the conservative side. This is important because most point-mass-model-based programs have predicted higher speed and lower angle impacts than indicated by real-world crash data.

Incorporating impact conditions from crash data does have some limitations. For example, vehicles are predicted to maintain the same encroachment speed throughout the encroachment event. Although some vehicles do undoubtedly slow down during ran-off-road crashes, crash data do not reflect any significant variation within the first 6 m from the edge of the pavement.[24,33] Another problem is due to the recent repeal of the national speed limit. The data used represent crashes that occurred on highways with 88.5 km/h speed limits and may not be appropriate in many western states where the current speed limits are in the 110 to 120 km range. However, the impact speed and angle distributions can be easily adjusted when crash data under the current higher speed limits become available.

Currently, RSAP uses five 7 by 7 matrices to describe the impact speed and angle distributions. Each matrix results in 49 possible speed and angle combinations. If a finer distribution of impact speeds and angles is required, RSAP can be easily modified by using a linked gamma function as described in reference 6 to develop new probability density tables up to 10 by 10 in size. The speed and angle distributions used for freeways, urban arterials, urban collectors and local roads, rural arterials, and rural collectors and local roads are shown in Table 15.

Note that RSAP uses 10 functional classes so as to be consistent with the AASHTO definitions of functional classes. However, because there are only five impact speed and angle distributions, some of the functional classes have to use the same distributions, as shown in Table 15.

6.5.2 Vehicle Orientation Distribution

As discussed previously, RSAP incorporates a distribution of vehicle orientations at impact. The vehicle orientation distribution, as shown in Figure 24, is based on a crash data study involving pole structures, including utility poles, luminaries and sign supports.[34] Note that the orientations are relative to the vehicle path and thus are actually the vehicle slip angle. Also note that vehicle orientation at impact is assumed to be the same as the vehicle orientation at the point of encroachment.

The incorporation of vehicle orientation serves two purposes. The first purpose is to better define the vehicle swath, as discussed earlier in this chapter. The second purpose is to allow for future incorporation of vehicle orientation into severity estimation. Vehicle orientation at impact can have an important effect on the severity of many types of ran-off-road crashes, including breakaway supports, guardrail terminals, and longitudinal barriers. With the severity index approach for severity estimation incorporated in the current version of RSAP, vehicle orientation is actually not used in the severity estimation. However, the information will be available when side impacts are taken into account in updates of RSAP.

6.6 VEHICLE TYPES

RSAP defines 12 categories of vehicles for use in the cost-effectiveness analysis. The percentage of the traffic assigned to each of the 12 vehicle categories is calculated from the nominal percent truck (T%) data entry, which is the percentage of traffic for both single-unit and combination trucks. Nominal percent truck is used because it represents the typical level of data available to transportation agencies on traffic mix under most situations. The equations for calculating the percentages for the various vehicle categories based on the nominal percent truck are shown in Table 16. The default value for the nominal percent truck is 10% and the corresponding percentages for the 12 vehicle categories are also shown in Table 16.

The percentages used in the equations to calculate vehicle mix are average values based on limited data. Vehicle mix

TABLE 15 RSAP speed and angle distributions

Impact Speed and Angle Distributions	Applicable Functional Classes
Freeways	Urban Freeways Rural Freeways
Urban Arterials	Urban Principal Arterial Urban Minor Arterial
Urban Collectors and Local Roads	Urban Collectors Urban Local Roads
Rural Arterials	Rural Principal Arterial Rural Minor Arterial
Rural Collectors and Local Roads	Rural Collectors Rural Local Roads

FREEWAYS

Speed (km/h)	Angle (Degrees)						
	2.5	7.5	12.5	17.5	22.5	27.5	32.5
8	0.0002	0.0005	0.0005	0.0003	0.0002	0.0001	0.0002
24	0.0049	0.0119	0.0118	0.0088	0.0057	0.0034	0.0042
40	0.0151	0.0364	0.0359	0.0268	0.0174	0.0104	0.0127
56	0.0215	0.0519	0.0513	0.0382	0.0248	0.0149	0.0181
72	0.0205	0.0494	0.0488	0.0364	0.0236	0.0142	0.0173
88	0.0152	0.0367	0.0362	0.0270	0.0176	0.0105	0.0128
115	0.0200	0.0484	0.0478	0.0356	0.0231	0.0139	0.0169

URBAN ARTERIALS

Speed (km/h)	Angle (Degrees)						
	2.5	7.5	12.5	17.5	22.5	27.5	32.5
8	0.0119	0.0238	0.0223	0.0167	0.0112	0.0071	0.0099
24	0.0356	0.0714	0.0669	0.0501	0.0336	0.0211	0.0298
40	0.0323	0.0647	0.0606	0.0454	0.0304	0.0192	0.0270
56	0.0194	0.0388	0.0364	0.0272	0.0183	0.0115	0.0162
72	0.0095	0.0190	0.0179	0.0134	0.0090	0.0056	0.0079
88	0.0041	0.0083	0.0078	0.0058	0.0039	0.0025	0.0035
115	0.0026	0.0053	0.0050	0.0037	0.0025	0.0016	0.0022

(*continued on next page*)

TABLE 15 (*Continued*)

URBAN COLLECTORS AND LOCAL ROADS

Speed (km/h)	Angle (Degrees)						
	2.5	7.5	12.5	17.5	22.5	27.5	32.5
8	0.0095	0.0370	0.0450	0.0363	0.0240	0.0141	0.0151
24	0.0196	0.0761	0.0924	0.0746	0.0493	0.0289	0.0310
40	0.0133	0.0517	0.0628	0.0508	0.0335	0.0197	0.0211
56	0.0063	0.0246	0.0299	0.0241	0.0160	0.0093	0.0100
72	0.0025	0.0098	0.0119	0.0097	0.0064	0.0037	0.0040
88	0.0009	0.0036	0.0043	0.0035	0.0023	0.0014	0.0014
115	0.0005	0.0018	0.0021	0.0017	0.0011	0.0007	0.0006

RURAL ARTERIALS

Speed (km/h)	Angle (Degrees)						
	2.5	7.5	12.5	17.5	22.5	27.5	32.5
8	0.0131	0.0180	0.0148	0.0107	0.0072	0.0047	0.0078
24	0.0315	0.0431	0.0354	0.0256	0.0173	0.0113	0.0188
40	0.0342	0.0467	0.0384	0.0277	0.0188	0.0123	0.0203
56	0.0290	0.0396	0.0325	0.0235	0.0159	0.0104	0.0172
72	0.0218	0.0298	0.0245	0.0177	0.0120	0.0078	0.0130
88	0.0153	0.0209	0.0172	0.0124	0.0084	0.0055	0.0091
115	0.0275	0.0375	0.0309	0.0223	0.0151	0.0099	0.0164

RURAL COLLECTORS AND LOCAL ROADS

Speed (km/h)	Angle (Degrees)						
	2.5	7.5	12.5	17.5	22.5	27.5	32.5
8	0.0070	0.0109	0.0094	0.0069	0.0047	0.0030	0.0049
24	0.0364	0.0568	0.0490	0.0360	0.0245	0.0159	0.0253
40	0.0446	0.0696	0.0601	0.0441	0.0300	0.0195	0.0310
56	0.0315	0.0493	0.0425	0.0312	0.0212	0.0138	0.0219
72	0.0169	0.0265	0.0228	0.0168	0.0114	0.0074	0.0118
88	0.0077	0.0121	0.0104	0.0077	0.0052	0.0034	0.0054
115	0.0050	0.0078	0.0067	0.0049	0.0034	0.0022	0.0035

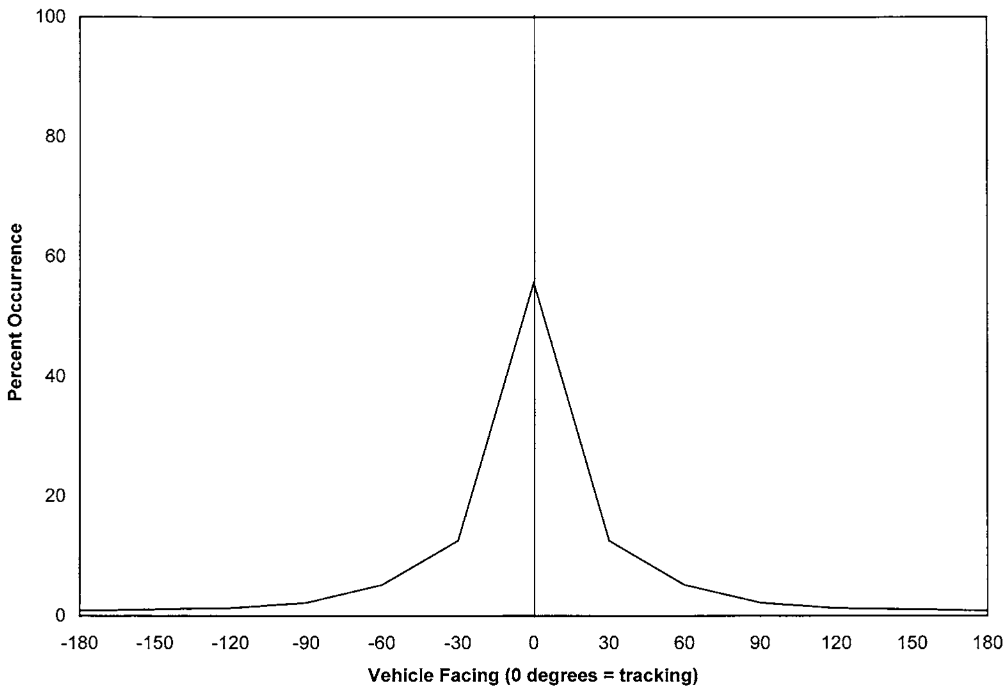


Figure 24. Vehicle orientation distribution.

TABLE 16 Vehicle mix calculations and default values

Vehicle Type	Category	% in Vehicle Mix	
		%Truck = T%	%Truck = 10%
Passenger Car	820-kg (Small)	[0.090*(100-T)]	8.1
	1410-kg (Intermediate)	[0.375(100-T)]	33.8
	2000-kg (Large)	[0.135*(100-T)]	12.1
	Subtotal	[0.6*(100-T)]	54.0
Pickup and Van	Small Pickup Truck	[0.104*(100-T)]	9.4
	Mini-Van	[0.140*(100-T)]	12.6
	Full-Size Pickup Truck	[0.116*(100-T)]	10.4
	Specialty Vehicle	[0.040*(100-T)]	3.6
	Subtotal	[0.4*(100-T)]	36.0
Single-Unit Truck	8000-kg (Empty)	0.7*T, if T<4% 2.8, if T>=4%	2.8
	13500-kg (Loaded)	0.3*T, if T<4% 1.2, if T>=4%	1.2
	Subtotal	T, if T<4% 4.0, if T>=4%	4.0
Tractor-Trailer	13500-kg (Empty)	0.0, if T<4% 0.2*(T-4), if T>=4%	1.2
	36000-kg Van-Trailer (Loaded)	0.0, if T<4% 0.6*(T-4), if T>=4%	3.6
	36000-kg Tank-Trailer (Loaded)	0.0, if T<4% 0.2*(T-4), if T>=4%	1.2
	Subtotal	0%,if T<4% (T-4)%, if T>=4%	6.0
	Total		100.0

NOTE: T is the nominal percent of truck traffic. The default value for T is 10%

TABLE 17 Vehicle characteristics

Vehicle Type	Category	Length (m)	Width (m)	Weight (kg)	C. G. Ht. (m)	A Distance (m)	Axel Ht. (m)
Passenger Car	820-kg (Small)	3.0	1.8	820	0.5	1.0	N/A
	1410-kg (Intermediate)	3.7	1.9	1425	0.5	1.2	N/A
	2000-kg (Large)	4.5	2.1	2000	0.5	1.6	N/A
Pickup and Van	Small Pickup Truck	4.8	1.7	1425	0.6	1.2	N/A
	Mini-Van	4.7	1.8	1720	0.7	1.2	N/A
	Full-Size Pickup Truck	5.5	1.9	1900	0.7	1.3	N/A
	Specialty Vehicle	4.4	1.8	1700	0.7	1.2	N/A
Single-Unit Truck	8000-kg (Empty	7.6	2.4	8100	1.3	2.0	1.0
	13500-kg (Loaded)	10.7	2.6	13600	1.7	2.8	1.0
Tractor-Trailer	13500-kg (Empty)	6.3	2.6	13600	1.3	4.0	1.2
	36000-kg Van-Trailer (Loaded)	6.3	2.6	36300	2.0	4.6	1.2
	36000-kg Tank-Trailer (Loaded)	6.3	2.6	36300	2.6	4.6	1.2

could vary significantly from highway to highway and from the average, depending on land use and the traffic the highway serves. If more detailed information on vehicle mix is available, the actual vehicle mix should be used. RSAP provides the options of entering user-defined vehicle mix distribution using either vehicle types (i.e., the 12 vehicle types) or vehicle categories (i.e., passenger cars, pickup trucks and vans, single-unit trucks, and tractor-trailers).

The built-in characteristics for the 12 vehicle categories are shown in Table 17, including vehicle length, width, weight, the vertical height of the center of gravity, the A distance (i.e., horizontal distance from the front of the vehicle to the center of gravity), and the axle height. The axle heights for passenger cars and light trucks (i.e., pickup trucks, vans, and sport utility vehicles) are not used in any of the calculations and are shown as 0.0 or not applicable.

CHAPTER 7

CRASH SEVERITY PREDICTION MODULE

After a crash is predicted to occur, the next step is to estimate the severity of the impact using the crash severity prediction module. Crash severity estimation is perhaps the most important step of this cost-effectiveness analysis procedure. For most roadside safety improvements, the benefits, or reduction in crash costs, are derived from lower crash severity with little or no effect, and sometimes even an increase, in the crash frequency. The crash costs are principally a function of the crash severity (i.e., the probability of injury and/or fatality) given that the associated accident costs are highly non-linear. Unfortunately, crash severity is also the most difficult parameter to estimate. This chapter first discusses the general approaches for severity estimates and then describes the severity estimation procedures incorporated into RSAP.

7.1 GENERAL DISCUSSIONS

Historically, there are three general approaches to estimate the severities of crashes involving roadside features:

- Engineering judgment,
- Crash data, and
- Kinematics analysis.

7.1.1 Engineering Judgment

The first attempt to estimate crash severities[16] was made in conjunction with the development of the first encroachment-probability-based cost-effectiveness procedure.[4] The effort involved a survey of highway safety professionals, including highway engineers, police officers, and safety researchers. Respondents were asked to rank the severity of various roadside features, including barriers, geometric features (e.g., ditches and side slopes), rigid objects, and culverts, based on an ordinal severity index (SI) scale ranging from 0 to 10. This SI scale has since become the most widely used means of quantifying crash severity.

The SI scale is associated with fixed levels or percentages of fatality, injury, and property-damage-only (PDO), as shown in Table 18. Although the SI scale may appear somewhat linear, the relationship of the SI scale to crash cost is actually exponential in nature because the crash cost figures are highly non-linear (i.e., the cost associated with a fatal crash is many times that of an injury crash, which in turn is many times of that of a PDO crash).

Although severity indexes were intended to be representative of an average crash, it is believed that the SI values obtained from the survey were more representative of high-speed impacts and, therefore, overstated the average impact severity. This is an indication of the difficulty associated with estimating the average severity for a representative sample of ran-off-road crashes. Crashes receiving the most attention are typically those that are the most severe with serious or fatal injuries and/or those involving failures of the safety hardware. Also, the opinions of experts who are familiar with crash testing could be further biased toward the more severe impacts because crash tests of safety devices are conducted under extremely severe impact conditions. Consequently, severity estimates based on the SI scale and developed from engineering judgment or expert opinion have been found to be too high and unreliable.

7.1.2 Crash Data

Another major source for severity estimates is police-level crash data, which use the following rating scale with five levels of injury severity:

- K—Fatal injury
- A—Severe or incapacitating injury
- B—Moderate or non-incapacitating injury
- C—Minor or possible injury, and
- O—PDO.

Although police-level crash data are readily available and relatively simple to compile and analyze, numerous problems are associated with police-level crash data that could seriously affect the accuracy and validity of the severity estimates. Unreported crashes can significantly distort the apparent severity by eliminating a large percentage of PDO and minor injury crashes from the analysis. Some safety hardware systems, such as crash cushions and breakaway luminaire and sign supports, have been found to have very low crash reporting rates. For example, assume that 95% of all crashes involving crash cushions are unreported while the 5% that are reported resulted in 50% of the serious and fatal injuries. Severity estimates based

TABLE 18 Relationships of severity indexes and injury levels

Severity Index (SI)	Injury Level (%) None	PDO1	PDO2	C	B	A	K
0	100.0	-	-	-	-	-	-
0.5	-	100.0	-	-	-	-	-
1	-	66.7	23.7	7.3	2.3	-	-
2	-	-	71.0	22.0	7.0	-	-
3	-	-	43.0	34.0	21.0	1.0	1.0
4	-	-	30.0	30.0	32.0	5.0	3.0
5	-	-	15.0	22.0	45.0	10.0	8.0
6	-	-	7.0	16.0	39.0	20.0	18.0
7	-	-	2.0	10.0	28.0	30.0	30.0
8	-	-	-	4.0	19.0	27.0	50.0
9	-	-	-	-	7.0	18.0	75.0
10	-	-	-	-	-	-	100.0

on the reported crash data would indicate a severity estimate of 50% serious and fatal injuries while the actual severity rate is only 2.5%.

Unfortunately, crash reporting rates for roadside safety devices and hazards are very difficult to determine and mostly unknown. One of the best studies conducted to date on crash reporting rates involved monitoring of reported utility pole crashes and comparing them with maintenance and repair records in the study areas of San Antonio, Texas, and Lexington, Kentucky.[34] The study results indicated that reporting rates for utility pole crashes were in the range of 85 to 90%. Other efforts to estimate the crash reporting rates for roadside safety devices have been less comprehensive. Some studies have examined evidence of impacts with roadside guardrails and median barriers to estimate reporting rates for barrier impacts.[43,53,54] The estimated reporting rates ranged from 12 to 60%. A recent study evaluated these findings in light of legal reporting thresholds and concluded that actual reporting rates may be much higher than any of the previous findings.[55] This serves to illustrate the difficulty associated with determining the reporting rates and the associated uncertainties.

Also, the reporting rates are likely to vary significantly among safety hardware systems. It appears that, the more effective the safety device (i.e., the lower the resulting injury severity to the occupants and damage to the impacting vehicles), the lower is the reporting rate. The uncertainty associated with the magnitude of unreported crashes for each safety feature casts doubt on all crash-data-based severity estimates.

In-depth crash data provide a much better means for estimating crash severity. In the study mentioned above on utility pole crashes[34], the crashes were investigated in depth to collect sufficient information for reconstructing the crashes to estimate the impact speed and the resulting velocity change (ΔV). Injury severity was expressed in terms of the Abbreviated Injury Scale (AIS), which is a much more precise means of measuring injury severity than the KABCO injury scale used in police-level crash data. The crash severity by AIS level was then related to impact velocity and velocity change (ΔV). This approach using reconstructed in-depth crash data is perhaps the best means available for estimating crash severity. Unfortunately, collecting in-depth crash data and reconstructing the crashes is a very expensive undertaking and little data beyond the study on utility pole crashes was available.

7.1.3 Kinematics Analysis

Kinematics analyses of impacts with safety hardware systems have also been used to estimate impact severities. This approach begins with a computer simulation or other analytical technique to determine the relationship between impact conditions and occupant risk values, such as occupant impact velocity (OIV), maximum 10-m/sec ridedown acceleration (RA), or peak 50-m/sec average acceleration. The occupant risk values are then related to crash severity estimates. Unfortunately, there is no well-established link relating occupant risk values to crash severity estimates.

Olsen developed a procedure for relating peak 50-m/sec average decelerations from longitudinal barrier crash tests to the probability of injury, as shown in Figure 25.[41] The relationships were developed based on comparison of damage ratings of vehicles from crash tests with those from vehicles involved in real-world crashes involving longitudinal barriers. The validity of the results from this study has been questioned because the sample size is relatively small—58 full-scale crash tests and 951 crash vehicles.

The crashes were limited to those resulting in smooth and stable redirection so that the damage patterns on the vehicle would be similar to those obtained from full-scale crash tests. Consequently, the predicted crash severities ignore crashes that involved vehicle rollover, snagging, or subsequent impacts with other vehicles or roadside objects. Although these "anomalous" crashes are believed to be infrequent, their relatively high severity could mean that the predicted probabilities of injury are too low. Furthermore, even though the same researchers established all vehicle damage ratings, the coarse rating scale used to link crash severity and occupant risk raises questions about the level of precision. Finally, the vehicles involved in this study are now more than 20 years old

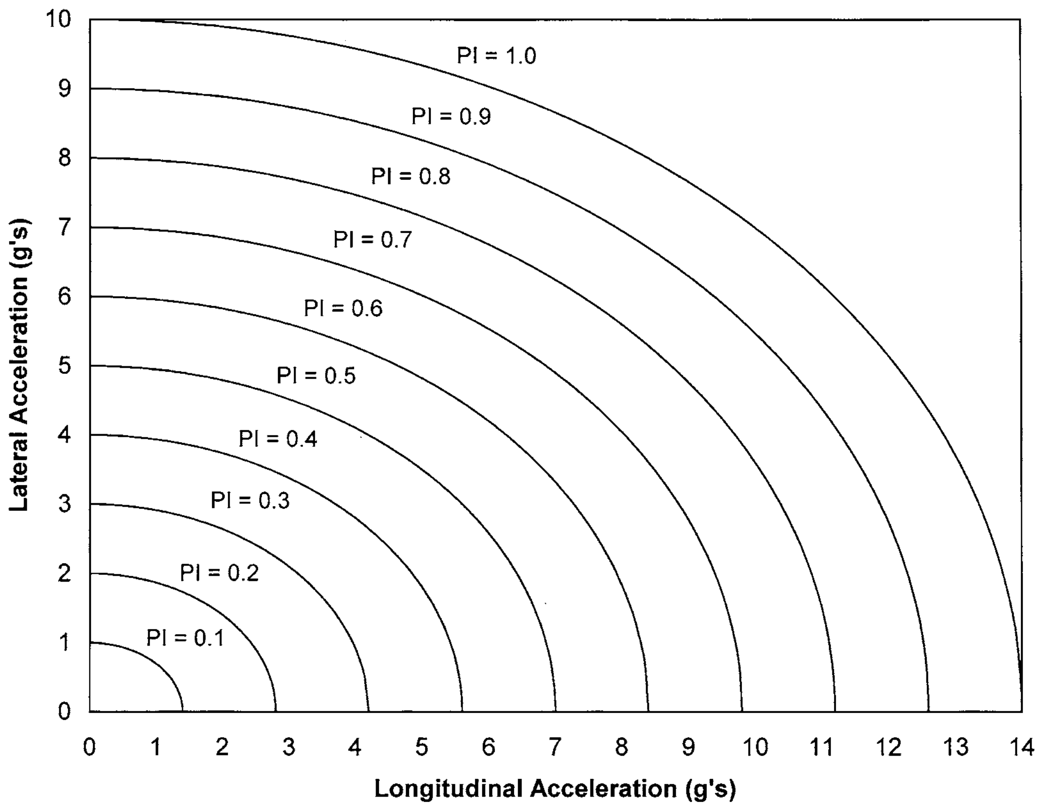


Figure 25. Olsen's probability of injury relationships.[41]

and vehicle crashworthiness has improved dramatically over this period. Thus, the findings may not be relevant for today's vehicle fleet.

Despite the limitations associated with the findings from Olsen's study, there is unfortunately no better objective procedure available. An alternative is to use engineering judgment as the basis for developing relationships between occupant risk parameters and severity estimates. For example, in a recent effort to estimate the severity of impacting a rigid hazard[55], occupant impact velocity (OIV) was first estimated through a kinematics analysis of the impact. A linear relationship was then assumed between the OIV and the SI. An OIV of 12 m/sec was assigned an SI of 5.0 under the rationale that both of these values are considered as the onset of serious injury. Although this approach provides a rational link between impact conditions and severity index, there is little evidence to indicate the appropriateness of the resulting severity estimates.

7.2 SEVERITY ESTIMATES

Given that severity estimates are the most important input parameters for the cost-effectiveness analysis procedure, the severity estimates incorporated into the analysis must be as accurate as possible and must be validated. As discussed above, all of the historical procedures for estimating crash severities have serious limitations and the resulting severity estimates cannot be thoroughly validated. Several alternatives were considered, including the use of the following:

- Reconstructed in-depth crash data, which constitute the best means for estimating severity (however, data availability is too limited to be a viable option);
- SIs as provided in the 1996 AASHTO *Roadside Design Guide*; and
- Police-level crash data and/or kinematics analyses, either individually or in combination.

An effort was thus undertaken to develop a new methodology for directly estimating the probability of injury using a combination of police-level crash data and kinematics analyses. The new severity estimation procedure incorporates input parameters used in RSAP, including object struck, vehicle type, and impact conditions. For each type of roadside object or feature, occupant risk values are estimated as a function of impact conditions based on results from crash tests, computer simulation, and/or kinematics analyses. The total probability of injury (i.e., all injury levels) is determined from police-level crash data and then linked to occupant risk values through (mostly) engineering judgment. The total probability of injury is then further broken down by individual injury severity levels (i.e., K, A, B, and C).

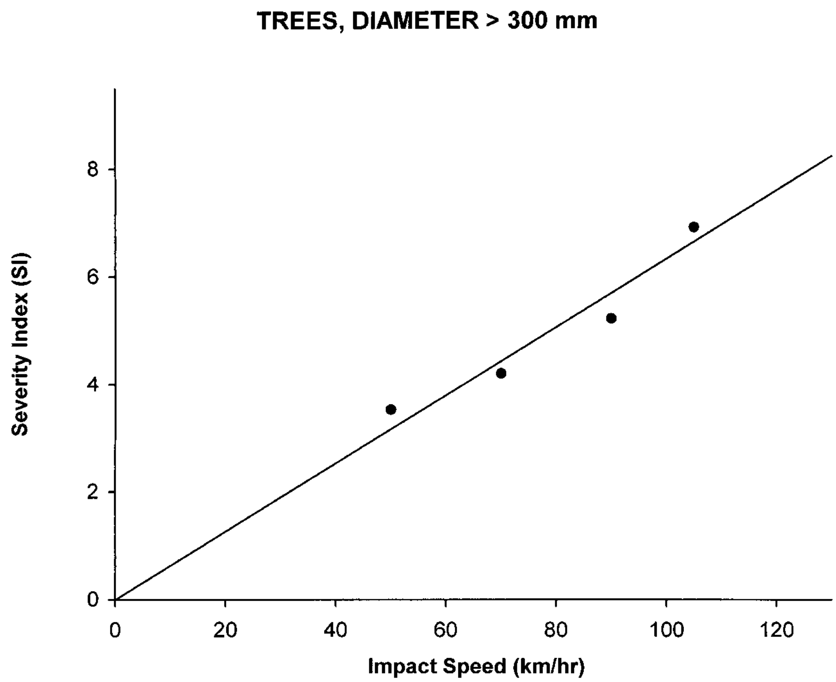


Figure 26. Example of relationship between SI and impact speed.

Although the new severity estimation procedure seems promising, the efforts required to develop these probability of injury distributions for each type of roadside object and feature were simply too extensive and time-consuming to be accomplished under this study and be incorporated into the current version of RSAP. It was eventually decided to use the severity indexes listed in the 1996 AASHTO *Roadside Design Guide*[1] for the current version of RSAP, despite many weaknesses and limitations of these indexes.

Some modifications were made to the SIs to improve their consistency and to facilitate their use with RSAP. First, the SIs were related to impact speed instead of roadway design speed. In the *Roadside Design Guide*, average severities or SI values are provided for the various roadside objects and features for design speeds of 50, 70, 90, and 115 km/h, which were assumed to be the design speeds for urban collector, rural collector and urban arterial, rural arterial, and freeways and interstate highways, respectively. For each roadside object or feature, a linear regression line was fitted through these SI values as a function of speed. These regression lines would always originate from the zero point because an impact speed of zero (0) km/h should not produce any damage to the vehicle or injury to the occupants. Figure 26 shows an example of this linear relationship between SI and impact speed.

This simple calibration method helped to address some of the inconsistencies within the SI tables. More important, this method relates SI values to specific impact speeds for each roadside object or feature instead of average SI values. There are, however, two exceptions to this procedure. First, large vertical drops would not necessarily have an SI of 0 for an impact speed of 0 because gravity would also play a large role in the probability of injury. Therefore, the regression lines for vertical drops were not fitted through the 0 point. Second, the lateral component of speed, V_{lat} (where $V_{lat} = V * \sin\theta$, where V is the impact speed and θ is the impact angle) was used instead of impact speed for the SI relationships of longitudinal barriers because the severity of a longitudinal barrier impact is a function of both the impact speed and the impact angle.

CHAPTER **8**

BENEFIT/COST ANALYSIS MODULE

The benefit/cost analysis module calculates the annualized crash and repair costs associated with the various alternatives and the incremental benefit/cost ratios among the alternatives. Descriptions of the calculations performed in this module are presented in this chapter.

8.1 DETERMINATION OF CRASH COSTS

After the crash severity prediction module estimates the severity of a crash, the crash or societal costs associated with the crash are then calculated by multiplying the probability of each level of injury by the cost associated with that level of injury using the following equation:

$$AC = \sum_{i} P(I_i) * C(I_i) \qquad (18)$$

where

AC = Unadjusted crash cost
$P(I_i)$ = Probability of injury level i
$C(I_i)$ = Accident cost associated with injury level i

The severity index (SI) is associated with six injury levels: fatality (K), severe injury (A), moderate injury (B), slight injury (C), property-damage-only level 2 (PDO2), and property-damage-only level 1 (PDO1). The proportions of each of these six injury levels for the severity indexes were shown in Table 18.

8.1.1 Accident Cost Figures

RSAP provides the option of selecting from four different sets of crash cost figures for use with the analysis:

1. Accident cost figures from the AASHTO *Roadside Design Guide*;
2. FHWA comprehensive accident cost figures;
3. User-defined accident cost figures categorized as fatal, severe injury, moderate injury, minor injury, and PDO; or
4. User-defined accident cost figures categorized as fatal, injury, and PDO.

The AASHTO *Roadside Design Guide* and the FHWA comprehensive accident cost figures are built into the program, as shown in Table 19.

The other two options are included for agencies that use accident cost figures different from those of the AASHTO *Roadside Design Guide* or FHWA.

8.1.2 Calculation of Crash Costs

As discussed in Chapter 4, the probability distributions for various encroachment characteristics are scaled to ensure proper sampling of conditions with very low probabilities to improve the accuracy of the analysis results and the speed at which RSAP arrives at a solution. Thus, the calculated crash cost is an "unadjusted" crash cost that must be weighted to arrive at the true crash cost. Four weighting factors are used in the sampling procedure, these factors are as follows:

- W_1 = Weighting factor associated with encroachment speed and angle,
- W_2 = Weighting factor associated with vehicle orientation,
- W_3 = Weighting factor associated with vehicle type, and
- W_4 = Weighting factor associated with departure lane/encroachment direction.

The weighted crash cost for the crash, AC_i, is calculated by dividing the unadjusted crash cost with the four scale factors using the following equation:

$$AC_i = (AC)/(W_1 * W_2 * W_3 * W_4) \qquad (19)$$

where

AC_i = Weighted crash cost
AC = Unadjusted crash cost

Finally, RSAP calculates the crash cost for the encroachment, AC_e. This is determined by multiplying the weighted crash cost for the impact, AC_i, by the probability that the vehicle would encroach far enough to impact the roadside feature, $P(LO)$ using the following equation:

TABLE 19 Crash costs by severity

Crash Severity	Roadside Design Guide	FHWA Comprehensive Cost
Fatal	$1.000,000	$2,600,000
Severe Injury	200,000	180,000
Moderate Injury	12,500	36,000
Slight Injury	3,750	19,000
PDO Level 2	3,125	2,000
PDO Level 1	625	2,000

$$AC_e = AC_i * P(LO) \quad (20)$$

where

AC_e = Encroachment crash cost
AC_i = Weighted crash cost
$P(LO)$ = Probability of vehicle encroaching a given lateral offset

For each convergence check, the average crash cost for the number of modeled encroachments is as follows:

$$AC_{rw} = \sum_{i=1}^{N} AC_e / N \quad (21)$$

where

AC_{rw} = Average encroachment crash cost for the number of modeled encroachments per convergence check
AC_e = Encroachment crash cost
N = Number of modeled encroachments per convergence check

8.1.3 Determination of Repair Costs

The cost of repairing roadside safety hardware is estimated by correlating repair costs to impact energy terms. 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 unit repair cost for a standard guardrail is then estimated (e.g., $50.00 per meter of repaired barrier). The total repair cost is then the product of the length of damaged rail and the unit cost for repair. Procedures for estimating the extent of hardware damage are developed for each longitudinal barrier design, as well as most common crash cushions, barrier terminals, and other roadside safety devices. Given that repair costs are generated based on estimated impact conditions, the costs would need to be weighted in the same manner as the crash costs.

The unit repair costs entered into RSAP are average repair costs and could result in inaccuracies for some roadside features, such as crash cushions and barrier end terminals. However, given that repair costs are usually a small part of the direct costs of a highway safety improvement, the inaccuracy introduced is typically insignificant in terms of the overall cost-effectiveness analysis.

As mentioned above, repair costs for some roadside features may differ significantly from the average for any given impact. Rigid barriers, such as concrete safety shape barriers, require little, if any, repair unless they are penetrated; then repair costs can be very expensive. In this case, RSAP sets the repair costs to zero if the barrier is not penetrated and the repair costs entered reflect the average cost of penetrating the barrier. Breakaway objects often need complete replacement after an impact and their repair costs reflect this. Repair costs for crash cushions and barrier end terminals differ by level of damage and location and are not well represented by region-wide or statewide averages.

8.2 INCREMENTAL BENEFIT/COST RATIO CALCULATIONS

RSAP then calculates the incremental benefit/cost ratios for all alternatives in a pairwise manner. The expression for calculating the incremental benefit/cost ratios is as follows:

$$B/C \text{ Ratio}_{2-1} = (AC_1 - AC_2)/(DC_2 - DC_1) \quad (22)$$

where

B/C Ratio $_{2-1}$ = Incremental benefit/cost ratio of Alternative 2 compared with Alternative 1
AC_1 = Annualized crash costs of Alternative 1
AC_2 = Annualized societal (crash) costs of Alternative 2

DC_1 = Annualized direct cost of Alternative 1
DC_2 = Annualized direct cost of Alternative 2

The numerator of this equation is the difference in crash or societal costs between the two alternatives. Note that Alternative 2 is being evaluated as a potential safety improvement with respect to Alternative 1 and the societal or crash costs of Alternative 1 would be expected to be higher than those of Alternative 2. Thus, the numerator is expressed as ($AC_1 - AC_2$). The denominator of the equation represents the differences in direct costs to the transportation agency associated with implementing the safety improvement of Alternative 2 in relation to Alternative 1. Direct costs include such items as installation, maintenance, and crash repair costs. Again, given that Alternative 2 is being evaluated as a potential safety improvement with respect to Alternative 1, the direct costs of Alternative 2 would be expected to be higher than those of Alternative 1. Thus, the denominator is expressed as ($DC_2 - DC_1$).

Crash and repair costs are directly proportional to the number of predicted crashes and are, therefore, calculated on an annual basis by RSAP. Maintenance costs, which are entered by users, are also on an annual basis. However, installation costs are entered as a lump sum and have to be annualized by multiplying the cost with a capital recovery factor. The default capital recovery factor used by RSAP is based on a 4% discount rate. This discount rate represents the real cost of borrowing money, measured by difference between interest rates and the annual inflation rate. The 4% value is widely accepted as the appropriate value for use in economic analysis of governmental activities. However, a different discount rate may be used as deemed appropriate by the transportation agency.

Traditionally, many transportation agencies consider that a safety improvement to be cost-beneficial when the *B*/*C* ratio reaches 1.0, which means that the expected benefits of a safety improvement are equal to the expected agency costs. This would be equivalent to investing money for a long period of time and expecting to recover only the amount of the original investment at the end of the project. Few investors would invest funds under similar circumstances. Given the variations inherent in the crash prediction routines, most highway agencies are now using higher *B*/*C* ratios, ranging from 1.5 to 4.0, to assess the funding of safety improvement projects.

8.3 PRESENTATION OF RESULTS

As discussed previously, the B/C equation is formulated based on the assumption that Alternative 2 is a safety improvement over Alternative 1 and, therefore, Alternative 2 has higher societal or crash costs and lower direct costs than Alternative 1. However, if these assumptions are incorrect, the calculated incremental *B*/*C* ratios can give misleading results. For example, if the crash costs of Alternative 2 are higher than Alternative 1, the numerator for the *B*/*C* ratio equation will be negative. If, at the same time, the direct costs of Alternative 1 are higher than those of Alternative 2, the denominator will also be negative and the resulting *B*/*C* ratio will be positive. It is clear that Alternative 1 is the better option in this example while the *B*/*C* ratio would indicate otherwise.

To eliminate these potentially misleading situations, RSAP reorders the safety treatment alternatives by ascending direct costs so that the denominator of the *B*/*C* ratio is always positive. For example, if there are three alternatives and Alternative 1 has the lowest direct costs, followed by Alternatives 3 and 2, RSAP will rearrange the order of the three alternatives to 1, 3, and 2 to maintain a positive denominator in all the incremental benefit/cost ratio calculations.

The incremental benefit/cost ratios compare each alternative with all other alternatives in a pairwise manner. An example of incremental *B*/*C* ratios taken from an actual RSAP analysis with five alternatives is shown in Table 20. In this example, Alternative 1 has the lowest direct costs, followed by Alternatives 4, 2, 3, and 5, which has the highest direct costs.

To analysis the results properly, the incremental benefit/cost ratios should be evaluated on a pairwise basis, starting from either the alternative with the highest or the lowest direct costs. Assume for this example that the transportation agency

TABLE 20 Example of incremental B/C ratios

Alternative	Alternative				
	1	4	2	3	5
1	1.00	4.39	2.60	0.89	1.71
4	-	1.00	-2.68	-1.00	0.39
2	-	-	1.00	-0.63	1.00
3	-	-	-	1.00	14.25
5	-	-	-	-	1.00

has adopted a threshold value for funding safety projects at a *B*/*C* ratio of 1.5. Further assume that the analysis will start with the alternative with the highest direct costs, which is Alternative 5 in this example. Alternative 5 is first compared with the alternative with the next highest direct costs, which is Alternative 3. The incremental *B*/*C* ratio of Alternative 5 compared with Alternative 3 is 14.25, so Alternative 5 is better than Alternative 3, and Alternative 3 is eliminated from further consideration. Next, Alternative 5 is compared with Alternative 2. The *B*/*C* ratio of Alternative 5 to Alternative 2 is 1.0, which is below the threshold value of 1.5. Thus, Alternative 2 is the better choice of the two alternatives, and Alternative 5 is eliminated. Alternative 2 is then compared with Alternative 4 with the next lower direct costs. The incremental *B*/*C* ratio of Alternative 2 compared with Alternative 4 is −2.68, meaning that Alternative 2 is not cost-beneficial compared with Alternative 4. Therefore, Alternative 2 is eliminated. Finally, the incremental *B*/*C* ratio of Alternative 4 to Alternative 1 (usually the "do nothing" or baseline option) is 4.39, so Alternative 4 is the best option for this example. Note that the same results would also be obtained by starting with the alternative with the lowest direct costs (Alternative 1) instead of the highest direct costs (Alternative 5).

In the example above, only Alternative 4 has incremental *B*/*C* ratios above 1.5 when compared with all the other alternatives. With this process, the alternative with the highest direct costs and all incremental *B*/*C* ratios greater than the threshold value set by the transportation agency will be selected. If none of the alternatives has an incremental *B*/*C* ratio of 1.5 or greater over the baseline conditions (usually Alternative 1), then the "do nothing" or the lowest direct cost alternative should be implemented.

CHAPTER 9

MODEL VALIDATION

Any theoretical model requires some form of validation to ensure that the model is functioning properly and is reasonably accurate. The cost-effectiveness procedure incorporated into RSAP was no exception. However, unlike a physical or a mathematical model, there is no "correct" answer per se for validating the cost-effectiveness procedure. Instead, the procedure would have to be validated indirectly. Two different approaches were used to validate RSAP: sensitivity analysis and subjective evaluation.

9.1 SENSITIVITY ANALYSIS

One approach to validate the cost-effectiveness procedure incorporated into RSAP was through a sensitivity analysis. With this approach, each input and/or built-in parameter incorporated into the procedure is varied from an initial set of conditions (i.e., using typical or average values) over a preselected range (e.g., +/–50%), and the changes in the resulting output are noted. The sensitivity of the analysis procedure to the values of a parameter is indicated by the relative percent change in the resulting output when compared with the percent change in the value of that parameter. For example, if varying the value of a parameter by 50% produces a change of 100% in the results, the sensitivity of that parameter would be (100/50) or 2.0.

The sensitivity analysis serves two purposes. First, results of the sensitivity analysis can help to identify coding or theoretical errors in the procedure by identifying unusual sensitivities that cannot be satisfactorily explained on basis of the encroachment probability theory. In this instance, the sensitivity study helps the programmer to identify the general area of the procedure that might have a problem, but it does not explicitly determine the nature of the problem. Conversely, when no unusual relationship is identified by the sensitivity study, one can begin to build confidence in the validity of the procedure.

The results of the sensitivity analysis also provide information regarding which parameters are most important to the cost-effectiveness analysis procedure. Note that the measure of sensitivity is relative in nature and not an absolute scale. For instance, one parameter may have a sensitivity of 2.0, but this could be high sensitivity if most of the other parameters have sensitivity of less than 2.0. On the other hand, if most of the other parameters have sensitivity of greater than 2.0, the sensitivity for this parameter would be low. Also, one parameter may be correlated with other parameters so that varying the value on that parameter may affect other parameters as well and the true sensitivity for that parameter may be masked.

Furthermore, unlike a deterministic model, such as BCAP, the Monte Carlo simulation technique does not provide the same solution or answer every time. It is, therefore, necessary to run the same set of input data several times to obtain an average value for the output results for the sensitivity analysis. Thus, although the sensitivity analysis for a deterministic model, such as BCAP,[27] was precise, the results of any sensitivity analysis done on RSAP will necessarily be somewhat "fuzzy."

For the sensitivity analysis on BCAP,[27] the sensitivity was based on the change in the benefit/cost ratio. However, given that RSAP does not arrive at the same solution every time and the solutions for two alternatives are from different distributions that are independent of each other, a moderately wide variation in the benefit/cost ratio is possible. As a result, the sensitivity analyses for RSAP are based on crash costs instead because the crash cost distributions are more stable. In addition, this rules out checking the sensitivity of RSAP to changes in the various direct cost items: installation cost, maintenance, salvage, and repairs. Fortunately, the sensitivity of maintenance, salvage, and repair costs are relatively low in most cases, though certain safety hardware types, such as crash cushions, may have very high repair costs relative to the other factors. This means that the difference in the installation costs will be the most important direct cost element, with the analysis having moderate to high sensitivity to it, depending on the crash cost levels.

The case study used with the sensitivity analysis is shown in Figure 27. The roadway functional class was assumed to be a rural arterial with a traffic volume of 2,000 vehicles per day. For the first alternative, the fixed object is unshielded. This alternative was used for almost all cost comparisons, except where the parameter being varied did not affect the crash costs. The second alternative consisted of placing a strong-post W-beam guardrail in front of the fixed object. Table 21 lists the 31 parameters studied, their initial values, and their range of variations. The values of the parameters are typically varied one at a time for the sensitivity analysis. The only exception is lateral offset for which it was necessary to

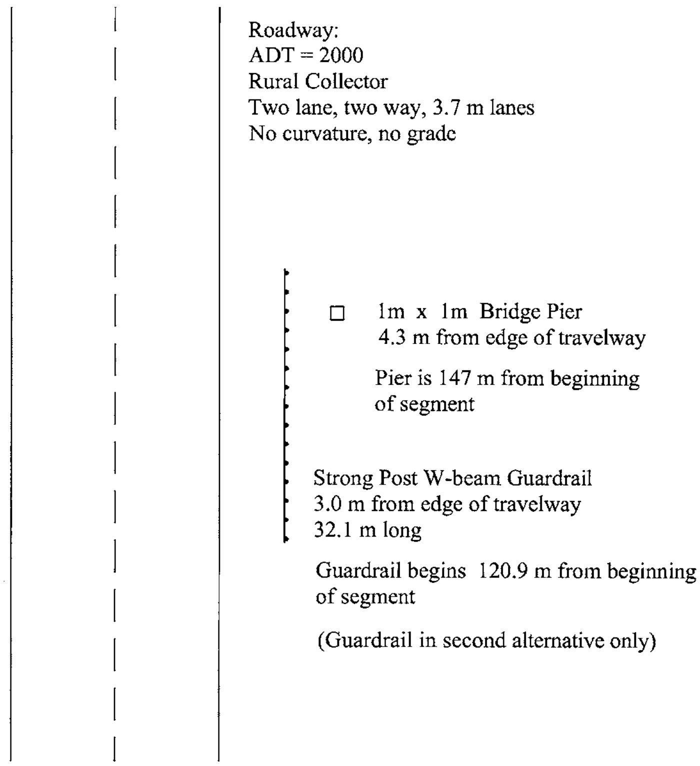


Figure 27. Base condition for sensitivity analysis.

vary both the lateral offsets of the fixed object and the guardrail at the same time to maintain the relative positions of the guardrail in relation to the fixed object.

The first step in the sensitivity analysis was to determine the mean and standard deviation of the crash cost distributions under the initial set of conditions or values. The initial conditions were run 200 times and the results checked for normalcy using a χ^2 test on each alternative. The resulting baseline crash cost distributions for each alternative were found to be normal with

Alternative 1: Mean = 272.18, Standard Deviation = 1.42

Alternative 2: Mean = 252.92, Standard Deviation = 1.57

Note that the mean crash costs for the baseline distributions are very small because of the low traffic volume selected for the initial conditions. Also, the standard deviations are very tight with less than 1% of the mean. Thus, even a small change in the crash cost would result in a large difference in terms of the standard deviation.

Then one run was made for each variation of each parameter in accordance with the scheme shown in Table 21. Changes in the resulting crash costs between the sensitivity runs and the baselines means for the initial conditions ranged from 0.8 to 650 times of the standard deviations. Based on these results, parameters with low sensitivity were screened. The upper bound for low sensitivity was set at 26 times the standard deviations from the means of the baseline distributions. Of these low-sensitivity items, the percent changes in the crash costs were less than one-half of the percent change in the parameter (i.e., the sensitivity is less than 0.5). This eliminated approximately 60% of the parameters from further consideration.

To further isolate the more important or sensitive parameters in RSAP, another run was made for the parameters that resulted in changes of more than 26 times the standard deviations in the crash costs, and the results of the two runs were averaged. The next determination was of the moderate sensitivity category and the upper bound for this category was set to be 100 times the standard deviations from the mean of the baseline distributions. This corresponds to a sensitivity of approximately 1.0 (i.e., the percent change in crash costs is approximately the same as the percent change in the value of the parameter).

The remaining parameters, considered to have high sensitivity, were further investigated by running each parameter change three more times, then averaging over the five data points. For these high-sensitivity parameters, some of the parameters had different sensitivity, or levels of change in crash costs, depending on the direction the value of the parameter was varied. For instance, increasing the cost of a fatality by

TABLE 21 Parameter variations for sensitivity analysis

Parameter	Baseline	Variations			
Divided/Undivided	Undivided	Divided			
Number of Lanes	2	4			
Traffic Volume (ADT)	2000	1000		3000	
Degree of Curvature	0	3 L	6 L	3 R	6 R
Grade	0	-6%	-3%	+3%	+6%
Functional Class	Rural Arterial	Freeway	Urban Arterial	Urban Collector	Rural Collector
Lane Width	3.7 m	3 m		4.3 m	
Pier Length	1.0 m	0.5 m		1.5 m	
Pier Width	1.0 m	0.5 m		1.5 m	
Pier Offset	4.3 m	6.45 m			
Guardrail Length	32.1 m	22.8 m		41.8 m	
Guardrail Width	0.5 m	0.25 m		0.75 m	
Lateral Offset	4.3 m pier, 3.0 m barrier	3.0 m pier, 1.5 m barrier		6.45 m pier, 4.3 m barrier	
Vehicle Length	Default	-20%		+20%	
Vehicle Width	Default	-5%		+5%	
Vehicle Weight	Default	-10%		+10%	
Vehicle C. G. Height	Default	-10%		+10%	
Vehicle A Distance	Default	-20%		+20%	
Vehicle Frame Height	Default	-20%		+20%	
Percent Trucks	10%	5%		15%	
Project Life	20 years	10 years		30 years	
Traffic Growth Rate	3.0%	1.5%		4.5%	
Accident Costs	Default	-50%		+50%	
Fatal Accident Costs	Default	-50%		+50%	
Injury Accident Costs	Default	-50%		+50%	
Pier Severity Index (SI)	Default	-50%		+50%	
Guardrail Redirection SI	Default	-50%		+50%	
Barrier Penetration SI	Default	-50%		+50%	
Barrier Rollover SI	Default	-50%		+50%	
Barrier Containment Level	Default	-30%		+30%	
Barrier Deflection	Default	-30%		+30%	

50% resulted in a 102% increase in crash costs, while decreasing the cost of a fatality by 50% resulted in only a 42% reduction in crash costs. In these cases, the parameter was rated according to its highest change in crash costs.

The findings of the sensitivity analysis are summarized in Table 22. Note that this sensitivity analysis was not a comprehensive effort. Only one case study was used in the sensitivity analysis. It can certainly be argued that more case studies are needed for the sensitivity analysis. However, the main function of this sensitivity analysis was to aid in debugging the program code. Also, it is anticipated that a much more extensive sensitivity analysis will be conducted under the ongoing NCHRP Project 22-12 to develop selection guidelines for roadside safety hardware.

9.2 SUBJECTIVE EVALUATION

An independent reviewer reviewed RSAP using real-world applications from several state DOTs. In addition,

TABLE 22 Sensitivity analysis results

Sensitivity	Parameter
High (Variations of greater than 100 standard deviations from nominal condition)	Degree of Curvature Functional Class Accident Costs Fatal Accident Costs Pier Severity Index (SI) Guardrail Redirection SI
Moderate (Variations of between 26 and 100 standard deviations from nominal condition)	Number of Lanes Traffic Volume (ADT) Grade Pier Offset Guardrail Length Injury Accident Costs Barrier Penetration SI
Low (Variations of less than 26 standard deviations from nominal condition)	Divided/Undivided Lane Width Pier Length Pier Width Guardrail Width Vehicle Length Vehicle Width Vehicle Weight Vehicle C. G. Height Vehicle A Distance Vehicle Frame Height Percent Trucks Project Life Traffic Growth Rate Barrier Rollover Severity Barrier Containment Level Barrier Deflection

RSAP underwent beta testing by project panel members and a small group of beta testers. Comments from the independent reviewer and the beta testers served as further validation of the program. Admittedly, the evaluation was subjective in nature and not a true validation of the procedure. However, as mentioned previously, there is no “correct” answer that can be used to validate the model. Evaluation by the independent reviewer and other beta testers using real-world applications, while subjective in nature, provides some indication of whether or not the program is providing results that are reasonable based on the expertise and experience of the reviewer and beta testers.

CHAPTER **10**

SUMMARY AND CONCLUSIONS

This report describes in detail the parameters and algorithms incorporated into RSAP. RSAP is believed to present many advances and new features over its predecessors. Highlights of the improvements incorporated into RSAP are summarized as follows:

- A user-friendly interface with Windows-like screens and menus to facilitate easier use of the program by inexperienced users. Features of the User Interface Program include the following:
  - Simplified data input process with multiple-choice entries where appropriate,
  - Numerous built-in default values to reduce data entry requirements,
  - On-screen instructions and help,
  - Built-in edit and consistency checks,
  - Options to choose built-in default values or input user-defined values for selected parameters,
  - Choice of reports to preview or print to hard copies or electronic files.
- Capability to handle evaluations of projects with a maximum of 20 different safety improvement alternatives; 20 consecutive roadway segments for roadways of up to 16 lanes; and 1,000 roadside features. The program can analyze simultaneously hazards on either or both sides of the roadway, as well as in the median, for a divided roadway.
- Use of a stochastic solution method with the Monte Carlo simulation technique to allow for modular design of the Main Analysis Program. The program can be updated without major rewrite of the program to incorporate new features such as curvilinear vehicle path, driver inputs, and side impacts.
- Use of re-analyzed Cooper encroachment data for encroachment rates and lateral extent of encroachment distributions with adjustments for under-reporting of encroachments with small lateral extent because of the presence of paved shoulders and controlled versus uncontrolled encroachments.
- Use of real-world crash data for impact speed and angle distributions instead of theoretical distributions.
- Incorporation of vehicle orientation into the analysis code to better define vehicle swath. More important, this incorporation would allow for future consideration of non-tracking and side impacts, which accounted for a significant percentage of ran-off-road crashes and have been shown to result in higher severities than tracking crashes.
- Although the current version of RSAP still uses the SI approach for severity estimation, a new approach to directly estimate the probabilities of injury was developed. The program can be readily adapted to the new severity estimation procedure when data become available in the future.

Although RSAP is an improvement over existing procedures, it also has drawbacks and limitations, most of which result from the lack of available data or require a level of effort beyond that available for this study. Some of the limitations and suggested future modifications and refinements are as follows:

- Computational time. The use of the Monte Carlo simulation technique requires a longer computational time.
- Multiple solutions. Because of the nature of the stochastic process, the answers may vary from run to run within a range as determined by the convergence criteria. For the purpose of most evaluations, slight variations in the answers should not pose any significant problem. The variations are the result of random seed numbers, which determine how the encroachments are sampled as well as the associated encroachment characteristics. Thus, using the same seed number could eliminate variations between runs of the same application.
- Encroachment data. The Cooper encroachment data are almost 30 years old and many changes have taken place in the interim. The encroachment probability model can greatly benefit from better encroachment data.
- Vehicle path. RSAP currently does not take into account vehicle and driver behavior during encroachments due to lack of available data. The incorporation of curvilinear vehicle paths, changing vehicle orientation, and slope effects would significantly improve crash prediction and impact severity estimation.

- Extent of lateral encroachment distributions. The effects of roadside slopes and geometrics are not adequately addressed in the current distributions for the extent of lateral encroachment.
- Crash Severity. The SIs currently incorporated in RSAP need to be reviewed critically and revised as appropriate. Even with improved SIs, this approach has many limitations. A better approach to estimate severity, such as the probability of injury approach, would be highly desirable.

– Impact Models. The impact models incorporated into RSAP are relatively simple in nature and could benefit from more sophisticated and validated models.
– Median Barrier Warrants. RSAP is intended for single-vehicle ran-off-road type crashes and cannot handle cross-median, vehicle-to-vehicle type crashes. Thus, RSAP is not suitable for use in assessing the need for a median barrier directly. The addition of a model that can evaluate cross-median type crashes would be desirable.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation